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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 95

Progress in High-p_T Physics at RHIC

March 17-19, 2010

Organizing Committee:

Alexander Bazilevsky, Leslie Bland and Werner Vogelsang

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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 and again in 2007. 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 ~50 graduates of which 14 theorists and 6 experimenters have 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 ninety seven 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.

N. P. Samios, Director
March 2010

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Introduction

This volume archives the presentations at the RIKEN BNL Research Center workshop "Progress in High-p_T Physics at RHIC", held at BNL in March 2010.

Much has been learned from high-p_T physics after 10 years of RHIC operations for heavy-ion collisions, polarized proton collisions and d+Au collisions. The workshop focused on recent progress in these areas by both theory and experiment.

The first morning saw review talks on the theory of RHIC high-p_T physics by G. Sterman and J. Soffer, and on the experimental results by M. Tannenbaum. One of the most exciting recent results from the RHIC spin program is the first observation of W bosons and their associated single-spin asymmetry. The new preliminary data were reported on the first day of our workshop, along with a theoretical perspective. There also were detailed discussions on the global analysis of polarized parton distributions, including the knowledge on gluon polarization and the impact of the W-data.

The main topic of the second workshop day were single-transverse spin asymmetries and their analysis in terms of transverse-momentum dependent parton distributions. There is currently much interest in a future Drell-Yan program at RHIC, thanks to the exciting physics opportunities this would offer. This was addressed in some of the talks. There also were presentations on the latest results on transverse-spin physics from HERMES and BELLE.

On the final day of the workshop, the focus shifted toward forward and small-x physics at RHIC, which has become a cornerstone of the whole RHIC program. Exciting new data were presented and discussed in terms of their possible implications for our understanding of strong color-field phenomena in QCD. In the afternoon, there were discussions of nuclear parton distributions and jet observables, among them fragmentation. The workshop was concluded with outlooks toward the near-term (LHC, JLab) and longer-term (EIC) future.

The workshop has been a great success. We had excellent presentations throughout and productive discussions, which showed the importance and unique value of the RHIC high-p_T program. We are grateful to all participants for coming to BNL.

The support provided by the RIKEN-BNL Research Center for this workshop has been magnificent, and we are most grateful for it. We also thank Brookhaven National Laboratory and the U.S. Department of Energy for providing additional support and for the facilities to hold this workshop. Finally, sincere thanks go to Pamela Esposito for her most efficient and tireless work in organizing and running the workshop.

Alexander Bazilevsky, Leslie Bland, Werner Vogelsang

June 2010


PHYSICS
PHYSICS
DEPARTMENT
510

HIGH-p_T AT RHIC

GEORGE STERMAN

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SUNY at Stony Brook, Stony Brook, NY 11794-3840, USA

Abstract

This talk reviews some aspects of jet physics at hadron colliders. Energy flow plays a central role in jet identification, although different jet definitions will provide different cross sections, both theoretically and experimentally. At the RHIC, both Star and Phenix have made innovative use of this framework to measure jet cross sections for both proton and nuclear initial states. Single-particle inclusive cross sections are related to jet cross sections by factorization theorems. This observation sheds light on some surprising recent data from the Tevatron.

- What we're really looking at here (with local source J)

$$\sigma[f] = \lim_{R\to\infty} \int d^4x \mathrm{e}^{-iq\cdot y} \prod_a \int d\hat{n}^{(a)} f_a(\hat{n}^{(a)})$$

$$\times \langle 0|\, J(0) T[\prod_a \hat{n}_i^{(a)} T_{0i}(x_0, R\hat{n}_a) J(y)]\, |0\rangle$$

(Sveshnikov & Tkachov 95, Korchemsky, Oderda & GS 96, Bauer, Fleming, Lee & GS 08, Hofman & Maldacena 08)

With T_{0i} the energy momentum tensor at the detector

- "Weights" $f^{(a)}(\hat{n})$ should introduce no new dimensional scale

Short-distance dominated if all f continuous almost everywhere.

- We only have to ask "smooth" questions.

Gaussian filtering.

(Lai and Cole, 2008)

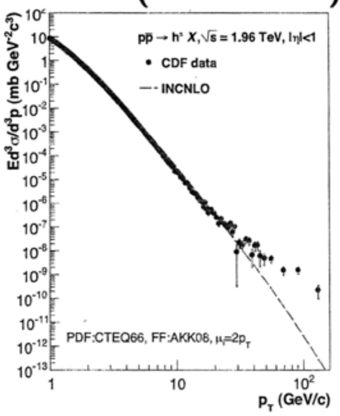
- Seems to me most closely to energy flow, with a weight function as above.
- Replaces the $theta$-function weights of cone algorithms with a truly smooth function.

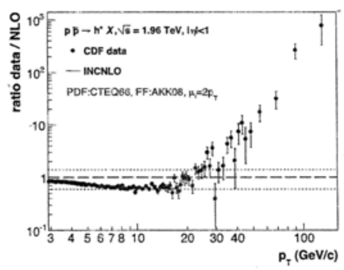
$$\tilde{p}_T(\eta,\phi) = \int d\hat{n}\, p_T(\hat{n})\, e^{-(\eta-\eta(\hat{n}))^2-(\phi-\phi(\hat{n}))^2}$$

which is

$$\tilde{p}_T(\eta,\phi) = \lim_{R\to\infty} \int d\hat{n}\, \frac{1}{\cosh\eta(n)}\, \langle AA|\hat{n}_i T_{0i}(x_0, R\hat{n})\,|AA\rangle \times e^{-(\eta-\eta(\hat{n}))^2-(\phi-\phi(\hat{n}))^2}$$

• Year-old CDF Data, as analyzed in papers by Albino, Kniehl and Kramer (1003.1954) Arleo, d'Enteria and Yoon (1003.2963):



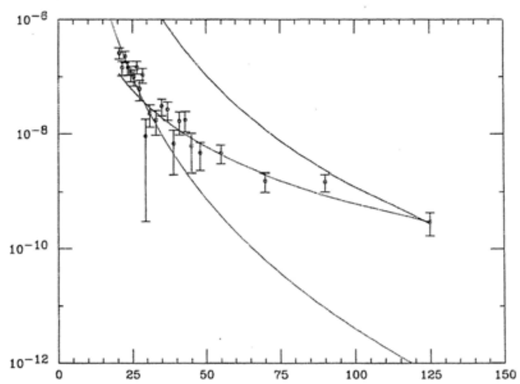


• This data had been hanging around since last April (0904.1098), but its significance was lost in a comparison with PYTHIA tunes. It was published in Phys. Rev. D (2009).

• Both AKK and AEY observe: either a (big) problem with universality of fragmentation or with the data itself.

- **A QCD description is difficult. Isolated single pions are suppressed compared to jets by at least $\alpha_s(f_\pi/p_T)^2 \sim 10^{-4}$ at 100 GeV.**
- **But compared to NLO jets (red) and NLO 1PI (green) the data (with green fit) looks like:**

(Vogelsang, yesterday)



- A general form at $\eta = 0$; $z = x_a x_b = \hat{s}/S$:

$$E\frac{d^3\sigma}{d^3p_T} = \frac{1}{p_T^4} \int_{x_T^2}^1 dz \mathcal{L}_{\text{partonic}}(z)\, \omega(x_T, z)$$

- Suppose a narrow resonance at $M^2 = z_0 S$ decays to single hadrons plus unobservable particles . . .

$$\omega(x_T, z) = f(4x_T^2/z_0)\, \delta(z - z_0)$$

- Then

$$E\frac{d^3\sigma}{d^3p_T} = \frac{1}{p_T^4} \mathcal{L}_{\text{partonic}}(z_0)\, f(4x_T^2/z_0)$$

- and the distribution $f(4x_T^2/z_0)$ can be read off from the data where it dominates QCD fragmentation, while it cuts off abruptly at $2x_T = \sqrt{z_0}$.
- But of course, it should be wide and not narrow, and where does the rest of the energy go, etc., etc?

High p_T physics from the AGS to the ISR to RHIC

M. J. Tannenbaum
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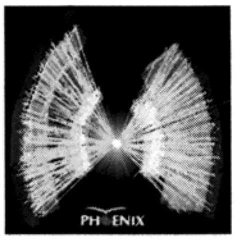
Upton, NY 11973 USA



Progress in High-p_T Physics at RHIC
RBRC Workshop, BNL
March 17, 2010

Timeline of hard-constituent Scattering

• 1968--Deeply Inelastic scattering of electrons on protons observed at SLAC. First direct indication of sub-constituents of proton, "partons" as explained by Bjorken scaling [J.D. Bjorken, Phys. Rev. **179**, 1547 (1969)]

• 1971--High p_T scattering of "partons" via QED predicted for p-p collisions by Bjorken, Berman, Kogut [BBK, Phys. Rev. **D4**, 3388 (1971)]

• 1972 First evidence of hard-scattering of constituents discovered at CERN ISR--attention turns from spectroscopy to "high p_T physics"

• 1974--J/ψ discovered at BNL and SLAC-people start believing that partons are real and are the same as quarks.

• 1972-1982 properties of hard-scattering and "Jets" mapped out at CERN-ISR for a decade 1975,1977-78 first theory papers on QCD applied to hard-scattering

• 1982-Constituent-scattering Angular distribution measured at ISR in agreement with QCD. (Rutherford scattering of quarks). SppS (UA2)-first observation of unbiased Jets in hadron collisions.

Searches for W boson in p-p collisions

• 1965-1969 Beam dump experiments at ANL-ZGS and BNL-AGS looking for "large angle" muons didn't find any. [ZGS-Lamb, et al PRL **15**, 800 (1965), AGS-Burns, et al, ibid 830, AGS-Wanderer et al, PRL **23**,729(1969)]

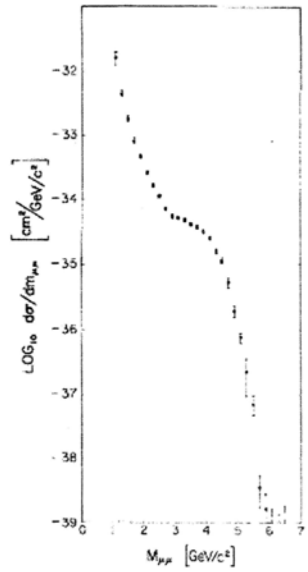
• How do you know how many W should have been produced?

• Chilton, Saperstein, Shrauner [PR**148**, 1380 (1966)] emphasize the importance of the timelike form factor, which is solved by

• Y. Yamaguchi [Nuovo Cimento **43**, 193 (1966)] Timelike form factor can be found by measuring the number of lepton pairs e^+e^- or $\mu^+\mu^-$ "massive virtual photons" of the same invariant mass; BUT the individual leptons from these electromagnetically produced pairs might mask the leptons from the $W^\pm$.

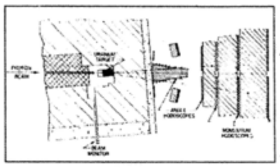
• This set off a spate of single and di-lepton experiments, notably the discovery by Lederman et al of "Drell-Yan" production at the BNL-AGS, E70 at FNAL and CCR at the CERN-ISR.

AGS-1969-71 Discovery of 'Drell-Yan' and ??



p+U→μ⁺μ⁻+X

$\sqrt{s_{NN}}$=7.4 GeV



This is why I NEVER plot theory curves on any of my data

VIEW LETTERS 4 JANUARY 1971

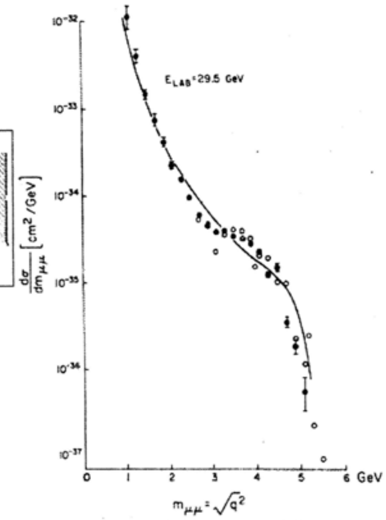


FIG. 2. Experimental cross section of Christenson *et al.*, Ref. 8.

long forgotten

Christenson, Lederman…PRL **25**, 1523 (1970) `Theory' Altarelli, Brant Preparata PRL **26** 42 (1971)

LML very excited in 1970: AGS-diμ continuum +Bj scaling→W cross section at any √s

Proposal to The National Accelerator Laboratory

E70-(F)NAL

"Study of Lepton Pairs from Proton-Nuclear Interactions: Search for Intermediate Bosons and Lee-Wick Structure"

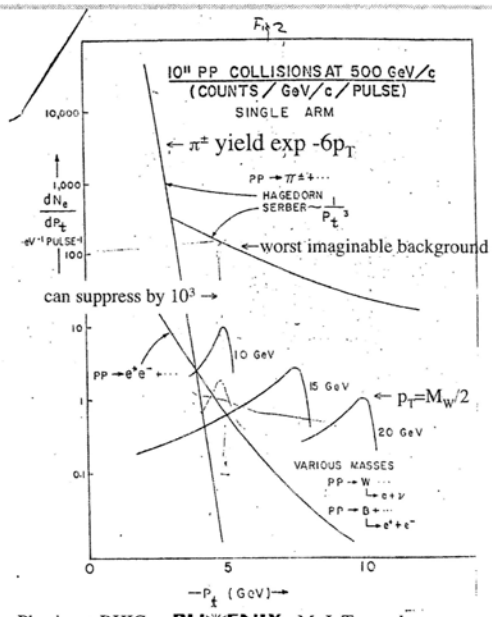
W. LEE, L.M. LEDERMAN, J. APPEL, Columbia University, M. TANNENBAUM, Harvard University, L. READ, J. SCULLI, T. WHITE, and T. YAMANOUCHI, National Accelerator Laboratory.

ABSTRACT

We propose to observe lepton pairs emerging from high energy proton-nuclear collisions. Large effective mass pairs probe the hadronic electromagnetic structure. The continuum mass spectrum will be measured and any resonant structures in the mass range up to ~ 28 GeV will be detected with great sensitivity. The data provides a prediction, via Conserved Vector Current theory, for the production cross section for weak vector bosons and these are also sought in the mass range ~8-25 GeV. We also propose an initial photon-electron beam survey at high transverse momentum which is also a W-search with good sensitivity.

June 17, 1970 + addendum Dec 1970 →

Correspondent: L. M. Lederman, Columbia University



The CERN ISR was the first Hadron Collider and made many discoveries and developed many techniques which are in use in Au+Au and p-p collisions at RHIC today.

G. Giacomelli and M. Jacob, Phys. Rept. **55** (1979) 1-132
M. Jacob and K. Johnsen, CERN Yellow Report 84-13

- The rapidity plateau (although several of my RHI colleagues don't believe in a plateau). Will not be discussed in this talk.
- Hard scattering in p-p collisions via particle production at large p_T which proved that the partons of DIS strongly interacted with each other. x_T scaling measurements to find the underlying physics.
- Proof using same-side and away side two particle correlations that high p_T particles in p-p collisions are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by QCD, which was developed during the course of these measurements.

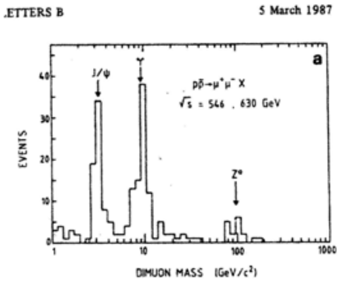
CERN-ISR Discoveries, cont'd

- direct lepton ($e^{\pm}$) production from the decay of (unknown at that time-1974) particles composed of b and c quarks.
- first and only J/Psi cross section measurement for all pair $p_T \geq 0$ at a hadron collider, until PHENIX at RHIC [PRL **92** (2004) 051802] and CDF [PRD **71**(2005) 032001 (15 years after their first publication)]
- direct photon production

J/Psi suppression has been the gold plated signature for the quark gluon plasma in AA

The Road To Success in HEP

ETTERS B 5 March 1987



$p_T(\mu) \geq 3$ GeV/c. UA1 Phys. Lett. B186, 237 (1987)

The Road To Success in HIP

Status of QCD Theory in 1978

• The first modern QCD calculation and prediction for high p_T single particle inclusive cross sections including non-scaling and initial state radiation was done in 1978 by J. F. Owens, E. Reya, M.Gluck, PRD **18**, 1501 (1978), "*Detailed quantum-chromodynamic predictions for high-p_T processes*," and J.F. Owens, J. D. Kimel, PRD **18**, 3313 (1978), "*Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes*".

• This work was closely followed and corroborated by Feynman, Field, Fox PRD **18**, 3320 (1978), "*Quantum-chromodynamic approach for the large-transverse-momentum production of particles and jets*."

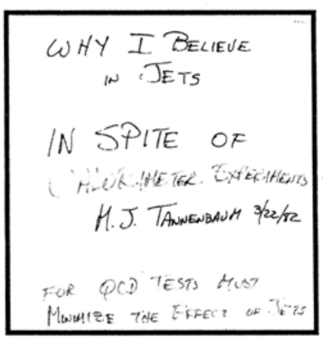
• Unfortunately jets in 4π Calorimeters at ISR energies or lower are invisible below $\sqrt{\hat{s}} \approx E_T \leq 25$ GeV, which led to considerable confusion in the period 1980-1982.

Office of Science U.S. DEPARTMENT OF ENERGY   BROOKHAVEN NATIONAL LABORATORY   Progress in High-p_T Physics at RHIC   PHENIX M. J. Tannenbaum 26/48

QCD and Jets
are now a cornerstone of the standard model

• Incredibly at the famous Snowmass conference in July 1982, many if not most people were skeptical

e.g. MJT Seminar 3/22/82


WHY I BELIEVE IN JETS

IN SPITE OF CALORIMETER EXPERIMENTS

M.J. TANNENBAUM 3/22/82

FOR QCD TESTS MUST MINIMIZE THE EFFECT OF JETS

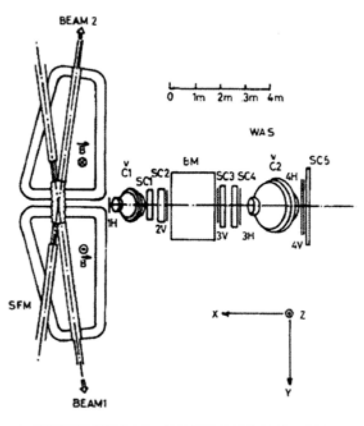
• The International HEP conference in Paris, three weeks later, July 26--31, 1982 changed everything.

Office of Science U.S. DEPARTMENT OF ENERGY   BROOKHAVEN NATIONAL LABORATORY   Progress in High-p_T Physics at RHIC   PHENIX M. J. Tannenbaum

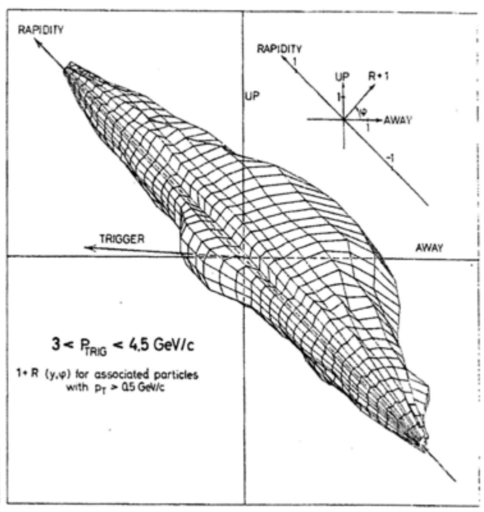
At the CERN ISR from 1975-1982 two-particle correlations showed unambiguously that high p_T particles come from jets.

For the past decade these single and two-particle techniques were used exclusively at RHIC for hard-scattering, with outstanding results...

e.g. British French Scandinavian "Ridge"



Split Field magnet, horrible magnetic field uniformity. Track recon took ~5 yrs to develop + 1 hour of CDC7600 per hour of data! Great acceptance when it finally worked.



BFS
NP**B145**(1978) 308

SOME RELEVANT CASES FOR STUDYING HIGH-P_T PHYSICS AT THE RHIC PP COLLIDER

Jacques Soffer

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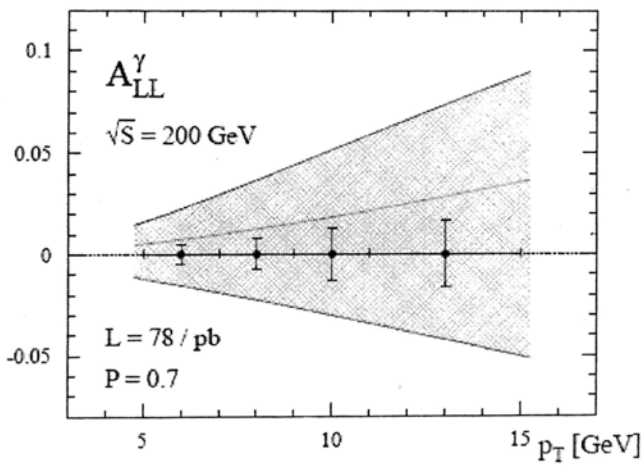
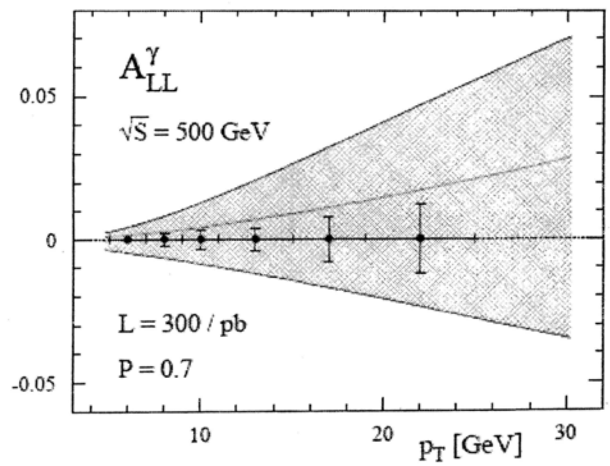
Abstract

Spin occurs in all particle processes, so by ignoring this fundamental quantum number, we will certainly miss a relevant part of the story. Needless to say that spin observables allow a deeper understanding of the underlying dynamics and this sometimes leads to uncover new important tools. We should also remember that the spin sector of pQCD remains to be carefully checked and the high-p_T kinematic region is the most appropriate region to study QCD spin physics at the energy of the RHIC pp collider. We will consider successively for various processes, double helicity asymmetries A_{LL}, which are sensitive to quark and gluon helicity distributions, double transverse spin asymmetries A_{TT}, depending upon the quark transversity distributions, spin transfer in Λ production involving fragmentation functions, single spin asymmetries A_N with some new mechanisms to generate them and finally search for new physics. Positivity constraints will occur in the discussion of some of these topics.

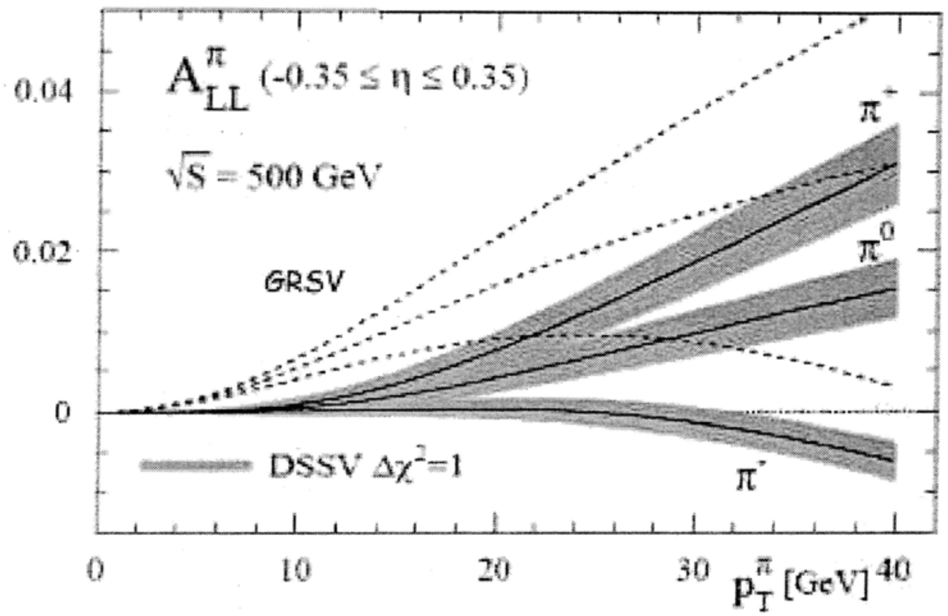
Expected high-p_T A_{LL} data on γ production at RHIC





Predictions for larger p_T

Expect $A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$ if $\Delta G > 0$



What positivity can bring into this game?

New general positivity bounds were derived
(J.S.,PRL 91,092005,2003), among the spin observables in a single particle inclusive reaction, where the two initial particles carry a spin-1/2. In particular for $y = 0$ one has

$$1 - A_{TT}(y = 0, p_T) \geq 2|A_N(y = 0, p_T)|$$

for any value of $\sqrt{s}$ and p_T. From the previous results $A_{TT} \sim 0$ for $pp \to \gamma X$ and $pp \to jetX$, we get a strong bound e.g. $|A_N| \leq 1/2$.
(See also a recent review on positivity: X. Artru, M. Elchikh, J.M. Richard, J.S., O. Teryaev, Phys. Reports, 470, 1 (2009))

Single spin asymmetry A_N in $W^{\pm}$ production

Consider the collision $p^{\uparrow}p$ with a proton p of momentum $\overrightarrow{p}$, carrying a transverse spin $\overrightarrow{s}_p$ producing a $W^{\pm}$ of transverse momentum $\mathbf{p_T}$.
The SSA in first approximation factorizes and then it reads

$$A_N^{W^{\pm}}(\sqrt{s}, y, \mathbf{p}_T) = H(p_T)A^{\pm}(\sqrt{s}, y)\mathbf{S}_p \cdot \hat{\mathbf{p}} \times \mathbf{p}_T, \qquad (1)$$

where $\mathbf{p}_T$ is the transverse momentum of the $W^{\pm}$ produced at the c.m. energy $\sqrt{s}$ and $H(p_T)$ is a function of p_T, the magnitude of $\mathbf{p}_T$. For W^{+} we have

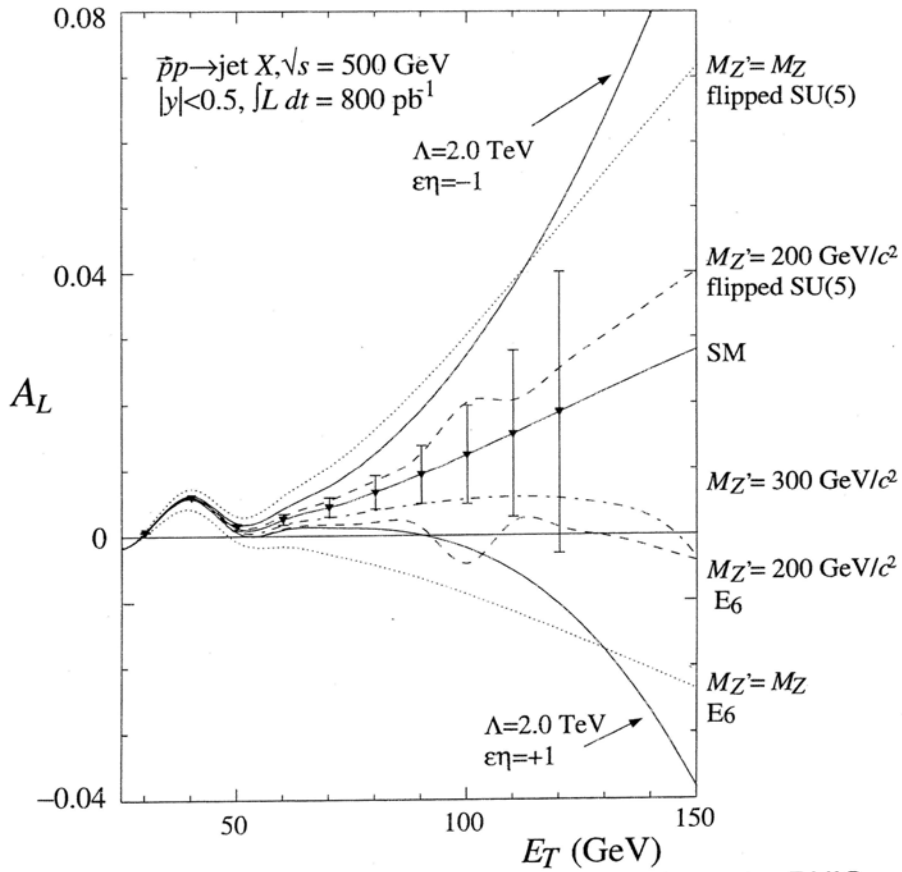
$$A^{+}(\sqrt{s}, y) = \frac{\Delta^N u(x_a)\bar{d}(x_b) + \Delta^N \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}, \qquad (2)$$

where y denotes the W^{+} rapidity, which is related to x_a and x_b. Actually we have $x_a = \sqrt{\tau}e^{y}$ and $x_b = \sqrt{\tau}e^{-y}$, with $\tau = M_W^2/s$, and we note that a similar expression for $A_N^{W^-}$, the SSA corresponding to W^{-} production, is obtained by permuting u and d.
This allows to perform a flavor separation of the Sivers functions.

Search for New Physics at RHIC

- Why ? : polarized protons at RHIC may discover a new pure hadronic interaction of weak strength. New interactions involving leptons would have been discovered at other facilities (LEP, HERA, Tevatron-(Drell-Yan)).
- $\vec{p}\vec{p}$ RHIC facility :
  highest Energy ($\sqrt{s} = 500\ GeV$)
  + highest Luminosity ($L = 800\ pb^{-1}$)
  + highest Polarisation ($P = 70$ %).

$A_L(SM + NP)$ at RHIC



Some relevant cases for studying high-p_T physicsat the RHIC pp collider

CHE: W production at NLO and the polarized sea distributions

200 AÑOS BICENTENARIO ARGENTINO

Daniel de Florian
Universidad de Buenos Aires, Argentina

in collaboration with Werner Vogelsang

We present a next-to-leading order calculation of the cross section and longitudinal spin asymmetry in single-inclusive charged-lepton production, pp -> e X, at RHIC, where the lepton is produced in the decay of an electroweak gauge boson. Our calculation is presented in terms of a multi-purpose Monte-Carlo integration program that may be readily used to include experimental spin asymmetry data in a global analysis of helicity parton densities. We perform a toy global analysis, studying the impact of anticipated RHIC data on our knowledge about the polarized anti-quark distributions.

Need to count with a new calculation $\sigma(pp \underset{\mathrm{W}}{\rightarrow} e\bar{\nu}X)$

- Exclusive to implement experimental cuts
- Unpolarized, single polarized and double polarized
- "Ready/Available" for Mellin implementation
- Full NLO in line with other observables already in fit
- Allow to compute Z/Gamma 'background'

Monte-Carlo-like (set of) code(s)

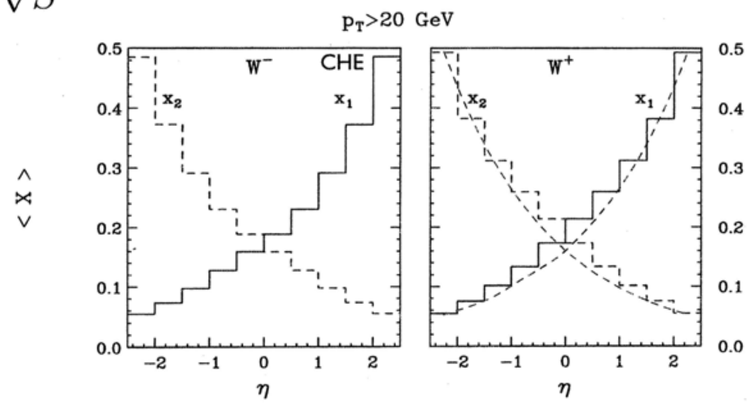
CHE : Collisions at High Energies

Full access to final and initial state kinematics :
compute any infrared-safe observable

$$x_{1,2} = \frac{M_W}{\sqrt{S}} e^{\pm y_w}$$

Lepton rapidity inherits relation to x

1:polarized beam

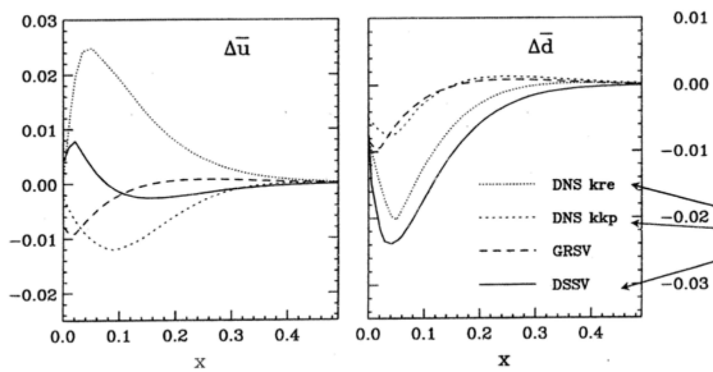


$$\text{--------} < X_{1,2} > \simeq \frac{M_W}{\sqrt{S}} e^{[\pm\eta/2]}$$

NWA

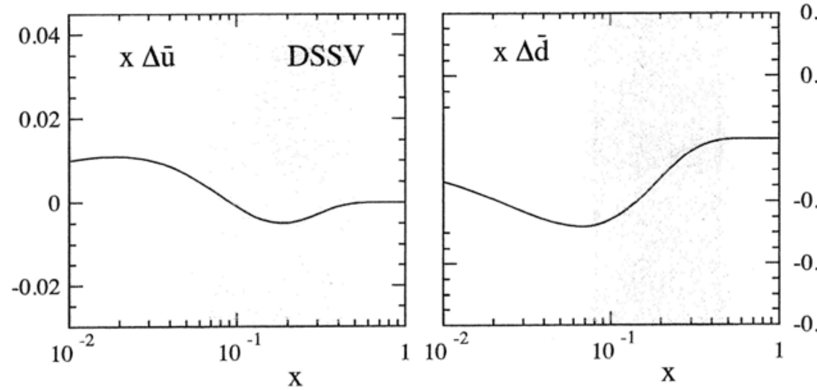
$$M_W \simeq 2E_T \cosh(y_W - y_l) \ , \qquad E_T \lesssim M_W/2$$

$$|y_W - y_l| \simeq \ln\left[\frac{M_W}{2E_T} + \sqrt{\left(\frac{M_W}{2E_T}\right)^2 - 1}\right]$$

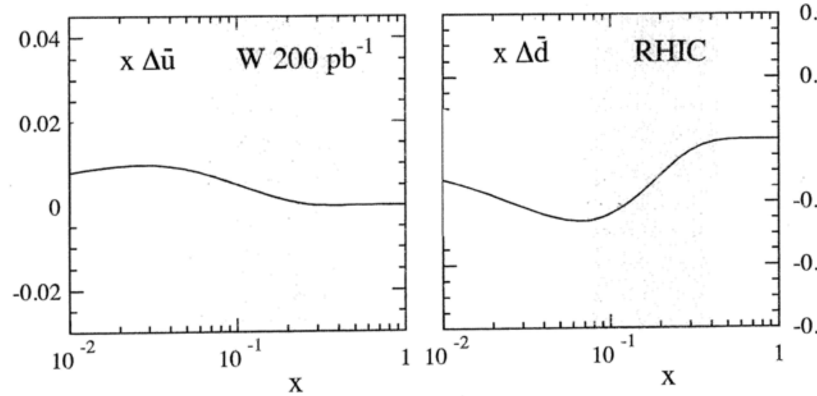


include SIDIS with different FFs

DSSV result

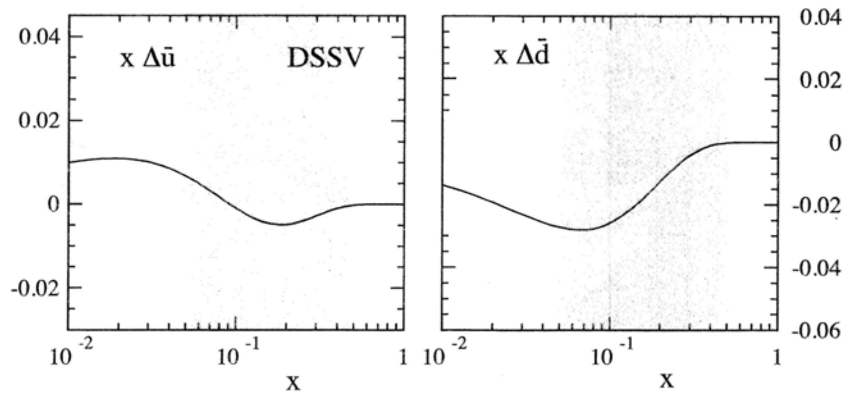


Include W data (200 pb^{-1} with present rapidity coverage)

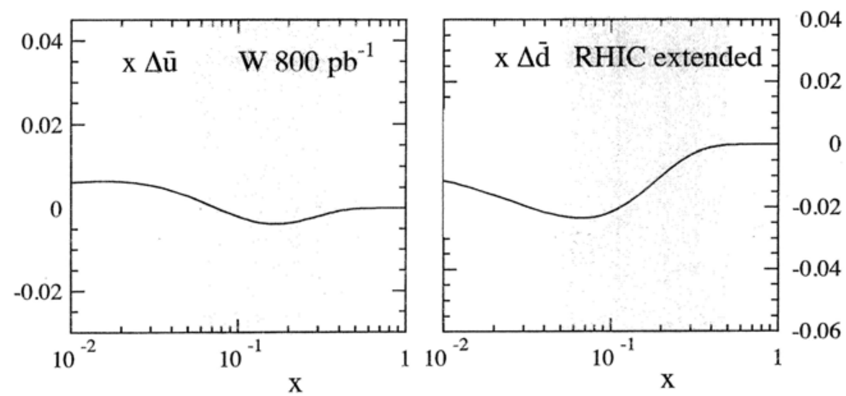


Little modification in the distributions

✓ Strong reduction in uncertainty band at $x > 0.07$!!



More precise data and extended coverage



Very nice prospects for $x \gtrsim 0.05$

Simulated data generated in agreement with DSSV : strong bias towards SIDIS

Summary (good news)

- ✓ CHE : Full NLO calculation for ~~W~~ single inclusive lepton asymmetries
- ✓ Includes Z/Gamma contribution
- ✓ Can be included in Global Fit (Mellin grids)
- ✓ First (realistic) analysis with 'simulated' data
- ✓ W asymmetries clearly help to constrain $\Delta\bar{u}$, $\Delta\bar{d}$
  $x \gtrsim 0.05$

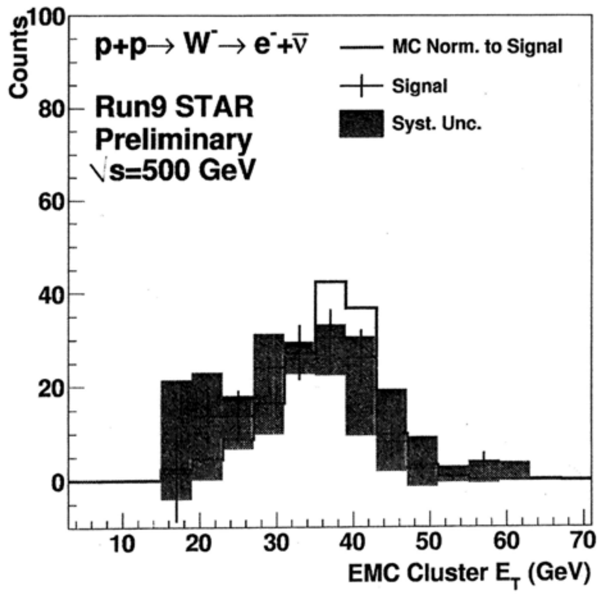
During next decade : Confront/Compete/Check/Replace
SIDIS ! (in some kinematical range)

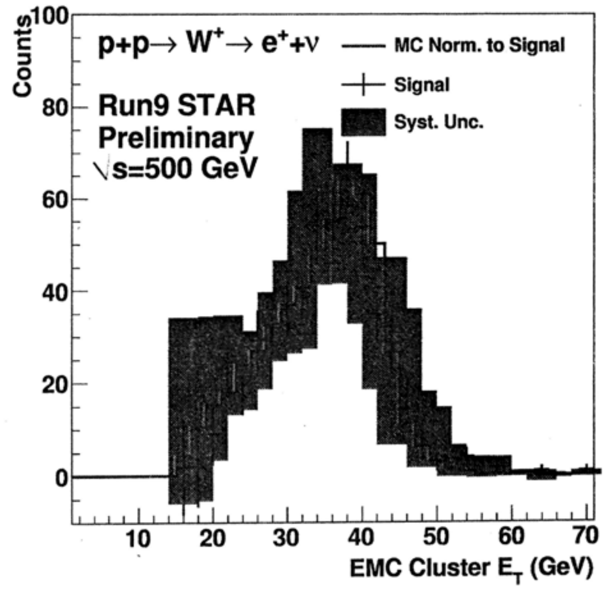
First W Production Results from STAR

Hal Spinka (ANL) for the
STAR Collaboration

Progress in High p_T Physics
at RHIC, RBRC Workshop
17 March 2010

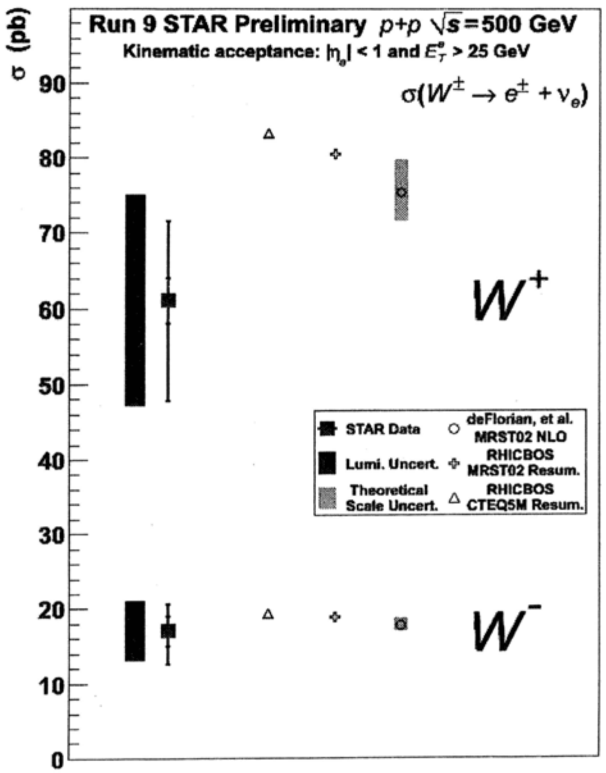
Cross Section – Shape





- A comparison is shown of full PYTHIA + GEANT simulations of STAR W $\rightarrow$ e ν events at 500 GeV.
  - The systematic uncertainties were estimated by varying cuts and normalization regions for the QCD background and by varying the BEMC energy scale uncertainty ($\pm$ 7.5%).

