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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002, 2007 and again in 2012. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has over 95 graduates (Fellows and Post-docs) of which approximately 40 theorists and 20 experimenters have already attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker’s presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are over one hundred proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. QCDOC was decommissioned in May 2012. The next generation computer in this sequence, QCDCQ (600 Teraflops), is currently operational and is expected to produce many more interesting discoveries in the future.

N. P. Samios, Director
January 2013

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.
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Additional RIKEN BNL Research Center Proceeding Volumes
RF & Stochastic Cooling for pA

M. Blaskiewicz

Thanks to Mike Brennan, Steve Tepikian and Wolfram Fischer

Outline

• Frequency considerations
• RF configurations
• Ion stochastic cooling
• Technical considerations
Frequency considerations

Differing revolution frequencies results in modulating the beam-beam force.
This greatly reduces the allowed bunch intensity.
The revolution frequencies of both beams therefore, need to be the same.
The circumference for p will be 2 cm more than for Au, yielding $\delta \gamma / \gamma \leq 5 \times 10^{-3}$, ignorable for this discussion.
Typically, $Z/A \leq \frac{1}{2}$ for ions so their maximum value of $\gamma$ in AGS is about 10. For protons we typically go to $\gamma = 25.4$.
The electron cloud problems in RHIC occur when the bunch is short, so protons going through transition would be bad.
Therefore, we will inject the ions at $\gamma \approx 10$, accelerate to $\gamma = 25.4$ and then inject protons.
p+Au injection and acceleration

Lorentz factor $\gamma$

107.4

25.4

10.5

injection Au

injection p

acceleration Au

acceleration p, Au

collision p+Au

time
RF configurations

As of now only the 9.4 MHz (h=120) cavity is shared by both rings. Its voltage is limited to 25 kV.

For heavy ions the 28 MHz system (h=360) is the prime mover. Typically, $V=200$ kV for 28 MHz.

We can run the 9.4 MHz on the ramp without bothering the ions.

During proton rebucketing the 9.4 MHz is not varied so this will not bother the ions.

Ions use no shared cavities at all.

Therefore, the RF parameters for protons and ions will be the same as they are when we run a single species.
Ion stochastic cooling

Ion RF and lattice parameters are the same as during single species running.

Stochastic cooling systems for the two rings are independent.

So, stochastic cooling will be identical to that for single species running.

Other considerations, like beam-beam $\propto 1/\varepsilon$, may limit cooling.
Technical Considerations

When injecting protons we will need to make sure the ion beam does not see or induce time dependent beam-beam. Best solution would be to run the protons at fixed frequency and allow for small (10 degree?) phase modulation in the ion ring to damp any longitudinal oscillations.

Probably, we can turn off beam control in the ion ring and run at fixed frequency, like during store. KISS principle suggests this should be the first step.

The proton injection porch will vary from cycle to cycle, so the length of the $\gamma=25.4$ porch for ions will vary. Snap-back might be an issue (JMB). Gold IBS could be significant during proton injection (WF).
(di)-Hadron Production in d +Au Collisions at RHIC

PHENIX

Mickey Chiu
BROOKHAVEN
NATIONAL LABORATORY
\[ x_d = \frac{p_T}{\sqrt{s}} (e^{y_3} + e^{y_4}) \]
\[ x_{Au} = \frac{p_T}{\sqrt{s}} (e^{-y_3} + e^{-y_4}) \]

- Fwd-Fwd, \( x \sim (0.001, 0.005) \)
- Mid-Fwd, \( x \sim (0.008, 0.040) \)
- Mid-Bwd, \( x \sim (0.050, 0.100) \)

Span rapidity, constrain x regions
Large suppression in RdA
  • That increases with centrality
  • And increases with larger rapidity
Consistent with previous measurements
  • However, x covered by single inclusive measurement is over wide range
    • Includes shadowing, anti-shadowing, (EMC effect)
Di-hadron Measurement

“Di-Hadron Nuclear Modification factor”

\[ J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{pair}^{dA}}{\sigma_{pp}^{pair}} / \frac{\sigma_{dA}}{\sigma_{pp}} \]

Notes:
1. Low \( p_T \) (but back-to-back peak is selected so possibly clean hard signal, and low \( p_T \) is desired if one wants to cross over into Q_s regime)
2. Pedestal Determination (Assumed up to twice the width as a systematic).
3. Di-Hadrons instead of di-jets (but ok if fragmentation unmodified)
\( \pi^0 \) (trigger, central) / \( \pi^0 \) (associate, forward)

\[ p^+ p \]

\[ d + Au \ 60-8 \]

\[ d + Au \ 0-20\% \]

\[ p^+_T, \pi^0 \]

\[ p^+_T, \pi^0 \]

NO SIGN OF RIDGE

\[ \Delta \phi \ (\text{rad}) \]
Large Suppression in Central d+Au

\[ R_{G}^{Au}(x, Q^2) = \frac{x G_{Au}(x, Q^2)}{A x G_{p}(x, Q^2)} \]

\[ J_{dA} = \frac{\sigma_{dAu}^{pairs}}{\sigma_{dAu}} / \langle N_{coll} \rangle \sigma_{pp}^{pairs} / \sigma_{pp} \]

High x, mostly quarks
Weak effects expected

Low x, mostly gluons
\[ J_{dA} \leftrightarrow R_{G}^{Au} \]

\[ f_{d}^{a}(x_{d}) \otimes f_{Au}^{b}(x_{Au}) \otimes ^{\wedge} \sigma \otimes D(z_{c}, z_{d}) \]

\[ f_{p}^{a}(x_{p}) \otimes f_{p}^{b}(x_{p}) \otimes ^{\wedge} \sigma \otimes D(z_{c}, z_{d}) \]

Low x, mostly gluons

\[ b=0-100\% \]

\[ Q^2 = 4 \text{ GeV}^2 \]

\[ d+Au 60-88 \quad p_T^{fwd} \quad \text{d+Au 0-20} \quad p_T^{fwd} \]

- 0.5-0.75 GeV/c  
- 0.5-0.75 GeV/c  
- 0.75-1.0 GeV/c  
- 0.75-1.0 GeV/c  
- 1.0-1.5 GeV/c  
- 1.0-1.5 GeV/c  

\[ \sigma_{pp}^{pairs} / \sigma_{pp} \]

\[ \langle N_{coll} \rangle \]

Eskola, Paukkunen, Salgado, JHP04 (2009)065

EPS09 NLO gluons
Counting Nucleons in Path

From Glauber Monte Carlo we can determine the number of nucleons in the path of each nucleon in the deuteron, and correlate that with some measurement in our detector that is correlated to centrality (South BBC, Au-going side).
Centrality, or b Dependence

- If we are measuring gluons with $J_{dA}$, then we can perhaps extract impact parameter and $x$ dep of $Q_s$, and possibly extract the value of $Q_s$ at RHIC?

- Since $\langle N_{coll}\rangle \sim L \sim A^{1/3} \sim T^A$ we might be able to understand how gluons recombine with $N$ nucleons?
  - eg, from above data are we seeing an approx linear dependence on length???

**Equation:**

$$Q_s^2(b) \approx \alpha_s \frac{1}{\pi R^2} x G_{Au}^2(x, b, Q^2) \sim N_{coll} \left( \frac{x}{x_0} \right)$$

**Graph:**

- $J_{dA} \sim R_{Au}^2$
- $\langle N_{coll} \rangle 
  - xfrag \sim 1.6 \times 10^{-2}$
  - xfrag \sim 5 \times 10^{-3}$
  - xfrag \sim 5 \times 10^{-4}$
Impact Parameter Dependent pdf’s

- New impact parameter dependent PDF’s where

\[ r^A_i(x, Q^2, s) = 1 + \sum_{j=1}^{n} c_j^i(x, Q^2) [T_A(s)]^j \]

- N=1 in EPS09 (pdf’s are linearly suppressed with T), N=4 in EPS09s.
Using PYTHIA and EPS09s one can extract the JdA expected from nuclear shadowing, and thus extract pdf’s at low $x$.
EPS09s seems to be a little above the data
Additional suppression of pdf’s in most central collisions
• Perhaps somewhat surprisingly, EPS09s + standard pQCD works well at mid-rapidity, even though other nuclear effects like Cronin are ignored.
• In any case, agreement is pretty good and Cronin is not too large (~10% effects)
• Same pQCD calculation for forward inclusive hadrons fails
• “Problem” with inclusion of Brahms charged pion data in EPS08…
• New physics has to come into play at forward rapidity? Why?
At LHC mid-rapidity (5 TeV), $x_T$ is 25 times lower than at RHIC for the same hadron $p_T$.

LHC hadron $p_T = 2$ GeV, $y = 0$, should reach same $x$ as at forward $y$ at RHIC, $x \sim 10^{-3}$

Why no suppression?
Must look at parton rapidity…
Particles at mid-rapidity come from partons of moderate $x$, while forward particles come from high $x$
Forward rapidity partons have stronger “coherence” effects due to bigger boost.
“pQCD” Approach

Kang, Vitev, Xing [arxiv:1112.6021]

• Perturbative approach incorporates ISI and FSI for momentum imbalance (multiple scattering broadening), plus energy loss and **coherent** power corrections
Another way the “coherence” effects can manifest itself at forward rapidities is in the Color Glass Condensate.

- Merger of gluons competing with splitting of gluons, enhanced at large rapidity.
- Much work being done and formalism being worked out.
Summary

• There seem to be some interesting effects in the Au nucleus at $x$ of about $10^{-3}$
  • Rapidity dependence is very important
    • Larger “coherence” effects at higher rapidities, since one selects higher rapidity partons
    • “Coherence” = gluon saturation? Or something else?
  • Also possibly other explanations ($E_{\text{loss}}$, eg, rapidity shift)
• Single Inclusive vs Di-Hadron
  • Di-Hadron seems superior
    • Better control of parton kinematics in di-hadron
    • Better control of backgrounds
    • Ability to probe down to lower $p_T$, and therefore $Q_s$
• Important: Impact Parameter Dependence starting to be probed
  • Nuclear thickness dependence crucial
• LHC p+A already provides interesting results that one can then test against ideas from what we know already at RHIC
Backup Slides
Decay photon impact positions for low and high energy $\pi^0$s. The decay photons from high energy $\pi^0$s merge into a single cluster.

→ Sometimes use (EM) clusters, but always corrected to $\pi^0$ energy

→ Clusters $\geq 80\%$ $\pi^0$ (PYTHIA)
JdA Centrality Dependence

Fit using EPS09 parametric function: 

\[ R_g^A(x) = a_0 + (a_1 + a_2 x)[e^{-x} - e^{-x_a}] \]

Evaluate J_{dA} in 3 bins at \( \langle x_{\text{frag}} \rangle = 5 \times 10^{-4}, 5 \times 10^{-3}, 1.6 \times 10^{-2} \)
\( R_{dA} \) Past, di-Hadron Future

Color Glass Condensate

Di-Hadron Correlations allow one to select out the di-jet from the underlying event

Constrains x range (probe one region at a time)

Probe predicted angular decorrelation of di-jets (width broadening)
di-Hadron Signal

“Conditional Yield”

\[ CY = \frac{N_{\text{pair}}}{N_{\text{trig}} \epsilon_{\text{assoc}}} = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{assoc}}}{d\Delta\phi} \]

Number of di-jet particle pairs per trigger particle after corrections for efficiencies, combinatoric background, and subtracting off pedestal

“Di-Hadron Nuclear Modification factor”

\[ J_{dA} = I_{dA}^{\text{trig}} \times R_{dA}^{\text{trig}} \]

“Sgl-Hadron Nuclear Modification factor”

\[ J_{dA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{dA}^{\text{pair}}}{\sigma_{dA}} / \frac{\sigma_{pp}^{\text{pair}}}{\sigma_{pp}} \]

\[ R_{dA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{dA}^{\text{sgl}}}{\sigma_{dA}} / \frac{\sigma_{pp}^{\text{sgl}}}{\sigma_{pp}} \]

Caveats:

1. Low \( p_T \) (but back-to-back peak is selected)
2. Pedestal Determination (Assumed up to twice the width as a systematic).
3. Di-Hadrons instead of di-jets (but ok if fragmentation unmodified)
p+Pb at LHC: pilot run results and prospects for 2013 run from an ATLAS perspective

Brian A. Cole,
Columbia University
January 7, 2013
\( \text{p+Pb pilot run} \)

- LHC was operated with:
  - 4 TeV proton beam colliding with
  - 1.57 TeV/nucleon lead (Pb) beam
  \[ \Rightarrow \text{Center of mass energy } 5.02 \text{ TeV/nucleon} \]
  \[ \Rightarrow \text{Center of mass rapidity shift } \Delta y = -0.47 \]
- 5 hour run w/ integrated lumi of ~ 1 \( \mu b^{-1} \)
  \[ \Rightarrow 2 \text{ million events (in ATLAS).} \]

From R. Alemany et al, CERN-ATS-Note-2012-094 MD

http://cds.cern.ch/record/1496101
ATLAS Acceptance

Bulk observables
charged particles
\(\gamma, \pi^0,\) isolated \(\gamma\)
\(Y, Y'\)
Jets
p+Pb transverse energy measurement

$\sum E_T$ over different parts of calorimeter
\( \Sigma E_T: \) Compare \( p+Pb \) and \( Pb+Pb \)

- In \( p+Pb \), see “global” correlations in centrality observables similar to \( Pb+Pb \).
  - Over scale that differs by factor of \(~ 20\).
  - But, much larger fluctuations in \( p+Pb \).
  \[ \Rightarrow \text{No surprise.} \]
Pb-going $\Sigma E_T$ (4.9 < $\eta$ < 3.1)

- For physics, we have concluded that Pb-going $\Sigma E_T$ is useful centrality observable.

- Compare to reconstructed charged particle multiplicity:
  - $p_T > 0.4$ GeV
  - $|\eta| < 2.5$
\( p+Pb \) inclusive \( dN_{ch}/d\eta \)

- **1st look at charge particle multiplicity:**
  - arXiv:1210.3615: ALICE inclusive, NSD
    \( \Rightarrow dN_{ch}/d\eta/N_{part} \) 16% lower than in (est.) \( p-p \)
  - note: in ATLAS, similar trigger has non-negligible SD contribution
• 1\textsuperscript{st} look at charged particle spectra
  – arXiv:1210.4520, ALICE inclusive, NSD
  \[ R_{pPb} \text{ consistent with 1, no suppression at mid-rapidity, also little or no "Cronin"} \]
Clearly, next step is to study multiplicity and spectra as a function of centrality.

- And to measure spectra over larger range of pseudo-rapidities.

Why no results so far?

- speaking for ATLAS only, ∃ a significant diffractive contribution to minimum-bias p+Pb cross-section that has complicated the “usual” analysis previously applied @ RHIC & LHC

⇒ e.g. application of usual naive Glauber model analysis fails for diffractive excitation of the proton and at large impact parameter

⇒ Likely that same problem exists @ RHIC
CMS 2-particle correlations

- 1\textsuperscript{st} observation of ridge in p+Pb collisions.
  - in 2-charged particle correlations

- Growth in yield with multiplicity
  - Much larger than in p-p

- rapid variation with $p_T$
  - due to common $p_T$ bins for both particles
ALICE: 2-particle correlations

- ALICE measurement of 2-charged particle correlations in 60-100% and 0-20% bins
  - based on V0 detector multiplicity
  ⇒ see additional near-side correlation in more central events over $|\Delta \eta| < 1.8$
ALICE: 2-particle correlations

- ALICE: consider difference between central and peripheral vs $\Delta \eta$ and $\Delta \phi$
  - with fits to $a_0 + a_2 \cos (2\Delta \phi)$
  - and $a_0 + a_2 \cos (2\Delta \phi) + a_3 \cos (3\Delta \phi)$
• Convert the $a_2$ and $a_3$ to analog of single particle flow coefficients $v_2$ and $v_3$
  - assumes factorization (below)
  \[ \Rightarrow \text{significant } v_2 \text{ and } v_3 \text{ values} \]
ATLAS 2-particle correlations

“peripheral”

“central”

• charged particles, $|\eta| < 2.5$, $0.5 < p_T < 4$ GeV
  – see “usual” correlations in peripheral
  – see ridge + away-side broadening in central
To better see $\Delta \eta$ dependence, project ZYAM-subtracted correlation function.

- For near ($\Delta \phi < \pi/3$) and away ($\Delta \phi > 2\pi/3$) sides.

$\Rightarrow$ In central collisions see ridge and broadening of away-side component relative to peripheral collisions.
• Per trigger yields $Y(\Delta \phi)$ integrated over $\eta$
  – peripheral and central
  ⇒ “Ridge” clearly present in central
  ⇒ Similar increase in the away side yield between peripheral, and central collisions
• Evaluate integrated per-trigger yields, $Y_{\text{int}}$, near ($\Delta \phi < \pi/3$) and away ($\Delta \phi > 2\pi/3$)
  - Yield grows with increasing $\Sigma E_T$ similarly on near and away sides
  - Difference between away and near yields $\approx$ constant

$\Rightarrow$ constant “recoil”: dijet + p cons. + low-$p_T$ resonances
Why $E_T$ not $N_{ch}$ for “centrality”?

- There is an auto-correlation between $N_{ch}$ and the number of particles & pairs
  ⇒ Distorts the per-trigger yields from the “recoil” contribution at low $N_{ch}$
  ⇒ Why the different behavior of away-near difference at large $N_{ch} / \Sigma E_T$?
• Study variation of integrated per-trigger yields with trigger $p_T$
  – For associated $0.5 < p_T < 4$ GeV

• Evaluate difference between peripheral and central
  – difference $\approx$ same on near and away sides, and similar $p_T$ dependence

Beware different vertical scales on top panels
ATLAS 2-particle correlations (6)

- Motivated by above observations subtract peripheral $Y(\Delta \varphi)$ from central $Y(\Delta \varphi)$
  - With associated $0.5 < p_T < 4$ GeV
  - In different trigger $p_T$ bins

⇒ Observe an approximately symmetric modulation in all bins
ATLAS 2-particle correlations (7)

- Central correlation function before and after subtraction of peripheral per-trigger yields, and converting back to $C(\Delta\phi, \Delta\eta)$

⇒ Long-range modulation

$\int L \approx 1 \mu b^{-1}$  
$0.5 < p_T^{a,b} < 4 \text{ GeV}$  
$\Sigma E_T^{Pb} > 80 \text{ GeV}$
ATLAS 2-particle correlations (7)

• Subtracted correlation functions for 2 other centrality bins.
Fourier decomposition

- Extract leading and second Fourier coefficients from per-trigger yields
  - \( a_0 = \langle Y(\Delta\phi) \rangle \)
  - \( a_2 = \langle Y(\Delta\phi) \cos (2\Delta\phi) \rangle \)
- Convert to relative modulation of subtracted correlation function: \( C_{sub} = A (1 + 2c_2 \cos 2\Delta\phi) \)
  \( \Rightarrow \) maximum \( \sim 1\% \) modulation of the 2-particle correlation in central events
• If we assume that the amplitude of the 2-particle modulation factorizes:
  - \( c_2(p_T^a, p_T^b) = s_2(p_T^a) s_2(p_T^b) \)
  - can calculate the single-particle modulation
    \[ \Rightarrow \text{See } s_2 \text{ values up to 0.14} \]

• Then, \textit{if} the modulation were due to flow
  \[ \Rightarrow v_2 \text{ values as large as 0.14} \]
Test factorization

ATLAS $p+Pb$ $\sqrt{s_{NN}}=5.02$ TeV, $\int L \approx 1 \mu$b$^{-1}$

$\Sigma E_T^{Pb} > 80$ GeV, $2<|\Delta \eta|<5$

- If factorization holds, should obtain same $s_2$ values for different associated $p_T$
  - $\Rightarrow$ true for $p_T < 1$ GeV
  - $\Rightarrow$ start to see deviations at higher $p_T$
2013 p-A Run projected performance

Baseline performance extrapolated from Pilot Fill

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<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
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<tr>
<td>(N_{Pb})</td>
<td>(1.2 \times 10^8)</td>
<td>(1.2 \times 10^8)</td>
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<td>0.8</td>
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<tr>
<td>(L/\text{cm}^{-2}\text{s}^{-1})</td>
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<td>(1.01 \times 10^{29})</td>
<td>(1.01 \times 10^{29})</td>
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<td>(\mu)</td>
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<td>0.065</td>
<td>0.065</td>
<td>0.026</td>
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</table>

Already close to ALICE maximum luminosity with emittances of pilot fill, good Pb intensity, fairly conservative proton intensity – leaves room to try to increase it up to a factor \(\sim 3\) (level ALICE if necessary).

Can easily be worse if we have blow-up or losses at injection or ramp (from moving encounters, IBS, ...).

Unequal beam sizes were OK in pilot fill with higher \(\beta^*\). Emittance increase will probably reduce luminosity for all experiments and pile-up for ALICE.

This is our preferred first goal for the run. But, on the basis of present knowledge, it is by no means a “safe set of parameters” (except for optics).
2013 p-A Run projected performance

- ATLAS is preparing for maximum instantaneous luminosities up to $3 \times 10^{29}$.
- ATLAS goals for 2013 run
  - 25-30 nb$^{-1}$ of 5.02 TeV p+Pb
  - 5 pb$^{-1}$ of 2.76 TeV p+p
- We will not have 5.02 TeV (or comparable) p+p data until 2015 or after.
ATLAS physics goals for 2013 run

• Extend/complete basic measurements already underway with pilot run data
  – e.g. charged particle multiplicity, spectra

• Elucidate physics responsible for the “symmetric ridges”
  ⇒ And look for other consequences of that physics in central p+Pb collisions

• Measure (indirectly) nuclear PDFs
  – Using jets, dijets, γ-jet, W, Z

• Study semi-hard processes @ low x

• Understand the role of diffraction
  – Both as “background” and as intrinsically interesting and important physics
We must improve our poor knowledge re: nuclear PDFs and their $b$ dependence.

$\Rightarrow$ Impact parameter dependence especially important for improving precision on theoretical calculations for Pb+Pb.
• Integrated luminosity from 2013 p+Pb run should be equivalent to 2011 Pb+Pb run
  – Examples shown of resulting γ and Z spectra
**Kinematic reach of LHC p+Pb**

- **p+Pb measurements @ LHC will extend the range of nuclear PDF measurements.**
  - for b dependence need centrality dependent measurements with good control over geometry
  
  \[ \Rightarrow \text{But, precision will be limited without 5.x TeV p-p} \]
Semi-hard physics @ low x

Kutak and Sapeta arXiv:1205.5035

- Wide range of possible measurements.
  - One example shown here: forward-central dijets
    ⇒ prediction for visible effects of saturation
  - Kinematic range accessible in ATLAS (e.g.)
    ⇒ measurement doable w/ 2013 data
Summary, thoughts

• 6 hour p+Pb pilot run in Sep. 2012 was successful both for machine & physics
  – first results on multiplicity, spectra, ridge++
  – for me, the ridge++ was a surprise
    ⇒ new territory in p+A physics
    ⇒ obviously relevant for RHIC p+A plans
    ⇒ s vs multiplicity dependence very important
  – beware neglect of diffraction

• In 1 week, start of high-luminosity run
  – Expected integrated luminosity: 30 nb⁻¹
    ⇒ Sufficient to address most of the goals of the LHC p+A program
  – But no 5.x TeV p-p until 2015 or after
Backup
Perform $c_2$ and $s_2$ measurement in different $\Sigma E_T$ bins

- Similar variation of both $c_2$ and $s_2$ with $p_T$ in all $\Sigma E_T$ bins
- Weak dependence of $s_2$ on centrality
Per-trigger yield systematics

**Graph 1:**
- **ATLAS p+Pb, √s_{NN}=5.02 TeV, ∫L=1µb⁻¹**
- **σ_{Pb} > 80 GeV**
- 0.5<p_{T}<4 GeV, 2<|Δη|<5, |Δφ|<π/3

- **σ_{Pb} > 80 GeV**
- 55 < E_{T}^Pb < 80 GeV
- 25 < E_{T}^Pb < 55 GeV
- E_{T}^Pb < 20 GeV

**Graph 2:**
- **ATLAS p+Pb, √s_{NN}=5.02 TeV, ∫L=1µb⁻¹**
- 0.5<p_{T}<4 GeV, 2<|Δη|<5, |Δφ|>2π/3

- **σ_{Pb} > 80 GeV**
- 55 < E_{T}^Pb < 80 GeV
- 25 < E_{T}^Pb < 55 GeV
- E_{T}^Pb < 20 GeV

**Graph 3:**
- **ATLAS p+Pb, √s_{NN}=5.02 TeV, ∫L=1µb⁻¹**
- 0.5<p_{T}<4 GeV, 2<|Δη|<5, |Δφ|<π/3

- **σ_{Pb} > 80 GeV**
- 55 < E_{T}^Pb < 80 GeV
- 25 < E_{T}^Pb < 55 GeV
- E_{T}^Pb < 20 GeV

**Graph 4:**
- **ATLAS p+Pb, √s_{NN}=5.02 TeV, ∫L=1µb⁻¹**
- 0.5<p_{T}<4 GeV, 2<|Δη|<5, |Δφ|>2π/3

- **σ_{Pb} > 80 GeV**
- 55 < E_{T}^Pb < 80 GeV
- 25 < E_{T}^Pb < 55 GeV
Check for (rel.) charge dependence

- Perform two-particle correlation analysis for like and unlike-sign pairs
  - global correlation should not be sign dependent
  - but jet, resonance, other correlations may be
  
  ⇒ Observe identical behavior for like, unlike sign correlations in the data.

---

ATLAS \( p + Pb \) \[ s_{NN} = 5.02 \text{ TeV}, \int \mathcal{L} = 1 \mu b^{-1} \]
0.5<\( p_T^{a,b} < 4 \) GeV, 2<\( \Delta \eta \)<5, Near: \( |\Delta \phi| < \pi/3 \)

ATLAS \( p + Pb \) \[ s_{NN} = 5.02 \text{ TeV}, \int \mathcal{L} = 1 \mu b^{-1} \]
0.5<\( p_T^{a,b} < 4 \) GeV, 2<\( \Delta \eta \)<5, Away: \( |\Delta \phi| > 2\pi/3 \)

\( Y \) vs. \( \langle \sum E_{T}^{Pb} \rangle \) [GeV]

- like-sign pairs
- unlike-sign pairs
- all pairs
Sign dependence of $c_2$ and $s_2$

- Further check on like vs unlike sign correlations.

  ⇒ Identical results for $c_2$ and $s_2$ for like and unlike sign pairs
Quarkonia Production in d-Au collisions Measured by the PHENIX Detector

CESAR LUIZ DA SILVA
LOS ALAMOS NATIONAL LAB
for the PHENIX Collaboration

p+A @ RHIC Workshop - BNL - Jan-2013
Bremsstrahlung \( \sim \alpha_s \ln(1/x) \)

Recombination \( \sim \alpha_s \rho \)

Cold Nuclear Matter effects upon a quarkonia state

Effects on a formed \( \bar{Q}Q \)

Pre \( Q\bar{Q} \) formation

low \( x \)

high \( x \)

\( -dE/dx \)

Cesar L. da Silva - pA@RHIC Workshop - Jan-2013
How quarkonia at PHENIX can probe initial and final state cold nuclear matter effects
PHENIX can measure quarkonia from zero momentum
dilepton decays: $J/\psi, \psi', \Upsilon$
radiative decays: $\chi_{C} \rightarrow e^+e^-\gamma$
Can probe hadronic breakup with different quarkonia sizes and binding energies

$1.2 < |y| < 2.2 \quad \Delta \phi = 2\pi$
PHENIX covers Bjorken x ranges where EPS09 expects
- suppression (shadowing region)
- suppression-enhancement transition
- enhancement (anti-shadowing)
Initial State Effects
• EPS09 assuming 2→1 process + J/ψ breakup in hadronic matter

• qualitatively describes Minimum Bias $R_{dAu}$ data

• gluon saturation describes small-x region
Bottomonia

\( \Upsilon \) family:
- 37% 1S
- 27% \( \chi_b \) (decay to 1S)
- 25% 2S (prompt + decayed to 1S)
- 11% 3S (prompt + decayed to 1S)

- probe larger gluon \( Q^2 \) and \( x \) than charmonia
- more sensitive to EMC region at \( y < 0 \)
Propagation of nPDF+breakup to $J/\psi$ in Au+Au

nPDF cannot describe the stronger suppression observed at forward rapidity in Au+Au collisions

Forward rapidity in Au+Au is a mix of small-$x$, large-$x$ effects which cancel out

Eskola, Paukkunen, Salgado, JHEP04 (2009) 065

LO

PRC84, 054912 (2011)
EPS09 cannot reproduce either $R_{dA}$ in peripheral events or $R_{cp}$

nPDF needs centrality dependence
1.2 ≤ y < 2.4

-2.2 ≤ y < -1.2

|y| < 0.35

\[ r_T \]

\[ \Lambda(r_T) \equiv \frac{1}{\rho_0} \int dz \rho(z, r_T) \]

\[ \rho(z, r_T) \equiv \text{Woods-Saxon} \]

\[ R_{dAu, i}(a) = \int f_i(r_T) M(r_T; a) \, dr_T \]

\[ M(r_T; a) = e^{-a \Lambda(r_T)} \quad \text{exponential} \]

\[ M(r_T; a) = 1 - a \Lambda(r_T) \quad \text{linear} \]

\[ M(r_T; a) = 1 - a \Lambda(r_T)^2 \quad \text{quadratic} \]

J/\psi \text{ in } d+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV}

- J/\psi \ 1.2 < y < 2.4
- J/\psi \ -0.5 < y < 0.5
- J/\psi \ -2.2 < y < -1.2

PRL107, 142301 (2011)

qualitatively agreement with CGC model as well

• EPS09s uses data from several $A$ nuclei to obtain impact parameter dependence of the nPDF
• should nPDF for a fixed impact parameter be different in different nuclei?
  • coherent effects?
  • weaker parton modification on the nucleus surface independently of the nucleus size?
• diffractive processes
• impact parameter is still poorly determined in d+Au collisions

• p+Au collisions can provide a more controlled impact parameter determination

• however, Poisson fluctuations in particle multiplicities will still limit the precision in determining the impact parameter
Final State Effects
• increase with $p_T$ in all rapidities

• result can explain the smaller $J/\psi$ suppression at high $p_T$ in $A+A$
**p_{T} dependence**

**Significant Cronin effect**

- \( R_{dA} \) increasing with \( p_{T} \) is larger than what is expected from shadowing/anti-shadowing

- Increase of \( \langle p_{T}^2 \rangle \) with number of collisions supports the multiple scattering effect
Breakup in hadronic matter

breakup should depend on the binding energy

<table>
<thead>
<tr>
<th>State</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$\gamma$</th>
<th>$\chi_b$</th>
<th>$\gamma'$</th>
<th>$\chi_b'$</th>
<th>$\gamma''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (GeV)</td>
<td>3.10</td>
<td>3.53</td>
<td>3.68</td>
<td>9.46</td>
<td>9.99</td>
<td>10.02</td>
<td>10.26</td>
<td>10.36</td>
</tr>
<tr>
<td>$\Delta E$ (GeV)</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>$\Delta M$ (GeV)</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>$r_0$ (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
<td>0.28</td>
<td>0.44</td>
<td>0.56</td>
<td>0.68</td>
<td>0.78</td>
</tr>
</tbody>
</table>

however, color octet charmonium is in a pre-resonant stage for $\gamma>-2$ in p+A collisions at RHIC

$$\tau_F = \frac{2}{M_{DD} - M_\psi} \frac{E_g}{M_\psi} \quad (J/\psi \text{ rest frame})$$

$$\tau_F (\text{RHIC}) \approx 41 e^\gamma \text{ fm}$$

[Nucl. Phys. A770,40(2006)]
$J/\psi, \psi'$ $R_{dA}$ in $d+Au$ at mid-rapidity

- same initial-state effects for $J/\psi$ and $\psi'$
- stronger suppression of $\psi'$ indicates $c\bar{c}$ cross the nucleus as distinct objects
**CAVEATS:**
- $\chi_c$ is produced as a color singlet and may be fully formed when crossing the nucleus
- measured $J/\psi$ includes ~10% of $\psi'$ and ~30% of $\chi_c$ feed-down
Next Measurements
Variation of the nucleus and the energy collisions can allow:

- control path length, saturation scale, nucleus size dependence of nPDF
- scanning of larger $x$ at the same rapidity range if luminosity allows
Muons from Heavy Flavor

- starting to have data from heavy flavor in low and high-x
- quarkonia $R_{dA}$ relative to HF can isolate final state effects
PRESENT and FUTURE

Installed vertex detectors: VTX and FVTX

• measure open heavy flavor
• better measurement of dimuon opening angle at large rapidity:
  • $J/\psi,\psi'$ separation
  • study of formation/neutralization times when looking rapidity dependence
• open the possibility to study radiative decay of $\chi_c$ using $\gamma$ conversions in VTX
FUTURE solenoidal PHENIX (sPHENIX)

- high luminosities
- full azimuthal, $-1.1 < \eta < 4$ coverage
- calorimetry at large $\eta$ will allow rapidity dependence of $\chi_c$ measurement
- 2T solenoid provides $\Upsilon(1S)$, $\Upsilon(2S+3S)$ separation at mid- and forward rapidity
Conclusions

PHENIX has explored several aspects of CNM effects with different states of quarkonia.

More is coming in future p+A collisions where nucleus size and energy variations along with new detectors will introduce more knobs in the study of initial and final state effects on particle production in heavy ion collisions.
BACKUP SLIDES
$\chi_c \rightarrow J/\psi + \gamma$ PHENIX d+Au @ 200GeV

$N_{e^+e^-} / 50$ MeV

- Signal after combinatorial background subtraction
- Simulated $\chi_c$
- Correlated background
- Simulated $\chi_c$ plus correlated background

$\chi_c \rightarrow J/\psi + \gamma$ PHENIX d+Au @ 200GeV

$N_{e^+e^-} / 50$ MeV

- Signal after all background subtraction
- Simulated $\chi_c$

$\chi_c - J/\psi$ mass [GeV]
STAR Decadal Plan

James Dunlop for the STAR Collaboration
Properties of the sQGP in detail
Mechanism of Energy Loss: weak or strong coupling?
Is there a critical point, and if so, where?
Novel symmetry properties
Exotic particles

Partonic structure
Spin structure of the nucleon
How to go beyond leading twist and colinear factorization?

What are the properties of cold nuclear matter?
• Hot QCD matter: high luminosity RHIC II (fb\(^{-1}\) equivalent)
  – Heavy Flavor Tracker: precision charm and beauty
  – Muon Telescope Detector: e+\(\mu\) and \(\mu+\mu\) at mid-rapidity
  – Trigger and DAQ upgrades to make full use of luminosity
  – Tools: jets combined with precision particle identification

• Phase structure of QCD matter: Energy Scan Phase II
  – Fixed Target to access lowest energy at high luminosity
  – Low energy electron cooling to boost luminosity for \(\sqrt{s_{\text{NN}}}<20\) GeV
  – Inner TPC Upgrade to extend \(\eta\) coverage, improve PID

• Cold QCD matter: high precision p+A, followed by e+A
  – Major upgrade of capabilities in forward direction
  – Existing mid-rapidity detectors well suited for portions of e+A program
STAR: A Correlation Machine

Recent upgrades: DAQ1000 TOF

Plus upgrades to Trigger and DAQ

Muon Telescope Detector (runs 13/14)

Heavy Flavor Tracker (run 14)

Electromagnetic Calorimetry: BEMC+EEMC+FMS \((-1 \leq \eta \leq 4)\)

Particle ID: TOF

Forward GEM Tracker (runs 12/13)

Full azimuthal particle identification over a broad range in pseudorapidity
Multiple-fold correlations among the identified particles!

Nearly perfect coverage at mid-rapidity
What are the properties of cold nuclear matter?

Is there evidence for saturation of the gluon density?

- RHIC may provide **unique access to the onset of saturation**
  - Complementarity: LHC likely probes deeply saturated regime

- Future questions for **p+A**
  - What is the gluon density in the \((x, Q^2)\) range relevant at RHIC?
  - What role does saturation of gluon densities play at RHIC?
  - What is \(Q_s\) at RHIC, and how does it scale with \(A\) and \(x\)?
  - What is the impact parameter dependence of the gluon density?

Upgrades to both STAR and PHENIX to extend observables (focus on EM)

**Timescale: medium-term (~2017+)**
Most promising at RHIC energies:
\( y \sim 3-4 \)
\( Q^2 \sim \text{few GeV}^2 \)

N.B. Lines only schematic, kinematic control limited in p+A
From 2->2 parton scattering, many sources of smearing

LHC mid-\( y \)
\( \sim \) RHIC \( y=4 \)
STAR Experiment as of 2014

MRPC ToF Barrel

MTD

EMC Barrel

EMC End Cap

BBC

FPD

FMS

Roman Pots Phase 2

TPC

HFT

FGT

DAQ1000

Trigger and DAQ Upgrades

COMPLETE

R&D/Ongoing

1/9/2013
Better tracking and dE/dx PID capability

$\eta$ 1.0-1.7 region -- broad physics impact on transverse spin physics program
hyperon and exotic particle searches
high $p_T$ identified particles
BES Phase II+

Not as forward as most useful for p+A, but useful for ridge studies

1/9/2013
Forward instrumentation optimized for \( p+A \) and \textit{transverse spin} physics

- Charged-particle tracking
- \( e/h \) and \( \gamma/\pi^0 \) discrimination
- Possibly Baryon/meson separation

\[ 2017^+ \]

Forward Calorimeter System (FCS)

- ~6 GEM disks
  Tracking: \( 2.5 < \eta < 4 \)

FHC (E864)

Pb-Sc HCal

W-Powder EMCal

RICH/Threshold
Baryon/meson separation
Some planned p+A measurements

- Nuclear modifications of the gluon PDF
  - Correlated charm production
- Gluon saturation
  - Forward-forward correlations (extension of existing $\pi^0$-$\pi^0$)
    - $h-h$
    - $\pi^0$-$\pi^0$ \{ Easier to measure \}
    - $\gamma-h$
    - $\gamma$-$\pi^0$ \{ Easier to interpret \}
  - Drell-Yan
    - Able to reconstruct $x_1, x_2, Q^2$ event-by-event
    - Can be compared directly to nuclear DIS
    - True $2 \rightarrow 1$ provides model-independent access to $x_2 < 0.001$
- What more might we learn by scattering polarized protons off nuclei?
  - Forward-forward correlations and Drell-Yan are also very powerful tools to unravel the dynamics of forward transverse spin asymmetries – Collins vs Sivers effects, TMDs or Twist-3, …
Plans for Forward Upgrade

Calorimeter:

1) EM: Pb-glass (FMS) augmented by Tungsten SPACAL
   1) Smaller Moliere radius for better 2-γ separation
   2) Keep high E resolution

2) Hadron calorimetry for e/h discrim., jet reconstruction

Very Forward GEM Tracker (VFGT)

1) Likely GEM-based
2) Details of the design depend on experience with FGT

Particle Identification

RICH problematic with accessible $p_T$ resolution
Threshold Cerenkov detector under consideration
Detector will not be included in initial upgrade

Schedule: proposal this year, construction start 2015+
Ready for data 2017 at the earliest
Also measured:

1. Uniformity of response across the towers.

2. Energy resolution with and without mirror.

3. Perform scans along the towers with electrons and muons.

4. Estimated effects of attenuation and towers non-uniformities on resolution.

Viable EMC detector technology developed through EIC R&D
A prototype hadron calorimeter module will be built in 2013
STAR magnetic field allows for moderate $p_T$ resolution in forward direction
  e.g. FTPC, position resolution $\sim 100$ µm
Some added momentum resolution can be garnered from radial magnetic field at poletip
Likely insufficient for RICH particle identification, but sufficient for charge sign discrimination in Drell-Yan: detailed simulations underway
Major upgrade of capabilities in forward direction envisioned

Full calorimetry (EM+Hadronic)
Modern tracking technology to make most of existing magnetic field

Timescale: 2017+
(BTW: Roman Pots Phase 2 have program in p+A, so engineering needs to take this into account)

Strong set of measurements to be made, complementary to and supporting those at a future EIC

From this workshop: what specific measurements should we optimize for in design?
Backup
Transverse Single Spin Asymmetry measures the left-right asymmetry in production cross-section in relation to the transverse polarization of the incoming proton. It is commonly measured by the Analyzing Power, $A_N$.

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$
Large $A_N$ in the forward region of “high energy” hadron-hadron interaction has a long experimental history, dating back to 1976.

Until the RHIC era, these measurements were performed in fixed target environments with polarized targets.

However, it was generally believed that these fixed target results could not be interpreted within the framework of pQCD.
The main issue is if very forward physics is in the domain of pQCD.

Small angle scattering means small transverse momentum transfer. Even at RHIC energy, the average $p_T$ in the forward region is relatively small (2~3 GeV).

Furthermore, the proximity to the beam line introduces the beam remnant (underlying events) interaction into the possible sources of observed high energy particles.

Not surprisingly, the unpolarized forward cross-sections at fixed target energy was found to be significantly larger than the pQCD prediction.
In contrast, at RHIC (200GeV), there are good agreements between forward hadron cross-sections and pQCD predictions, with appropriate fragmentation functions.

Consequently, many believe that the RHIC forward transverse spin results CAN be understood by pQCD.
The large forward $A_N$ persists at RHIC, as shown for all three species of pions. The sign of the asymmetries are the same as before, and the magnitudes are comparable.
The initial prediction (1978) based on **collinear, leading twist** pQCD was \( A_N \sim 0 \).

\[ \text{"The result is zero for } m_q=0 \text{ and is numerically small if we calculate } m_q/\sqrt{s} \text{ corrections for light quarks."} \]

\[ A_N \sim \alpha_s \frac{m_q}{P_T} \rightarrow 0 \]

Since the 90’s, new approaches have been developed to explain the observed large \( A_N \).

**Beyond collinear factorization:** **Transverse Momentum Dependent (TMD)** factorization

**Beyond leading twist:** **Twist-3 (next-to-leading-twist) approach**
**$A_N$ in pQCD**

**Sivers effect (TMD)**
The orbital angular motion of the struck parton, correlated with the spin of the proton, generates the asymmetry.

**Collins effect (TMD)**
Asymmetry arises from the fragmentation process that depends on the quark transversity.

**Twist-3 (Collinear)**
Twist-3, three-parton correlation/fragmentation functions can generate the asymmetry within collinear factorization.
The TMD functions (Collins and Sivers) have been measured in various SIDIS experiments (HERMES, COMPASS, JLab) and $e^+e^-$ (Belle), and shown to be non-zero.

Furthermore, the twist-3 correlations have been shown to be related to the TMD functions. (D. Boer, P. J. Mulders, and F. Pijlman, Nucl. Phys. B667, 201 (2003))
Unlike in SIDIS, it is much more difficult to untangle the dynamic origin of the observed large $A_N$ in $p+p$ collisions.

While the Sivers and Collins effects (or their twist-3 relatives) likely contribute, the SIDIS results do not provide quantitative understanding of $A_N$ in $p+p$.

The current estimate of Collins contribution based on SIDIS and $e^+e^-$ is "not sufficient for the medium-large $x_F$ range of STAR data, $x_F \sim 0.3"$.

It is unclear if the Sivers function from SIDIS can be applied directly to $p+p$ due to universality breaking, (Phys. Rev. D 81, 094006 (2010)) and when "translated" to the twist-3 formalism, it produces the opposite sign.
The Origin of $A_N$ in P+P

Furthermore, it is not certain that the TMD and Twist-3 models are sufficient to explain the full scope of forward $A_N$ in hadronic interactions.

If the collider $A_N$ is pQCD, then what was the $A_N$ observed in fixed target experiments? Are they simply two different processes that look similar?

At STAR, we see sizable asymmetries in the BBC and the ZDC, both of which are more forward than our calorimeters, likely from diffractive physics.

Can similar (or other soft) process contributes to our $\pi^0$ and $\eta$ $A_N$?

Answering these questions requires going beyond inclusive pion $A_N$ vs. $x_F$.

$\rightarrow$ Characterize $A_N$ as functions of $x_F$, $p_T$, $\eta$, and for diverse final states.
Full jet capability (tracking, dE/dx, EM cal) for $-1.0 < \eta < 1.4$

EM coverage for $-1.0 < \eta < 2.0$, and $2.5 < \eta < 4.0$

Full $2\pi$ acceptance for all of the above.
STAR forward calorimetry consists of Pb glass detectors located ~8m from IR.

Forward Pion Detector (FPD)
East: Run3 ~ Current
West: Run3 ~ Run5

Forward Meson Spectrometer (FMS)
West: Run8 ~ Current

Both detectors are capable of $\pi^0 - \gamma$ separation up to 80 GeV or higher, with ~8% energy resolution.
π⁰ A_N VS. P_T AT 200 GeV

Naively, one might expect the A_N to fall roughly as 1/p_T. For TMD effects, the power law behavior of the large-x cross-section combined with the k_T kick suggests 1/p_T. One might also expect the twist-3 effect to fall as 1/p_T, due to the p_T suppression of higher twist diagrams.

However, based on the FPD data, STAR previously reported the p_T dependence of forward π⁰ A_N at √s=200 GeV that shows no sign of falling out to ~3.5 GeV/c.
In addition to the $\pi^0$'s, we measured the forward cross-section (slide 4) and $A_N$ for the $\eta$ mesons using the FPD. At high $x_F$ ($x_F > 0.55$), the $A_N$ for the $\eta$ is very large, and may not be consistent (~3%) with that of the $\pi^0$.

Kanazawa & Koike calculates larger $A_N$ for $\eta$ than $\pi^0$, from the strangeness contribution. However, the $x_F$ dependence deviates from the data.
Forward $\pi^0 A_N$ at 500 GeV

STAR FMS (2.7 < $\eta$ < 4.0) has measured $\pi^0 A_N$ at $\sqrt{s} = 500$ GeV, based on 2011 data. (22.4 pb$^{-1}$, 48% polarization)

The $\pi^0$ reconstruction is effective up to ~100 GeV ($x_F < 0.4$).

Two different isolation cones for the photon pairs are used. Two and only two photons ($E_\gamma > E_{\text{min}}$) are found within the cone.

Isolation cut = 30 & 70 mRad

40 GeV < $E_{\gamma\gamma}$ < 100 GeV

$Z_{\gamma\gamma} = |E_1 - E_2|/E_{\gamma\gamma} < 0.7$

0.02 GeV < $M_{\gamma\gamma}$ < 0.3 GeV

$E_\gamma > 6$ GeV for small cells

$E_\gamma > 4$ GeV for large cells
The cross-ratio method shows that the onset of positive $A_N$ is lower in $x_F$ compared to 200 GeV.

The magnitude of $A_N$ is comparable to the 200 GeV result up to $x_F=0.4$.

Slope = $A_N$, Intercept = Luminosity Ratio (for all data $\sim -0.31 \pm 0.05\%$)

As an alternative to cross-ratio, the raw asymmetry can be plotted as a function of $\cos(\Phi)$. (with polarization axis at $\Phi=\pi/2$)

The slope fits are consistent with the cross-ratio result, and the luminosity ratio is small.
π⁰ A_N VS. p_T AT 500 GeV

Continuing the previous FPD measurement, the FMS reported the p_T dependence of forward π⁰ A_N at √s=500 GeV, up to ~10 GeV.

Even at 7~10 GeV, we see no sign of 1/p_T like fall.
While this is counter-intuitive, Kanazawa & Koike obtain an almost flat p_T dependence based on twist-3 formalism combined with DSS fragmentation function, which has a large gluon component.
30 vs. 70 mRad Isolation

When we compare $A_N$ vs. $p_T$ for the two isolation cones at 30 and 70 mRad, we find that the larger isolation cone produces consistently larger asymmetries than the smaller one.

This result shows that events that contain additional EM clusters ($E > 4$ or 6 GeV) in the region between 30~70 mRad from the $\pi^0$s have significantly lower asymmetry than $\pi^0$s that are fully isolated up to 70 mRad.

→ Similar analysis is on-going with the new run 12, 200 GeV transverse data.
Forward instrumentation upgrade optimized for p+A and transverse spin physics.

The prototype for FCS (e/h and $\gamma/\pi^0$ discriminations) is planned. Forward charged-particle tracking will likely be based on GEM technology. Threshold detector currently under consideration for baryon/meson separation.
Summary

The large transverse single spin asymmetry in the forward region of hadron collisions has persisted through a wide range of collision energies.

Number of pQCD based models have been proposed to explain these large asymmetries, many of which have been validated in SIDIS and $e^+ e^-$ experiments. However, this has not yet led to a quantitative understanding of forward $A_N$ in hadron collisions.

STAR is continuing its effort to map out the kinematic dependence of $A_N$ in the forward region, and to expand the measurements beyond inclusive pions. We believe these measurements are crucial in bringing the theoretical understanding of the large forward $A_N$ in p+p to the quantitative level.

The near future upgrade plan at the STAR forward region focuses on p+A and transverse spin physics. It is aimed at measuring jets, direct photons, identified hadrons, and DY.
Path forward toward p+A collisions in RHIC

Wolfram Fischer

8 January 2013

Workshop on p+A collisions at RHIC, BNL
What do we have for p+Au collisions?

What do we still need for p+Au collisions?

Luminosity projection
What do we have for p+Au collisions?

- RHIC was designed for p+Au collisions
  Independent rings except DX magnets
  DX magnets movable (~1 shift)
- With stochastic cooling initial Au beam size is at its maximum
  Allows for DX move in IR6 and IR8 only (~1 shift)
- Solutions for lattice, injection and acceleration
  Lattice takes advantage of stochastic cooling
- Machine with fast setup (beam-based feedbacks), good reliability
- Experience with asymmetric collisions (d+Au, Cu+Au)

- Proton beam with $N_b = 2 \times 10^{11}$, $P = 55$
  with upgrades (OPPIS): $N_b = 3 \times 10^{11}$, $P = 65$
- Au beam with $N_b = 1.3 \times 10^{9}$
  with upgrades (EBIS/Booster/AGS/RHIC): $2.0 \times 10^{9}$ (emittance?)
Luminosity. The collider is designed for a Au-Au luminosity of about $2 \times 10^{26} \text{ cm}^{-2} \text{ sec}^{-1}$ at top energy, while maintaining the potential for future upgrades by an order of magnitude. Operation with the heaviest ions imposes the most demanding requirements on the collider design, and gold-on-gold is taken as the prototypical example. The luminosity is energy dependent and decreases in first approximation propor

**Run-12:** $L_{\text{avg}} = 10.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ (with $P_{\text{avg}} = 53\%$)

will be higher, with $\sim 1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ for pp collisions.

Range of ion masses. The expectations for interesting physics phenomena require a broad range of nuclei from the heaviest to the lightest, including protons. Asymmetric operation with heavy ions colliding on protons is considered to be crucial for the experimental program. The collider will allow collisions of beams of equal ion species from Au-Au all the way down to p-p. It will also allow operation of unequal species such as protons on gold ions.

Uranium is a viable species and can be considered as a future upgrade. However, at the present, an adequate source for uranium does not exist at Brookhaven and further R&D will be needed to achieve this goal.

**Intersection Regions.** The existing tunnel and the magnet lattice configuration provides for six experimental areas where the circulating beams cross. Three of the experimental areas presently
IR design with beam splitting DX dipoles first

**DX dipoles**
- $L_{\text{mag}} = 3.7 \text{ m}$, $B_{\text{max}} = 4.3 \text{ T}$
- large aperture (18 cm coil ID)
- only magnets that need training (~5 for IR6/8 only)
Now have full 3D stochastic cooling for heavy ions

M. Brennan, M. Blaskiewicz, F. Severino, PRL **100** 174803 (2008); PRSTAB, PAC, EPAC
Cu and Au have different intrabeam scattering growth rates
\[ (\sim Z^4 N_b / A^2) \ r_{\text{IBS,Au}} \approx 2x \ r_{\text{IBS,Cu}} \]
- cooling rates
\[ (\sim 1/N_b) \ r_{\text{SC,Au}} \approx 3x \ r_{\text{SC,Cu}} \]

Stores start with large \( \varepsilon \) after undergoing instability at transition

Possible with stochastic cooling
Increase bunch intensity until loss at transition
p+Au easier with stochastic cooling

- only need to accommodate initial Au emittances
- sufficient to move IR6 and IR8 DX magnets

Figure 1. The beam trajectory through the crossing dipoles D0 and DX. The Au beam is 69.4mm from the central line in the DX magnet in the worst case. Additional room for beam size must also be taken into account.

p+Au easier with stochastic cooling

Figure 2. A non-colliding insertion. The crossing angle is -0.3305 mrad. The beam trajectory is 59.8 mm from the central axes for both beams in the DX magnet. The Blue beam reaches its peak at 10.5 m from the IP, while the Yellow beam reaches its peak at 13.5 m from the IP.

Orbit feedback on every ramp allows for
- Smaller $y_{\text{rms}}$ (smaller imperfection resonance strength)
- Ramp reproducibility (have 24 h orbit variation)

Tune/coupling feedback on every ramp allows for
- Acceleration near $Q_y = 2/3$ (better P transmission compared to higher tune)
• Run-12 with low failure rates in all systems
• Highest time-in-store ratios to date
  even with increased APEX time during 255 GeV protons, and few weeks per species
What do we still need for p+Au?

- Demonstrate DX move by 1 cm
  - Can be done at end of Run-13
  - Move for p beam in Yellow, Au beam in Blue
    (different from d-Au)

- If p beam in Blue is needed (and Au beam in Yellow)
  - Modify vacuum pump stands in IR6 and IR8
  - Modify shielding IR6 and IR8

- Operate with new injection and acceleration scheme
  - Inject and accelerate Au to intermediate level above transition
  - Then inject p and accelerate both beams
Moving IR6 and IR8 DX magnets by 1cm

- Bellows allow for 1 cm movement
- Installed shielding creates tight spaces but acceptable
  "6:00 the bellows and ion pump stand were swapped to make space for the shielding, … cannot be moved because of the ion pump stand" (M. Mapes)
- Easier to do have p in Yellow, Au in Blue (different from d-Au!)

Can be done in ~ 2 shifts (i.e. during a run) when properly prepared in previous shut-down
p+Au injection and acceleration

Lorentz factor $\gamma$

107.4

25.4

10.5

injection Au

injection $p^+$

acceleration Au (cross transition)

collision $p+Au$

acceleration $p$, $Au$

time

Note: now tolerate ion beam instabilities at transition obtain higher intensity (can be cooled down again), not possible with $p+Au$ since have smaller aperture available
Asymmetric collisions (p+Au)

- p+Au energies:
  
  100.8 GeV p on 100.0 GeV/nucleon Au ($\gamma_p = \gamma_{Au} = 107.4$)

- For energy scan need to match Lorentz factor $\gamma$ of both beams

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<th>Unit</th>
<th>p 2013E</th>
<th>Au 2013E</th>
<th>p 2013E</th>
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$L_{NN}/$week, min/max $\mu$b$^{-1}$

$pb^{-1}$ $15$ $37$
Summary

- p+Au is possible
  - max energy 100 GeV/nucleon for both beams
- Stochastic cooling helps:
  - DX move only in IR6 & IR8, no Au beam growth
- DX move in ~2 shifts
  - possible upgrade for pp2pp in IR6 requires change of DX bellows
  - will reduce flexibility, cannot move DX magnets during run
- New injection/acceleration scheme
  - store Au beam above transition for ~15 min

- Luminosity estimate based on p^ beam available (anticipated), and Au beam available (anticipated)
  - \( L_{NN} = 15 \text{ pb/week min (now)} \)
  - \( L_{NN} = 37 \text{ pb/week max (few years)} \)
Hadronization and Color Transparency Studies at JLab

The Physics of pA Collisions at RHIC, BNL

Monday January 7th, 2013

Kawtar Hafidi
Part 1 - Hadronization
How do quarks transform “hadronize” into hadrons?

- Color charges cannot be separated by much more than 1 fm, since light quarks easily pop up from the vacuum.

- Taking into account Lorentz dilation, the proper time scales for hadronization in the Lab frame become few fm.

- However our detectors are placed distances $10^{15}$ times further away from the origin compared to the hadronization length.
Nuclei provide a unique opportunity as detectors at a tiny distance within the range of hadronization process and perform direct measurements. These are the multiple scattering centers separated by only 1 – 2 fm.

- What is the interaction of the struck quark before it neutralizes its color?
- What is the lifetime of an energetic free quark $\tau_p$?
- How long does it take to form the color field of a hadron $\tau_f$?
- What is the dynamic leading to color confinement?
Motivation

- Understand the Hadronization process by
  - Measuring the characteristic times
  - Measuring quark energy loss
  - Measuring hadron attenuation

- Characterization of the QCD medium
  - Testing and calibrating theoretical tools used to determine the properties of Quark–Gluon Plasma

- Reduce systematic effects when attenuation needs to be corrected for
  - Neutrino experiments since they use nuclear targets
Identify quark propagation phase by measuring $p_T$ broadening

Identify hadron formation phase by measuring hadron attenuation

Extract characteristic times and reaction mechanisms using the variation of these observables with the nuclear size
Observables

- Multiplicity ratio → Characterizes the attenuation \((1 - R)\)

\[
R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T)/N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T)/N_D^e(Q^2, x_{Bj})}
\]

- Transverse momentum broadening → Characterizes the modification of the \(P_T\) spectrum

\[
\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D
\]

- These are normalized to deuterium to reduce isospin effects → Other nuclei might be used for normalization as well
**$p_T$ Broadening and Quark Energy Loss**

Quarks **lose energy by gluon emission** as they propagate

- In vacuum
- Even more within a medium

- This energy loss is manifested by $\Delta p_T^2$
- $\Delta p_T^2$ is a signature of the production time $l_p$

- $\Delta E \sim L$ dominates in QED
- $\Delta E \sim L^2$ dominates in QCD?

$$\frac{dE}{dx} \approx \frac{\alpha_s}{\pi} N_c \left\langle p_T^2 \right\rangle_L$$

Medium-stimulated loss calculation by BDMPS

$$l_p \approx \frac{\nu(1-z)}{dE/\, dx}$$
Experimental effort

Semi-inclusive deep inelastic scattering on nuclei

- 1970’s SLAC $eA \rightarrow e’Xh$, energy transfer $\sim 35-145$ GeV
- 1990’s CERN EMC $\mu A \rightarrow \mu’Xh$, energy transfer $\sim 35-145$ GeV
- 1990’s WA21/59 (4–64 GeV) $v$ beam on Ne target
- 2000’s HERA HERMES $e^+A \rightarrow e^+’Xh$, 12 and 26 GeV beam
- 2000’s Jefferson Lab Hall C and CLAS, $eA \rightarrow e’Xh$, 5 GeV beam

Drell–Yan reaction

- 1980’s CERN SPS NA–10 spectrometer: $pA \rightarrow X_{\mu^+\mu^-}$, 140 and 280 GeV beam
- 1990’s Fermilab $pA \rightarrow X_{\mu^+\mu^-}$, 800 GeV beam

International, multi-institutional quest for 30 years, but most progress since 2000
Which process dominates? Parton energy loss or Hadron absorption?

Are fragmentation functions modified in the nuclear medium?

Several models exist with different answers to these questions:

→ Pure parton energy loss or hadron absorption models
→ Mixed models
Selected Models

- **Gluon Bremsstrahlung Model** *(B. Kopeliovich, J. Nemchik E. Predazzi, A. Hayashigaki)*
  
  Gluon radiation + hadronization model

- **Twist-4 pQCD Model** *(X.-N. Wang, E. Wang, X. Guo, J. Osborne)*
  
  Medium-induced gluon radiation only

- **Rescaling Models** *(A. Accardi, H. Pirner, V. Muccifora)*
  
  Gluon emission, partial deconfinement, nuclear absorption

- **PYTHIA–BUU Coupled Channel Model** *(T. Falter, W. Cassing, K. Gallmeister, U. Mosel)*
  
  Fundamental interaction + coupled channel nuclear final state interaction
The general picture

\[ \tau_p \approx \frac{v \gamma}{Q^2} (1 - \gamma) \]

HERMES Data compared to GIBUU model

- Increase with $v$
- Decrease with $z$
- Slight increase with $Q^2$
- Strong increase with $P_T$

He, Ne, Kr, Xe
HERMES $\Delta P_t^2$ Results

- No broadening at high $z$
  - No effect at the partonic level
- Increase with $Q^2$
  - Predicted in the framework of parton energy loss
- Dependence in $A$ not conclusive
  - Compatible with $A^{1/3}$ and $A^{2/3}$
- Different behavior for kaons?
Reproduce the ratios of HERMES
→ ν slope similar to HERMES
→ z Slope not as pronounced as in HERMES (?)

Results for $\Delta p_t^2$ compatible with HERMES
Nuclear effect saturates at high $A$ – Does not follow $A^{1/3}$ or $A^{2/3}$

→ Can be resolved within parton energy loss picture with small production time

Multiplicity ratio and $P_t$ broadening follow the same trend

→ Originates from the same process?
Examples of Experimental Data and Theoretical Predictions
Summary of Part 1

- Hadronization is a fundamental process of QCD
  → Link between perturbative and non-perturbative domains
  → A way to probe nuclear media, either cold or hot
  → Helpful for other experiments

- Past results gave the global picture of hadronization in medium
  → Effect of the various kinematic variables understood
  → Recent results provides multi-dimensional binning

- Multi-dimensional analysis is crucial to constrain existing models
  → CLAS12 experiment (E-12-06-117) will provide such high statistics data in the right kinematic range
Future prospects for Hadronization studies

- **FNAL: E906 Drell-Yan at 120 GeV**
  - Lower energy run will significantly simplify dE/dx extraction and remove ambiguity between shadowing and energy loss

- **LHC Nuclear data**

- **RHIC upgrades**

- **JLab 12 GeV upgrade – CLAS12 in Hall B**
  - 10 times more luminosity than CLAS and 1000 times more than HERMES
  - Improved particle identification
  - Access to higher masses
  - Much larger kinematical range

- **Future electron-ion collider (Heavy quarks measurements)**
Part 2 - Color Transparency
QCD predicts the existence of hadron-like configuration which under specific conditions, will pass through nuclear matter with dramatically reduced interaction.

These configurations are of small size and their interactions with the nucleus are suppressed because of the small spatial extent of their color field.
The 3 Pillars of Color Transparency “CT”

- Creation of **Small Size Configurations (SSC)**
- SSC experiences **reduced interaction** with the medium
- SSC **does not evolve rapidly** as it propagates out of the nucleus

The signature of Color Transparency is the **increase** of the medium “nuclear” Transparency $T_A$ as a function of the **momentum transfer**

$$T_A = \frac{\sigma_A}{A \sigma_N}$$

- $\sigma_N$ is the free (nucleon) cross section
- $\sigma_A$ is the nuclear cross section

Diagram:

- Complete transparency
- Glauber
- Momentum Transfer
- 1
The power of hard exclusive reactions in CT studies

Hard exclusive processes play a key role in QCD

- They allow the studies of quark and gluons scattering and their formation into hadrons at the amplitude level
- They depend in detail on the composition of the hadron wave functions themselves

For the reaction to be elastic, all partons in the proton wave function have to be located within the same transverse interval \( b \leq 1/Q \)

At large \( Q^2 \), the transverse size of the ejectile can be much smaller than the equilibrium radius of the proton
Pillar # 2: Color screening: the SSC experiences reduced attenuation

In QCD the color field of a color neutral object vanishes with decreasing size of the object.

- Consequence of charge screening in QED were observed by Perkins in 1955.
- The ionization produced by the pair was small near the decay point, increasing with distance from vertex.
- It was quickly interpreted by Chudakov (1955) in the framework of QED: A pair of oppositely charged particles interacts in the medium with a dipole cross-section proportional to $b^2$.
- In Perturbative QCD two-gluon exchange is believed to be the dominant scattering mechanism.
- The SSC-nucleon cross section is $\sigma_{SSC,N} \approx \sigma_{h,N} \frac{b^2}{R_h^2}$, $R_h$ is the hadron radius.

200 GeV $\pi^0$ produced in cosmic rays.
Pillar # 3: Lifetime of Small-Size-Configuration

Naïve parton model:

- Quarks expand back to their usual separation at the speed of light
  \[ \tau \approx \frac{R_h}{c} \] (with time dilation it becomes \( E_{h^*} \tau / M_h \))
- If the hadron is a nucleon \( R_h \approx 0.8 \text{ fm} \), probability of SSC escaping the nucleus is significant even for modest values of Lorentz factor

More realistic “quantum diffusion” model:

- the expansion takes a total time of \( \frac{1}{(E_{h^*} - E_h)} \), where \( E_{h^*} \) is the energy of the typical intermediate state
- The key point is that the SSC is not the ground state of the free hadron Hamiltonian
Medium Energy search for Color Transparency

**Baryons**
- $A(p, 2p)$ BNL
- $A(e, e'p)$ SLAC and JLab

**Mesons**
- $A(\gamma, \pi p)$ JLab
- $A(e, e'\pi)$ JLab
- $A(e, e'\rho)$ Fermilab, DESY and JLab
The increase at low momentum cannot be taken as an unambiguous signal of CT. Results explained in terms of nuclear filtering (J. Ralston PRL 1988) or the crossing of the open charm threshold (S. Brodsky PRL 1988)
Search for Color Transparency in A(e, e’p) reaction

Constant value fit for $Q^2 > 2 \text{ (GeV/c)}^2$ has $\chi^2 / df \approx 1$

Conventional Nuclear Physics “Glauber” Calculation gives good** description (V. Pandharipande and S. Pieper PRC 1992)
A(e, e’p) @ JLab 12 GeV
Search for Color Transparency in $A(e, e'\pi)$ reaction

Extensions of these measurements to $Q^2$ of about $10 \, (\text{GeV/c})^2$ are planned for JLab 12 GeV upgrade.
A(e, e′π) projections for JLab 12 GeV

![Graph showing A(e, e′π) projections for 12 GeV and 12 GeV projected data for different isotopes.](image)
**ρ⁰ electroproduction on nuclei**

Detected particles are:
Scattered electron and the\[\pi^+\] and \[\pi^-\] from \[\rho^0\] decay

Finite propagation distance (lifetime) \[l_c\] for the \((q\,q\text{-bar})\) virtual state

\[
l_c = \frac{2\nu}{(M^2 + Q^2)}
\]

\(M\) is the mass of the vector meson
\(\nu\) is the energy transferred by the electron

\[e + N \rightarrow e' + N + \rho^0\]
CT Signature is the **rising** of the nuclear transparency with $Q^2$. However ...
HERMES experiment at fixed coherence length

HERMES Nitrogen data: $T_A = P_0 + P_2 Q^2$

$P_2 = (0.097 \pm 0.048_{\text{stat}} \pm 0.008_{\text{syst}}) \text{GeV}^{-2}$


27 GeV positron beam
Nuclear Transparency vs. coherence length

\[ N_{\text{Transparency}} \]

\[ l_c (\text{fm}) \]

- $^{12}\text{C}$
- $^{56}\text{Fe}$

Hadronization and CT Studies at JLab

Kawtar Hafidi

pA@RHIC Workshop
Nuclear Transparency vs. $Q^2$

FMS (Glauber Model): Frankfurt, Miller & Strikman, PRC 78, 015208 (2008)
GKM (Transport Model): Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)
JLab 12 GeV $\rho^0$ electroproduction measurements C, Fe and Sn

E12-06-106

Theory: FMS CT Model + Rho Decay
Theory: FMS NO CT Model + Rho Decay

$Q^2$ (GeV$^2$)
Nuclear Transparency

56Fe

5 GeV CT Result

Exp: Hall B, 11 GeV
SSC vs. formation effects

**Long $l_c$ and fixed**

$Q^2$ increases $\Rightarrow T_A$ increases because the mean transverse separation of the \{q,q-bar\} fluctuation decreases

**$l_c$ small and fixed (@ low $Q^2$  $l_f \sim l_c$)**

$Q^2$ increases $\Rightarrow l_f$ increases

$\Rightarrow$ CT increases for two reasons:

$\Rightarrow$ transverse separation and $l_f$ effects

\[ l_c = 2\nu/(Q^2 + M(\rho)^2) \]

\[ l_f = 2\nu/(M(\rho')^2 - M(\rho)^2) \]

Formation length

Coherence length

Formation length

Radius (C) = 2.7 fm

Radius (Fe) = 4.6 fm

Radius (Sn) = 5.7 fm
Strong evidence for the onset of Color Transparency using $\rho$ and pion electroproduction off nuclei at JLab ($11 \pm 2.3\%$ decrease in the absorption of $\rho$ in iron)

SSC expansion time with FMS model were found to be between 1.1 and 2.4 fm for $\rho$ momenta between 2 and 4.3 GeV

At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function

Using the upgraded JLab 12 GeV, we plan to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)
New STAR FMS Result: \( A_N \) for Forward \( \pi^0 \)'s rises with \( P_T \) to \( P_T \) of 10 GeV/c

The observed increase in \( A_N \) with \( P_T \) may be associated more with "isolated" \( \pi^0 \)'s rather than "jet-like" \( \pi^0 \) fragments.

(see talk by Len Eun)

How we scatter at High \( P_T \).

Theory of scattering from a target (i.e. proton), has theoretical roots in Optics.
Proton Forward Scattering at High PT
QCD Perspective

**PQCD (Leading Twist):**
Factorized Cross Section = (initial state) x (quark scattering) x (fragmentation)

- Does good job of predicting the spin averaged cross section.
- Leading twist cross section does not depend on transverse polarization.
- Spin Dependence require refinements like:
  - Beyond Collinear Factorization (Sivers)
  - Models of spin dependent factorization (Collins)
  - Models that go beyond leading twist.

Transversely polarized proton (transversely polarized quark)
RHIC Blue Beam

Target Proton
Random Spin
RHIC Yellow Beam

Large $\pi^0$ at large $p_T$
Up to 10 GeV/c
Not jet??

Incident Quark
Scatters & Preserves
Transverse Spin of quark

Additional Same Side Fragments

To FMS

Struck Quark fragments
**Proton Forward Scattering at High PT**

**QCD Perspective**

**PQCD (Leading Twist):**
Factorized Cross Section = (initial state) x (quark scattering) x (fragmentation)

- Does good job of predicting the spin averaged cross section.

- Leading twist cross section does not depend on transverse polarization.
- Spin Dependence require refinements like:
  - Beyond Collinear Factorization (**Sivers**)
  - Models of spin dependent factorization (**Collins**)
  - Models that go **beyond leading twist**.

Transversely polarized proton (transversely polarized quark)  
RHIC Blue Beam

Target Proton Random Spin  
RHIC Yellow Beam
From Optics (Fraunhofer Diffraction Limit)
If we scatter waves from a 2D object
And the source of the outgoing
wave (pions)
Is the sum of Huygens waves
From all points on the 2D surface.

High $p_T$ means production a very localized
point on this surface

If the source size is the full proton
“Diffraction”

The only small scale structures we
know about in protons about are
the partons.

For those small source contributions
we use PQCD.
Diffraction Review: (Fraunhofer Diffraction $\rightarrow$ Amplitude = Fourier Transform)

Fourier transform of a **circular uniform disk** has high $p_T$ components,

but for a **1 F disk with a smeared edge ($\Delta R=0.1$ F)**, high $p_T$ components are suppressed.

---

**Large $p_T$ cross section is Dominated by Scattering from Small Targets Features!!!**

.... Large $p_T$ does require Scattering from short distance scale features.
(like a sharp edge)
If not PQCD then what???
Compare to possible diffraction to $\pi^0$.
Consider $\pi^0: (0.25 < x_F < 0.35, p_T \sim 2 \text{ GeV/c})$
Measured cross section:

$$\left. \frac{d\sigma}{dp_T^2} \right|_{p_T=2 \text{ GeV/c}} \sim 1 \frac{\mu b}{\text{GeV}^2}$$

Suppose the total diffractive cross section for $\pi^0 (0.25 < x_F < 0.35)$ is 10 mb.
Then diffraction gives $p_T$ dependent cross section for different disk edge sharpness.

Measured $\pi^0$ cross section

- Sharp Edged 1F disk
- 1F disk with $\Delta R=0.1F = 1/(2 \text{ GeV/c})$
- 1F disk with $\Delta R=0.2F = 1/(1 \text{ GeV/c})$

For details see Len Eun’s Thesis
Or his talk today.
1. Like Fraunhoffer scattering of light from a 2D optical object
Amplitude $A(P_T)$ is Fourier Transform of transparency/opacity (with phase) of 2D object.

   a) point-like components: $A(P_T)$ is **transverse Fourier Transform of Hard PQCD Amplitude**

   b) Dist-like object (radius $R$): $A(P_T) = \frac{J_1(r P_T)}{P_T} \propto P_T^{-(3/2)}$ and cuts off at $P_T^{\text{max}} = \frac{1}{\Delta R_{\text{edge}}}$ with $\Delta R_{\text{edge}}$ the width of the disk perimeter.

   c) In general, observation of amplitude at large $P_T$ requires a feature in the scattering profile of size $\Delta R$.

\[
P_T = \frac{1}{\Delta R}
\]

2. Exceptions or enhancements to this can come from:
   a) Long Range Order (like diffraction grating adding amplitudes).
   b) Decay of high mass objects
   c) Classical multiple scattering. (adding cross sections not amplitudes)
   d) ???
For large $A_N$ at large $P_T$, there must be a localized absorption or transparency that depend on transverse spin. This at the level of the appropriate size $\Delta R \sim 1/P_T$.

At high energy, $\pi$ production in **leading twist PQCD**
- does not depend on transverse proton spin.
  - Amplitude is real (no absorption)
  - No helicity flip

Higher twist terms can both flip helicity and introduce a phase in amplitude, required for non-vanishing $A_N$. But higher twist terms fall with additional powers of $P_T$.

$A_N$ growing with $P_T$ out to $P_T \sim 10$ GeV is a mystery.

Studying $A_N$ in nuclei can give hints as to the possible role of small color neutral configurations in this observation.
The Proton is:

- A color neutral collection of 3 colored valence quarks
- Valence quarks are connected with gluon (sea quark) fields.
- Fields mostly confined to average radius $\sim 1$ Fermi.
- Average area $A$ and average cross section $\sigma$
  
  \[ \sigma \approx \pi r^2 = \pi \left(10^{-15}\right)^2 m^2 \]

- Radius fluctuates with time! *
- Proton absorption cross section fluctuates with time.
At a given instant......
eyevery nucleon in a Gold Nucleus is a different size
......and fluctuating in time. (relativisticly flattented)

The nucleus absorbs normal protons much more than small protons.

.... Nucleus more transparent if proton is a small proton
...... Likely to pass if proton hits nuclear edge or a region of the nucleus near
small nuclear proton or neutron configurations.
The amplitude for pp elastic scattering involves the probability that quarks come together within a distance given by the $p_T$ scale, and depends on the number of quarks. (Dimensional Scaling).

$$p_T \sim \frac{\sqrt{s}}{2}$$

$$a + b \rightarrow c + d$$

$$n_a = n_b = n_c = n_d = 3 \text{ quarks}$$

$$\frac{d\sigma}{dp_T^2} \propto s^{-(n_a + n_b + n_c + n_d - 2)} = s^{-10}$$
The probability to scattering exclusively is observed to be consistent with the probability (phase space) for all the quarks wandering together, to a distance scale $\sim 1/p_T$.

This is much less than the probability that each of 3 quarks of one proton pairs up with one of 3 quarks from the other proton, interacting at the $1/p_T$ distance scale.

(A condition to turn the 3 valence quarks but not gluons and virtual quarks)

\[ \left( \frac{d\sigma}{dp_T} \right)_{all \ small} \propto S^{-10} \]

\[ \left( \frac{d\sigma}{dp_T} \right)_{3 \ pairs} \propto S^{-8} \]

Landshoff Scaling + Sudakov Suppression -> Dimensional Scaling
PP Cross Section (90° CM)

\[
\frac{d\sigma_{pp \rightarrow pp}}{dt} \propto \frac{1}{s^{3+3+3+3-2}} = \frac{1}{s^{10}}
\]

Evidence for Dimensional Scaling In pp Elastic Scattering.

BUT

1. Hendry 1976
   a) Factor of 2 deviations from scaling. (1<R<2)
   b) Remnant of diffraction.
2. Ralston –Pire
   a) Energy dependent oscillations of Landshoff suppression.
   a) Extra cross section near threshold (in s channel) for charm (and strangeness).
Brodsky – deTerramond: Idea about thresholds for quark anti-quark pair* mass scales.

\[
\sqrt{s} \rightarrow 2m_p + M_{J/\psi} \sim 5 \text{GeV}
\]

- An elastic scattering channel with slightly virtual \( J/\psi \) in “s” channel*.
- Proton spins aligned to favor creation of spin 1 charmed quark pair intermediate state.
- Intermediate state “not” small size.
- High \( p_T \) final state from decay of high mass virtual system into two protons.
- Explanation for excess cross section in this energy region.

(above Dimensional Scaling)

- For anti-aligned protons, this process should be strongly suppressed.
The **Color Transparency** Variable

$T$ is the fraction of nuclear protons that contribute to pp quasi-elastic scattering.

The ratio of:
- the observed hard scattering cross section in nuclei
- to the same hard scattering cross section with free protons.

\[
T_{pp} = \frac{\text{d}\sigma/\text{dt for } ^{12}\text{C}}{Z \frac{\text{d}\sigma/\text{dt}}{\text{for } \text{proton}_1}}
\]
90 Degree CM pp Elastic Cross Section at High Energy

Not possible for high energy

AGS:

\[ \sqrt{s} = 5 \, \text{GeV}^2 \quad \frac{d\sigma}{dt} = 1 \frac{\text{nb}}{\text{GeV}^2} \]

RHIC:

\[ \sqrt{s} = 250 \, \text{GeV}^2 \quad \frac{d\sigma}{dt} = 10^{-17} \frac{\text{nb}}{\text{GeV}^2} \]

RHIC \( A_N \)

Measurement (1%):

\[ \frac{d\sigma}{dt} \approx 0.1 \frac{\text{nb}}{\text{GeV}^2} \]

Small cross sections

Rare events

Small protons
The EVA Apparatus AGS Experiment E850 BNL
AGS Exp 850
Nuclear Transparency in 90 degree c.m.
Quasielastic A(p,2p) Reactions.

Open Charm

Open Strangeness

Open Strangeness

Open Charm

Energy dependence of spin-spin effects in p-p elastic scattering at 90° c.m.

Transparency for PP and $\pi P$ quasi-elastic scattering as a function of Atomic Mass.

**FIG. 20:** Nuclear transparency vs Atomic Mass A for the A(p,2p) measurements from E834 for incident momenta of 5.9, 10 and 12 GeV/c as indicated on the figure. The error bars reflect the statistical uncertainties and a 10% target-to-target systematic error. The solid curves represent the fits with constant effective cross sections to the five nuclei at 5.9 and 10 GeV/c as described in the text.

**FIG. 21:** $T_{\pi+p}$ and $T_{pp}$ transparencies for Li, C, Al, Cu and Pb at 5.9 GeV/c, and Al for 10 GeV/c. The $T_{\pi+p}$ values (solid symbols) are consistently larger than those of $T_{pp}$ (open symbols).
Summary Question
How will $\pi^0 A_N$ change when filtered through a nucleus?

• Comparison between pp and pA scattering can help identify small color singlet contributions to scattering processes.

• Large $p_T$ pp elastic scattering (AGS energies) has transparency which correlate with very large transverse spin asymmetries and with variations of the cross section above dimensional scaling. Interpretations involve competing mechanisms of pp scattering.
  • For example, this could be an indication of competition between hard scattering amplitudes (small protons) and a “nearly real $q \bar{q}$ pair” of charmed quarks in the s channel for pp scattering.

  • Or it could involve a competition between (small proton) hard dimensional scattering and (large proton) unsuppressed Landshoff scattering processes.

• RHIC Transverse $A_N$ in forward $\pi^0$ production at largest $p_T$ may not come from quark fragmentation events (jets). What then?? Will filtering remove or enhance the “jet-like” vs “non-jet-like” contributions to $A_N$? Study vs. event multiplicity.

• Comparison of transverse $A_N$ for $\pi^0$’s in pp and pA may help to establish (or not) contributions from of small color singlets, or large complex proton states, leading to large $p_T$ $\pi^0$’s.
BNL-E-0755 Experiment

PI- P TWO-BODY EXCLUSIVE REACTIONS AT 90 DEG FROM 8 GEV/C TO 18 GEV/C.

Brookhaven AGS Exp. E755
P beam = 5.9 GeV/c

Cerenkov Id of secondary beam
+/- proton/ anti-proton
pi+ / pi-
k+ / k-

1) Final state particle magneticly analyzed with Cerenkov ID.
2) Recoil non-magnetic tracking.
Quark Exchange is the dominant mechanism for large angle scattering.

Those processes for which “INT” graph is possible, where a quark can move from one proton to the other, have the dominant cross sections.

Proton – Anti-proton scattering is nearly 2 orders of magnitude smaller that Proton-Proton cross sections at 90° and beam momentum of 5.9 GeV/c.

Unknown:
Does Proton – Anti-proton scattering cross section scale with dimensional scaling.

Is transparency for Proton – Anti-proton different from Proton-Proton?
LHCf and p-A forward at RHIC

Yoshitaka Itow
STE Lab / Kobayashi-Maskawa Inst.
Nagoya University
and on behalf of the LHCf collaboration

“pA@RHIC”
Jan 7-9, 2013, BNL
Very high energy p-A collisions above our heads

Cosmic ray proton

Nitrogen

Air shower
Hadron interactions at ultra high energy Accelerator ↔ Cosmic rays

$E_{CM} \sim (2 \sqrt{E_{lab} M_p})^{1/2}$

- $s=14$ TeV ↔ $10^{17}$eV cosmic rays (pp)
- $s=447$ TeV ↔ $10^{20}$eV cosmic rays (pp)
$10^{17} \text{ eV}$: Crossroad of accelerators and UHECRs

- LHC, Tevatron, SppS and RHIC can verify interactions at $10^{14} \sim 10^{17}$ eV
- Low E extension (TALE, HEAT) plan can verify $10^{17}$ eV shower
Y. Itow, LHCf and pA forward at RHIC

GZK cut-off confirmed? But...

GZK cut off?

\[ p + CMB \gamma \rightarrow \Delta \]

Need identify UHECR is "proton"

Too many \( \mu s \) @ Auger, if proton

TA prefers proton

Auger prefers Fe

ICRC2011

ICRC2011


**Inelastic cross section**
- If large $\sigma$
  - rapid development
- If small $\sigma$
  - deep penetrating

**Forward energy spectrum**
- If softer
  - shallow development
- If harder
  - deep penetrating

**Inelasticity $k = 1 - p_{lead}/p_{beam}$**
- If large $k$
  - $\pi^0$s carry more energy
  - rapid development
- If small $k$
  - (baryons carry more energy)
  - deep penetrating

(relevant to $N_\mu$)
Very forward: Majority of energy flow (\( \sqrt{s} = 14\text{TeV} \))

Most of the energy flows into very forward
(Particles of \( X_F > 0.1 \) contribute 50\% of shower particles)

Need to measure EM component at \( \eta \sim 8 \)
The LHCf collaboration

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~30 physicists from 5 countries
Y. Itow, LHCf and pA forward at RHIC

**LHCf site**

- **Protons**
- **Neutral particles**
- **Charged particles (+)**
- **Charged particles (-)**
- **Beam pipe**

**LHCf/ZDC**

- **96mm**

**D1 magnet**

**ATLAS**

- **140m**
- **TAN absorber**

**TAN**

**USA15**

**Point 1**

**RI13**

**WJ13**

**Q3**

**Q2**

**Q1**

**Q3**

**Q2**

**Q1**

**Q3**

**D1**

**WJ16**

**WJ17**

**RI17**

**WJ4**

**USA15**

**D1**

**WJ16**

**WJ17**

**RI17**

**WJ4**
Setup in IP1-TAN (side view)

- BRAN-Sci
- ZDC type1
- ZDC type2
- BRAN-IC
- LHCf Calorimeter
- LHCf Front Counter
- Beam pipe
- Distance from center
- Neutral particles
- IP1
- TAN

Side view
The LHCf detectors

16 tungsten + pl.scinti. layers
25mmx25mm+32mmx32mm
4 Silicon strip tracking layers

44$X_0$, 1.6 $\lambda_{int}$

16 tungsten + pl.scinti. layers
20mmx20mm+40mmx40mm
4 SciFi tracking layers
Calorimeter performance

- Gamma-rays ($E>100\text{GeV}, \frac{dE}{E}<5\%$)
- Neutral Hadrons ($E>a$ few 100 GeV, $\frac{dE}{E}\sim30\%$)
- Neutral Pions ($E>700\text{GeV}, \frac{dE}{E}<3\%$)
- Shower incident position (170$\mu$m / 40$\mu$m for Arm1/Arm2)
Brief history of LHCf

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jul 2006 construction

Jan 2008 Installation

Aug 2007 SPS beam test

Sep 2008 1st LHC beam

Mar 2010 1st 7TeV run

Dec 2009 1st 900GeV run (2nd 900GeV in May 2010)

Jul 2010 Detector removal
Acceptance of LHCf

Projected edge of beam pipe

Viewed from IP1 (red:Arm1, blue:Arm2)

pp 7TeV, EPOS
None of the models agree with data
Data within the range of the model spread

0.68 (0.53)nb⁻¹ on 15May2010
LHCf single $\gamma$ spectra at 900 GeV

May 2010 900 GeV data (0.3 nb$^{-1}$, 21% uncertainty not shown)

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

$\eta > 10.15$

$\eta > 10.15$

$8.77 < \eta < 9.46$

$8.77 < \eta < 9.46$

MC/Data

MC/Data

May 2010 900 GeV data (0.3 nb$^{-1}$, 21% uncertainty not shown)

PLB 715 (2012) 298-303
$X_F$ spectra for single $\gamma$: 900GeV/7TeV comparison

$$\frac{1}{\sigma_{inel}} \frac{d\sigma_{\gamma}}{dX_F} \bigg|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{inel}} \frac{d\sigma_{\gamma}}{p_Tdp_TdX_F} \langle p_T \rangle dp_T$$

(sys error not included)

- Comparing $X_F$ for common $P_T$ region at two collision energies.
- Less root-$s$ dependence of $P_T$ for $X_F$?
LHCf 7TeV $\pi^0$ analysis

**Type-I**

$\sigma_M = 3.7\%$

**Type-II**

- Type-II $\pi^0$ sample
- LHCf–Arm1 Data 2010
- Preliminary

- Type-I LHCf–Arm1
- Type-II at large tower
- Type-II at small tower
LHCf $\pi^0$ $P_T$ spectra at 7TeV

PRD 86 (2012) 092001

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145
Feed back to UHECR composition

- Retune done for cosmic ray MC (EPOS, QGSJET II) with all the LHC input. (cross section, forward energy flow, LHCf, etc.)
- Uncertainty reduced from 50 gcm$^2$ to 20gcm$^2$ (p-Fe difference is 100gcm$^2$)

Detail reanalysis of UHECR is also needed for conclusion.
Next issue: Inelasticity~0 degree neutrons

- E-spectrum, $n/\gamma$ ratio
- Important for $X_{\text{max}}$ and also $N_\mu$
- Measurement of inelasticity at LHC energy

Neutral hadrons at 14 TeV
(LHCf acceptance, no resolution)

Neutral hadrons at 14 TeV
(LHCf acceptance, 30% resolution)
LHCf future plan

- **Analysis ongoing for 2010 data**
  - Neutron energy spectra $\rightarrow$ inelasticity.
- **Reinstall Arm2 for p-Pb in early 2013**
  - Very important information for nuclear effect.
  - Under discussion of common triggers for combined analysis w/ ATLAS detector.
- **Reinstall Arm1+2 for 14TeV in 2014**
  - Now upgrading detectors w/ rad-hard GSO.
- **A new measurement at RHIC 0 degree**
  - Under discussions for 500GeV p+p and d + light-A (or p-A?).
- **Far future (>2020?) p-N and N-N collisions at LHC?**
0-degree measurement for A-A, p-A

- Air is not actually Hydrogen but mostly Nitrogen!
- CRs are mostly protons but maybe Fe for $>10^{19}\text{eV}$?
- Can we estimate p-N / Fe-N from p-p data for very forward regions?
- How we can extrapolate to $10^{20}\text{eV}$?
- We need to understand
  - nuclear modification in the very forward region and low $p_T$
  - its A-dependence and energy dependence

- Forward data for p-p, p-N and p-HI
- Forward data for Fe-N and Fe-HI
- These data at various energies
Nuclear effects for very forward region

- Air showers take place via p-N or Fe-N collisions!
  - Nuclear shadowing, final state interaction, gluon saturations
  - Nuclear modification factor at 0 degree may be large.


\[ R_{dAu} = \frac{\sigma_{pp}^{inel}}{(N_{bin}) \sigma_{hadr}^{dAu}} \frac{E d^3 \sigma / dp^3 (d + Au \rightarrow Y + X)}{E d^3 \sigma / dp^3 (p + p \rightarrow Y + X)} \]

QGSJET II-04

All $\eta$

8.81 $\eta$ < 8.99

$\eta$ > 10.94

Courtesy of S. Ostapchenko
LHCf p – Pb runs at $\sqrt{s_{NN}}=4.4\text{TeV}$ (Jan2013)

- 2013 Jan / a month of p-Pb opportunity.
  - 3.5TeV p +1.38TeV/n Pb ($\sqrt{s_{NN}}=4.4\text{TeV}$)
  - Expected luminosity: $3 \times 10^{28}\text{cm}^{-2}\text{s}^{-1}$, $\sigma_{AA}=2\text{b}$
  - Install only Arm2 at one side (Si tracker good for multiplicity)
  - Trig. exchange w/ ATLAS for centrality tagging

- Requested statistics: $N_{\text{coll}} = 10^8$ ($L_{\text{int}} = 50\mu\text{b}^{-1}$)
  - $2 \times 10^6$ single \()
  - 35000 $\pi^0$
  - Assuming $L = 10^{26}\text{cm}^{-2}\text{s}^{-1}$
    (1% of expected lumi)
  - $t = 140\text{ h (6 days)}$!
E spectra (proton remnant side)

Small tower

Large tower

\( \gamma \)-rays, small tower

\( \gamma \)-rays, big tower

Neutrons, small tower

Neutrons, big tower

\( 1/N_{\text{inc}} dN/dE \) (GeV^{-1})

\( 1/N_{\text{inc}} dN/dE \) (GeV^{-1})

Energy (GeV)

Energy (GeV)
Future p-N and Fe-N in LHC?

- LHC 7TeV/Z p-N and N-N collisions realize the laboratory energy of $5.2 \times 10^{16}$eV and $3.6 \times 10^{17}$eV, respectively (N: Nitrogen)

- Suggestions from the CERN ion source experts:
  - LHC can in principle circulate any kind of ions, but switching ion source takes considerable time and manpower
  - Oxygen can be a good candidate because it is used as a ‘support gas’ for Pb ion production. This reduces the switching time and impact to the main physics program at LHC.
  - According to the current LHC schedule, the realization is not earlier than 2020.
  - New ion source for medical facility in discussion will enable even Fe-N collisions in future
“RHICf” : Possible RHIC 0-degree runs

RHIC also has the zero-degree site

\[ \sqrt{s} = 500 GeV \]

Just below LHC (\(E_{\text{OR}} \sim 5 \times 10^{13} \text{eV}\))

\[ \sqrt{s_{NN}} = 200 GeV \]

Au-Au, Cu-Cu or even lighter?