Cross Section – Results



	$W^- \rightarrow e^- + \bar{\nu}_e$	$W^+ \rightarrow e^+ + \nu_e$
N_W^{obs}	156	513
N_{back}	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$
ϵ_{total}	$0.56\ ^{+0.11}_{-0.09}$	$0.56\ ^{+0.12}_{-0.09}$
$\int Ldt$ (pb^{-1})	13.7 ± 3.2	13.7 ± 3.2

Run 9 STAR Preliminary (p+p 500 GeV)

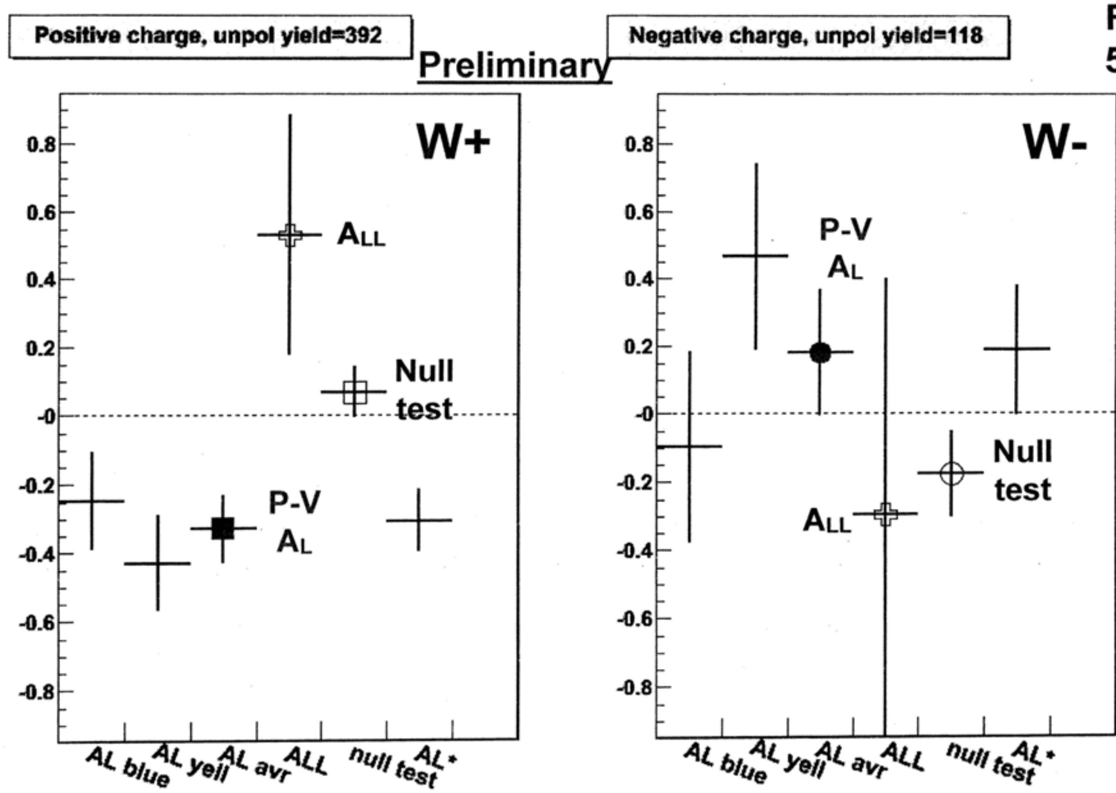
$$\sigma_{W^+ \rightarrow e^+ + \nu} = 61 \pm 3\,(\text{stat.})\ ^{+10}_{-13}\,(\text{syst.}) \pm 14\,(\text{lumi.})\ \text{pb}$$

$$\sigma_{W^- \rightarrow e^- + \bar{\nu}} = 17 \pm 2\,(\text{stat.})\ ^{+3}_{-4}\,(\text{syst.}) \pm 4\,(\text{lumi.})\ \text{pb}$$

There is reasonable agreement between the measured and expected cross sections.

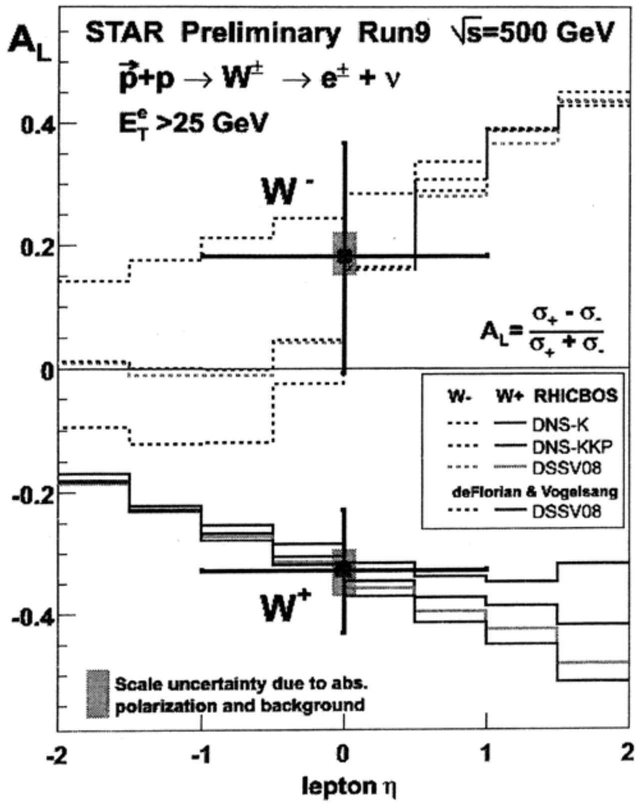
A_L Determination – Results

Run 9 (pp)
500 GeV



Physics asymmetries (A_L, A_{LL}) are corrected for unpolarized background.

A_L Determination – Results



STAR Preliminary Run 9

$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \ \pm 0.04(\text{syst.})$$
$$A_L(W^-) = \ 0.18 \pm 0.19(\text{stat.}) \ ^{+0.04}_{-0.03}(\text{syst.})$$

- For mid-rapidity, W decay electrons / positrons
  - A_L (W^+) is negative, as predicted, by 3.3 σ.
  - A_L (W^-) is consistent with being positive, as expected.

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Summary

- There was a successful polarized $\sqrt{s}$ = 500 GeV p+p run at RHIC last year. First data were collected at this energy.
- STAR observed W decay electrons and positrons at mid-rapidity ($|\eta| < 1$).
  - The measured cross sections for both W^+ and W^- are in reasonable agreement with theoretical expectations.
  - The parity-violating asymmetries, A_L, were also obtained and the results agree with theoretical predictions. In particular, A_L (W^+) was found to be 3.3 σ away from zero (negative).
  - Future results will work towards flavor separation of the different quark and anti-quark contributions to the proton spin.
- We look forward to additional $\sqrt{s}$ = 500 GeV data in the future (see the upcoming talk by B. Surrow).

W boson production and spin asymmetry measurements at PHENIX

Kyoto University/RIKEN   Ken'ichi Karatsu for the PHENIX Collaboration

◆ W bosons provide possibilities for flavor separated measurements, and asymmetry of W production is sensitive to the polarization of sea quark

◆ Upgrades are ongoing to measure W boson in the PHENIX Muon Arms. They have been partially installed & tested at 2009 & 2010 RHIC Run.

-> They are ready for the next 500 GeV run!

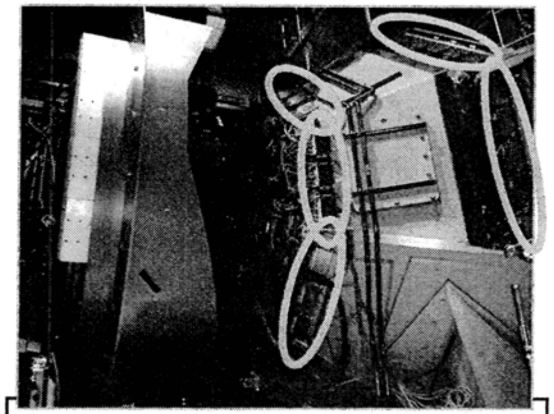
◆ PHENIX observed W→ e decay in the mid-rapidity region (PHENIX Central Arms) at 2009 RHIC Run (Run9).

-> Preliminary result for single spin asymmetry $A_L = -0.83 \pm 0.31$

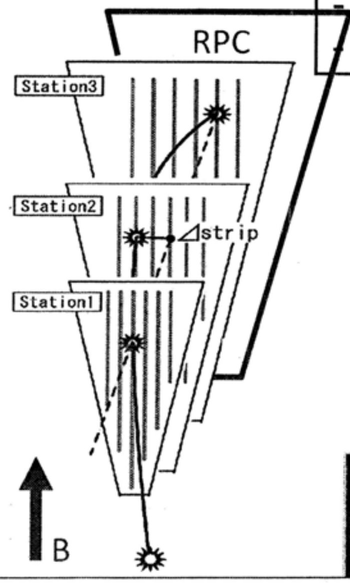
◆ Analysis of W measurement at PHENIX Central Arms is ongoing and will be finalized soon (first measurement of W bosons at RHIC!)

-> Experience from analysis also enables us to obtain greater result from the next 500 GeV run!

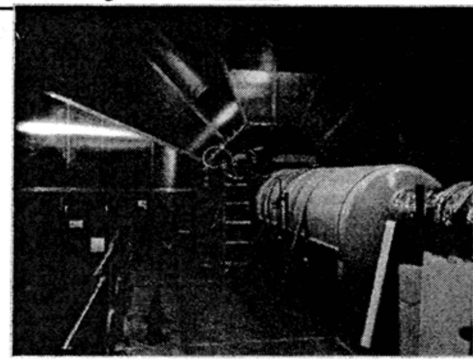
PHENIX Muon Trigger Upgrade



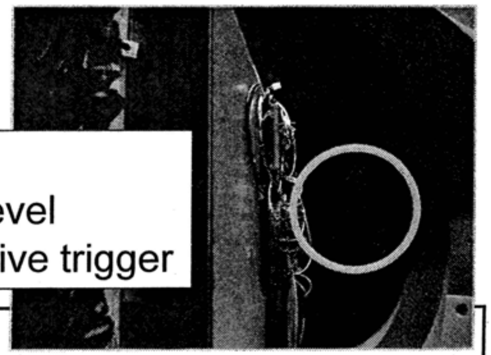
New MuTr FEE (MuTRG)
- use highly segmented Muon Tracker (MuTr)
(good momentum selectivity)
- poor time resolution…
(> 1 beam crossing)
- **fully installed**



RPC
- add better timing!
- improve background rejection
- **partially installed**



Basic Idea:
Measure Δstrip in online level
-> more momentum selective trigger



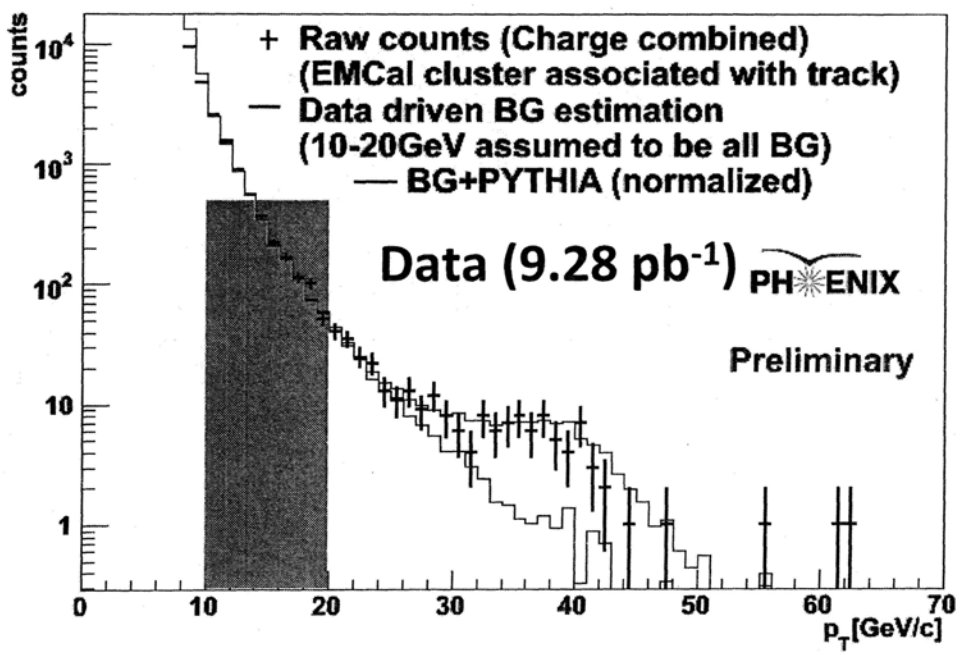
Performance study is ongoing

Absorber
- reject hadron background
- **prototype was installed at 2009 Run**

Measured spectra (PHENIX Central Arms)

Data driven BG estimation:

- (EMCal cluster) x (conversion + mis association probability)
- The rest is explained by the $h^{\pm}$ shape (NLO pQCD+EMCal response, scaled so that the sum matches the 10-20 GeV region)

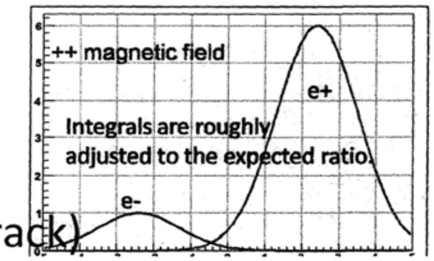


The bump is W+Z signal.

Signal shape looks reasonable

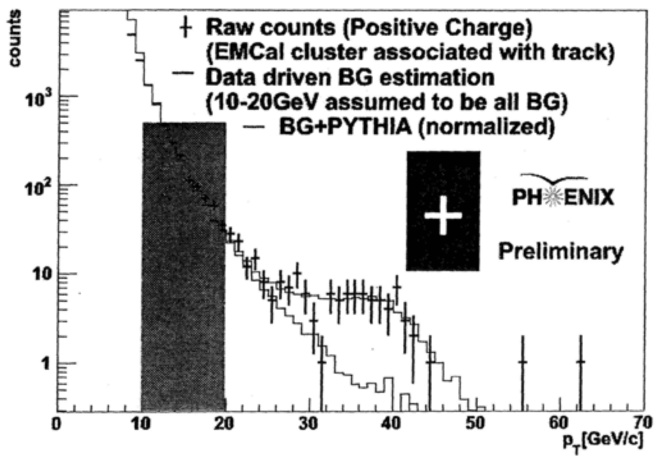
<u>Need to finalize (acc.)x(eff.) value to get cross section</u>

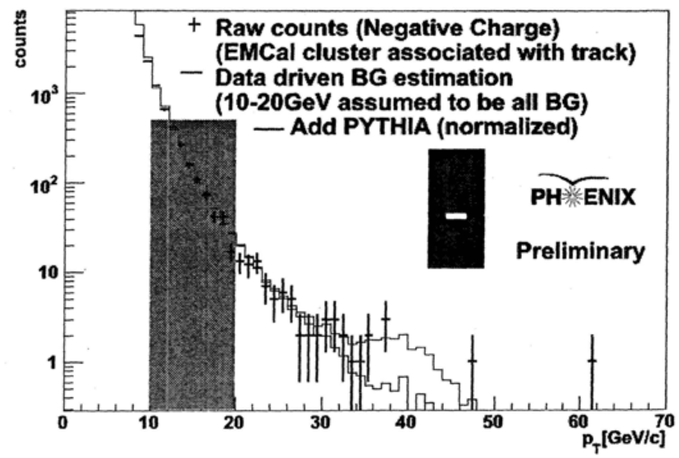
Charge separated spectra (PHENIX Central Arms)



Charge sign :

from DC angle (2.3σ separation for 40GeV/c track)





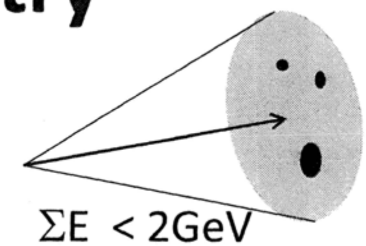
The same factor for PYTHIA was used for signal shape

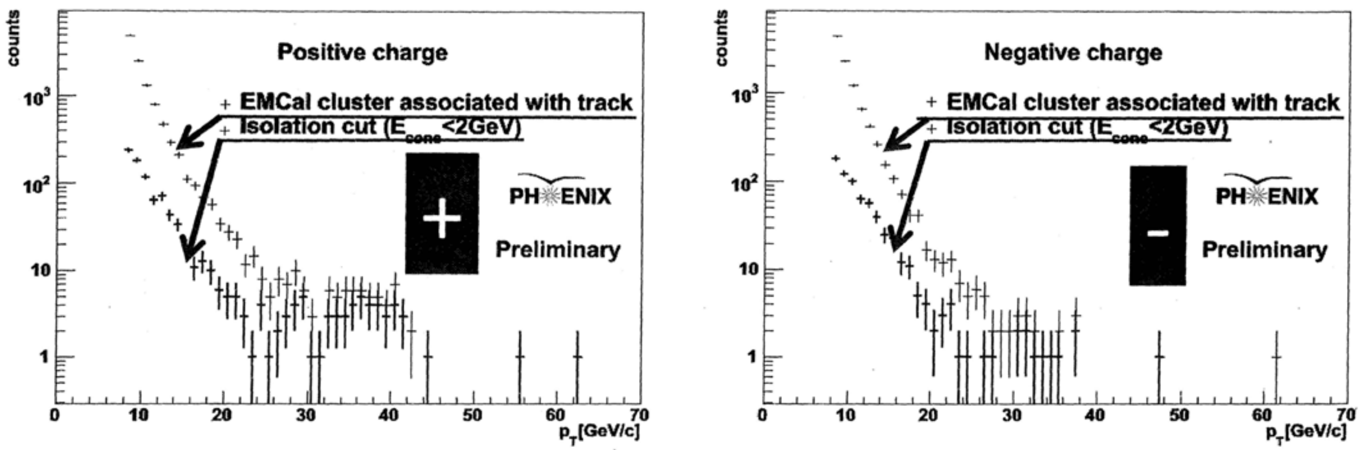
$W^- \rightarrow e^-$ signal has less acceptance than $W^+ \rightarrow e^+$ signal

Single Spin Asymmetry

When extracting spin asymmetry, any cut can be applied to improve S/N ratio, if it's spin independent

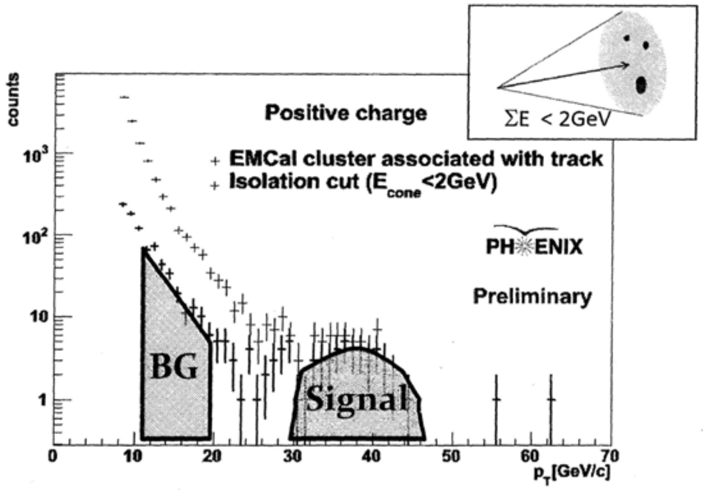
→ **Isolation Cut**





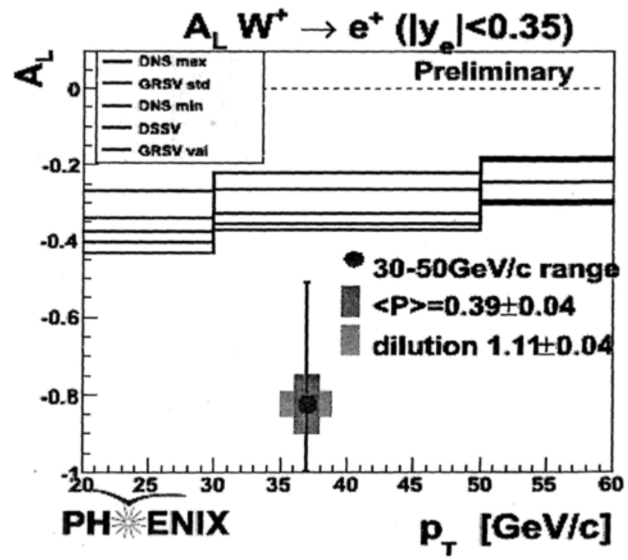
90+% of signal is kept (red histograms)

Single Spin Asymmetry (positive charge)



	pT	Raw
BG	12-20	0.035±0.047
Signa	30-50	-0.29±0.11

non-zero asymmetry @ signal region



Physics Asymmetry

- *1/<P> to raw asymmetry
- *(Dilution factor): BG from Z, hadron
- consistent with projections

A_L = -0.83±0.3 1

Longitudinal parity-violating asymmetry in W-boson mediated jet pair production

Pavel Nadolsky

Southern Methodist University

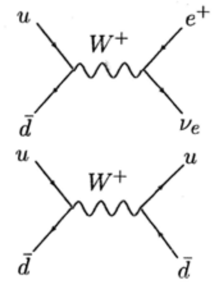
March 17, 2010

Based on E. Berger and P. Nadolsky, Phys. Rev. D78, 114010 (2008)

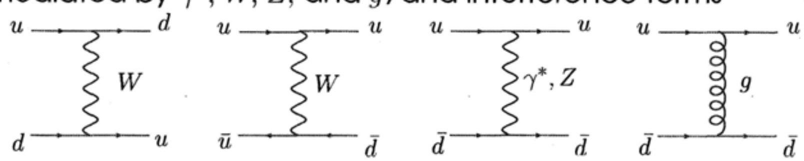
Two classes of subprocesses with W bosons

1: Resonant (s-channel) W boson production

- dominant parity-violating process at $Q \approx M_W$
- Leptonic decays: Br($W \to e\nu_e$) $\approx$ 10.8%
- Hadronic decays: Br($W \to$ hadrons) $\approx$ 67%



2: Non-resonant scattering into a dijet final state, mediated by γ^*, W, Z, and g, and interference terms

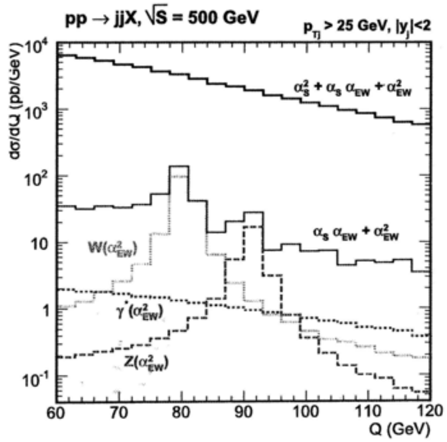


, etc.

Calculation of the dijet cross sections

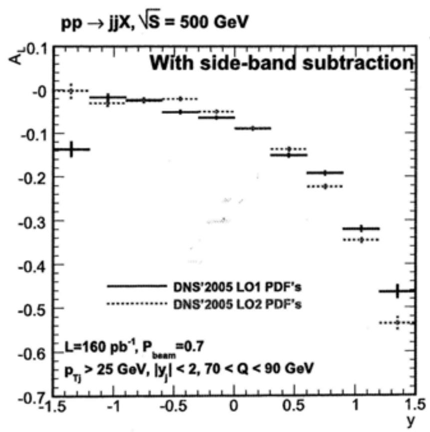
- Compute $pp \to \text{jet} + \text{jet} + X$, approximated by $2 \to 2$ exchanges of $V = g, \gamma^*.W^{\pm}, Z^0$ in the s, t, and u channels; orders α_{EW}^2, $\alpha_s \alpha_{EW}$, and α_s^2
- Cross sections are fully differential in the momenta of two jets; allow acceptance cuts
- MadGraph for generation of cross sections and MadEvent for phase-space Monte-Carlo integration. Programs operate with helicity-dependent scattering amplitudes, but typically the amplitudes are summed over all helicity combinations to produce spin-averaged cross sections.
  - ▶ modified MadEvent to evaluate single-spin cross sections (available upon request)

Unpolarized dijet mass (Q) distributions



- Continuous event distribution from QCD and electromagnetic scattering (g and γ^*) dominates
- "Signal region" = region in which Q is close to M_W (e.g., $70 \leq Q \leq 90 - 100$ GeV)
- Even in this region, the spin-averaged W and Z contribution is no more than a few percent of the full event rate

Spin-dependent dijet production



With subtraction

- $\mathcal{O}(\alpha_s^2)$ terms, other non-resonant contributions are measured at $Q < 70$ GeV and $Q > 90$ GeV; interpolated and subtracted from D at $70 < Q < 90$ GeV
- A_L is enhanced; statistical errors remain reasonable
- Sensitivity to $\Delta f_{a/p}$ is improved

Error bars are projected statistical uncertainties for $\mathcal{L} = 160$ pb^{-1}, $P_{beam} = 0.7$

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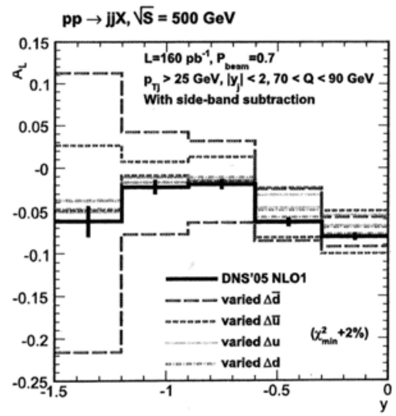
Sensitivity of A_L to $\Delta\bar{q}$

A_L for production of jet pairs, after side-band subtraction



For $y < 0$, pronounced variations in A_L due to the variation of $\Delta\bar{d}(x, Q)$

The black curve corresponds to the DNS2005 NLO PDF set 1. The pairs of other curves contain the ranges of A_L obtained if $\Delta q \equiv \int_0^1 dx\, \Delta q(x, 3.16\text{ GeV})$ is varied within $\Delta\chi^2/\chi^2_{min} < 2\%$

Spin Physics Results from COMPASS

Christian Schill
Universität Freiburg
for the COMPASS collaboration

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- Selection of Results
  - DIS and Polarized Distribution Functions
  - Polarization of the strange quark sea
  - Asymmetry of the polarized sea
  - Direct measurements of $\Delta g/g$
  - Transversity measurements

- Future plans
  - Near future: transverse and longitudinal data
  - Study of GPD using DVCS and HEMP
  - Drell-Yan

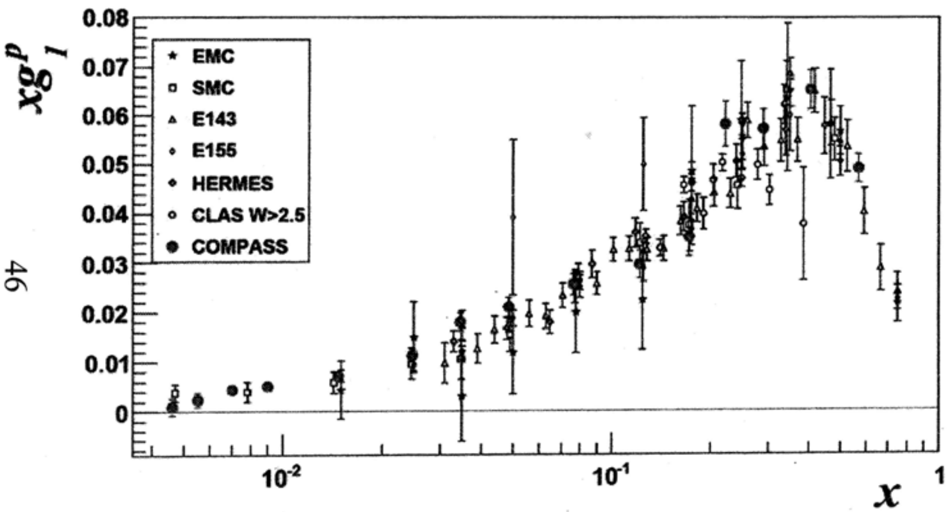
Progress in High-Pt Physics at RHIC, BNL, Mar. 2010

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung
06FR9069

Proton & Deuteron $g_1(x)$ world data

Proton data - world

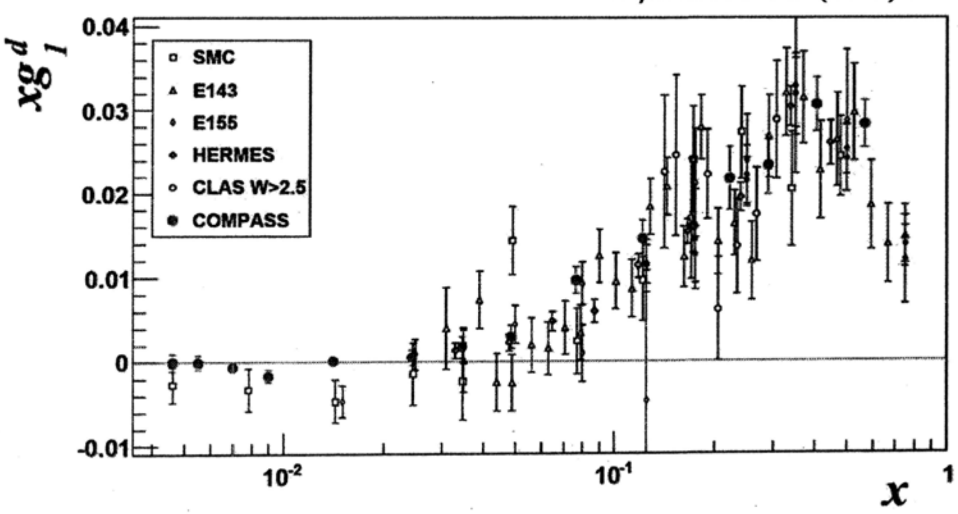
Subm. Phys. Lett. B (hep-ex/1001.4654)



COMPASS data: 2007

Deuteron data - world

Phys. Lett. B 647 (2007) 8



COMPASS data: 2002 – 2006

From first moment of g_1^d:

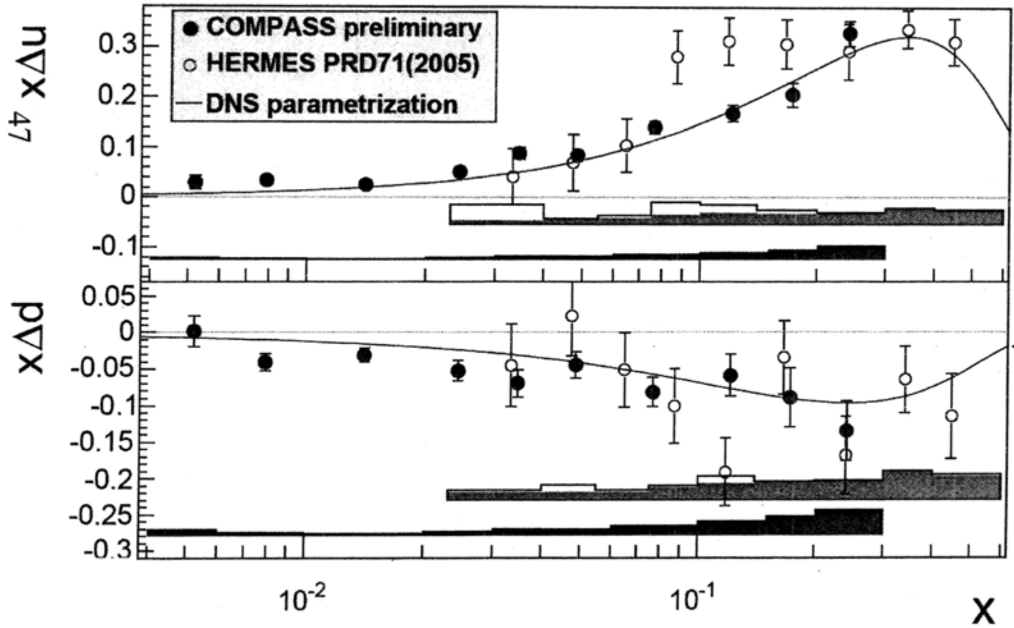
$\Delta\Sigma=a_0= 0.33\pm0.03\pm0.05$ (evol. to $Q^2=\infty$)

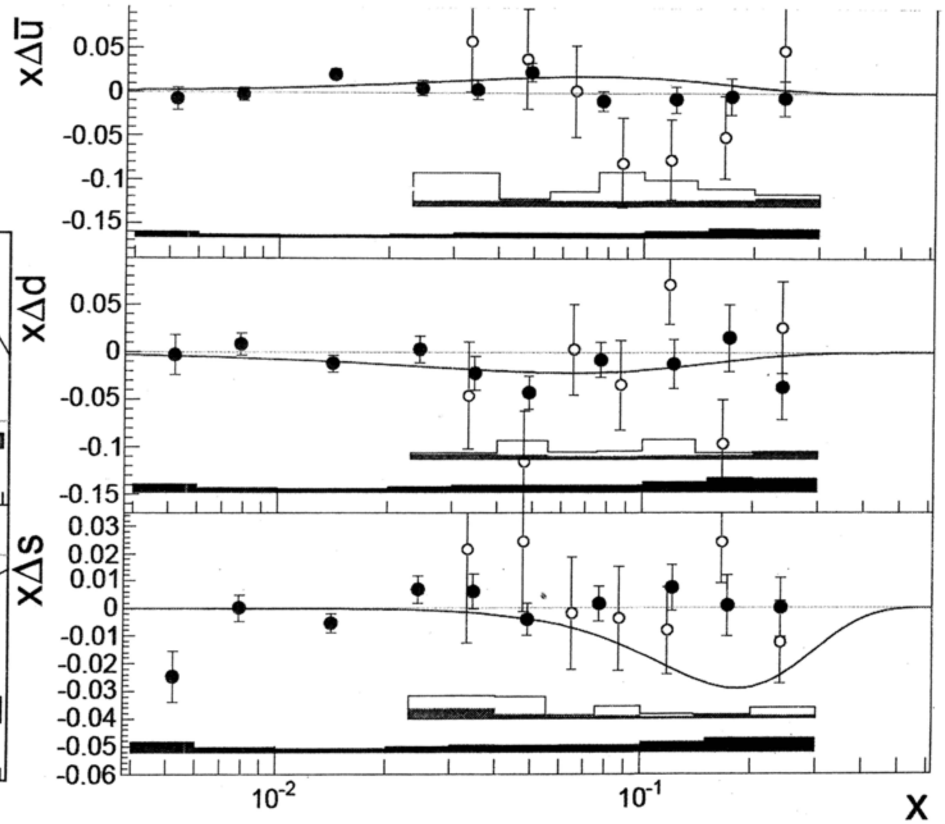
$(\Delta s+\Delta s)=1/3(a_0-a_8) = -0.08 \pm 0.01 \pm 0.02$

Compass results for Δu(x), Δd(x), and Δs(x)

- LO semi-inclusive data analysis of COMPASS proton and deuteron data

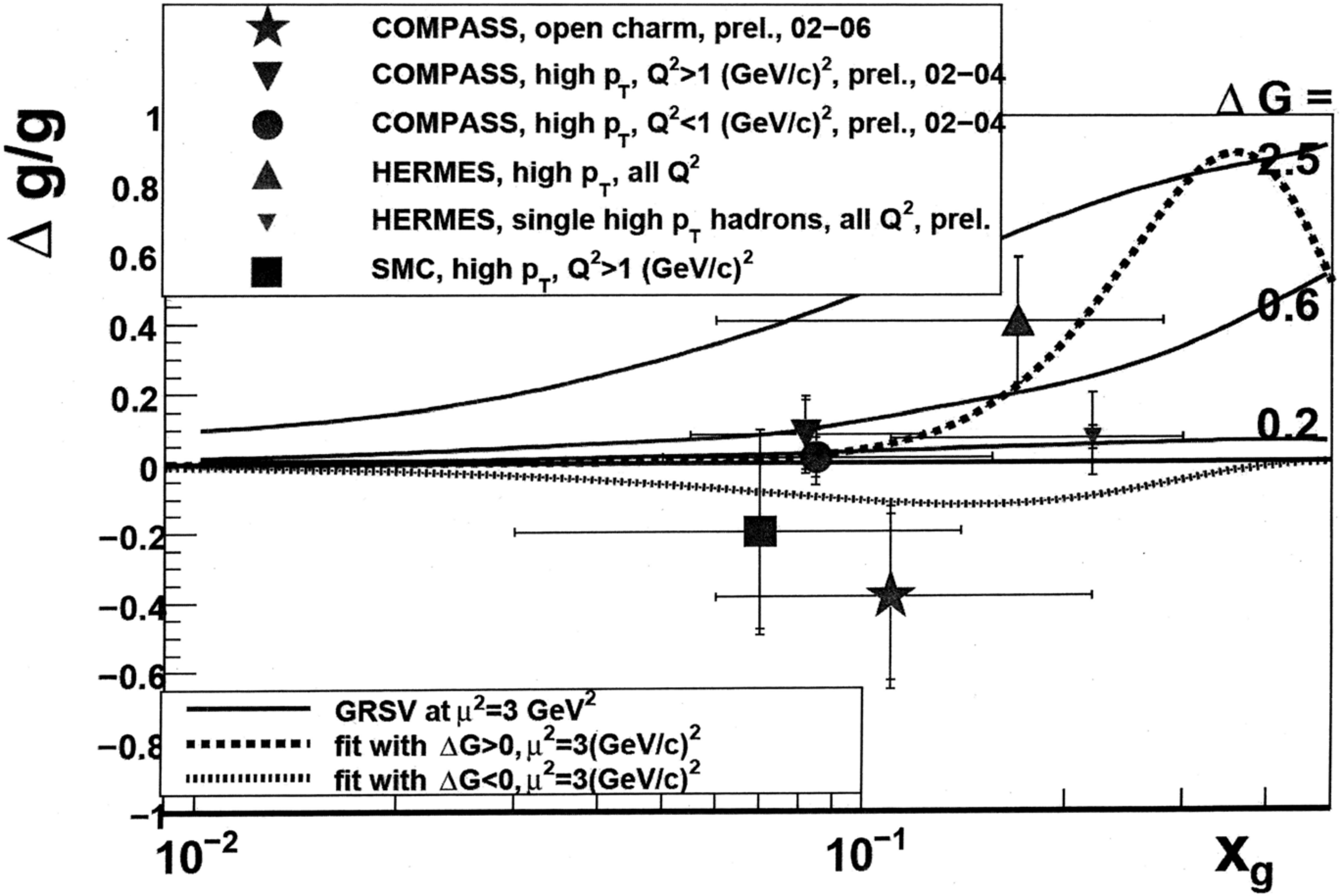
DNS: De Florian, Navarro, Sassot, Phys. Rev. D71, 2005





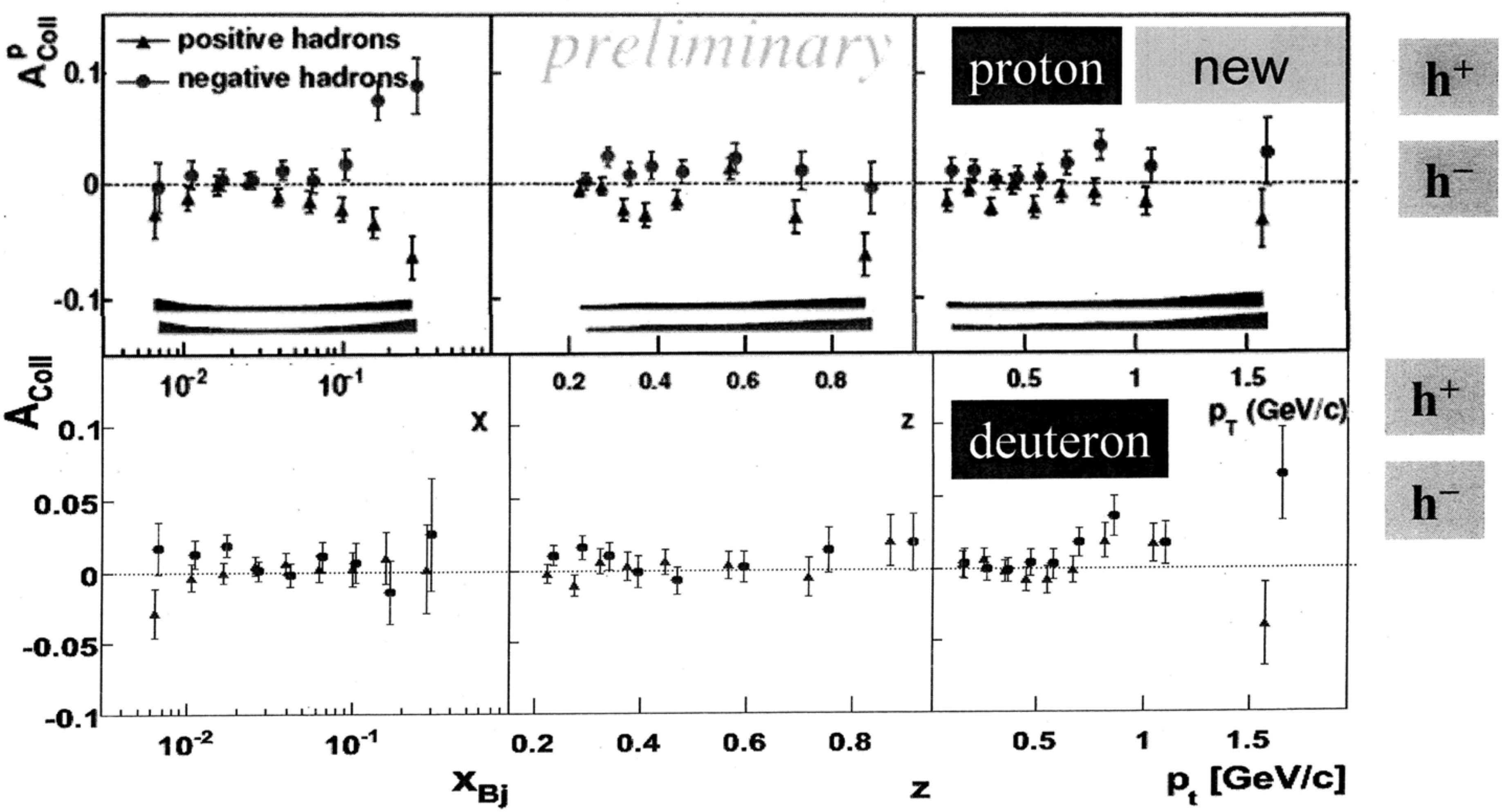
Δs Integral: $\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$