Advantage of RHIC

- Lower energy data point
- Acceptance for \(\pi^0\)
- Flexible operation (energy, ion)
  - p-N, N-N, Fe-N, etc.
"RHICf" : η acceptance for 100GeV/n d-N MC

η > 5.8 is covered

RHIC Coverage (50mm/20m)

No acceptance for \( \phi^0 \) at 900GeV

LHC Coverage (50mm/140m)

Acceptance for π0

Energy flow
Summary

- UHECR needs accelerator data to solve the current enigma, and may also hint QCD at beyond-LHC energy.
  - $10^{17}-10^{13}$eV is an unique overlap region for colliders and UHECRs

- LHCf provides dedicated measurements of neutral particles at LHC 0 deg to cover most of collision energy flow.
  - E spectra for single gamma at 7TeV and at 900GeV. Agreement is “so-so”, but none of models really agree.
  - PT spectra for 7TeV $\pi^0$. EPOS gives nice agreement.

- (Cold) nuclear effect must be tested by p-A at 0degree
  - LHCf p-Pb run in Jan 2012
  - RHIC pp, pA, AA runs are feasible opportunity.
  - LHC light ion runs would be possible but far future.
International Workshop on
“High-energy scattering at zero degree”

2nd - 4th March, 2013
KMI, Nagoya University

Organizing committee
Yoshitaka Itow (Nagoya)
Kazunori Itakura (KEK)
Yuji Goto (Riken)
Takashi Sako (Nagoya)
Kenta Shigaki (Hiroshima)
Kiyoshi Tanida (Seoul National)
Yuji Yamazaki (Kobe)

- Diffraction and very forward p-p and p-A scatterings
- Forward and ultra peripheral A-A scatterings
- Spin asymmetry at very forward in polarized p-p scatterings
- High energy cosmic ray interaction models
- QCD aspects in very forward scattering

Workshop site will soon open. Check “topic” in http://www.gcoe.phys.nagoya-u.ac.jp/index_e.html
Backup
Beam Related Effects

✓ Pile-up (7% pileup at collision)
✓ Beam-gas BG
✓ Beam pipe BG
✓ Beam position (next slide)

- MC w/ pileup vs w/o pileup
- Crossing vs non-crossing bunches
- Direct vs beam-pipe photons
Where is zero degree?

Beam center LHCf vs BPMSW

Effect of 1mm shift in the final spectrum
LHCf calorimeters

Arm#2 Detector

Arm#1 Detector

290mm

90mm
Event sample \((\pi^0 \rightarrow 2\gamma)\)

- **Longitudinal development measured by scintillator layers**
  - 25mm Tower
    - \(\rightarrow 600\text{GeV} \) photon
  - 32mm Tower
    - \(\rightarrow 420\text{GeV} \) photon

- **Lateral distribution measured by silicon detectors**
  - X-view
  - Y-view

- **Hit position, Multi-hit search.**
- **Total Energy deposit**
- **Energy Shape**
- **PID**

- **\(\pi^0\) mass reconstruction from two photon.**

\[ M_{\pi^0} = \sqrt{E_{\gamma 1} E_{\gamma 2}} \cdot \theta \]
Forward production spectra vs Shower curve

Half of shower particles comes from large $X_F$ \( \gamma \)

$X_F = E/E_{tot}$
Parent $\pi^0$ pseudorapidity producing ground muons
The single photon energy spectra at 0 degree at 7TeV

(O.Adriani et al., PLB703 (2011) 128-134)

- **DATA**
  - 15 May 2010 17:45-21:23, at Low Luminosity $6 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$, no beam crossing angle
  - 0.68 nb-1 for Arm1, 0.53nb-1 for Arm2

- **MC**
  - DPMJET3.0 4, QGSJETII03, SYBILL2.1, EPOS1.99
  - PYTHIA 8.145 with the default parameters.
  - $10^7$ inelastic p-p collisions by each model.

- **Analysis**
  - Two pseudo-rapidity, $\eta > 10.94$ and $8.81 < \eta < 8.99$.
  - No correction for geometrical acceptance.
  - Luminosity by FrontCounter (VdM scan)
  - Normalized by number of inelastic collisions with assumption as $\sigma_{\text{inela}} = 71.5$mb.
    (c.f. $73.5 \pm 0.6^{+1.8}_{-1.3}$ mb by TOTEM)
New 900 GeV single $\gamma$ analysis

- 0.3nb$^{-1}$ data (44k Arm1 and 63k Arm2 events) taken at 2, 3 and 27 May, 2010
- Low luminosity ($L \sim 10^{28}$ typical, 1 or 4 xing), negligible pile up (0.05 int./xing).
- Relatively less $\eta$-dependence in the acceptance. Negligible multi-incidents at a calorimeter ($\sim 0.1\,\gamma$ (>50GeV)/int.)
- Higher gain operation for PMTs. Energy scale calibration by SPS beam, checked with $\pi^0$ in 7TeV data.
LHCf $\gamma / \pi^0$ measurement

Gamma-rays @ $\sqrt{s}=7$TeV


Projective edge of beam pipe

Viewed from IP1 (red: Arm1, blue: Arm2)

$\pi^0 \rightarrow \gamma\gamma$

$\eta=[8.7, 8.4, 7.6, 6.9, 5.9]$
LHCf $\pi^0$ $P_T$ spectra at 7TeV (data/MC)

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

EPOS gives the best agreement both for shape and yield.
LHCf type-I $\pi^0$ analysis

- Low lumi ($L \sim 5 \times 10^{28}$) on 15-16 May, 2.53(1.91) nb$^{-1}$ at Arm1 (Arm2). About 22K (39K) $\pi^0$ for Arm1 (Arm2) w/ 5% BG.
- For $E_\gamma > 100$ GeV, PID ($\gamma$ selection), shower leakage correction, energy rescaling (-8.1% and -3.8% for Arm1&2).
- ($E$, $P_T$) spectra in $+\mp 3\sigma\ $ $\pi^0$ mass cut w/ side band subtracted.
- Unfolding spectra by toy $\pi^0$ MC to correct acceptance and resolution.
7TeV \( \pi^0 \) analysis

7TeV photon spectra by LHCf

- Photon analysis and \( \pi^0 \) analysis compensate each missing information.
  - High energy photon originates from large \( P_T \) \( \pi^0 \) events.
  - Photon spectrum includes a contribution from other hadrons/baryons.

- Photon \( P_T \) analysis can connect each measurement.

Average $P_T$ of $\pi^0$

1. Thermodynamics

$$\frac{1}{\sigma_{\text{inel}}} E \frac{d^3\sigma}{dp^3} = A \cdot \exp(-\sqrt{p_T^2c^2 + m_{\pi^0}^2c^4/T})$$

$$\langle p_T \rangle = \sqrt{\frac{\pi m_{\pi^0}c^2T}{2}} \frac{K_2(m_{\pi^0}c^2/T)}{K_{3/2}(m_{\pi^0}c^2/T)}$$

- Comparison w/ UA7@630GeV
- Extend to higher $\eta$ regions
- Less energy dependence of $<P_T>$?
Comparison of Data/MC ratio at two energies

7TeV

MC/Data

High $\eta$

Low $\eta$

900GeV

MC/Data

LHCf $\sqrt{s}=900$GeV, Photon like
$\eta > 10.15$ ($<\theta> = 39$ $\mu$rad)

Data 2010, $\int L dt = 0.3 \pm 0.29 \text{nb}^{-1}$

Data 2010, Stat. + Syst. error

DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

LHCf $\sqrt{s}=900$GeV, Photon like
$8.77 < \eta < 9.46$ ($<\theta>=234$ $\mu$rad)

Data 2010, $\int L dt = 0.3 \pm 0.29 \text{nb}^{-1}$

Data 2010, Stat. + Syst. error

DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145
Polarized p+A, single transverse spin asymmetries

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Outline

- Motivation
  - Why transverse spin and small-x could be probed at the same time?
  - How spin asymmetries could be more sensitive to saturation physics

- Single transverse spin asymmetry
  - Inclusive hadron production
  - Drell-Yan production (analyzing factorization properties)

- Summary
Single transverse-spin asymmetry (SSA)

Consider a transversely polarized proton scatter with an unpolarized proton

\[ A_N \equiv \frac{\Delta \sigma (\ell, \vec{s})}{\sigma (\ell)} = \frac{\sigma (\ell, \vec{s}) - \sigma (\ell, -\vec{s})}{\sigma (\ell, \vec{s}) + \sigma (\ell, -\vec{s})} \]

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Observation at high energy $\sqrt{s}$

The spin asymmetry becomes the largest at forward rapidity region, corresponding to

- The partons in the projectile (the polarized proton) have very large momentum fraction $x$: dominated by the valence quarks (spin effects are valence effects)
- The partons in the target (the unpolarized proton or nucleus) have very small momentum fraction $x$: dominated by the small-$x$ gluons

Thus spin asymmetry in the forward region could probe both

- The transverse spin effect from the valence quarks in the projectile: Sivers effect, Collins effect, and etc
- The small-$x$ gluon saturation physics in the target
Theoretical understanding in conventional factorization

- At leading twist formalism, assuming partons are collinear, the asymmetry is vanishing small

\[ \sigma(s_T) \sim \begin{array}{ccc}
\frac{p}{s_p} & \frac{k}{k} & 2 \\
\end{array} \]

- generate phase from loop diagrams, proportional to \( \alpha_s \)
- helicity is conserved for massless partons, helicity-flip is proportional to current quark mass \( m_q \)

Therefore we have

\[ A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \frac{\delta q(x)}{\phi(x)} \]

\( \delta q(x) \): tranversity
\( \phi(x) \): unpolarized parton distribution

- \( A_N \neq 0 \): result of parton’s transverse motion or correlations!
Understand SSA: related to parton transverse motion

- One could immediately think of two ways to include parton’s transverse momentum into the formalism
  - Generalize the collinear distribution $f(x)$ to $f(x, k_\perp)$
  - Taylor expansion: $H(Q, k_\perp) = H(Q) + k_\perp H'(Q) + \cdots$, where $H'(Q) = dH(Q, k_\perp)/dk_\perp$
    at $k_\perp = 0$, then $\int d^2kt f(x, kt) = \text{a higher-twist correlation}$

- The first one is called TMD approach (SIDIS, DY at low pt), the second one is called collinear twist-3 approach (pp→hX at high pt). They are closely related to each other.

\[ H(Q, k_\perp) = H(Q) + k_\perp H'(Q) + \cdots \]

\[ H'(Q) = \frac{dH(Q, k_\perp)}{dk_\perp} \]

\[ \int d^2kt f(x, kt) = \text{a higher-twist correlation} \]
Inclusive hadron production in small-x formalism

- At forward rapidity, the hadron is produced as follows (at LO)

\[
\frac{d\sigma}{dy d^2p_\perp} = \frac{K}{(2\pi)^2} \int d^2b \int_{x_F}^1 \frac{dz}{z^2} x f_{q/p}(x) F(x_A, q_\perp) D_{h/q}(z)
\]

\[
F(x_A, q_\perp) = \int \frac{d^2r_\perp}{(2\pi)^2} e^{i q_\perp \cdot r_\perp} \frac{1}{N_c} \langle \text{Tr} \left( U(0) U^\dagger(r_\perp) \right) \rangle_{x_A}
\]

- Dipole gluon distribution follows B-K evolution equation, which can be solved numerically

- Comparison with RHIC data

Albaete-Marquet, 2010
Naively incorporate Sivers effect

- Thinking about the incoming quark has a small $k_t$-component, which generates a Sivers type correlation in the proton wave function (Sivers function)

$$ p_{\perp} = z (k_{\perp} + q_{\perp}) $$

- Now spin-dependent cross section becomes

$$ \frac{d\sigma}{dy d^2 p_{\perp}} = \frac{K}{(2\pi)^2} \int d^2 b \int_{x_F}^1 \frac{dz}{z^2} \int d^2 k_{\perp} x \epsilon^{\alpha\beta} s_{\perp}^{\alpha} k_{\perp}^{\beta} f_{1T}^\perp q(x, k_{\perp}^2) \frac{F(x, q_{\perp} = p_{\perp}/z - k_{\perp})}{D_h/q(z)} $$

- Linear $k_t$ associated with Sivers function, need another $k_t$ to have $k_t$-integral non-vanishing, which can only come from the gluon distribution

- Spin asymmetry is sensitive to the slope of the dipole gluon distribution in $k_t$-space
Take GBW (MV) model as an example

- Take GBW model as an example: $Q_s = 1\text{GeV}$ in proton

$$F(x, q_\perp) = \frac{1}{\pi Q_s^2(x)} e^{-q_\perp^2/Q_s^2(x)}$$

- Broadening might be difficult to see (as M. Chiu mentioned in his talk), but the slope could be easy to see
  - Comparing the $A_N$ of pp and pA at small pt, which should give these information

$$Q_{sA}^2 = c A^{1/3} Q_{sp}^2$$

DUsling-Gelis-Lappi-Venugolalan, arXiv:0911.2720
Some cautions on this naive incorporation

- How to study the process-dependence of the Sivers function (which Sivers function should one use?)
  - One might implement effectively through the method as in Gamberg-Kang, arXiv:1009.1936
  - Or study the Qiu-Sterman twist-3 effect (from the proton side) directly within the small-x formalism

Kang-Xiao-Yuan, in preparation
Collins effect: include spin in the fragmentation process

- Spin effect is always associated with the parton transverse momentum
  - generalized to include small transverse momentum in the fragmentation process
    \[
    \frac{d\sigma}{dy_h d^2 P_{h\perp}} = \frac{K}{(2\pi)^2} \int_{x_F}^1 \frac{dz}{z^2} \int d^2 P_{hT} x_1 q(x_1) N_F(x_2, k_\perp) D_{h/q}(z, P_{hT})
    \]
  - Now we could introduce Collins function in the game
    \[
    I(S_\perp, P_{hT}) = \epsilon^{\alpha\beta} S_\perp^\alpha \left[ P_{hT}^\beta - \frac{n \cdot P_{hT}}{n \cdot P_J} P_J^\beta \right] = |S_\perp| |P_{hT}| \sin(\phi_h - \phi_s)
    \]
  - Nice thing: Collins function is universal, independent of gauge link

\[ P_{h\perp} = z k_\perp + P_{hT} \]
Data seems to support scaling analysis

- **Scaling analysis for pt and xf dependence**

  \[ A_N \sim \frac{P_{h\perp}}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}} \]

  \[ A_N e^{\delta^2 P_{h\perp}^2/Q_s^4} e^{(1+2\lambda) y_h} \sim x_F^{(1+\lambda)} F(x_F) \]

- **Compare pp and pA collisions**

  \[ \frac{A_N^{pA\rightarrow h}}{A_N^{pp\rightarrow h}} \bigg|_{P_{h\perp} \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2}{Q_{sp}^4}} \delta^2 \]

  \[ \frac{A_N^{pA\rightarrow h}}{A_N^{pp\rightarrow h}} \bigg|_{P_{h\perp} \gg Q_s^2} \approx 1 \]

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The source of single spin correlation for $A^\uparrow + B \rightarrow h(p_\perp) + X$

\[
\Delta \sigma = T_{a,F}(x, x) \otimes \phi_{b/B}(x') \otimes H_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z) \tag{I}
\]

\[
+ \delta q_{a/A}(x) \otimes T_{b,F}^{(\sigma)}(x', x') \otimes H'_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z) \tag{II}
\]

\[
+ \delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H''_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z, z) \tag{III}
\]

\[
+ m_q \delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H'''_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z) \tag{IV}
\]

<table>
<thead>
<tr>
<th>Term</th>
<th>meaning</th>
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<th>small-x</th>
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<td>(I)</td>
<td>Sivers</td>
<td>$T_{q,F}(x, x)$</td>
<td>Qiu-Sterman 91, 98 hep-ph/9806356</td>
<td>Boer-Dumitru-Hayashigaki, 2006 Kang-Xiao, 1212.4809</td>
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<td>(II)</td>
<td>Boer-Mulders</td>
<td>$T_{q,F}^{(\sigma)}(x', x')$</td>
<td>Kanazawa-Koike, 2000 hep-ph/000727</td>
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<td>(III)</td>
<td>Collins</td>
<td>$D_{c\rightarrow h}^{(3)}(z, z)$</td>
<td>Kang-Yuan-Zhou, 2010 1002.0399</td>
<td>Kang-Yuan, 2011 1106.1375</td>
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<tr>
<td>(IV)</td>
<td>Kane-Pumplin-Repko</td>
<td>$m_q \delta q(x)$</td>
<td>Kane-Pumplin-Repko, 1978</td>
<td>(different from KPR) Kovchegov-Sievert 1201.5890</td>
</tr>
</tbody>
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Why Drell-Yan is so interesting: physics of gauge link

- Rescattering (gauge link) determined by hard process and its color flow

Because gauge link is generated in the factorization procedure, for spin effect in small-x formalism, it is important to analyze the factorization properties.

Central quest for the field at the moment

\[ \Delta^N f_{q/h}^{\text{SIDIS}}(x, k_\perp) = - \Delta^N f_{q/h}^{\text{DY}}(x, k_\perp) \]
Sivers function from SIDIS $\ell + p^\uparrow \rightarrow \ell' + \pi(p_T) + X : p_T \ll Q$

- Extract Sivers function from SIDIS (HERMES&COMPASS): a fit

- $\pi^0$
- HERMES preliminary
- 2002-2005

- $\pi^+$

- $\pi^-$

- $u$ and $d$ almost equal size, different sign
- d-Sivers is slightly larger

- Still needs DY results to verify the sign change, thus fully understand the mechanism of the SSAs

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Drell-Yan production in small-x regime

- At leading order, Drell-Yan production is simple \( p^\uparrow + A \rightarrow [\gamma^* \rightarrow] \ell^+ \ell^- + X \)
  - quark (from polarized proton) scatters off the classical gluon field to produce a virtual photon

When high-energy partons scatter off the classic gluon field, the interaction is eikonal in that the projectile propagate through the target without changing their transverse position but picking up an eikonal phase

\[
S|k^+, b, i\rangle \otimes |A\rangle = U^{ij}[A]|k^+, b, j\rangle \otimes |A\rangle
\]

\[
U(x) = \mathcal{P} \exp \left\{ ig_s \int_{-\infty}^{+\infty} dx^+ T^c A_c^- (x^+, x_\perp) \right\}
\]
Quark splitting wave function: keep quark $k_t$ from proton

- Quark to photon splitting wave function in light-front perturbation theory \( q \rightarrow q + \gamma^* \)

\[
\phi^\lambda_{\alpha\beta}(k, q) = \frac{1}{\sqrt{8(k - q)^+ k^+ q^+}} \frac{\bar{u}_\beta(k - q) \gamma_\mu \epsilon^\mu(q, \lambda) u_\alpha(k)}{(k - q)^- + q^- - k^-}
\]

- In momentum space

\[
z = \frac{q^+}{k^+} \quad \quad \quad \epsilon_M^2 = (1 - z) M^2
\]

- In transverse coordinate space:

\[
\psi^\lambda_{\alpha\beta}(k, q^+, r) = \int d^2 q_\perp e^{iq_\perp \cdot r} \phi^\lambda_{\alpha\beta}(k, q)
\]

\[
\psi^T_{\alpha\beta}(k, q^+, r) = 2\pi \sqrt{\frac{2}{q^+}} e^{i z k_\perp \cdot r} i\epsilon M K_1(\epsilon M |r|) \begin{cases} 
\frac{r \cdot \epsilon^1}{|r|} [\delta_{\alpha-\beta-} + (1 - z)\delta_{\alpha+\beta+]}, & \lambda = 1, \\
\frac{r \cdot \epsilon^2}{|r|} [\delta_{\alpha+\beta+} + (1 - z)\delta_{\alpha-\beta-}], & \lambda = 2.
\end{cases}
\]

\[
\psi^L_{\alpha\beta}(k, q^+, r) = 2\pi \sqrt{\frac{2}{q^+}} e^{i z k_\perp \cdot r} (1 - z) M K_0(\epsilon M |r|) \delta_{\alpha\beta}
\]
The multiple scattering could happen before or after

- The interaction with the target could happen before or after the splitting of the virtual photon

The differential cross section for \( q + A \rightarrow \gamma^* + X \)

\[
\frac{d\sigma(qA \rightarrow \gamma^* X)}{dq^+d^2q_\perp} = \alpha_{em}e_q^2 \int \frac{d^2b}{(2\pi)^2} \frac{d^2r}{(2\pi)^2} \frac{d^2r'}{(2\pi)^2} e^{-iq_\perp \cdot (r-r')} \sum_{\alpha\beta\lambda} \psi^{\lambda}_\alpha(k, q^+, r - b) \psi^{\lambda}_\alpha(k, q^+, r - b) \\
\times \left[ 1 + S^{(2)}_{x_A}(v, v') - S^{(2)}_{x_A}(b, v') - S^{(2)}_{x_A}(v, b) \right]
\]

- multiple scattering is taken care of by

\[
S^{(2)}_{x_A}(x, y) = \frac{1}{N_c} \left\langle \text{Tr} \left( U(x)U^\dagger(y) \right) \right\rangle_{x_A}
\]
Transform to momentum space

- To better compare with TMD factorization, let’s transform to momentum space

\[
\frac{d\sigma(qA \rightarrow \gamma^* X)}{dy d^2q_\perp} = \frac{\alpha_{em}}{2\pi^2} e_s^2 \int d^2b d^2p_\perp F(x_A, p_\perp) \left[ H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z) \right]
\]

- Unintegrated gluon distribution (dipole gluon distribution)

\[
F(x_A, p_\perp) = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ip_\perp \cdot r_\perp} \frac{1}{N_c} \left\langle \text{Tr} \left( U(0) U^\dagger(r_\perp) \right) \right\rangle_{x_A}
\]

- Hard-part functions (transverse and longitudinal polarized photon)

\[
H_T(q_\perp, k_\perp, p_\perp, z) = \left[ 1 + (1 - z)^2 \right] \left[ \frac{q_\perp - zk_\perp}{(q_\perp - zk_\perp)^2 + \epsilon_M^2} - \frac{q_\perp - zk_\perp - zp_\perp}{(q_\perp - zk_\perp - zp_\perp)^2 + \epsilon_M^2} \right]^2
\]

\[
H_L(q_\perp, k_\perp, p_\perp, z) = 2(1 - z)^2 M^2 \left[ \frac{1}{(q_\perp - zk_\perp)^2 + \epsilon_M^2} - \frac{1}{(q_\perp - zk_\perp - zp_\perp)^2 + \epsilon_M^2} \right]^2
\]
Unpolarized quark distribution

- The probability to find unpolarized quark in transversely polarized proton
  - Spin-averaged quark distribution
  - Sivers function: an asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

\[
f_{q/p}^\uparrow(x, k_\perp) = f_{q/p}(x, k_\perp^2) + \frac{\epsilon_{\alpha\beta} s_\perp^\alpha k_\perp^\beta}{M_p} f_{1T}^{\perp,q}(x, k_\perp^2)
\]
Differential cross section in pp and pA collisions

\[ f_{q/p^\uparrow}(x, k_\perp) = f_{q/p}(x, k_\perp^2) + \frac{\epsilon_{\alpha\beta}s_\perp^\alpha k_\perp^\beta}{M_p} f_{1T}^\perp q(x, k_\perp^2) \]

- **Spin-averaged virtual photon cross section**

\[
\frac{d\sigma(p^\uparrow A \rightarrow \gamma^* X)}{dyd^2q_\perp} = \frac{\alpha_{em}}{2\pi^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} d^2k_\perp x f_{q/p}(x, k_\perp^2) \int d^2bd^2p_\perp F(x_A, p_\perp) \\
\times [H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z)]
\]

- **Spin-dependent virtual photon cross section**

\[
\frac{d\Delta\sigma(p^\uparrow A \rightarrow \gamma^* X)}{dyd^2q_\perp} = \frac{\alpha_{em}}{2\pi^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} d^2k_\perp \frac{\epsilon_{\alpha\beta}s_\perp^\alpha k_\perp^\beta}{M_p} x f_{1T}^\perp q(x, k_\perp^2) \int d^2bd^2p_\perp F(x_A, p_\perp) \\
\times [H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z)]
\]

- **Single transverse spin asymmetry**

\[
A_N = \frac{d\Delta\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2dyd^2q_\perp} \bigg/ \frac{d\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2dyd^2q_\perp}
\]

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Compare to the usual TMD factorization formalism

- The spin-averaged cross section in TMD factorization formalism

\[
\frac{d\sigma(p^\uparrow A \to \ell^+\ell^- X)}{dM^2 dy d^2q} = \frac{4\pi\alpha_{em}^2}{3N_c M^4} \sum_q e_q^2 \int d^2k_\perp d^2\ell_\perp d^2\lambda_\perp \delta^2 (k_\perp + \ell_\perp + \lambda_\perp - q_\perp) \\
\times x_p f_{q/p}(x_p, k_\perp^2) x_A f_{\bar{q}/A}(x_A, \ell_\perp^2) H(M^2, x_p, x_A) S(\lambda_\perp)
\]

- For spin-dependent cross section

\[
\frac{d\Delta\sigma(p^\uparrow A \to \ell^+\ell^- X)}{dM^2 dy d^2q} = \frac{4\pi\alpha_{em}^2}{3N_c M^4} \sum_q e_q^2 \int d^2k_\perp d^2\ell_\perp d^2\lambda_\perp \delta^2 (k_\perp + \ell_\perp + \lambda_\perp - q_\perp) \\
\times \frac{\epsilon_{\alpha\beta}s_\perp^{\alpha}k_\perp^{\beta}}{M_p} x_p f_{1T,q}(x_p, k_\perp^2) x_A f_{\bar{q}/A}(x_A, \ell_\perp^2) H(M^2, x_p, x_A) S(\lambda_\perp)
\]

- How could the gluon distribution come in the game?
Quark distribution can be generated from the UGD

- Anti-quark distribution is generated from unintegrated gluon distribution

This generation in the perturbative region can be easily computed

\[
f_{\bar{q}/A}(x_A, \ell_\perp^2) = \frac{N_c}{8\pi^4} \int \frac{d\hat{z}}{x_A} \int d^2b d^2p_\perp F(x_A, p_\perp) A(p_\perp, \ell_\perp, \hat{z})
\]

\[
A(p_\perp, \ell_\perp, \hat{z}) = \left[ \frac{\ell_\perp |\ell_\perp - p_\perp|}{(1 - \hat{z})\ell_\perp^2 + \hat{z}(\ell_\perp - p_\perp)^2} - \frac{\ell_\perp - p_\perp}{|\ell_\perp - p_\perp|} \right]^2
\]
TMD factorization in terms of dipole gluon distribution

- Since anti-quark distribution is expanded to NLO, we keep the LO for hard and soft factor

\[ H(M^2, x_p, x_A) = 1 \quad S(\lambda_\perp) = \delta^2(\lambda_\perp) \]

- Differential cross section in terms of dipole gluon distribution

\[
\frac{d\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dy d^2q_\perp} = \frac{\alpha^2_{\text{em}}}{6\pi^3 M^4} \sum_q e_q^2 \int d^2 k_\perp x_p f_{q/p}(x_p, k_\perp^2) \int d\hat{z} \int d^2 b^2 p_\perp F(x_A, p_\perp) A(p_\perp, q_\perp - k_\perp, \hat{z})
\]

\[
\frac{d\Delta\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dy d^2q_\perp} = \frac{\alpha^2_{\text{em}}}{6\pi^3 M^4} \sum_q e_q^2 \int d^2 k_\perp \frac{\epsilon_{\alpha\beta} s_\perp^\alpha k_\perp^\beta}{M_p} x_p f_{1T}^\perp q(x_p, k_\perp^2) \times \int d\hat{z} \int d^2 b^2 p_\perp F(x_A, p_\perp) A(p_\perp, q_\perp - k_\perp, \hat{z})
\]
Find the leading term in small-x formalism

- One could also find the leading term in the small-x formalism we have just derived (leading: \( M \gg q_\perp \sim k_\perp \sim p_\perp (Q_s) \))

\[
\frac{d\sigma(p^\uparrow A \rightarrow \gamma^* X)}{d\sigma(p^\uparrow A \rightarrow \gamma^* X)} = \frac{\alpha_{em}}{2\pi^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} d^2k_\perp x f_{q/p}(x, k_\perp^2) \int d^2b d^2p_\perp F(x_A, p_\perp) \times \left[ H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z) \right]
\]

- Dominated by the large \( z \rightarrow 1 \) region: introduce a delta-function, integrate out \( z \) first

\[
\int d\hat{z} \delta(\hat{z} - 1/(1 + \Lambda^2/\epsilon^2_M)) = 1 \quad \Lambda^2 = (1 - z)(q_\perp - k_\perp)^2 + z(q_\perp - k_\perp - p_\perp)^2
\]

- At \( q_t << M \), they are consistent with TMD factorization

\[
\frac{d\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dy d^2q_\perp} = \frac{\alpha_{em}^2}{6\pi^3 M^4} \sum_q e^2 q \int d^2k_\perp x_p f_{q/p}(x_p, k_\perp^2) \int d\hat{z} \int d^2b d^2p_\perp F(x_A, p_\perp) A(p_\perp, q_\perp - k_\perp, \hat{z})
\]

\[
\frac{d\Delta\sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dy d^2q_\perp} = \frac{\alpha_{em}^2}{6\pi^3 M^4} \sum_q e^2 q \int d^2k_\perp \frac{\epsilon_{\alpha\beta}s_{\perp}^{\alpha \perp / M_p}}{M_p} x_p f_{1T}^{q/p}(x_p, k_\perp^2)
\]

\[
\times \int d\hat{z} \int d^2b d^2p_\perp F(x_A, p_\perp) A(p_\perp, q_\perp - k_\perp, \hat{z})
\]
Connection to collinear factorization approach - I

- When $M \sim q_\perp \gg Q_s(p_\perp)$, the usual collinear factorization should work (dilute region)
  - We should treat $k_t$ and $p_t$ (parton intrinsic transverse momenta) as small compared with the Drell-Yan pair’s momentum $q_t$

\[
H_T(q_\perp, k_\perp, p_\perp, z) = \left[1 + (1 - z)^2\right] \left[\frac{q_\perp - zk_\perp}{(q_\perp - zk_\perp)^2 + \epsilon_M^2} - \frac{q_\perp - zk_\perp -zp_\perp}{(q_\perp - zk_\perp -zp_\perp)^2 + \epsilon_M^2}\right]^2
\]

\[
H_L(q_\perp, k_\perp, p_\perp, z) = 2(1 - z)^2M^2 \left[\frac{1}{(q_\perp - zk_\perp)^2 + \epsilon_M^2} - \frac{1}{(q_\perp - zk_\perp -zp_\perp)^2 + \epsilon_M^2}\right]^2
\]

- Drop $k_t$, we could have

\[
\int d^2k_\perp f_{q/p}(x, k_\perp^2) = f_{q/p}(x)
\]

- Drop $p_t$, the hard-part function vanish, thus need to expand to higher order
Connection to collinear factorization approach - II

- In the dilute parton region, we have the relation between the UGD and collinear gluon distribution

\[
\int d^2 b d^2 p_\perp p_\perp^2 F(x_A, p_\perp) = \frac{2\pi^2 \alpha_s}{N_c} x_A f_{g/A}(x_A)
\]

- Thus expand the hard-part function to the 2nd order

\[
\int d^2 b \int d^2 p_\perp F(x_A, p_\perp) p_\perp^\rho p_\perp^\sigma \frac{1}{2} \frac{\partial}{\partial p_\perp^\rho \partial p_\perp^\sigma} [H_T(q_\perp, k_\perp = 0, p_\perp, z) + H_L(q_\perp, k_\perp = 0, p_\perp, z)]_{p_\perp \to 0}
\]

- Eventually the spin-averaged cross section can be written as

\[
\frac{d\sigma(p^A \to \ell^+ \ell^- X)}{dM^2 dy d^2 q_\perp} = \frac{\alpha^2_{\text{em}} \alpha_s}{3\pi N_c M^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} x f_{q/p}(x) x_A f_{g/A}(x_A) H(q_\perp, z)
\]

\[
H(q_\perp, z) = \frac{1}{4} g_\perp^{\rho\sigma} \frac{\partial}{\partial p_\perp^\rho \partial p_\perp^\sigma} [H_T(q_\perp, k_\perp = 0, p_\perp, z) + H_L(q_\perp, k_\perp = 0, p_\perp, z)]_{p_\perp \to 0}
\]

\[
= \frac{z^2}{(q_\perp^2 + \epsilon_M^2)^2} \left\{ [1 + (1 - z)^2] - \frac{2z^2 q_\perp^2 \epsilon_M^2}{(q_\perp^2 + \epsilon_M^2)^2} \right\}.
\]
Connection to collinear factorization approach - III

- **DY production (q+g channel) in collinear factorization approach**

\[
\frac{d\sigma(p^A \to \ell^+\ell^- X)}{dM^2 dy d^2q_\perp} = \sigma_0 \frac{\alpha_s}{4\pi^2} \sum_q e_q^2 \int \frac{dx}{x} \frac{dx_A}{x_A} f_q/p(x) f_g/A(x_A) \hat{\sigma}_{qq}^g(\hat{s}, \hat{t}, \hat{u}) \delta \left( \hat{s} + \hat{t} + \hat{u} - M^2 \right)
\]

- **Partonic cross section**

\[
\hat{\sigma}_{qq}^g(\hat{s}, \hat{t}, \hat{u}) = 2 T_R \left[ -\frac{\hat{s}}{\hat{t}} - \frac{\hat{t}}{\hat{s}} - \frac{2M^2 \hat{u}}{\hat{s}\hat{t}} \right]
\]

- **Using the relations:**

\[
\hat{s} = \frac{q_\perp^2 + \epsilon_M^2}{z(1-z)}, \quad \hat{t} = -\frac{q_\perp^2 + \epsilon_M^2}{z}, \quad \hat{u} = -\frac{q_\perp^2}{1-z},
\]

- **We have**

\[
\hat{\sigma}_{qq}^g(\hat{s}, \hat{t}, \hat{u}) = \frac{1}{1-z} \left\{ \left[ 1 + (1-z)^2 \right] - \frac{2z^2 q_\perp^2 \epsilon_M^2}{\left( q_\perp^2 + \epsilon_M^2 \right)^2} \right\}
\]

- **The small-x cross section is consistent with the above formalism**
Connection to collinear factorization approach - IV

- The spin-dependent cross section

\[
\frac{d\Delta \sigma(p^\uparrow A \rightarrow \gamma^* X)}{dyd^2q_\perp} = \frac{\alpha_{\text{em}}}{2\pi^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} d^2k_\perp \frac{\epsilon_{\alpha\beta} s_{\alpha} k_{\beta}}{M_p} x f_{1T}^q(x, k_\perp^2) \int d^2b d^2p_\perp F(x_A, p_\perp) \times \left[ H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z) \right]
\]

- Need a further expansion for the $kt$-part, since linear $kt$ associated with Sivers function

\[
\frac{d\Delta \sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dyd^2q_\perp} = \frac{\alpha_{\text{em}}^2}{6\pi^3 M^2} \sum_q e_q^2 \int_{x_p}^1 \frac{dz}{z} d^2k_\perp \frac{\epsilon_{\alpha\beta} s_{\alpha} k_{\beta}}{M_p} x f_{1T}^q(x, k_\perp^2) \int d^2b d^2p_\perp F(x_A, p_\perp) \\
\times k_\perp^\gamma p_\perp^\rho p_\perp^\sigma \frac{1}{2} \frac{\partial}{\partial k_\perp^\gamma} \frac{1}{\partial p_\perp^\rho} \frac{1}{\partial p_\perp^\sigma} \left[ H_T(q_\perp, k_\perp, p_\perp, z) + H_L(q_\perp, k_\perp, p_\perp, z) \right]_{k_\perp \rightarrow 0, p_\perp \rightarrow 0}.
\]

\[
\frac{d\Delta \sigma(p^\uparrow A \rightarrow \ell^+ \ell^- X)}{dM^2 dyd^2q_\perp} = \frac{\alpha_{\text{em}} \alpha_s}{3\pi N_c M^2} \int_{x_p}^1 dz x T_{q,F}(x, x) x A f_{g/A}(x_A)
\]

- In the forward limit, this is also consistent with collinear twist-3 formalism, even though they look very different at first

- *(Polarized)* Drell-Yan is still the cleanest process

Jan 8, 2013
Zhongbo Kang, LANL
Spin asymmetry at RHIC 510 GeV - I

- Transverse momentum dependence

Spin asymmetry is smaller in pA compared to pp, due to larger saturation scale.
Spin asymmetry at RHIC 510 GeV - II

- Rapidity dependence

The maximum happens at $y \sim 3$, which corresponds to $x_p \sim 0.2$ in the polarized proton (the Sivers function is largest at around this point)
Summary

- Polarized p+A (p+p) collisions is a good place to study both the transverse spin physics and small-x gluon saturation.
- Polarized p+A collisions might add more to the saturation physics, as they could be sensitive to the slope of the unintegrate gluon distribution in the kt-space.
- It will be interesting to study them at RHIC experiments.
  - Inclusive hadron production
  - Drell-Yan production
  - Real photon/low mass dilepton production
Engineering solutions of DX magnets for p+A collision at 200 Gev/nucleon

By Francis X Karl – Survey and Alignment Group - BNL
Outline task

• For p+Au operations – move DX magnets at IP6 and IP8 - 10 mm beam left or beam right due to aperture limitations. (Do this in a short time period - maintenance day)
• The report states that the aperture for the beam tube in the DX magnet has a radius of 68.3 mm – the Au beam is 69.4 mm from the central line of the DX magnet in the worst case. (The beam size for protons and gold are calculated using expected operating conditions in a p-Au scenario at RHIC)
• The report concludes by stating that the DX magnets at IP6 and IP8 should be moved by at least 15 mm
• From discussions – Gary McIntyre – states that the DX magnets were designed to be moved beam left and beam right by 50 mm.
INTRODUCTION:

– Procedure for alignment of the DX magnet:
  
  • Previous bench measurements – connections between the “cold mass fiducials” and the cryostat fiducials are saved in the RHIC magnet data base (as presented in the next figure).
  
  • Available adjustments of the magnet positions in the tunnel (specials bellows at the magnet ends are used) - previously it was assumed transverse motion of 4.6 cm) the cryostat fiducials in the RHIC tunnel).
Cold mass fiducials

- Design 9.250"
- 176.180" - Design
- Design 9.250"
- 157.78" - Design
- 9.422"
- 9.390"
- 9.426"
- 9.428"

Non Lead End

LerfEnd

M1, M2, M3, M4

NlerfEnd

Non Lead End

Left

Right
“Cold mass” and cryostat fiducials
Field visit DX magnet areas

• A field visit was conducted in each of the four area where the DX magnet moves are necessary.
• 5 o’clock DX Area – the magnet is easily accessible and the support bases are clear of obstructions – the survey references are also available and easy to observe during the proposed move. There is a large vacuum bellows on the IR side of the cryostat (this is designed to take the 50 mm movement). The DO side has the pant leg vacuum vessel attached and was also designed to take the 50 mm movement but there has been shielding added in the area – this will limit the amount of movement (if the pant leg vacuum vessel moves with the DX).
DX Cryostat – 5 o’clock - RHIC
Typical support for DX magnet
Horizontal and vertical adjusters and cryostat fiducial
5 O’CLOCK DX Area (continued)

• there is a visible gap between the pant leg vacuum pipe and the shielding of 3.5 mm if the DX were to move 10 mm and the pant leg vacuum pipe were to go with the DX and pivot at the D0 it would close the clash point to 1.5 mm. We wanted to exercise the system at the beginning of December 2012 but were asked to hold off until next year’s summer shutdown due to work load and the fact that if something were to break just before the run we might hold up the physics run.
5 o’clock “pant leg” vacuum pipe possible clash with shielding

- 4mm gap
  - Outer beam pipe (BLUE Ring)
- 3.5mm gap
  - Inner beam pipe (YELLOW Ring)
6 O’clock DX Area

• The 6 o’clock area is similar to the 5 o’clock area in that it is easy to access the magnet movers at the support base, there are no obstructions, observing and locating the cryostat targets during the move can be accomplished using 2 laser trackers – one on each side of the DX and both tied into the same control points.

• The area of concern at 6 o’clock DX is the fact that the ion pump on the IR side of the DX is attached to the gate valve – then the bpm is attached to the ion pump tee, then the 12” bellows – this will have to be taken into consideration when moving the DX. The ion pump will have to move with the DX – this is not easily accomplished – this ion pump was moved closer to the DX to make room for experimental equipment on the ledge above the STAR Magnet.
6 O’clock DX
6 O’clock DX Ion Pump IR side

- The ion pump does not have a conventional set of adjusters to move it and will have to be moved as the DX is moved – this should be looked at ahead of the move to facilitate the new position – supports and adjusters should be planned and modification made before the move – consult with vacuum group regarding accessibility to the pump – remove the heat blankets, etc.
7 & 8 O’clock DX Areas

• These areas are not so easy to access – they are surrounded by shielding and a protective cage that limits our vista to the cryostat fiducials, there is a moveable shielding system that has tracks, 20 inches above the floor, 8 inch thick steel shielding in the form of a reversed “U” shape rides on these rails, over the DX magnet, making it hard to see and get to the adjustment support base of the cryostats.

• There is limited room for setting a laser tracker up to access RHIC control monuments so the alignments team can monitor the movement and record the final position of the magnets – additional targeting should be added to the area to the process.
7 O’clock DX Area

Yellow moveable shielding
7 o’clock DX Area

Electric waterfall tray near support base of DX magnet
8 O’clock DX Area

8 O’clock DX inner (Blue)

8 O’clock DX outer (Yellow)
Conclusion

• 5 O’clock DX move 15 mm beam left or beam right
• 6 O’clock DX move 15 mm beam left or beam right – must adapt the large ion pump on the IR side of the DX, take off the heat blankets
• 7 O’clock DX will hit moveable shielding on the inner if moved over 10 mm – outer if moved over 15 mm
• 8 O’clock DX will hit moveable shielding on the inner if moved over 12.5 mm – outer if moved 2.5 mm – this is the limiting move
• Action items – decide which way and by how much to move the DX magnets - adjustable base for the ion pump at 6 o’clock, remove the bake out blanket – set additional control monuments at 7 & 8 o’clock so that moves can be monitored and the location recorded and change in all four BPM locations can be established and relayed to the machine operators.
8 O’clock DX AREA

8 O’clock inner (BLUE)

12.5mm gap

8 O’clock outer (YELLOW)

2.5mm gap
Single-Spin Asymmetry in Polarized p+A Collisions

Yuri Kovchegov
The Ohio State University

based on arXiv:1201.5890 [hep-ph] and more recent work with Matthew Sievert
(special thanks to Michael Lisa)
Outline

• Introduction (STSAs, saturation/CGC)
• Calculation of STSA in CGC
  – New mechanism: odderon exchange with the unpolarized nucleus
  – Sivers effect: including it into the CGC framework
• Conclusions and outlook
Introduction
Single Transverse Spin Asymmetry

- Consider polarized proton scattering on an unpolarized proton or nucleus.

- Single Transverse Spin Asymmetry (STSA) is defined by

\[
A_N(k) \equiv \frac{d\sigma^\uparrow}{d^2k\,dy} - \frac{d\sigma^\downarrow}{d^2k\,dy} = \frac{d\sigma^\uparrow}{d^2k\,dy}(k) - \frac{d\sigma^\uparrow}{d^2k\,dy}(-k) = \frac{d(\Delta\sigma)}{2\,d\sigma_{unp}}
\]
STSA: the data

- The asymmetry is non-zero, and is an increasing function of Feynman-$x$ of the polarized proton:

\[ A_N \text{ vs } x_F \text{ in } \pi \text{ Production} \]

(FNAL 1991)

Fermilab E581 & E704 collaborations 1991
STSA: a more recent data

\[ p + p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

\[ A_N \]

\[ \langle \eta \rangle = 3.7 \]

\[ \langle \eta \rangle = 3.3 \]

STSA: the data

- STSA is also a non-monotonic function of transverse momentum $p_T$, which has zeroes (nodes), where its sign changes:

\[ A_N \text{ vs } p_T \text{ for } \pi^0 \text{ Production} \]

(RHIC, STAR collaboration 2008)
STSA: a more recent data

\[ \pi^0 A_N \text{ vs } P_T (0.16 < X_F < 0.24) \]

- Red: \( X_F > 0 \) (Isolation 30 mR)
- Blue: \( X_F > 0 \) (Isolation 70 mR)
- Yellow: \( X_F < 0 \) (Isolation 70 mR)

\( \sqrt{s} = 500 \text{ GeV} \) \( \pi^0 \) Energy 50 GeV (\( X_F \sim 0.20 \))

STAR Run 11 PRELIMINARY
The origin of STSA (in the collinear/TMD factorization framework) is in:
- polarized PDF (Sivers effect)
- polarized fragmentation (Collins effect)
- hard scattering
Need to understand STSAs in the saturation/CGC framework

• At RHIC, even in $p^\uparrow+p$ collisions reach small values of $x$ in the unpolarized proton $\rightarrow$ saturation effects may be present
• For $p^\uparrow+A$ scattering, nuclear target would further enhance saturation/CGC effects, making understanding the role of saturation in STSA a priority
• Spin-dependent probes may provide new independent tests of saturation/CGC physics.
High Energy QCD: saturation physics

- Saturation physics is based on the existence of a large internal momentum scale $Q_s$ which grows with both energy $s$ and nuclear atomic number $A$

$$Q_s^2 \sim A^{1/3} s^\lambda$$

such that

$$\alpha_s = \alpha_s(Q_s) \ll 1$$

and we can calculate total cross sections, particle spectra and multiplicities, etc, from first principles.

- Bottom line: everything is considered perturbative.
Saturation physics allows us to study regions of high parton density in the small coupling regime, where calculations are still under control!

Transition to saturation region is characterized by the saturation scale

\[ Q_s^2 \sim A^{1/3} \left( \frac{1}{x} \right)^\lambda \]
A reference

Quantum Chromodynamics at High Energy
Yuri V. Kovchegov and Eugene Levin

Published in September 2012 by Cambridge U Press
Calculation of STSA in CGC
What generates STSA

• To obtain STSA need

  – transverse polarization dependence
    (comes with a factor of “i”)

  – a phase difference by “i” between the amplitude and cc amplitude to cancel the “i” from above (cross section and STSA are real)

(from Qiu and Sterman, early 90’s)
(i) Shooting spin through Color Glass
Forward quark production

- It is easier to work in transverse coordinate space:

\[
\frac{d\sigma}{d^2k \, dy} \propto |M(k)|^2 = \int d^2x_1 \, d^2x_2 \, M(x_1) \, M(x_2)^* \, e^{-i \mathbf{k} \cdot (x_1 - x_2)}
\]

- The quark (transverse) coordinates are different on two sides of the cut!
The eikonal quark propagator is given by the Wilson line

\[ V(x) = \text{P} \exp \left[ i g \int_{-\infty}^{\infty} dx^+ A^- (x^+, x^- = 0, x) \right] \]

with the light cone coordinates

\[ x^\pm = \frac{t \pm z}{\sqrt{2}} \]
Forward quark production

- The amplitude squared is
  \[ \frac{1}{N_c} \langle \text{tr} \left\{ [V(x_1) - 1] [V^\dagger(x_2) - 1] \right\} \rangle = 1 + \frac{1}{N_c} \langle \text{tr} \left[ V(x_1) V^\dagger(x_2) \right] \rangle \]
  
- The quark dipole scattering amplitude is
  \[ N(x_1, x_2) = 1 - \frac{1}{N_c} \langle \text{tr} \left[ V(x_1) V^\dagger(x_2) \right] \rangle \]

- Hence quark production is related to the dipole amplitude! Valid both in the quasi-classical Glauber-Mueller/McLerran-Venugopalan multiple-rescattering approximation and for the LLA small-x evolution (BFKL/BK/JIMWLK).

\[ \text{Dumitru, Jalilian '02} \]
Dipole Amplitude

- Dipole scattering amplitude is a universal degree of freedom in CGC.
- It describes the DIS cross section and structure functions:

\[ q \gamma^* \rightarrow x_\perp \rightarrow x_\perp \]

- It also describes single inclusive quark (shown above) and gluon production cross section in DIS and in pA.
- Even works for diffraction in DIS and pA.
- For correlations need also quadrupoles, etc. (J.Jalilian-Marian, Yu.K. ‘04)
Spin-dependent quark production

- The eikonal quark production is indeed spin-independent, and hence can not generate STSA.

- Simple recoil, while spin-dependent, is suppressed by 1/s:
Spin-dependent quark production

The only way to include spin dependence without 1/s suppression is through the splitting in the projectile before or after the collision with the target:

Let’s calculate the corresponding quark production cross section, find its spin-dependent part, and see if it gives an STSA.
Squaring the amplitude we get the following diagrams contributing to the production cross section:
Extracting STSA

- STSA can be thought of as the term proportional to
  \[(\vec{S} \times \vec{p}) \cdot \vec{k}\]

- To get a $k_T$-odd part of the cross section

\[
\frac{d\sigma^{(q)}}{d^2k \, dy_q} = \frac{C_F}{2 \, (2\pi)^3} \frac{\alpha}{1 - \alpha} \int d^2x \, d^2y \, d^2z \, e^{-ik \cdot (z-y)} \, \Phi \chi(z-x, y-x) \, \mathcal{I}^{(q)}(x, y, z)
\]

we need the $y \leftrightarrow z$ anti-symmetric part of the integrand.

- This may either come from the wave function squared or from the interaction with the target.

- Our LO wave function is symmetric: need to find the anti-symmetric interaction!
C-even and C-odd dipoles

- To find the anti-symmetric interaction we decompose the dipole amplitude into real symmetric (C-even) and imaginary anti-symmetric (C-odd) parts:

\[
\frac{1}{N_c} \langle \text{tr} \left[ V_x V_y^\dagger \right] \rangle = S_{x,y} + i O_{x,y}
\]

- The symmetric part is

\[
S_{x,y} = \frac{1}{2} \left\{ \frac{1}{N_c} \langle \text{tr} \left[ V_x V_y^\dagger \right] \rangle + \frac{1}{N_c} \langle \text{tr} \left[ V_y V_x^\dagger \right] \rangle \right\}
\]

- The anti-symmetric part is

\[
O_{x,y} = \frac{1}{2i} \left\{ \frac{1}{N_c} \langle \text{tr} \left[ V_x V_y^\dagger \right] \rangle - \frac{1}{N_c} \langle \text{tr} \left[ V_y V_x^\dagger \right] \rangle \right\}
\]

- As \( x \leftrightarrow y \) interchanges quark and antiquark, it is C-parity!
C-even and C-odd dipoles

- $S_{xy}$ is the usual C-even dipole amplitude, to be found from the BK/JIMWLK equations: describes DIS, unpolarized quark and gluon production.
- $O_{xy}$ is the C-odd odderon exchange amplitude, obeying a different evolution equation (Yu.K., Szymanowski, Wallon ’03; Hatta et al ‘05).
- At LO the odderon is a 3-gluon exchange:

\[ \sigma_{\text{odd}} \sim s^0 \sim \text{const} \]

- The intercept of the odderon is zero (Bartels, Lipatov, Vacca ’99):
  
- In our setup, odderon naturally generates STSA.
STSA in high energy QCD

• When the dust settles, the spin-dependent part of the production cross section is

\[ d(\Delta \sigma^{(q)}) = \frac{C_F}{(2\pi)^3} \frac{\alpha}{1 - \alpha} \int d^2x \, d^2y \, d^2z \, e^{-ik \cdot (z - y)} \Phi_{pol}(z - x, y - x) \mathcal{I}^{(q)}_{anti}(x, y, z) \]

with the C-odd interaction with the target

\[ \mathcal{I}^{(q)}_{anti} \bigg|_{large-N_c} = i \left[ O_{zy} + O_{uw} - O_{zx} S_{xw} - O_{ux} S_{xy} - S_{zx} O_{xw} - S_{ux} O_{xy} \right] \]

• Note that the interaction contains nonlinear terms: only those survive in the end.
• The expression for the interaction at any \( N_c \) is known.
Properties of the obtained STSA contribution
Odderon STSA properties

Our odderon STSA is a non-monotonic function of transverse momentum and an increasing function of Feynman-x:

Warning: very crude approximation of the formula. ($Q_s = 1$ GeV)
Curves are for (Feynman-x) $\alpha =$0.9 (dash-dotted), 0.7 (solid), 0.6 (dashed), 0.5 (dotted).
Dependence on density gradient

- Our STSA is proportional to the square of the gradient of the nuclear profile function $T(b)$:

\[ A_N \sim \int d^2 b \ [\nabla T(b)]^2 \ldots \]

- The asymmetry is larger for peripheral collisions, and is dominated by edge effects.

- It is also smaller for nuclei ($p^{\uparrow}+A$) than for the proton target ($p^{\uparrow}+p$).
Odderon STSA properties

To illustrate this we plot $A_N$ with a different large-b (IR) cutoff:

Warning: very crude approximation of the formula. $(Q_s=1 \text{ GeV})$
Curves are for (Feynman-$x$) $\alpha = 0.9$ (dash-dotted), 0.7 (solid),
0.6 (dashed), 0.5 (dotted).
Odderon STSA at high-$p_T$

• The odderon STSA is a steeply-falling function of $p_T$:

$$A_N^{(q)} \bigg|_{p_T \gg Q_s} \propto \frac{1}{p_T^5}$$

• However, the suppression at high transverse momentum is gone for $p_T \sim Q_s$ (from one to a few GeV).
Nuclear (unpolarized) target

Target radius is $R=1$ fm (top curve), $R=1.4$ fm (middle curve), $R=2$ fm (bottom curve): strong suppression of odderon STSA in nuclei. Warning: crude approximation of the exact formula!
Gluon STSA

- is also found along the same lines:

Properties TBD, likely similar to quark STSA
Prompt photon STSA

- is zero (in this mechanism).
- The photon asymmetry originated in the following spin-dependent production cross-section

\[
\frac{d(\Delta \sigma^{(\gamma)})}{(2\pi)^3} = \int d^2 x \, d^2 y \, d^2 z \, e^{-i\mathbf{k} \cdot (\mathbf{z} - \mathbf{y})} \Phi_{\text{pol}}(x - z, x - y, \alpha) \mathcal{I}_{\text{anti}}^{(\gamma)}(x, y, z)
\]

with the interaction with the target linear in the odderon exchange

\[
\mathcal{I}_{\text{anti}}^{(\gamma)} = i \left[ O_{\mathbf{w}} - O_{\mathbf{xw}} - O_{\mathbf{ux}} \right]
\]

- This cross section is zero since

\[
\int d^2 x \, O_{\mathbf{x}, \mathbf{x+y}} = 0
\]

for any odd function

\[
O_{\mathbf{x}, \mathbf{y}} = -O_{\mathbf{y}, \mathbf{x}}
\]
(ii) Sivers effect in Color Glass
Sivers vs Odderon

• In the above STSA mechanism the spin-dependence came from the polarized wave function, while the phase was generated in the interaction. (The wave function was too simple to contain a phase.)

• The phase may also arise in the polarized wave function – this is Sivers effect.

• How does it come into CGC? Is it leading or subleading to the above effect?
Sivers effect in CGC

• We have explored the case of C-even wave function squared and C-odd interactions.
• One also needs to look into the case of C-odd wave function squared and C-even interaction with the target:

• This is the analogue of the works by Brodsky, Hwang, Schmidt ’02 and Collins ’02 in our saturation language.
• As \( O_{xy} \sim \alpha_s S_{xy} \) this is of the same order as the odderon STSA.
Sivers effect in CGC

- Both the phase and spin-dependence come from the top of the diagram. The phase is denoted by a cut (Im part = Cutkosky rules).
- However, the extra rescattering generating the phase can only be in the final state as shown (no phase arising in the initial state that we could find).
- Interaction with the target is C-even: no odderon!
Sivers effect in CGC

- This is still work in progress (YK, M. Sievert).
- The answer should look like

\[ d\Delta\sigma \propto \int d^2x \, d^2y \, d^2z \, d^2v_1 \, d^2v_2 \, d\alpha' \, e^{-i \mathbf{k} \cdot (\mathbf{z} - \mathbf{y})} \, i \, A_{2\rightarrow2}(\mathbf{v}_1, \mathbf{v}_2, \mathbf{x}, \mathbf{z}) \]

\[ \times \Phi_{pol}(\mathbf{v}_2 - \mathbf{v}_1, \mathbf{y} - \mathbf{x}; \alpha, \alpha') \, \mathcal{I}_{symm}(\mathbf{x}, \mathbf{y}, \mathbf{v}_2) - (z \leftrightarrow y) \]

- Very hard to calculate amplitude A in coordinate space (not eikonal, no simplifications, may also need term where spin-dependence is in A).
Sivers effect in CGC

- May be lower-twist than the odderon STSA,

\[ A_N \bigg|_{p_T \gg Q_s} \propto \frac{1}{p_T^3} \quad (?) \text{tbc} \]

but the two may be comparable for \( k_T \sim Q_s \).

- Would lead to non-zero STSA for prompt photons!

- Perhaps the odderon STSA contribution can be found by subtracting photon STSA from the hadron STSA, though there is also the Collins mechanism for hadron STSA.

- Sivers STSA in CGC in \( p^{\uparrow} + A \) scattering is also likely suppressed compared to \( p^{\uparrow} + p \), but more work is needed to check this.
Conclusions

• It seems STSA in $p^\uparrow+A$ collisions can be generated by three possible mechanisms: Sivers, Collins, and odderon-mediated.

• Odderon mechanism has right qualitative features of STSA, but falls off fast at high $p_T$. It is much smaller in $p^\uparrow+A$ than in $p^\uparrow+p$. Predicts zero photon/DY STSA.

• Sivers effects is leading at high-$p_T$ (compared to the odderon), and probably is also suppressed in $p^\uparrow+A$ vs $p^\uparrow+p$, but this needs to be confirmed. Photon/DY STSA is non-zero.

• I do not have much to say about Collins effect in $p^\uparrow+A$, but fragmentation function may be modified by nuclear environment, possibly modifying the effect.
Prompt Photon $A_N$ with the PHENIX MPC-EX Detector

J. Lajoie
Iowa State University
for the PHENIX MPC-EX group
Single Transverse Spin Asymmetries

Theory Expectation:
Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

\[ A_N \propto \frac{m_q}{\sqrt{S}} \]

Experiment:
(E704, Fermi National Laboratory, 1991)

\[ pp^\uparrow \rightarrow \pi + X \]
\[ \sqrt{s} = 20 \text{ GeV} \]

\[ A_N = \frac{1}{P} \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi} \]

\[ A_N \text{ O}(10^{-1}) \text{ Measured} \]

\[ A_N \text{ O}(10^{-4}) \text{ Theory} \]

\[ A_N \text{ difference in cross-section between particles produced to the left and right} \]

E704: Left-right asymmetries
\[ A_N \text{ for pions:} \]

\[ x_F = \frac{2p_L}{\sqrt{s}} \]
Sources of Transverse SSA’s

“Sivers effect”

**TMD:** Correlation between nucleon spin and parton $k_T$.


$$d\sigma^\uparrow \propto f_{1T}^q(x, k_T^2) \cdot D^h_q(z)$$

**Twist-3:** Quark-gluon correlations in polarized hadron


$$gT_{q,F}(x,x) = -\int d^2 k_T \left| k_T^\perp \right|^2 M f_{1T}^q(x, k_T^2)$$

Sivers distribution

“Collins effect”

**TMD:** Transversity distributions + Spin dependent fragmentation functions


$$d\sigma^\uparrow \propto \delta q(x) \cdot H^q_1(z_2, k_T^2)$$

**Twist-3:** Transversity combined with twist-3 quark-gluon fragmentation function
Single Spin Asymmetries in PHENIX MPC

• Current measurements cannot address the source of these asymmetries
  – Need more targeted measurements
Prompt Photons at Forward Rapidity

**Direct Photons**
Dominated by gluon Compton at forward rapidities

Same level of production in pythia and NLO calculations (within factor of ~2)

**Fragmentation Photons**
Comparable between pythia and NLO calculations

**QED Radiation (initial state)**
Production over-estimated in Pythia (Included in direct in NLO)

\[ x_1 \quad 3.1 < \eta < 3.8 \]
\[ x_2 \quad 3.1 < \eta < 3.8 \]

\[ \log(x_1) \]
\[ \log(x_2) \]

p\(\uparrow\)+p : high-\(x\) quarks
p+A : low-\(x\) gluons
The MPC-EX Detector

A combined charged particle tracker and EM preshower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

- $\pi^0$ rejection (direct photons)
- $\pi^0$ reconstruction out to >80GeV
- Charged track identification

3.1<\eta<3.8

Approved by BNL and DOE - will be ready for Run-15 (earliest p+Au run)
Minipad Sensors

Detector elements are Si “minipad” detectors, one layer per tungsten gap, oriented in X and Y (alternating layers).

$\pi^0$ mesons reconstructed in p+p jet events (E>20GeV)

Cross-Section View:

- 1.8mm x 15mm “minipad” sensor
- Dual SVX-4 Readout Card
- Minipad micromodule (X or Y)
- ~50mm
- 2mm tungsten
- Detector elements are Si “minipad” detectors, one layer per tungsten gap, oriented in X and Y (alternating layers).

Single-Track Pizero Candidates

<table>
<thead>
<tr>
<th>Entries</th>
<th>24366</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.1009</td>
</tr>
<tr>
<td>RMS</td>
<td>0.05625</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>38.8 / 35</td>
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<tr>
<td>$p_0$</td>
<td>466.6 ± 42.3</td>
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<tr>
<td>$p_1$</td>
<td>-9.592 ± 0.882</td>
</tr>
<tr>
<td>$p_2$</td>
<td>503.6 ± 9.3</td>
</tr>
<tr>
<td>$p_3$</td>
<td>0.1407 ± 0.0004</td>
</tr>
<tr>
<td>$p_4$</td>
<td>0.02178 ± 0.00057</td>
</tr>
</tbody>
</table>

mass (GeV/c^2)
MPC-EX Event Reconstruction

Event 26

Arm = 1
Energy = 45.60 GeV
Mass = 0.147 GeV
Vertex = 0.40 cm

Hough Slope 1x = 0.05601
Hough Slope 1y = -0.02504
Hough Slope 2x = 0.05892
Hough Slope 2y = -0.01924

E1 = 23.94 GeV
E2 = 21.65 GeV
Asymmetry = 0.050

True Energy = 43.66 GeV
True Asymmetry = 0.197
True Hough Slope 1x = 0.05832
True Hough Slope 1y = -0.01916
True Hough Slope 2x = 0.05644
True Hough Slope 2y = -0.02519

First X Layer = 0
First Y Layer = 1
MIPs in Last Layer = 244.3
radius of hit = 13.42 cm

Exit
The MPC-EX Physics Program

• The Gluon Distribution in Cold Nuclear Matter at Low-\(x\):  
  - Single \(\pi^0\) production  
  - \(\pi^0\) pairs  
  - Prompt Photons

\[ \text{Extended kinematic range for existing measurements} \]  
\[ (p_T>1 \text{ GeV/c}, \ E>20\text{GeV}) \]

• Source of \(A_N\) in \(p^\uparrow+p\) Collisions:  
  - Prompt Photon \(A_N\)  
  - \(\pi^0\) correlations with jet-like clusters  
    • “pioneering” measurement  
  - Jet \(A_N\)
Prompt Photon Simulations ($\pi^0$ cuts)

868M pythia MB+direct photon events (200GeV)

Basic cuts designed to remove $\pi^0$, charged hadrons and other backgrounds.

For $p_T > 3$ GeV:

2.9% efficiency for $\pi^0$
31.2% efficiency for direct photons
$\text{dir/(frag+dir)}$: 57.4%
Direct and Frag. Photon $A_N^{\text{Direct}} (x_F>0)$

$A_N^{\text{Direct}}$ falls with $x_F$, while $A_N^{\text{Frag}}$ rises with $x_F$.


$$gT_{q,F} (x,x) = -\int d^2k_{\perp} \frac{|k_{\perp}|^2}{M} f_{1T}^{\perp q} (x,k_{\perp}^2)$$
Separating Direct and Frag. Photons


Can control the direct/frag ratio with tightened isolation cuts in the MPC/MPC-EX

<table>
<thead>
<tr>
<th></th>
<th>$\pi^0$ Cuts</th>
<th>Cuts 1</th>
<th>Cuts 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct-to-signal ratio</td>
<td>57.4%</td>
<td>68.3%</td>
<td>78.6%</td>
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<tr>
<td>$R_\gamma$</td>
<td>1.34</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td>Signal-to-$\pi^0$ ratio</td>
<td>43 ± 5 %</td>
<td>37 ± 7</td>
<td>40 ±13 %</td>
</tr>
<tr>
<td>Direct photon $\varepsilon$</td>
<td>31.2%</td>
<td>15.1%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Frag. photon $\varepsilon$</td>
<td>24.3%</td>
<td>7.3%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

Tightening cuts
Prompt Photon $A_N (x_F>0)$

$$A_S = (1 + \frac{1}{r})A_{meas} - \frac{1}{r}A_B.$$  \[ r = \frac{S}{B} = 0.34 \]

$$(\delta A_S)^2 = (1 + \frac{1}{r})^2(\delta A_{meas})^2 + \left(\frac{1}{r}\right)^2(\delta A_B)^2.$$  

**Prompt Photon $A_N$**

- Projected error bars assume statistical errors, subtraction of $\pi^0$ and $\eta$ photon asymmetry, and 60% polarization
- Test of theoretical frameworks
- Measure of quark Sivers

**Prompt photon measurements with MPC-EX will resolve the issue.**
Prompt Photon $A_N (x_F<0)$

$x_F<0$ samples the gluon distribution in the polarized proton

Two different tri-gluon correlation functions: $O(x)$ and $N(x)$

Models:

(a) $O(x) = K_G x G(x)$ \hspace{1cm} $N(x) = O(x)$

(b) $O(x) = K'_G \sqrt{x} G(x)$ \hspace{1cm} $N(x) = O(x)$

(c) $O(x) = K_G x G(x)$ \hspace{1cm} $N(x) = -O(x)$

Parameters constrained by open heavy flavor production at RHIC.

$A_N$ for $x_F<0$ carries information about the tri-gluon correlation function.
**Polarized p+A Collisions**

\[ A_N = \frac{1}{P} \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi} \]

Kang and Yaun, PRD 84, 034019 (2011) (asymmetries modeled as Collins)

Single spin asymmetries can act as a probe of the saturation scale.

A unique capability of RHIC!

- Dependence of \( Q_{sA} \) on \( A \)
- Combined with other measurements this can estimate \( Q_{sp} \)

\[ Q_{sp}^2 = (1.0 \text{ GeV})^2 \]
\[ Q_{sA}^2 = (2.5 \text{ GeV})^2 \]
\[ \delta = 0.16 \text{ GeV} \]

Approximate error in ratio assuming \( \delta A_N/A_N \sim 0.1 \)
Collins Asymmetry in Jets

- All tracks given equal weight
- Select the cluster with highest number of tracks

MIP ~ 36 MeV

Charged Tracks:
All layers hit
Energy deposit < 70MeV

charged cluster axis
R=1.0

Single-Track n° Charged Cluster (>=3 tracks) Asymmetry - 40pb² sampled, P=0.6

50pb⁻¹, P=0.6

Charged clusters with >=3 tracks,
single-track π⁰'s
Summary

• The MPC-EX is a novel detector that offers exciting new physics opportunities:
  – Separate the sources of SSA’s measured in 200GeV transversely polarized p+p collisions
    • Deepen understanding of hadron structure
    • Enable continued progress in the application of fundamental QCD to p+p collisions
  – Measurement of the gluon distribution in cold nuclear matter
    • Further understanding saturation, shadowing, ...
    • Set initial conditions for HI collisions at RHIC and LHC

• Exciting new physics output from RHIC!
The PHENIX Muon Piston Calorimeter Extension (MPC-EX)

Colored band = range with MPC-EX direct photon data

**d+Au: Gluons in Nuclei**

- **MPC-EX**
  - 350nb\(^{-1}\) d+Au
  - 49pb\(^{-1}\) p+p

- ESP09 extents

- **ESP09 extents**

- **49pb\(^{-1}\), P=0.6**

- **pol. protons: Origin of \(A_N\)**

1/8/2013

BNL p+A Workshop
BACKUP
Process Breakdown

Direct photons 100% $q+g$ for $p_T>3$GeV
Fragmentation photons 93% $q+g$, 7% $q+\bar{q}$ for $p_T>3$GeV
Why p+A instead of d+A?

Multi-parton interactions can contribute to the suppression of the away-side correlation strength.

Forward rapidity corresponds to \textit{high}-x in the projectile nucleon (d or p). Nuclear corrections at high-x are large for the deuteron, which may necessitate d+p running for proper comparison.

\textit{...and you can’t polarize the deuteron at RHIC...}
SSA’s in polarized p+A Collisions

- Kang and Yuan, PRD 84, 034019

\[
\frac{A_{N}^{p+A \rightarrow h}}{A_{N}^{p+p \rightarrow h}} \bigg|_{P_{h\perp}^2 \ll Q_{s}^2} \approx \frac{Q_{s,p}^2}{Q_{s,A}^2} \cdot e^{\frac{P_{h\perp}^2 \cdot \delta^2}{Q_{s,p}^4}}, \quad \frac{A_{N}^{p+A \rightarrow h}}{A_{N}^{p+p \rightarrow h}} \bigg|_{P_{h\perp}^2 \gg Q_{s}^2} \approx 1
\]

A systematic study of SSA’s in spin-polarized p+A collisions would allow us to study the gluon saturation scale.
EPS09 Limits from Direct Photons

Ultimate sensitivity depends on the measurement and a full NLO fit.
Gluons in Nuclei

Fit data on nuclei:
SLAC, NMC, EMC
DIS+DY+PHENIX
midrapidity $\pi^0$

Lack of data
$\Rightarrow$ large uncertainly in gluon pdf at low-x

Large uncertainties in low-x gluons in nuclei!

Important for fundamental understand of partonic processes in nuclei, as well as for the initial conditions at RHIC and the LHC.

Use EPS09 as a baseline for comparison.

The MPC-EX measurement will directly address any model of low-x gluons.
EPS09 Limits from Prompt Photons

- Weight events in \( x, Q^2 \) according to EPS09 to generate \( R_{dAu} \) for each curve
- Assume the \( R_{dAu} \) value we measure corresponds to the EPS09 baseline
- Vary \( R^{pp}_{\gamma}, R^{dAu}_{\gamma}, R^{dAu}_{incl} \) and \( R^{pp}_{incl} \) within 3-sigma systematic errors
- Evaluate EPS09 curves to see which are consistent within 90% C.L.

Prompt photons in MPC-EX -> Precise Measurement of Gluons at Low-\( x \)
Direct Photon NLO Cross Sections

NLO Cross Sections

NLO calculations from Werner Vogelsang
Direct Photons in Pythia
Physics opportunities with Di-muon analysis at PHENIX
- Drell-Yan and quarkonia

Kwangbok Lee
Los Alamos National Laboratory
Quarkonia are produced mostly by gluon fusion and good probes to explore gluon distribution in nucleus.

- Nuclear absorption (final)
- Initial state parton energy loss.

\(-\) disentangle effects seen at hot nuclear collision.

\[ x_2 = \frac{m_T e^{-y}}{\sqrt{s}} \]
Drell-Yan for Heavy Ion physics

• Quarkonia measurements are not enough to disentangle the cold nuclear effects.
• The leptons from Drell-Yan process ($qq \rightarrow \gamma^* \rightarrow l^+l^-$, $qg \rightarrow q\gamma^*$) does not interact with the nuclear medium.
• Ideally suited to separate the initial-state parton energy loss and parton modification, given the absence of final-state effects.

The NA50 experimental ratio of the total $J/\psi$ cross sections and Drell-Yan cross sections as a function of the nuclear length $L$.

arXiv:nucl-th/0212046
Backgrounds under Drell-Yan and control with FVTX/VTX

\[ \sqrt{s} = 200 \text{ GeV} \text{ simulation, } p+p \text{ pythia} \]

- Between 4 GeV/c^2 and 8 GeV/c^2 is thought to be dominated by Drell-Yan process and correlated BB.
- We would separate Drell-Yan process and correlated BB which have different decay lengths, using silicon vertex detector, (F)VTX between 4 and 8 GeV/c^2.
- We would get order of five thousand events for each arm with FVTX with 300 pb\(^{-1}\) (p+p equivalent), current muon arm configuration, efficiencies included.
FVTX operation

• 75 μm pitch strips in radial direction, \( r \) and 3.75° along \( \phi \) direction.

• Cover same pseudorapidity, \(|\eta|\) of 1.2 to 2.4(2.2) with Muon arm.
  -> Sample momentum fraction, \( x_2 \), order of \( 10^{-3} \) to \( 10^{-2} \) for the Drell-Yan.

• Match track with Muon arm +(F)VTX.
  -> Improve mass resolution.

• Measure the primary vertex and secondary decay.
  -> Extract dimuon vertices, DCAs, to distinguish Drell-Yan and heavy flavor decay background.

Decay length of Drell-Yan : none
Decay length of B meson : \( \sim 500 \mu m \)
PHENIX J/ψ $R_{dAu}$ measurement

- Tried to fit the data with shadowing model, EPS09 + breakup cross section.

- The centrality dependence of these $J/\psi$ suppression results at forward rapidity is not well described quantitatively by nuclear-shadowing models that include final-state breakup effects.

\[ \Lambda(r_T) = \frac{1}{\rho_0} \int dz \rho(z,r_T) \]

\( y \text{ Phys. Rev. Lett. 107, 142301 (2011)} \)

-> See Cesar’s talk for more detail
$\chi_c$ at mid rapidity

- Higher charmonium state (1P) than $J/\psi$ (1S).
- There are three states of $\chi_c$.
- Radiative decay channel $\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- (e^+e^-) + \gamma$.
- $R_{\chi_c} = (\chi_c \rightarrow J/\psi + \gamma) / (\text{Inclusive } J/\psi)$.
- Decouple the fraction of decay $J/\psi$ and direct $J/\psi$ and check the production mechanism.
- $\chi_c$ has weak binding energy than other quarkonia, rather easily break up.
$\chi_c$ at forward rapidity

Forward E.M. Calorimeter (MPC)
3.1 < $|\eta|$ < 3.9

Muon arm, 1.2 < $|\eta|$ < 2.4

pA workshop, 1/9/2013
\( \chi_c \) at forward rapidity

- We saw the peak, but large uncertainties due to the large backgrounds from low energy photon mess up the \( \chi_c \) signal.

- Future upgrade with Calorimeter will improve \( \chi_c \) measurement at forward/mid rapidities.

\( \sqrt{s_{NN}} = 200\text{GeV}, \ dAu \ North \)
Nuclear modification factor, $R_{CP}$ measurement for low mass vector mesons

- Significant suppression at deuteron going direction.
- Stronger suppression for $\rho/\omega$ than $\phi$ and $J/\Psi$.
The rapidity dependence of the observed suppression at forward and backward rapidities are compatible with lower energy results and a NLO theoretical calculation.

Expect to separate out $\Upsilon$ of the ground state and the exited states with the future upgrade.
Summary

- Drell-Yan measurement at pA collision is interesting to test initial-state \textit{quark modification} and \textit{parton energy loss} at nucleus.
- Ratio of J/ψ / DY and P_T broadening would be interesting to test nuclear modification/absorption.
- (F)VTX can help to separate open HF correlation from Drell-Yan and quarkonia measurement at dimuon channel.
- Future upgrade and (F)VTX would help to improve mass resolution and separate ψ’ and excited states of upsilon as well as \( \chi_c \).
- See Cesar, John, Joe more for the upgrade.
Back up
Introduction

- Review the PHENIX dimuon/other previous measurements.
- Check the possible improvements/physics.
- This talk is focused on cold nuclear matter physics, not on the spin measurement.
Yield Extraction Examples

- Fitting function: Two Gaussian ($\phi/\omega$) + One Relativistic BW ($\rho$) + Background (Defined by estimated shape)
  - $\phi$ yields stable when fitting procedure changes
  - $\rho + \omega$ yields using background subtraction (large uncertainty)

$y>0$, Centrality: 40-60

![Graph 1](chart1.png)

**Estimated background**

- Smaller fitting range: 0.5-2.5 GeV
- Larger parameter range

![Graph 2](chart2.png)

- Larger fitting range: 0.4-2.6 GeV
- Smaller parameter range

pA workshop, 1/9/2013
Background Estimation Challenge

$y<0$, Centrality: 20-40

- A new data-driven background estimation method developed
- Use di-muon pairs with large $\chi^2_{vtx}$ to estimate the background
  - Addresses the issue of correlated hadrons that decays to $\mu^+/-$
- Achieved good background description at all mass range

Correlated background

$pA$ workshop, 1/9/2013
Drell-Yan for Heavy Ion physics

- Drell-Yan process ($q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-)$ is a good probe to study the quark modification in nucleus and initial-state parton energy loss.
- Ideally suited to isolate the initial-state parton energy loss, given the absence of final-state effects on the produced dimuon.

$x$ coverage of PHENIX Drell-Yan in nucleus at $\sqrt{s} = 200$ GeV ($1.2 < y < 2.2$)
The NA50 experimental ratio of the total J/ψ cross sections and Drell-Yan cross sections as a function of the nuclear length L

- NA50 data are fit with the QCD based nuclear absorption model.
- PHENIX J/ψ data show $P_T$ broadening due to the multiple scattering
A Summary of Earlier p+A Experiments' Physics & Results
Workshop on the Physics of p+A Collisions at RHIC
BNL, Jan 7-9, 2013
Mike Leitch, LANL Retired Fellow

Cold Nuclear Matter (CNM) physics

Lessons & Clues from the data:
• shadowing
• initial-state vs final-state
• absorption
• dE/dx from Drell-Yan
• p_T broadening
• Intrinsic Charm
• very small-x shadowing (E665)

FNAL E772/789/866; SPS NA38/50/60; FNAL E665 (DIS); Cronin expt, ...
Saturation of Small-x Gluons or Shadowing

Leading twist gluon shadowing, e.g.:
- EPS09 - phenomenological fit to DIS & DY data with large uncertainties, Eskola, Paukkunen, Salgado, JHEP 0904:065, 2009
- Also coherence models & higher-twist (HT) shadowing, e.g. Vitev

Small-x gluon saturation or Color Glass Condensate (CGC)
- At low-x there are so many gluons that 2→1 diagrams become important and deplete the low-x region
- Nuclear amplification: \( x_A G(x_A) = A^{1/3} x_p G(x_p) \), i.e. gluon density is ~6x higher in Gold than the nucleon
Energy Loss of Partons in Nuclei

Initial-state energy loss

\[ R(A/p) \]

\[ R(W/Be) \]

E866/NuSea, 800 GeV, J/Ψ
p+W / p+Be ratio

With various amounts of energy loss

R. Vogt - Jan. 2011
Cronin effect, or $p_T$ broadening from soft initial-state pre-hard-interaction scatterings

Cronin et al., PRD 11, 3105(1975)

The cross sections show a very strong $A$ dependence at high $p_\perp$. While the atomic number dependence is close to $A^{0.71}$ at low $p_\perp$, the dependence becomes, at high $p_\perp (> 4 \text{ GeV}/c)$, $A^{1.1}$ for pion production, and $A^{1.3}$ for proton and antiproton production. The nucleons in the nucleus appear to act collectively in the production of high-$p_\perp$ hadrons.

FIG. 17. Plots of the power $\alpha$ of the $A$ dependence versus $p_\perp$ for the production of hadrons by 300-GeV protons; (a) $\pi^+$, (b) $\pi^-$, (c) $K^+$, (d) $K^-$, (e) $p$, and (f) $\bar{p}$. 

1/7/2013
Lessons and Clues from the Data

Cronin expt.

E866/NuSea

NA50

HERA-B
Suppression Not Universal vs $x_2$ as Expected for Shadowing

PHENIX, E866, NA3 $J/\psi$ Comparison

$$\sigma_{pA} = \sigma_{pp} A^\alpha$$

Closer to scaling with $x_F$ or rapidity
- initial-state gluon energy loss?

Energy loss of incident gluon shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$

- or gluon saturation?

Gluon saturation from non-linear gluon interactions for the high density at small $x$; amplified in a nucleus.

(x2 is $x$ in the nucleus)

Fermilab E789: $D^0 \rightarrow K\pi$ and $B \rightarrow J/\psi \, X$
(charm & beauty using silicon vertex detector)

**Dimuon spectrometer**

16-plane, 50μm pitch/8.5k strip silicon vertex detector

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

Compare closed and open charm to isolate initial-state CNM effects

$B \rightarrow J/\psi \, X$

*Phys. Rev. Lett. 74, 3118 (1995)*

$D^0 \rightarrow K\pi$

$K^+\pi^-$

$K^-\pi^+$

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

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$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

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Mass (GeV/c$^2$)

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Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

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Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)

$D^0 \rightarrow K\pi$

$K^-\pi^+$  $K^+\pi^-$

Mass (GeV/c$^2$)
Comparing Open & Closed Charm
Isolating Initial-state Effects

E866/NuSea 800 GeV p+A

Open-charm p+A nuclear dependence (single-µ $p_T > 1$ GeV/c) - very similar to that of $J/\Psi$:

• implies that dominant effects are in the initial state
  • e.g. dE/dx, CGC (since shadowing disfavored by lack of $x_2$ scaling)
  • weaker open-charm suppression at $y=0$ attributed to lack of absorption for open charm

follow this example at RHIC
Absorption at mid-rapidity, $J/\psi$ & $\psi'$ in Fixed Target Measurements

Absorption (or dissociation) of $J/\psi$ or pre-$J/\psi$ ($\bar{c}\bar{c}$) as they exit nucleus into two $D$ mesons, by nucleus or co-movers

Power law parameterization $\sigma = \sigma_N^* A^\alpha$

$\alpha = 0.954 \pm 0.003$  E866/NuSea @ $x_F=0$
$\alpha = 0.941 \pm 0.004$  NA50, QM04

Absorption model parameterization (from pA)

$\sigma_{J/\psi} = 4.18 \pm 0.35$ mb  NA50 QM05
$\sigma_{\psi'} = 7.6 \pm 1.1$ mb
Absorption or Dissociation of $J/\psi$ after correcting for shadowing

Energy Dependence; after corrections for EKS98 shadowing

Apparent absorption vs $x_F$; after EKS98 shadowing is removed

Fig. 77 The extracted energy dependence of $\sigma_{abs}^{J/\psi}$ at midrapidity. The solid line is a power-law approximation to $\sigma_{abs}^{J/\psi}(y=0, \sqrt{s_{NN}})$ using the EKS98 [876, 877] shadowing parametrization with the CTEQ61L parton densities [878, 879]. The band indicates the uncertainty in the extracted cross sections. The dashed curve shows an exponential fit for comparison. The data at $y_{cms} \sim 0$ from NA3 [880], NA50 at 400 GeV [872] and 450 GeV [873], E866 [874], HERA-B [881], and PHENIX [663] are also shown. The vertical dotted line indicates the energy of the Pb+Pb and In+In collisions at the CERN SPS. Adapted from [875] with kind permission, copyright (2009) Springer
\( \psi' \) absorbed more than \( J/\psi \) near \( x_F = 0 \)

<table>
<thead>
<tr>
<th>Meson</th>
<th>( M(\text{GeV}) )</th>
<th>( R(\text{Fm}) )</th>
<th>( \text{BE (MeV)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J/\Psi )</td>
<td>3.1</td>
<td>.45</td>
<td>~640</td>
</tr>
<tr>
<td>( \Psi' )</td>
<td>3.7</td>
<td>.88</td>
<td>~52</td>
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</tbody>
</table>
Contrasting $\Upsilon$'s with $J/\psi$'s

$\sqrt{S} = 39$ GeV (E772 & E866)
- less absorption
- not in shadowing region (large $x_2$)
- similar $p_T$ broadening

But careful: $\Upsilon$ suppression is from data for $x_F < 0$ or $x_2 > 0.2$ (in the EMC region)
Drell-Yan

\[ pN \rightarrow \mu^+ \mu^- X \]
Drell-Yan from E772/E789/E866 at Fermilab

\[ pN \rightarrow \mu^+ \mu^- X \]

N (target) \[ \rightarrow \gamma^* \]
\[ \rightarrow x_1 q \quad x_2 q \]
\[ \rightarrow \mu^+ \mu^- \]

Diagram showing the process and plots from the paper. The text includes references to the paper Phys. Rev. Lett. 83, 2304 (1999).
Quark Energy Loss from Drell-Yan data
Two ways

assuming EKS Shadowing

assuming Kopeliovich Shadowing
Johnson, Kopeliovich et al., PRL 86, 4483 (2001)

Analysis of our p-A Drell-Yan data using the Kopeliovich model.
\[ \frac{dE}{dx} = 2.32 \pm 0.52 \pm 0.5 \text{ GeV/fm} \]

Confusion due to having both shadowing and \( \frac{dE}{dx} \) contributing to Drell-Yan suppression for measurements at this energy.

- Gavin and Milana \( \Delta E < 0.14 \) \%/fm
- Brodsky and Hoyer \( \Delta E < 0.44 \) GeV/fm
- Baier et al. \( \Delta E < (0.046 \text{ GeV/fm}^2) \times L^2 \)
In E906 at 120 GeV, nuclear suppression in Drell-Yan should only be from \( \frac{dE}{dx} \) \((x_2 > 0.1)\).

\[
\frac{\Delta E}{E} \propto \frac{\mu^2 L^2}{\lambda_g} \frac{\ln E}{Q_0}
\]

\[
\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \frac{\ln E}{Q_0}
\]

**Distinguish radiative from collisional (\( L^2 \) vs \( L \))**

*See Paul Reimer’s talk*
Transverse Momentum Broadening

\[ \psi / J \text{ gluon} \]
Transverse Momentum Broadening - DY, J/ψ, Upsilon

Initial-state gluon multiple scattering causes $p_T$ broadening (or Cronin effect)

$$\sigma_A = \sigma_N A^\alpha$$

PHENIX 200 GeV results show $p_T$ broadening comparable to that at lower energy ($\sqrt{s}=39$ GeV in E866/NuSea)

High $x_2 \sim 0.09$

Low $x_2 \sim 0.003$
Systematics of $p_T$ Broadening  
E866/NuSea

$$\Delta\langle p_T^2 \rangle = \Delta\langle p_T^2 \rangle_A - \Delta\langle p_T^2 \rangle_D$$

$$\Delta\langle p_T^2 \rangle = C \times \left[ \left( \frac{A}{2} \right)^{1/3} - 1 \right]$$
$P_T$ Broadening for different energies and probes - other data

E537: 125 GeV pbar,$\pi^-$ J/$\psi$

PRL 60, 2121 (1988)

E288 400 GeV p DY

PRD 23, 604 (1981)

NA10: 140,286 GeV $\pi^-$ DY

PLB 193, 368 (1987)

Antipov: 43 GeV $\pi^-$ J/$\psi$

PL76B, 235 (1978)

Omega: 39.5 GeV $\pi^-$ J/$\psi$

Deuteron vs the Proton

Deuteron is very weakly bound & not a typical nucleus in terms of CNM effects
- Binding energies:
  - D - 2.22 MeV
  - Alpha - 28.3 MeV

Figure 1
J/ψ Nuclear dependence weaker than expected for Deuterium/Hydrogen!

Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective, $A_{\text{eff}}$, smaller than the $A=2$ of deuterium.

From fits to E866/NuSea $p + \text{Be, Fe, W}$ data: $\sigma_{pA} \sim \sigma_{pp} A^\alpha$

$$\alpha(x_F) \propto 1 - 0.052x_F - 0.034x_F^2$$

$$\alpha(p_T) \propto 0.06p_T + 0.011p_T^2$$
Intrinsic charm components of incident proton produce $J/\psi$ at large $x_F$. $A^{2/3}$ dependence from surface stripping of proton’s light quarks (Brodsky)
At large $x_F (\geq 0.5)$ intrinsic $c\bar{c}$ components of the projectile proton can dominate the production of charm pairs.

- $A^{2/3}$ dependence via surface stripping of light quarks to free charm pair component

Vogt, Brodsky, Hoyer, NP B360, 67 (1991) (also includes absorption and shadowing)

No conclusive evidence for IC:
“IC constrained to be from zero (no IC) to a level 2-3 times larger than previous model estimates”

Flattening of shadowing at very small $x$?

$F_2$ structure functions ($q$ & $q\bar{q}$) may show leveling out of shadowing at smallest $x$ values probed by DIS on nuclear targets (E665)

- Vitev – higher-twist shadowing
- Kopeliovich – color transparency & coherence effects

*e.g. probe $q\bar{q}$ with very-forward Drell-Yan on nuclear targets*

Figure 3.34: Data from E665 compared with (left) a shadowing calculation from Vitev [307] and with (right) color transparency and coherence calculations from Kopeliovich [223]. In the right panel, the solid (dashed) curve is with (without) the contribution from gluon shadowing.
Suppression of vector mesons

Summary p-A data lessons

J/ψ suppression doesn’t scale like shadowing

Open vs closed charm isolates initial state

p+d J/ψ suppression is weak

Everything has p_T broadening

Shadowing may flatten for x<10^{-3}?
Backups
Solving the J/ψ Puzzle

E906 & $\sqrt{s}$-dep. of DY

quark dE/dx

quarkonia vs open-heavy

isolates I.S. from breakup

J/ψ vs $\sqrt{s}$

diff. x ranges for shadowing

J/ψ vs γ

Theory: q vs gluon dE/dx

initial state gluon dE/dx

breakup

gluon shadowing

Theory: EPS09; coherence models; gluon saturation

direct-γ vs HQ vs DY

path length dep. of CNM

d+Au vs d+Cu & centrality dep.

large regen. @ LHC?

p_T of $R_{AA}$ from regen.: diagonal or random?

flat or rising $R_{AA}$ as b→0?

Theory for RHIC regen.

predict small regen. @ RHIC?

Screening in QGP

Regeneration

screening for diff. quarkonia states

diff. Screening for diff. quarkonia states

Theory: q vs gluon dE/dx

dE/dx from shadowing

• q or g in deuteron - dE/dx
• q or g in nucleus - shadowing
• 2 unknowns, 3 measurements

1/7/2013
**HERA-B - J/ψ A dependence**

\[ \sigma_A = \sigma_N A^\alpha \]

- Previous result of FNAL E866 extended to \( x_F = -0.35 \)
- Result from 15% of full \( \mu^+ \mu^- \) sample, statistical uncertainties only, similar results for \( e^+e^- \)
- Work on systematics ongoing. Complete the analysis on the full data sample.
Open Charm Nuclear Dependence: $x_F$ Dependence?

**E769 250 GeV $\pi^\pm$ PRL 70,722 (1993)**

**WA82 340 GeV $\pi^-$ PRB 284,453 (1992)**

**Vogt et al., NP 383,643 (1992)**

**Fig. 4.** Dependence of the parameter $\alpha$ on $P_T$ and $x_F$ for $D^+$ and $D^0$.

**Fig. 14.** We show $\alpha(x_f)$ for $\pi^- A$ interactions at 300 GeV as calculated in our model. The dashed curve shows delta function fragmentation, the solid curve, the Peterson function. These results are compared to those for $D^\pm$ mesons produced by 250 GeV $\pi^- A$ interactions [3] and the effective $\alpha$ found by the WA78 beam dump experiment [23], indicated by the band with $\langle x_f \rangle = 0.31$. 

1/7/2013
What About A-dependence of Drell-Yan??

**SHADOWING**

$x < 0.1$ quarks suppressed in nuclei.

Gluons probably also suppressed.