Results on direct measurements of Δg/g



Collins Asymmetries

New: full 2007 proton data set (statistics tripled)



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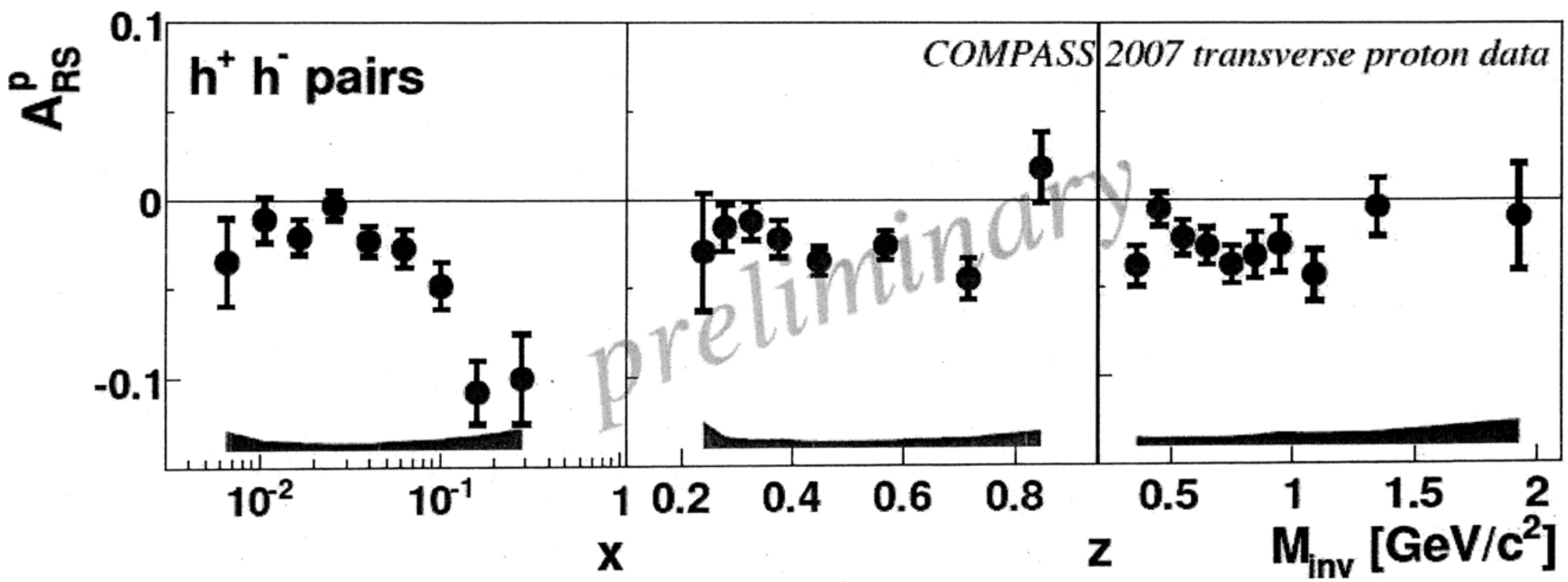
Two-hadron asymmetry



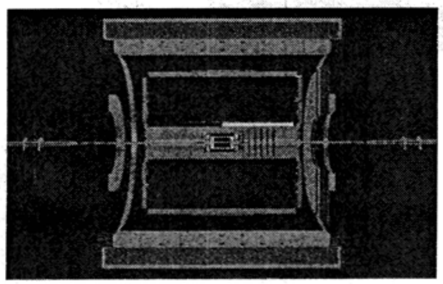
- large asymmetries
- interference FF and transversity sizable

The STAR W Physics Program - Status and Future Plans -

Bernd Surrow

Massachusetts Institute of Technology

(On behalf of the STAR Collaboration)



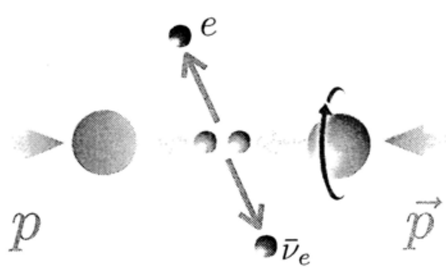
Outline

- Run 9 Lessons and Expectations: STAR W Results

- The STAR Forward GEM Tracker
  - Layout
  - Technical realization
  - Schedule

- Introduction

- Future Plans - STAR W Program
  - Plans
  - Projections of future mid-rapidity measurements
  - Projections of future forward/ backward rapidity measurements



- Summary and Outlook

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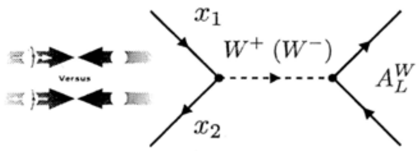
Introduction

- STAR W program in e-decay mode at mid-rapidity and forward/backward rapidity

$u\,/\Delta u\;(d\,/\Delta d)$



$\Delta\bar{d}\,/\bar{d}\;(\Delta\bar{u}\,/\bar{u})$

$\nu_e\;(\bar{\nu}_e)$

$e^+\;(e^-)$

$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)}$$

$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

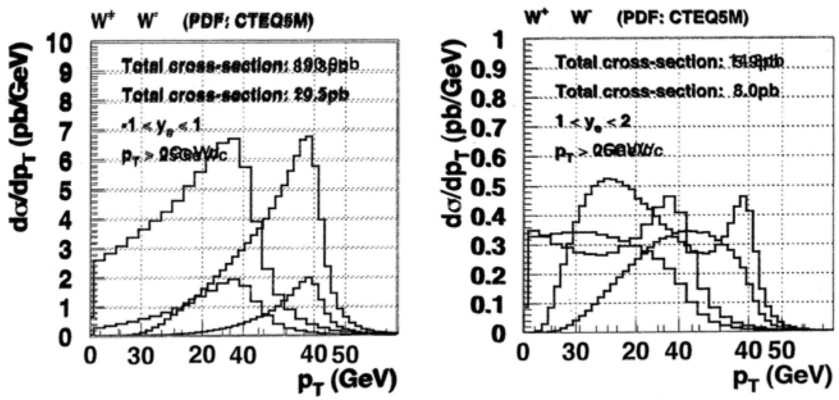
$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^-: Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination

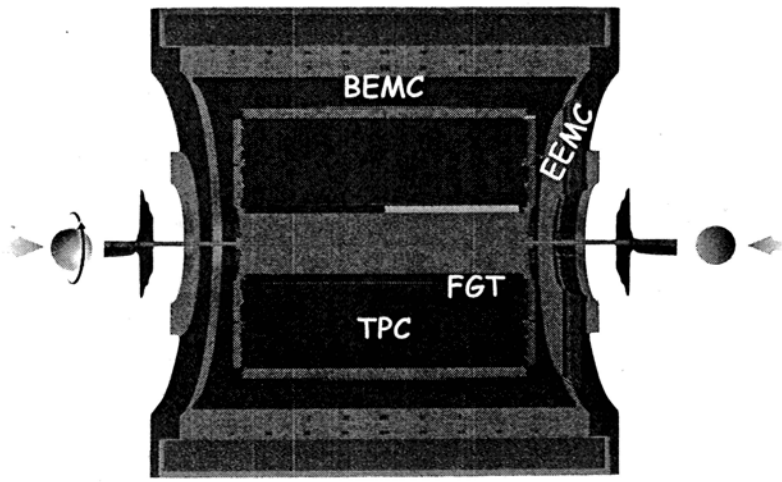


Total ($\sqrt{s}$=500GeV) $\sigma(W^+)$=135pb and $\sigma(W^-)$=42pb

Introduction

- STAR Overview
  - Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
  - TPC: Tracking and particle ID
  - ZDC: Relative luminosity and local polarimetry (500GeV)
  - BBC: Relative luminosity and Minimum bias trigger

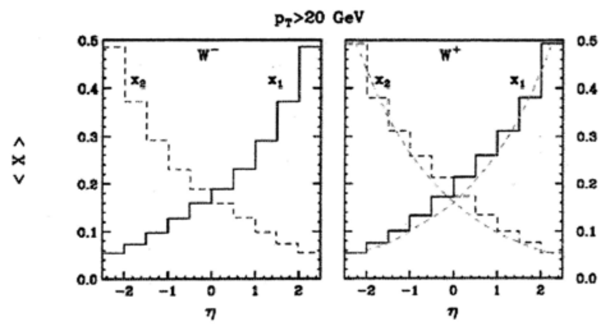
First collisions of polarized proton beams at STAR at $\sqrt{s}$ = 500GeV: Run 9 (P~40% / L~14pb^{-1})



- STAR Mid-rapidity W program ($|\eta|<1$): BEMC and TPC
- STAR Forward/Backward W program ($1<|\eta|<2$): EEMC and TPC / FGT (Installation in summer 2011)

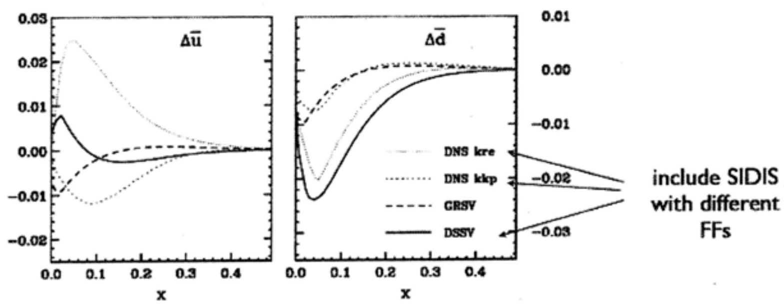
Introduction

- W boson kinematics relevant for STAR rapidity acceptance
  - Leptonic rapidity inherits relation to mean x
  - Forward rapidity:
    - $\eta > 0$
    - $\langle x_1 \rangle$ larger than $\langle x_2 \rangle$
  - Backward rapidity:
    - $\eta < 0$
    - $\langle x_1 \rangle$ less than $\langle x_2 \rangle$
  - Mid-rapidity:
    - $\eta \sim 0$
    - $\langle x_1 \rangle$ similar to $\langle x_2 \rangle$



$$< X_{1,2} > \simeq \frac{M_W}{\sqrt{S}} e^{[\mp\eta/2]}$$

D. de Florian, LBL,
RHIC Spin Workshop,
November 2009



Summary

- STAR W program
  - First Run 9 STAR W result (Cross-section and A_L for W^+/W^- at mid-rapidity) important milestone!
  - Mid-rapidity:
    - Charge sign discrimination: Demonstrated at high-p_T (~50GeV/c)
    - Signal (S) / Background (B): S/B = 6 for W^- and S/B = 11 for W^+ (Integrated for E_T>25GeV)
  - Forward rapidity: Complete FGT construction in ~fall 2010 followed by full system test and subsequent full installation in ~summer 2011

    ⇒ Ready for anticipated long 500GeV polarized pp run in FY12 (Run 12)
  - Critical: Design polarization performance of 70% with ~5% absolute polarization uncertainty (⇒ Required by eRHIC program!) to collect at least 300pb^{-1}!
  - Future measurements of A_L at STAR at mid-rapidity and forward rapidity (Wide rapidity coverage!) are expected to play an important role in our understanding of the polarized QCD sea!

Heavy Quark Correlations in Polarized pp Collisions

Marco Stratmann

Regensburg / Wűrzburg

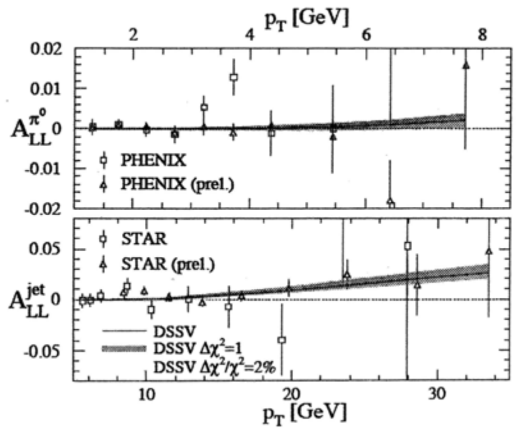
We present a comprehensive phenomenological study of heavy flavor distributions and correlations in longitudinally polarized proton-proton collisions at BNL-RHIC.
All results are obtained with a flexible parton-level Monte Carlo program at NLO accuracy and include the fragmentation into heavy mesons, their subsequent semileptonic decays, and experimental cuts. Next-to-leading order QCD corrections are found to be significant for both cross sections and double-spin asymmetries.
The sensitivity of heavy flavor measurements at BNL-RHIC to the gluon polarization of the nucleon is assessed. Electron-muon and muon-muon correlations turn out to be the most promising observables.
Theoretical uncertainties are estimated by varying renormalization and factorization scales, heavy quark masses, and fragmentation parameters.

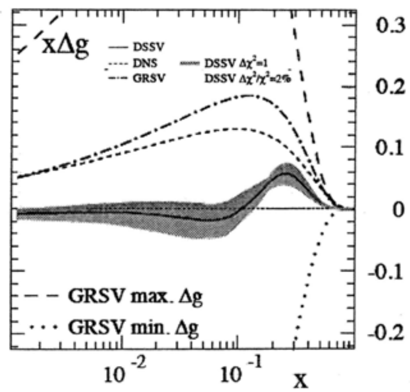
I. Bojak, MS, Phys. Rev. D67 (2003) 034010

J. Riedl, A. Schafer, MS, Phys. Rev. D80 (2009) 114020

Why A_{LL} for heavy quarks?

- present knowledge of Δg based on ***single*** class of processes: hadrons & jets





- rare probes (prompt photons, HQs) can be never as significant as jets

but
- ✓ different hard scattering dynamics than jets and hadrons
- ✓ much smaller number of subprocesses

crucial in understanding spin-dep. QCD hard scattering
test universality and factorization

technical aspects in a nutshell

previous calculation: I. Bojak, MS, Phys. Rev. D67 (2003) 034010

phase space calculations done largely analytically; phase space slicing method

→ fast numerical implementation but limited to single-inclusive HQ yields

new calculation: J. Riedl, A. Schafer, MS, Phys. Rev. D80 (2009) 114020

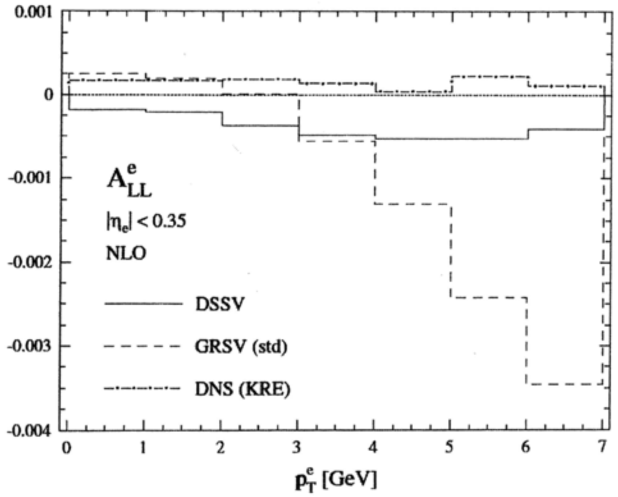
phase space calculations performed numerically; uses available matrix elements

subtraction method for singular regions (a la Mangano, Nason, Ridolfi, NPB373 (1992) 295)

→ no so fast numerical implementation but fully flexible:

- HQ correlations; HQ-jet correlations (not yet)
- experimental cuts
- HQ decays (so far: semi-leptonically)
- can be easily extended to cover HQ photoproduction at an EIC (soon!)

double-spin asymmetries: single-inclusive

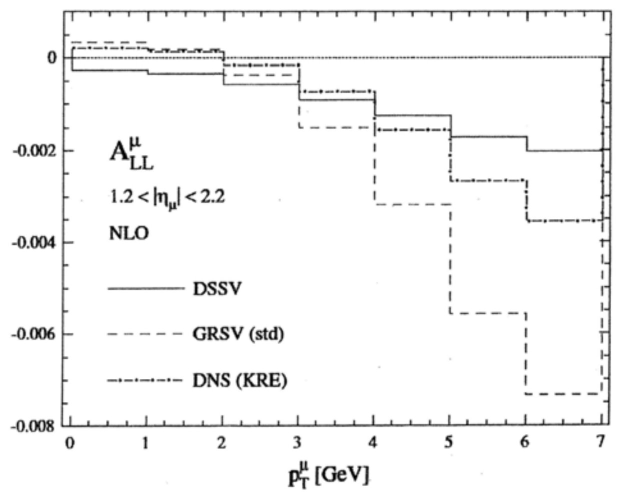


single electrons c,b → e

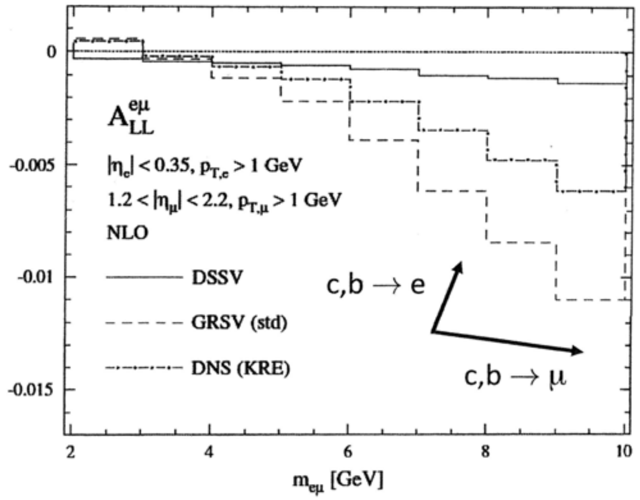
- in general, very small asymmetries
- interpretation of A_{LL} complicated
  (e.g. cancelations lead to $A_{LL} \approx 0$ for DNS)

single muons c,b → μ

- cancelations less pronounced than for electro…
- better correlation between A_{LL} and Δg
- larger spin asymmetries than for electrons



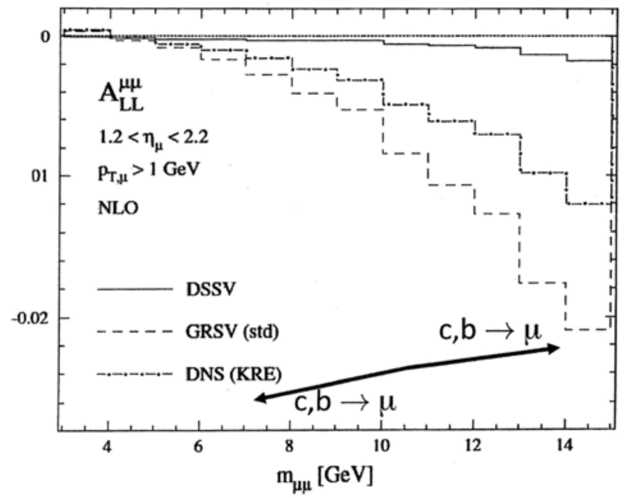
double-spin asymmetries: correlations



forward-central e-μ coincidences

- best suited heavy flavor observables to explore nucleon spin structure
- clear correlation between A_{LL} and Δg

forward-backward μ-μ coincidences



luminosities of a **few hundred** pb^{-1} are required for meaningful measurements at $m_{e\mu,\mu\mu}$ up to 10-15 GeV

NLO corrections to A_{LL}

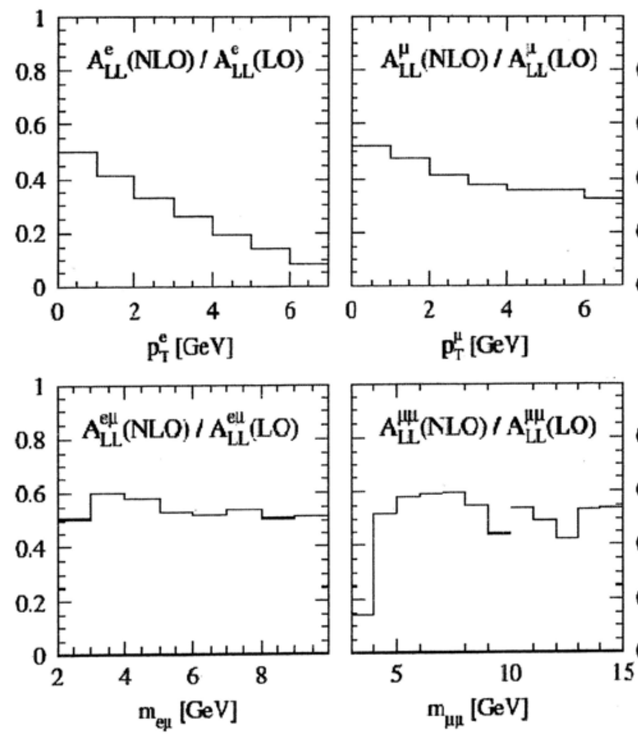
indeed ...

single electrons — c,b → e

single muons — c,b → μ

forward-central e-μ coincidences — c,b → e, c,b → μ

forward-backward μ-μ coincidences — c,b → μ, c,b → μ



- correlations more stable w.r.t. NLO corrections; ≈ constant w.r.t. inv. mass

Status of the Gluon Spin Program at STAR

Scott Wissink, Indiana University

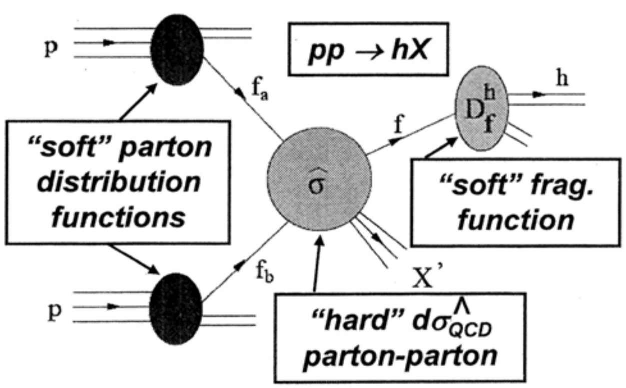
for the STAR Collaboration

Abstract

After a brief review of why ΔG is an interesting and important quantity to determine, I present a survey of STAR's inclusive pion and jet spin asymmetries, and describe how these have helped constrain models of gluonic contributions to the proton's spin. The need for new correlation studies, such as di-jet and photon-jet efforts, is discussed, along with realistic projections for what STAR will measure for these processes in the next few years at $\sqrt{s}$ = 200 and 500 GeV.

STAR

The Spin Puzzle: What RHIC brings to the table

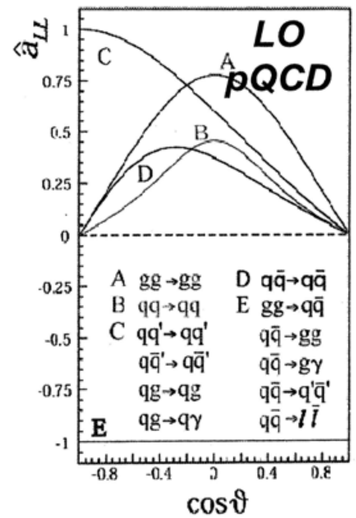


Provides pQCD probes of spin-dependent partonic structure!

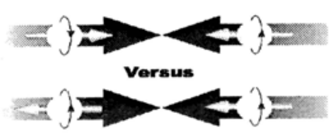
Assumes factorization works

\+

large spin correlations at partonic level



All the pieces are in place to ask:
Does the gluon spin contribute <u>significantly</u> to that of the proton?

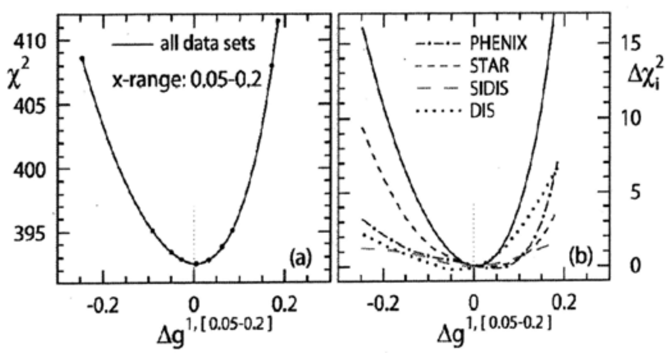


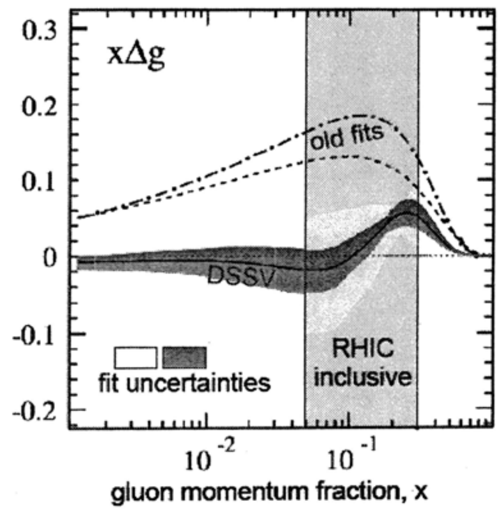
65

STAR Inclusive jets: Impact on (first) global analysis

Represents the *first global NLO analysis* to include **inclusive DIS, SIDIS, and RHIC pp data** on an equal footing.

- Strong constraint on the magnitude of Δg over kinematic range 0.05 < *x* < 0.2 probed by *STAR* at √*s* = 200 GeV
- Data favor a **small Δg** in this window





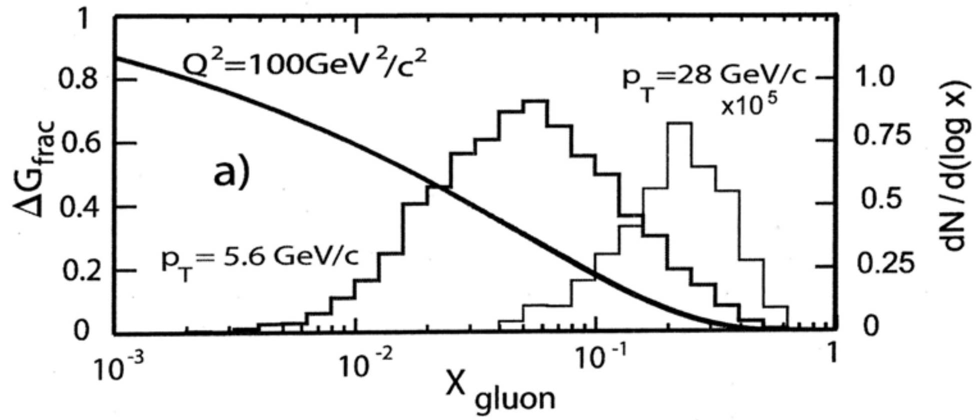
→ Best fit solution finds a node in the gluon distribution near *x* ~ 0.1 but with the *opposite phase* from that found in GS-C

Mapping out Δg(x): the need for correlations

Despite great advances made via study of inclusive processes:

- **Measurements average over a broad range in x_g at a given p_T**
- **Provide minimal information on partonic subprocess involved**

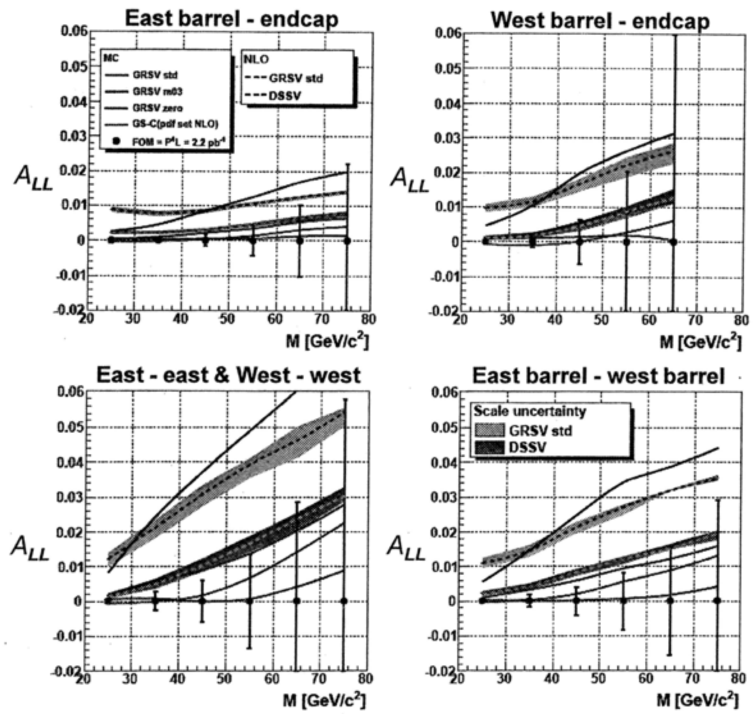
→ Could 'hide' non-trivial behavior of Δg(*x*), esp. if a node exists!



→ Need correlation measurements to help constrain the shape of Δg(x)

STAR

Di-jets in Run 9, 200 GeV: Expected sensitivity to Δg



To leading order, di-jets provide direct access to initial-state parton kinematics (x_1, x_2)

By detecting di-jets in different regions (η,ϕ) of the *STAR* detector, we

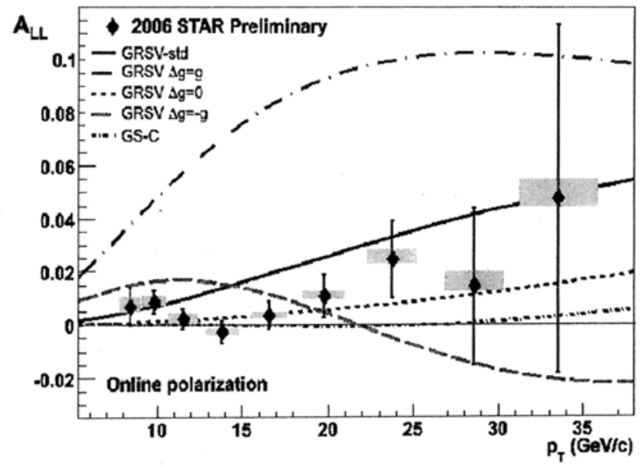
- **sample different mixtures of *qq, qg, gg***
- **sample different ranges of x_g**

→ *Provides much tighter constraints on theoretical models*

Errors shown are statistical only!

Summary and Outlook

- *STAR* has developed a broad and diverse program for studying ΔG
  → Complementary measurements support small gluon polarization over the range $0.05 < x_g < 0.2$
- Over next 2-3 years expect greater precision in inclusive channels at 200 GeV, plus new results at 500 ...
- ... and increased focus on di-jet and γ-jet correlations to more fully map out gluon helicity distribution



→ ***Must view ΔG studies as <u>one component</u> of broader program to understand <u>all aspects</u> of parton spin behavior in the nucleon!***

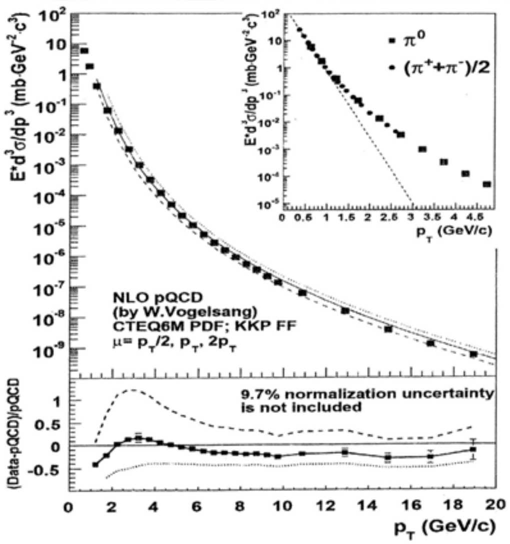
Name: Swadhin Taneja
Affiliation: SUNY Stony Brook
For the PHENIX collaboration

Title: Gluon polarization: status and plans for measurements at PHENIX

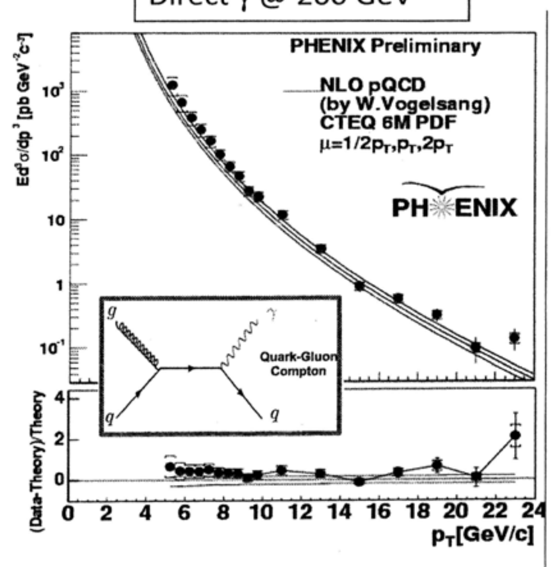
Ever since the discovery, by the EMC experiment, that quarks contribute only ~ 25 % to the proton spin the gluon spin (Δ{G}) contribution has become the most sought after number in spin physics. The PHENIX spin program with the longitudinally polarized proton proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been a center of focus for new results in Δ{G}. We will review recent results from π^0, $\pi^{\pm}$ and direct photons final states measured by PHENIX detector.

Cross section results from PHENIX

π^0 @ 200 GeV (PRD76, 051106)



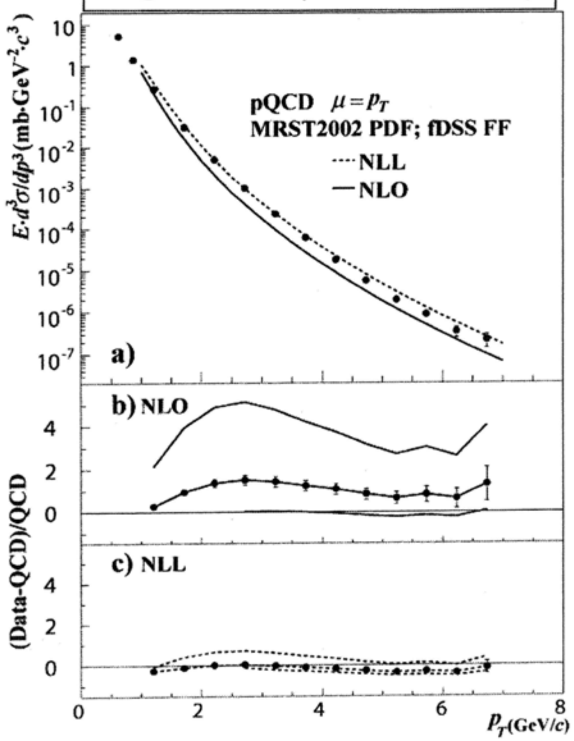
Direct γ @ 200 GeV



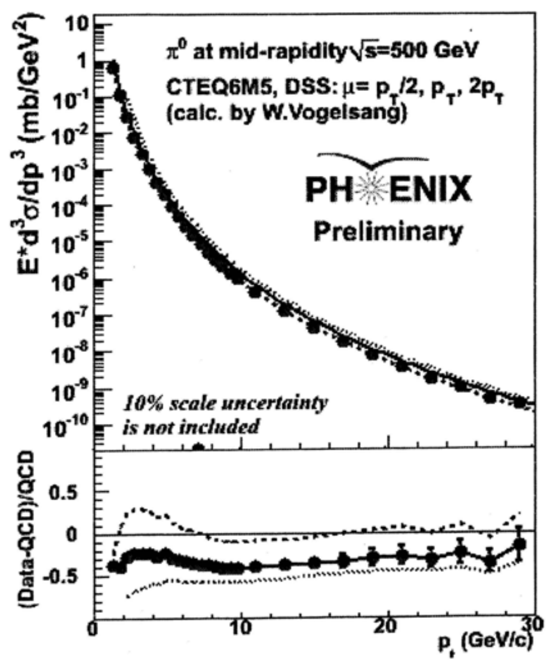
- NLO pQCD shows agreement with the cross section data
- Ready for the extraction of ΔG using NLO A_{LL} predictions

Cross section results from PHENIX

π^0 @ 62.4 GeV(PRD79, 012003)

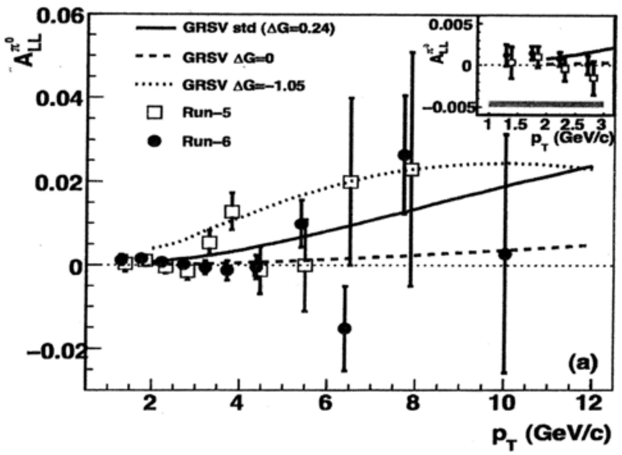


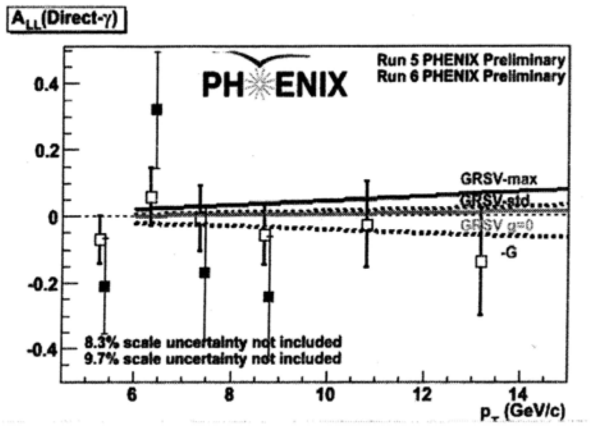
π^0 @ 500 GeV (2009)



π^0 and γ asymmetry results from PHENIX

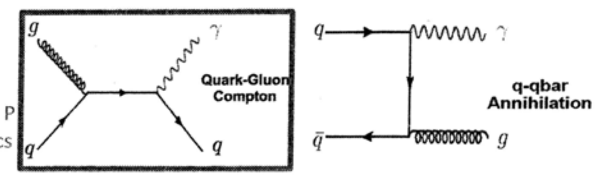
- ❑ π^0 A_{LL} at 200 GeV
  - high statistics measurement
  - 2005: PRD76, 051106
  - 2006: PRL 103, 012003 (2009)





- ❑ Direct photon A_{LL} at 200 GeV
  - quark gluon scattering dominates
  - clean channel, isolation cut, linear in ΔG
  - higher statistics needed

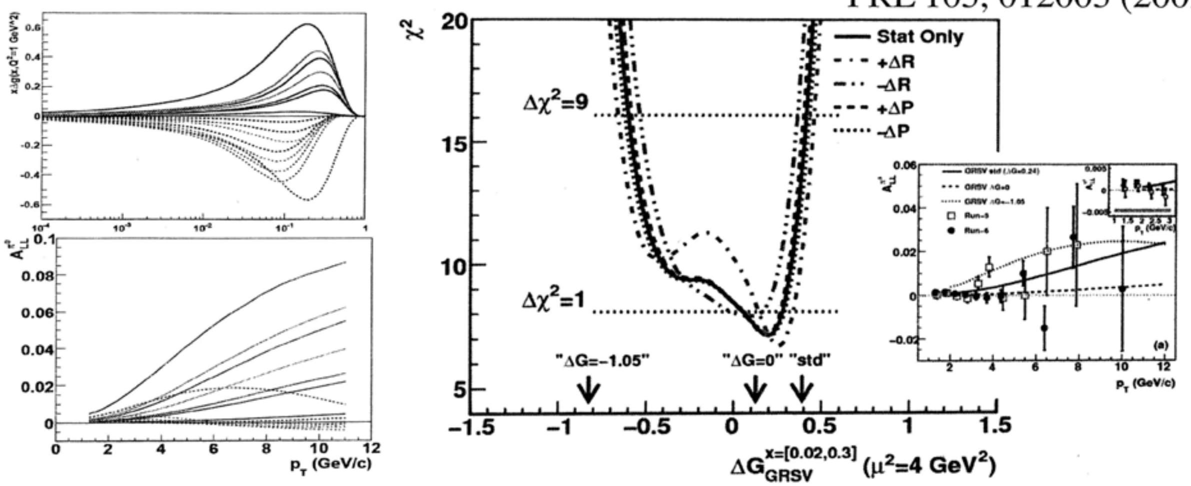
eja P
ysics



Constraining ΔG (using run5,6 π^0 data)

- Vary ΔG in GRSV fit, generate A_{LL} , calculate χ^2 for each expectation curve, plot profile.