E665 Dis muons

E665
Deep Inelastic Scattering (470 GeV/c e⁻)

Explains low-x Drell-Yan

E772
$p+A \rightarrow \mu^+\mu^-$
@ 800 GeV/c
PRL 64, 2479 (1990)

NA10 - 140 GeV/c + 288 GeV/c π⁻

\[ \frac{\sigma(p^+ \rightarrow \mu^+\mu^−)}{\sigma(p^0 \rightarrow \mu^+\mu^−)} \]

E288 - 400 GeV protons

**NUCLEAR DEPENDENCE OF DRELL-YAN.**
NUCLEAR DEPENDENCE
OF J/$\psi$ PRODUCTION

E672/706
530 GeV/c \( \pi^- \)P
(FNAL-PRL-91/62-E,
FNAL-CONF-89/151-E)

Fig. 7. The A-dependence of J/$\psi$ Production

E537
125 GeV/c \( \bar{p}, \pi^- \)
PRL 60, 2121 (1983)

1/7/2013
Nuclear Binding & Fermi Motion

Excess pions (nuclear binding)
- Loss of valence quark momentum & enhanced sea (pions)
- Pions have valence (large x) anti-quarks so anti-quark momentum is enhanced

Fermi motion
- Spreads quark momentum near x=1

Rescaling (Close et al.; Jaffe)
\[
F_2^{Fe}(x, Q^2) \approx F_2^D(x, \xi Q^2), \quad \xi \approx 2
\]

~15% phenomenological increase in confinement scale
Overlapping nucleons (6-quark clusters, Close, Jaffe,...)
- Loss of valence quark momentum

Multi-quark Clusters (Pirner & Vary; Carlson & Havens)
Loss of valence quark momentum
relative enhancement at x~1 (one quark can have > nucleon momentum)
Universal suppression at large $x_F$ seen in data for various reactions:
• forward light hadrons, Drell-Yan, heavy flavor
• often attributed to shadowing since $x_2$ is small

But this common suppression mechanism can also be viewed as Sudakov suppression:
• no particles produced as $x_F \rightarrow 1$ due to energy conservation
• more multiple interactions make the effect larger in nuclei

Close to 800 GeV $J/\psi$ suppression vs $x_F$ for low energy data and Brahms forward rapidity ($\eta=3.2$) hadrons

Sudakov suppression + higher twist shadowing

Describes universal suppression vs $x_F$ for low energy data

π, p, K, Λ, ρ, Ξ data

J/ψ suppression

0-20% (central) 30-50%
Fermilab E866/NuSea Detector

- Forward $x_F$, high mass $\mu$-pair spectrometer
- Liquid hydrogen and deuterium targets
- Two acceptance defining magnets (SM0, SM12)

- Beam dump (4.3m Cu)
- Hadronic absorber (13.4 I$_0$-Cu, C, CH$_2$)
- Momentum analyzing magnet (SM3)
- Three tracking stations
- Muon identifier wall & 4th tracking
Note benefits of a fixed target experiment:

- Lots of luminosity.
- Boost in lab frame gives very high momentum particles, so resolution is improved and background can be greatly reduced by many meters of absorber.
Figure 1: The NMC spectrometer for the 1989 data taking. The beam calibration spectrometer is located downstream and not shown.
The HERA-B Detector

Target & Vertex
8 layers of double-sided Si-microstrips, movable on Roman-Pots; 8 wire-target (see above)

High p,
3 superlayers gas, pixel and pad chambers; pre-trigger for high p, tracks

Outer Tracker
7 superlayers of honeycomb drift chambers, 5 and 10mm cells

RICH
Spherical mirror inside C,F\textsubscript{10} radiator. Lens-enhanced multianode PMT focal plane.

Inner Tracker
7 superlayers of Micro Strip Gas Chambers with GEM-foil

Electromagnetic Calorimeter
W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger

Muon System
4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger
Production of hadrons at large transverse momentum at 200, 300 and 400 GeV at Fermilab
J.W. Cronin et al., PRD 11, 3105 (1975)
A Dependence of $J/\psi$ and $\psi'$ Not Identical: Size Matters

Color octet mechanism suggested that $J/\psi$ and $\psi'$ $A$ dependence should be identical — Supported by large uncertainties of early data

More extensive data sets (NA50 at SPS, E866 at FNAL) show clear difference at midrapidity [NA50 $\rho L$ fit gives $\Delta \sigma = \sigma_{\text{abs}}^{\psi'} - \sigma_{\text{abs}}^{J/\psi} = 4.2 \pm 1.0$ mb at 400 GeV, $2.8 \pm 0.5$ mb at 450 GeV for absolute cross sections]

Suggests we need to include formation time effects

![Graphs showing data for $J/\psi$ and $\psi'$ production](image)

Figure 15: The $J/\psi$ $A$ dependence (left) as a function of $x_F$ at FNAL ($\sqrt{s_{NN}} = 38.8$ GeV) and (right) and a function of $A$ at the SPS (NA50 at $p_{\text{lab}} = 400$ and 450 GeV) for $J/\psi$ and $\psi'$ production.
Quark Energy Loss from Drell-Yan data assuming EKS Shadowing

Parton energy loss limits

Data corrected for EKS shadowing

  \[ \Delta x_1 = k C x_1 \left( \frac{Q_0}{Q} \right)^n A^{1/3} \]
  \( C = 4/3 \) for quarks, \( C = 3 \) for gluons, \( n = \) for "soft physics" Experimental fit:
  \[ \Delta x_1 = -k_1 x_1 A^{1/3} \]

  \[ |\Delta x_1| \leq \frac{< k_\perp > L_a}{2E} \]
  Experimental fit: \[ \Delta x_1 = -\frac{k_2}{s} A^{1/3} \]

  \[ |\Delta x_1| = \frac{3\alpha_s m_p}{2} s \frac{L_a}{s} < p_\perp^2 > \]
  Experimental fit: \[ \Delta x_1 = \frac{-k_3}{s} A^{2/3} \]

Gavin and Milana \( \Delta E < 0.14\%/\text{fm} \)

Brodsky and Hoyer \( \Delta E < 0.44\text{ GeV/fm} \)

Baier et al. \( \Delta E < (0.046\text{ GeV/fm}^2) \times L^2 \)

Quark Energy Loss from Drell-Yan data assuming Kopeliovich Shadowing

Johnson, Kopeliovich et al., PRL 86, 4483 (2001)

Analysis of our p-A Drell-Yan data using the Kopeliovich model. Dashed lines with shadowing only; solid lines with parton energy loss of

\[ dE/dx = 2.32 \pm 0.52 \pm 0.5 \text{ GeV/fm} \]

Confusion due to having both shadowing and dE/dx contributing to Drell-Yan suppression for measurements at this energy

data from E772 - PRL 64, 2479 (1990)
Intrinsic charm contribution to Quarkonia

At large $x_F (\geq 0.5)$ intrinsic $c\bar{c}$ components of the projectile proton can dominate the production of charm pairs.

- $A^{2/3}$ dependence via surface stripping of light quarks to free charm pair component

Vogt, Brodsky, Hoyer, NP B360, 67 (1991) (also includes absorption and shadowing)

But E789 set limit on I.C. contribution via shape of cross section vs $x_F$

- $< 2.3 \times 10^{-3}$ nb/nucleon (1.8 nb/nucleon predicted)
“Evidence” for the “intrinsic” charm (IC)

DIS data

\[ F_2^c(x) \]

With IC

No IC

EMC: \( \bar{\nu} = 168 \) GeV

\[ \Lambda_c \) production

With IC

No IC

\[ pp \rightarrow \Lambda_c + X \]

Gunion and Vogt (hep-ph/9706252)

“Evidence” appears to be rather weak

Slide from JCP
No conclusive experimental evidence for intrinsic-charm

Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 0.57% and 2.0%

We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.
First two-particle correlation results in proton-lead collisions from CMS

Wei Li (Rice University)
for the CMS collaboration
The “ridge” in pp collisions

Event with more than 200 charged particles

CMS collaboration, JHEP 09 (2010) 091

pp N>110, 1<p_T<3 GeV/c

A surprise: near-side (ΔΦ~0) “ridge” in high multiplicity pp!
The “ridge” in pp collisions

Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC

CMS collaboration, JHEP 09 (2010) 091

pp $N \sim 15$, $1<p_T<3$ GeV/c

pp $N > 110$, $1<p_T<3$ GeV/c

No ridge observed in minimum bias pp or any pp MC generators
Very high multiplicity pp collisions

Very high-multiplicity pp events are rare in nature

$P(N_{\text{Trk}}^\text{offline})$

$N_{\text{Trk}}^\text{offline} (p_T > 0.4\text{GeV/c}, |\eta| < 2.4)$

$\langle N_{\text{Trk}}^\text{offline} \rangle \sim 15$ for MB pp

$10^{-5} - 10^{-6}$ prob.

Very exotic pp events

Raw counts of tracks!
proton-proton and nucleus-nucleus collisions
The “ridge” in pp and AA collisions

\[ R(\Delta \eta, \Delta \phi) \]

\[ pPb \]

\[ pp \]

\[ 7 \text{ TeV}, N>110 \]

\[ \eta \]

\[ \phi \]

\[ \Delta \eta \]

\[ \Delta \phi \]

\[ JHEP 09 (2010) 091 \]

\[ PbPb 2.76 \text{ TeV} \]

\[ 35-40\% \]

\[ \frac{1}{N_{\text{rig}}} \frac{d^2 N_{\text{pair}}}{d\Delta \eta d\Delta \phi} \]

\[ JHEP 07 (2011) 076 \]

\[ EPJC 72 (2012) 2012 \]
The “ridge” in pp and AA collisions

Initial-state geometry + collective expansion

“Smoking gun” of a strongly interacting QGP liquid!
The “ridge” in pp and AA collisions

Physical origin of pp ridge is still not completely explained

Initial-state geometry + collective expansion

“Smoking gun” of a strongly interacting QGP liquid!
The “ridge” in pp, pA and AA collisions?

What if colliding a proton and a nucleus?
Is there a ridge and how big is it?
pPb pilot run at the LHC on September 13, for ~ 8 hours

Proton: 4 TeV

Pb: 1.58 TeV/nucleon

Center-of-mass energy: $\sqrt{s_{NN}} = 5.02$ TeV
CMS experiment at the LHC

EM Calorimeter (ECAL)
Hadron Calorimeter (HCAL)
Beam Scintillator Counters (BSC)
Forward Calorimeter (HF)
Tracker (Pixels and Strips)
Muon System

Unprecedented kinematic range and acceptance
Multiplicity distribution in pPb

~ 2 million minimum bias pPb events were collected (1 µb⁻¹)

\[ \langle N_{\text{trk}}^{\text{offline}} \rangle \sim 40 \text{ for MB pPb} \]
\[ \langle N_{\text{trk}}^{\text{offline}} \rangle \sim 15 \text{ for MB pp} \]

Much easier to reach high multiplicity in pPb, as expected
Two-particle correlations at CMS

Pair of two primary reconstructed tracks within $|\eta|<2.4$

- Trigger particle from a $p_T^{\text{trig}}$ interval
- Associated particle from a $p_T^{\text{assoc}}$ interval

Signal-pair distribution

$$S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N^{\text{same}}}{d\Delta \eta d\Delta \phi}$$

Background-pair distribution

$$B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N^{\text{mix}}}{d\Delta \eta d\Delta \phi}$$

Triangular shape in $\Delta \eta$ due to limited acceptance

$\eta=-2.4 \quad \eta=0.0 \quad \eta=2.4$

$\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$
$\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}$

Same-event pairs

Mixed-event pairs (similar $z_{\text{vtx}}$)
Two-particle correlations at CMS

Pair of two primary reconstructed tracks within $|\eta|<2.4$
- Trigger particle from a $p_T^{\text{trig}}$ interval
- Associated particle from a $p_T^{\text{assoc}}$ interval

Signal-pair distribution

$$S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N^{\text{same}}}{d\Delta \eta d\Delta \phi}$$

Background-pair distribution

$$B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N^{\text{mix}}}{d\Delta \eta d\Delta \phi}$$

Pair yield per trigger particle:

$$\frac{1}{N_{\text{trig}}} \frac{d^2N}{d\Delta \eta d\Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

Triangular shape in $\Delta \eta$ due to limited acceptance

$\eta=-2.4 \quad \eta=0.0 \quad \eta=2.4$

$\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$

$\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}$
Two-particle correlations at CMS

Pair of two primary reconstructed tracks within $|\eta|<2.4$
  - Trigger particle from a $p_T^{\text{trig}}$ interval
  - Associated particle from a $p_T^{\text{assoc}}$ interval

**Signal-pair distribution**

$$S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{same}}}{d\Delta \eta d\Delta \phi}$$

**Background-pair distribution**

$$B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{mix}}}{d\Delta \eta d\Delta \phi}$$

**Pair yield per trigger particle:**

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N}{d\Delta \eta d\Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

Triangular shape in $\Delta \eta$

due to limited acceptance

$\eta=-2.4 \quad \eta=0.0 \quad \eta=2.4$

$\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}}$

$\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}$

acceptance correction
First two-particle correlation result in pPb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_T < 3$ GeV/c

for both $p_T^{\text{trig}}$, $p_T^{\text{assoc}}$

A significant near-side ridge in high multiplicity pPb!
First two-particle correlation result in pPb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trig}}^{\text{offline}} \geq 110$

1 < $p_T < 3$ GeV/c

for both $p_T^{\text{trig}}$, $p_T^{\text{assoc}}$

$\frac{1}{N_{\text{trig}}} \frac{d^2 N}{d\Delta\eta d\Delta\phi}$

A significant near-side ridge in high multiplicity pPb!
First two-particle correlation result in pPb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} < 35$

1 < $p_T$ < 3 GeV/c

Dijet-like correlations in low multiplicity (or peripheral) pPb!

Fraction of cross section: 50.4%
First two-particle correlation result in pPb

CMS Preliminary
pPb $\sqrt{s_{NN}} = 5.02$ TeV, $35 \leq N_{\text{trk, offline}} < 90$
$1 < p_T < 3$ GeV/c

Near-side ($\Delta\phi\sim0$) ridge structure turns on as multiplicity increases

Fraction of cross section: $41.9\%$
First two-particle correlation result in pPb

\[ 90 \leq N_{\text{trk}}^{\text{offline}} < 110 \]

CMS Preliminary

pPb \( \sqrt{s_{NN}} = 5.02 \) TeV, \( 90 \leq N_{\text{trk}}^{\text{offline}} < 110 \)

1 < \( p_T \) < 3 GeV/c

Near-side (\( \Delta \phi \sim 0 \)) ridge structure turns on as multiplicity increases

Fraction of cross section: 4.6%

Wei Li

pA@RHIC, BNL, Jan 7-9, 2013
First two-particle correlation result in pPb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_T < 3$ GeV/c

Near-side ($\Delta\phi \sim 0$) ridge structure turns on as multiplicity increases

Fraction of cross section: 3.1%
No ridge in pPb MC models

pPb data

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_{T} < 3$ GeV/c

Ridge is not predicted by common pPb MC event generators, as in pp!

pPb HIJING, N>120

1 < $p_{T}$ < 3 GeV/c

pPb AMPT, N>100

1 < $p_{T}$ < 3 GeV/c

AMPT shows the ridge in AA collisions
Quantify the ridge correlations

Average over ridge region (2<|Δη|<4)

CMS pPb √s = 5.02 TeV, N ≥ 110

1 < p_T < 2 GeV/c

\[ \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\eta d\Delta\phi} \]

1 < p_T < 2 GeV/c

2 < |Δη| < 4

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} \]
Quantify the ridge correlations

CMS pPb $\sqrt{s} = 5.02$ TeV, $N \geq 110$

1 < $p_T$ < 2 GeV/c

Average over ridge region (2<|Δ$\eta$|<4)

Shift the distribution to Zero Yield At Minimum (ZYAM)

CMS pPb $\sqrt{s} = 5.02$ TeV, $N \geq 110$

1 < $p_T$ < 2 GeV/c

2 < |Δ$\eta$| < 4

|Δ$\phi$|

N=110

• pPb 5.02 TeV

• pp 7 TeV

pA@RHIC, BNL, Jan 7-9, 2013
Quantify the ridge correlations

CMS pPb \( \sqrt{s} = 5.02 \) TeV, \( N \geq 110 \)

1 < \( p_T < 2 \) GeV/c

Average over ridge region (2<|\( \Delta \eta \)|<4)

Shift the distribution to Zero Yield At Minimum (ZYAM)

Ridge in pPb is significantly stronger than in pp at similar N

CMS pPb \( \sqrt{s} = 5.02 \) TeV, \( N \geq 110 \)

1 < \( p_T < 2 \) GeV/c

2 < |\( \Delta \eta \)| < 4

\[ N \geq 110 \]

\( \bullet \) pPb 5.02 TeV

\( \circ \) pp 7 TeV

pA@RHIC, BNL, Jan 7-9, 2013
Quantify the ridge correlations

CMS pPb $\sqrt{s} = 5.02$ TeV, $N \geq 110$

Average over ridge region $(2<|\Delta \eta|<4)$

Shift the distribution to Zero Yield At Minimum (ZYAM)

CMS pPb $\sqrt{s} = 5.02$ TeV, $N \geq 110$

1 < $p_T < 2$ GeV/c

2 < $|\Delta \eta| < 4$

Shift the distribution to Zero Yield At Minimum (ZYAM)

N>=110

- $p_{Pb}$ 5.02 TeV
- $pPb$ 5.02 TeV
- $pp$ 7 TeV

pA@RHIC, BNL, Jan 7-9, 2013
Quantify the ridge correlations

CMS $N^{\text{offline}}_{\text{trk}} < 35$

CMS $N^{\text{offline}}_{\text{trk}} \geq 110$

$p_T$

$0.1 < p_T < 1.0$ GeV/c

$1.0 < p_T < 2.0$ GeV/c

$2.0 < p_T < 3.0$ GeV/c

$3.0 < p_T < 4.0$ GeV/c

$2<|\Delta\eta|<4$

$p\overline{p}$ $\sqrt{s_{NN}} = 5.02$ TeV

$\frac{1}{N_{\text{ring}}} \frac{dN_{\text{pair}}}{d\Delta\phi} - C_{ZYAM}$

27
Quantify the ridge correlations

Ridge most prominently at:

- high multiplicity, $N \geq 110$
- intermediate $p_T \sim 1$ GeV/c
Quantify the ridge correlations

Ridge most prominently at:
- high multiplicity, $N \geq 110$
- intermediate $p_T \sim 1$ GeV/c

Stronger ridge in pPb than in pp at similar $N$!
Quantify the ridge correlations

Ridge most prominently at:
- high multiplicity, \( N \geq 110 \)
- intermediate \( p_T \sim 1 \) GeV/c

Stronger ridge in pPb than in pp at similar N!

HIJING does not show any near-side ridge in all bins
Quantify the ridge correlations

Quantify the ridge correlations as a function of $p_T$, similar to pp (even PbPb)!

PLB718 (2013) 795
Quantify the ridge correlations

Quantify the ridge

\[ \frac{1}{N_{\text{trk}}^\text{offline}} \frac{\partial N_{\text{assoc}}}{\partial p_T} \]

\[ 0 \leq \Delta \phi \leq 3 \]

\[ 0.00 \leq \text{Associated Yield} / (\text{GeV/c}) \leq 0.15 \]

\[ p_T \text{ and multiplicity dependence of ridge yield} \]

(a) CMS

- \( N_{\text{trk}}^\text{offline} \geq 110 \)
- \( \bullet \, \text{pPb} \sqrt{s_{NN}} = 5.02 \, \text{TeV} \)
- \( \circ \, \text{pp} \sqrt{s} = 7 \, \text{TeV} \)

(b) \( 1 < p_T < 2 \, \text{GeV/c} \)

PLB718 (2013) 795


“Rise and Fall” as a function of \( p_T \), similar to pp (even PbPb)!

Become significant at \( N \sim 40 \) and linearly increases, similar to pp!
A complete picture of ridge correlations

Is there a common origin of the ridge in all systems?
- Flow-like effect similar to PbPb? Final-state effect seen in pPb?
- Other QCD mechanisms in smaller systems?
Understanding the origin of ridge

Hydrodynamics/final-state interactions
Initial-state asymmetry

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} \sim 1 + 2 \sum_n (v_n)^2 \cos(n\Delta \phi) \]

Intrinsic collimated gluon emission from glasma diagram (CGC)


\[ \frac{1}{N_{\text{trig}}} \frac{d^2 N}{d\Delta \phi} \]

0-5% central PbPb
Understanding the origin of ridge

Hydrodynamics/final-state interactions
Initial-state asymmetry

\[
\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta \phi} \sim 1 + 2 \sum_n (V_n)^2 \cos(n\Delta \phi)
\]

Intrinsic collimated gluon emission from glasma diagram (CGC)


Key difference: initial-state “geometry” driven or not!

Wei Li

pA@RHIC, BNL, Jan 7-9, 2013
Hydrodynamics in pp and pA?

Viscous hydro calculation in pPb


![Graph showing v2 and v3 as functions of pT for different N_{part} values in p-Pb collision at 4.4 TeV.](image)

The graphs illustrate the viscous hydro effect in p-Pb collisions at 4.4 TeV, showing the dependence of v2 and v3 on the transverse momentum (pT) for different values of N_{part} (number of participants).
Hydrodynamics in pp and pA?

Viscous hydro calculation in pPb


1.0 < p_T < 2.0 GeV/c

pPb \( \sqrt{s_{NN}} = 5.02 \) TeV

pp \( \sqrt{s} = 7 \) TeV

90 \( \leq N_{\text{trk}}^{\text{offline}} \) < 110

\( v_2 = 0.066, v_3 = 0.037 \)

\( N_{\text{trk}}^{\text{offline}} \geq 110 \)

Wei Li

pA@RHIC, BNL, Jan 7-9, 2013
Hydrodynamics in pp and pA?

Viscous hydro calculation in pPb


Is hydro still valid for such small system size and lifetime? Where is the limit?
Ridge arising from gluon saturation

Calculations of ridge in pp and pPb from glasma mechanism


Correlation functions

• Good description of the data
• No need of asymmetric initial geometry

Need qualitatively different predictions from two scenarios!
First observation of a long-range near-side correlation ("ridge") in high multiplicity (central) pPb collisions at 5.02 TeV

- much stronger than in pp
- not in common pPb MC models

Multiplicity and $p_T$ dependence of the ridge in pPb have been investigated in detail:

- turns on slightly above average MB multiplicity
- rises and falls with $p_T$, similar trend as observed in PbPb and pp
Observation of the ridge in pp and pPb opens up a new testing ground of high-density, strongly interacting QCD system

- Probing proton structure at very early timescale
- Final-state effect also seen in pA?
- Smoking gun of gluon saturation?

Outlook

Stay tuned!
Observation of the ridge in pp and pPb opens up a new testing ground of high-density, strongly interacting QCD system

- Probing proton structure at very early timescale
- Final-state effect also seen in pA?
- Smoking gun of gluon saturation?

30,000-fold increase in luminosity (30 nb$^{-1}$) is expected in the nominal pPb run

- Much wider reach in multiplicity
- Access to a variety of observables
- Direct comparison of pp, pPb, PbPb with drastically different system size, geometry
Observation of the ridge in pp and pPb opens up a new testing ground of high-density, strongly interacting QCD system

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30,000-fold increase in luminosity (30 nb$^{-1}$) is expected in the nominal pPb run

- Much wider reach in multiplicity
- Access to a variety of observables
- Direct comparison of pp, pPb, PbPb with drastically different system size, geometry

With ~ 250 nb$^{-1}$ projected luminosity, a pA program at RHIC can probe the same exciting physics and provide a new handle in the collision energy dependence

Stay tuned!
Backups
Very high multiplicity pp collisions

Dedicated online selection of high multiplicity events
Why studying pA collisions?

- Reference for nucleus-nucleus collisions: to address the issue of cold nuclear matter effects

Observation of jet quenching in AuAu but not in pp or dAu

- Final-state effect

- Probe nucleus structure at extremely small-x regime

Modification of away side In dAu at forward rapidity

- Saturation of small-x gluons?
The STAR FGT upgrade program

Xuan Li for the STAR Collaboration
Temple University
Outline

• Motivation
  – Forward GEM Tracker (FGT) physics program
• FGT overview
  – Assembly and installation
  – Cosmic ray results for RHIC Run 13
• FGT upgrade and open discussion for p+A collisions
• Summary
Motivation

• Asymmetry of unpolarized sea quark distribution function had been found in Drell-Yan process ($p+N \rightarrow \mu^+\mu^-$).

![Graph showing quark distributions and theoretical models](image)


• Other channels?

• How about polarized sea quark distribution?
W production – unique new probe to measure quark polarization

• Probing polarized quark distribution via W production.
W measurement at STAR

• STAR $A_L$ results and projection.

$\bar{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X$

$25 < E_T^e < 50$ GeV
W measurement at STAR

• STAR $A_L$ results and projection.

  Measured asymmetries (Run 9) are in agreement with theory evaluations using polarized pdf’s (DSSV) constrained by polarized DIS data.

  ⇒ Universality of helicity distr. functions!

$\bar{p} + p \to W^\pm + X \to e^\pm + X$

- $25 < E_T < 50$ GeV
- $|\eta| < 1$, $L = 12$ pb$^{-1}$
- $P = 39\%$
W measurement at STAR

- STAR $A_L$ results and projection.

  Measured asymmetries (Run 9) are in agreement with theory evaluations using polarized pdf’s (DSSV) constrained by polarized DIS data

  $\Rightarrow$ Universality of helicity distr. functions!

Critical: Measurement of $W^+$ and $W^-$ asymmetries as a function $\eta_e$
W measurement at STAR

- STAR $A_L$ results and projection.

  Measured asymmetries (Run 9) are in agreement with theory evaluations using polarized pdf’s (DSSV) constrained by polarized DIS data
  $\Rightarrow$ Universality of helicity distr. functions!

  Critical: Measurement of $W^+$ and $W^-$ asymmetries as a function $\eta_e$

  Extension of backward / forward $\eta_e$ acceptance enhances sensitivity to anti-u / anti-d quark polarization
  $\Rightarrow$ STAR Forward GEM Tracker ($1<|\eta_e|<2$)
W measurement at STAR

- STAR $A_L$ results and projection.

**Measured asymmetries** (Run 9) are in agreement with theory evaluations using polarized pdf’s (DSSV) constrained by polarized DIS data

⇒ Universality of helicity distr. functions!

**Critical**: Measurement of $W^+$ and $W^-$ asymmetries as a function $\eta_e$

Extension of backward / forward $\eta_e$ acceptance enhances sensitivity to anti-u / anti-d quark polarization

⇒ STAR Forward GEM Tracker ($1<|\eta_e|<2$)
GEM technology

• Gas Electron Multiplier technology used for its high resolution capabilities at a very low mass.

Hole diameter: 70μm
Pitch: 140μm

• GEMs use a high electric field in the holes of a copper coated foil to amplify very small signals produced by ionizing particles.
FGT overview - design

• Design constraints
  – Low mass which is important being close to interaction region.
  – Size limited by GEM foil production technology.
  – High rate – around 0.5MHz/cm², very radiation tolerant.
The FGT has been fully installed in STAR for RHIC Run 13.
Look inside FGT quadrant

- FGT quarter section - layout

Read out $R, \phi$ value to determine hit position.
Look inside FGT quadrant

- FGT quarter section - layout

Readout module
APV chip
Pressure volume
HV board
Interconnect board
Pressure volume
HV layer
2D readout board

Xuan Li (Temple University)
FGT installation and calibration

- FGT has been fully installed in STAR for RHIC run13.

- Tune HV and APV parameters with three layers of FGT quadrants in cosmic ray test.

- Trigger scintillating counters not shown in this picture located above and below the FGT cosmic ray setup.
FGT cosmic ray – Gain curve

• Gain VS HV

Cluster threshold = 4*PedRMS(~40)*3timebin ~ 500

ADC saturate at peak time-bin of peak strip for
~10% of pulses at 3.4kV
~50% of pulses at 3.5kV (but no visible effect on residual yet)
FGT cosmic ray - residual

- Use the top and bottom quadrants to determine the projected value for the middle quadrant.

Assuming all quadrants have same resolution:
Single detector position resolution = Residual at middle quad/1.22 (from simple geometry)
180um residual @ Middle => 150um resolution at each detector
FGT cosmic ray - efficiency

- “Good event”: with clean one cluster in R&\(\phi\) of two quadrants and calculate efficiency for third quadrant within good trigger area.
- Sensitive to noise at higher HV & low Threshold.

Top-Short “Golden event” Hit Map

Reading the short octant

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Top</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3kV</td>
<td>73%</td>
<td>83%</td>
<td>81% → higher thr 76%</td>
</tr>
<tr>
<td>3.4kV</td>
<td>83%</td>
<td>88%</td>
<td>78% → higher thr 86%</td>
</tr>
<tr>
<td>3.5kV</td>
<td>87%</td>
<td>95%</td>
<td>61% → higher thr 86%</td>
</tr>
</tbody>
</table>

Middle-Long “Golden event” Hit Map

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Top</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4kV</td>
<td>72%</td>
<td>60%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Dead HV sector 4

p+A physics at RHIC workshop

Default Thr = 4*PedRMS(~40)*3timebin ~ 500
Higher Thr = 7 * PedRMS(~40)*3timebin ~ 850

Efficiency calculated in whole octant

- Use the cosmic ray results to decide which quadrant for final installation.
FGT related measurements

• The FGT will enhance the tracking capability of STAR in pseudorapidity range 1<\eta<2.

• The primary FGT design is for W measurements in p+p collisions. But, together with other STAR detectors the following measurements may be possible.
  – J/\psi \rightarrow e^+e^-, heavy flavor via electron decay channel.
  – Charged hadron, i.g. \pi^+\pi^-.
  – Drell-Yan?
  – Jets?

• Do we need larger GEM detectors?
Forward Large Triple-GEM design at Temple University (I)

- Supported by EIC R&D program.
- The active area of Large Triple-GEM detectors is 10cm<R<100cm.
- Each detector covers 30° azimuthal angle and use separate 2D readout.
- 12 GEM detectors are mounted on light-weight support structure
Forward Large Triple-GEM design at Temple University (II)

- Large Triple GEM layout

Lightweight (<1% $X_0$ in active area)

Gas, HV, and readout connections

16.45 mm thick + service box

Exploded view of the GEM detector

Mylar foils plus spacer

Cathode (HV)

3 mm spacer (Drift volume)

3 x GEM foils + 2mm spacer grid

2mm spacer (Induction gap)

Readout electrode

spacer + Mylar foil

p+A physics at RHIC workshop

Xuan Li (Temple University)
Forward Large Triple-GEM design at Temple University (III)

- Study the mechanical deformation.
- Study the gas diffusion inside the detector.

**Images**

1. Mechanical deformation simulation.
2. Gas diffusion simulation.
3. Triple GEM amplification diagram.
4. Optimization of signal size vs. electrode pitch.
Can GEM detectors be used for p+A collisions?

• Question 1: Which measurements? For example, $J/\psi$ production or di-hadron correlations to study gluon saturation in p+A.

• Question 2: Will the higher multiplicity in p+A collisions (compare to p+p collisions) impact the resolution of GEM detectors?

• Question 3: What kind of design of the GEM 2D readout board for p+A collisions? Strip only, strips plus pads, pad only or others?

• All these questions should be answered by simulations first to study the feasibility.
Summary

• The STAR FGT has been fully installed for RHIC Run 13. Cosmic ray results provide the first stage calibration for the FGT.

• Large Triple GEM detector R&D at Temple University is ongoing.

• The application of GEM detector in p+A collisions need simulation studies.

• Suggestions or comments on how to use GEM detectors in p+A collisions are very welcome!
Thanks for your attention!

• Thanks for the hard work of the STAR FGT group and Temple large GEM working group.

• Special thanks
  – Bernd Surrow, Maxence Vandenbergroucke from Temple University,
  – Akio Ogawa, Ramiro Debbe from BNL.
  – Jason Bessuille, Ross Corliss, Gerrit van Nieuwenhuizen and Ben Buck from MIT.
Backup

- The FGT has 15 time bins.

One time-bin = 107nsec/4 = 27nsec
All strips with ADC sum 3 sigma above ped in a quadrant from 1 event are shown / panel
Timing moves 4 time-bin event by event due to cosmic system trigger only at RHIC clock
p-A Collisions at RHIC

T. Ludlam

January 7, 2013
In the Beginning:
RHIC experiments configured to focus on hot nuclear matter in the central region

Little attention to the study of cold matter in nuclei--interest primarily as a “baseline”

Not much detector coverage in the forward direction.

Provision for asymmetric beams in the RHIC rings was designed in, but not as a forefront capability.
Early surprises with probes of Cold Nuclear Matter at RHIC

BRAHMS result from 2003 d + Au Run

High Pt hadrons are suppressed at very forward angles in d-Au collisions: hint of initial-state gluon saturation.

Transverse Single Spin asymmetries are large at RHIC energies:
New experimental probe of color interactions; potential to distinguish initial and final state effects.
QCD at extreme parton densities

Attention has now turned to the fundamental importance of the saturated gluon state. p – A collisions provide a smaller, simpler probe.

Renewed focus on forward kinematics at RHIC:
Scattering of high-x valence quark off low-x gluon.

New idea:
Scattering a polarized probe on saturated gluon matter. Transverse Single Spin asymmetry may provide a further experimental test of effective theory for gluon saturation, e.g. test CGC predictions.

Need forward upgrades to the detectors
Forward Upgrades

STAR and PHENIX

STAR Forward Upgrades

- Forward Calorimeter System (FCS)
- FHC (E864)
- Pb-Sc HCal
- W-Powder EMCal
- ~ 6 GEM disks
- Tracking: 2.5 < \( \eta \) < 4
- RICH/Threshold
- Baryon/meson separation

sPHENIX Forward Upgrades

PHENIX MPC-EX
# RHIC Timeline for the next Decade

From the White Paper “The Case for Continuing RHIC Operations”

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
</table>
| 2013      | • 500 GeV $p^+ + p^-$  
  • 15 GeV Au+Au                                                                         | • Sea antiquark and gluon polarization  
  • QCD critical point search                                                        | • Electron lenses  
  • upgraded pol’d source  
  • STAR HFT                                                                            |
| 2014      | • 200 GeV Au+Au and baseline data via 200 GeV $p+p$ (needed for new det. subsystems)     | • Heavy flavor flow, energy loss, thermalization, etc.  
  • quarkonium studies                                                                | • 56 MHz SRF  
  • full HFT  
  • STAR Muon Telescope Detector  
  • PHENIX Muon Piston Calorimeter Extension (MPC-EX)                                    |
| 2015-2017 | • High stat. Au+Au at 200 and ~40 GeV  
  • U+U/Cu+Au at 1-2 energies  
  • 200 GeV $p+A$  
  • 500 GeV $p^+ + p^-$                                                   | • Extract $\eta/s(T_{min})$ + constrain initial quantum fluctuations  
  • further heavy flavor studies  
  • sphaleron tests @ $\mu_B\neq 0$  
  • gluon densities & saturation  
  • finish $p+p$ W prod’n                                                               | • Coherent Electron Cooling (CeC) test  
  • Low-energy electron cooling  
  • STAR inner TPC pad row upgrade                                                    |
| 2018-2021 | • 5-20 GeV Au+Au (E scan phase 2)  
  • long 200 GeV + 1-2 lower $\sqrt{s}$ Au+Au w/ upgraded dets.  
  • baseline data @ 200 GeV and lower $\sqrt{s}$  
  • 500 GeV $p^+ + p^-$  
  • 200 GeV $p^+ + A$                                                                 | • x10 sens. increase to QCD critical point and deconfinement onset  
  • jet, di-jet, $\gamma$-jet quenching probes of E-loss mechanism  
  • color screening for different $qq$ states  
  • transverse spin asyms. Drell-Yan & gluon saturation                                    | • sPHENIX  
  • forward physics upgrades                                                             |
Polarized p-A and Inclusive Lambda Polarization experiments at the AGS

Yousef I. Makdisi
Brookhaven National Laboratory
Outline

• Asymmetry in Inclusive Pion Production at the AGS

• Issues with intended production from a carbon target

• The experimental set up and results

• Lambda polarization measurement at the AGS

• Comparison from p-A production

• Summary
Asymmetry in Inclusive Pion Production

ANL
$\sqrt{s} = 4.9$ GeV

BNL
$\sqrt{s} = 6.6$ GeV

FNAL
$\sqrt{s} = 19.4$ GeV

RHIC
$\sqrt{s} = 62.4$ GeV

$x_F = \frac{2p_{long}}{\sqrt{s}}$

C. Aidala’s compilation
The measurement at the AGS

- The impetus was RHIC polarimetry
- The choice polarimeter then was inclusive pion production
- From E704, the expected asymmetries for our design was 15%
- The only target that would withstand beam heating was carbon
- The question, are we likely to experience a diluted asymmetry?
- An RBRC theory workshop and the assumption was Yes!
- This prompted an experimental verification
The Theoretical Argument  Boris Kopeliovich hep-ph/9801414

• Agues that inclusive production follows the Cronin effect being proportional to $A^\alpha$ with $\alpha > 1$ due to qualitatively multiple interactions / rescatterings in the nucleus and increases with higher transverse momentum

• The apparent larger $p_t$ is a result of distributed over many interactions with lower momentum transfer

• Assuming a carbon nuclear density of 0.33 fm$^{-2}$ he calculates the mean no. of parton scattering $\sim 2$ or half the effective $p_t$

• Since the asymmetry is linear with $p_t$ he expected $A_N/2$ at $p_t = 1$ GeV/c

Yesterday: Yuri’s odderon $>>$ a dilution in p-A Feng no dilution at $p_t >> Q^2$
Measurement of analyzing powers of $\pi^+$ and $\pi^-$ produced on a hydrogen and a carbon target with a 22-GeV/c incident polarized proton beam

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(E925 Collaboration)
(Received 11 September 2001; published 20 May 2002)
AGS E925

• A single arm spectrometer to identify all charged particles
• Three targets: Hydrogen, Carbon, CH₂
• Strong coupling between $x_F$ and $p_T$
$A_N$ in pion production

$x_F > 0.45$ and $0.6 < p_T < 1.2$ GeV/c

No difference between hydrogen and carbon targets
Will this persist for larger A targets?
Discernable change with beam energy
Another measurement from the AGS PRL 64, 925 (1990)

Asymmetry independent of $x_F$
But increases with $x_T$
Difficult to reach high $x_T$ at RHIC
Summary of the AGS pion asymmetries

• Large asymmetries in charged forward pion production are observed similar to those at the ZGS and Fermilab

• Large asymmetries observed at large angles and large $x_T$ in $\pi^+$ at but not in $\pi^-$ or protons.

• The AGS data from hydrogen, CH$_2$, and Carbon targets do not support the notion of dilution of asymmetry with higher A

• It is possible that dilution will appear at higher A polarized p-A at RHIC is the venue
Lambda Polarization measurement at the AGS

- Earlier Lambda polarization measurements at Fermilab were carried out primarily with Beryllium targets

- While $\Lambda$’s and $\Xi^0$’s were polarized, anti lambdas and protons were not.
- Could this be a result of some nuclear effect?

- The AGS experiment sought to study Lambda polarization from hydrogen, deuterium, and beryllium targets

- Data collected at incident beam momenta 20, 24, and 28.5 GeV/c
Lambda Polarization

Polarization seen in hydrogen, not a nuclear effect
Possible nuclear dependence? Be lower than H₂/D₂
Strong energy dependence
Lambda polarization Cont’d

p-A dependence was further inferred by comparing the AGS Measurement to one that at CERN at 24 GeV with platinum target. At the same $p_T$ the polarization in diluted

K. Heller et al. phys. Lett. 68 (1977) 480
Further work at the AGS M. Sullivan et al. PRD 36 (1987) 674

At this stage there was no distinction made between directly Produced $\Lambda$ and those that come from $\Sigma \rightarrow \Lambda + \gamma$ decays. If $\Sigma$ are polarized their daughter $\Lambda$ could retain 1/3 the polarization implying higher polarization for direct lambda

**FIG. 12.** $R_2$, the ratio of $\Sigma^0$ inclusive production to directly produced $\Lambda^0$ production, is shown vs (a) $p$, the momentum of the produced particle and (b) $p_T$, the transverse momentum of the produced particle. The errors are statistical only.

**FIG. 13.** The effect of this measurement on a previous $\Lambda^0$ polarization experiment. The solid line is the fit to the polarization data determined in Ref. 3. The dashed line results if $\Sigma^0$ polarization is equal and opposite to that of the observed $\Lambda^0$ polarization. The dotted line results if the $\Sigma^0$ are produced unpolarized.
Summary of Lambda polarization p-A

- Hyperon polarization is well established with measurements at FNAL, the CERN PS and ISR, and the AGS
- The measured polarization seems to be diluted with higher A
- Studies on spin transfer from polarized beams to hyperons COMPASS and HERMES w/ muon and electron beams E704 at Fermilab and STAR (Sichtermann’s presentation)
- Polarized p-A at RHIC provides a good opportunity for such systematic studies
Workshop “Summary” in 30 minutes

✧ Good news
✧ Questions and opportunities?
✧ “Golden” measurements
✧ Challenges

Jianwei Qiu
Brookhaven National Laboratory

Joint BNL-LANL-RBRC Workshop on “Physics of pA collisions at RHIC”
BNL Physics Building, January 7-9, 2013
Good news

From our colleagues at CAD:

- p+Au is possible
  max energy 100 GeV/nucleon for both beams

- A collision strategy is proposed for moving only the IP6 and IP8 DX magnets by at minimum of 1 cm, better at 1.5 cm

- This allows equal species to run as well

- Luminosity estimate based on p↑ beam available (anticipated), and Au beam available (anticipated)
  \[ L_{NN} = 15 \text{ pb/week min (now)} \]
  \[ L_{NN} = 37 \text{ pb/week max (few years)} \]
Non-trivial nuclear effects

Cronin effect

HERA discovery

EMC discovery


Leitch, …

200 GeV

39 GeV

19 GeV

J/ψ

Q^2 = 10 GeV^2

HERA

xG (×0.05)

xs (×0.05)

shadowing

EMC finding

original

Fermi motion

sea quark

valence quark
Transverse single-spin asymmetry (SSA)

- Consistently observed for over 35 years!
  - ANL – 4.9 GeV
  - BNL – 6.6 GeV
  - FNAL – 20 GeV
  - BNL – 62.4 GeV
  - BNL – 200 GeV

- Nuclear dependence:

  p+p → π°+X at $\sqrt{s}=200$ GeV

  Sivers (HERMES fit)
  - Twist-3
Proton-nucleus collisions

New era:

Forward region:

Well-known valence distribution from the proton
Less-known small-x distribution from the nucleus

where the spin physicists meet with the small-x physicists

Polarization – “single” spin:

Probe the dynamics that cannot be “seen” by spin-averaged x-sections
Many-body dynamics of universal gluonic matter

How does this happen? What are the right degrees of freedom?

How do correlation functions of these evolve?

Is there a universal fixed point for the RG evolution of d.o.f?

Does the coupling run with $Q_s^2$?

How does saturation transition to chiral symmetry breaking and confinement

Venugopalan, ...
Forward region and coherence

- Dominated production channel is similar to DIS:
  ![DIS](image)
  ![T-channel of pA](image)

- "Snapshot" does not have a "sharp" depth at small $x$

- Probe size:
  - transverse - $\frac{1}{Q} \ll 1 \text{ fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1 \text{ fm}$

- Longitudinal size > Lorentz contracted nucleon:
  $x < x_c = \frac{1}{2mR} \sim 0.1$
Di-hadrons in p/d-A collisions

Marquet (2007), Tuchin (2010)
Dominguez, Marquet, Xiao, Yuan (2011)
Strikman, Vogelsang (2010)

\[
\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_1 \cdot (x-\bar{x})} e^{ik_2 \cdot (y-\bar{y})} \left[ S_6(x, y, \bar{x}, \bar{y}) - S_4(x, y, \nu) - \ldots \right] 
\]

Forward-forward di-hadrons sensitive to both dipole and quadrupole correlators

Recent computations (Stasto, Xiao, Yuan + Lappi, Mäntysaari) include Pedestal, Shading (color screening) and Broadening (multiple scattering) effects in CGC

Venugopalan, …
Anatomy of long range di-hadron collimation

\[
\frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d\Delta \phi}
\]

- BFKL Mini-jet
- Glasma graphs

Associated Di-hadron Yield

Venugopalan, ...
Exciting results on proton lead collisions

Multiplicity

$N < 35$

$35 < N < 90$

$90 < N < 110$

$N > 110$

Predictions for pA at RHIC?
Conclusions on physics opportunities of pA:

- Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy: parton, groups of partons propagation through media in soft and hard regime including spin effects.

- Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy.

- Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution.

- Check the color fluctuation dynamics for generic inelastic pA collisions.