PRL 103, 012003 (2009)



- χ^2 profile is asymmetric so $\Delta\chi^2$ =1 and 9 (1σ and 3σ) are significant

From just the statistical uncertainty :

$$\Delta G_{\rm GRSV}^{[0.02,0.3]} = 0.2 \pm 0.1 \ (1\sigma) \text{ and } 0.2^{+0.2}_{-0.8} \ (3\sigma)$$

Summary & Outlook

- PHENIX π^0 data offers strong constraint on ΔG as found by DSSV.
- Other probes (π+/- , η, γ) also can constrain ΔG, and will be used in future global fits.
- 200 GeV data from Run9 and future runs will further significantly constrain ΔG.
- ΔG at lower x range ($x<0.02$) is presently being explored with $\sqrt{s}$ = 500 GeV at RHIC (2009 polarized pp run).
  - Future measurement at 500 GeV will help constrain ΔG given > 50%
- It is much too early to claim that $\Delta G=0$, as uncertainty in range $0<x<1$ is large

SSAs in hadron-hadron collisions and TMDs

M. Anselmino
Torino University & INFN

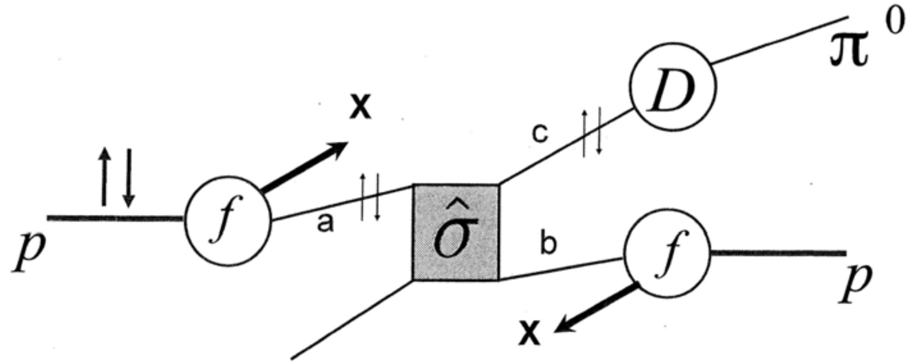
based on work with M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin

A presentation and a discussion of a TMD-factorized scheme for inclusive hadronic processes with one large scale only, pp ---> hX, is made. The role of Sivers and Collins mechanisms in understanding the observed transverse single spin asymmetries A_N (SSAs) is discussed. Predictions for SSAs in Drell-Yan processes are presented.

SSA in hadronic processes: TMDs, higher-twist correlations?

Two main different (?) approaches

1. Generalization of collinear scheme (assuming factorization)



$$d\sigma^\uparrow = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z, \boldsymbol{p}_{\perp\pi})}$$

single spin effects in TMDs

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, ...
(first proposed by Field-Feynman in unpolarized case)

Phenomenology - TMD factorization

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

main contribution from Sivers and Collins effects

$$d\sigma^\uparrow - d\sigma^\downarrow \equiv \frac{E_\pi \, d\sigma^{\,p\to\pi\,X}}{d^3\boldsymbol{p}_\pi} - \frac{E_\pi \, d\sigma^{\,p\to\pi\,X}}{d^3\boldsymbol{p}_\pi} = [d\sigma^\uparrow - d\sigma^\downarrow]_{\text{Sivers}} + [d\sigma^\uparrow - d\sigma^\downarrow]_{\text{Collins}}$$

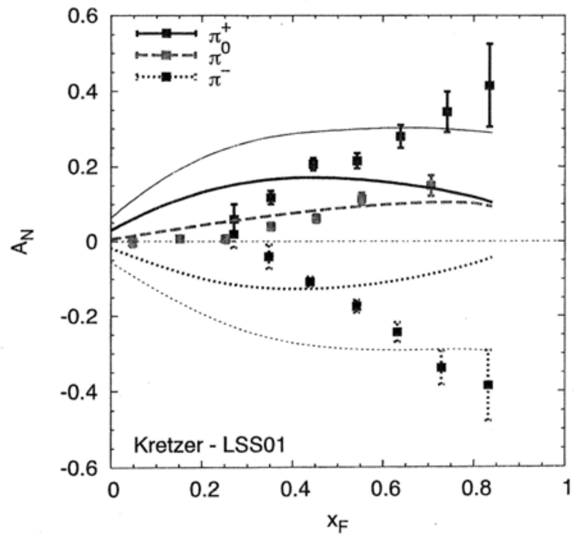
$$\begin{aligned}[d\sigma^\uparrow - d\sigma^\downarrow]_{\text{Sivers}} \;&= \sum_{q_a,b,q_c,d} \int \frac{dx_a\, dx_b\, dz}{16\,\pi^2\, x_a\, x_b\, z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u}) \\ &\times \Delta^N f_{a/}(x_a, k_{\perp a}) \cos\phi_a \\ &\times f_{b/p}(x_b, k_{\perp b})\, \frac{1}{2} \left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 + |\hat{M}_3^0|^2\right]_{ab\to cd} D_{\pi/c}(z, p_\perp)\end{aligned}$$

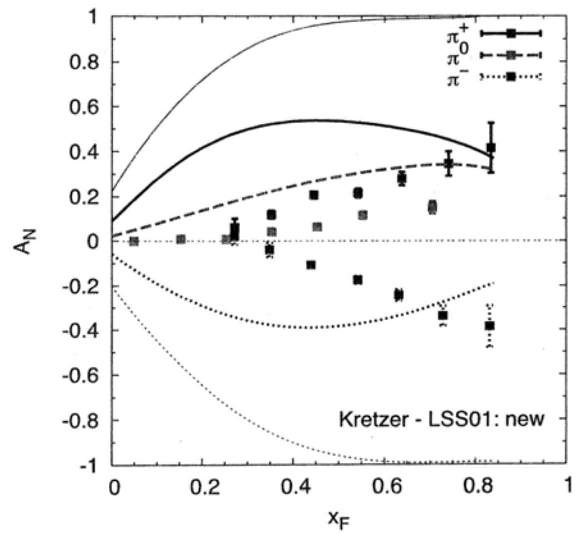
$\longrightarrow$ Sivers phase

$$\begin{aligned}[d\sigma^\uparrow - d\sigma^\downarrow]_{\text{Collins}} \;&= \sum_{q_a,b,q_c,d} \int \frac{dx_a\, dx_b\, dz}{16\,\pi^2\, x_a\, x_b\, z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u}) \\ &\times \Delta_T q_a(x_a, k_{\perp a}) \cos(\phi_a + \varphi_1 - \varphi_2 + \phi_\pi^H) \\ &\times f_{b/p}(x_b, k_{\perp b}) \left[\hat{M}_1^0\, \hat{M}_2^0\right]_{q_a b\to q_c d} \Delta^N D_{\pi/q_c}(z, p_\perp)\end{aligned}$$

$\longrightarrow$ Collins + scattering phases

negligible contributions from other TMDs





maximum possible contribution of Collins effect

(thin lines = all phases to zero)

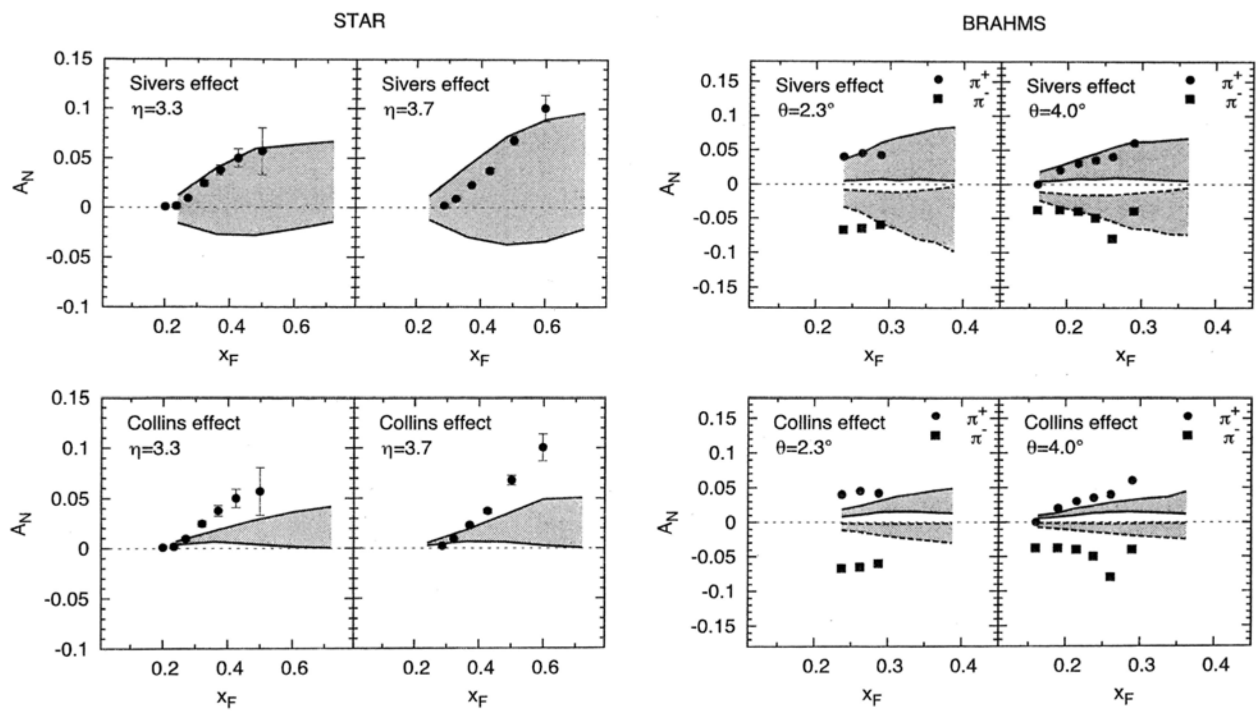
there was a mistake in previous evaluation (wrong sign in one spin transfer cross-section)

PRD 71:014002,2005

in principle, Collins effect might be large (depending on Collins function and transversity)

in preparation

contributions to A_N of SIDIS extracted Sivers, Collins and transversity distributions

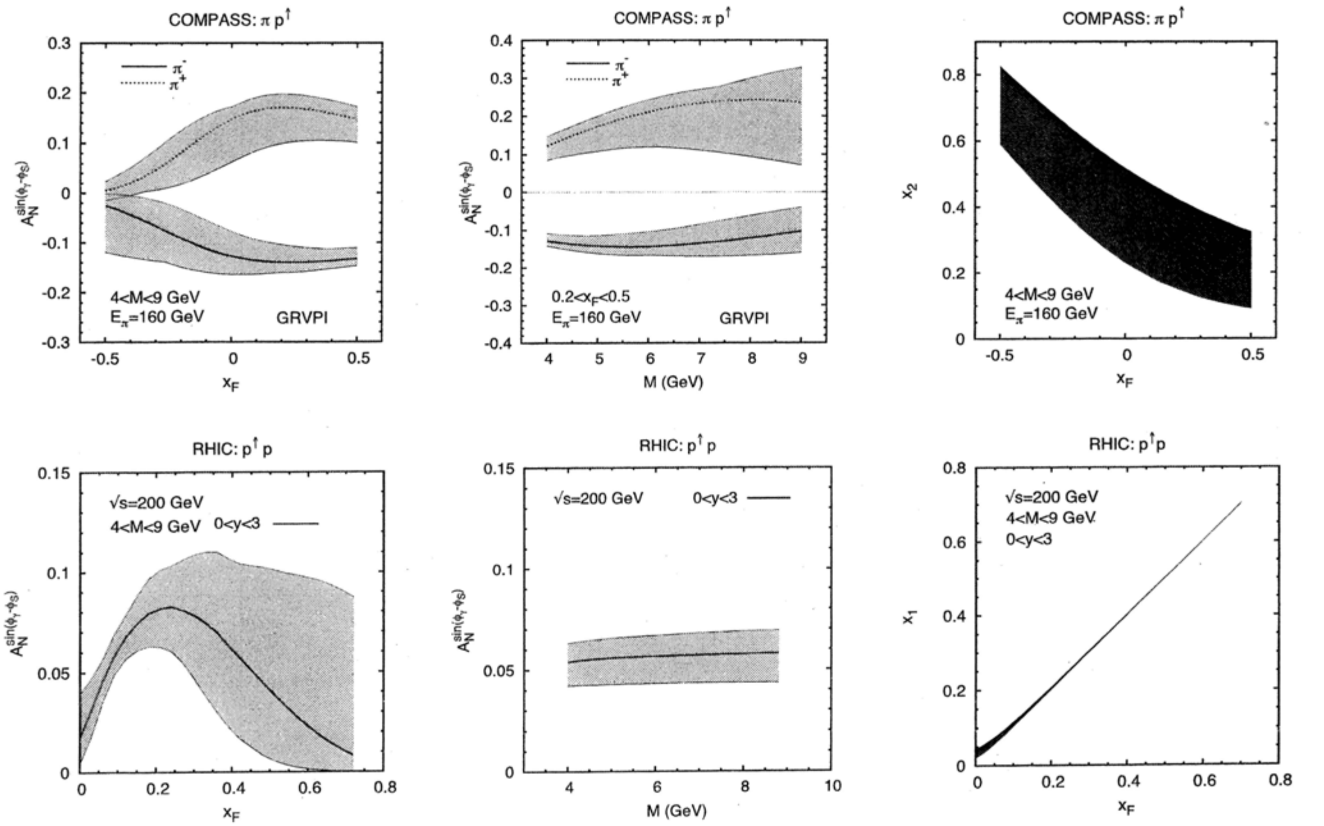


a combination of Sivers and Collins effect might explain data

(great uncertainty in actual knowledge of Sivers functions at large x)

Predictions for A_N in D-Y processes

Sivers functions as extracted from SIDIS data, **with opposite sign**



M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, e-Print: arXiv:0901.3078

Transverse Spin Measurements at PHENIX

PHENIX strategy:

Measure several observables each sensitive to different transverse spin effects

(i) Forward SSA → Sivers & Collins

Neutral Pions & Charged hadrons

(ii) Transversity-type Asymmetries

Interference Frag. Func. Analysis

(iii) Sivers-type Asymmetries

Heavy Flavor

Back to Back Hadrons

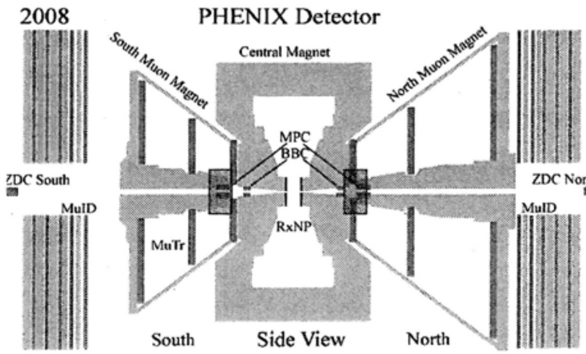
A_N for y~0

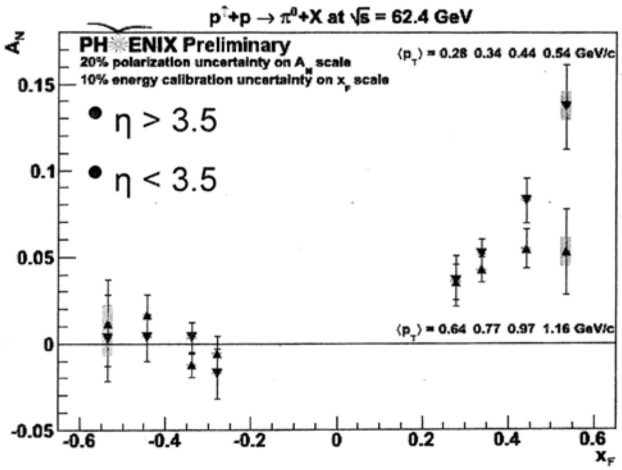
John Koster
for the PHENIX collaboration
University of Illinois at Urbana-Champaign

Progress in High-p_T Physics at RHIC
RBRC Workshop
2010/03/18

(i) Forward SSA A_N π^0 in MPC at $\sqrt{s}$=62 GeV

PHENIX

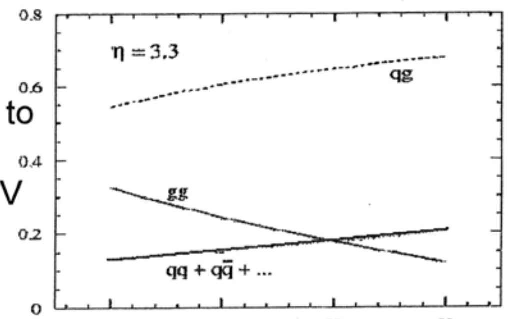




PHENIX π^0 results available for $\sqrt{s}$=62 GeV

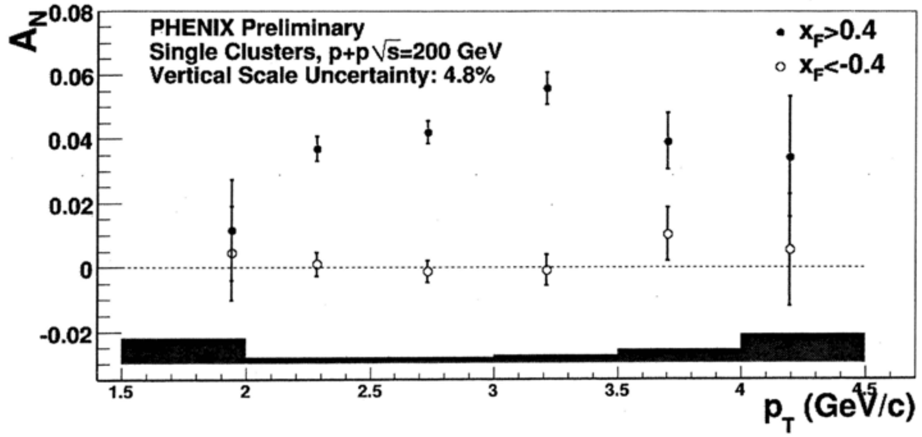
- Production dominated by quark-gluon
- Similar x_F scaling to higher and lower center of masses
- Asymmetries could enter a global analysis on transverse spin asymmetries

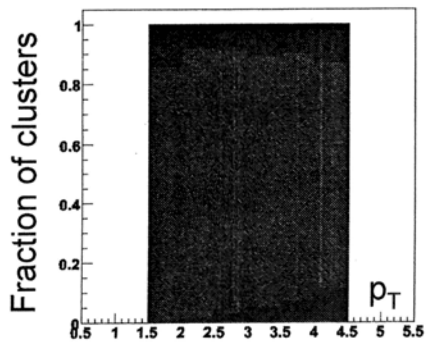
Process contribution to π^0, η=3.3, $\sqrt{s}$=200 GeV



PLB **603**,173 (2004)

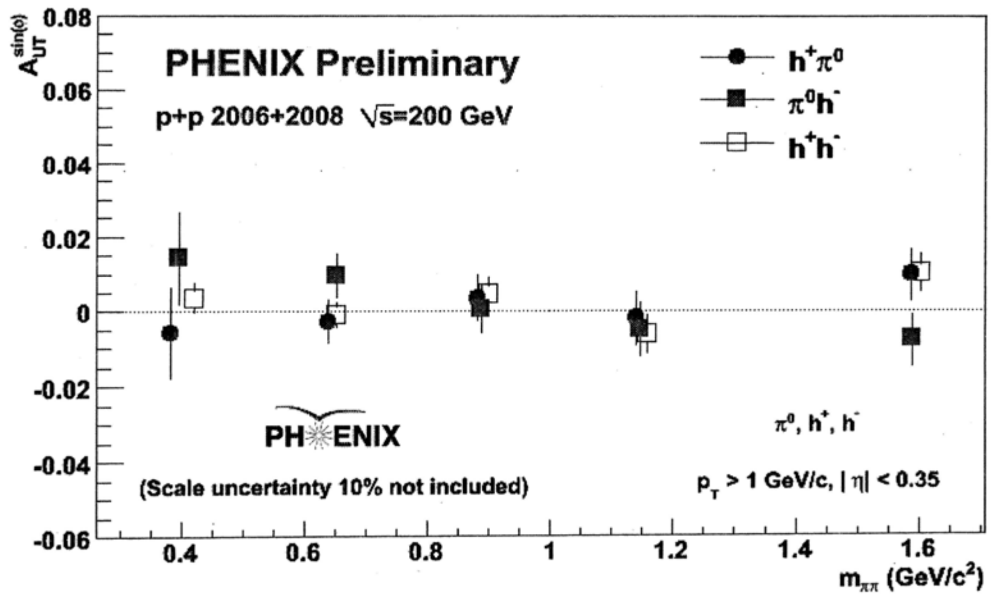
(i) Forward SSA A_N Cluster in MPC at $\sqrt{s}$=200 GeV





Decay photon
π^0
Direct photon

(ii) $A_{UT}^{\sin(\phi)}$ vs pair mass

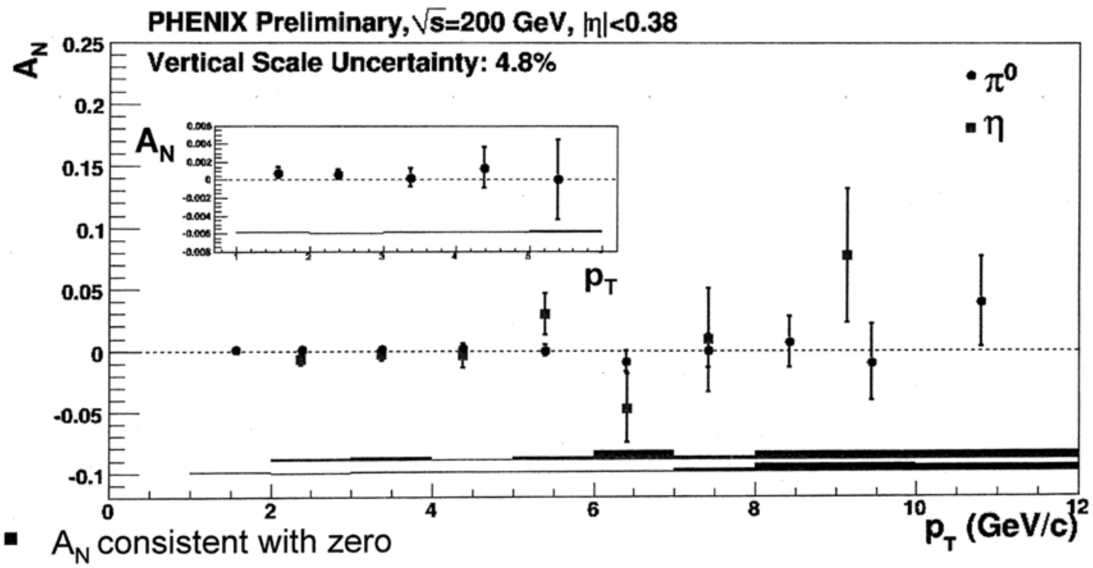


Added statistics from 2008 running

No significant asymmetries seen at mid-rapidity.

(iii) Mid-rapidity π^0 and η A_N

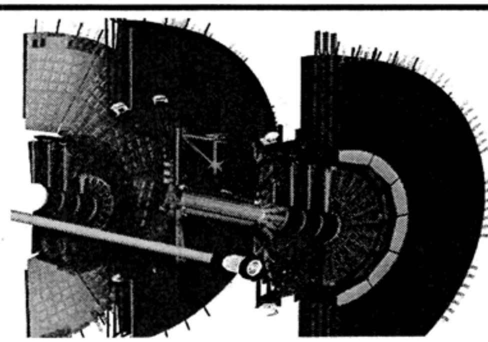
PHENIX



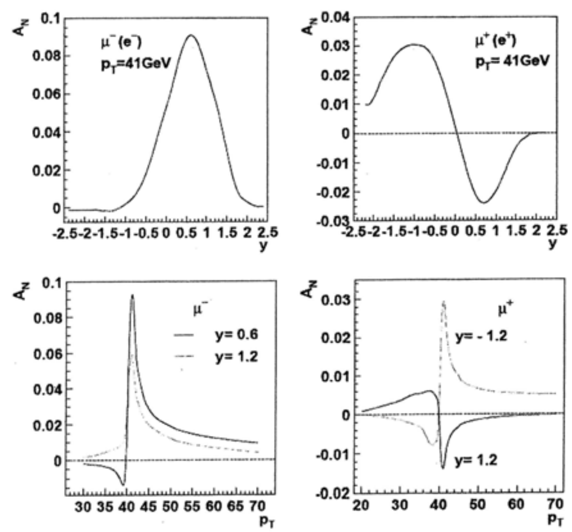
- A_N consistent with zero

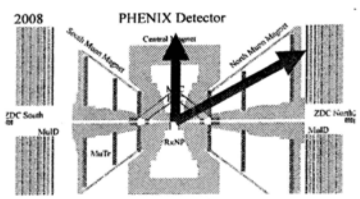
Outlook with Upgrades

PHENIX



- Vertex Detectors (2010 installation)
  Large acceptance precision tracking
  - Heavy flavor tagging
  - Electrons from charm decays and beauty decays separately
  - c,b-Jet Correlations
  - Expanded IFF analysis
- $W^{+/-}$ A_N
  Suggested in: **Phys.Rev.Lett.103:172001,2009**
  - Flavor sensitive quark Sivers measurement
  - **Instrumentation:**
    Ready : **Upgrade in progress**





Measurement of the Collins Asymmetry in Mid-Rapidity Jets at STAR

Robert Fersch
University of Kentucky
for the STAR Collaboration

SUMMARY OF PRESENTATION

First quantitative insights into transverse quark spin degrees of freedom in the proton have been obtained from Belle measurements of Collins fragmentation in e^+e^- collisions along with HERMES and COMPASS measurements of the Collins asymmetry in deep-inelastic lepton-nucleon scattering (see, for example, Anselmino et al. PRD 75:05032(2006) and Seidl et al. PRD 78:032011(2008)). Further constraints can be added from measurements of the azimuthal asymmetry of leading charged pions in jets produced by transversely polarized proton collisions. This asymmetry can be expressed as a convolution of the quark transversity, the Collins fragmentation function and a hard-scattering spin-transfer coefficient. We present a summary of the the first such asymmetry measurement from $\sqrt{s}$ =200 GeV transversely polarized (~58%) proton collision data (totalling ~1 pb^{-1}) collected at the Solenoidal Tracker at RHIC(STAR), with full azimuthal coverage at mid-rapidity ($|\eta| < 1$). Progress on this measurement and the statistical precision of analyzed data vs. hadron to jet momentum fraction *z* is shown. Future work is mainly concerned with determination of systematic errors.

Experimental access to δq

proton-proton scattering:

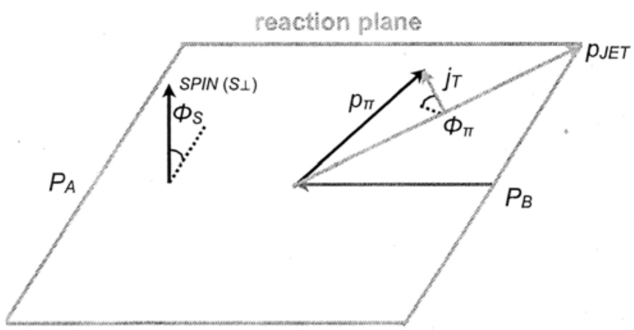
$$p(P_A, S_\perp) + p(P_B) \rightarrow jet(P_J) + X \rightarrow \pi^\pm + X$$

leading only (highest mom.)

one proton polarized

inclusive (all jets)

all other scattering products



Leading pions give us the most direct access to the quark initiating the event.

Collins Mechanism:

polarized quark → jet ⇒

spin-dependence in fragmentation of the polarized quark ⇒

Φ_π-dependence of pion production rate, relative to $S_\perp$±

Measured asymmetry

$z \equiv p_\pi / p_{JET}$

$$A(z, j_T) = \frac{\langle \sin(\Phi_\pi - \Phi_S) \rangle}{N}$$

=0 if distribution of pions within jet symmetric

total number of jets

How is δu, δd constrained by this asymmetry?

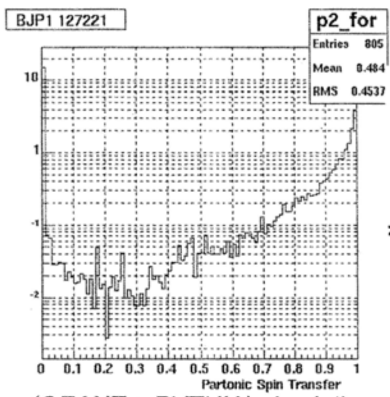
Measured asymmetry $A = \dfrac{\langle \sin(\Phi_\pi - \Phi_S) \rangle}{N}$

$$A \approx \left[\frac{\delta q(x)}{f_q(x)} \frac{\Delta^N D_q(z,j_T)}{D_q^h(z,j_T)} \frac{H^{\text{Collins}}_{qb\to qb}}{H_{qb\to cd}}\right]_{\text{favored } q} + \left[\frac{\delta q(x)}{f_q(x)} \frac{\Delta^N D_q(z,j_T)}{D_q^h(z,j_T)} \frac{H^{\text{Collins}}_{qb\to qb}}{H_{qb\to cd}}\right]_{\text{unfavored } q}$$

Spin transfer coefficient

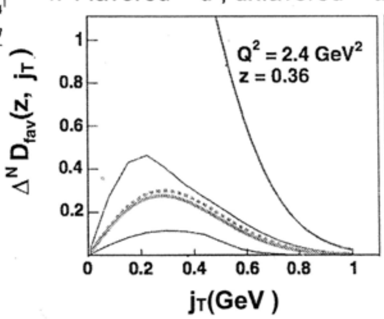
unpolarized quark distribution

Collins, Sivers *fragmentation functions*



(GEANT + PYTHIA) simulation

π^+: favored = *u* , unfavored = *d*
π^-: favored = *d* , unfavored = *u*

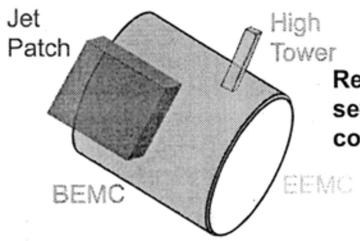


Extraction of Collins fragmentation function from fit to SIDIS data (HERMES, COMPASS) and Belle Collab. data (KEK) (Anselmino, *et al.*, 2008)

Isospin-favored Collins frag. function

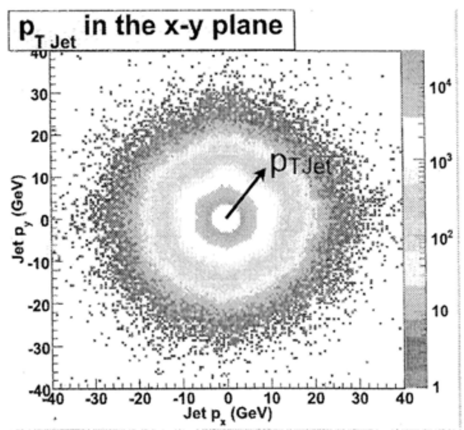
Prediction (estimate): $A \ (\pi^{\pm}) \approx \pm 0.03$

Jet reconstruction



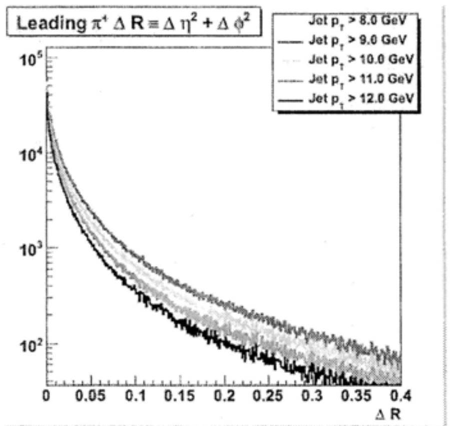
Jet Patch trigger:
Requires sum of 400 localized "patches" above a threshold as a cluster for soft fragmentation (total coverage $\Delta\Phi = \Delta\eta = 1$)

High Tower trigger:
Uses a single ADC channel as a jet "seed" and totals energy in surrounding trigger "patch"



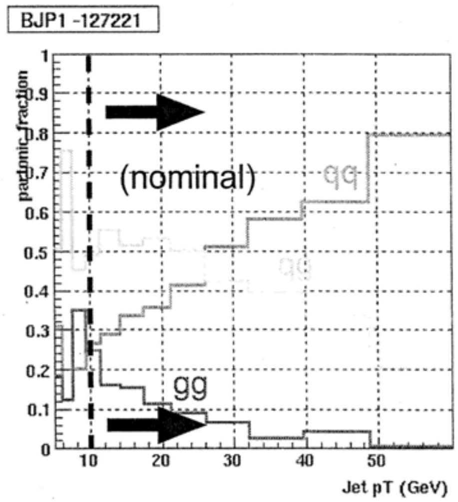
full azimuthal (Φ) coverage

Jet physics in terms of p_T



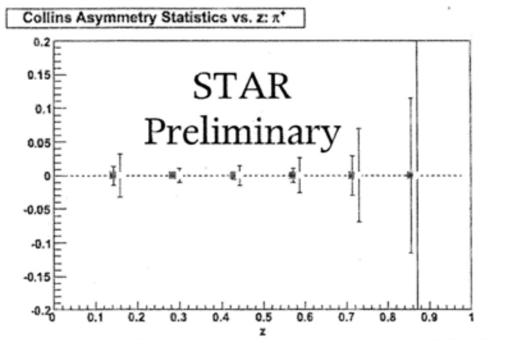
ΔR measures collimation of particles within jet

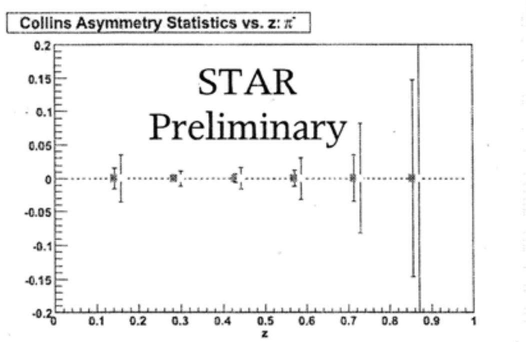
Lower p_T cut is a tradeoff between statistics and gluon event contamination:



STAR simulation (PYTHIA + GEANT) at $\sqrt{s}$ = 200 GeV

Asymmetry Statistics





"blue" beam polarized

"yellow" beam polarized

(jets in forward hemisphere of each beam analyzed)

Asymmetry should be opposite in sign for + vs. – pions

Simulation/theory (estimate): $A\ (\pi^{\pm}) \approx \pm 0.03$

Nontrivial Relations between GPDs and TMDs

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Abstract

Generalized parton distributions (GPDs) and transverse momentum dependent parton distributions (TMDs), respectively, are the key ingredients in the QCD description of hard exclusive and semi-inclusive processes (see page 1 for their definition for quarks). In [1, 2] for the first time a nontrivial relation between a GPD and a TMD was proposed — a connection between the GPD E^q and the transverse momentum dependent Sivers function $f_{1T}^{\perp q}$. A quantitative relation between these two distributions was later on obtained in a simple spectator model, where the impact parameter representation of E^q is involved [3] (see also page 2).

Comparing the GPD-correlator in impact parameter space with the TMD correlator leads to a complete list of potential nontrivial analogies/relations between GPDs and TMDs both for quarks and gluons [4, 5]. Those analogies can be grouped into 4 different types (see page 3). While the analogies of first type represent nothing but (trivial) general model-independent relations, the remaining ones are potential nontrivial relations. We have explored the nontrivial cases in the framework of two simple models to lowest nontrivial order in the coupling constants [5]: a diquark spectator model for the nucleon as well as the quark target model in perturbative QCD. The latter allows one, in particular, to study potential nontrivial relations on the gluon sector. It turns out that a whole host of explicit relations can be found in those models [5] (see also page 4). Moreover, recent work has shown that a nontrivial relation between E^q and $f_{1T}^{\perp q}$ can also be obtained in a spectator model when summing up a certain subclass of diagrams to all orders in perturbation theory [6].

To find out whether any of the nontrivial relations obtained in models can be promoted to a model-independent status we performed an analysis in terms of GTMDs (generalized transverse momentum dependent parton distributions) [7, 8] (see also page 5). We make use of the fact that GPDs and TMDs appear as certain limits of GTMDs (*mother functions*). This connection allows us to explore which GPDs and TMDs have the same *mother functions*. As a general outcome we find that none of the (model-dependent) nontrivial relations can have a model-independent status since the respective GPDs and TMDs are related to different GTMDs. On the other hand, it is currently not known to what extent the nontrivial relations are violated numerically.

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[6] L. Gamberg and M. Schlegel, Phys. Lett. B **685**, 95 (2010) [arXiv:0911.1964 [hep-ph]].

[7] S. Meissner, A. Metz, M. Schlegel and K. Goeke, JHEP **0808**, 038 (2008) [arXiv:0805.3165 [hep-ph]].

[8] S. Meissner, A. Metz and M. Schlegel, JHEP **0908**, 056 (2009) [arXiv:0906.5323 [hep-ph]].

Definition of GPDs and TMDs

- GPD-correlator

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ik\cdot z}\, \langle p';\lambda'|\, \bar{\psi}\Big(-\frac{z}{2}\Big)\, \gamma^+\, \mathcal{W}_{GPD}\, \psi\Big(\frac{z}{2}\Big)\, |p;\lambda\rangle\, \Big|_{z^+=z_T=0}$$

$$= \frac{1}{2P^+}\, \bar{u}(p',\lambda')\left(\gamma^+ H^q(x,\xi,t) + \frac{i\sigma^{+\mu}\Delta_\mu}{2M}\, E^q(x,\xi,t)\right) u(p,\lambda)$$

$$x = \frac{k^+}{P^+} \qquad \xi = -\frac{\Delta^+}{2P^+} \qquad t = \Delta^2$$

- TMD-correlator

$$\Phi^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, \frac{d^2\vec{z}_T}{(2\pi)^2}\, e^{ik\cdot z}\, \langle P;S|\, \bar{\psi}\Big(-\frac{z}{2}\Big)\, \gamma^+\, \mathcal{W}_{TMD}\, \psi\Big(\frac{z}{2}\Big)\, |P;S\rangle\, \Big|_{z^+=0}$$

$$= f_1^q(x,\vec{k}_T^2) - \frac{\epsilon_T^{ij} k_T^i S_T^j}{M}\, f_{1T}^{\perp q}(x,\vec{k}_T^2)$$

  - Sivers function $f_{1T}^{\perp}$ induces distortion of TMD correlator in k_T-plane
  - Effect of this distortion has (probably) been observed by HERMES

Impact parameter representation of GPDs

- Fourier transform of GPD-correlator ($\xi = 0$) (Burkardt, 2000)

$$\begin{aligned}\mathcal{F}^q(x, \vec{b}_T; S) &= \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2}\, e^{-i\vec{\Delta}_T\cdot\vec{b}_T}\, F^q(x, \vec{\Delta}_T; S) \\ &= \mathcal{H}^q(x, \vec{b}_T^2) + \frac{\epsilon_T^{ij} b_T^i S_T^j}{M} \left(\mathcal{E}^q(x, \vec{b}_T^2)\right)'\end{aligned}$$

- Distortion of GPD-correlator in impact parameter space

$$d^{q,i} = \int dx \int d^2\vec{b}_T\, b_T^i\, \mathcal{F}^q(x, \vec{b}_T; S) = -\frac{\epsilon_T^{ij} S_T^j}{2M} \int dx\, E^q(x, 0, 0) = -\frac{\epsilon_T^{ij} S_T^j}{2M} \kappa^q$$

$\longrightarrow$ (Large) flavor dipole moment of about $0.2\,\mathrm{fm}$

- Quantitative nontrivial GPD-TMD relation in spectator model (Burkardt, Hwang, 2003)

$$\begin{aligned}\big\langle k_T^{q,i}(x)\big\rangle_{UT} &= -\int d^2\vec{k}_T\, k_T^i\, \frac{\epsilon_T^{jk} k_T^j S_T^k}{M}\, f_{1T}^{\perp q}(x, \vec{k}_T^2) \\ &= \int d^2\vec{b}_T\, \mathcal{I}^{q,i}(x, \vec{b}_T)\, \frac{\epsilon_T^{jk} b_T^j S_T^k}{M.} \left(\mathcal{E}^q(x, \vec{b}_T^2)\right)'\end{aligned}$$

Overview of model-independent relations/analogies

- Relations of first type

$$f_1^{q/g} \leftrightarrow \mathcal{H}^{q/g} \qquad g_{1L}^{q/g} \leftrightarrow \tilde{\mathcal{H}}^{q/g}$$

$$\left(h_{1T}^q + \frac{\vec{k}_T^2}{2M^2}\, h_{1T}^{\perp q}\right) \leftrightarrow \left(\mathcal{H}_T^q - \frac{\vec{b}_T^2}{M^2}\,\Delta\tilde{\mathcal{H}}_T^q\right)$$

- Relations of second type

$$f_{1T}^{\perp q/g} \leftrightarrow -\left(\mathcal{E}^{q/g}\right)' \qquad h_1^{\perp q} \leftrightarrow -\left(\mathcal{E}_T^q + 2\tilde{\mathcal{H}}_T^q\right)'$$

$$\left(h_{1T}^g + \frac{\vec{k}_T^2}{2M^2}\, h_{1T}^{\perp g}\right) \leftrightarrow -2\left(\mathcal{H}_T^g - \frac{\vec{b}_T^2}{M^2}\,\Delta\tilde{\mathcal{H}}_T^g\right)'$$

- Relations of third type

$$h_{1T}^{\perp q} \leftrightarrow 2\left(\tilde{\mathcal{H}}_T^q\right)'' \qquad h_1^{\perp g} \leftrightarrow 2\left(\mathcal{E}_T^g + 2\tilde{\mathcal{H}}_T^g\right)''$$

- Relation of fourth type

$$h_{1T}^{\perp g} \leftrightarrow -4\left(\tilde{\mathcal{H}}_T^g\right)'''$$

Nontrivial relations in spectator models

- Moments of GPDs and TMDs

$$X^{(n)}(x) = \frac{1}{2M^2}\int d^2\vec{\Delta}_T \left(\frac{\vec{\Delta}_T^2}{2M^2}\right)^{n-1} X\left(x, 0, -\frac{\vec{\Delta}_T^2}{(1-x)^2}\right)$$

$$Y^{(n)}(x) = \int d^2\vec{k}_T \left(\frac{\vec{k}_T^2}{2M^2}\right)^{n} Y(x, \vec{k}_T^2)$$

- Relations of second type

$$f_{1T}^{\perp q\,(n)}(x) = H_2(n)\,\frac{1}{1-x}\,E^{q\,(n)}(x) \qquad (0 \le n \le 1)$$

  - $H_2(n)$ depends on model

- Relations of third type

$$h_{1T}^{\perp q\,(n)}(x) = H_3(n)\,\frac{1}{(1-x)^2}\,\tilde{H}_T^{q\,(n)}(x) \qquad (0 \le n \le 1)$$

  - $H_3(n)$ is the same in both used spectator models

Model-independent analysis in terms of GTMDs

- GTMD-correlator (e.g., Belitsky, Ji, Radyushkin, Yuan, 2003, 2005)

$$W^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\,\frac{d^2\vec{z}_T}{(2\pi)^2}\,e^{ik\cdot z}\,\langle p';\lambda'|\,\bar{\psi}\Big(-\frac{z}{2}\Big)\,\gamma^+\,\mathcal{W}_{GTMD}\,\psi\Big(\frac{z}{2}\Big)\,|p;\lambda\rangle\Big|_{z^+=0}$$

$\rightarrow W^q$ parameterized in terms of 4 complex-valued GTMDs $F_{1,n} = F^e_{1,n} + iF^o_{1,n}$

- Projection onto GPDs and TMDs

$$F^q = \int d^2\vec{k}_T\,W^q \qquad\qquad \Phi^q = W^q\Big|_{\Delta=0}$$

- Results and general conclusion
  - Relations between GTMDs and GPDs as well as TMDs worked out
  - Example

$$\begin{aligned} E(x,0,\vec{\Delta}_T^2) &= \int d^2\vec{k}_T\,\Big[-F^e_{1,1} + 2\Big(\frac{\vec{k}_T\cdot\vec{\Delta}_T}{\vec{\Delta}_T^2}\,F^e_{1,2} + F^e_{1,3}\Big)\Big] \\ f_{1T}^{\perp}(x,\vec{k}_T^2) &= -F^o_{1,2}(x,0,\vec{k}_T^2,0,0) \end{aligned}$$

  - E and $f_{1T}^{\perp}$ not related as they depend on different GTMDs
  - None of the nontrivial relations can have model-independent status

– Typeset by FoilTEX –

Recent Results and Future Prospects for Drell-Yan Experiments

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Summary

- We first review the unique features of the Drell-Yan process for probing the parton distributions of the nucleons and nucleus.
- Recent results from the Fermilab experiment E866 on the azimuthal angular distributions of Drell-Yan in p+p and p+d interactions are presented. The connection to the Transverse Momentum Distributions (TMD) is discussed.
- Recent results on the measurement of the Upsilon production in p+p and p+d are presented. Implication on the ratio of gluon distribution in the proton versus that in the neutron is emphasized..
- Future prospects of Drell-Yan experiments at various facilities are discussed. List of outstanding physics issues to be resolved in these future experiments is presented.

Physics results from Fermilab dimuon experiments

1) Drell - Yan process :

- Antiquarks in nuclei and nucleons
- Quark energy loss in nuclear medium
- Drell-Yan angular distributions

2) Quarkonium production :

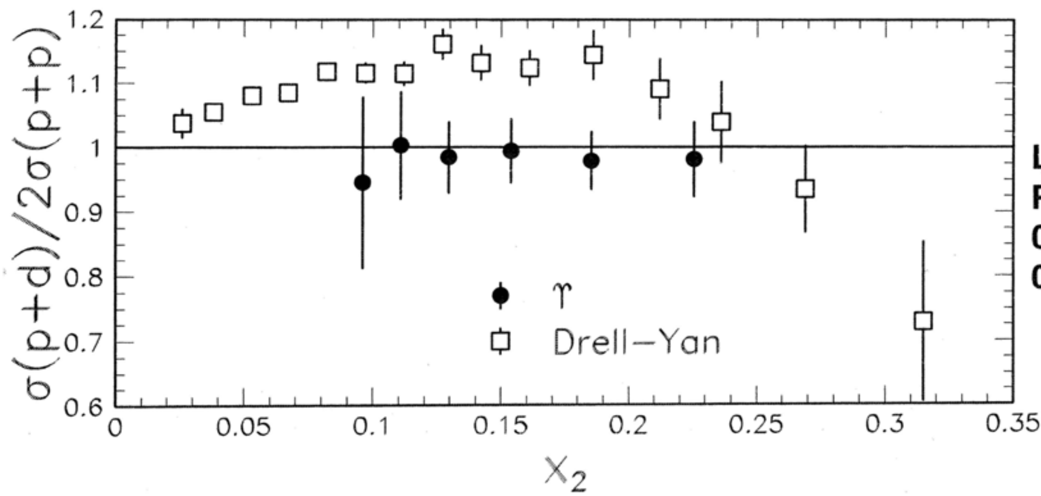
- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

3) Heavy quark production :

- Open charm production
- B-meson production

Gluon distributions in proton versus neutron?

E866 data: $\sigma(p+d \rightarrow \Upsilon X)/2\sigma(p+p \rightarrow \Upsilon X)$



Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

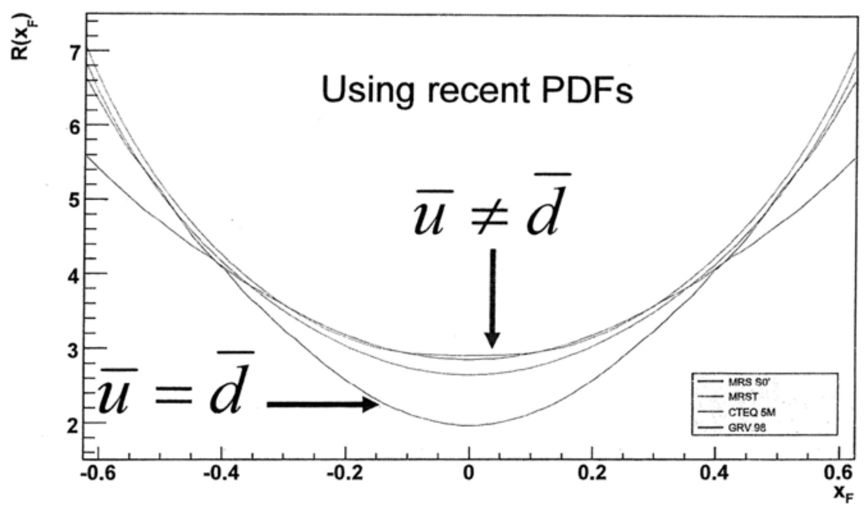
$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+\bar{d}(x)/\bar{u}(x)]/2$$

$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+g_n(x)/g_p(x)]/2$$

Gluon distributions in proton and neutron are very similar

$\bar{d}/\bar{u}$ from W production at RHIC

$$R(x_F) = \frac{d\sigma / dx_F(pp \to W^+ x)}{d\sigma / dx_F(pp \to W^- x)} \quad \text{at } \sqrt{s} = 500 \text{ GeV}$$



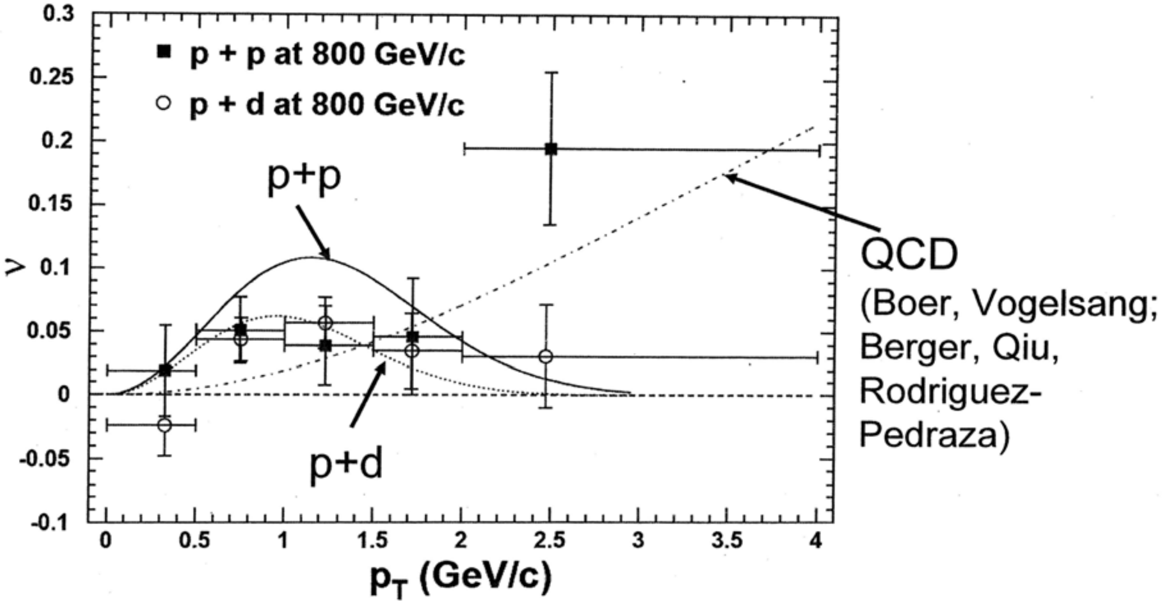
Yang, Peng, Perdekamp, Phys. Lett. B680, 231 (2009)

A comparison with D-Y could lead to extraction of CSV effect

$$Is \;\; u_p(x) = d_n(x)? \;\; \bar{u}_p(x) = \bar{d}_n(x)? \text{ etc.}$$

New results on cos2Φ Distribution in p+p Drell-Yan

L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



- p+p is similar to p+d; More data at higher p_T is needed
- More data are expected soon from Fermilab E906

Outstanding questions to be addressed by future Drell-Yan experiments

- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

New Probes for the Future Transverse Spin Physics @RHIC

Ming X. Liu
Los Alamos National Laboratory

The study of transverse single spin asymmetry (TSSA) has been one of the most exciting and challenging areas in QCD. The recent observations of non-zero TSSA effects from HERMES and COMPASS as well as RHIC-SPIN have stimulated a tremendous interest in studying these phenomena, and also have produced a much deep understanding of the QCD dynamics and nucleon structure at the partonic level. However, there are many outstanding issues remain as major challenges, such as the universality of transverse momentum dependent (TMD) functions and higher-twist (HT) mechanisms.

We propose to study TSSAs in charm and Drell-Yan production at RHIC. This requires much improved beam luminosity and polarization, as well as silicon vertex detector upgrade for both experiments at RHIC. We expect they all can be realized in the near future.

As we know, at RHIC energy, heavy quarks are predominantly produced via gluon-gluon interaction, thus providing a unique opportunity to study TMD and HT mechanisms: 1) in the TMD model, since there is only one gluon Sivers function, both charm and anti-charm will have identical TSSAs; 2) however, the situation is very different in the HT approach. There are two independent tri-gluon functions that couple to charm and anti-charm differently, thus TSSAs of charm and anti-charm are not necessarily the same, a distinct experimental signature that can be checked. The PHENIX experiment has produced preliminary results on heavy quark A_N but currently they are statistically limited.

It is proposed that in the Drell-Yan (including W/Z) process, the Sivers functions will change sign compared to the ones extracted from SIDIS experiments. It is of great importance to check this fundamental prediction of QCD. Our initial study indicate it is possible to perform such measurements at RHIC. Further more, with 500GeV beams, it is also possible to study flavor dependent Sivers functions at RHIC.

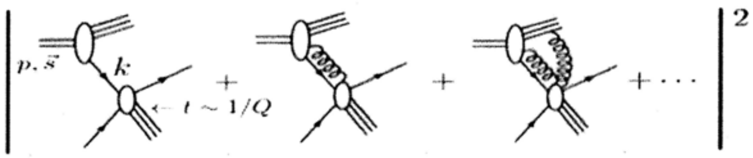
Current Understanding of TSSAs (II)

- Collinear Approach
  - Twist-3 three-parton correlation functions, Qiu-Sterman matrix
  - Twist-3 parton fragmentation functions

Qiu, Duke Spin workshop '10

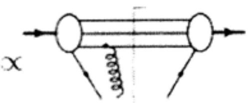
❑ **A_N – twist-3 effect:**

$\sigma(Q,\vec{s}) \propto$



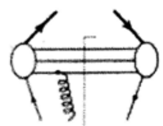
$$\Delta(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D_f(z) + \delta q_f(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z)$$

$T^{(3)}(x,x) \propto$



Qiu, Sterman, 1991

$D^{(3)}(z,z) \propto$



Kang, Yuan, Zhou, 2010

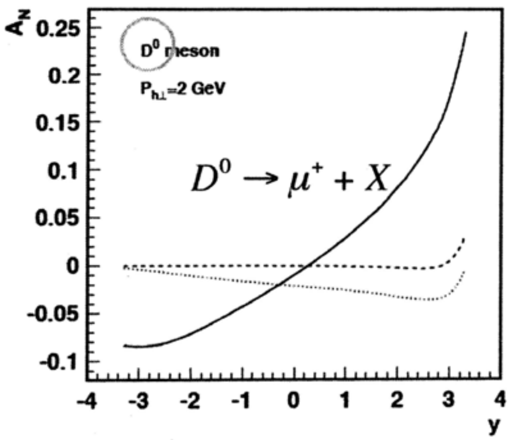
❑ **Spin flip:**

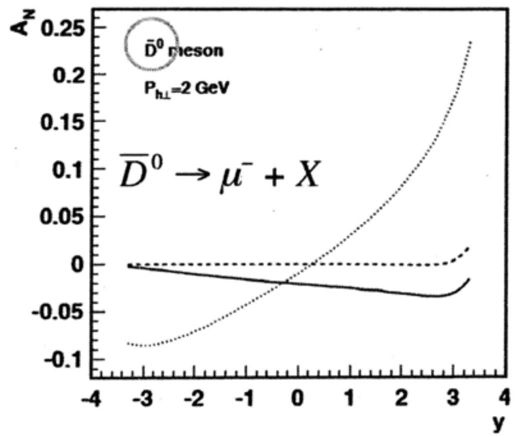
– Interference of single parton and a two-parton composite state

A unique opportunity @RHIC to study charm physics!

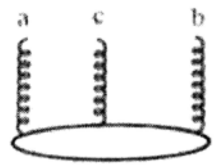
$$A_N(c) \overset{?}{\neq} A_N(\bar{c})$$

Kang, Qiu, Yuan, Vogelsang, Phys. Rev. D 78,114013(2008)





- Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$
- Dotted: $(2)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$
- Dashed: $(3)\lambda_f = \lambda_d = 0$ $\quad T_G^{(d)} = T_G^{(f)} = 0$



D meson : Largest A_N happens when $T_G^{(d)} = +T_G^{(f)}$
$\overline{D}$ meson : Largest A_N happens when $T_G^{(d)} = -T_G^{(f)}$

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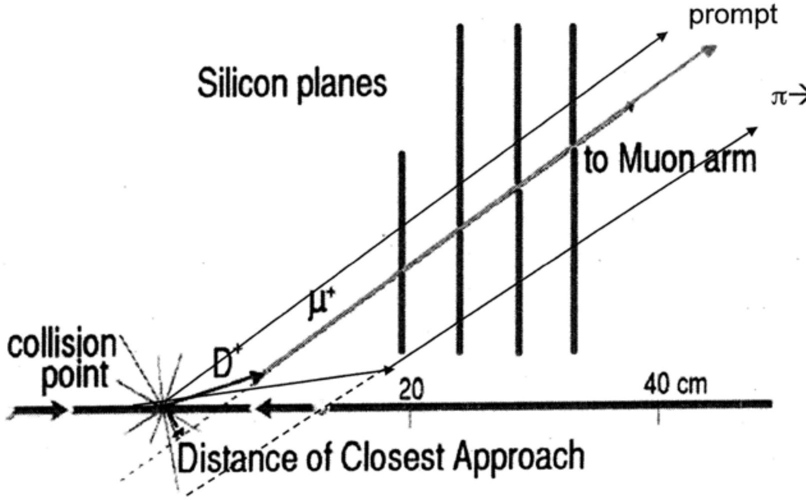
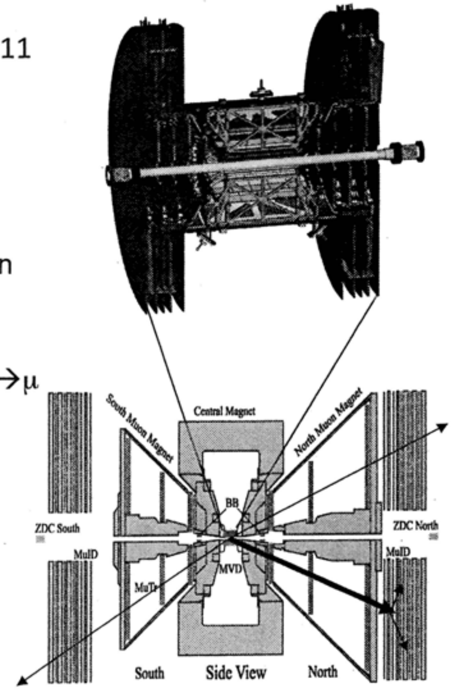
Heavy Quark, Drell-Yan and Silicon Vertex Detectors

- Silicon Vertex Detector Upgrade for PHENIX, available in 2011

- STAR's will come later

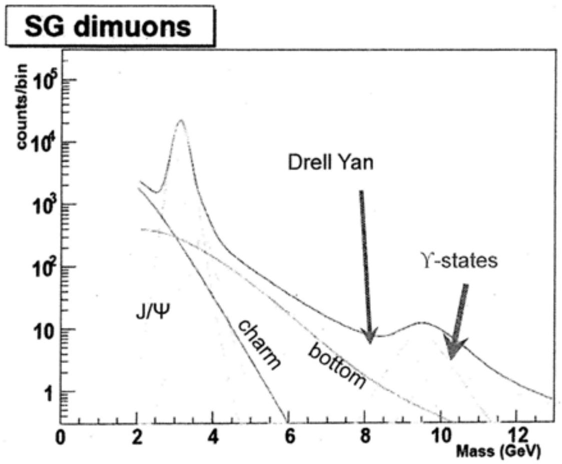
- Precision Charm/Beauty Measurements
- $B \to J/\psi$, Drell-Yan, ψ'



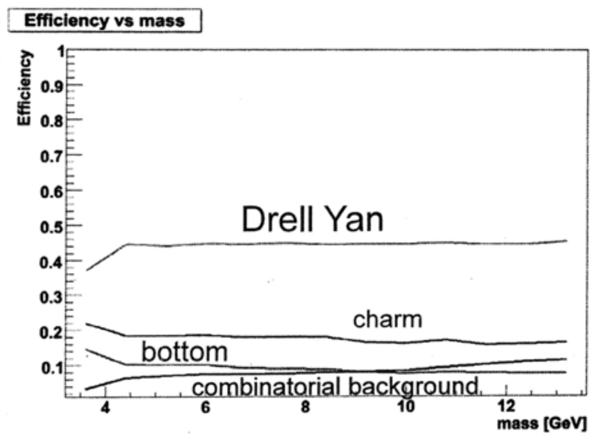


Drell-Yan and Heavy Quark Background Suppression (PHENIX Muon Acceptance)

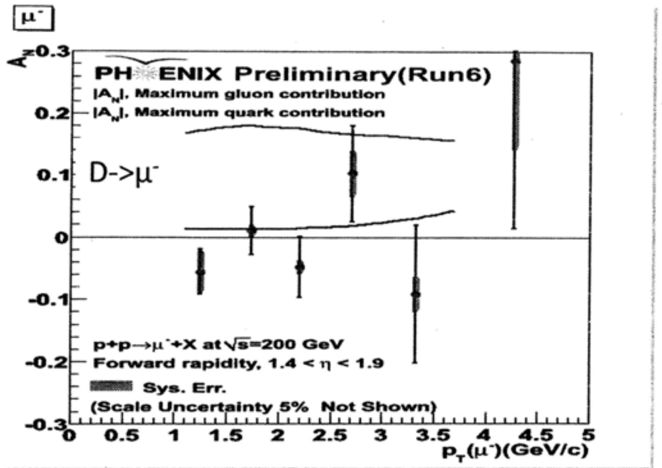
Drell-Yan signal before background suppression

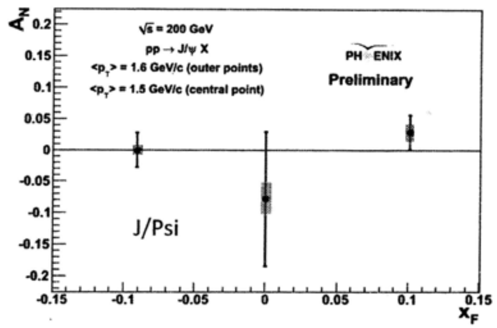


DCA < 1 σ cut:
Increase DY/bb ~ 5



Latest Results of Heavy Quark SSA





- Gluon's Sivers fun was not constrained well by DIS data
- PHENIX Charm data exclude the maximum gluon Sivers Fun (Anselmino et al, 06)
- Much improved results expected soon (Run6+Run8)

- First measurement of A_N in heavy vector meson J/Psi production
- Motivated new theoretical study
  - Constrains on gluons Sivers function.
  - Led to a new development in spin physics, beyond traditional spin topics, study J/Psi production mechanisms. (F. Yuan 08)

Looking Forward (Rapidity) at RHIC

Feng Yuan[1,2]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[2]*RIKEN BNL Research Center, Building 510A,*
Brookhaven National Laboratory, Upton, NY 11973

Abstract

In this talk, I briefly discuss recent theoretical developments concerning the phenomena observed at RHIC experiments, including the single transverse spin asymmetry in $pp_{\uparrow}$ collision, and di-jet (di-hadron) correlation in dA collisions. In particular, we emphasize the non-universality of the associated parton distributions in these processes due to the initial/final state interaction effects.

Looking Forward (rapidity) at RHIC

Feng Yuan
Lawrence Berkeley National Laboratory
RBRC, Brookhaven National Laboratory

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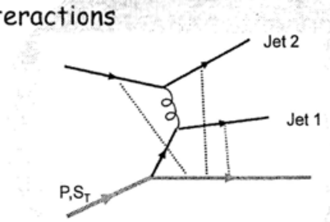
Non-universality: Dijet-correlation at RHIC

- Initial state and/or final state interactions



Boer-Vogelsang 03

Standard Factorization breaks, no universality!

Bacchetta-Bomhof-Mulders-Pijlman-Rogers, 04-10
Qiu-Vogelsang-Yuan 07
Collins-Qiu 07
Vogelsang-Yuan 07

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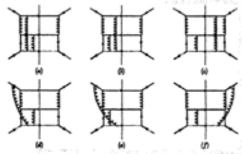
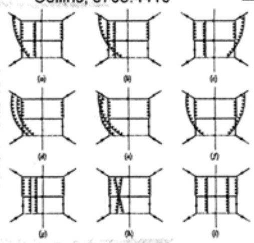
The simple picture does not hold for two-gluon exchanges

Vogelang-Yuan, 0708.4398; Collins, 0708.4410





Becchetta-Bomhof-Mulders-Pijlman, 04-06

$$\mathcal{L}'_{v_a}(g_1, g_2; \xi) \equiv \mathcal{P}\exp\left(-ig_1\int_0^\infty d\lambda v_a \cdot A(\xi+\lambda v_a)\right)$$
$$\times\mathcal{P}\exp\left(-ig_2\int_0^\infty d\lambda v_a \cdot A(\xi+\lambda v_a)\right)$$
$$\times\mathcal{P}\exp\left(ig_2\int_0^{-\infty} d\lambda v_a \cdot A(\xi+\lambda v_a)\right)$$

$$\Longrightarrow \mathcal{P}\exp\left(-ig_1\int_0^\infty d\lambda v_a \cdot A(\xi+\lambda v_a)\right)$$

Integrated over transverse momentum

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Universality of TMD at small-x?

- This has not been shown/studied in small-x physics
- Different assumption and summation are made
- We want to make a model calculations suitable for both TMD and small-x approximation
  - **Summation to all order is crucial**

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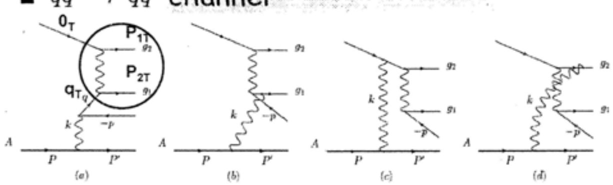
Model calculations

- $qq' \to qq'$ channel

Xiao,Yuan, arXiv:1003.0482



- q_t dependence, $q_T = P_{1T} + P_{1T} \ll P_{1T} \sim P_{1T}$

$$\tilde{q}(x, q_\perp) = \frac{x}{32\pi^2}\int \frac{dp^-}{p^-}\frac{d^2k_\perp}{(2\pi)^4}(4P^+p^-)^2\left|A^{(tot)}(k,p)\right|^2 \quad A^{(1)}(k,p) = gg_1\frac{1}{k_1^2+\lambda^2}\left[\frac{1}{D_1} - \frac{1}{D_2}\right]$$

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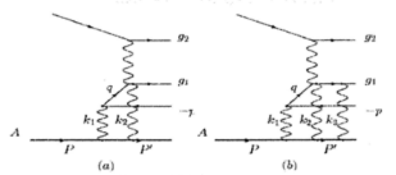
Multi-gluon exchange



$$A^{(2)}(k,p) = \frac{i}{2}g^2\int d[1]d[2]\left\{g_1^2\left[\frac{1}{D_1} + \frac{1}{D_2} - \frac{1}{D_{21}} - \frac{1}{D_{22}}\right] + g_1g_2\left[\frac{2}{D_2} - \frac{2}{D_{21}}\right]\right\}$$

$$A^{(3)}(k,p) = \frac{1}{3!}g^3\int d[1]d[2]d[3]\left\{g_1^3\left[\frac{1}{D_2} - \frac{1}{D_1} + \frac{3}{D_{13}} - \frac{3}{D_{21}}\right] + g_1^2g_2\left[\frac{3}{D_2} + \frac{3}{D_{13}} - \frac{3}{D_{21}} - \frac{3}{D_{22}}\right] + g_1g_2^2\left[\frac{3}{D_2} - \frac{3}{D_{21}}\right]\right\}$$

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All-orders

$$\tilde{q}(x,q_\perp)=\frac{xP^{+2}}{8\pi^4}\int dp^- p^- \int d^2R_\perp d^2R'_\perp d^2r_\perp e^{iq_\perp\cdot(R_\perp-R'_\perp)}\underline{e^{-igg_2\left(G(R_\perp)-G(R'_\perp)\right)}}$$
$$V(r_\perp)V(r'_\perp)\left\{1-e^{igg_1\left[G\left(R_\perp+r_\perp\right)-G(R_\perp)\right]}\right\}\left\{1-e^{-igg_1\left[G\left(R'_\perp+r'_\perp\right)-G\left(R'_\perp\right)\right]}\right\},$$

- DIS process (g_2-term disappear)

$$\tilde{q}(x,q_\perp)=\frac{xP^{+2}}{8\pi^4}\int dp^- p^- \int d^2R_\perp d^2R'_\perp d^2r_\perp e^{iq_\perp\cdot(R_\perp-R'_\perp)}V(r_\perp)V(r'_\perp)$$
$$\times\left\{1-e^{igg_1\left[G\left(R_\perp+r_\perp\right)-G(R_\perp)\right]}\right\}\left\{1-e^{-igg_1\left[G\left(R'_\perp+r'_\perp\right)-G\left(R'_\perp\right)\right]}\right\},$$

- They are not the same, **Non-universality**

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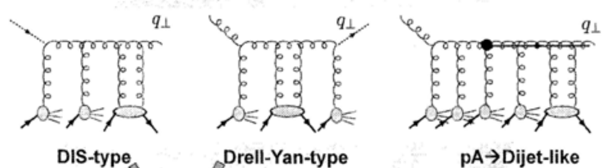
Realistic QCD dipole model

- Following Kovchegov-Mueller 1998



$$\tilde{N}(\underline{x})=\int d^2b\frac{N_c^2-1}{\pi^2\alpha N_c\underline{x}^2}(1-exp[-\frac{\sqrt{R^2-b^2}}{2\lambda}\underline{x}^2\tilde{v}(\underline{x})])$$

Time-reversal invariance

Certainly will be different

Marquet,Venugopalan,Xiao,Yuan, work in progress

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Comments

- Light-cone gauge does not help
- Non-universal for the kt-dependent parton distribution at small-x, will affect the phenomenological interpretations
- Remain to be seen that how/does the classical field calculation contain these effects

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Journey forward at RHIC

- SSA in forward direction impose theoretical challenge
  - Pt-dependence
  - Eta/pi0 SSA
- Dijet-correlation not only probe small-x saturation, but also the QCD dynamics (initial/final state interaction effects)

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Fragmentation function measurements at Belle

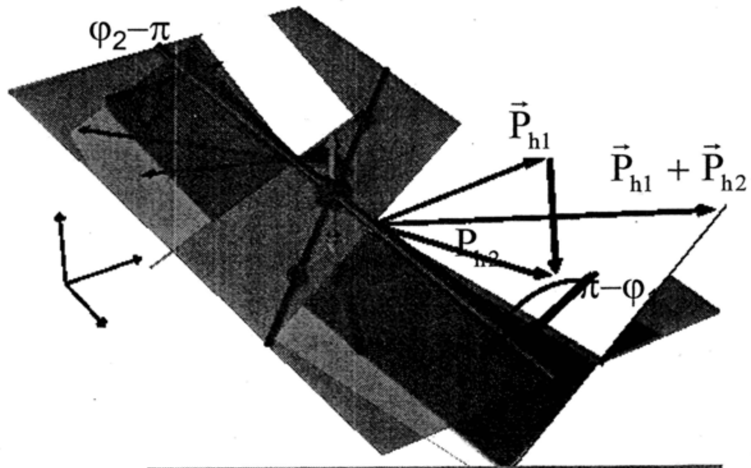
RIKEN high P_T Workshop,
BNL, March 17-19

<u>Ralf Seidl (RBRC)</u>
Anselm Vossen (University of Illinois)
Matthias Grosse Perdekamp (University of Illinois)
Martin Leitgab (University of Illinois)
Akio Ogawa (BNL/RBRC)
eran Boyle (RBRC)

Interference Fragmentation – thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Stay in the mass region around ρ-mass
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1+\varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated
  (universal function, evolution easy
  → directly applicable to
  semi-inclusive DIS and pp)
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

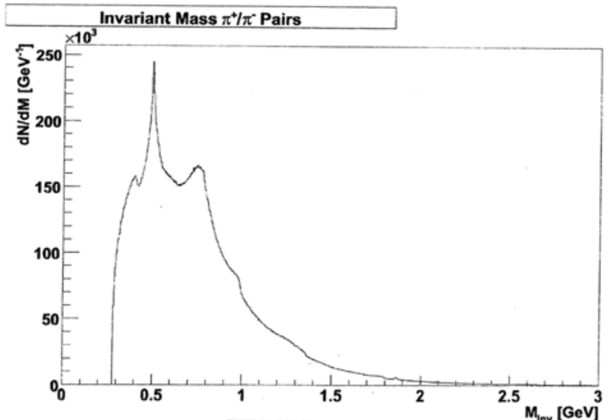
$$A \propto H_1^{\angle}(z_1, m_1) H_1^{\angle}(z_2, m_2) \cos(\varphi_1 + \varphi_2)$$

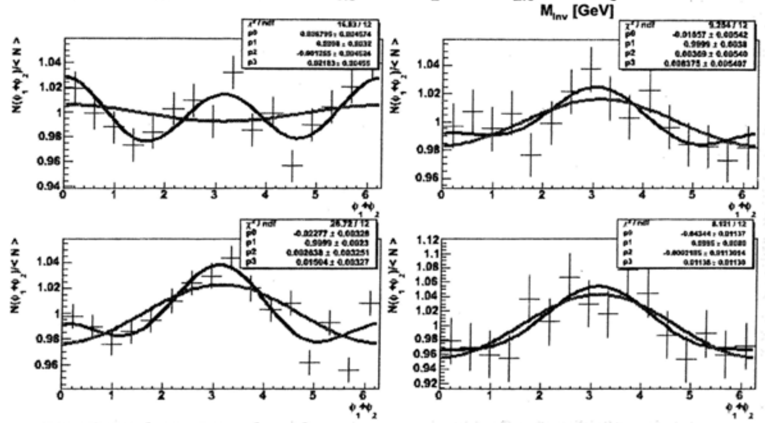


Model predictions by:

- Jaffe et al. [PRL **80**,(1998)]
- Radici et al. [PRD **65**,(2002)]

Asymmetry extraction





- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N \rangle},$$

- Fit with:

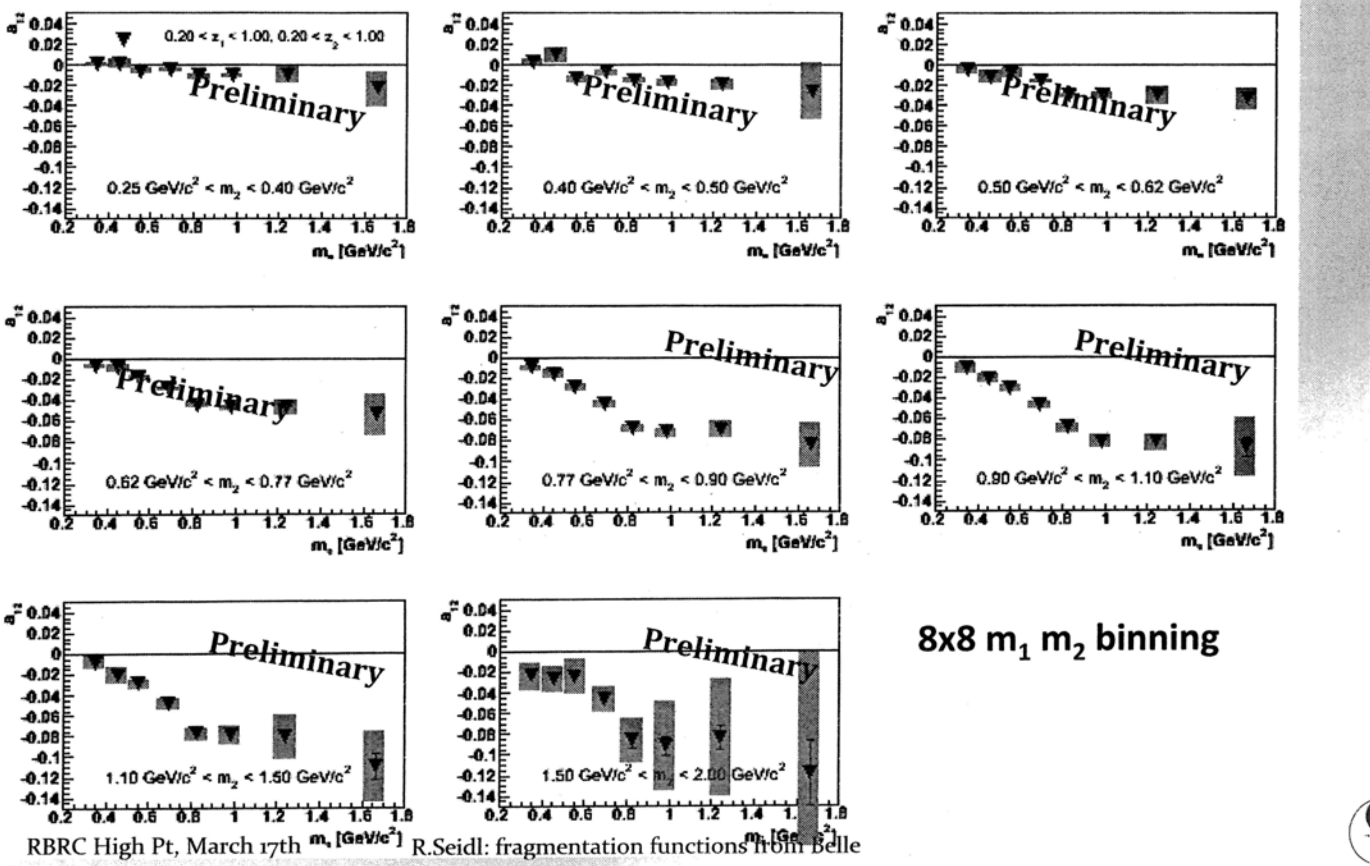
[redacted]

or

[redacted]

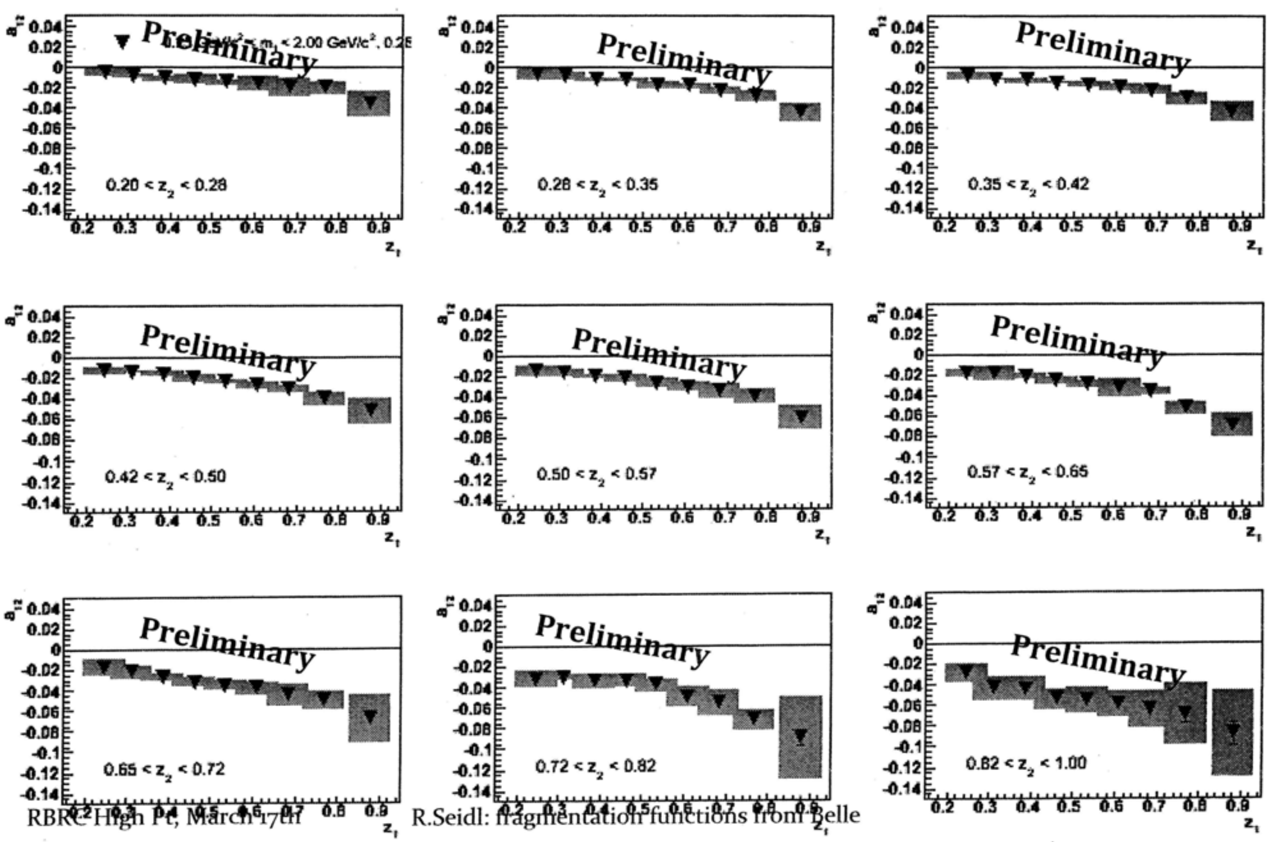
Amplitude a_{12} directly measures (IFF) x (-IFF) (no double ratios)

Results including systematic errors



8x8 m_1 m_2 binning

Results for 9x9 z_1 z_2 binning



BELLE

Summary and outlook

- First direct measurement of the interference fragmentation function
  - Large asymmetries seen, rising with z and invariant mass
  - No sign change at ρ mass
  - No double reatios make interpretation simple
- Significant, nonzero Collins asymmetries, long paper published
- Data used already in Global analysis
- Measure precise unpolarized fragmentation functions of many final states

→ Important input for general QCD physics and helicity structure measurements

- Analysis progressing:
  - PID studies finished
  - Acceptance correction
- Continue to measure precise spin dependent fragmentation functions at Belle
  - kT dependence of Collins function
  - Artru model test with Vector meson Collins
- Measure other interesting QCD-related quantities at Belle:
  - Chiral-odd Λ-fragmentation function
  - Λ single spin asymmetry
  - Event shapes
  - R-ratio with ISR

recent results from HERMES

Delia Hasch

INFN Frascati

HERMES is a second generation polarised DIS experiment approaching the quest for the spin of the nucleon by measuring not only inclusive processes but also semi-inclusive and exclusive ones. It utilized the polarised 27.5 GeV HERA electron or positron beam incident on pure nuclear polarised H and D gas targets and featured excellent particle identification capabilities.
HERMES' major contributions to the exploration of the longitudinal spin structure of the nucleon has been widely discussed. A recent measurement of the strange momentum and spin distributions is presented. We concentrate here on recent achievements obtained mainly with a transversely polarised H target. Such measurements provide the necessary information to explore transverse momentum dependent distribution and fragmentation functions (TMD) and the transversity. Such TMDs describe spin-orbit correlations and hence provide a multi-dimensional imaging of the nucleon. We also investigated any sign of a possible two-photon exchange contribution which could be excluded to 10^{-3} accuracy. Inclusive hadron production at $Q^2 \approx 0$ GeV^2 provides a means to directly compare to transverse spin asymmetries measured in pp collisions at RHIC.
The complementary approach of accessing the 3D structure of the nucleon with GPDs is not presented here. HERMES has however measured a large variety of exclusive processes that provide information of GPDs.