Strikman
Transverse momentum broadening

- Transverse momentum distribution at low $p_T$ is ill-defined in fixed order perturbative calculation
  - All order resummation (CSS formalism)

- Multiple scattering in medium:
  - Each scattering is too soft to calculate perturbatively
  - Resummation + multiple scattering (not yet achieved)

- Moment of $p_T$-distribution is less sensitive to low $p_T$ region:
  - based on observed particles only
    \[
    \langle p_T^n \rangle = \int dp_T^n \frac{d\sigma(Q)}{dp_T^2} / \int dp_T d\sigma(Q)
    \]

- Momentum broadening:
  - Sensitive to the medium properties
  - Perturbatively calculable
    \[
    \Delta \langle p_T^2 \rangle = \langle p_T^2 \rangle_{pA} - \langle p_T^2 \rangle_{pp}
    \]
    \[
    \Delta \langle p_T^n \rangle = \langle p_T^n \rangle_{AB} - \langle p_T^n \rangle_{NN}
    \]
Vector boson production

Data from fixed targets:

\[ \Delta \phi_T^2 = D \frac{A}{2^{1/2}} - 1 \]

Quarkonium cannot be formed \(1/mc\):

\[ r_H \leq \frac{1}{2m_c} \sim \frac{1}{15} \text{ fm} \]

Energy dependence

Final-state interaction for Quarkonium formation

Calculated in both NRQCD and color evaporation model
A-dependence of PT spectrum

- **Ratio of x-sections:**

\[
R(A,q_T) = \frac{1}{A} \frac{d\sigma^{hA}}{dQ^2 dq_T^2} \bigg/ \frac{d\sigma^{hN}}{dQ^2 dq_T^2} \equiv A^{\alpha(A,q_T)-1}
\]

\[
\approx 1 + \frac{\Delta \langle q_T^2 \rangle}{A^{1/3} \langle q_T^2 \rangle_{hN}^{hN}} \left[ -1 + \frac{q_T^2}{\langle q_T^2 \rangle_{hN}^{hN}} \right]
\]

- **Similar formula for J/ψ**

- **Spectrum and ratio:**
SSA in the forward region of pA collisions

Excellent probe for distinguishing various contributions to SSA

Excellent probe for studying small-x Physics

SSA increases as $x_F$ (or $y$) increases
Polarized proton and $A_N$

- **Definition:**
  \[ A_N \equiv \frac{\Delta \sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})} \]

- $A_N$ proportional to the $k_T$ slop of TMD:
  - Now spin-dependent cross section becomes
  \[
  \frac{d\sigma}{dyd^2p_\perp} = \frac{K}{(2\pi)^2} \int d^2b \int_{x_F}^1 \frac{dz}{z^2} \int d^2k_\perp x \epsilon^{\alpha\beta} s_\perp^{\alpha} k_\perp^{\beta} f_{1T}^{\perp,q}(x, k_\perp^2) F(x_A, q_\perp = p_\perp / z - k_\perp) D_{h/q}(z)
  \]
  - Linear $k_t$ associated with Sivers function, need another $k_t$ to have $k_t$-integral non-vanishing, which can only come from the gluon distribution
  - Spin asymmetry is sensitive to the slope of the dipole gluon distribution in $k_t$-space

Kang, Yuan, …
Saturation scale dependence

- Nuclear TMD is broadened:
  - Smaller slop in $kT$
  - Smaller contribution to $AN$

- Expectation:
## Sources of contribution to $A_N$

The source of single spin correlation for $A^+ + B \rightarrow h(p_\perp) + X$

\[
\Delta \sigma = T_{a,F}(x, x) \otimes \phi_{b/B}(x') \otimes H_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z)
\]

+ $\delta q_{a/A}(x) \otimes T_{b,F}^{(\sigma)}(x', x') \otimes H'_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z)$

+ $\delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H''_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}^{(3)}(z, z)$

+ $m_q \delta q_{a/A}(x) \otimes \phi_{b/B}(x') \otimes H'''_{ab\rightarrow c}(p_\perp, \vec{s}_T) \otimes D_{c\rightarrow h}(z)$

### Table of Contributions

<table>
<thead>
<tr>
<th>Term</th>
<th>meaning</th>
<th>collinear</th>
<th>small-x</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>(I)</td>
<td>Sivers  (T_{q,F}(x, x))</td>
<td>Qiu-Sterman 91, 98 hep-ph/9806356</td>
<td>Boer-Dumitru-Hayashigaki, 2006 Kang-Xiao, 1212.4809</td>
<td>process dependence of Sivers function</td>
</tr>
<tr>
<td>(II)</td>
<td>Boer-Mulders (T_{q,F}^{(\sigma)}(x', x'))</td>
<td>Kanazawa-Koike, 2000 hep-ph/000727</td>
<td></td>
<td>small in the collinear formalism</td>
</tr>
<tr>
<td>(III)</td>
<td>Collins (D_{c\rightarrow h}^{(3)}(z, z))</td>
<td>Kang-Yuan-Zhou, 2010 1002.0399</td>
<td>Kang-Yuan, 2011 1106.1375</td>
<td>Collins function is universal</td>
</tr>
<tr>
<td>(IV)</td>
<td>Kane-Pumplin-Repko (m_q \delta q(x))</td>
<td>Kane-Pumplin-Repko, 1978</td>
<td>(different from KPR) Kovchegov-Sievert 1201.5890</td>
<td>small?? (because of quark mass?)</td>
</tr>
</tbody>
</table>
Separation of various sources

- polarized p+p:
  Jet, photon, vs single hadron - Sivers vs Collins

- polarized p+A:
  Magnitude + peak location
  Interesting test: 
  \[
  \frac{A_{N}^{pA\to h}}{A_{pp\to h}} \Big|_{P_{h}\ll Q_{s}^{2}} \approx \frac{Q_{sp}^{2}}{Q_{sA}^{2}} e^{\frac{P_{h}\cdot s^2}{Q_{sp}^{4}}}
  \]
  \[
  \frac{A_{N}^{pA\to h}}{A_{pp\to h}} \Big|_{P_{h}\gg Q_{s}^{2}} \rightarrow 0
  \]
  Kang

Kovchegov
Another critical test of TMD factorization

- Predictive power of QCD factorization:
  - Infrared safety of short-distance hard parts
  - Universality of the long-distance matrix elements
  - QCD evolution or scale dependence of the matrix elements

- QCD evolution:
  If there is a factorization/invariance, there is an evolution equation

- Collinear factorization – DGLAP evolution:

\[
\sigma_{\text{phy}}(Q, \Lambda_{\text{QCD}}) \approx \sum_f \hat{\sigma}_f(Q, \mu) \otimes \phi_f(\mu, \Lambda_{\text{QCD}}) \to \frac{d}{d\mu} \sigma_{\text{phy}}(Q, \Lambda_{\text{QCD}}) = 0
\]

Scaling violation of nonperturbative functions

Evolution kernels are perturbative – a test of QCD
Evolution equations for TMDs

- **Collins-Soper equation:**
  - b-space quark TMD with $\gamma^+$

$$
\frac{\partial \tilde{F}_{f/P^+}(x, b_T, S; \mu; \zeta_F)}{\partial \ln \sqrt{\zeta_F}} = \tilde{K}(b_T; \mu) \tilde{F}_{f/P^+}(x, b_T, S; \mu; \zeta_F)
$$

$$
\tilde{K}(b_T; \mu) = \frac{1}{2} \frac{\partial}{\partial y_s} \ln \left( \frac{\tilde{S}(b_T; y_s, -\infty)}{\tilde{S}(b_T; +\infty, y_s)} \right)
$$

- **RG equations:**

$$
\frac{d \tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_K(g(\mu))
$$

$$
\frac{d \tilde{F}_{f/P^+}(x, b_T, S; \mu; \zeta_F)}{d \ln \mu} = \gamma_F(g(\mu); \zeta_F/\mu^2) \tilde{F}_{f/P^+}(x, b_T, S; \mu; \zeta_F).
$$

- **Evolution equations for Sivers function:**

$$
F_{f/P^+}(x, k_T, S; \mu, \zeta_F) = F_{f/P}(x, k_T; \mu, \zeta_F) - F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F) \frac{\epsilon_{ij} k_i^i S_j^j}{M_p}
$$

$$
\frac{\partial \ln \tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F)}{\partial \ln \sqrt{\zeta_F}} = \tilde{K}(b_T; \mu)
$$

$$
\tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F) \equiv \frac{\partial \tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F)}{\partial b_T}
$$

$$
\frac{d \tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F)}{d \ln \mu} = \gamma_F(g(\mu); \zeta_F/\mu^2) \tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F)
$$

- **CS:**

- **RGs:**

$$
\frac{d \tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_K(g(\mu))
$$

$$
\frac{\partial \gamma_F(g(\mu); \zeta_F/\mu^2)}{\partial \ln \sqrt{\zeta_F}} = -\gamma_K(g(\mu)),
$$

Aybat, Rogers, 2010
Kang, Xiao, Yuan, 2011
Aybat, Collins, Qiu, Rogers, 2011
Scale dependence of Sivers function

- **Up quark Sivers function:**

  Torino Fits

  \[-F_{1T}^{\perp\text{Up}}(\text{GeV}^2)\]

  - $Q = \sqrt{2.4}$ GeV
  - $Q = 5$ GeV
  - $Q = 91.19$ GeV

  Bochum Fits

  \[-F_{1T}^{\perp\text{Up}}(\text{GeV}^2)\]

  Very significant growth in the width of transverse momentum
Importance of the evolution

- SSAs – Sivers function:

$Q^2$ dependence – effectiveness of the probe?
How collinear factorization generates SSA?

- Collinear factorization beyond leading power:

\[ \sigma(Q, s^c) \propto p, s^c k \leftarrow t \sim 1/Q \]

\[ \sigma(Q, s_T) = H_0 \otimes f_2 \otimes f_2 + \left( \frac{1}{Q} \right) H_1 \otimes f_2 \otimes f_3 + \mathcal{O}(1/Q^2) \]

- Single transverse spin asymmetry:

\[ \Delta \sigma(s_T) \propto T^{(3)}(x, x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + \ldots \]

\[ T^{(3)}(x, x) \propto \]
\[ D^{(3)}(z, z) \propto \]
\[ T^{(3\sigma)}(x, x) \propto \]

Qiu, Sterman, 1991, ...
Kang, Yuan, Zhou, 2010
Kanazawa, Koike, 2000

Too large to compete!  Three-parton correlation

Efremov, Teryaev, 82;
Qiu, Sterman, 91, etc.
SSAs generated by twist-3 PDFs

- First non-vanish contribution – interference:

--dominated by the derivative term – forward region:

\[
E \frac{d \Delta \sigma}{d^3 \ell} \propto \epsilon^T s_{T n \bar{n}} D_{c \rightarrow \pi}(z) \otimes \left[ -x \frac{\partial}{\partial x} T_F(x, x) \right] \otimes \frac{1}{1 - \hat{u}} \left[ G(x') \otimes \Delta \sigma_{q g \rightarrow c} + \sum_{q'} q'(x') \otimes \Delta \sigma_{q q' \rightarrow c} \right]
\]

\[
A_N \propto \left( \frac{\ell}{-\hat{u}} \right) \frac{n}{1 - x} \text{ if } T_F(x, x) \propto q(x) \propto (1 - x)^n
\]

- Complete leading order contribution:

\[
E_\ell \frac{d^3 \Delta \sigma(s_T)}{d^3 \ell} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int_{z_{\text{min}}}^1 \frac{dz}{z^4} D_{c \rightarrow h} \left( z \right) \int_{x_{\text{min}}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \phi_{b/B}(x') \sqrt{4\pi \alpha_s} \left( \frac{\epsilon^{s_T n \bar{n}}}{z\hat{u}} \right)
\]

\[
\times \frac{1}{x} \left[ T_{a,F}(x, x) - x \left( \frac{d}{dx} T_{a,F}(x, x) \right) \right] H_{ab \rightarrow c}(s, \hat{i}, \hat{u})
\]
Naïve analysis from the leading order diagrams

- Color-singlet model: only initial state interaction, non-zero SSA
- Color-octet model: initial and final state interactions cancel out, no SSA

Low pT:

\[ A_N(P_{h\perp}) \propto \frac{P_{h\perp} \Delta}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}} \]

High pT:

\[ A_N(P_{h\perp}) \approx \frac{2P_{h\perp}(\Delta^2 + \delta^2)}{P_{h\perp}^2 + 6\Delta^2} \]
Summary

- Polarized pA at RHIC provides a completely new testing ground for QCD

  Dynamics cannot be accessed by unpolarized x-section

  QCD is much richer than the leading power!

- SSA in pA is an excellent observable to study small-x physics in a nucleus

- Let’s make it real!

Thank you!
Backup slices
Polarization for pp-Au

V. Ranjbar, Mei Bai, Zhe Duan
Overview

- Ramp Optics: Same as we have been using so we anticipate same transmission efficiency.

- Collision Polarization lifetime issues: This is the real question. Mei and Zhe Duan have spent a lot of effort to understand mechanism driving current lifetime of Polarization at store. Many questions remain but a few things we can understand:
  - Polarization decay is caused by beam-beam collisions
  - Under beam-beam collisions there are both direct spin effects of the collision and indirect effects due to perturbation of the tunes
  - Both these effects will be different for pp-Au collisions since the beam-beam parameters will be different.
Intrinsic Resonance to 100 GeV

Resonances Crossed during 100GeV Ramp
Resonance Response Sensitivity to Orbit Imperfections

Even with Imperfections at 0.2 shouldn’t See any Polarization losses since all our Intrinsic Resonance < 0.2
Lifetime Issues

I can refer you to Zhe’s and Mei’s paper:” Beam-beam Effects On Proton Beam Polarization in RHIC “

- Lifetime appears to be driven by beam-beam effects
- They describe various mechanisms for this to work both direct and indirect.
Preliminary Analysis from Polarimeter Group

Yellow Ring

From a typical physics store

Non-collision Fill 16715

vy = 0.68

Plots are produced by Anders, Elke, etc.

Courtesy Zhe Duan
Difference in Lifetime for pp-Au versus pp-pp

• For our purposes it would seem that the relevant parameter would be the beam-beam factor which in the case of pp-Au should be nominally < pp-pp

  • For the same emittance it’s protons 2.5 times larger than Au.
  • Part of this gain might be offset due to the Au beam being brighter with Stochastic cooling.
  • Estimating the actual gain at this point is difficult since we are not yet confident about the actual physics of this process.
Potential Strategies for Lifetime:

• We anticipate by the time the pp-Au run is realized we will have developed some strategies:
  • Adjustment to the working point:
    it is well known that snake resonances are all much weaker near the integer.
  • Suppression of nearest intrinsic and imperfection resonances
    recently progress has been made in developing tools to optimize lattice considering the underlying intrinsic resonances
How Stable Spin Direction Varies with Ring Location

Sigma beam size for 20pi beam
Fermilab E-906/SeaQuest: Measurements of pA Spin Independent Drell-Yan

Paul E. Reimer
Physics Division
Argonne National Laboratory
7 January 2013

I. The Big Picture--Drell-Yan
II. EMC effect
III. Partonic Energy Loss

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
The Big Picture
Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/$c^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm$^2$ (GeV/c)$^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.
Early Muon Pair Data—soon to be called Drell-Yan

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope

Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini

CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)
Drell and Yan’s explanation

Also predicted

\[ \lambda (1 + \cos^2 \theta) \]

angular distributions.
Drell-Yan Cross Section

Next-to-Leading Order
- These diagrams are responsible for up to **50%** of the measured cross section
- Parton distributions are Universal!
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)
- Soft gluon resummation at all orders

Angular Distributions

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi$$

$$+ \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

**Higher Twist??**
Drell-Yan Cross Section

- Measured cross section is a convolution of beam and target parton distributions

- **Proton Beam**
  - Target antiquarks and beam

\[
\frac{d^2 \sigma}{dx_b dx_t} = \frac{4 \pi \alpha^2}{x_b x_t s} \sum_{q \in \{u,d,s,\ldots\}} e_q^2 \left[ q_t (x_t) q_b (x_b) + \bar{q}_b (x_b) q_t (x_t) \right]
\]

- **u-quark dominance**
  \((2/3)^2 \text{ vs. } (1/3)^2\)
Drell-Yan Cross Section

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\]

- **u-quark dominance**
  - \((2/3)^2 vs. (1/3)^2\)

- **π beam**
  - Valence beam anti-\(u\) quark and \(u\) target quark

\[
\frac{d^2\sigma}{dx_\pi dx_N} = \frac{4\pi\alpha^2}{x_\pi x_N s} \left[ \frac{4}{9} \bar{u}(x_\pi) u(x_N) + \frac{1}{9} d(x_\pi) \bar{d}(x_N) + \frac{4}{9} u(x_\pi) \bar{u}(x_N) + \frac{1}{9} \bar{d}(x_\pi) d(x_N) \right]
\]

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron</td>
<td>Beam valence quarks target antiquarks</td>
<td>Fermilab E-906, RHIC (forward acpt.) J-PARC</td>
</tr>
<tr>
<td>Anti-Hadron</td>
<td>Beam val. antiquarks Target valence quarks</td>
<td>GSI-FAIR Fermilab Collider</td>
</tr>
<tr>
<td>Meson</td>
<td>Beam val. antiquarks Target valence quarks</td>
<td>COMPASS</td>
</tr>
</tbody>
</table>

Valence × Valence
Valence-sea × \(1/4\)
Sea-Sea
What can Drell-Yan tell us about the EMC effect?
Structure of nucleonic matter: The EMC effect

Comparison with Deep Inelastic Scattering (DIS)

- EMC: Parton distributions of bound and free nucleons are different.

- Nuclear binding effects distributions of quarks within the nucleons
Structure of nucleonic matter:
How do DIS and Drell-Yan data compare?

- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan
  — Valence only effect

[Graph showing data and comparison]

Kulagin and Petti sea vs. valence nuclear effects

![Graphs showing valence and sea nuclear effects](image)

Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.
Structure of nucleonic matter: Where are the nuclear pions?

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- Contemporary models predict large effects to antiquark distributions as x increases.

- **Models must explain both DIS-EMC effect and Drell-Yan**
Structure of nucleonic matter: Where are the nuclear pions?

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- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan
Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Intermediate-x sea PDF’s

- $\nu$-DIS on iron—Are nuclear effects with the weak interaction the same as electromagnetic?
- Are nuclear effects the same for sea and valence distributions

![Graph comparing $\sigma_{Ca}/\sigma_d$ vs. x for different experiments](image-url)
Partonic energy loss in Cold Nuclear Matter
Partonic Energy Loss

- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values \((x_1\) or \(x_F\)) are shifted.
- Fit shift in \(x_1\) relative to deuterium.

\[
\sigma \propto R(A/p)^{X_1}
\]

Models:
- Galvin and Milana
  \[
  \Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}
  \]
- Brodsky and Hoyer
  \[
  \Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}
  \]
- Baier et al.
  \[
  \Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}
  \]

Paul E. Reimer pA Spin Independent Drell-Yan

7 January 2013
Event Reconstruction

- We measure
  1. Direction of particles
  2. Absolute momentum of particles
- We assume
  3. Particles are muons

- Add 4-vectors of muons to get 4-vectors of virtual photon $p$
  - Now we know everything

$$\vec{P}^2 \equiv m_{\gamma}^2 = x_t x_b s$$

$$\frac{p_l}{p_{l\text{max.}}} = x_{\text{Feymann}} = x_b - x_t$$
Partonic Energy Loss

- **E866 data are consistent with NO partonic energy loss for all three models**
- Caveat: A correction must be made for shadowing because of $x_1-x_2$ correlations
  - E866 used an empirical correction based on EKS fit do DIS and Drell-Yan.
- Treatment of parton propagation length and shadowing are critical
  - Analysis of our p-A Drell-Yan data using the Kopeliovich model.
  - $dE/dx = 2.32 \pm 0.52 \pm 0.5$ GeV/fm
  - Same data with different shadowing correction and propagation length
- **Better data outside of shadowing region are necessary.**
- Drell-Yan $p_T$ broadening also will yield information
Parton Energy Loss

- Shift in $\Delta x / 1/s$
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

- Shadowing vs. initial state energy loss

- Possible to distinguish between $A^{1/3}$ (collisional) and $A^{2/3}$ (radiative) dependence?

- Would like data at different $s$
Advantages of 120 GeV Main Injector

The (very successful) past:
Fermilab E866/NuSea

- Data in 1996-1997
- $^1$H, $^2$H, and nuclear targets
- 800 GeV proton beam

The future:
Fermilab E906

- First test run in 2011
- $^1$H, $^2$H, and nuclear targets
- 120 GeV proton Beam

\[
\frac{d^2 \sigma}{dx_b dx_t} = \frac{4 \pi \alpha^2}{x_b x_t} \sum_{q \in \{u,d,s,\ldots\}} e_q^2 \left[ \bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t) \right]
\]

- Cross section scales as 1/s
  - 7× that of 800 GeV beam
- Backgrounds, primarily from J/ψ decays scale as $s$
  - 7× Luminosity for same detector rate as 800 GeV beam

50× statistics!!

at the same $x_t$, $x_b$
Drell-Yan Spectrometer Guiding Principles

- Follow basic design of MEast spectrometer (don’t reinvent the wheel):
  - Two magnet spectrometer
  - Beam dump within first magnet
  - Hadron absorber within first magnet
  - Muon-ID wall before final elements

- Where possible and practical, reuse elements of the E866 spectrometer.
  - Tracking chamber electronics
  - Hadron absorber, beam dump, muon ID walls
  - Station 2 and 3 tracking chambers
  - Hodoscope array PMT’s
  - SM3 Magnet

- New Elements
  - 1\textsuperscript{st} magnet (different boost)
    - Experiment shrinks from 60m to 26m
  - Sta. 1 tracking (rates)
  - Scintillator (age)
  - Trigger (flexibility)
Fermilab E906/Drell-Yan Collaboration

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Yamagata University
Yoshiyuki Miyachi

*Co-Spokespersons
Non perturbative QCD models can explain excess d-bar quarks, but no return to symmetry or deficit of d-bar quarks.

\[ \bar{q}_{\text{pQCD}}(x) \]

\[ \bar{q}_{\text{NonPert.}}(x) \]

\[ + \]

Proton
## Time Line

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Proposed to Fermilab</td>
</tr>
<tr>
<td>2000</td>
<td>Approved w/ conditions</td>
</tr>
<tr>
<td>2001</td>
<td>Fermilab PAC reaffirms approval</td>
</tr>
<tr>
<td>2002</td>
<td>Funding Approval</td>
</tr>
<tr>
<td>2003</td>
<td>Spectrometer construction</td>
</tr>
<tr>
<td>2004</td>
<td>Beam Line Problems</td>
</tr>
<tr>
<td>2005</td>
<td>Vacuum Filled w/ concrete</td>
</tr>
<tr>
<td>2006</td>
<td>Repairs</td>
</tr>
<tr>
<td>2007</td>
<td>more repairs</td>
</tr>
<tr>
<td>2008</td>
<td>Shielding additions</td>
</tr>
<tr>
<td>2009</td>
<td>Run 1</td>
</tr>
<tr>
<td>2010</td>
<td>Fermilab upgrade</td>
</tr>
<tr>
<td>2011</td>
<td>Main Run</td>
</tr>
<tr>
<td>2012</td>
<td>Commission upgrades</td>
</tr>
</tbody>
</table>

- Additional radiation shielding required
- 500 tons of concrete and steel
- 14 tons of steel on movable cart

Paul E. Reimer pA Spin Independent Drell-Yan

7 January 2013
Eventually beam was delivered.
Our reaction:
Eventually beam was delivered. Our reaction:
“Splat” Events

Symptoms and Clues:

- Very large hit multiplicity for dimuon trigger events for both matrix and simple NIM triggers
- All systems: hodoscopes, chambers, and prop. tubes swamped
- *Average* intensity normal, measured by beamline instrumentation
Understanding the Beam

- Independent 10kHz pulsed DAQ read out raw hodoscope rates
- Bins are integrated counts over 100µs (≈5000 RF buckets)
- Large variation in Instantaneous intensity, duty factor very low.
- Periodic structure
- Frequency phase locked to AC line 60 Hz
The Splat-Block Card

- A card was developed to keep a running average of the multiplicity over a 160 ns window (8 RF buckets).
- If average multiplicity above threshold, raises a trigger veto
- Luminosity greatly reduced, but trigger suppresses windows of time with large beam intensities.
Commissioning (beam line and spectrometer) Run (~two months)

- First protons arrived March 8, 2012, Run ended April 30, 2012
- All systems worked!
  - Typical issues with mapping and timing resolved quickly
  - Some challenges with TDC microcode – modules rolled-back to a prior software version, zero-suppression moved to VME CPUs → relatively long dead-times
- Unexpectedly large hit multiplicities with dimuon trigger – termed “splat events”

Where do we go from here?

- Better Beam Quality
  - Fermilab is has gotten this message
  - Mistuned 720 Hz harmonic suppression (was suppressing 680)
  - Better 60 Hz AC filtering on all power supplies
  - Completely revamped control and feedback system
  - Other improvements

- Experimental Improvements
  - TDC Micro code improvements—less dead time, pipelining?
  - Cherenkov Beam monitor for better splat block
  - New St. 1 and St. 3- for better rate capabilities
  - Phototube bases optimized for rate rather than linearity
pA Drell-Yan at RHIC?

- What about the $J/\psi$ and $\psi'$?
  - See talk by Mike Leitch in 1st session
  - E906/SeaQuest does not have sufficient resolution to see the $\psi'$

- Possibly easier to select kinematical regions to emphasize quarks or antiquarks in proton or Nucleus.

- di-leptons may be hard to see/separate from background

- Use $W^\pm$ or $Z^0$ instead of $\gamma^*$
  - Easy to identify
  - Necessarily correlates $x_1 \times x_2$:
    \[
sx_1 x_2 \equiv M_W^2
    \]
  - For $W^\pm$—difficult to reconstruct $x_1 \times x_2$ since $\nu$ is unseen
Polarized Drell-Yan@Fermilab Main Injector

- Polarized beam
  - Major advantage—the beam is a blow torch—Luminosity
  - Major disadvantage—the beam polarization is presently virtual—only a proposal

- Spectrometer:
  - By 2014, spectrometer will be well understood, including angular acceptance

Exploring polarized target
- sea quark Sivers’
Conclusion—not yet

Unpolarized pA collisions can offer unique insight into

- EMC Effect
- Partonic Energy Loss

Fermilab E-906/SeaQuest spectrometer works, waiting for beam

Fermilab may also provide laboratory for pA physics

Paul E. Reimer pA Spin Independent Drell-Yan

7 January 2013
p-Pb at the LHC:

ALICE Results and Plans

Tim Schuster

for the ALICE collaboration

The Physics of p+A Collisions at RHIC
January 7-9, 2013, Brookhaven National Lab
ALICE p-Pb

Overview

• Pilot run on September 13, 2012
  - $\sqrt{s_{NN}} = 5.02$ TeV (4 TeV p + 1.58A TeV Pb)
  - center of mass moves with $\Delta y = -0.465$ in direction of p beam
  - $\approx 2M$ p-Pb events recorded
  - originally planned for accelerator/experiment setup, the pilot run yields physics results!

• Results from the pilot run
  - charged particle pseudorapidity density
  - transverse momentum spectra and nuclear modification
    arXiv:1210.4520
  - di-hadron correlations

• Plans for the 2013 p-Pb run
ALICE p-Pb

The ALICE Experiment

- **Event selection**
  - VZERO-A (2.8<\(\eta_{\text{lab}}\)<5.1), VZERO-C (-3.7<\(\eta_{\text{lab}}\)<-1.7)
  - Neutron zero degree calorimeters (ZNA, ZNC)

- **Charged particle multiplicity**
  - Silicon Pixel Detector (SPD) |\(\eta_{\text{lab}}\)|<1.4

- **\(p_T\) spectra, di-hadron correlations**
  - Inner Tracking System (ITS): Silicon Pixel, -Drift and -Strip Detectors (SPD, SDD, SSD)
  - Time Projection Chamber (TPC) |\(\eta_{\text{lab}}\)|<0.9 to 1.5
• Event selection
  – VZERO-A AND VZERO-C signal
  – Neutron zero degree calorimeters (ZNA, ZNC): background removal and control trigger

• Resulting event sample
  – non single-diffractive (NSD)
  – negligible contamination from SD and EM processes

• NSD in p-Pb
  – at least one binary N+N interaction is NSD (Glauber picture)
  – definition confirmed by model: in DPMJET, SD p-Pb collisions are concentrated on the surface of the nucleus (and have $N_{\text{part}} = 2$)

• Validated from cocktail of models
Tracklet analysis with SPD hits
  - dominating systematic uncertainty 3% from normalization

Reach of the SPD extended to $|\eta_{\text{lab}}| < 2.0$ using displaced vertex events

$y_{\text{CMS}} = -0.465$

Saturation models predict a steeper slope of the double-hump structure
Energy Dependence

- Normalization by $<N_{\text{part}}>$ = 7.9 (Glauber MC)
- Midrapidity $dN_{\text{ch}}/d\eta$ lies
  - 15% below NSD pp collisions
  - in the systematics of inelastic pp collisions
- Inelastic $p$-$Pb$ would be $\approx 4\%$ lower (HIJING)

arXiv:1210.3615
• Primary charged tracks
  - reconstructed in ITS+TPC ($|\eta_{\text{lab}}| < 0.8$)
  - assume $\eta_{\text{CMS}} = \eta_{\text{lab}} - y_{\text{CMS}}$, then correct
  - slightly softer spectrum at higher $\eta$ (Pb side)?

• Compare to pp reference spectrum
  - constructed from measurements at 2.76 TeV and 7 TeV (3.6% systematic uncertainty):
    - $p_T < 5\text{GeV}/c$: interpolation assuming power law dependence on $\sqrt{s}$
    - $p_T > 5\text{GeV}/c$: scale $\sqrt{s} = 7$ TeV data using factor from NLO pQCD
  - scaled by $T_{p\text{Pb}} = 0.0983 \pm 0.0035 \text{ mb}^{-1}$ from Glauber model
\[ R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{\text{coll}} \rangle dN_{pp}/dp_T} \]

- \( R_{pPb} \) compatible with 1 for \( p_T > 2 \) GeV/c
- Unlike in Pb-Pb, no suppression observed
- Suppression in Pb-Pb is not an initial state effect

\[ \text{ALICE, charged particles} \]

\[ \text{arXiv:1210.4520} \]
\( R_{AB} > 1 \) at intermediate \( p_T \) observed in d+Au at RHIC typically attributed to Cronin effect

- No enhancement seen in p-Pb at LHC
- No Cronin effect?
• Reminder from SPS energies: $R_{AB} = 1$
does not mean absence of effects!

Calculation taking into account:

Cronin effect, shadowing

Cronin effect, shadowing

+ partonic energy loss

PRL 89:252301,2002

• Model comparisons are required to understand $R_{pPb}$ at the LHC
• Saturation (CGC) models:
  - consistent with the data
  - large uncertainties

• pQCD models with shadowing:
  - consistent at low $p_T$
  - some discrepancies at high $p_T$

• HIJING
  - with shadowing describes $\eta$ spectrum and low $p_T$ better
  - no shadowing better at high $p_T$
Di-Hadron Correlations

Introduction

• CMS: pp, p-Pb at LHC
  – long-range correlations (near side ridge) appear in high multiplicity events
  – collective effects in pp and p-Pb?

• d+Au at RHIC, e.g. STAR
  – back-to-back signal in forward π^0 correlations disappears for high multiplicity events
  – compatible with CGC predictions

• LHC central η and RHIC forward probe a similar x regime
Di-Hadron Correlations

Multiplicity Classes

- Correlation between geometry and multiplicity in p-A is not as strong as in A-A

- Define multiplicity classes
  - using charge in VZERO to avoid correlation with analyzed tracks
  - VZERO-A (2.8<\eta_{lab}<5.1) and
  - VZERO-C (-3.7<\eta_{lab}<-1.7)

- Systematic checks using
  - SPD |\eta_{lab}|<1.4
  - ZNA (beam neutron acceptance, Pb side)

<table>
<thead>
<tr>
<th>Event class</th>
<th>V0M range (a.u.)</th>
<th>\langle dN_{ch}/d\eta\rangle</th>
<th>\langle dN_{trk}/d\eta\rangle</th>
</tr>
</thead>
<tbody>
<tr>
<td>60–100%</td>
<td>&lt; 138</td>
<td>6.6 \pm 0.2</td>
<td>6.4 \pm 0.2</td>
</tr>
<tr>
<td>40–60%</td>
<td>138–216</td>
<td>16.2 \pm 0.4</td>
<td>16.9 \pm 0.6</td>
</tr>
<tr>
<td>20–40%</td>
<td>216–318</td>
<td>23.7 \pm 0.5</td>
<td>26.1 \pm 0.9</td>
</tr>
<tr>
<td>0–20%</td>
<td>&gt; 318</td>
<td>34.9 \pm 0.5</td>
<td>42.5 \pm 1.5</td>
</tr>
</tbody>
</table>
Di-Hadron Correlations  Correlation Measure

- Associated yield per trigger particle
  \[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d\Delta \eta d\Delta \varphi} = \frac{S(\Delta \eta, \Delta \varphi)}{B(\Delta \eta, \Delta \varphi)} \]

- Signal (same event) pair yield
  \[ S(\Delta \eta, \Delta \varphi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d\Delta \eta d\Delta \varphi} \]

- Background (mixed event) yield
  \[ B(\Delta \eta, \Delta \varphi) = \frac{1}{B(0, 0)} \frac{d^2 N_{\text{mixed}}}{d\Delta \eta d\Delta \varphi} \]

\[ 2 < p_{T,\text{trig}} < 4 \text{ GeV/c} \]
\[ 1 < p_{T,\text{assoc}} < 2 \text{ GeV/c} \]
\[ \text{p-Pb } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]

60-100%
Di-Hadron Correlations

Correlation Measure

- Associated yield per trigger particle
  \[
  \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d\Delta \eta \, d\Delta \varphi} = \frac{S(\Delta \eta, \Delta \varphi)}{B(\Delta \eta, \Delta \varphi)}
  \]

- Signal (same event) pair yield
  \[
  S(\Delta \eta, \Delta \varphi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d\Delta \eta \, d\Delta \varphi}
  \]
  summed over all events in event class, then divided

- Background (mixed event) yield
  \[
  B(\Delta \eta, \Delta \varphi) = \frac{1}{B(0, 0)} \frac{d^2 N_{\text{mixed}}}{d\Delta \eta \, d\Delta \varphi}
  \]


\[\begin{align*}
2 < p_{T,\text{trig}} < 4 \text{ GeV/c} \\
1 < p_{T,\text{assoc}} < 2 \text{ GeV/c}
\end{align*}\]

p-Pb \(s_{NN} = 5.02\) TeV

60-100%

Tim Schuster - p+A at RHIC Workshop - Jan 9, 2013
Di-Hadron Correlations

Multiplicity Dependence

- **Low-multiplicity p-Pb:**
  - pp-like (jet-like) correlation

- **High-multiplicity p-Pb:**
  - near-side ridge appears
  - higher yields on near- and away-side

\[ 2 < p_{T,\text{trig}} < 4 \text{ GeV/c} \]
\[ 1 < p_{T,\text{assoc}} < 2 \text{ GeV/c} \]

\[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d\Delta\eta d\Delta\phi} \]

\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

\( p-Pb \)
• Low-multiplicity p-Pb:
  – pp-like (jet-like) correlation

• High-multiplicity p-Pb:
  – near-side ridge appears
  – higher yields on near- and away-side
• Compare associated yield in p-Pb event classes and pp
  – project to \( \Delta \phi \) over \(|\Delta \eta| < 1.8\)
  – subtract baseline at \(|\Delta \phi| \approx 1.3\)

• Low multiplicity p-Pb is similar to pp

• Yield rises on near- and away-side with increasing multiplicity

• In contrast to the away-side suppression observed in d+Au at RHIC at forward \( \eta \) (similar \( x \))

Di-Hadron Correlations Multiplicity Dependence

Di-Hadron Correlations  Two Ridges!

- Quantify the excess in high-multiplicity p-Pb: subtract jet-like correlation

\[
\begin{align*}
\text{0-20\% minus 60-100\%} &= \frac{d^2 N_{\text{assoc}}}{d\Delta\eta d\phi} \\
2 < p_{T,\text{trig}} &< 4 \text{ GeV/c} \\
1 < p_{T,\text{assoc}} &< 2 \text{ GeV/c}
\end{align*}
\]

- The near-side ridge is accompanied by an almost identical structure on the away-side!


Tim Schuster - p+A at RHIC Workshop - Jan 9, 2013
• A residual jet peak at (0,0) remains after subtraction (0-20%)-(60-100%) (cf. B.Cole ATLAS talk, Monday)

• Compare different event class definitions
Di-Hadron Correlations

- A closer look at the two ridges: the near- and away-side ridges
  - have the same magnitude
  - are essentially flat in $\Delta \eta$
  (small residual near-side peak)

- Project to $\Delta \phi$
  - exclude residual peak ($|\Delta \eta|<0.8$ on the near-side)
  - in HIJING the correlation shows no qualitative changes with multiplicity
  - quantify the ridges: extract ridge yields and Fourier coefficients
• Ridge yields: integrate the two ridge structure on the
  - near side $|\Delta \phi| < \pi/2$
  - away side $\pi/2 < \Delta \phi < 3\pi/2$

• Near- and away-side yields
  - vary over a large range
  - agree for all $p_T$ and multiplicity ranges

• The correlation between near- and away-side yields suggests a common underlying physical origin
Fourier decomposition

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{assoc}}}{d\Delta \varphi} = a_0 + 2a_2 \cos(2\Delta \varphi) + 2a_3 \cos(3\Delta \varphi),
\]

\[v_n = \sqrt{\frac{a_n}{b}}\]

- \(b\): baseline in higher multiplicity class
- \(v_2\) and \(v_3\) increase with \(p_T\)
- \(v_2\) increases with multiplicity
- 3+1D viscous hydrodynamic calculation (p-Pb 4.4TeV) qualitatively describes multiplicity and \(p_T\) dependence of both \(v_2\) and \(v_3\)

---

**Di-Hadron Correlations**

**Quantifying the Ridges**

- Fourier decomposition
- \(\frac{1}{N_{\text{trig}}} \frac{dN_{\text{assoc}}}{d\Delta \varphi} = a_0 + 2a_2 \cos(2\Delta \varphi) + 2a_3 \cos(3\Delta \varphi),\)
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**Di-Hadron Correlations**

**Quantifying the Ridges**

- Fourier decomposition
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- \(v_2\) increases with multiplicity
- 3+1D viscous hydrodynamic calculation (p-Pb 4.4TeV) qualitatively describes multiplicity and \(p_T\) dependence of both \(v_2\) and \(v_3\)
Two ridges are also qualitatively predicted by CGC.
Di-Hadron Correlations

- Event multiplicity hierarchy
- Subtract a symmetric double-ridge from $\Delta \phi$ projection
  - projection: $|\Delta \eta| < 1.8$
  - evaluate near-side ridge:
    1.2 < $|\Delta \eta| < 1.8$
    $|\Delta \phi| < \pi/2$
  - mirror at $\pi/2$ to the away side
- Remaining correlation (jet-like) shows no multiplicity dependence!
  - 2013 run will give definitive answer to whether or not the away-side is modified beyond the ridge structure
Di-Hadron Correlations

Other LHC Experiments

- CMS
  - reported near-side ridge

- ATLAS
  - confirms the two-ridge structure

- Structures seen in ATLAS and CMS are qualitatively similar to the ALICE results

- Different normalizations and $p_T$ ranges among the three LHC experiments make a quantitative comparison difficult

CMS

arXiv:1210.5482

low-mult. ($N_{\text{track}} < 35$)

ATLAS

arXiv: 1212.5198
• Rich physics from one-day pilot run!

  – saturation models predict steeper slope of $\eta$ spectrum

• Transverse momentum spectra and nuclear modification factor $R_{p\text{Pb}}$ (arXiv:1210.4520)
  – neither suppression nor enhancement of high $p_T$ hadrons observed
  – no model describes $\eta$ and $p_T$ spectra simultaneously

  – high multiplicity p-Pb events show long-range correlations
  – two essentially identical ridges on the near- and the away-side
  – no suppression of the away-side (seen at RHIC in forward d+Au) observed
• Nuclear modification factor $R_{pPb}$
  - discern models at high $p_T$ with larger statistics
  - study the event multiplicity dependence of $R_{pPb}$ (understand p-Pb “centrality”)

• Di-hadron correlations
  - study the ridge using flow analysis techniques
  - correlation function for identified particles

• Jets, J/ψ and open heavy flavor
  - nuclear modification of jet spectra and heavy flavor yields: pp vs. p-Pb vs. Pb-Pb
ALICE p-Pb

Forward Upgrade Idea

• Potential forward upgrades (arXiv:1106.5807)
  - under discussion for LHC long shutdown 2

• Electromagnetic calorimeter FoCal
  - Si/W calorimeter
  - direct $\gamma$ and $\pi^0$
  - two positions considered
    $3.3<\eta<5.3$ or $2.5<\eta<4.5$

• Optional hadronic calorimeter HCal
  - Cu/Scintillator sampling calorimeter
  - improved photon isolation
  - additionally jet, $\gamma$-jet physics

• Large kinematic reach ($Q^2$ and $x$) for
direct $\gamma$ and (di-)jet correlations
• Looking forward to 2013 p-Pb data!
End.
Ratio of Averages or Average of Ratios

- What is measured for jet-like correlations in symmetric bins?
- Assume event \((i)\) composed of sum of independent \(N^i\) sources emitting \(n_{ij}\) correlated particles.
- With our way of averaging (ratio of averages):

\[
\frac{N_{\text{pair}}}{N_{\text{trig}}} = \frac{\sum_{i=1}^{N_{\text{evt}}} \sum_{j=1}^{N_{\text{source}}} \frac{1}{2} n_{ij} (n_{ij} - 1)}{\sum_{i=1}^{N_{\text{evt}}} \sum_{j=1}^{N_{\text{source}}} n_{ij}} = \frac{N_{\text{evt}} \langle N_{\text{source}} \rangle \frac{1}{2} \langle n(n-1) \rangle}{N_{\text{evt}} \langle N_{\text{source}} \rangle \langle n \rangle} = \frac{1}{2} \frac{\langle n(n-1) \rangle}{\langle n \rangle}
\]

no source/multiplicity dependence
Average of Ratios

\[
\frac{N_{\text{pair}}}{N_{\text{trig}}} = \frac{1}{N_{\text{evt}}} \sum_i \frac{\sum_{j=1}^{N_i^{\text{source}}} n_{ij}(n_{ij} - 1)}{\sum_{j=1}^{N_i^{\text{source}}} n_{i,j}} \tag{2}
\]

It is impossible to simplify this expression for the general case. The result depends on the distribution of number of sources. This can be seen by considering two limiting cases.

(1) \(N_{\text{source}} = 1\)

\[
\frac{N_{\text{pair}}}{N_{\text{trig}}} = \langle n - 1 \rangle|_{n>0} = \frac{\langle n \rangle}{1 - p_0} - 1 \tag{3}
\]

The average of ratios measures the number of additional particles under the trigger condition. This is usually called the number of associated particles \(N_{\text{ass}}\).

(2) \(N_{\text{source}} \text{ large}\) In this case the source average and the event average are equal and the average of ratios is equal to the ratio of averages.

\[
\frac{N_{\text{pair}}}{N_{\text{trig}}} = \frac{1}{N_{\text{evt}}} \sum_i \frac{\sum_{j=1}^{N_i^{\text{source}}} n_{i,j}(n_{ij} - 1)}{\sum_{j=1}^{N_i^{\text{source}}} n_{i,j}} = \frac{\langle n(n-1) \rangle}{\langle n \rangle} \tag{4}
\]
Di-Hadron Correlations Subtraction
ALICE p-Pb

The LHC p-Pb Pilot Run

• One-day pilot run on September 13, 2012
  - bunch intensities: $10^{10}$ (p), $6 \cdot 10^7$ (Pb)
  - 8 (out of 13) bunches collide at ALICE
  - interaction region: $\sigma_z=6.3$cm, $\sigma_r=60$µm
  - luminosity $8 \cdot 10^{25}$ cm$^{-2}$s$^{-1}$ → hadronic interaction rate 150 Hz

• $\sqrt{s_{NN}} = 5.02$ TeV
  - 4 TeV p + 1.58A TeV Pb
  - center of mass moves with $\Delta y=-0.465$ in direction of p beam

• $\approx 2$M p-Pb events recorded. Originally planned for accelerator / experiment setup, the pilot run yields physics results!
The ALICE Experiment

ALICE p-Pb

VZERO-A
(2.8<\eta_{lab}<5.1)

ZNA
(+112.5m)

TPC
|\eta_{lab}|<0.9 to 1.5

ITS

VZERO-C
(-3.7<\eta_{lab}<-1.7)

SSD
SDD
SPD

ZNC
(-112.5m)
The sPHENIX Upgrade (and ePHENIX)

The Physics of p+A Collisions at RHIC (1/9/2013)

Joe Seele
(RIKEN BNL Research Center)

- Central Upgrade and Physics
- Forward Upgrade and Physics
- Towards ePHENIX
sPHENIX Central Physics and Upgrade
• How does $\eta/s$ go from being nearly as small as possible near $T_c$ to the weakly coupled limit?

• The figure shows several state-of-the-art calculations and three generic scenarios approaching $T_c$
Jet observables

- A parton traversing the medium accumulates transverse momentum characterized by
  \[ \hat{q} = d(\Delta p_T) / dx \]

- Coupling parameters like qhat are scale dependent and must approach weak coupling at high energies and strong coupling at thermal energies.
Jet rates at RHIC

- At present RHIC luminosity, in a 20 week Au +Au run we would have $10^6$ jets above 30 GeV in 0-20% centrality
Fake jets

- Using 750M minimum bias HIJING events
- True jets outnumber fake jets for $p_T > 20$ GeV/c
- Details published as Hanks et al., arXiv:1203.1353, published in PRC August 10

Au+Au @ 200 GeV, 0 - 10%

$R = 0.2$ Anti-$k_T$ Jets

$1/N_{\text{events}} dN_{\text{jets}}/dE_T [(\text{GeV})^{-1}]$

$E_T [\text{GeV}]$

10 20 30 40 50 60

10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0$

1
Design Goals for a Jet Detector

- Full azimuthal coverage in a fiducial region $|\eta| < 1$
- 2T solenoid to ultimately allow high resolution tracking in a small volume
- Electromagnetic and hadronic calorimetry
  - Electromagnetic
    - $\Delta \eta \times \Delta \phi \approx 0.02 \times 0.02$
    - $\sigma_E/E \approx 15\%/\sqrt{E}$
  - Hadronic
    - $\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1$
    - $\sigma_E/E \approx 100\%/\sqrt{E}$
- Data acquisition capable of recording $>10$ kHz
Central sPHENIX Upgrade
sPHENIX Forward Physics and Upgrade
Large, forward $A_N$s in hadron production in $p+p$ ($p+A$) have been measured since the mid 70's.

Since the mid to late 90's new extended factorization schemes (TMD and Twist-3) have provided a new mechanism to generate single spin asymmetries in these collisions.

1. Initial-state (Sivers-type) spin-momentum correlations - Considers intrinsic transverse momentum in the nucleon and initial-state interactions
2. Final-state (Collins-type) spin-momentum correlations - Considers transverse momentum inside a jet and final-state interactions
3. Other Higher Order Correlations
Forward Spin Physics - II

With a good enough jet detector, we can unambiguously separate these pieces

**Initial State Piece**

- Jets with identified hadrons (measure $A_N$ for jets)
- Do jets from certain quarks prefer to go left or right?