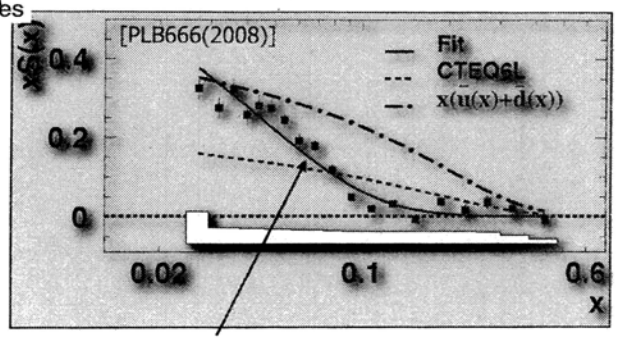
strange quark distributions

→ use isoscalar probe + target: $S^p(x) = S^n(x)$; $S(x) = s(x) + \underline{s}(x)$

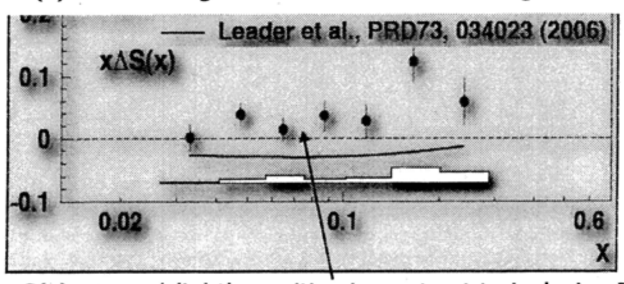
→ ingrediants: $K^+ + K^-$ multiplicities, $A_{1,d}^{K^+ + K^-}(x, z, Q^2)$, $A_{1,d}(x, Q^2)$

→ strange *FF*: $\int_{0.2}^{0.8} dz\, D_S^K(z) = 1.27 \pm 0.13$ [DSS, PRD75(2007)]

hermes

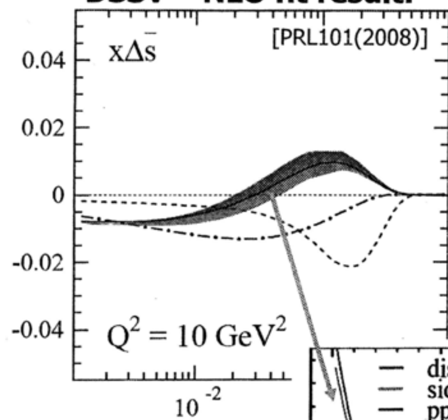


S(x) NOT average of an isoscalar non-strange see

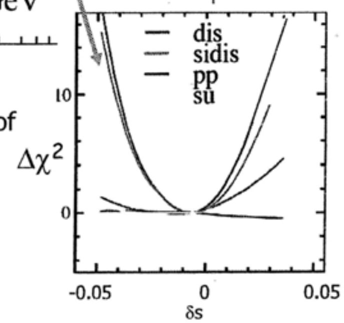


ΔS(x) ≈ zero/slightly positive in contrast to inclusive DIS analyses

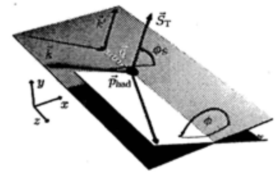
DSSV – NLO fit result:

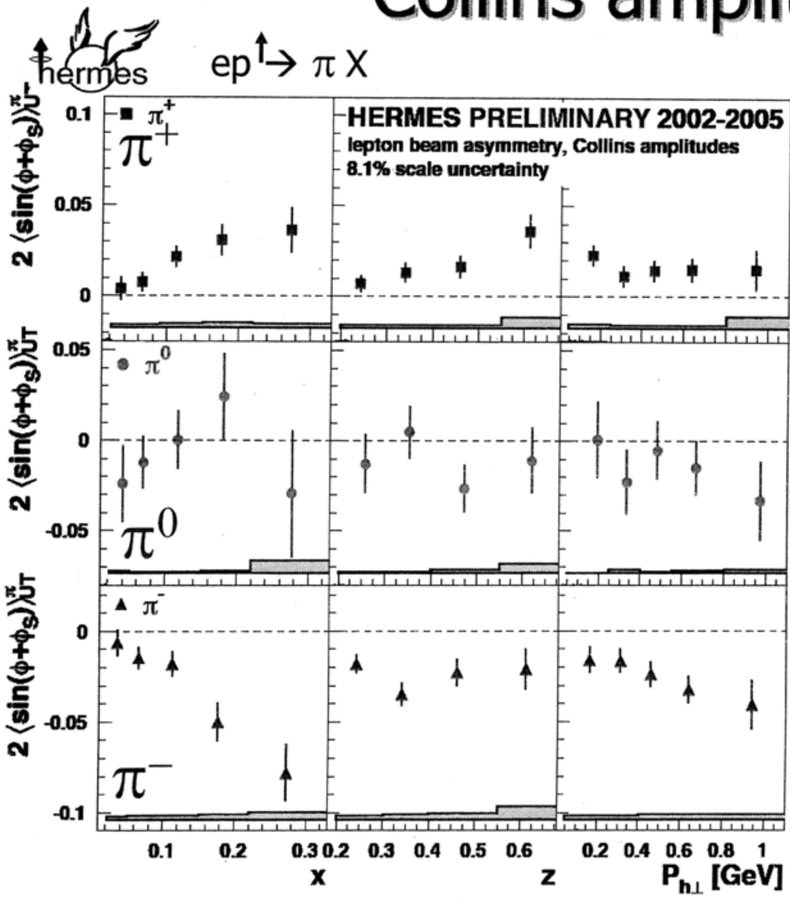


striking impact of SIDIS data

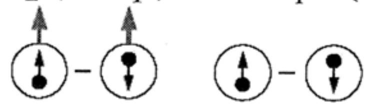


Collins amplitudes





$$\delta q(x, k_T) \otimes H_1^{\perp q}(z, p_T)$$



distinctive pattern:

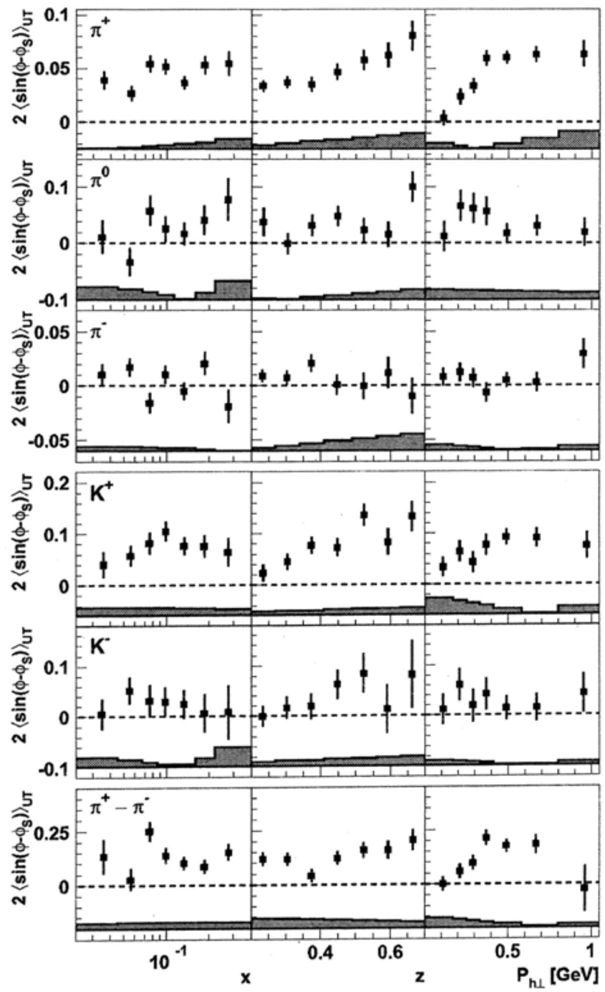
- ■ π^+ positive
- ● π^0 ≈zero
- ▲ π^- negative

isospin relation for π triplet fulfilled

approximation:

u-quark dominance

$$H_1^{\perp,\mathrm{disfav}} \approx - H_1^{\perp,\mathrm{fav}}$$



Sivers amplitudes

[PRL103(2009)]

$$f_{1T}^{\perp q}(x, k_T) \otimes D_1^q(z, p_T)$$

first observation of T-odd Sivers effect in SIDIS

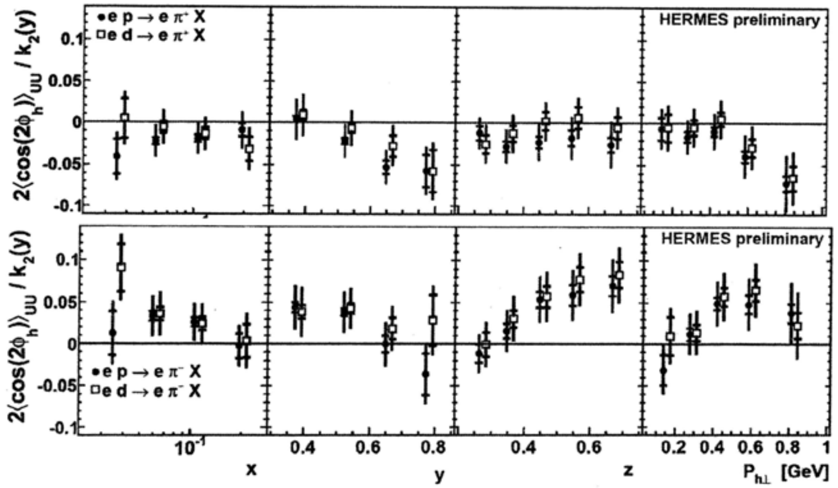
- K^+ amplitudes larger than π^+ ones → non trivial role of sea quarks ?

$$K^+ = |u\bar{s}\rangle \quad \pi^+ = |u\bar{d}\rangle$$

- pion difference → access to valence quark distributions:

$$\propto \frac{4 f_{1T}^{\perp, u_v} - f_{1T}^{\perp, d_v}}{4 f_1^{u_v} - f_1^{d_v}}$$

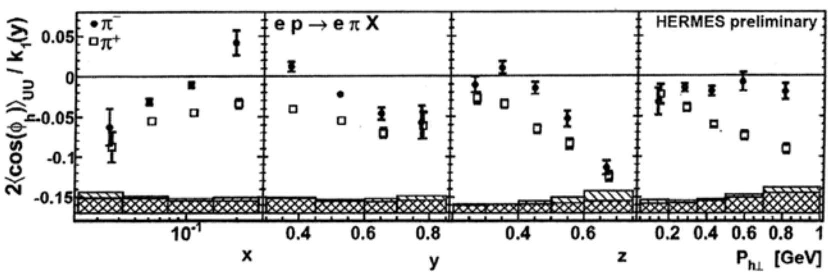
<cos2ϕ>: spin-orbit correlations



$$h_1^{\perp}(x,k_T)\otimes H_1^{\perp}(z,p_T)$$

deuterium ≈ hydrogen values → B-M must have *same sign* for u & d

<cosϕ>: intrinsic quark transverse momentum



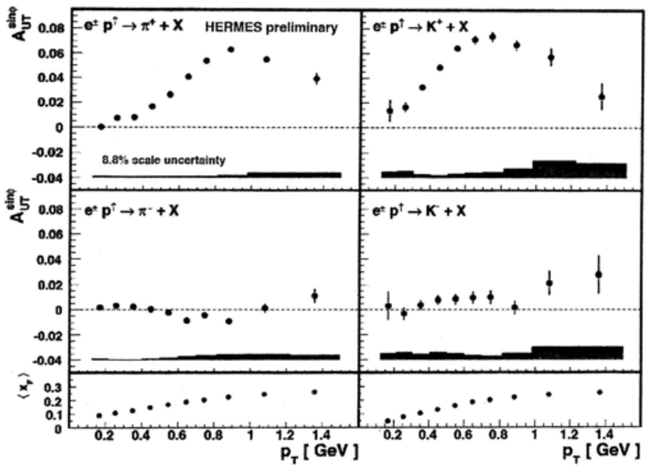
- very similar result for deuterium

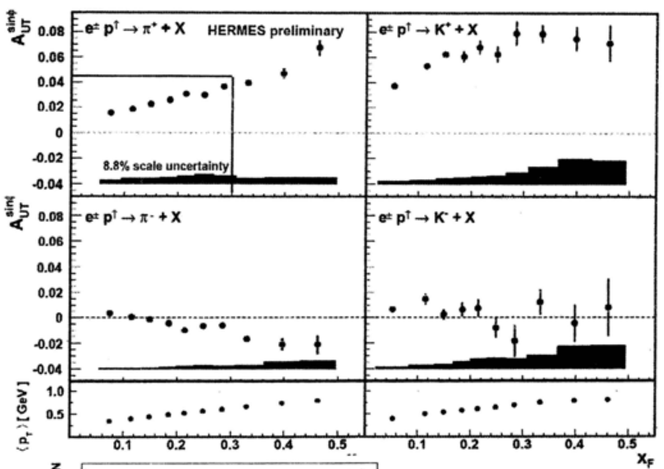
→ different effects for different pion charges ... **unexpected** for Cahn effect!

- Boer-Mulders term important ?
- $\langle k_T \rangle$ flavour dependent ?

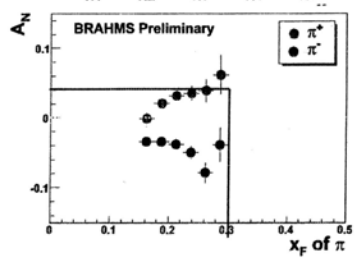
inclusive hadrons: $e\,p^{\uparrow} \rightarrow h\,X$

- scattered electron not detected (ignored) → Q2 ≈ 0 → huge statistics
  P_T, x_F w.r.t. **beam direction**





$$A_N = \frac{2}{\pi} A_{UT}^{\sin\varphi}$$



$p\,p^{\uparrow} \rightarrow h\,X$

@√s = 62 GeV

Two-particle correlations and the small-x gluon four-point function

Adrian Dumitru, RIKEN-BNL and Baruch College

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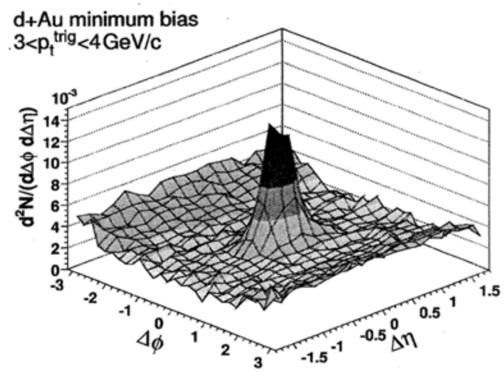
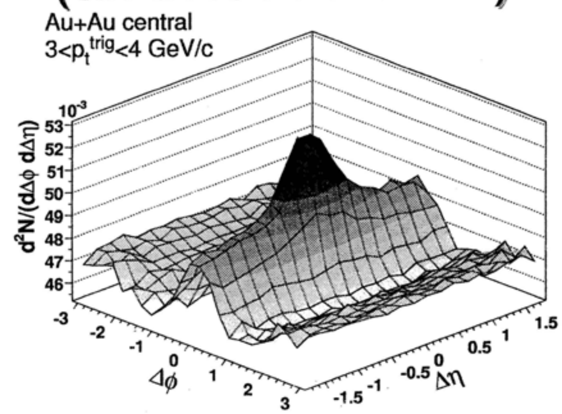
- particle correlations probe complete B-JIMWLK evolution equation incl. "N_c corrections"
- kinematic regime:
  $p,q \sim Q_s$ (say, 1-3 GeV for pp @ LHC, AA @ RHIC)
- azim. angles $\Phi \ll \pi$

<u>**arXiv:1001.4820**</u>

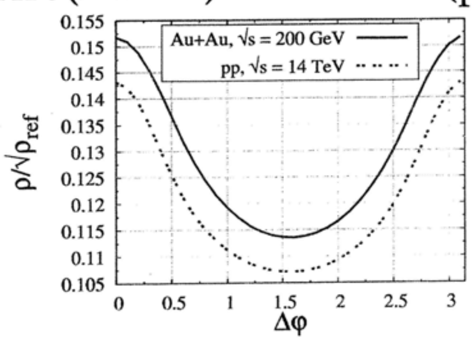
Near-side correlations, Φ<1 (the "ridge")

STAR (arXiv:0909.0191)



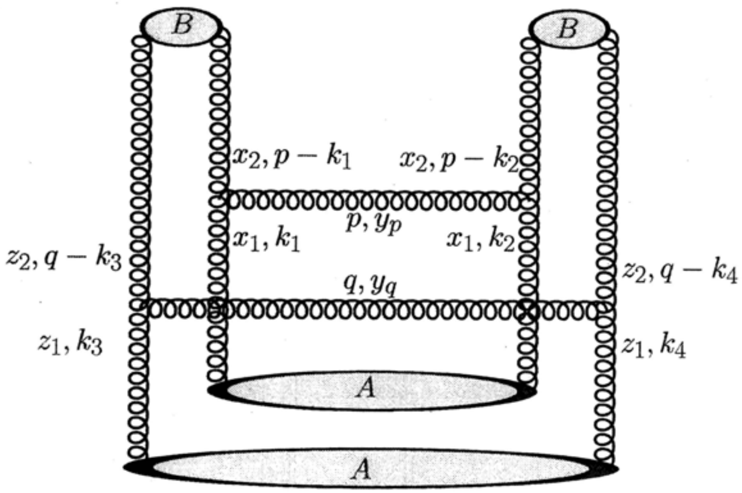


RHIC(Au+Au) versus LHC(pp) :



model calculation

ridge in pp @ LHC ?!



$$\langle \rho^{*a}(k)\, \rho^{b}(q) \rangle (x) \quad \sim \quad \frac{1}{g^2} \frac{\delta^{ab}}{N_c^2 - 1}\, \delta(k-q)\, \Phi(x, k^2)$$

unintegr. gluon distrib.

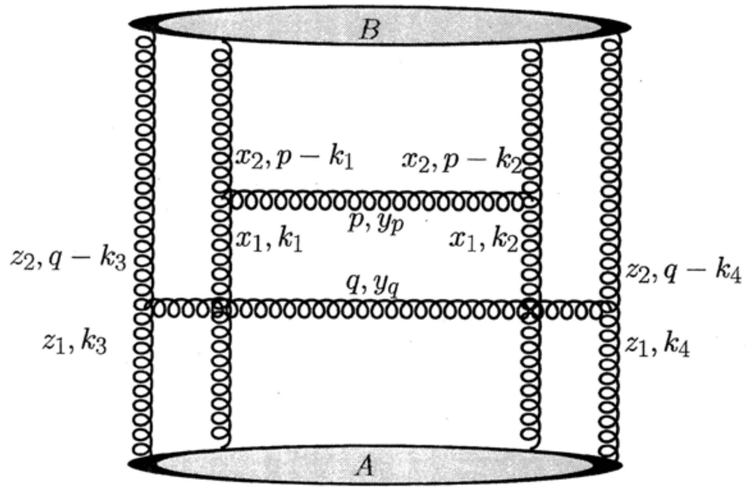
A.D., Gelis, McLerran, Venugopalan: 0804.3858

$$C(p,q) \quad = \quad 16(2\pi)^2 \alpha_s^2\, S_\perp \frac{N^2}{(N^2-1)^3} \frac{1}{p_\perp^2} \frac{1}{q_\perp^2}$$

$$\int d^2k_\perp \frac{\Phi_A(x_1, (p_\perp + k_\perp)^2)}{(p_\perp + k_\perp)^2} \frac{\Phi_A(x_1, (q_\perp - k_\perp)^2)}{(q_\perp - k_\perp)^2} \frac{\Phi_B^2(x_2, k_\perp^2)}{k_\perp^4}$$

Depends on angle $\angle(p_\perp, q_\perp)$, not flat in Φ

however, we should rather compute THIS diagram:



$$
\begin{aligned}
C(p_\perp, q_\perp) = \quad & \frac{g^{12}}{64(2\pi)^6} \left(f_{abc} f_{a'\bar{b}\bar{c}} f_{a\hat{b}\hat{c}} f_{a'\tilde{b}\tilde{c}}\right) \int \prod_{i=1}^{4} \frac{d^2 k_{i\perp}}{(2\pi)^2 k_{i\perp}^2} \\
& \times \frac{L_\mu(p_\perp, k_{1\perp}) L^\mu(p_\perp, k_{2\perp})}{(p_\perp - k_{1\perp})^2 (p_\perp - k_{2\perp})^2} \frac{L_\nu(q_\perp, k_{3\perp}) L^\nu(q_\perp, k_{4\perp})}{(q_\perp - k_{3\perp})^2 (q_\perp - k_{4\perp})^2} \\
& \times \left\langle \rho^{*\hat{b}}_{1}(k_{2\perp}) \rho^{*\tilde{b}}_{1}(k_{4\perp}) \rho_1{}^{b}(k_{1\perp}) \rho_1{}^{\bar{b}}(k_{3\perp}) \right\rangle \\
& \times \left\langle \rho^{*\hat{c}}_{2}(p_\perp - k_{2\perp}) \rho^{*\tilde{c}}_{2}(q_\perp - k_{4\perp}) \rho_2{}^{c}(p_\perp - k_{1\perp}) \rho_2{}^{\bar{c}}(q_\perp - k_{3\perp}) \right\rangle
\end{aligned}
$$

B-JIMWLK four-point function: (dilute regime)

$$
\begin{aligned}
\frac{d}{dY}\langle \alpha^a_r \alpha^b_{\bar r} \alpha^c_s \alpha^d_{\bar s}\rangle \quad = \quad & \\
& \frac{g^2 N_c}{(2\pi)^3}\int d^2z \left\langle \frac{\alpha^a_z\alpha^b_{\bar r}\alpha^c_s\alpha^d_{\bar s}}{(r-z)^2} + \frac{\alpha^a_r\alpha^b_z\alpha^c_s\alpha^d_{\bar s}}{(\bar r-z)^2} + \frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_z\alpha^d_{\bar s}}{(s-z)^2} + \frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_s\alpha^d_z}{(\bar s-z)^2} - 4\frac{\alpha^a_r\alpha^b_{\bar r}\alpha^c_s\alpha^d_{\bar s}}{z^2}\right\rangle \\
& +\frac{g^2}{\pi}\int \frac{d^2z}{(2\pi)^2}\left\langle f^{e\kappa a}f^{f\kappa b}\frac{(r-z)\cdot(\bar r-z)}{(r-z)^2(\bar r-z)^2}\left[\alpha^e_r\alpha^f_{\bar r} - \alpha^e_r\alpha^f_z - \alpha^e_z\alpha^f_{\bar r} + \alpha^e_z\alpha^f_z\right]\alpha^c_s\alpha^d_{\bar s}\right. \\
& \qquad + f^{e\kappa a}f^{f\kappa c}\frac{(r-z)\cdot(s-z)}{(r-z)^2(s-z)^2}\left[\alpha^e_r\alpha^f_s - \alpha^e_r\alpha^f_z - \alpha^e_z\alpha^f_s + \alpha^e_z\alpha^f_z\right]\alpha^b_{\bar r}\alpha^d_{\bar s} \\
& \qquad + f^{e\kappa a}f^{f\kappa d}\frac{(r-z)\cdot(\bar s-z)}{(r-z)^2(\bar s-z)^2}\left[\alpha^e_r\alpha^f_{\bar s} - \alpha^e_r\alpha^f_z - \alpha^e_z\alpha^f_{\bar s} + \alpha^e_z\alpha^f_z\right]\alpha^b_{\bar r}\alpha^c_s \\
& \qquad + f^{e\kappa b}f^{f\kappa c}\frac{(\bar r-z)\cdot(s-z)}{(\bar r-z)^2(s-z)^2}\left[\alpha^e_{\bar r}\alpha^f_s - \alpha^e_{\bar r}\alpha^f_z - \alpha^e_z\alpha^f_s + \alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^d_{\bar s} \\
& \qquad + f^{e\kappa b}f^{f\kappa d}\frac{(\bar r-z)\cdot(\bar s-z)}{(\bar r-z)^2(\bar s-z)^2}\left[\alpha^e_{\bar r}\alpha^f_{\bar s} - \alpha^e_{\bar r}\alpha^f_z - \alpha^e_z\alpha^f_{\bar s} + \alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^c_s \\
& \qquad \left. + f^{e\kappa c}f^{f\kappa d}\frac{(s-z)\cdot(\bar s-z)}{(s-z)^2(\bar s-z)^2}\left[\alpha^e_s\alpha^f_{\bar s} - \alpha^e_s\alpha^f_z - \alpha^e_z\alpha^f_{\bar s} + \alpha^e_z\alpha^f_z\right]\alpha^a_r\alpha^b_{\bar r}\right\rangle .
\end{aligned}
$$

$$
A^\mu(x^+, r) \equiv \delta^{\mu -}\alpha(x^+, r) = -g\,\delta^{\mu -}\delta(x^+)\frac{1}{\nabla^2_\perp}\rho(x^+, r) \qquad k^2\alpha(k) = g\rho(k)
$$

“subleading-Nc” piece contributes at the same order to C(p,q)

Complete Balitsky/JIMWLK four-point function:
(in Gaussian approximation)

$$\left\langle \rho^a \rho^b \rho^c \rho^d \right\rangle \;=\; \delta^{ab}\delta^{cd}\left\langle \rho^2 \right\rangle^2 + \frac{1}{N_c} f^{ab\kappa} f^{cd\kappa}\left\langle \rho^2 \right\rangle^2 + \cdots$$

$$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \qquad \delta^{ac}\delta^{bd} \quad \delta^{a'b'}\delta^{c'd'} = N_c^2 (N_c^2 - 1)$$

$$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \; \frac{1}{N_c} f^{ab\kappa} f^{cd\kappa} \, \delta^{a'c'}\delta^{b'd'} = N_c^2 (N_c^2 - 1)$$

Projectile Target

[Note: independent/uncorrel. production
$f_{gaa'} f_{g'bb'} f_{gcc'} f_{g'dd'} \, \delta^{ac}\delta^{bd}\, \delta^{a'c'}\delta^{b'd'} = N_c^2 (N_c^2 - 1)^2$
]

Double transverse spin asymmetries as a probe for new physics

Wilco J. den Dunnen, Daniël Boer

March 18, 2010

Abstract

The Relativistic Heavy Ion Collider (RHIC) at BNL will soon start its transversely polarized proton collision program. Although the energy is lower than the Tevatron and the LHC, it has been suggested that the ability to polarize the protons makes it sensitive to certain forms of Beyond the Standard Model (BYSM) physics. We investigate spin asymmetries in transversely polarized proton-proton collisions induced by a right-handed charged weak interaction. With negligible Standard Model contributions these asymmetries are directly sensitive to new physics, generically attributed to the existence of a new gauge boson called W'. We discuss present bounds on a right-handed weak interaction and show the urge for confirmation of the only model independent bound to date. We present, given reasonable estimates of the transversity distributions, quantitative estimates of the size of the asymmetries and of the possible background. We conclude that, if the original design goals are met and the anti-quark transversity distribution is not negligible, a competitive bound can be obtained at RHIC. Measuring CP violation BYSM in those spin asymmetries is most likely too optimistic.

phenomenology of LR models

$SU(2)_L$: W_L boson and V_{CKM}^L matrix
$SU(2)_R$: W_R boson and V_{CKM}^R matrix

mixing:

$$\begin{array}{ll} \text{light} & W = \cos\zeta W_L - e^{i\omega}\sin\zeta W_R \\ \text{heavy} & W' = \sin\zeta W_L + e^{i\omega}\cos\zeta W_R \end{array}$$

- 6 new CP violating phases in V_{CKM}^R
- CP violating phase ω

manifest: $g_L = g_R$, $\omega = 0$ and $V_{CKM}^R = V_{CKM}^L$
pseudo-manifest: $g_L = g_R$, $\omega \neq 0$ and $V_{CKM}^R = (V_{CKM}^L)^*$

asymmetries

define:

$$A_{TT} \equiv \left(\int_{-\pi/4}^{\pi/4} - \int_{\pi/4}^{3\pi/4} + \int_{3\pi/4}^{5\pi/4} - \int_{5\pi/4}^{7\pi/4} \right) d\phi \delta d\sigma / \int_0^{2\pi} d\phi d\sigma$$

$$A_{TT}^{\perp} \equiv \left(\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi} \right) d\phi \delta d\sigma / \int_0^{2\pi} d\phi d\sigma$$

such that

$A_{TT} \propto \zeta \cos \omega$	*can, in principle, determine full coupling*
$A_{TT}^{\perp} \propto \zeta \sin \omega$	including CP-violating part

size of the asymmetries

If we assume $\bar{h}_1(x) = \bar{f}_1(x)/2$ (compatible with Soffer bound)

$$\zeta \cos\omega = 0.04 \quad \rightarrow \quad |A_{TT}| = \begin{cases} 1.2\% & W^+ \\ 1.0\% & W^- \end{cases}$$

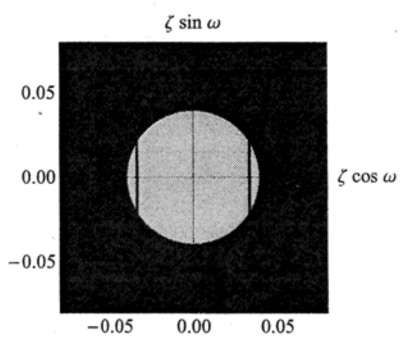
$$\zeta \sin\omega = 0.04 \quad \rightarrow \quad |A_{TT}^{\perp}| = \begin{cases} 0.6\% & W^+ \\ 0.4\% & W^- \end{cases}$$

optimal (realistic) cuts:

A_{TT} : $|Y| < 1,\quad 35 < p_T < 45\text{GeV}$

$A_{TT}^{\perp}$: $0.2 < |Y| < 1,\quad 35 < p_T < 45\text{GeV}$

potential exclusion



potential exclusion
given $|A_{TT}^{(\perp)}| < 1\%$

likely requires $\mathcal{O}(800)\mathrm{pb}^{-1}$
@70% polarization

- model independent
- but h_1 and $\bar{h}_1$ needed (DY)

NLO likely not much smaller
→ Martin et al. PRD 57, 3084 (1998)

conclusion

prospects for measuring W' physics at RHIC

- RHIC can, in principle, set bounds on ζ and ω independently
- determining CP violation BYSM ($\omega \neq 0$) likely too optimistic
- so far only one bound on ζ $\rightarrow$ needs confirmation
- possible if
  - original design goals are met
  - $\bar{h}_1$ not negligible

Low mass dilepton production at high p_T

Jian-Wei Qiu

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

In this talk, I present our recent work on the transverse momentum distribution of low-mass lepton pairs produced in hadronic scattering, using the perturbative QCD factorization approach [1]. We argue that the distribution at large transverse momentum, $Q_T \gg Q$, with the pair's invariant mass Q as low as $Q \sim \Lambda_{\rm QCD}$, can be systematically factorized into universal parton-to-lepton pair fragmentation functions, parton distributions, and perturbatively calculable partonic hard parts evaluated at a short distance scale $\sim \mathcal{O}(1/Q_T)$. We introduce a model for the input lepton pair fragmentation functions at a scale $\mu_0 \sim 1$ GeV, which are then evolved perturbatively to scales relevant at RHIC. Using the evolved fragmentation functions, we calculate the transverse momentum distributions in hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions at RHIC. We compare our calculated production rates with recent PHENIX data on low mass lepton pair production [2]. We find that our results are consistent with the data from proton-proton collision, but, much lower than the data from Gold-Gold collisions in the region of low transverse momentum, $Q_T < 3$ GeV. We also evaluate the nuclear modification from partonic multiple scattering in cold nuclear matter. We find that although the partonic multiple scattering enhances the production rate in Gold-Gold collisions, in contrast to the suppression from nuclear shadowing, the enhancement is not sufficient to explain the large excess of low mass lepton pairs in low transverse momentum region observed by PHENIX Collaboration.

References

[1] Z. B. Kang, J. W. Qiu, and W. Vogelsang, Phys. Rev. D**79**, 054007 (2009).

[2] A. Adare, *et. al.* [PHENIX Collaboration], arXiv:0804.4168.

Questions

How reliable we can calculate the production rate of low mass lepton pairs in hadronic collisions?

Process: $A(p_1) + B(p_2) \to \ell^+\ell^-(Q) + X$

Kinematics: $Q_T^2 \gg Q^2$

"Drell-Yan" – like process:

$$Q_T^2 \gg Q^2 \gg \Lambda_{\rm QCD}^2$$

Clean process for extracting the gluon distribution

Berger, Gordon, Klasen, 1998
Qiu, Zhang, 2001
Berger, Qiu, Zhang, 2002

"Direct photon" – like process:

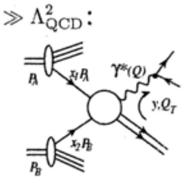
$$Q_T^2 \gg Q^2 \sim \Lambda_{\rm QCD}^2$$

QCD factorization is as good as that for high p_T direct photon production

Kang, Qiu, Vogelsang, 2009

QCD factorization for Drell-Yan

- **QCD factorization is valid when** $Q,\, Q_T \gg \Lambda_{\rm QCD}^2$**:**
  - separation of momentum scales
  - photon is produced at $t_\gamma \sim 1/Q \ll$ fm
  - inclusive lepton pair production

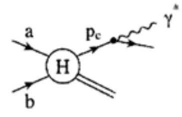


$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

Power series of α_s

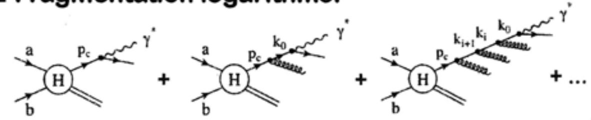
$$\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \sum_{a,b}\int dx_1 f_a^A(x_1,\mu)\int dx_2 f_b^B(x_2,\mu)\,\frac{d\hat{\sigma}^{\rm Pert}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}(x_1,x_2,Q,Q_T,y;\mu),$$

- **QCD factorization is valid even if** $Q_T^2 \gg Q^2 \gg \Lambda_{\rm QCD}^2$ **:**
  - photon is produced at $t_\gamma \sim 1/Q \gg 1/Q_T$
  - large logarithms: $\alpha_s(Q)*\log(Q_T/Q)$
  - resummation/reorganization

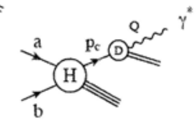


Resummation of fragmentation logarithms

- **Fragmentation logarithms:** Qiu, Zhang, 2001, Berger, Qiu, Zhang 2002



- **Resummation/reorganization:**



$$\mu_F^2 \frac{d}{d\mu_F^2} D_{c\to\gamma^*}(z,\mu_F^2;Q^2) = \left(\frac{\alpha_{em}}{2\pi}\right)\gamma_{c\to\gamma^*}(z,\mu_F^2,\alpha_s;Q^2) + \left(\frac{\alpha_s}{2\pi}\right)\sum_d \int_z^1 \frac{dz'}{z'} P_{c\to d}\left(\frac{z}{z'},\alpha_s\right) D_{d\to\gamma^*}(z',\mu_F^2;Q^2)$$

- **Cross section:**

$$\frac{d\hat{\sigma}^{\rm Pert}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \frac{d\hat{\sigma}^{\rm Dir}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} + \frac{d\hat{\sigma}^{\rm Frag}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

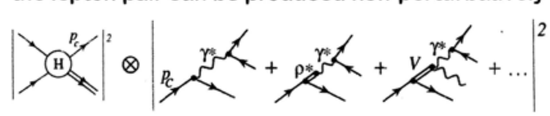
All logarithms! (Frag term)

No logs! (Dir term)

Frag term $\longrightarrow \dfrac{d\hat{\sigma}_{ab\to cX}}{dp_{c_T}^2\,dy} \otimes D_{c\to\gamma^* X}$

Input fragmentation functions

- **"Drell-Yan" – like process $Q_T^2 \gg Q^2 \gg \Lambda_{\rm QCD}^2$:** Berger, Qiu, Zhang 2002
  - lepton pair is mainly from decay of a virtual photon of mass Q
  - $Q(\gg \Lambda_{\rm QCD})$ is a natural regulator for the fragmentation logs
  - Input fragmentation functions are purely perturbative
- **"Direct photon" – like process $Q_T^2 \gg Q^2 \sim \Lambda_{\rm QCD}^2$:** Kang, Qiu, Vogelsang 2009
  - $Q_T(\gg \Lambda_{\rm QCD})$ is a perturbative scale, but $Q(\sim \Lambda_{\rm QCD})$ is not
  - the lepton pair can be produced non-perturbatively



$$D_{f\to\gamma^*}(z,\mu_0^2;Q^2) \equiv D^{\rm QED}_{f\to\gamma^*}(z,\mu_0^2;Q^2) + D^{\rm Nonpert}_{f\to\gamma^*}(z,\mu_0^2;Q^2)$$

Model the input fragmentation functions

- **Extract the input fragmentation functions from data:**
  - input fragmentation functions are process independent
  - "derive" or "model" the functional form of the distributions
  - fix all unknown parameters by fitting available data
- **Our model:**
  - "QED" part:

$$D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2) = e_q^2\left(\frac{\alpha_{\mathrm{em}}}{2\pi}\right)\left[\left(\frac{1+(1-z)^2}{z}\right)\ln\left(\frac{\mu_0^2}{Q^2/z+\lambda^2}\right) - \left(\frac{Q^2}{Q^2/z+\lambda^2} - \frac{Q^2}{\mu_0^2}\right)\right],$$

$$D^{\mathrm{QED}(0)}_{\bar{q}\to\gamma^*}(z,\mu_0^2;Q^2) = D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2), \quad D^{\mathrm{QED}(0)}_{g\to\gamma^*}(z,\mu_0^2;Q^2) = 0.$$

  - "hadronic" part:

$$D^{\mathrm{Nonpert}}_{q\to\gamma^*}(z,\mu_0^2;Q^2) \equiv \kappa D_{q\to V}(z,\mu_0^2)\frac{4\pi\alpha_{\mathrm{em}}}{f_V^2}\left(1-\frac{Q^2}{m_V^2}\right)^3$$

  Further assume: $m_V = m_\rho$, $f_\rho^2/4\pi = 2.2$, and $D_{f\to V} \approx D_{f\to\pi}$

  - fitting parameters: $\lambda(>\Lambda_{\mathrm{QCD}})$, $\kappa(\sim 1)$

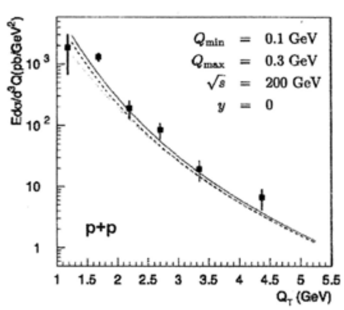
Invariant Cross Section

Kang, Qiu, Vogelsang, PRD 2009

- Definition:

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \equiv \int_{Q^2_{\mathrm{min}}}^{Q^2_{\mathrm{max}}} dQ^2\,\frac{1}{\pi}\,\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy}$$

- Role of non-perturbative fragmentation function:



Data from PHENIX: arXiv:0804.4168

- **Input FF:** $D(z,\mu_0) = D^{\mathrm{QED}}(z) + \kappa\, D^{\mathrm{NP}}(z)$
- **QED alone (dotted):** $\kappa = 0$ at $\mu_0 = 1$ GeV
- **QED + hadronic input (solid):** $\kappa = 1$ at $\mu_0 = 1$ GeV

Hadronic component of fragmentation is very important at low Q_T

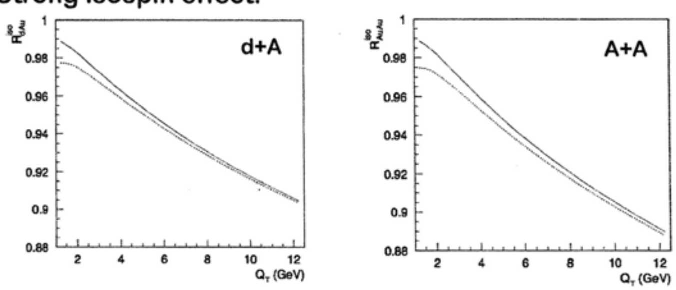
Isospin effect in nuclear collisions

❑ **Definition:**

$$R_{\rm dAu}^{\rm iso} \equiv \frac{\frac{1}{2A} d^2\sigma^{\rm dAu}/dQ_T dy}{d^2\sigma^{pp}/dQ_T dy}$$

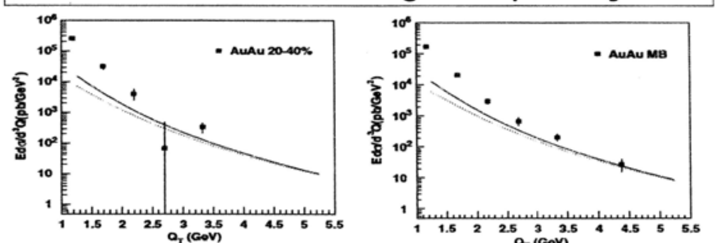
$$f_i^p(x,Q^2) \rightarrow [Z \cdot f_i^p + (A-Z)\cdot f_i^n]/A \qquad i = q, \bar{q}, g$$

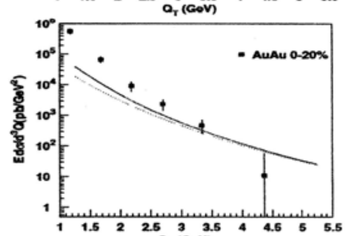
❑ **Strong isospin effect:**



$$\sigma_{qg} \propto \frac{4}{9} f_u^n + \frac{1}{9} f_d^n = \frac{4}{9} f_d^p + \frac{1}{9} f_u^p \qquad f_u^p > f_d^p \longrightarrow \sigma^{nn} < \sigma^{np} = \sigma^{pn} < \sigma^{pp}$$

AuAu data: shadowing + isospin only





– EPS08 nPDFs

$\kappa = 1(\text{solid}),\ \kappa = 0(\text{dotted})$

– Clear enhancement at low Q_T

Effect beyond single scattering?