**Final State Piece**

- Left-right asymmetry of identified particle inside a jet
- Do certain hadrons fragment from certain quarks to the left or right of the jet axis?
An elegant test of Transverse Momentum Dependent pdf factorization/description through measurement of forward Drell-Yan pairs

sign flip in asymmetry between DIS and DY

Kang, Qiu, PRD81
• The forward region also corresponds to the low-\(x\) region where saturation is expected (below a scale \(Q_S\)) and/or a CGC description of the data is relevant.

• As in other QCD related phenomena, many measurements will be needed to substantiate and understand the validity of a CGC as the description of gluons in the nucleus as well as correlated structures.

• Other theoretical tools are beginning to help elucidate the low-\(x\) region in hadrons and nuclei (TMDs).

A major push is to observe saturation experimentally, and understand and map out the \(x\) and saturation scale, \(Q_S\), dependencies.
• $G$ now comes in two flavors $G^{(1)}$ and $G^{(2)}$ in the low-$x$ limit
• All CS described using $G^{(1)}$ and $G^{(2)}$
• Measure $G$'s via $\gamma$-jet, dijet

PRD 49, 2233, 3352
NPB 529, 451

J. Seele (RBRC) - p+A Workshop

Both real and virtual (DY) photons
A Link Between CNM and Spin

RHIC is unique in its ability to collide polarized protons with nuclei

Exploiting the link between the TMD and CGC framework, it has been shown that transverse single spin asymmetries in polarized p+A collisions are sensitive to the saturation scale in the nucleus

\[
\frac{A_{AN}^{pA \rightarrow hX}}{A_{AN}^{pp \rightarrow hX}} \quad p_T^h \ll Q_s^2 \quad \frac{Q_{s,p}^2}{Q_{s,A}^2} \quad f(p_T^h) \quad \frac{A_{AN}^{pA \rightarrow hX}}{A_{AN}^{pp \rightarrow hX}} \quad p_T^h \gg Q_s^2 \approx 1
\]

\[A_N\] measures the azimuthal modulation of particle/jet production with respect to the proton’s spin

These spin effects are large. Spin “R_{AA}” could be \(~O(0.5)\)
An area largely pioneered by PHOBOS and BRAHMS. We hope to expand upon their measurements (away from Bjorken plateau)

At forward rapidities
- Direct photons can give information about the expansion of the medium
- Correlation measurements can test models of longitudinal expansion (3d hydro)
- Extended (di-)jet coverage to study jet energy loss in the medium

Currently it is question of how far forward the measurements will be able to be made
Forward sPHENIX

Optimized for jets and photons/DY over a large range in rapidity ($\eta \sim 4$)

- Extension/modification of the central solenoid for B field
- GEM based tracking
- Diamond pixel for heavy flavor tagging
- Restack of current PHENIX EMCal
- RICH based PID (pi/K/p)
- HCal for jet energy reco
- Muon identification
sPHENIX -> ePHENIX
• One possible manifestation of EIC is eRHIC

• eRHIC will add electron accelerations capabilities to RHIC

• eRHIC is thought to happen in two stages (the difference being the electron beam momentum)

• Through the sPHENIX/decadal plan exercise, BNL charged the RHIC collaborations to imagine how their upgrades could lead to detectors for phase I of eRHIC
• A major purpose of eRHIC is to measure the 3d structure of the nucleon and nuclei over a large kinematical range

• ePHENIX needs to measure the scattered electron and complete and exclusive final states
sPHENIX to ePHENIX

- Many studies were done to test the central barrel design for the phase I of eRHIC (electron beam momentum <= 10 GeV) [arXiv:1207.6378] and the current designs appears to be good enough.

EMCal + Tracker

- Forward sPHENIX is being designed with ePHENIX in mind
- A forward EMCal + tracker on the opposite side will need to be added for ePHENIX
Conclusions

• PHENIX is planning upgrade programs aimed at both central and forward rapidity measurements.
• The central rapidity upgrade aims to understand jet-medium interactions as a tool to understand the QGP.
• Forward sPHENIX is being designed and optimized to study forward jets, photons and DY for understanding all major facets of the RHIC program.
• Sensitivity studies are ongoing.
• An evolution of sPHENIX to ePHENIX is being planned for in the design of sPHENIX.
Backups
Physics at RHIC

- CGC: TMD PDFs at low-x
- Polarized p(d)+A
- Heavy Ions
- Polarized pp
- The sQGP
- TMD Spin PDFs

QCD

J. Seele (RBRC) - p+A Workshop
The MPC-EX, pA observables with an eye to future

Richard Seto
University of California, Riverside
Riken-BNL pA workshop
Jan 7-9, 2012

Acknowledgements to MPC-EX group
pA: the questions

- Questions
  - The sQGP – How is it born?
    - Answering this question is crucial to understanding the sQGP
    - Source of bulk @RHIC is from low x below $10^{-2}$ LHC is factor 10 to 100 less
  - Can we understand Cold Nuclear Matter?
  - How are probes affected?
- Competing pictures
  - One nice picture
    - CGC $\rightarrow$ Glasma $\rightarrow$ sQGP (hydro)
  - Modified structure functions (together with a Glauber picture for centrality dependence)
  - pQCD shadowing
    - Higher twist
    - Coherence
  - Initial state energy loss
  - Absorption
  - …
pA: Competing pictures : equivalent descriptions

**d+A Suppression**

- **Two pictures**
  - Higher Twist shadowing
  - CGC

At low-x two universal gluon distributions $G^{(1)}$ and $G^{(2)}$ show up in cross section calculations

Equivalent distributions derived in TMD framework and CGC framework

Are some of the other Competing processes (e.g. energy loss and the CGC) also equivalent?

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pA: Where to look?

• To study the precursor state of sQGP → pT ~ 1 GeV
  • E.g. multiplicity distributions
  • Pion correlations at low p_T
    – Problem: dependent on FF and/or gluon multiplication factor (CGC)

• Can we use “hard probes”, something that comes directly from the vertex?

  Directed photons
  – “low” Q^2 \, p_T > 3 GeV
  – Forward region to probe “low-x” gluons

  Add direct photon capability to the MPC
Why p+A instead of d+A?

Multi-parton interactions not present in pA can contribute to the suppression of the away-side correlation strength.

Phys. Rev. D 84 014008 (2011)

Forward rapidity corresponds to high-\(x\) in the projectile nucleon (d or p). Nuclear corrections at high-\(x\) are large for the deuteron.

...and you can’t polarize the deuteron at RHIC...
Where to look – from the CGC

Use EPS09 as a Benchmark

\[ R_G^{\text{Pb}}(x, Q^2) = \frac{xG_A(x, Q^2)}{AxG_p(x, Q^2)} \]

Go to
Y=3-4
Low Q^2

CGC MCKT
No Fragmentation

 Minimal Suppression at High Q^2

EPS09 – a benchmark
DIS, Drell Yan, π^0 (PHENIX, y=0)
All curves fits to data ~90% CL

(Note: this is a user generated plot)
The PHENIX MPC-EX Detector

A combined charged particle tracker and EM preshower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

- $\pi^0$ rejection for direct photons
- $\pi^0$ reconstruction out to >80GeV
- Charged track identification

$3.1<\eta<3.8$

Approved by BNL/DOE - will be ready for Run-15 (earliest p+Au run)
How it works

1.8mm x 15mm “minipad” sensors  \( \pi^0 \rightarrow \)
Interleaved with 2mm Tungsten
4 layers in x and 4 in y

MPC-EX

MPC

(Cartoon)

\[
\begin{align*}
\text{Counts} \\
\text{Invariant Mass [GeV/c}^2\text{]} \\
\end{align*}
\]

Invariant mass distribution
for \( \gamma s \) (black) and \( \pi^0 s \) (red)

40<E<45 GeV
Direct Photon Simulations ($\pi^0$ cuts)

Basic cuts: remove $\pi^0, \eta, \text{charged hadrons}$

For $p_T > 3$ GeV:
2.9% efficiency for $\pi^0$
31.2% efficiency for direct photons
$\text{dir}/(\text{frag}+\text{dir}) = 57.4\%$

350 nb$^{-1}$ sampled:
1.4 x $10^4$ prompt photons
$p_T > 3$ GeV/c after cuts

Simulation: 868M pythia MB events
Extracting prompt photons

1) measure inclusive γ and π^0

2) simulate hadronic sources of γ

3) R_γ > 1 \Rightarrow \text{prompt } γ

\[ R_γ = \left( \frac{γ_{Incl}}{π^0} \right)_{Meas} \left( \frac{γ_{Incl}}{π^0} \right)_{Sim} \]

\[ γ_{prompt} = γ_{incl} \ast (1 - 1/R_γ) \]

\[ R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{γ_{Incl}^{dAu} \ast (1 - 1/R_{γ}^{dAu})}{γ_{Incl}^{pp} \ast (1 - 1/R_{γ}^{pp})} \]

Advantage: many sources of systematic error cancel
in particular the energy scale
Systematic errors

\[
R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{\gamma_{Incl}^{dAu} * (1 - 1/R_{\gamma}^{dAu})}{\gamma_{Incl}^{pp} * (1 - 1/R_{\gamma}^{pp})}
\]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{\gamma})</td>
<td>1.34</td>
</tr>
<tr>
<td>systematic error (\Delta R_{\gamma}/ R_{\gamma}) correlated between dAu and pp</td>
<td>7.2% from knowledge of (\pi^0) Cross section</td>
</tr>
<tr>
<td>systematic error (\Delta R_{\gamma}/ R_{\gamma}) uncorrelated between dAu and pp</td>
<td>1% Residual error from energy scale</td>
</tr>
<tr>
<td>systematic error (\Delta \gamma_{Incl}/ \gamma_{Incl}) uncorrelated between dAu and pp</td>
<td>2% Residual error from energy scale</td>
</tr>
<tr>
<td>relative systematic error on (\langle N_{coll} \rangle)</td>
<td>3%</td>
</tr>
</tbody>
</table>
EPS09 Limits from Prompt Photons

- Weight events in \(x, Q^2\) (direct, frag) according to EPS09 to generate \(R_{dAu}\) for each curve
- Assume the \(R_{dAu}\) value we measure corresponds to the EPS09 baseline
- Vary \(R_{pp}\), \(R_{dAu}\), \(\gamma_{dAu\text{ incl}}\) and \(\gamma_{pp\text{ incl}}\) within 3\(\sigma\) systematic errors
- Evaluate EPS09 curves to see which are consistent within 90% C.L.

MPC-EX
350\(\text{nb}^{-1}\) d+Au
49\(\text{pb}^{-1}\) p+p

Promt photons in MPC-EX \(\rightarrow\) Precise Measurement of the Nuclear Gluon PDF

I would like to use a CGC model to estimate sensitivity to \(Q_S\)
Additional Measurements \( \gamma + \text{hadrons} \)

- Pick \( p_T \) of photon, measure hadron correlation in bins of \( \Delta \theta \), and \( p_T \) of hadron
- Sensitive to \( Q_{\text{Sat}} \)
The future? DY hadron correlations

Double hump structure
(preponderance of signatures)
Rate??? Possible at RHIC in pCu?
Polarized p+A Collisions

\[ A_N = \frac{1}{P} \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi} \]

Kang, Yuan: PRD 84, 034019 (2011)

\[ Q_{sp}^2 = (1.0 \text{ GeV})^2 \]
\[ Q_{sA}^2 = (2.5 \text{ GeV})^2 \]
\[ \delta = 0.16 \text{ GeV} \]

Single spin asymmetries (Sivers, Collins,...) can act as a probe of the saturation scale.

A unique capability of RHIC!

- Dependence of \( Q_{sA} \) on \( A \)
- Combined with other measurements this can estimate \( Q_{sp} \)
A Strategy

\[ \frac{A_{pA \to h}^{pN}}{A_{pp \to h}^{pN}} \bigg|_{P_{h \perp} \ll Q_{SA}^2} \approx \frac{Q_{sp}^2}{Q_{SA}^2} e^{P_{h \perp}^2 \delta^2 / Q_{sp}^4} \]

\[ \frac{A_{pA \to h}^{pN}}{A_{pp \to h}^{pN}} \bigg|_{P_{h \perp} \gg Q_{sp}^2} \approx 1 \]

\( \delta = 0.16 \text{ GeV} \)

- Measure \( A_N \pi^0 \) in \( p+p \), \( p+Au \), and e.g. \( p+Cu \)

- Intermediate \( p_T \) dependence being worked out (Zhongbo Kang)

- Measure \( A_N \gamma \) to get change proportion of Sivers to Collins as a check of understanding of mechanism

\( Q_{\perp SA}^2 \propto A^{\gamma/3} \, Q_{\perp sp}^2 \)

\( Q_{\perp SA}^2 \)

Fit \( p_T \) Dependence to get \( Q_{\perp sp}^2 \) and hence
To Conclude: Some theoretical help

- A better understanding of the equivalence if there is one between different pictures so we don’t chase “smoking guns” only to be told that the smoking gun is not discriminatory – maybe it’s because the picture are in some way equivalent (which of course may be good, but make it difficult when setting up experimental strategy)

- Easy access to CGC MC generator as there are for pp and heavy ions (control of parameters and final states
  - ala, EPS09, pythia, AMPT, HIJING....
  - MCKT is a nice start
To Conclude

• MPC-EX, a plan into the future (fsPHENIX), and a plan for pA
  – Direct photons
  – Pion-pion correlation (as begun in the MPC) to higher $p_T$, look at multiplicity dependence
  – Direct photons-pion correlations
  – Polarized pA $A_N$ (direct photon to look at Sivers ala Yuri K?)
  – Centrality Selection
    • PHENIX will need to use a larger coverage detector for centrality selection
    • Probably will still need to run several nuclear species however

• Is it worth thinking about a lower energy?
• Can pA help get a handle of the “Glasma”. Signatures? (more than ridge?)
• It is crucial to understand the initial state and themalization phase of a heavy ion collisions to understand the sQGP
  – Only unified picture that I know
    CGC$\rightarrow$Glasma$\rightarrow$sQGP (hydro)

The hope is to use the various signatures to “box” in the phenomena to yield the correct theoretical description of
  1) initial state of sQGP  2) CNM  3) themalization stage of sQGP
Parameters extracted from different measurements should be “universal”
Perturbative

Non-Perturbative

Non-equilibrium?
Longitudinal Spin Transfer to Hyperons in Polarized p+p Collisions at $\sqrt{s}=200$ GeV

Ernst Sichtermann (LBNL), for the STAR Collaboration
Nucleon Spin Puzzle

The surprising smallness of the spin dependent part of the inclusive DIS cross section renewed the interest in nucleon spin structure,

EMC (1988): Quark and anti-quark spins combined contribute little to the proton spin, Strange (anti-)quarks are negatively polarized.

Among the many open questions, what is the role of strange (anti-)quark spins, is there a hyperon spin puzzle?

What insight(s) can hyperon polarization measurements at RHIC give?
Semi-inclusive DIS data with identified Kaons in the final state add precision, and pose yet more questions:


Clear call for complementary measurements,

Notoriously hard at RHIC; charm-associated W production (Sudoh, 2005 RHIC-II w.s.), Try hyperon spin-transfer.
RHIC - Polarized Proton Collider to Study Spin in QCD

Opportunities to study many facets:

$$\sqrt{s} = 200 - 500 \text{ GeV}$$

with good systematic controls, e.g.:

This talk: $$\sqrt{s} = 200 \text{ GeV}, \sim 3 \text{ pb}^{-1}, P_b \sim 50\% \text{ (longitudinal)}, \text{ collected in Y2005}$$

$$\sim 22 \text{ pb}^{-1}, P_b \sim 57\% \text{ (longitudinal)}, \text{ collected in Y2009}$$
STAR - Solenoid Tracker At RHIC

Time Projection Chamber enables PID, and topological reconstruction,

\[ \log_{10}(dE/dx \ [\text{keV/cm}]) \]

\[ \log_{10}(p \ [\text{GeV/c}]) \]

for \( |\eta| \leq 1.3 \)
Differential Cross Section


Factorized framework,

\[
\frac{1}{2\pi N_{\text{Events}}} \left( d^2 N / dp_T dy \right) \rightarrow 1 \frac{1}{2\pi} \frac{N_{\text{Events}}}{y_{T}}
\]

Agreement of STAR data and theory, for a suitable choice of \( D \), is a necessary condition for interpretation.

Note: The AKK 2008 update again undershoots the STAR data,
Opportunities exist also to extend the data to higher \( p_T \) (eventually).
Spin-dependent Fragmentation

Factorized framework,

\[ p \leftrightarrow \Lambda, X \]

enables perturbative description.

\[ f, \Delta f \otimes \hat{\sigma}, \Delta \hat{\sigma} \otimes D, \Delta D \]

Polarized fragmentation is sizable, especially for large fragmentation momentum-fractions \( z \),

Note: data remain scarce,
\( \Delta D \) is thus often \textit{modeled}. 


SU(6)-like pol. frag. w. and w.out feed-down

DIS-like
**D_{LL} - Longitudinal Spin Transfer**

At RHIC,

\[ D_{LL}^\Lambda \equiv \frac{\sigma_{p^+p\rightarrow\Lambda^+X} - \sigma_{p^+p\rightarrow\Lambda^-X}}{\sigma_{p^+p\rightarrow\Lambda^+X} + \sigma_{p^+p\rightarrow\Lambda^-X}} = P^+_\Lambda \]

that is, the longitudinal polarization of the \( \Lambda \) for a specific beam-helicity configuration.

This polarization can be determined in the usual way,

\[ \frac{dN}{d\Omega} \propto A(\cos \theta^*)(1 + \alpha P_\Lambda \cos \theta^*) \]

from the angular distribution of the \( p + \pi \) decay mode with B.R. \( \sim 64\% \).

Here,

- \( A \) is the detector acceptance (which can be canceled in a ratio analysis),
- \( \theta^* \) is the angle defined by the \( \Lambda \) momentum and the \( p \) direction in the \( \Lambda \) rest frame,
- \( \alpha = 0.642 \pm 0.013 \) is the decay parameter.
$D_{LL}$ - Longitudinal Spin Transfer

Expectations at LO show sensitivity of $D_{LL}$ for the $\Lambda$ to the $\bar{s}$ helicity distribution, $\Delta \bar{s}$, more so than to the fragmentation in this model.

The $\Lambda D_{LL}$ is less sensitive to $\Delta s$, partly due to larger $u$ and $d$ quark fragmentation contributions.

Promising measurement: neither the role of (anti-)strange quarks nor polarized fragmentation is well known/understood - effects are potentially large enough to be observed.
For the Spin-Aficionados - Measure $D_{LL}$ or $A_{LL}$?

The same expectations versus $p_T$ as $D_{LL}$ and $A_{LL}$:

$$D_{LL} \equiv \frac{\sigma_{p^+p^+\rightarrow\Lambda^+X} - \sigma_{p^+p^-\rightarrow\Lambda^-X}}{\sigma_{p^+p^+\rightarrow\Lambda^+X} + \sigma_{p^+p^-\rightarrow\Lambda^-X}}$$

$$A_{LL} \equiv \frac{\sigma_{p^+p^+\rightarrow\Lambda X} - \sigma_{p^+p^-\rightarrow\Lambda X}}{\sigma_{p^+p^+\rightarrow\Lambda X} + \sigma_{p^+p^-\rightarrow\Lambda X}}$$

+ $D_{LL}$ expected sensitivity is ~4 larger,

- $D_{LL}$ analysis requires more selections than for $A_{LL}$, i.e. loose some statistics,

+ $D_{LL}$ is a single beam-spin measurement, analyzing power of the $p+\pi$ decay mode is relatively large.

Net advantage owing to the (anti-)\Lambda spin being carried mostly by the (anti-)s quark spin.
STAR *Initial* Data - 2005

\(~3.10^6\) *minimum bias* events (beam-collision triggered, band-width limited),

\(~30.10^3\) \(\Lambda\) candidates,

\(~25.10^3\) \(\bar{\Lambda}\)

\(<p_T> \approx 1.3 \text{ GeV/c}\)

\(<|x_F|> \approx 0.008\)

*Take away: analyze data triggered on hard-processes...*
STAR Triggered Data - 2005

STAR was triggered on energy deposits in jet-patches of the Barrel E.M. Calorimeter, although this is not a “Hyperon Trigger”, it did record a (biased) sample of \( \Lambda \) and \( \bar{\Lambda} \) candidates with considerably higher \( p_T \); focus on \( \bar{\Lambda} \) here.
Analysis Characteristics

Uses the $\Lambda \rightarrow p + \pi$ weak decay mode,

$$\frac{dN}{d\Omega} \propto A(\cos \theta^*) (1 + \alpha P_\Lambda \cos \theta^*)$$

Restrict $\cos \theta^*$ to eliminate $K_S^0$ background caused by misidentified $\pi$, (refined in later analyses).

Use beam spin configurations and symmetries to (largely) cancel $A(\cos \theta^*)$ and extract,

$$D_{LL}^\Lambda = \frac{1}{\alpha \cdot P_b \cdot \langle \cos \theta^* \rangle} \cdot \frac{N_\Lambda^+ - N_\Lambda^-}{N_\Lambda^+ + N_\Lambda^-}$$

in small $\cos \theta^*$ intervals. Here, $N_\Lambda^+ = N_\Lambda^{++} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{++}} + N_\Lambda^{+-} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{++}}$ and $N_\Lambda^- = N_\Lambda^{--} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{--}} + N_\Lambda^{--}$

The luminosity ratios are measured at STAR and beam polarization in RHIC.
STAR Initial Results - 2005

\[ D_{LL} \text{ proof-of-concept from RHIC,} \]

Statistics limited,

Systematics under control,

\[ \langle p_T \rangle \approx 1.3 \text{ GeV/c, } \langle |x_F| \rangle \approx 0.008 \]

Take away: need better precision and higher \( p_T \)
STAR - 2009

Full-coverage Barrel EMCal,

Trigger improvement,

DAQ-1000,

RHIC luminosity and polarization, even though the run was cut short and FoM remained a factor below our initial projections,

*Good reasons for continued 200 GeV!*

Decision to focus, at least initially, on Hyperons that are part of the near-side (trigger) jet.
STAR - 2009

Systematic uncertainties vary from 0.01 to 0.03 for each point which include:

- 4.7% Beam polarization
- 2.0% Decay parameter
- 1.9% Residual trans. pol.
- $5 \times 10^{-3}$ Relative luminosity
- $< 6 \times 10^{-3}$ Residual background.
- $\leq 0.03$ Trigger bias, increases with $p_T$.
- $\leq 0.01$ Pile-up, decreases with $p_T$.

J. Deng for the collaboration, SPIN 2012
R. Cendejas for the collaboration, DNP 2012
Some Cross-Checks

Measurements with the expected null-results.
Compared to Published Results

$D_{LL}$ out to $p_T \sim 5.9$ GeV with $\sim 4\%$ precision (2009), c.f. $\sim 8\%$ at 3.7 GeV published (2005).
Compared to Expectations - I

The graph shows a comparison of STAR preliminary data with expectations from different scenarios. The data points for $\Lambda$ 2009 and $\Lambda$ 2009 are indicated by circles and triangles, respectively. The various lines represent different scenarios:

- De Florian et al. $\Lambda+\bar{\Lambda}$, scen. 1
- De Florian et al. $\Lambda+\bar{\Lambda}$, scen. 2
- De Florian et al. $\Lambda+\bar{\Lambda}$, scen. 3

The scenarios are:

- scen. 1: SU(6) picture
- scen. 2: DIS picture
- scen. 3: equal contribution

(Updated calculation to low $p_T$)

J. Deng for the collaboration, SPIN 2012
R. Cendejas for the collaboration, DNP 2012
Data do not currently discriminate “model”-expectations, precision may re-interest our theory friends, “models” → fits analysis of away-side sample in progress.
Looking Ahead

- H.Z. Huang for the collaboration, QM2012
- TPC inner sector upgrade will extend acceptance to larger rapidity where $D_{LL}$ is expected to be larger.
- Forward Calorimeter upgrade

- STAR forward instrumentation upgrade
- Forward instrumentation optimized for $p+A$ and transverse spin physics
  - Charged-particle tracking
  - $e/h$ and $\gamma/\pi^0$ discrimination
  - Possibly Baryon/meson separation

- STAR Decadal Plan discussed in Jamie’s talk tomorrow,
- Stay Tuned, Thanks!
Physics opportunities with a polarized pA@RHIC

Mark Strikman, PSU

The Physics of p↑+A Collisions at RHIC, 01/07/13
General remarks

Amazingly little is known about pA at collider energies.

- dependence of various observables on nuclear thickness - T(b). Hardly possible to study in a clean way using dA. Possible in pA if running with several nuclei - defining centrality classes of events in pAu cannot be trusted as it is based on low energy Glauber picture

- T(b)-dependence of forward large $p_t$ pion production - e.g. how big is suppression for central pAu collisions.

- Are the low pt forward neutron & pion spectra are qualitatively different for central and peripheral collisions

- Forward physics in pA at LHC and RHIC --- change in x by a factor $\sim 600$ - comparison will be of great help for understanding small x dynamics.

- Polarization - icing on the cake.
High energy space-time picture of soft pA - Gribov - Glauber fundamentally different from low energy Glauber picture

\[ \sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \rightarrow p + X(p + \text{inel diff}))}{dt} \]

Deviations from Glauber for \( \sigma_{\text{in}}(pA) \) are small for \( E_{\text{inc}} \sim 10 \text{ GeV} \) as inelastic diffraction is still small. They stay small for heavy nuclei for all energies. But for pD at ISR at large \( t \) effect is large \( \sim 40\% \). An effective way to implement Gribov-Glauber picture of high energy pA interactions is the concept of color fluctuations

**Glauber model**

in rescattering proton in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov) - no time for a proton to come together between nucleons. Violates energy conservation for cut through two exchanges

**High energies = Gribov - Glauber**

\( X = \) set of intermediate states the same as in pN diffraction
Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon

Are there global fluctuations of the strength of interaction of a fast nucleon, for example due to fluctuations of the size/orientation. Extreme case - color transparency.

Due to a slow space-time evolution of the fast nucleon wave function one can treat the interaction as a superposition of interaction of configurations of different strength - Pomeranchuk & Feinberg, Good and Walker, Pumplin & Miettinen. In QCD this is reasonable for total cross sections and for diffraction at very small t.
If there were no fluctuations of strength - there will be no inelastic diffraction at t=0:

\[ |h⟩ = a_1 |1⟩ + a_2 |2⟩ \]

**absorber with same absorption for “1” and “2”**

\[ |final⟩ = λ(a_1 |1⟩ + a_2 |2⟩) = λ |h⟩ \]

only elastic scattering

\[ |h⟩ = a_1 |1⟩ + a_2 |2⟩ \]

**absorber with different absorption for “1” and “2”**

\[ |final⟩ = λ_1 a_1 |1⟩ + λ_2 a_2 |2⟩ \]
\[ = c_1 |h⟩ + c_2 |h'⟩ \]

elastic scattering +inelastic diffraction

Monday, January 7, 13
Convenient quantity - \( P(\sigma) \) - probability that nucleon interacts with cross section \( \sigma \).

\[
\int P(\sigma) d\sigma = 1, \quad \int \sigma P(\sigma) d\sigma = \sigma_{tot},
\]

\[
\frac{d\sigma(pp\to X+p)}{dt} \bigg|_{t=0} = \int \frac{(\sigma - \sigma_{tot})^2 P(\sigma) d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma \quad \text{variance}
\]

Pumplin & Miettinen

\( \omega_\sigma(\text{RHIC})=0.25 \quad \omega_\sigma(\text{LHC})=0.20 \) - more data are coming from LHC

A very rough model illustrating scale of the effect

\[
P(\sigma) = \frac{1}{2} \delta(\sigma - \sigma_{tot}(1 - \sqrt{\omega_\sigma})) + \frac{1}{2} \delta(\sigma - \sigma_{tot}(1 + \sqrt{\omega_\sigma}))
\]

for \( \omega_\sigma=0.25, \quad \sigma_1=0.5\sigma_{tot} \); \( \sigma_2=1.5\sigma_{tot} \)

\[
\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0,
\]

Baym et al from pD diffraction

\[
P(\sigma) \bigg|_{\sigma \to 0} \propto \sigma^{n_q-2}
\]

Baym et al 1993
\( P_N(\sigma) \) extracted from pp, pd diffraction  Baym et al 93.  
\( P_\pi(\sigma) \) is also shown

Extrapolation of Guzey & MS to higher energy using diffractive data
The inelastic small $t$ coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in $NN$ interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength $\sigma$. (Miller & FS 93)

$$\sigma_{diff}^{hA} = \int d^2b \left( \int d\sigma P_h(\sigma) \langle h | F^2(\sigma, b) | h \rangle \right) - \left( \int d\sigma P(\sigma) \langle h | F(\sigma, b) | h \rangle \right)^2.$$

Here $F(\sigma, b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b, z) dz$, and $\rho_A(b, z)$ is the nuclear density.
Color fluctuations/inelastic shadowing

E.M. interaction dominates by far in diffraction above RHIC true for hard diffraction as well (Guzey, MS)

For RHIC for A=200 comparable contributions, for A=40, e.m. contribution is a small correction. A unique opportunity for RHIC. Use ZDC?
Large fluctuations in the number of wounded nucleons at fixed impact parameter

Simple illustration - two component model ≡ quasieikonal approximation:

RHIC \( \sigma_1 = 25 \text{ mb}, \sigma_2 = 75 \text{ mb} \)

LHC \( \sigma_1 = 60 \text{ mb}, \sigma_2 = 140 \text{ mb} \)

number of wounded nucleons at small \( b \) differs by a factor of 3 !!!

Scattering at \( b=4.6 \text{ fm} \) with probability \( \sim 1/2 \) generates the same multiplicity as collision at \( b=0 \). *Smearing of the centrality*

color fluctuations lead to addition dispersion as compared to the geometrical model
Color fluctuation model implementation of the Gribov - Glauber approximation in optical limit

\[
\sigma_{in}^{hA} = \int d\sigma_{in} P_N(\sigma_{in}) \int d\vec{b} \left[ 1 - (1 - x)^A \right]
\]

\[
\sigma_n = \int d\sigma_{in} P_N(\sigma_{in}) \frac{A!}{(A - n)! n!} \int d\vec{b} x^n (1 - x)^{A-n}.
\]

where \[ x = \sigma_{in}^{hN} T(b)/A \quad \int d\vec{b} T(b) = A \]

Probability of exactly \( n \) interactions is \[ P_n = \frac{\sigma_n}{\sigma_{in}^{hA}} \]
Numerical calculations (Alvioli and MS arXiv:1301.0728) - event generator using our set of nucleon configuration with short-range correlations (small effect) and finite radius of NN interaction.

For NN scattering $P_{\text{inel}}(b) = 1 - |1 - \Gamma(b)|^2$

We also took $\sigma/B = \text{const}$ for fluctuations (corresponding to $\sigma_{\text{el}}/\sigma_{\text{tot}} = \text{const}$)

$B$ is t-slope of elastic cross section

$$P_s(\sigma_{\text{tot}}) = r \frac{\sigma_{\text{tot}}}{\sigma_{\text{tot}} + \sigma_0} \exp\left\{ - \frac{\sigma_{\text{tot}}}{\sigma_0} - \frac{1}{\Omega^2} \right\}$$

with parameters fixed to satisfy sum rules
We observe that Eq. (11) leads to small (few %) change of average $N$ since the inelastic corrections to which is given by the same equation as for the Glauber model (Eq. (9)).

The probability of collisions with exactly $k$ nucleons shadowed in average collision. . .

Small effect for $\langle N \rangle$

Large for dispersion even though in dispersion one integrates over impact parameters

Small effect for $\langle N \rangle$

$\omega_N \equiv \frac{\langle N^2 \rangle}{\langle N \rangle^2} - 1$

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**GG**= Gribov- Glauber,

**GG2**= Gribov- Glauber two component
Color fluctuations give dominant contribution to fluctuations of the number of wounded nucleons for fixed $b$.
The probability $P_N(b)$ of having $N$ inelastically interacting (wounded) nucleons in a pA collision, vs. impact parameter $b$, when using simple Glauber (red curves) and a distribution $P(\sigma)$ (green curves); We show the probabilities $P_N(b)$ for $N=1$ (top row) for both energies and the curves for $N$ corresponding to $\langle N \rangle$ and $\langle N \rangle \pm 0.5\langle N \rangle$ (remaining panels); $\langle N \rangle$ is 5 and 7 for RHIC and LHC energies, respectively.

Large deviations from Glauber model
Effect of fluctuations on the event-by-event fluctuating values of cross section. Small number of wounded nucleons, $N$, selects $\sigma < \sigma_{\text{in}}$; large $N$ --- $\sigma > \sigma_{\text{in}}$

Note that since RHIC studied so far $d$-$Au$ - smaller effect of fluctuations for hard trigger.
The distribution over impact parameter, calculated with our Monte Carlo, of the different centrality classes 20% most central (first row), 20%-40% (second row), 40%-60% (third row), 40% most peripheral (last row), both for RHIC (left) and LHC (right) energies. Red: Glauber result; blue: Gribov - Glauber color fluctuations with $P(\sigma)$ distribution.

If one wants to perform a precision measurement of dependence of spin effect on nuclear thickness, measurements with a set of nuclei are necessary.
Different $\sigma$'s --- different size, different shape, different parton densities
Correlation between the hard and soft components of the pA interaction.

**Idea:**

Use the hard trigger to determine $x_p$ and low $p_t$ hadrons to measure overall strength of interaction $\sigma_{\text{eff}}$ of configuration in the proton with given $x_p$. FS83

LHC - jets with large $p_t$ - -- practically no nuclear shadowing effects

RHIC ? statistics, acceptance?

**Expectation:**

Larger the size, more gluon radiation, softer the $x$ distribution

**Illustration**

$$G(x, Q^2 | \sigma) = G(x, \xi Q^2) \quad \xi(Q^2) \equiv \left(\frac{\sigma}{\langle\sigma}\right)^{\alpha_s(Q^2_0)/\alpha_s(Q^2)}$$

where $Q^2_0 \sim 1 \text{ GeV}^2$

gives a reasonable magnitude of fluctuations of the gluon density

**would result in different parton distribution in nucleons measured with different number of wounded nucleons, with no change in the inclusive case**
Alternative strategy - use a hard trigger which selects rare configurations in nucleon which are small size or large size

Example: The presence of a quark with large $x > 0.6$ requires three quarks to exchange rather large momenta, one may expect that these configurations have a smaller transverse size (+ few gluons & sea quarks at low $Q$ scale) and hence interact with the target with a smaller effective cross section: $\sigma_{\text{eff}}$.

Note: if $x > 0.6$ configurations do have a size smaller than average, it would explain the EMC effect (FS83)

Selection of such $x$ seems feasible at LHC but a challenge at RHIC - need a better acceptance in forward region.
Forward pion production: Summary of the challenge

- For pp - pQCD works both for inclusive pion spectra and for correlations (will discuss later)
- Suppression of the pion spectrum for fixed $p_t$ increases with increase of $\eta_N$.

**Independent of details - the observed effect is a strong evidence for breaking pQCD approximation. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.**

The key question: what is the mechanism of the suppression of the dominant pQCD contribution of quark scattering off gluons with $x_A > 0.01$ where shadowing effects are very small.

CGC scenario - assumes $\LT x_A > 0.01$ mechanism becomes negligible, though experimentally nuclear pdf = A nucleon pdf for such x (assumes that somehow suppression of the LT mechanism should be $>>$ than observed suppression of inclusive spectrum), $\overset{\circ}{\circ}2 \rightarrow 1$ mechanism dominates

Post-selection scenario - LT $x_A > 0.01$ mechanism is suppressed but still dominates inclusive cross section
Post-selection (effective energy losses) in proximity to black disk regime (BDR) - usually only finite energy losses discussed (BDMPS) (QCD factorization for LT) - hence a very small effect for partons with energies $10^4 \text{ GeV}$ in the rest frame of second nucleus. Not true in black disk regime - post selection - energy splits before the collision - effectively 10- 15 % energy losses decreasing with increase of $k_t$ at $k_t > k_t(BDR)$ Large effect on the pion rate since $x_q$'s, $z$'s are large,

↓

dominant yield from scattering at peripheral impact parameters

↓

In the first approximation polarization effects are the same in pp and pA
Analysis of the STAR correlation data of 2006

Forward central correlations - kinematics corresponding to \( x_A \sim 0.01 \) - main contribution in 2→2

Leading charge particle (LCP) analysis picks a midrapidity track with \( |\eta_h| \leq 0.75 \) with the highest \( p_T \geq 0.5 \) GeV/c and computes the azimuthal angle difference \( \Delta \varphi = \varphi_{T\to} - \varphi_{LCP} \) for each event. This provides a coincidence probability \( f(\Delta \varphi) \). It is fitted as a sum of two terms - a background term, \( B/2\pi \), which is independent of \( \Delta \varphi \) and the correlation term \( \Delta \varphi \) which is peaked at \( \Delta \varphi = \pi \). By construction,

\[
\int_0^{2\pi} f(\Delta \varphi) d\Delta \varphi = B + \int_0^{2\pi} S(\Delta \varphi) d\Delta \varphi \equiv B + S \leq 1
\]

Coincidence probability versus azimuthal angle difference between the forward \( \pi^0 \) and a leading charged particle at midrapidity with \( p_T > 0.5 \) GeV/c. The curves are fits of the STAR. \( S \) is red area.

Obvious problem for central impact parameter scenario of \( \pi^0 \) production is rather small difference between low \( p_T \) production in the \( \eta=0 \) region (blue), in pp and in dAu - (while for \( b=0 \), \( N_{\text{coll}} \sim 16 \))
average number of wounded nucleons in events with leading pion: \( <N> \approx 3 \)

We find \( S(dAu) \approx 0.1 \) assuming no suppression of the second jet. Data: \( S(dAu) = 0.093 \pm 0.040 \)

Thus, the data are consistent with no suppression of recoil jets. PHENIX analysis which effectively subtracts the soft background - similar conclusion. In CGC - 100% suppression - no recoil jets at all. Moreover for a particular observables of STAR dominance of central impact parameters in the CGC mechanism would lead to \( (1-B-S) < 0.01, S < 0.01 \) since for such collisions \( N_{\text{coll}} \sim 16 \). This would be the case even if the central mechanism would result in a central jet.

**Test of our interpretation** - ratio, \( R \), of soft pion multiplicity at \( y \sim 0 \) with \( \pi^0 \) trigger and in minimal bias events.

- In CGC scenario \( R \sim 1.3 \)
- In BDR energy loss scenario we calculated \( R \sim 0.5 \)
- STAR - \( R \sim 0.5 \) Gregory Rakness - private communication

\( \langle \eta \rangle = 0 \) corresponds to \( x_A = 0.01 \) ⇒ lack of suppression proves validity of \( 2 \to 2 \) for dominant \( x_A \) region.

Correlation data appear to rule out CGC \( 2 \to 1 \) mechanism as a major source of leading pions in inclusive setup ⇒ NLO CGC calculations of inclusive yield grossly overestimates \( 2 \to 1 \) contribution.
Nuclear modification factor $R_{dA}$ for double-inclusive leading-twist pion production as a function of rapidity $\eta_1$ at $p_{T,1} = 2.5$ GeV. The upper dashed line shows the effect of leading-twist shadowing for the Frankfurt-Guzey-Strikman (FGS) nuclear parton distributions. The solid line includes shadowing and the “medium-modified” fragmentation functions of Sassot-Stratmann-Zurita (SSZ). The lower dashed lines show the results for two simple energy-loss models.

Left: Same for single-inclusive pion production - much larger suppression effect - because average $x_q$ are closer to 1

typical suppression of recoil peak $\sim 3--5$ (Vogelsang & MS 2011)
Accounting for fractional energy losses effect, and LT gluon shadowing reduces $(4\rightarrow 4)/(2\rightarrow 2)$ ratio:

- Δϕ independent pedestal in dA is $2.5 \div 4$ times larger in pp
- Suppression of Δϕ =180° peak by a factor ~ three --four

Main effect - disappearance from large $x$ - perhaps also some broadening due to elastic rescattering

Overall suppression of f-f (dAu/pp) is about a factor of 10; hardly could be much larger - since the probability of fluctuations in the nucleus wave function leads to a probability of punch through of 5 - 10% (Alvioli + MS).

No suppression for Δϕ ≈ 0 - fragmentation of the same quark
Subtle points which are difficult to see in dA.

a) In peripheral collisions (defined as events with small number of wounded nucleons)

\[ \langle \sigma \rangle < \sigma_{in} \]  

enhancement of the forward pion production

If polarization is related to primordial \( p_t \)  → enhancement of polarization

b) In central collisions defined through number of wounded nucleons there is

additional suppression due to selection of large size configurations

c) In central collisions defined through use of a set of nuclei -

possible scenario - dominance of fluctuations into point -like

configurations which have >> probability to propagate through the

center and interact once. May lead to larger polarization  !!!
Expectation: The leading particle spectrum should be strongly suppressed in the central pA collisions as compared to minimal bias pp collisions since each leading parton gets large transverse momentum and hence fragments independently and may also split into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in BDR

\[
\frac{1}{N} \left( \frac{dN}{dz} \right)_{pA \rightarrow h + X} = \sum_{a=q,g} \int dx \, x f_a^{(p)}(x, Q_{\text{eff}}^2) D_{h/a}(z/x, Q_{\text{eff}}^2)
\]

The limiting curve of leading particles from hadron-nucleus collisions at infinite $A$

A. Berera\textsuperscript{a,1}, M. Strikman\textsuperscript{a}, W.S. Tothacker\textsuperscript{b}, W.D. Walker\textsuperscript{c}, J.J. Whitmore\textsuperscript{a}

Simple model of $p_t$ broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003), effective energy losses (mentioned before) are neglected

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp\left(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}\right).$$

Quark gets a transverse momentum of the order $Q_s$ but does not lose significant energy. Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03. Other calculations with similar logic -Gelis, Stasto, Venugopalan (06)

Longitudinal (integrated over $p_t$) and transverse distributions in Color Glass Condensate (CGC) model for central pA collisions. Spectra for central pp - the same trends.

Steep fall with $z$, strong $E_{inc}$ dependence

Weak $p_t$ dependence, becomes weaker with increase of $E_{inc}$
Very few forward baryons in central collisions!!!

Warnings: Parton carrying a fraction $y$ of the quark momentum carries $y p_t$ part of the quark’s transverse momentum. Condition for independent fragmentation $y p_t > 1/r_N \sim 0.3 - 0.5$ GeV/c

For RHIC (LHC) independent fragmentation is probably safe for $z > 0.2$ (0.1)

Photon - proton contribution has to be subtracted!!!

Experimental prospects (perhaps too optimistic for LHC)

pA run at LHC: TOTEM: $x_F \geq 0.8$ broad range of $p_t$ can check both suppression and $p_t$ broadening neutrons from ZDC (CMS, ALICE, LHCf); $\pi^0+$ (LHCf) - large $z$, moderate $p_t$

RHIC: need pA run preferably at different energies and for several nuclei to avoid model dependent procedure for determining centrality of collision. Spin effect for neutrons ???

Warning: Color fluctuations in nucleon and nucleon density in nucleus may reduce the suppression
Conclusions on physics opportunities of pA:

Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy: parton, groups of partons propagation through media in soft and hard regime including spin effects.

Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy.

Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution.

Check the color fluctuation dynamics for generic inelastic pA collisions.
Feasibility and Challenges of pA Collisions

Steve Tepikian, Dejan Trbojevic
January 7-9, 2013
pA Collisions

- RHIC p-Au strategy
- Beam Crossing Geometry
- Beam Sizes
- Conclusion
pA Collisions

- Requires a large aperture in the DX magnet
  - Due to expense and field quality requirements, aperture was reduced
  - The strategy is to move the DX magnets for p-Au collisions
- Propose a plan to minimize the moving of the DX magnets
  - Gold in Blue ring, Protons in Yellow ring
Equal Species Geometry
The beam angles relative to the central axis is 3.58 mrad
Gold beam center is maximum of 69.362 mm from the DX magnet center
Crossing angle = -3.305 mrad minimizes the apertures in the non-colliding IPs
Beam center is maximum of 59.777 mm from DX magnet center
pA Collisions Beam Sizes

\[ \sigma = \sqrt{\frac{e_N}{\pi}} \left( \frac{\beta^* + s^2}{\beta^*} \right) \]

Store conditions:
Gold at B\(\rho\) = 831.763 Tm or \((\beta\gamma) = 107.391\)
Proton at B\(\rho\) = 358.647 Tm or \((\beta\gamma) = 114.593\)

Beam size \(\pm 3\sigma\)

Space \(\geq 2\ mm\)
(The larger, the better)

DX magnet (radius = 68.326 mm)
# pA Collisions Beam Sizes

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<td>107.391</td>
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<td>69.362</td>
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<td>13</td>
<td>Au</td>
<td>Store</td>
<td>20</td>
<td>0.7</td>
<td>13.5</td>
<td>831.763</td>
<td>107.391</td>
<td>2.85</td>
<td>69.362</td>
</tr>
<tr>
<td>14</td>
<td>Au</td>
<td>Store</td>
<td>40</td>
<td>0.7</td>
<td>13.5</td>
<td>831.763</td>
<td>107.391</td>
<td>4.03</td>
<td>69.362</td>
</tr>
</tbody>
</table>
Conclusion

- A collision strategy is proposed for moving only the IP6 and IP8 DX magnets by at minimum of 1 cm, better at 1.5 cm
  - Limit both beam sizes to $10\pi$ mm-mrad at injection
  - Reduce beam growth at store (stochastic cooling)
  - Aperture specs are tight
    - May have more difficulty to get stable beam
- This allows equal species to run as well
Collider p/d+A experiments: a new era in QCD at high parton densities

Raju Venugopalan
Brookhaven National Laboratory

Joint BNL-LANL-RBRC workshop, January 7-9, 2013
Exciting times!

✧ LHC will start long awaited ~ 3 week p+A run at 5.02 TeV/n in a week!
   4 hour “pilot” run past fall was extremely successful

✧ Prospect of \( \uparrow \)p+A collisions at RHIC – significant extension of first collider studies – performed at RHIC - on light-heavy systems
Talk outline

✧ Universal many-body parton dynamics at high energies
   --- saturation from DIS to hadron-hadron collisions

✧ Multiplicities and single inclusive distributions

✧ Di-hadron correlations at RHIC – the ridge in p+p & p+A collisions

✧ Initial state many-body parton dynamics in A+A collisions – the IP-Glasma model
Many-body dynamics of universal gluonic matter

How does this happen? What are the right degrees of freedom?

How do correlation functions of these evolve?

Is there a universal fixed point for the RG evolution of d.o.f?

Does the coupling run with $Q_s^2$?

How does saturation transition to chiral symmetry breaking and confinement?
CGC Effective Theory: B-JIMWLK hierarchy of correlators

\[ \frac{\partial}{\partial Y} \langle 0[\alpha] \rangle_Y = \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha^a_Y(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha^b_Y(y)} O[\alpha] \rangle_Y \]

“time”

“diffusion coefficient”

At high energies, the d.o.f that describe the frozen many-body gluon configurations are novel objects: dipoles, quadrupoles, ...

Universal – appear in a number of processes in p+A and e+A; how do these evolve with energy?
CGC Effective Theory: B-JIMWLK hierarchy of correlators

\[ \frac{\partial}{\partial Y} < O[\alpha] >_Y = \langle \frac{1}{2} \int_{x,y} \delta \alpha^a_V(x) \chi^{ab}_{x,y} \delta \alpha^b_V(y) O[\alpha] >_Y \]

“time”

“diffusion coefficient”

Energy evolution of spatial distribution of gluons inside the proton


Dumitru, Jalilian-Marian, Lappi, Schenke, RV, PLB706 (2011)219

Dipole correlator of Light-like Wilson lines \( \text{Tr}(V(0,0)V^\dagger(x,y)) \)

B-JIMWLK eqn. for dipole correlator – universal quantity whose (very good) mean field solution is the BK equation

\[ \frac{\partial}{\partial Y} \langle \text{Tr}(V_x V_y^\dagger) \rangle_Y = -\frac{\alpha_s N_c}{2\pi^2} \int_{z_\perp} \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2(z_\perp - y_\perp)^2} \langle \text{Tr}(V_x V_y^\dagger) - \frac{1}{N_c} \text{Tr}(V_x V_z^\dagger) \text{Tr}(V_z V_y^\dagger) \rangle_Y \]
Inclusive DIS: dipole evolution

\[
\sigma_{\gamma^* T} = \int_0^1 dz \int d^2 r_\perp |\psi(z, r_\perp)|^2 \sigma_{\text{dipole}}(x, r_\perp)
\]

\[
\sigma_{\text{dipole}}(x, r_\perp) = 2 \int d^2 b \int [D\rho] W_A + [\rho] T \left( b + \frac{r_\perp}{2}, b - \frac{r_\perp}{2} \right)
\]

1 - \frac{1}{N_c} \text{Tr} \left( V \left( b + \frac{r_\perp}{2} \right) V^\dagger \left( b - \frac{r_\perp}{2} \right) \right)

Two dipole saturation models:

i) rcBK –higher twist corrections to pQCD BFKL small x evolution

\[
\frac{d\sigma_{\text{dipole}}}{d^2 b_\perp} = 2 \left( 1 - \exp \left( -\frac{\pi^2 r_\perp^2}{2N_c} \alpha_S(\mu^2) x g(x, \mu^2) T_G(b_\perp) \right) \right)
\]

Bartels, Golec-Biernat, Kowalski Kowalski, Teaney; Kowalski, Motyka, Watt
Inclusive DIS: dipole evolution a la BK

Comparison of running coupling rcBK eqn. with precision small x combined HERA data

Relative comparison of rc BK to DGLAP fits-bands denote pdf uncertainties

Albacete, Milhano, Quiroga-Arias, Rojo, arXiv:1203.1043
Inclusive DIS: dipole evolution a la IP-Sat

(Few) parameters fixed by $\chi$-sq ~ 1 fit to combined (H1+Zeus)
reduced cross-section

Rezaiean, Siddikov, Van de Klundert, RV: 1212.2974
Inclusive DIS: dipole evolution a la IP-Sat

Rezaiean, Siddikov, Van de Klundert, RV: 1212.2974

More stable gluon dist. at small x relative to NNLO pdf fits

Exclusive VM production:

Comparable quality fits for energy (W) and t-distributions
Saturation models: from HERA to RHIC & LHC

Unintegrated gluon dist. from dipole cross-section:

\[
\frac{d\phi(x, k_\perp | s_\perp)}{d^2 s_\perp} = \frac{k_\perp^2 N_c}{4 \alpha_s} \int_0^\infty d^2 r_\perp e^{i k_\perp \cdot r_\perp} \left[ 1 - \frac{1}{2} \frac{d\sigma_{\text{dip}}^p}{d^2 s_\perp} (r_\perp, x, s_\perp) \right]^2
\]

\[k_T\] factorization to compute gluon dist. at a given impact parameter:

\[
\frac{dN_g(b_\perp)}{dy d^2 p_\perp} = \frac{4 \alpha_s}{\pi C_F} \frac{1}{p_\perp^2} \int \frac{d^2 k_\perp}{(2\pi)^5} \int d^2 s_\perp \frac{d\phi_A(x, k_\perp | s_\perp)}{d^2 s_\perp} \frac{d\phi_B(x, p_\perp - k_\perp | s_\perp - b_\perp)}{d^2 s_\perp}
\]
Saturation models: from HERA to RHIC & LHC

$k_T$ factorization is an approximation valid for $Q_S < k_T$
– in general need to solve classical Yang-Mills eqns when parton densities in both projectile and target are large...

Gelis, Lappi, RV: 0804.2630
"Global analysis" of bulk distributions

Tribedy, RV, 1112.2445

Albacete, Dumitru, Fujii, Nara, 1209.2001
How do these models do with p+A at the LHC?

In saturation models

$$\frac{dN}{d\eta} \propto \frac{Q_S^2 S_\perp}{\alpha_S(Q_S)}$$

Multiplicities have some sensitivity to “infrared” non-pert. physics/geometry

Other model comparisons, see arXiv:1210.3615 -likely in Helen’s talk...?
How do these models do with p+A at the LHC?

ALICE, arXiv:1210.4520

Compilation from Albacete et al 1209.2001

p+Pb run will add clarity
Di-hadrons in p/d-A collisions

Marquet (2007), Tuchin (2010)
Dominguez, Marquet, Xiao, Yuan (2011)
Strikman, Vogelsang (2010)

\[ \frac{d\sigma_{qA \rightarrow qqX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_1 \cdot (x-\bar{x})} e^{ik_2 \cdot (y-\bar{y})} \left[ S_6(x, y, \bar{x}, \bar{y}) - S_4(x, y, v) - \ldots \right] \]

Forward-forward di-hadrons sensitive to both dipole and quadrupole correlators

Recent computations (Stasto, Xiao, Yuan + Lappi, Mäntysaari) include Pedestal, Shadowing (color screening) and Broadening (multiple scattering) effects in CGC

Lappi, Mäntysaari, 1209.2853
High Multiplicity pp collisions
High Multiplicity pp collisions

High Multiplicity events are rare in nature

Very high particle density regime
Is there anything peculiar happening there?

Wei Li, MIT
Two particle correlations in high mult. p+p

CMS 1009.4122

CMS Min. Bias (1 GeV < p_T < 3 GeV)

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

Ridge: Distinct long range correlation in \( \eta \) collimated around \( \Delta \Phi \approx 0 \) for two hadrons in the intermediate \( 1 < p_T, q_T < 3 \) GeV
Long range rapidity correlations as a chronometer

\[ \tau \leq \tau_{\text{frz-out}} \exp \left( -\frac{1}{2} |y_A - y_B| \right) \]

- Long range correlations sensitive to very early time (fractions of a femtometer \( \sim 10^{-24} \text{ seconds} \)) dynamics in collisions
Anatomy of long range di-hadron collimation

\[ \frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d \Delta \phi} \]

Associated Di-hadron Yield

BFKL Mini-jet

Glasma graphs
Long range di-hadron correlations

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, RV, arXiv:1009.5295

RG evolution of two particle correlations $C(p,q)$ expressed in terms of “unintegrated gluon distributions” in the proton

$$C(p, q) \propto \frac{g^4}{p_{\perp}^2 q_{\perp}^2} \int d^2 k_{\perp} \Phi_{A_1}^2(y_p, k_{\perp}) \Phi_{A_2}^2(y_p, p_{\perp} - k_{\perp}) \Phi_{A_2}^2(y_q, q_{\perp} - k_{\perp})$$

+ permutations

Contribution $\sim \alpha_s^6/N_c^2$ in min. bias, High mult. $\rightarrow 1/\alpha_s^2 N_c^2$

- enhancement of $1/\alpha_s^8 \sim$ factor of $10^5$!
Collimated yield?

\[ C(p, q) \propto \frac{g^4}{p_\perp^2 q_\perp^2} \int d^2k_\perp \Phi_{A_1}^2(y_p, k_\perp) \Phi_{A_2}(y_p, p_\perp - k_\perp) \Phi_{A_2}(y_q, q_\perp - k_\perp) + \text{permutations} \]

From RG evolution of BK equation

Dominant contribution from \(|p_\perp - k_\perp| \sim |q_\perp - k_\perp| \sim |k_\perp| \sim Q_s\)

This gives a collimation for \(\Delta \Phi \approx 0\) and \(\pi\)
Angular structure from (mini-) Jet radiation

Mini-jets: $O(1)$ in high multiplicity events
- give an angular collimation, albeit only at $\Delta \Phi \approx \pi$

LHC results also test the structure of bremsstrahlung radiation between jets
Exciting first results on proton lead collisions


Key observation:
Ridge much bigger than p+p for the same multiplicity!
Exciting results on proton lead collisions

Multiplicity

N<35

35<N<90

90<N<110

N>110
Systematics of p+Pb data explained

\[ Q_0^2(\text{lead}) = N_{\text{Part}}^{\text{Pb}} \times Q_0^2(\text{proton}) \]

# of “wounded” nucleons in Lead nucleus

Glasma signal is \( \sim N_{\text{part}} \times N_{\text{track}} \)
p+Pb data explained

\[ Q_0^2(\text{lead}) = N_{\text{Part}}^{\text{Pb}} \times Q_0^2(\text{proton}) \]

# of “wounded” nucleons in Lead nucleus

Large “ridge” seen in Color Glass Condensate by varying saturation scale in proton and # of wounded nucleons
CMS p+Pb data explained

Same parameters as in p+p
- gives larger ridge when saturation scales are varied
CMS $p+Pb$ data explained

Dusling, RV: 1211.3701

Smoking gun for gluon saturation and BFKL dynamics?
ALICE data on the p+Pb ridge

Different acceptance ($|\Delta \eta| < 1.8$) than CMS ($2 < |\eta| < 4$) and ATLAS ($2 < |\eta| < 5$).

ALICE subtracts away-side “jet” contribution at 40-60% centrality from most central events

–this gives dipole shape of correlation

Different analysis technique from CMS/ATLAS

-- our fit here is with arbitrary normalization
Comparison to ATLAS p+Pb ridge

ATLAS yields in asymmetric $p_T$ windows compared to Glasma + BFKL:
$K_{\text{BFKL}}=1$ and $K_{\text{glasma}}=4/3$

Glasma graph contributions compared to ATLAS central – ATLAS peripheral
**p+p vs A+A**

In **p+p** we are seeing the intrinsic collimation from a single flux tube.

In **A+A** there are many such tubes each with an intrinsic correlation enhanced by flow.

Increasing transverse flow in **p+p** creates a discrepancy with data.

Yet, transverse flow is needed to explain identical measurements in **Pb+Pb**.

*IP-Glasma + MUSIC model*
Can flow in p+A explain the ridge?

In a thermal picture, for same transverse overlap area, 
\[ \varepsilon_{pp} \approx \varepsilon_{pA} \text{ when } N_{\text{track}}^{pp} = N_{\text{track}}^{pA} \]

For same energy densities, expect same flow dynamics but pA yield is \( \sim 6 \) times larger than pp

In CGC picture, \( \varepsilon_{pA} < \varepsilon_{pp} \) for same \( N_{\text{track}} \) until very large \( N_{\text{part}} \)

Flow explanation unlikely based on this simple argument + questions about applicability to small size systems for large transverse momenta
Summary

✧ Have not covered many interesting channels: quarkonia, jets, photons that carry unique information about high parton densities

✧ Exciting year for such studies and much to look forward to @ RHIC pA and EIC
EXTRA SLIDES
MC rc BK LHC pseudo-rapidity dist.
With different $\gamma \rightarrow \eta$ Jacobian

\[ \frac{dN_{\text{ch}}}{d\eta} = 0.04\eta \left[ \frac{(N_{\text{part},P}+N_{\text{part},T})/2-1}{\text{MC}} \right] \]

From A. Dumitru

ALICE arXiv:1210.3651
\[ \gamma=1.101 \text{ i.c. (orig. prediction)} \]
\[ \gamma=1 \text{ i.c. (orig. prediction)} \]
\[ \gamma=1.101 \text{ i.c., } \Delta P(\eta) = 0.04\eta \]
Long range di-hadron correlations

LRC of $\Delta y \sim 10$ can be studied at the LHC

Dusling, Gelis, Lappi, RV, arXiv:0911.2720
The saturated proton: Glasma graphs - I

RG evolution:

\[ \langle \frac{dN_2}{d^3p \, d^3q} \rangle_{\text{LLogs}} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1] W_{Y_2}[\rho_2] \frac{dN}{d^3p} |_{\text{LO}} \frac{dN}{d^3q} |_{\text{LO}} \]

= LO graph with evolved sources

avg. over sources in each event
and over all events gives correlation

Gelis, Lappi, RV, arXiv: 0807.1306

Keeping leading logs to all orders (NLO+NNLO+...) 2-particle spectrum (for \( \Delta y < 1/\alpha_s \))
Power counting at high parton densities

\[ \frac{dN_2}{d^3p \ d^3q} \]

When \( \rho_1, \rho_2 \sim g \), "dilute limit", CGC contribution is \( g^{12} \) – power counting changes from "dense limit" by \( \alpha_s^8 \)!
Physics underlying the ridge

\[ p_\perp = q_\perp = 3 \text{ (GeV)} \]

\[ y_p = 0 \]

\[ y_q = 2 \]
Physics underlying the ridge

From previous discussion

\[ UE \propto \frac{\int d^2k_T \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|)}{\int d^2k_T \Phi_A(k_T) \Phi_B(|p_T - k_T|)} \propto N_{\text{track}} \]
Physics underlying systematics of the ridge

For Glasma graphs

\[ d^2 N \propto \int d^2 k_T \ \Phi_A^2(k_T) \ \Phi_B(|p_T - k_T|) \ \Phi_B(|q_T - k_T|) \]

For \(|p_T| = |q_T|\), from the Cauchy-Schwarz inequality:

\[ \int d^2 k_T \ \Phi_A^2(k_T) \ \Phi_B(|p_T - k_T|) \ \Phi_B(|q_T - k_T|) \leq \int d^2 k_T \ \Phi_A^2(k_T)\Phi_B^2(|p_T - k_T|) \]

Equality implies no collimation; satisfied only iff

\[ \Phi_B(|p_T - k_T|) \propto \Phi_B(|q_T - k_T|) \]

True only if \(\Phi\) is flat in \(k_T\) - for above fns. Else, there must be a collimation
Physics underlying the ridge

Look at ratio of yield at $\Delta \Phi_{pq} = 0$ to $\Delta \Phi_{pq} = \pi$ for $|p_T| = |q_T|$

$$CY \propto \frac{\int d^2 k_T \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|)}{\int d^2 k_T \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|) \Phi_B(|p_T + k_T|)}$$

As seen in the p+Pb data...
A+A initial state: saturated wave-functions

Incoming nuclei are Color Glass Condensates:

A Glasma / Quark-Gluon plasma is created.

Conjecture: matter produced is a nearly ideal perfect fluid with viscosity/entropy density, $\eta/s \geq 1/4\pi$, a universal bound
IP-Glasma + viscous hydro model

Event-by-event flow distributions

$v_n$ distributions, track eccentricities $\varepsilon_n$

spatial fluctuations

efficiency $\Rightarrow$ perfect fluidity

momentum anisotropies

Gale, Jeon, Schenke, Tribedy, RV, 1209.6330, PRL (in press)
From our paper 1210.3890v3

BFKL has very weak centrality dependence

Subtracting 40-60% gets rid of di-jet leaving only dipole Glasma contribution

ALICE result consistent with our expectations
rcBK vs IP-Sat evolution

\[ Y = 0, 2, 4 \]

\[ b = 0 \]

\[ k_{\perp}^2 (\text{GeV}^2) \]
Quantitative description of pp ridge

\[
\frac{d^2 N}{d\Delta \phi} = K \int_{-2.4}^{+2.4} d\eta_p \, d\eta_q \, A(\eta_p, \eta_q)
\times \int_{p_T^{\text{min}}}^{p_T^{\text{max}}} \frac{d p_T^2}{2} \int_{q_T^{\text{min}}}^{q_T^{\text{max}}} \frac{d q_T^2}{2} \int d\phi_p \int d\phi_q \, \delta (\phi_p - \phi_q - \Delta \phi)
\times \int_0^1 dz_1 dz_2 \frac{D(z_1)}{z_1^2} \frac{D(z_2)}{z_2^2} \frac{d^2 N_{\text{corr.}}}{d^2 \eta_p d^2 \eta_q} \left( \frac{p_T}{z_1}, \frac{q_T}{z_2}, \Delta \phi \right)
\]

\[
N_{\text{trig}} = \int_{-2.4}^{+2.4} d\eta \int_{p_T^{\text{min}}}^{p_T^{\text{max}}} d^2 p_T \int_0^1 dz \frac{D(z)}{z^2} \frac{dN}{d\eta d^2 p_T} \left( \frac{p_T}{z} \right)
\]

\[
\text{Assoc. Yield} = \frac{1}{N_{\text{trig}}} \int_0^{\Delta \phi_{\text{min.}}} d\Delta \phi \left\{ \frac{d^2 N}{d\Delta \phi} \mid_{\Delta \phi = \Delta \phi_{\text{min.}}} - \frac{d^2 N}{d\Delta \phi} \right\}_{\Delta \phi = \Delta \phi_{\text{min.}}}
\]

Dependence on transverse area cancels in ratio...

Subtracts any pedestal “phi-independent” correlation
Short-Range Correlation Studies at the AGS and JLab

John Watson: Kent State University
“The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory”

The N-N Interaction and the Shell Model

The N-N interaction is attractive at a typical distance of 2 fm, but highly repulsive at distances < 0.5 fm.

The attractive part of this interaction between all of the pairs of nucleons in a nucleus, in combination with the Pauli principle, produces a mean field in which the neutrons and protons move like independent particles in well-defined quantum states.

Maria Mayer and J.H.D. Jensen received the Nobel Prize in 1963 for developing the shell model.
Simple, schematic, shell-model picture of $^{16}\text{O}$ (8n,8p)
One of the best ways to study the shell model is with “knockout” reactions (also called “quasi-elastic scattering”).

Let’s consider a “(p,2p)” reaction.
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Let’s consider a “(p,2p)” reaction.

From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event, what $\vec{p}_f$ and the separation energy of each knocked-out proton is.

H. Tyrén et al.

Separation Energy (MeV)
Simple, schematic, shell-model picture of $^{16}$O (8n,8p)
During the ‘80s and ‘90s the premier tool for knockout-reaction spectroscopy became the “(e,e'p)” reaction.

This was the result of two factors:

1) Improvements in electron accelerators.

2) The ability to do “exact” reaction calculations because the e-p interaction is electromagnetic.
1988: NIKHEF

Something is **MISSING!**

Spectroscopic factors for (e,e’p) reactions show only 60-70% of the expected single-particle strength.

There must be more!

The N-N Interaction and Correl

The N-N interaction is attractive at a typical distance of 2 fm, but highly repulsive at distances < 0.5 fm.

The short-range repulsion leads to phenomena such as the saturation of central nuclear densities. But it also must manifest itself in the wave functions of the nucleons in the nucleus. Because it is short range, high-momentum components should be affected. Typically we might expect N-N interactions at short range to produce pairs of nucleons with large, roughly equal, and opposite momenta.
The EVA Collaboration

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pA@RHIC Workshop January 2013
Instead of considering a single proton in a nucleus, let’s consider a short-range correlated neutron-proton pair. Let’s start with a (p,2p) reaction.
Instead of considering a single proton in a nucleus, let’s consider a **short-range correlated** neutron-proton pair.

Let’s start with a \((p,2p)\) reaction.

From \(\vec{p}_0, \vec{p}_1,\) and \(\vec{p}_2\) we can deduce, event-by-event what \(\vec{p}_f\) and the binding energy of each knocked-out proton is.
Instead of considering a single proton in a nucleus, let’s consider a short-range correlated neutron-proton pair.

Let’s start with a (p,2p) reaction.

From $p_0$, $p_1$, and $p_2$ we can deduce, event-by-event what $p_f$ and the binding energy of each knocked-out proton is.

We can then compare $p_n$ with $p_f$ and see if they are roughly “back to back.”
Nuclear Fermi Momenta from Quasielastic Electron Scattering

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(Received 12 January 1971)

\[ k_F = 221 \text{ MeV/c} \]

\[ \bar{\epsilon} = 25 \text{ MeV} \]

\[ d^2\sigma / d\Omega dE \sim 10^{-12} \text{ cm}^2 / \text{MeV} \]

\[ k_F = 260 \text{ MeV/c} \]

\[ \bar{\epsilon} = 36 \text{ MeV} \]
For energies of several GeV and up, For p-p elastic scattering near 90° c.m.,

\[ \frac{d\sigma}{dt} \sim s^{-(n_1+n_2+n_3+n_4-2)} \]

\[ \sim s^{-10} \]

where the Mandelstam variable \( s = (P_0 + P_F)^2 \) is the square of the total c.m. energy.

So for quasi-elastic p-p scattering near 90° c.m., we have a very strong preference for reacting with nuclear protons with their Fermi motion in the beam direction.

Forward going, high-momentum protons are preferentially selected, because this minimizes \( s \).
Figure 1: A schematic side view of the EVA spectrometer.
Full Correlations:

We then construct the directional correlation between $\vec{p}_f$ and $\vec{p}_n$ as

$$\cos\gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{|\vec{p}_f||\vec{p}_n|}$$

**Figure 21:** Plots of $\cos\gamma$, where $\gamma$ is the angle between $\vec{p}_n$ and $\vec{p}_f$. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c; $0.22$ GeV/c = $k_F$, the Fermi momentum for $^{12}$C.
Figure 22: $\cos \gamma$ vs. $p_n$ for $^{12}$C(p,2p+n) events. The vertical line at 0.22 GeV/c corresponds to $k_F$, the Fermi momentum for $^{12}$C.
So why did this work so well when our count rate was only 1 per week?

1. The $s^{-10}$ dependence of p-p elastic scattering, which preferentially selects high momentum nuclear protons.

2. The improved resolution from using light cone variables.

3. The small deBroglie wavelength of the incident protons:

$$\lambda = \frac{h}{p} = \frac{hc}{pc} = 2\pi \cdot 0.197 \text{ GeV-fm/(6 Gev)}$$

$$\approx 0.2 \text{ fm.}$$

This meant that our probe could interact with a single member of a correlated pair!
The Relative and c.m. Motion of Correlated n-p Pairs:

\[ p_{z}^{cm} = 2m \left(1 - \frac{\alpha_p + \alpha_n}{2}\right), \]

\[ p_{z}^{rel} = m |\alpha_p - \alpha_n|. \]

Centroid = \(-0.013 \pm 0.027\) GeV/c
\[ \sigma = 0.143 \pm 0.017\) GeV/c

Remember this one

Centroid = \(0.289 \pm 0.017\) GeV/c
\[ \sigma = 0.097 \pm 0.007\) GeV/c

Figure 23: Plots of (a) \(p_{z}^{cm}\) and (b) \(p_{z}^{rel}\) for correlated n-p pairs in \(^{12}\text{C}\), for \(^{12}\text{C(p,2p+n)}\) events. Each event has been “s-weighted”. 

pA@RHIC Workshop January 2013
The Correlated Fraction of \((p,2p)\) Events:

For the 6 GeV 1998 data set we estimated the fraction of \((p,2p)\) events with \(p_f > 0.22\) GeV/c, which have a correlated backwards neutrons with \(p_n > 0.22\) GeV/c.

\[
F = \frac{\text{corrected \# of } (p,2p+n) \text{ events}}{\# \text{ of } (p,2p) \text{ events}} = \frac{A}{B}
\]

The quantity \(A\) was obtained from the sample of all 18 \((p,2p+n)\) events with \(p_n \geq k_F = 0.22\) GeV/c, where a correction for flux attenuation and detection efficiency was applied event-by-event, and then corrected for the solid-angle coverage:

\[
A = \frac{2\pi}{\Delta \Omega} \sum_{i=1}^{18} \frac{1}{\epsilon_i} \cdot \frac{1}{t_i} = 1090.
\]

The average value of \((1/\epsilon_it_i)\) was \(8.2 \pm 0.82\) and \(2\pi/\Delta \Omega = 7.42\). We can then calculate

\[
F = \frac{A}{B} = \frac{1090}{2205} = 0.49 \pm 0.13.
\]
Subsequent Development

“Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei”

by

E. Piaetzky, M Sargsian, L. Frankfurt, M Strikman
and J. W. Watson


- Further Analysis of the EVA Data
- Assumes 100% SRC above 275 MeV/c
- Includes the motion of the pair
- Includes absorption of entering and exiting nucleons in the nuclear medium

Conclusion: 92 ± 18% of high-momentum protons have correlated neutrons.
A. A. Tang et al.,
Electron Scattering at Fixed $Q^2$

$$\frac{d^2\sigma}{d\omega d\Omega}$$

Elastic

$Q^2 \over 2M$

Quasielastic

$Q^2 \over 2m$

Deep Inelastic

$\frac{Q^2}{2m} - \frac{\Theta}{2n} + 3\phi\phi$

Nucleus

$Q^2 + m$

Proton

$pA@RHIC$ Workshop January 2013
The observed scaling means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with $A>3$ relative to $^3\text{He}$.
Estimate of $^{12}$C Two and Three Nucleon SRC


- K. Egiyan et al. related the known correlations in deuterium and previous $r(^3\text{He},D)$ results to find:
  - $^{12}$C 20% two nucleon SRC
  - $^{12}$C <1% three nucleon SRC
E01-105: A customized $(e,e'pN)$ Measurement

To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.

A pair with “large” relative momentum between the nucleons and small center of mass momentum

- high $Q^2$ to minimize MEC
- $x>1$ to suppress isobar contributions
- anti-parallel kinematics to suppress FSI
New Equipment for the Experimental Setup

- New Scattering Chamber
- New BigBite Hadron Spectrometer (100 msr)
- New Low Energy Neutron Detector
The neutron detector array consisted of 88 bars of plastic scintillator, with a PMT on each end of each bar, for “mean timing.”

These were gathered from around the world.
Kinematics

The BigBite Spectrometer and Neutron Detector

pA@RHIC Workshop January 2013
(e,e'pp)  
\[ P_{\text{mis}} = "300" \text{ MeV/c} \]
(Signal : BG = 1.5:1)

(e,e'pp)  
\[ P_{\text{mis}} = "400" \text{ MeV/c} \]
(Signal : BG = 2.3:1)

(e,e'pp)  
\[ P_{\text{mis}} = "500" \text{ MeV/c} \]
(Signal : BG = 4:1)

(e,e'pn)  
\[ P_{\text{mis}} = "500" \text{ MeV/c} \]
(Signal : BG = 1:7)
(e,e’p) & (e,e’p)p Data

Strong back-to-back correlation!

R. Shneor et al.,

\[ (e,e'p) \]
CM motion of the pair:

\[ p_{c.m.} \text{ vertical}, \text{“500 MeV/c “ setup} \]

\[ \begin{align*}
\sigma_{CM} &= 0.143 \pm 0.017 \text{ GeV/c} \\
\text{Theoretical prediction (Ciofi and Simula)}: \sigma_{CM} &= 0.139 \text{ GeV/c} \\
\text{(p,2pn) experiment at BNL: } \sigma_{CM} &= 0.143 \pm 0.017 \text{ GeV/c} \\
\text{This experiment: } \sigma_{CM} &= 0.136 \pm 0.020 \text{ GeV/c} \\
\end{align*} \]
Short-Range Correlation Pair Factions


\[ \frac{^{12}\text{C}(e,e'pp)}{^{12}\text{C}(e,e'pn)} / 2 \]

\[ \frac{^{12}\text{C}(e,e'pp)}{^{12}\text{C}(e,e'p)} / 2 \]

\[ \frac{^{12}\text{C}(e,e'pn)}{^{12}\text{C}(e,e'p)} \]

\[ \frac{^{12}\text{C}(p,2pn)}{^{12}\text{C}(p,2p)} \]

Missing Momentum [GeV/c]
The Results from E01-015 can be found in:


The results of the BNL (p,2p+n) experiment are fully consistent with the results of the JLab (e,e’p+N) experiment:

- Different Laboratories
- Different probes
- Different Graduate Students
- Different millenia

- Same Results!
- We are observing nuclear structure
Implications for Neutron Stars
Acknowledgment

Exp 01 – 015 collaboration  Hall A /JLab

E. Piasetzky, S. Gilad, S. Wood, J. Watson, W. Bertozzi

D. Higinbotham, R. Subedi, R. Shneor, P. Monaghan

PRL 99, 072501 (2007)

From the 2007 NSAC Long-Range Plan:

“...the direct observation of correlated two-nucleon and three-nucleon effects in the nuclear medium has been evasive. The powerful combination of the multi-GeV electron beam and a large-acceptance detector at JLAB has permitted the direct observation of two- and three-nucleon correlations in nuclei”
Two New Directions

1.) Why is the np:pp ratio 20:1?

⇒⇒ JLab Experiment E07-006 on $^4\text{He}$

2.) Is there a connection to the EMC effect?

⇒⇒ JLab Experiment E12-11-107
Importance of Tensor Correlations

A new approved experiment at Jlab E07-006

Measurement of the $^4\text{He}(e,e'pp)$ and $^4\text{He}(e,e'pn)$ reactions over the $^4\text{He}(e,e'p)$ missing momentum range from 400 to 875 MeV/c.

Density distributions:
- Sargsian et al.
- Schiavilla et al.

This proposal - $^4\text{He}$

E01-105 $^{12}\text{C}$ (scaled to $^4\text{He}$)

(e,e’pN) calculations are needed
The European Muon Collaboration (EMC) effect

\[ \sigma_{DIS}^{\text{old}} \neq \sigma_{DIS} \]

\[(\sigma_{Fe}/\sigma_{D})_{is} \]

- EMU
- BCDMS
- SLAC

Shadowing

Anti-Shadowing

EMC effect

Fermi smearing

per nucleon in nuclei \neq \ per nucleon in deuteron
Data from CERN  SLAC  JLab
1983- 2009

EMC collaboration, Aubert et al.  PL B 123,275 (1983)


EMC is not a bulk property of nuclear medium.

Scaled nuclear density $= (A-1)/A \langle \rho \rangle$

$\rightarrow$ remove contribution from struck nucleon

$\langle \rho \rangle$ from ab initio few-body calculations

New Results from JLab Hall C (E02-019)

$Q^2 = 2.5 \text{GeV}^2$

$a_{2N}^{(A/d)}$

<table>
<thead>
<tr>
<th>Element</th>
<th>$a_{2N}$ (Fomin et al.)</th>
<th>$a_{2N}$ (Fomin et al. excluding CM motion correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>1.93 ± 0.10</td>
<td>2.13 ± 0.04</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>3.02 ± 0.17</td>
<td>3.60 ± 0.09</td>
</tr>
<tr>
<td>$^9\text{Be}$</td>
<td>3.37 ± 0.17</td>
<td>3.91 ± 0.12</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>4.00 ± 0.24</td>
<td>4.75 ± 0.16</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>4.33 ± 0.28</td>
<td>5.21 ± 0.19</td>
</tr>
<tr>
<td>$^{197}\text{Au}$</td>
<td>4.26 ± 0.29</td>
<td>5.16 ± 0.21</td>
</tr>
</tbody>
</table>

PRL 106, 052301 (2011), also PRC 85 047301 (2012)
New Idea: Large Acceptance Device
Summary of Results

• Almost all nucleons above the Fermi sea are part of 2N-SRCs.

• These SRC pairs move inside the nucleus with c.m. motion of σ~140 MeV/c.

• The 2N-SRC consists of –
  \- n-p pairs (90%)
  \- p-p pairs (5%)
  \- n-n pairs (5%).

• A new experiment on \(^4\)He has been completed at JLab—analysis is underway.

• An experiment to explore the relationship between SRCs and the EMC effect has been approved.
Instead of considering a single proton in a nucleus, let’s consider a short-range correlated neutron-proton pair. Let’s start with a (p,2p) reaction.

From $p_0$, $p_1$, and $p_2$ we can deduce, event-by-event what $p_f$ and the binding energy of each knocked-out proton is.
Heavy quarkonium production in pA collisions

Feng Yuan
Lawrence Berkeley National Laboratory
Outline

- Low pt heavy quarkonium production
- Sudakov resummation
- SSA
- Conclusion
- Energy dependence for SSA in Drell-Yan process
Hard processes at low Pt

- Contain one hard momentum scale, short distance physics dominates
- Sensitive to the Pt-dependent partonic structure of nucleon/nucleus
- QCD effects
  - Sudakov double logs
  - Factorization shall be carefully examined
Heavy quarkonium production

- Large mass guarantees the hard probe
- Direct access to the gluon distribution

However,

Lansberg, 12

Wang, Ma, Chao, 12
Resummation based on color evaporation model (similar)

Berger, Qiu, Wang, 2004
NRQCD

- Non-relativistic QCD

\[ d\sigma = \sum_n d\hat{\sigma}(Q\bar{Q}[n] + X)\langle O^H[n]\rangle \]

Partonic cross sections
Depending on the
Heavy quark pair
Singlet vs Octet

Hadronization matrix
Elements for particular
Pair configuration
Low pt behavior

- Take the limit of $M \gg Pt$

\[
\begin{align*}
\sigma_0(Q^{[c]}) = & \frac{x_s C_A}{2\pi^2} \int f(x) dx f(x') dx' \frac{1}{P^2} \left[ \frac{2(1 - \xi_1 + \xi_2^2)^2}{(1 - \xi_1)^2} \delta(1 - \xi_2) \\
+ & \frac{2(1 - \xi_2 + \xi_2^2)^2}{(1 - \xi_2)^2} \delta(1 - \xi_1) + \left(2 \ln \frac{M^2}{P^2} - \delta_{8c}\right) \delta(1 - \xi_2) \delta(1 - \xi_1) \right] 
\end{align*}
\]

- Born cross section normalization
- Collinear gluon radiation
- Sudakov double logs

Sun, Yuan\(^2\), 1210.3432
Impact parameter space

- Usual structure

\[
\begin{aligned}
\sigma_0(Q^{[c]}) \frac{\alpha_s C_A}{\pi} \int dx dx' f(x) f(x') & \left\{ \xi_1 P_{gg}(\xi_1) \delta(1 - \xi_2) \left( -\frac{1}{\epsilon} + \ln \frac{4e^{-2\gamma_E}}{\mu^2 b^2} \right) \\
+ (\xi_1 \rightarrow \xi_2) \right] + \delta(1 - \xi_1) \delta(1 - \xi_2) \left[ (b_0 + \frac{1}{2} \delta_{c8}) \ln \frac{b^2 M^2}{4} e^{2\gamma_E} \\
- \frac{1}{2} \ln^2 \left( \frac{M^2 b^2}{4} e^{2\gamma_E} \right) - \frac{\pi^2}{6} + \frac{B_Q^{[c]}}{C_A} \right] \right\},
\end{aligned}
\]

(10)

- Sudakov

\[
S_{Sud} = \int_{C_2 b^2}^{C_2 M^2} \frac{d\mu^2}{\mu^2} \left[ \ln \left( \frac{C_2^2 M^2}{\mu^2} \right) A(C_1, \mu) + B(C_1, C_2, \mu) \right]
\]
Reummation

- Low pt distribution

\[
\frac{d\sigma}{d^2 P_{\perp} dy} \bigg|_{P_{\perp} \ll M} = \frac{1}{(2\pi)^2} \int d^2 b \, e^{i \vec{P}_{\perp} \cdot \vec{b}} W(b, M, x_1, x_2)
\]

\[
W(b, M^2) = e^{-S_{Sud}(M^2, b, C_1, C_2)} W(b, C_1, C_2)
\]

- Non-perturbative input

\[
W(b) = W(b_\ast) W^{NP}(b)
\]

\[
W^{NP}(b) = \exp \left[ -g_1 - g_2 \ln \left( \frac{Q}{2Q_0} \right) - g_1 g_3 \ln (100 x_1 x_2) \right] b^2
\]
Compared to exp. (ϒ)

Fixed target: 38GeV

Tevatron: 2TeV

LHC: 7TeV
More data from LHC
Pt broadening at small-x

\[ W^{NP}(b) = \exp \left[ -g_1 - g_2 \ln \left( \frac{Q}{2Q_0} \right) - g_1g_3 \ln (100x_1x_2) \right] b^2 \]

\[ -\ln(W)/b^2 = +1 \quad 2(x/0.0003)^{0.12} \]

\[ -0.17\ln(10x) \]
What we learned

- Strong pt broadening at small-$x$
- However, it may not be as strong as naïve dipole model predictions (from DIS Geometric scaling)
- More detailed studies needed
- pA collisions will be very crucial
What we will find out at LHC

- No broadening effects?
- But suppression

\[
\frac{d\sigma^{(\text{resum})}}{dyd^2q_\perp}|_{q_\perp \ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{iq_\perp \cdot r_\perp} e^{-S_{\text{sud}}(Q^2,r^2)} \mathcal{F}_Y^{\gamma} \times xg_p(x,\mu^2 = c_0^2/r_\perp) \\
\mathcal{F}_Y^{\gamma} = \mathcal{F}_{gg}^{(1)} + \mathcal{F}_{gg}^{(2)} \\
\mathcal{F}_{gg}^{(1)} = \int xG^{(2)}(q_1) \otimes F(q_2), \quad \mathcal{F}_{gg}^{(2)} = -\int \frac{q_1\perp \cdot q_2\perp}{q_1^2\perp} xG^{(2)}(q_1) \otimes F(q_2)
\]

(work in progress, see also earlier work by Dominguez,Kharzeev,Levin,Mueller,Tuchin)
Universal suppressions at low pt

- Gluon distributions from the nucleus are the same for both NRQCD and color evaporation model in the large Nc limit.
- It will be model-independent prediction for the suppressions at low Pt.
- Suppressions only depend on $x_A$ at small-$x$. 
Single spin asymmetries

- Heavy flavor as a probe for the gluon Sivers effects
- No (Collins) fragmentation involved
- Heavy quarkonium probe the gluon Sivers function
pp scattering

Naïve analysis from the leading order diagrams

• Color-singlet model: only initial state interaction, non-zero SSA
• Color-octet model: initial and final state interactions cancel out, no SSA

This may have to be re-analyzed in the context of Factorization breaking, Rogers-Mulders 2010
SSA in pA collisions at low $P_T$

- Cross section dominated by low transverse momentum UGD

\[
\frac{d\sigma}{d^2 P_{h\perp}} = \frac{1}{Q_s^2 + \Delta^2} e^{-P_{h\perp}^2/(Q_s^2 + \Delta^2)}
\]

\[
\frac{d\Delta\sigma}{d^2 P_{h\perp}} \propto \frac{P_{h\perp} \sqrt{\Delta^2 - \delta^2}}{(Q_s^2 + \Delta^2 - \delta^2)^2} e^{-\frac{P_{h\perp}^2}{Q_s^2 + \Delta^2 - \delta^2}}
\]

\[
A_N(P_{h\perp}) \propto \frac{P_{h\perp} \Delta}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}}
\]

Similar to Drell-Yan, Kang-Xiao, 2012.
SSA at high $P_T$

- Cross section is dominated by large pt UGD

\[ A_N(P_{h\perp}) \approx \frac{2P_{h\perp}(\Delta^2 + \delta^2)}{P_{h\perp}^2 + 6\Delta^2} \]

- Ratios

\[ \frac{A^{pA\rightarrow h}_N}{A^{pp\rightarrow h}_N}|_{P_{h\perp} \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2}{Q_{sp}^4} \delta^2} \]

\[ \frac{A^{pA\rightarrow h}_N}{A^{pp\rightarrow h}_N}|_{P_{h\perp} \gg Q_s^2} \approx 1 \]
Conclusions

- Heavy quarkonium production at low Pt showed remarkable broadening effects in pp collisions toward LHC energy.
- Suppression at both RHIC and LHC shall provide further information on saturation.
- SSA in pA collisions at RHIC will open new window for both spin and saturation physics, unknown mechanism.
BNL-LANL-RBRC Joint Workshop on
The Physics of p+A Collisions at RHIC
January 7-9, 2013
At
Brookhaven National Laboratory
Bldg. 510, Large Seminar Room

Monday - January 7th, 2013
8:30am-9:00am Registration

Morning Session-I Chair: Xiaodong Jiang (LANL)
9:00-9:05 Welcome.
9:05-9:25 p+A collision at RHIC and Status of RHIC operation. Tom Ludlam (BNL)
9:25-9:55 A summary of earlier p+A experiments results. Mike Leitch (LANL)
9:55-10:30 Unpolarized p+A - theory overview. Raju Venugopalan (BNL)

10:30-10:50 Coffee Break

Morning Session-II Chair: Jianwei Qiu (BNL)
10:50-11:20 pA@LHC program and ATLAS plan of p+Pb. Brian Cole (Columbia)
11:20-11:55 Physics opportunities with a polarized pA@RHIC. Mark Strikman (Penn. State)
11:55-12:30pm Single-spin asymmetry in polarized p+A collisions. Yuri Kovchegov (Ohio State)

12:30pm-2:00pm Lunch Break

Afternoon Session-I. Chair: Yousef Makdisi (BNL)
2:00-2:30 pA@LHC CMS p+Pb results. Wei Li (Rice)
2:30-3:00 Short range correlations and AGS A(p, 2p) experiment. John Watson (Kent State)
3:00-3:35 Heavy quarkonium production in a polarized pA@RHIC. Feng Yuan (LBNL)

3:35-3:55 Coffee Break

Afternoon Session-II. Chair: Ming Liu (LANL)
4:25-4:55 Hadronization and Color Transparency studies at JLab. Kawtar Hafidi (ANL)
4:55-5:25 PHENIX d-Au result of hadron production. Mickey Chiu (BNL)
Tuesday, January 8th, 2013
8:30am-9:00am Registration

Morning Session-I. Chair: Mei Bai (BNL)
9:00-9:30 Feasibilities and Challenges of pA collisions. Steve Tepikian (BNL)
9:30-9:50 Engineering solutions of DX magnets for p+A collision at 200 GeV/nucleon. Francis Karl (BNL)
9:50-10:10 RF manipulation for p+A collision and stochastic cooling. M. Blaskiewicz (BNL)
10:10-10:25 Potential impact on polarized beam polarization in p+A collision: V. Ranjbar (BNL)

10:30-10:50 Coffee Break

Morning Session-II. Chair: Mei Bai (BNL)
10:50-11:10 Path forward to establish p+A collision for physics and projected luminosity. W. Fischer (BNL)
11:10-11:30 Discussions. Expected luminosity. Practical issues on machine and polarization in p+A.
11:30-12:00 Color Transparency. Steve Heppelmann (Penn. State)
12:00-12:30pm AGS polarized p+A, and inclusive Lambda polarization. Yousef Makdisi (BNL)

12:30-2:00pm Lunch Break

Afternoon Session-I. Chair: Nu Xu (LBNL)
2:00-2:35 Polarized p+A, single-spin asymmetries. Zhongbo Kang (LANL)
2:35-3:05 Prompt Photon A_N with the PHENIX MPC-EX Detector, John Lajoie (Iowa State)
3:05-3:35 Recent STAR Forward Spin Physics Results. Len Eun (LBNL)

3:35-3:55 Coffee Break

Afternoon Session-II. Chair: Yoji Goto (RIKEN)
4:25-4:55 STAR Lambda results. Ernst Sichtermann (LBNL)
4:55-5:25 The STAR FGT upgrade program. Xuan Li (Temple)

6:30pm-8:00pm Workshop Dinner. Brookhaven Center, South Room
Wednesday, January 9th, 2013
8:30am-9:00am Coffee

**Morning Session-I Chair: Steve Heppelmann (Penn. State)**

9:00-9:30 ALICE p+Pb results. Tim Schuster (Yale)
9:30-10:00 LHCf and p+A forward at RHIC. Yoshitaka Itow (Nagoya University)
10:00-10:30 PHENIX p+A, unpolarized observables, Rich Seto (UC Riverside)

10:30-10:50 Coffee Break.

**Morning Session-II Chair: Steve Heppelmann (Penn. State)**

10:50-11:20 PHENIX future upgrade plan. Joseph Seele (RBRC)
11:50-12:00 Physics opportunities of di-muon analysis in p+A with PHENIX. Kwangbok Lee (LANL)
12:00-12:30 Workshop Summary. Jianwei Qiu (BNL)

12:30-2:00pm Lunch Break

**Afternoon Session-I Chair: Xiaodong Jiang (LANL)**

2:00pm-3:30 pm

*Discussions and short presentations.*
Outline of a pA@RHIC whitepaper.
A list of golden measurements for pA@RHIC.
Form a joint workforce from the RHIC user community.
A plan of actions for RHIC machine, STAR and PHENIX.

3:30-3:50 Coffee Break

**Afternoon Session-II Chair: Xiaodong Jiang (LANL)**

3:50-6:00 pm

*Discussions*
Outline of a pA@RHIC whitepaper.
A list of golden measurements for pA@RHIC.
Form a joint workforce from the RHIC user community.
A plan of actions for RHIC machine, STAR and PHENIX.
## PARTICIPANT LIST

<table>
<thead>
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<th>Name</th>
<th>Email</th>
<th>Institution</th>
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</thead>
<tbody>
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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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