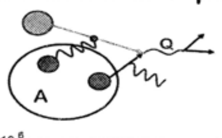
Data from PHENIX: arXiv:0804.4168

Kang, Qiu, Vogelsang, PRD 2009

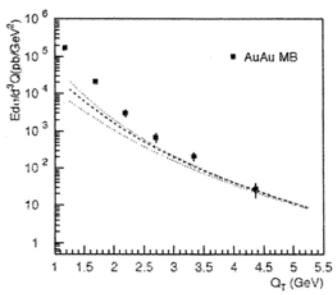
Other nuclear effect: multiple scattering

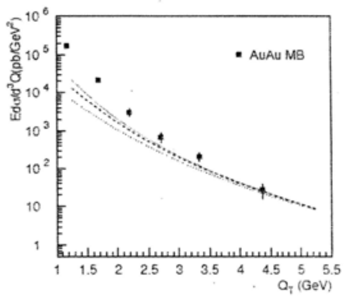
❑ **Initial state multiple scattering – power correction:**

Guo, 1998



Unlike DIS, power correction to lepton pair production is positive





Power correction from cold nuclear matter (solid) is not enough!

March 19, 2010 9 Jianwei Qiu

Summary and outlook

❑ **Hadronic production of low mass lepton pairs at high p_T is perturbatively calculable**

– QCD factorization is as good as that for direct photon production

❑ **Low mass lepton pair production is complementary to direct photon production in extracting gluon distribution**

– Cleaner lepton signals, no complication on isolation cut, but, relatively lower rate

❑ **Nuclear enhanced power corrections from cold nuclear matter alone can not explain the observed excess of lepton pair production at low p_T in AuAu collisions:**

– Thermal photons from sQGP, ...

Thank you!

March 19, 2010 10 Jianwei Qiu

Zvi Citron, Stony Brook University, for the PHENIX Collaboration

"Probing Low x in d+Au and p+p Collisions in PHENIX"

RIKEN-BNL Progress in High P_T Physics at RHIC Workshop
19 March 2010

The saturation of the gluon distribution at low momentum fraction, x, and high parton density is an area of active theoretical interest. Suppression of particle yields is expected due to extremely high gluon density. Forward calorimeters in PHENIX allow the study of parton densities at low x. Mid-rapidity triggered, forward correlated rapidity yields are measured in d+Au collisions at $\sqrt{s}$=200 GeV. The correlated yields per trigger and widths of the azimuthal angular distributions are compared to the same quantities measured in p+p collisions. No significant broadening between d+Au and p+p is observed, but suppression of the correlated yield relative to p+p is observed in more central collisions. In addition, a comparison of the mid-rapidity inclusive yield conditioned on a forward (d going side) trigger is compared to that with a backward (Au going side) trigger and some suppression is observed. Further studies leveraging PHENIX's rapidity acceptance to probe the x of the Au nucleus are underway.

Why Probe Rapidity?

- Forward → Low x

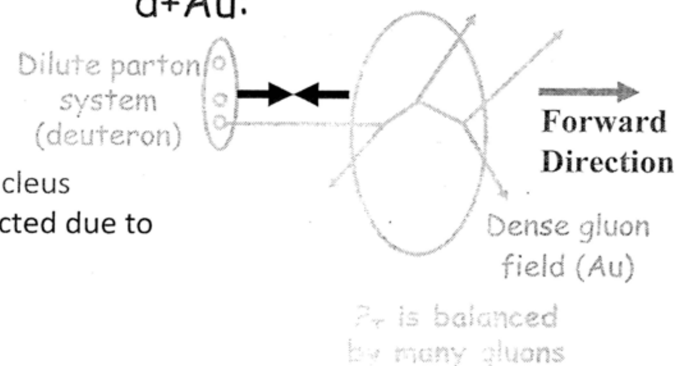
$$x_{g,Au} = \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

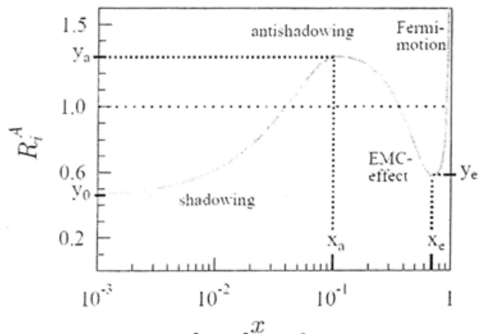
- Probe low-*x* gluon distribution in Au nucleus
  - Suppression of particle yields expected due to extremely high gluon density
  - Gluon saturation
    - Saturation momentum goes like

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

  - Shadowing effects
    - Decorrelation in 2 particle Δϕ distribution
- Rapidity Separated Jets
  - Mueller-Navelet Jets
    - Larger rapidity gap between jets → larger probability for emitting gluons → decorrelation in 2 particle Δϕ distribution
    - d+Au *and* p+p

d+Au:

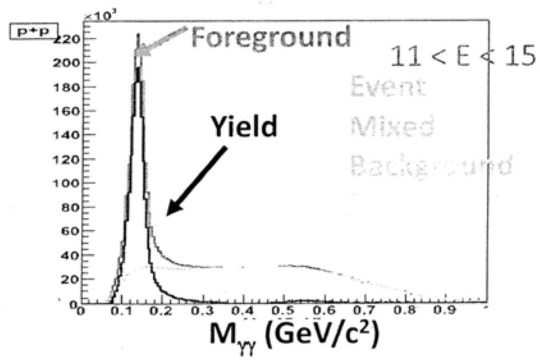




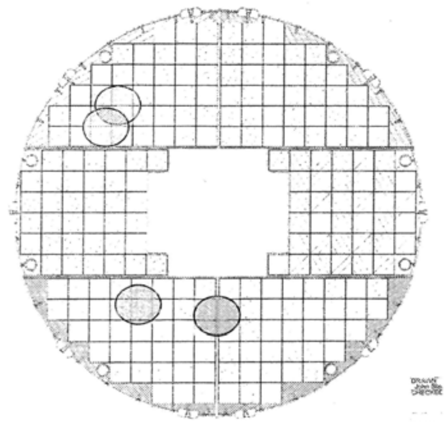
shadowing

PHENIX forward EMCs (MPCs)

- Forward and backward Muon Piston Calorimeters have rapidity $3.1<|\eta|<3.9$
- $2.2 \times 2.2 \times 18\ cm^3$ $PbWO_4$ scintillating crystals
- 220 cm from nominal interaction point
- Detect pions (via $\pi^0 \rightarrow \gamma\ \gamma$) up to ~ *20 GeV*
- Limitations are the tower separation and merging effects (p_T max ~ *2* GeV/c)
- To go to higher p_T, use single clusters
  - Use π^0s for *7* GeV < *E* < *17* GeV
  - Use clusters for *E* > *20* GeV



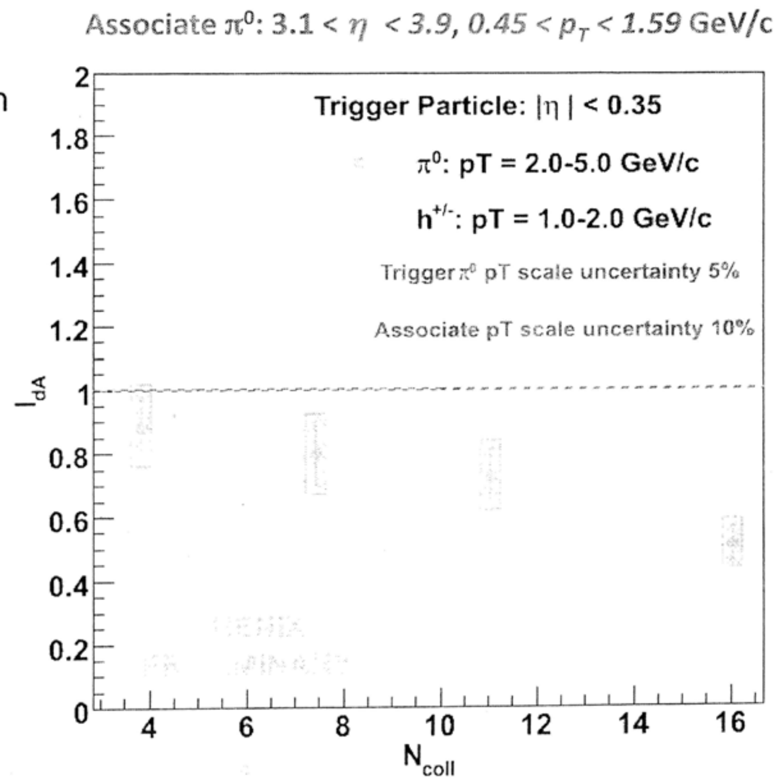
North MPC



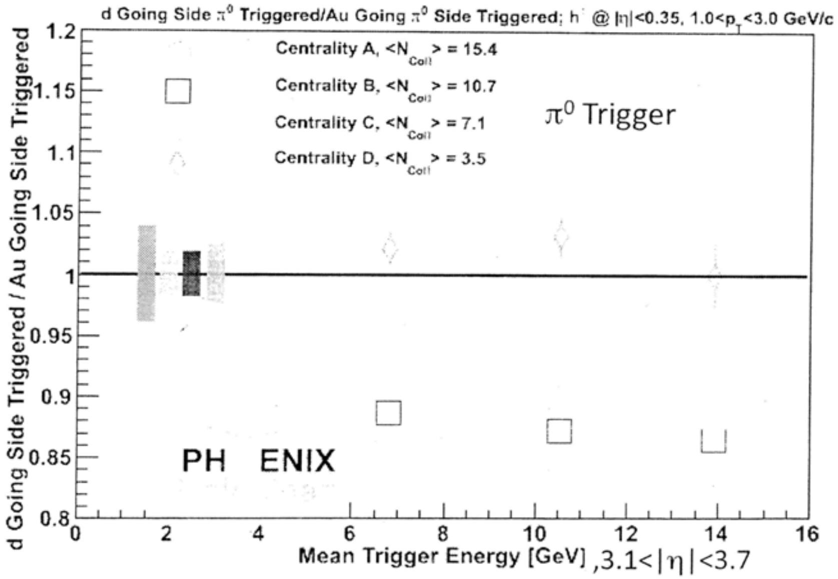
Decay photon impact positions for **low** and high energy π^0s

Forward/Central I_{dA} vs N_{coll}

- Increasing suppression of I_{dA} reaches a factor 2 for central events
- Indicates di-jet suppression
- More model calculations are needed
  - Saturation (Color Glass Condensate)
  - Shadowing
  - Others?



(d side triggered)/(Au side triggered) Ratio Trends



The suppression of the d going side triggered yield relative to the Au going side triggered yield as a function of the trigger energy. (Bands indicate systematic uncertainties from the centrality bias associated with the trigger requirement and possible asymmetries stemming from the higher multiplicity in the Au going side MPC.)

Summary and a Look Forward

- Azimuthal angle correlations for rapidity separated hadron pairs: $|\eta| < 0.35$, $1.4<|\eta|<2.0$ and $|\eta|<0.35$, $3.1<\eta<3.9$
  - No significant broadening between d+Au vs pp within experimental precision
  - Suppression of I_{dA} is observed as one goes to more central collisions for larger $\Delta\eta$ correlations
- Comparison of integrated mid-rapidity yields between forward and backward trigger
  - Suppression of yield in d going side trigger compared to Au going side trigger
  - Comparison of correlated yield coming soon...
- Upcoming
  - Scan different $\Delta\eta$ gaps within PHENIX acceptance
  - Forward-Forward correlations to probe the lowest x

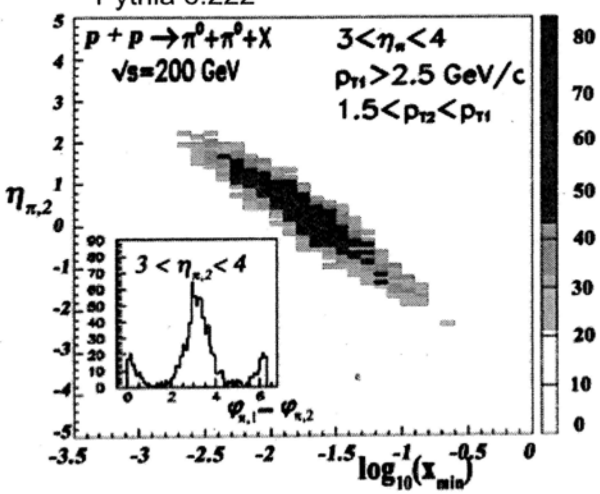
Low-x Measurements at STAR

Hank Crawford
UC Berkeley Space Sciences Laboratory

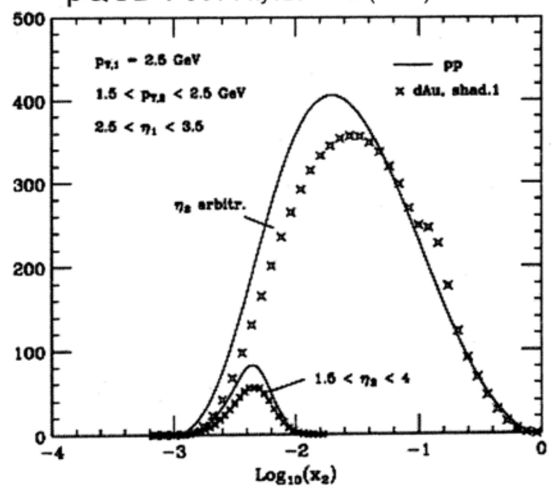
Our program is to investigate the internal structure of the proton. and to determine nuclear gluon densities at low-x to understand energy densities achieved in RHI collisions. Our approach is to measure correlation functions for forward leading π^0 triggers in the pseudo-rapidity interval $3<\eta<4$ with subleading charged tracks having $-1<\eta<1$ or with subleading π^0 having $-1<\eta<4$. I present results from the STAR detector at RHIC from the run8 pp and dAu program, in which we use the Au-side beam-beam counters to provide a measure of collision centrality. Our analysis shows clear evidence for suppression of the correlation for the most central collisions when both the leading and subleading π^0s are in the forward direction, a result consistent with prediction of the Color Glass Condensate model of nuclear parton distributions.

X1 and X2
momentum fractions of interacting partons

Pythia 6.222

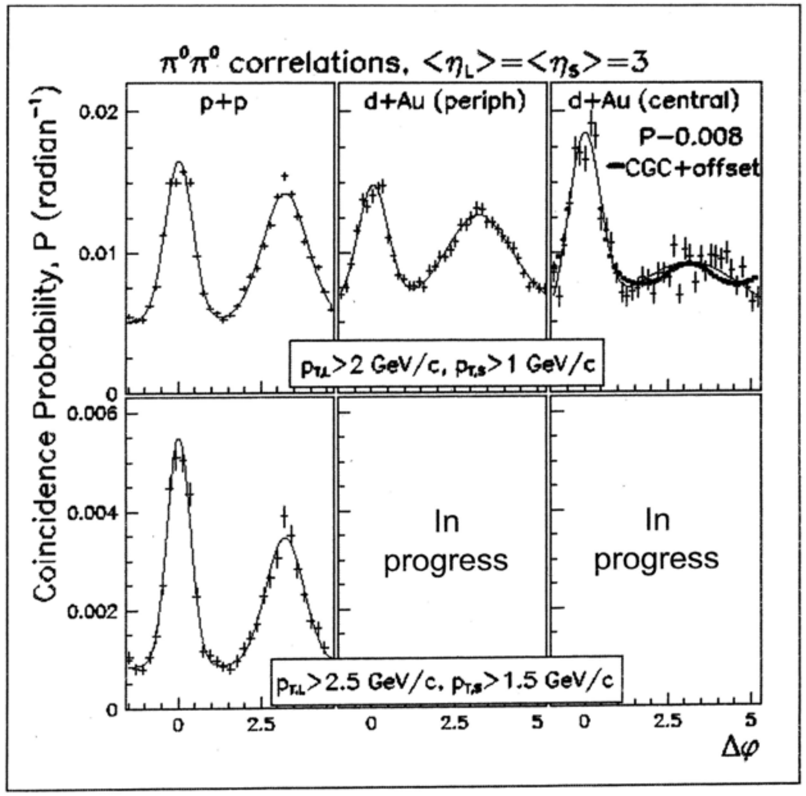


pQCD : GSV PhysLetB 603(2004)173



Get x from correlations between a trigger or leading particle (a π^0 in the FMS) and a subleading particle (a TPC track hadron, or a BEMC π^0, or another FMS π^0)

FMS-FMS Data



Blue is from Marquette
See below

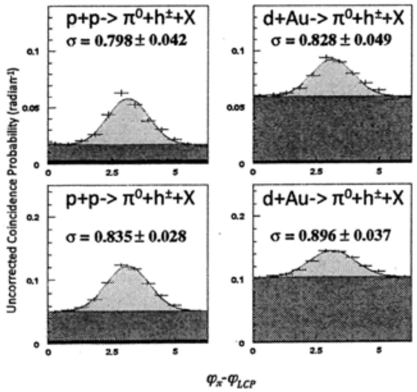
Spanning -1<η<4.1 with FMS trigger

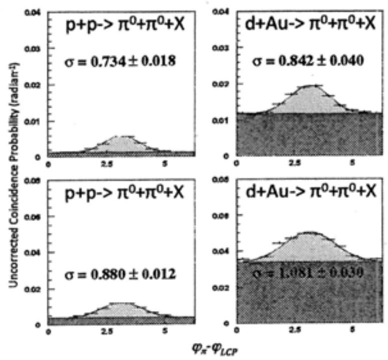
π^0h-mid, $\pi^0\pi^0$-mid, $\pi^0\pi^0$-fwd

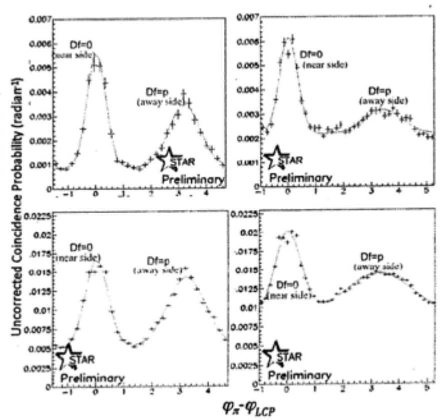
Made possible by STAR coverage

Centrality averaged

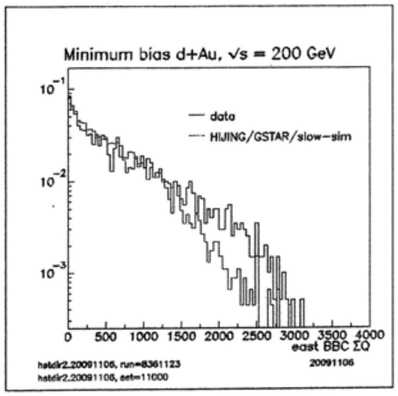
2 trigger p_Ts each

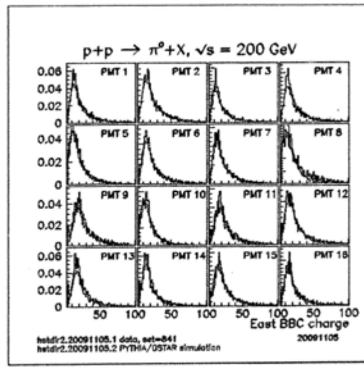


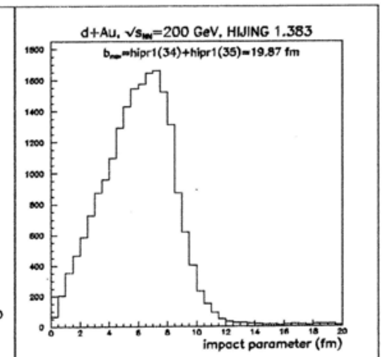




Impact parameter b in Hijing

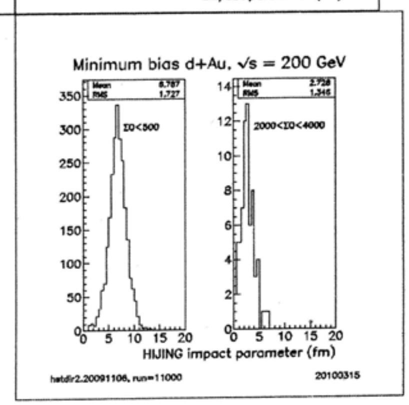






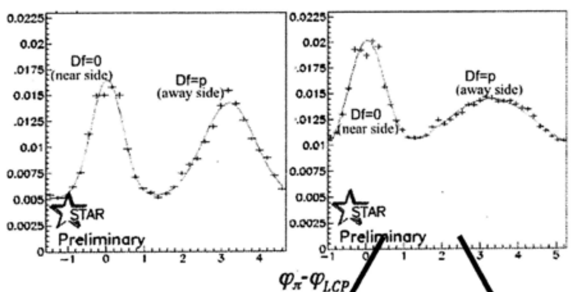
ΣQ_{BBCE}

min	max	<b> (fm)	RMS.b (fm)
0	500	6.8	1.7
2000	4000	2.7	1.3

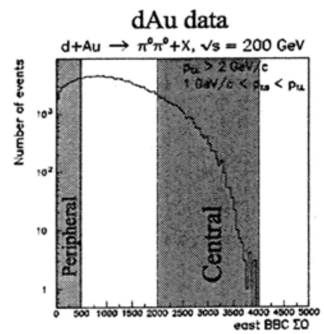


Centrality dependence of correlations

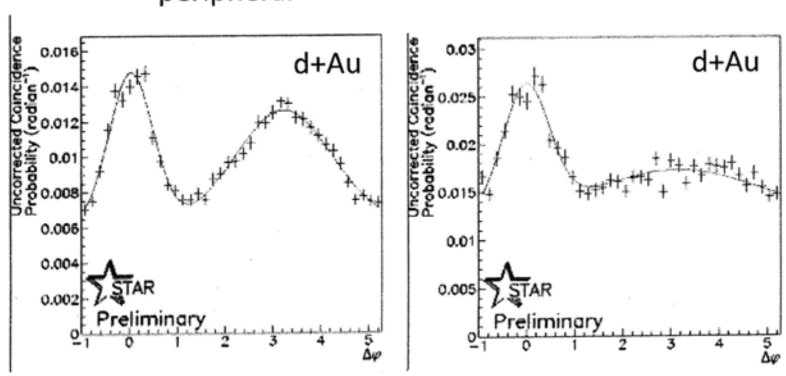
p+p d+Au



$p_{TL}^{(FMS)}$>2.0GeV
$p_{TS}^{(FMS)}$>1.0GeV



peripheral central



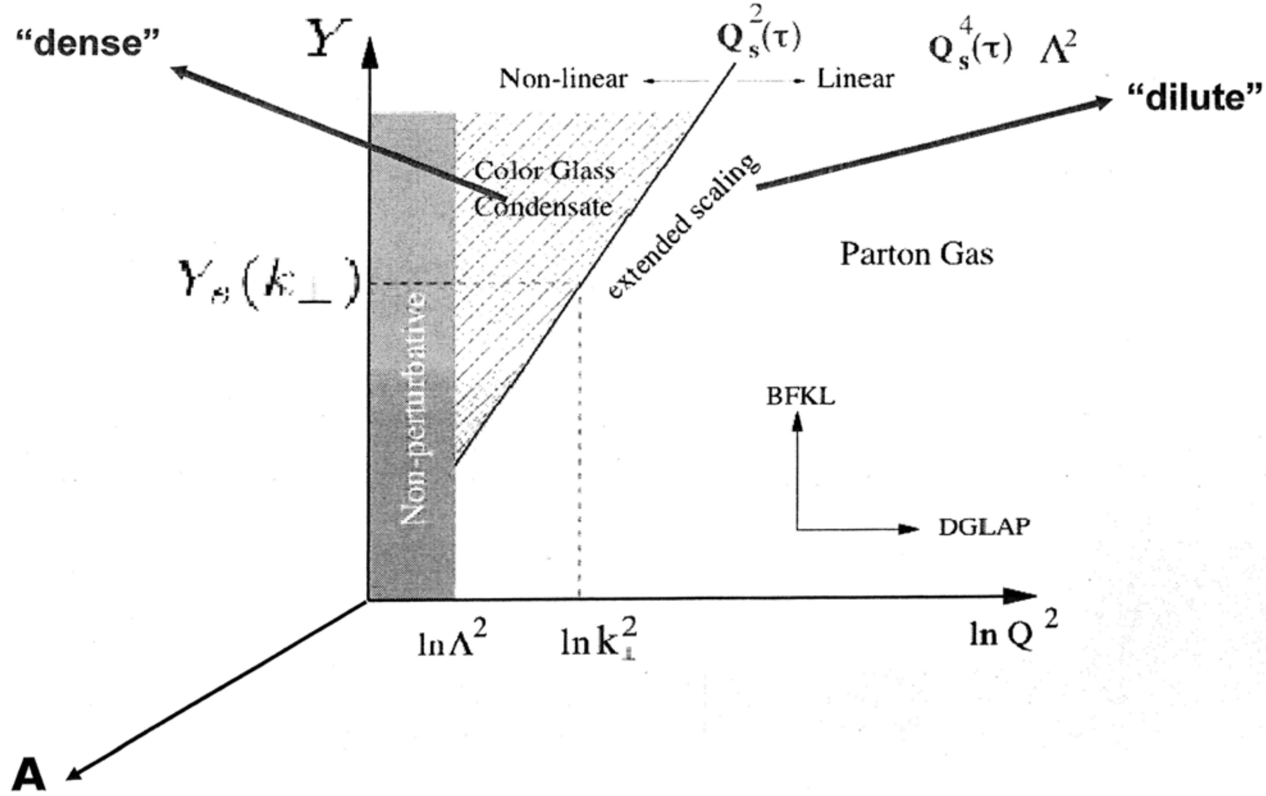
- Near-side peak similar p+p vs. d-Au
- Away-side signal changing with centrality:
- Peripheral d+Au collisions similar to p+p
- Central d+Au collision show strong suppression

Photon-Hadron Correlations

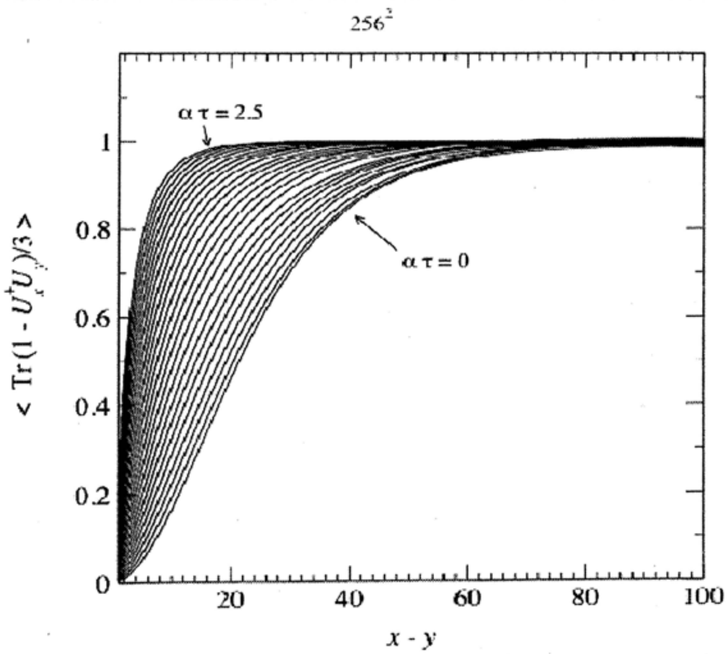
Jamal Jalilian-Marian, Baruch College

Short summary:
The Color Glass Condensate formalism is used to calculate photon-hadron azimuthal angular correlations in deuteron-gold collisions at RHIC. It is shown that saturation effects lead to a disappearance of the away side correlations as one lowers the transverse momenta of the hadron and photon. The qualitative behavior of the correlation function is very similar to that of hadron-hadron correlation. Photon-hadron correlations have the advantage of being more robust theoretically.

Road Map of QCD



The two point function (dipole cross section)



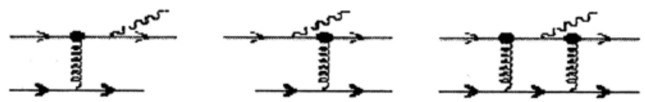
$$N_F(p_t) \rightarrow \frac{1}{p_t^2} \log \left[\frac{Q_s^2}{p_t^2}\right]$$

$$N_F(p_t) \rightarrow \frac{1}{p_t^2} \left[\frac{Q_s^2}{p_t^2}\right]^\gamma$$

$$N_F(p_t) \rightarrow \frac{1}{p_t^2} \left[\frac{Q_s^2}{p_t^2}\right]$$

KR+HW, NPA739 (2004) 183
NLO: B-BC-KW (2007-2008)

$$\mathbf{q(p)\,T \rightarrow q(q)\,\gamma(k)\,X}$$



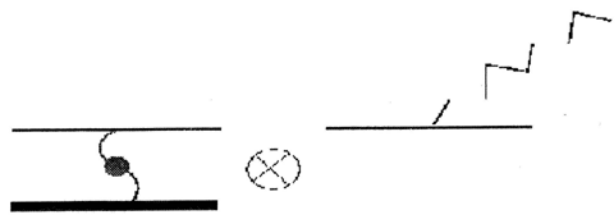
$$\frac{d\sigma^{d\,A\rightarrow h\,\gamma\,X}}{d^2b_t\,dq_t^2\,dk_t^2\,dy_\gamma\,dy_h\,d\theta} = a\int_{z_{min}}^{1}\frac{dz}{z^5}\,f_{q/d}(x_p,Q^2)$$

$$D_{h/q}(z,Q^2)[z^2+(\frac{q^-}{q^-+zk^-})^2]\,\frac{(\tilde{q}_t+z\tilde{k}_t)^2}{(k^-\tilde{q}_t-q^-\tilde{k}_t)^2}N_F(|\tilde{q}_t/z+\tilde{k}_t|)$$

FG-JJM, PRD66 (2002) 014021
JJM, EPJC61 (2009) 789

pQCD limit

near side: collinear divergence $\theta \rightarrow 0$

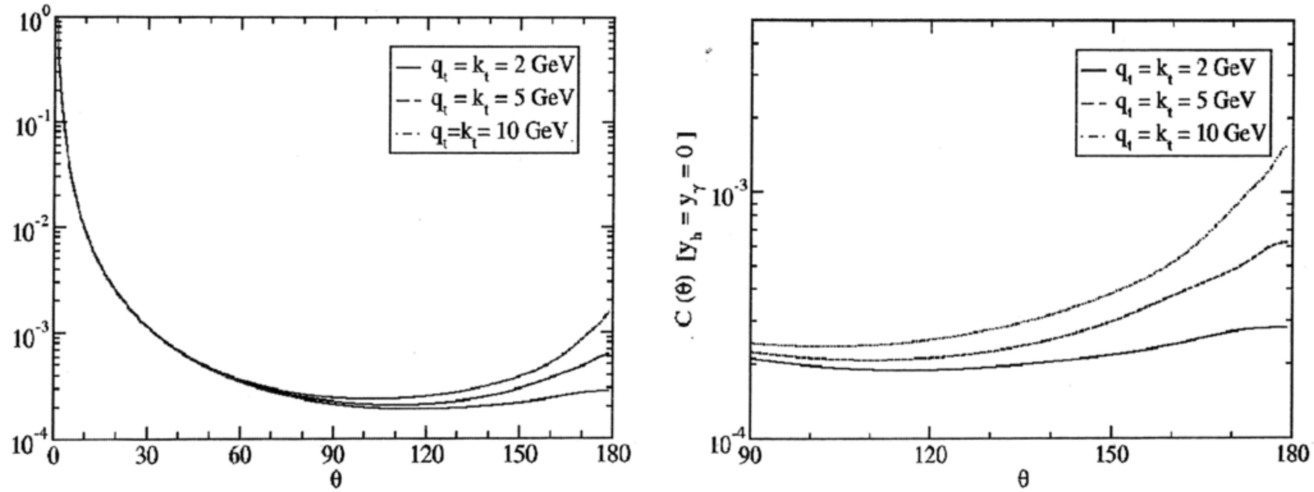


$$N_F \otimes D_{\gamma/q}$$

away side: $\theta \rightarrow \pi$

$$p_t >> Q_s$$

Photon-Hadron correlations:dA



$$\mathbf{C}(\theta) \equiv \frac{\mathbf{d}\sigma}{\mathbf{dq_t^2\, dk_t^2\, dy_h\, dy_\gamma\, d}\theta} \Bigg/ \int \mathbf{d}\theta \frac{\mathbf{d}\sigma}{\mathbf{dq_t^2\, dk_t^2\, dy_h\, dy_\gamma\, d}\theta}$$

Transverse Λ polarization and small-x physics

Daniël Boer

KVI, University of Groningen, Zernikelaan 25, 9747 AA Groningen, The Netherlands

It is well-known that Λ hyperons produced in unpolarized pp collisions are to a large degree polarized transversely to the production plane. There have been many experimental and theoretical investigations aimed at understanding this striking polarization phenomenon, but consensus has yet to be reached about its origin. At high p_T a factorized description should be applicable. In this talk we discuss such a description involving a transverse momentum and spin dependent fragmentation function $D_{1T}^{\perp}$ [1]. It offers a description of the available pp and pBe data for Λ transverse momenta above 1 GeV [2], but whether this p_T cut is sufficient to guarantee the validity of the description is matter of concern [3].

Polarized Λ data from the high-energy hadron colliders RHIC, Tevatron or LHC, would be very welcome but their capabilities to measure Λ polarization via $\Lambda \to p\,\pi^-$ are usually restricted to the midrapidity region, where the degree of transverse polarization is very small. A new jet+Λ observable [4,5] that does not need to vanish at midrapidity, could allow for a more trustworthy extraction of $D_{1T}^{\perp}$ and subsequent predictions. It could also shed light on the role of gluons fragmenting into Λ's, as there appears to be an inconsistency between pp and e^+e^- Λ production data [6] that still awaits clarification.

Another suggestion for colliders is to try to use neutral decays $\Lambda \to n\,\pi^0$ to measure Λ polarization at forward rapidities. This could then offer a direct probe of gluon saturation [7]. The transverse polarization of forward Λ's produced in high-energy $p\,A$ collisions is expected to display a peak at a transverse momentum around the saturation scale. This was first observed within the context of the McLerran-Venugopalan model which has an x-independent saturation scale [7]. The extremum arises due to the k_T-odd nature of the polarization dependent fragmentation function $D_{1T}^{\perp}$, which probes approximately the derivative of the dipole scattering amplitude. The amplitude changes most strongly around the saturation scale, resulting in a peak in the polarization. This observation also extends to the more realistic case in which the saturation scale Q_s is x dependent [8]. Since a range of x values and hence of Q_s values is probed at a given transverse momentum and rapidity, this result is *a priori* not expected. The measurement of Λ polarization over a range of x_F values actually provides a direct probe of the x dependence of the saturation scale. This novel feature is demonstrated for typical LHC kinematics for both pp and $p\,Pb$ collisions and for several phenomenological models of the dipole scattering amplitude. The situation at RHIC is not favorable, because the peak will likely be at too low transverse momentum of the Λ to be a trustworthy measure of the saturation scale.

[1] Mulders, Tangerman, Nucl. Phys. B 461 (1996) 197.
[2] Anselmino, Boer, D'Alesio, Murgia, Phys. Rev. D 63 (2001) 054029.
[3] Anselmino, Boer, D'Alesio, Murgia, Phys. Rev. D 65 (2002) 114014.
[4] Boer, Bomhof, Hwang, Mulders, Phys. Lett. B 659 (2008) 127.
[5] Boer, DIS2009 proceedings, arXiv:0907.1610
[6] Albino, Kniehl, Kramer, Nucl. Phys. B 803 (2008) 42.
[7] Boer, Dumitru, Phys. Lett. B 556 (2003) 33.
[8] Boer, Utermann, Wessels, Phys. Lett. B 671 (2009) 91.

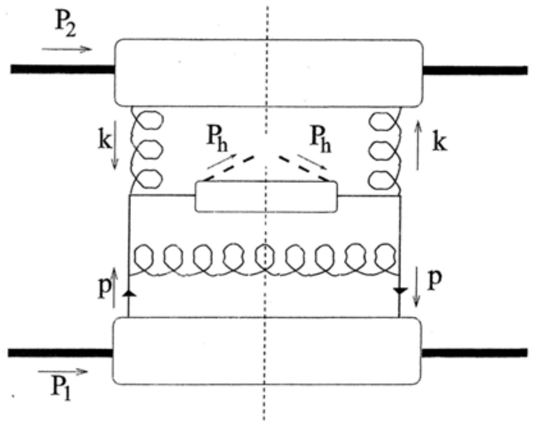
Collinear factorization

Consider for example the $qg \to qg$ subprocess

$$\sigma \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \to qg} \otimes D_{\Lambda/q}(z)$$

$$q(x_1) = \text{quark density}$$
$$g(x_2) = \text{gluon density}$$
$$D_{\Lambda/q}(z) = \Lambda \text{ fragmentation function}$$

$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \to qg} \otimes ?$$

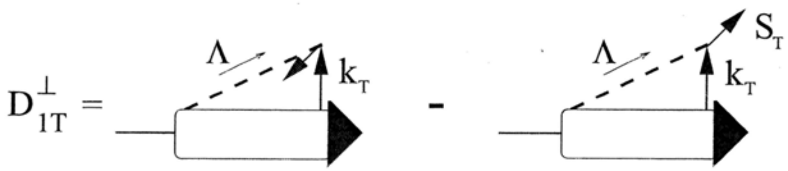


No leading twist collinear fragmentation function exists for $q \to \Lambda^\uparrow X$ (due to symmetry reasons)

Would be necessarily higher twist, which leads to a fall-off as $1/p_T$

Noncollinear factorization

Dropping the requirement of *collinear* factorization, does allow for a solution



Mulders & Tangerman, NPB 461 (1996) 197

- Transverse momentum dependent: $D_{1T}^{\perp}(z, \boldsymbol{k}_T)$
- A nonperturbative $\boldsymbol{k}_T \times \boldsymbol{S}_T$ dependence in the fragmentation process
- Allowed by the symmetries (parity and time reversal)

Λ polarization arises in the fragmentation of an *unpolarized* quark
Hence, the suggested name "polarizing fragmentation function"

High energy hadron collider data?

Validity of factorized description depends on a proper cross section description
This requires data at higher energies and higher p_T

Except for ISR, all data is from fixed target experiments, with $\sqrt{s} \lesssim 60$ GeV, requiring large K factors

Why no $\Lambda^\uparrow$ data from high energy hadron colliders, such as RHIC or Tevatron?

Capabilities to measure Λ polarization via $\Lambda \to p\,\pi^-$ are usually restricted to the midrapidity region, where the degree of transverse polarization is very small

$P_\Lambda = 0$ at $\eta = 0$ in $p\,p$ collisions in cms

Alternative: consider jet+Λ production: $p\,p \to (\Lambda^\uparrow \text{jet})$ jet X
Such an asymmetry does not need to vanish at $\eta = 0$

D.B., Bomhof, Hwang, Mulders, PLB 659 (2008) 127; D.B., arXiv:0907.1610

Hadron production in the saturation regime

The cross section of forward hadron production in the (near-)saturation regime:

pdf $\otimes$ dipole cross section $\otimes$ FF

Dumitru, Jalilian-Marian, PRL 89 (2002) 022301

Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the dipole cross section

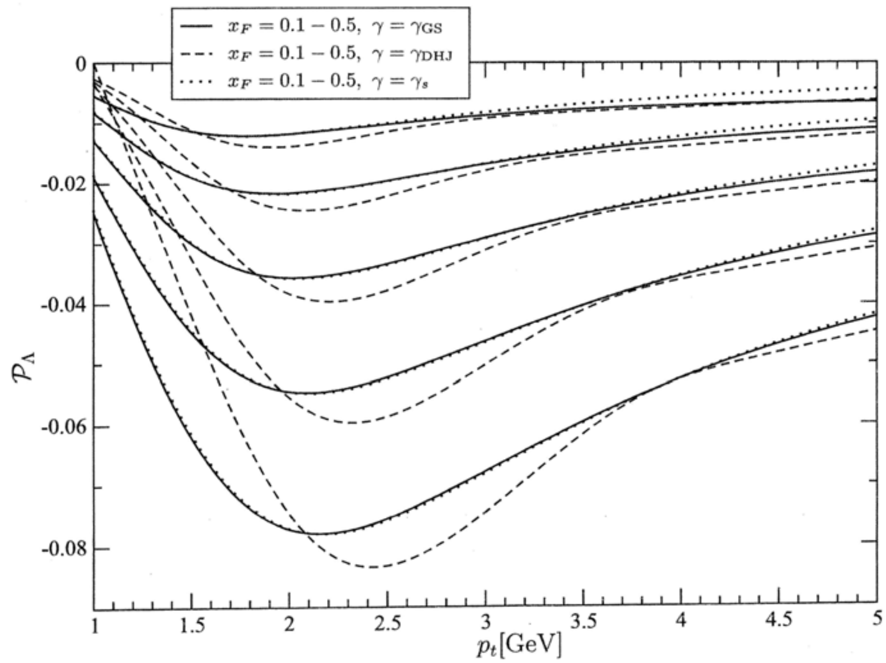
At transverse momenta of $\mathcal{O}(Q_s)$ the dipole cross section changes much

This leads to a Q_s-dependent peak in the Λ polarization

First demonstrated for the McLerran-Venugopalan model, which has constant Q_s
D.B. & Dumitru, PLB 556 (2003) 33

For an x-dependent Q_s a range of Q_s values is probed, so *a priori* not clear whether this signature remains

Λ polarization in $p + Pb \to \Lambda^{\uparrow} + X$ at $\sqrt{s} = 8.8$ TeV



D.B., Utermann, Wessels, PLB 671 (2009) 91

TMDs in two-photon production

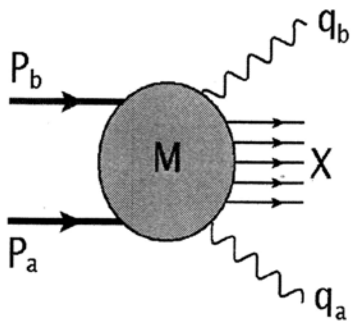
Marc Schlegel

Institute for Theoretical Physics
University of Tuebingen

in collaboration with W. Vogelsang and A. Metz

"Progress in High-p_T Physics at RHIC", BNL

Diphoton production



Two highly energetic real photons produced with

$$q \equiv q_a + q_b$$

$$\frac{d\sigma}{d^4 q_a\, d^4 q_b} = \frac{d\sigma}{d^4 q\, d^4 q_a} \propto \frac{\delta^+(q_a^2)\delta^+((q-q_a)^2)}{2 \times 4F} \sum_X |M|^2 \delta^{(4)}(P_a + P_b - q - P_X)$$

Convenient choice: Diphoton rest frame → **Collins-Soper frame** $\frac{d^6\sigma}{dy\, dQ^2\, d^2\vec{q}_T\, d\Omega_a}$

Unfortunately: No separation into ***hadronic – photonic*** parts possible!
→ *all* angular modulations are allowed, in principle.

$$\frac{d^6\sigma}{dy\, dQ^2\, d^2\vec{q}_T\, d\Omega_a} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} C_{lm}(y, Q^2, q_T^2)\, Y_{lm}(\Omega_a)$$

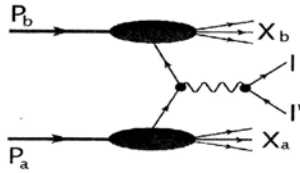
$$C_{..} = \frac{d^4\sigma}{dy\, dQ^2\, d^2 q_T}, \ldots$$

However, we can calculate the cross section in the parton model.

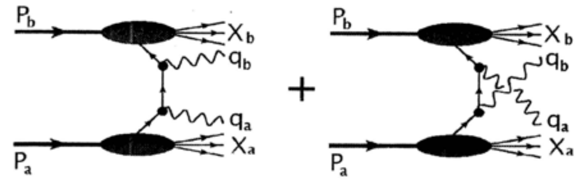
TMD tree-level formalism

Parton model tree-level at O(α_s^0):

Drell-Yan dilepton production:



Dilepton production:



Only relevant at very small q_T: $\Lambda_{QCD} \sim q_T \ll Q$

$$\left(\frac{d\sigma}{d^4q\,d\Omega}\right) \propto \int d^2k_{aT} \int d^2k_{bT}\,\delta^{(2)}(\vec{k}_{aT}+\vec{k}_{bT}-\vec{q}_T)\,\mathrm{Tr}\Big[\Phi\,(x_a,\vec{k}_{aT})\,H(x_a,x_b,q_a,q_b)\,\bar{\Phi}\,(x_b,\vec{k}_{bT})\,H^{\dagger}\Big]+\mathcal{O}(\tfrac{M}{Q})$$

k_T - correlator: $\Phi_{ij}(x,\vec{k}_T) = \int \frac{dz^-\,d^2z_T}{(2\pi)^2}\,\mathrm{e}^{ik\cdot z}\langle P,S|\,\bar{q}_j(0)\,\mathcal{W}^{?/DY}[0\,;\,z]\,q_j(z)\,|P,S\rangle\Big|_{z^+=0}$

→ can be parameterized in terms of TMDs according to quark / nucleon spin

Main result of the TMD tree-level formalism:

$$\left(\frac{d^6\sigma^{hh\to\gamma\gamma X}}{dy\,dQ^2\,d^2q_T\,d\Omega}\right)(\Lambda\sim q_T\ll Q) = \frac{2}{\sin^2\theta}\left(\frac{d\sigma^{hh\to l^+l^-X}}{dy\,dQ^2\,d^2q_T\,d\Omega}\right)(\Lambda\sim q_T\ll Q\,|\,e_q\to e_q^2)$$

Sivers effect in photon pair production

Assume azimuthal symmetry:

$$\int_0^{2\pi} d\phi \, \frac{d\sigma_{TU}^{DP/DY}}{d^4q\, d\Omega} = \frac{\alpha^2}{2SQ^2}|\vec{S}_{aT}|\sin\phi_a \left[\frac{2}{\sin^2\theta}\right](1+\cos^2\theta)F_{TU}^{DP/DY} + \mathcal{O}(M/Q)$$

$$F_{TU}^{DP/DY} = -\sum_{q,\bar{q}} e_q^{4/2}\frac{1}{N_c}\int d^2k_{aT}\int d^2k_{bT}\,\delta^{(2)}(\vec{k}_{aT}+\vec{k}_{bT}-\vec{q}_T)\,\frac{\vec{q}_T\cdot\vec{k}_{aT}}{|\vec{q}_T|M} f_{1T}^{\perp,q}(x_a,\vec{k}_{aT}^2) f_1^{\bar{q}}(x_b,\vec{k}_{bT}^2)$$

<u>Apply Gaussian ansatz with sign switch:</u>

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

Work at larger rapidity

$|\eta_{a,b}| < 3\,,\ \sqrt{S} = 200\,\mathrm{GeV}$

TMD-range: $0\,\mathrm{GeV} < q_T < 0.4\,\mathrm{GeV}$

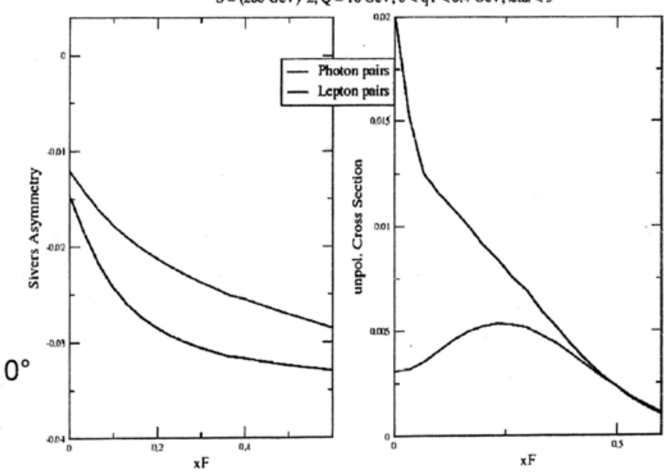
Find ~ 1.5 – 2 larger effect

$\frac{2}{\sin^2\theta}$ → factor of 4 at θ = 30°, 33 at θ = 10°

$e_q^2 \to e_q^4$ u-quark dominance

Sivers Asymmetry and unpol. Cross Section vs. xF

S = (200 GeV)^2, Q = 10 GeV, 0 < qT < 0.4 GeV, |etal < 3

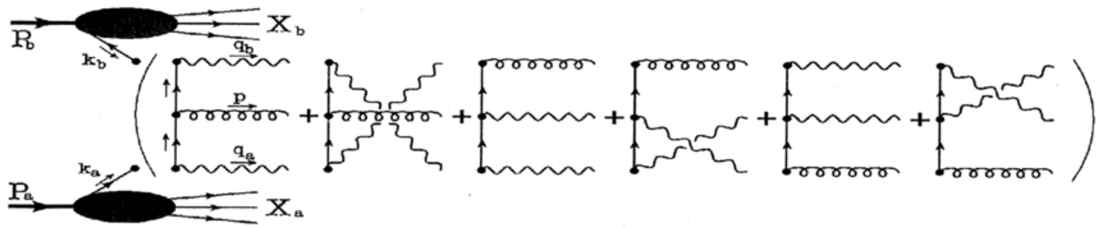


Marc Schlegel (UTüb.) "Progress in High-p_T Physics", BNL March 19, 2009

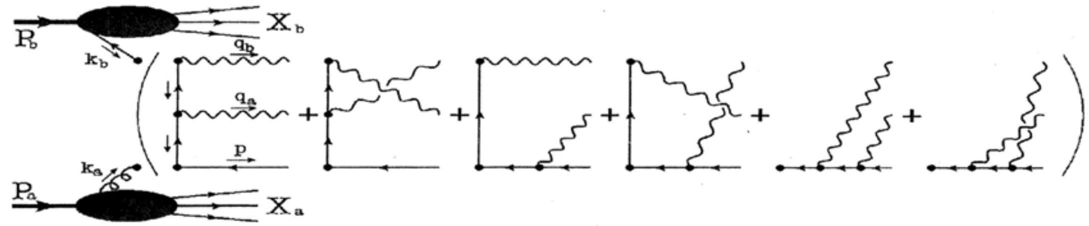
High - q_T of the photon pair

Same strategy as for DY:

quark – antiquark scattering:



quark – gluon scattering:

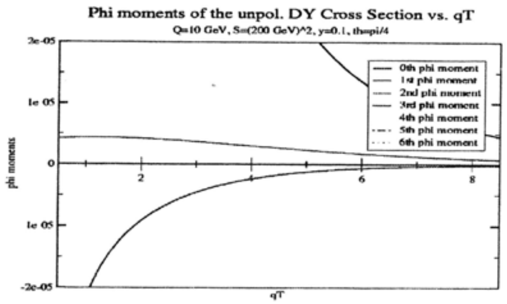


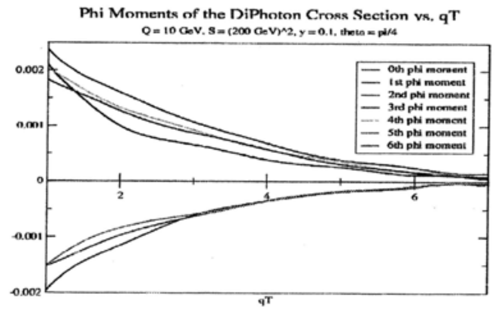
However: No model-independent angular decomposition!

Diphoton angles enter the partonic cross section in numerator and denominator
→ All angular depedencies are allowed.

Numerical results

Define phi moments: $$\langle\cos(n\phi)\rangle = \int_0^{2\pi} d\phi\, \cos(n\phi) \frac{d\sigma}{dy\, dQ^2\, d^2q_T\, d\Omega}$$

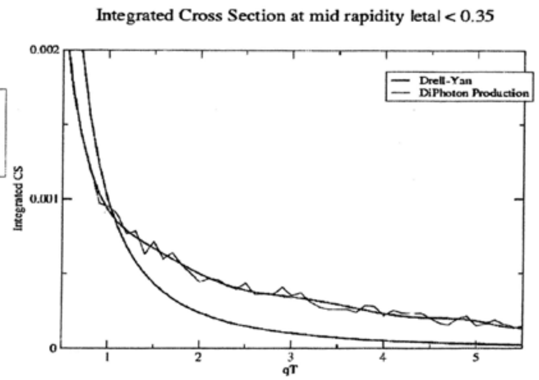




Cross Section at mid rapidity:

$$\int dy \int d\Omega \frac{d\sigma}{dy\, dQ^{\text{٢}}\, d^{\text{٢}}q_T\, d\Omega} \Theta\left(|\eta_{a,b}| < \text{٠.٣٥}\right)$$

At larger qT:
→ DiPhoton cross section larger



Medium modified fragmentation functions and PDFs [1]

Rodolfo Sassot

Departamento de Fisica, FCEN, Universidad de Buenos Aires

We perform a detailed phenomenological analysis of how hard hadronization processes occurring in nuclear environments can be described in terms of effective fragmentation functions. These fragmentation functions, that are assumed to factorize from the cross sections and evolve in the hard scale in the same way as the standard or vacuum fragmentation functions, are found to differ significantly with the latter in shape and magnitude. Based on very precise data on semi-inclusive lepton-nuclei deep inelastic scattering and hadroproduction in deuteron-gold collisions, we perform an extraction of these effective fragmentation functions for pions and kaons at NLO accuracy. The results, which include a rather accurate description of the kinematical dependence of the different cross sections, support the validity of factorization and universality, at least in an effective way, and within the precision of the available data.

---

[1]Progress in high pT physics at RHIC, Brookhaven, March 2010

Medium-modified fragmentation functions and nPDFs

Rodolfo Sassot
Universidad de Buenos Aires

in collaboration with M. Stratmann and P. Zurita

Phys.Rev.D81 054001 (2010)

Progress in high pT phyisics at RHIC, Brookhaven, March 2010

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Motivation

high pT hadroproduction in pA and AA: RHIC, LHC

study hadronization in different environments

factorization & universality in a nucleus?

relevant for the extraction of nPDFs

Phenomenology:

Early evidence:

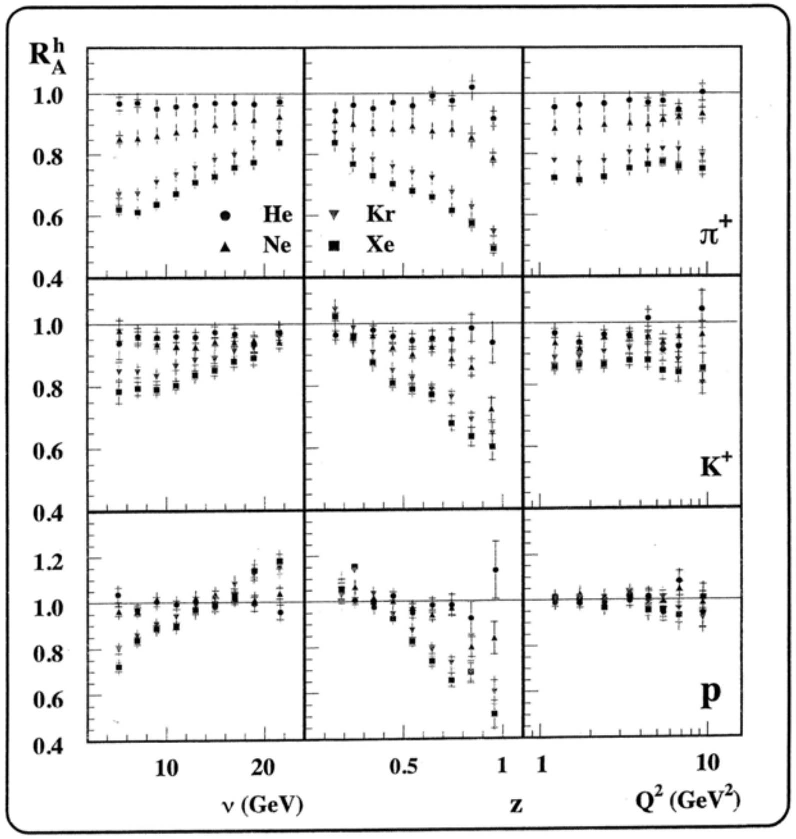
SLAC Phys.Rev.Lett. 40, 1624 (1978)
EMC Z.Phys. C52, 1 (1991)
E665 Phys.Rev. D50, 1836 (1994)

Precise SIDIS:

HERMES Nucl. Phys.B 780 1 (2007);

Precise dAu:

PHENIX Phys.Rev.Lett.98 172302 (2007).
STAR Phys.Lett.B616, 8 (2005)
B637, 161 (2006)



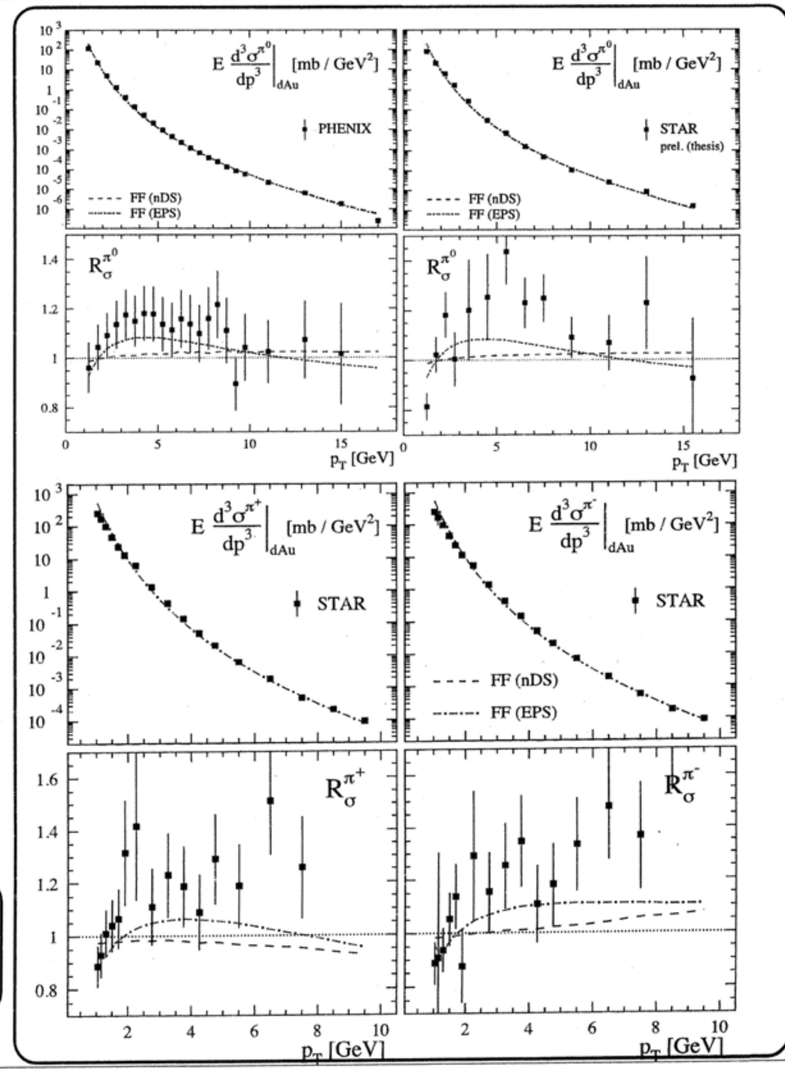
Phenomenology:

PHENIX Phys.Rev.Lett.98
172302 (2007).

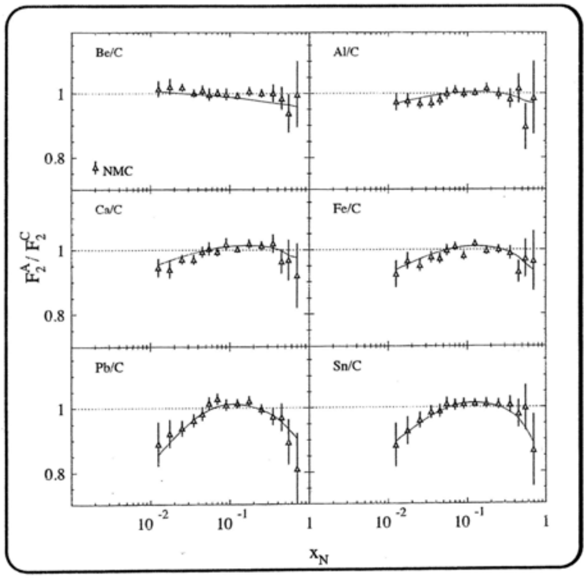
STAR Phys.Lett.B616, 8 (2005)
B637, 161 (2006)

O.Grebenyuk, Ph.D.Thesis,
arXiv:0909.3006.

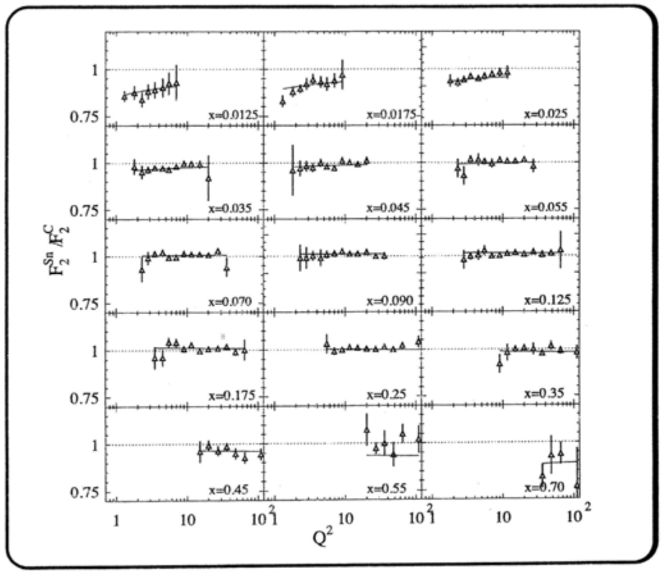
$$R^H_\sigma(A, p_T) \equiv \frac{1}{2\,A}\,\frac{E\,d^3\sigma^H/dp^3\big|_{dA}}{E\,d^3\sigma^h/dp^3\big|_{pp}}$$



Do nuclear effects factorize into PDFs and FFs?



DIS rates to D



Drell-Yan rates to D / scale dependence

$$f_{i/p}(x, Q^2) \longrightarrow f_{i/A}(x, Q^2)$$

$$D^h_{i/p}(z, Q^2) \longrightarrow D^h_{i/A}(z, Q^2) \quad ?$$

Jet measurements in p-p and A-A collisions

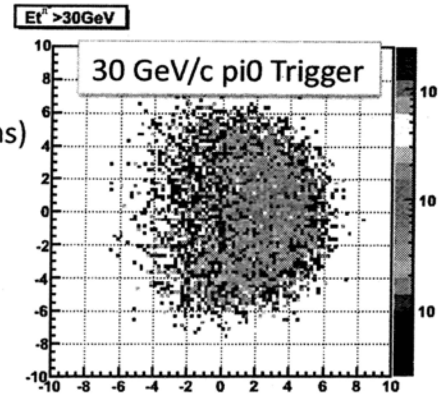
Mateusz Ploskon (LBNL) for the STAR Collaboration

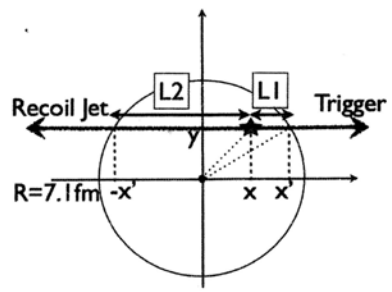
- Outline:
  - Introduction – tools of heavy-ion collisions
  - Inclusive jet cross-section and pQCD at RHIC in p-p collisions
  - Jet quenching via single hadron observables
    - Success and limitations
  - Full jet reconstruction in heavy-ion collisions
  - Jet quenching using fully reconstructed jets in heavy-ion collisions
  - Outlook

Quantitative analysis: tools of heavy-ion collisions

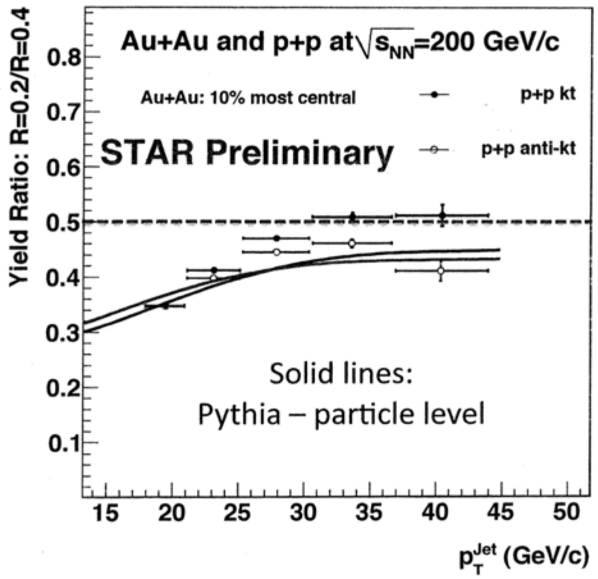
- Inclusive cross-sections
  - Scaling of x-section ("Glauber"; e.g. hard x-sec ~ Nbinary collisions)
- Correlation measurements
  - Observable "B" under a condition "A" (trigger)
- Control over geometry
  - Correlations with reaction plane
- Jet quenching
  - Geometric biases – use to the extreme
  - Color charged probes
  - Color neutral probes
- "Discovery by/through deviation"
  - use p-p and p-A collisions as references for A-A measured observables

- Interpretation -> Dependent upon modeling (!)



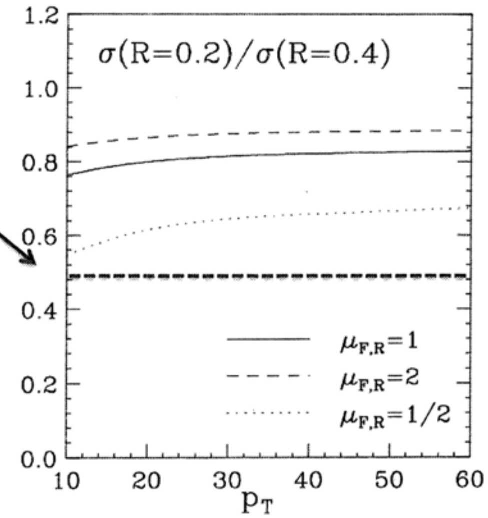


p+p: cross-section ratio R=0.2/R=0.4



Narrowing of structure with increasing energy

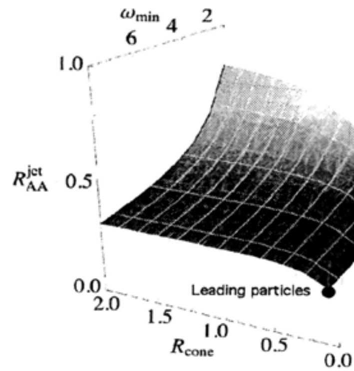
NLO Calculation
W. Vogelsang – priv. comm. 2009



NLO: narrower jet profile

➔fragmentation+hadronization effects?

Complete Jet Reconstruction in Heavy Ion Collisions: why bother?



Jet quenching is a *partonic* proces

➔obscured by hadronization

High p_T hadron triggers bias towards non-interacting jets

➔suppresses the jet population that interacts the most

➔no access to dynamics of energy loss

Soft hadron correlations (p_T<few GeV/c) are difficult to interpret as QCD jets

➔requires strong analysis and modeling assumptions

➔ no clear connection to theory

Goal of full jet reconstruction: integrate over hadronic degrees of freedom to measure medium-induced jet modifications at the *partonic* level ➔ much more detailed connection to theory

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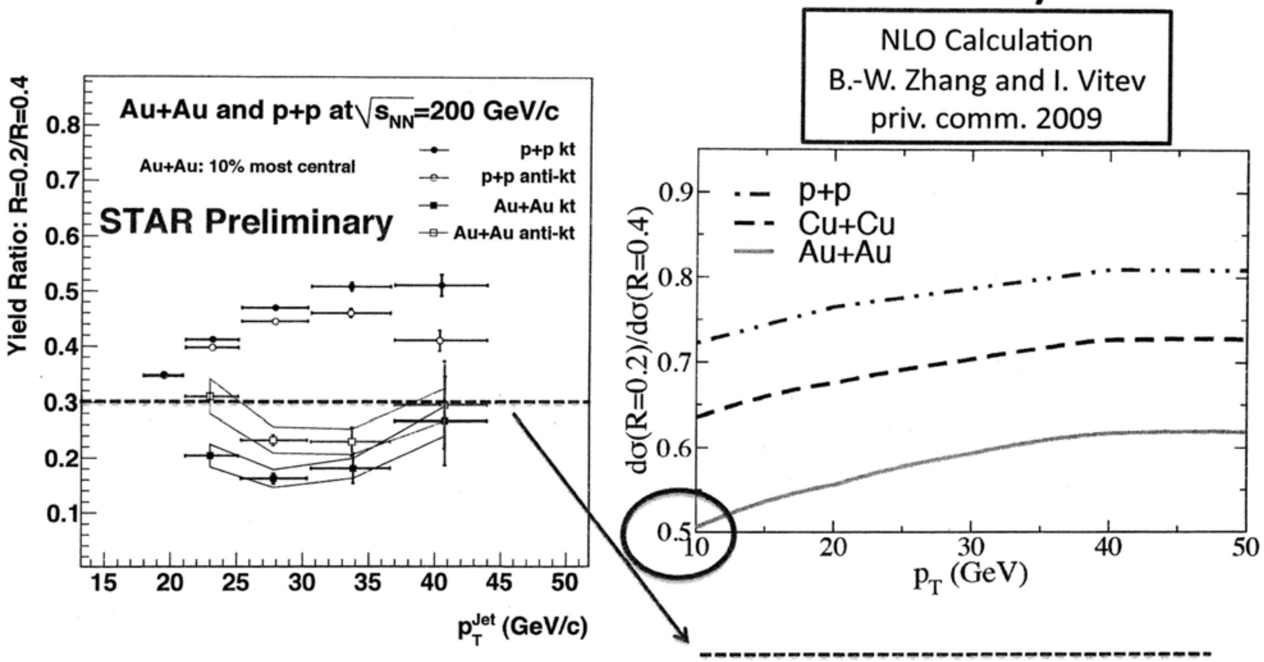
Au+Au: cross-section ratio R=0.2/R=0.4



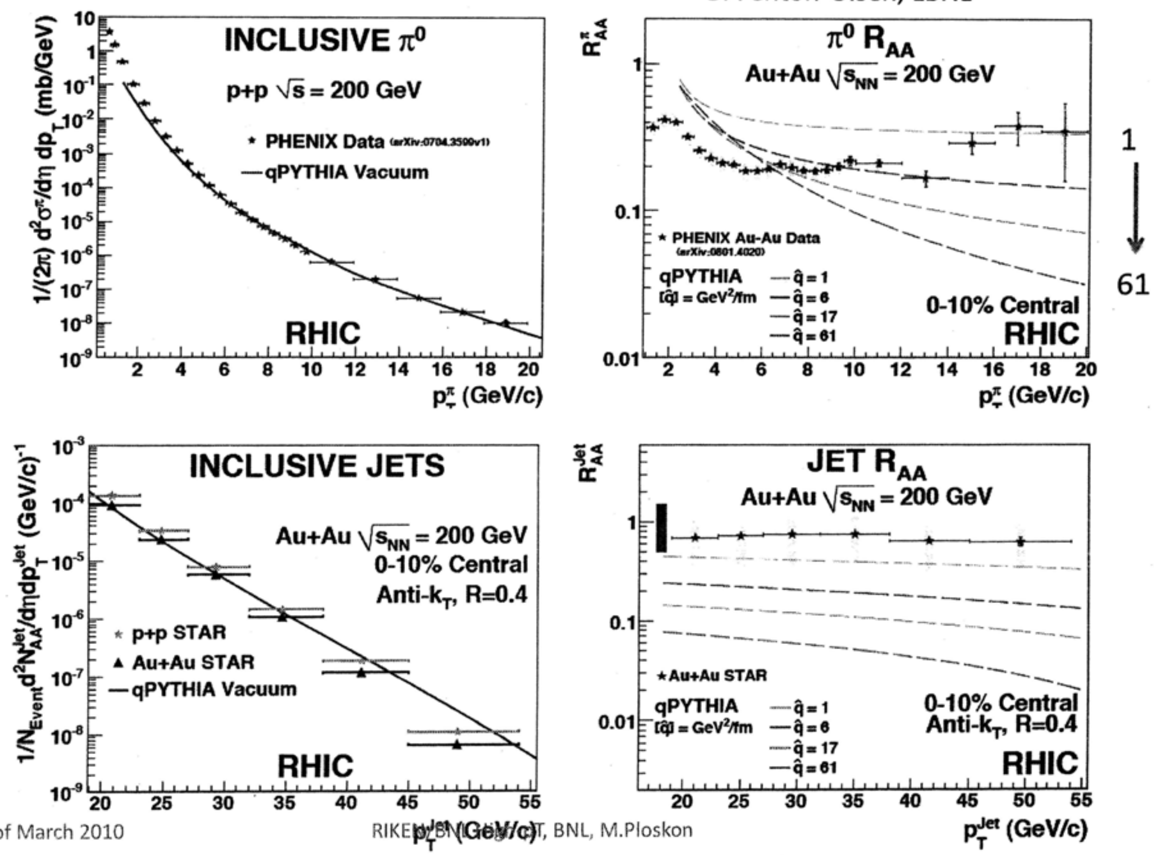
Stronger broadening seen in measurement than NLO calculation…

➔strong hadronization effects? (that would be unfortunate)

qPYTHIA vs RHIC data

Eur. Phys J C (2009) 63; 679-690
hep-ph 0907.1014v1

B. Fenton-Olsen, LBNL



Summary and Outlook

Complete jet reconstruction promises qualitatively new insight into jet interactions in matter

➔major focus of RHIC II and LHC HI programs
➔has stimulated significant new theory activity

First results from fully reconstructed jets from STAR/RHIC show significant broadening of the jet structure in HI collisions

But significant technical issues for systematically well-controlled measurements

➔main issue: HI background characterization
➔high backgrounds expected also in high luminosity p+p at LHC

More on jets from STAR: E. Bruna [STAR] Nucl.Phys.A830:267c-270c,2009
H. Caines [STAR] Nucl.Phys.A830:263c-266c,2009; arXiv:0911.3211v1 [nucl-ex]

$\sqrt{s}$ Dependence of Pion Distributions

Martin L. Purschke, BNL

for the PHENIX collaboration

We present an overview of pion distributions at various center-of-mass energies. So far, RHIC has provided energies of 200, 62.4, and 22.4 GeV for proton-proton and heavy-ion collisions, and 500 GeV for proton-proton collisions.

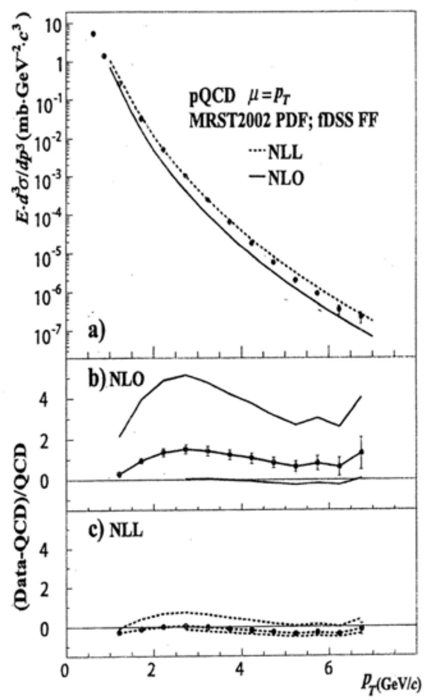
Recent Run 9 proton-proton data at 500 GeV show a modest change in π^0 yields as a function of x_T from 200 GeV and 62.4 GeV, and agree with NLO calculations within 30%. The 62.4 GeV data may need an inclusion of NLL contributions to explain the yields.

While the proton-proton data only exhibit a moderately different behavior for the different energies, the distributions obtained in heavy ion collisions show more pronounced differences. The nuclear modification factor R_{AA} quantifies the difference of a distribution in a heavy ion collision compared to a simple superposition of the equivalent number of independent proton-proton collisions. A R_{AA} of 1 means that the heavy-ion collision can be explained as such a simple superposition; deviations from one indicate additional effects.

We show R_{AA} values as a function of p_T for different values of $\sqrt{s}$ for different centralities and collision systems. There is a systematic trend that higher energies, higher centralities, and larger collision systems show a higher hadron suppression, that is, a R_{AA} value significantly below 1, going as low as 0.2 for the most central collisions in Au + Au, while the R_{AA} value for photons remain around 1. Hadrons are suppressed, while photons are not. However, there is a significant difference between the data at $\sqrt{s} = 22.4$ GeV, which is so far only available for Cu + Cu data. Instead of a suppression, the 22.4 GeV data show a Cronin enhancement. Since the suppression and a R_{AA} value below 1 is found in all systems at "standard" RHIC energies (62.4 and 200 GeV), this means that there is a transition from enhancement to suppression somewhere between 22.4 and 62.4 GeV.

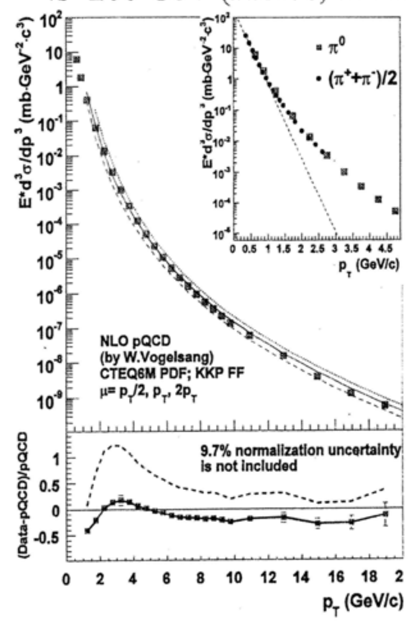
π^0 spectrum and NLO: $\sqrt{s}$=62, 200 and 500 GeV

$\sqrt{s}$=62 GeV (PRD79, 012003)



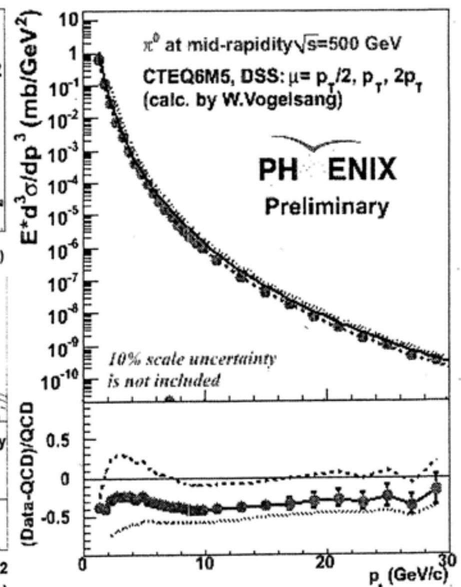
inclusion

$\sqrt{s}$=200 GeV (PRD76, 051106)



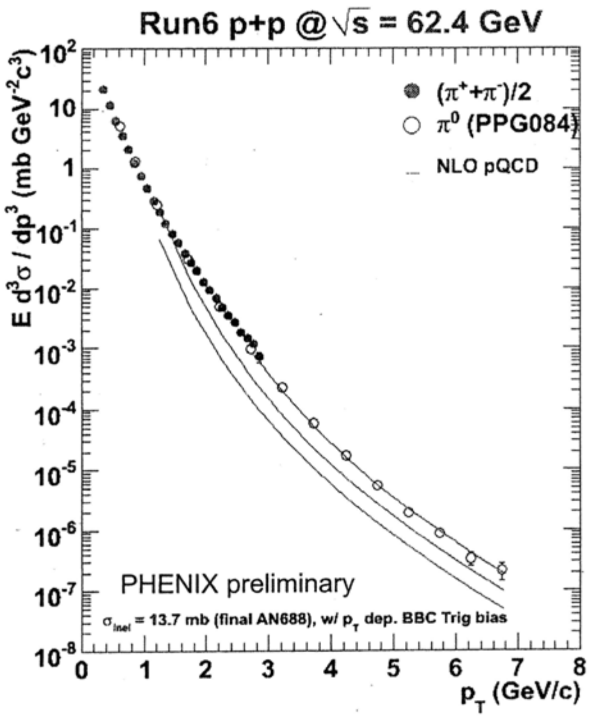
Data below NLO at $\mu=p_T$ by (25±15)%

$\sqrt{s}$=500 GeV (Preliminary)



Data below NLO at $\mu=p_T$ by (30±15)%

Comparison of π^0 with π^{+-}

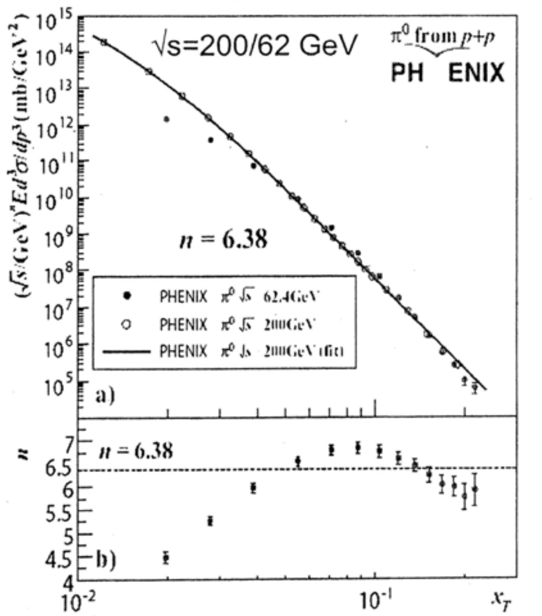


π^0: PRD 79, 012003 (2009), PHENIX

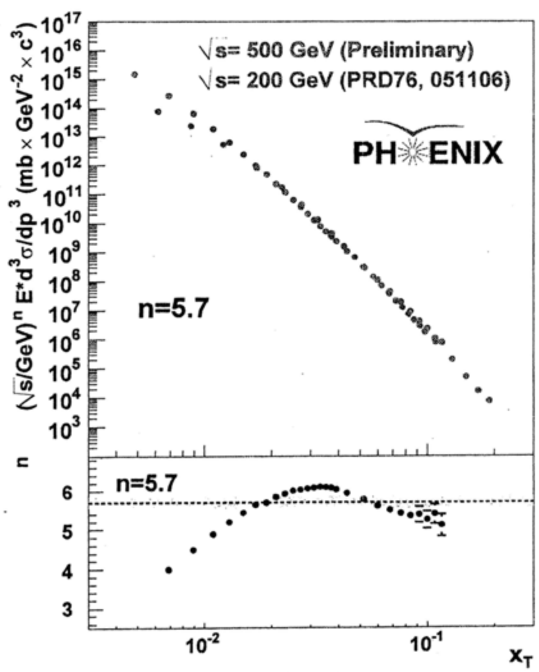
$\pi^{\pm}$: PHENIX preliminary

Good agreement between charged pions and neutral, ~10%.

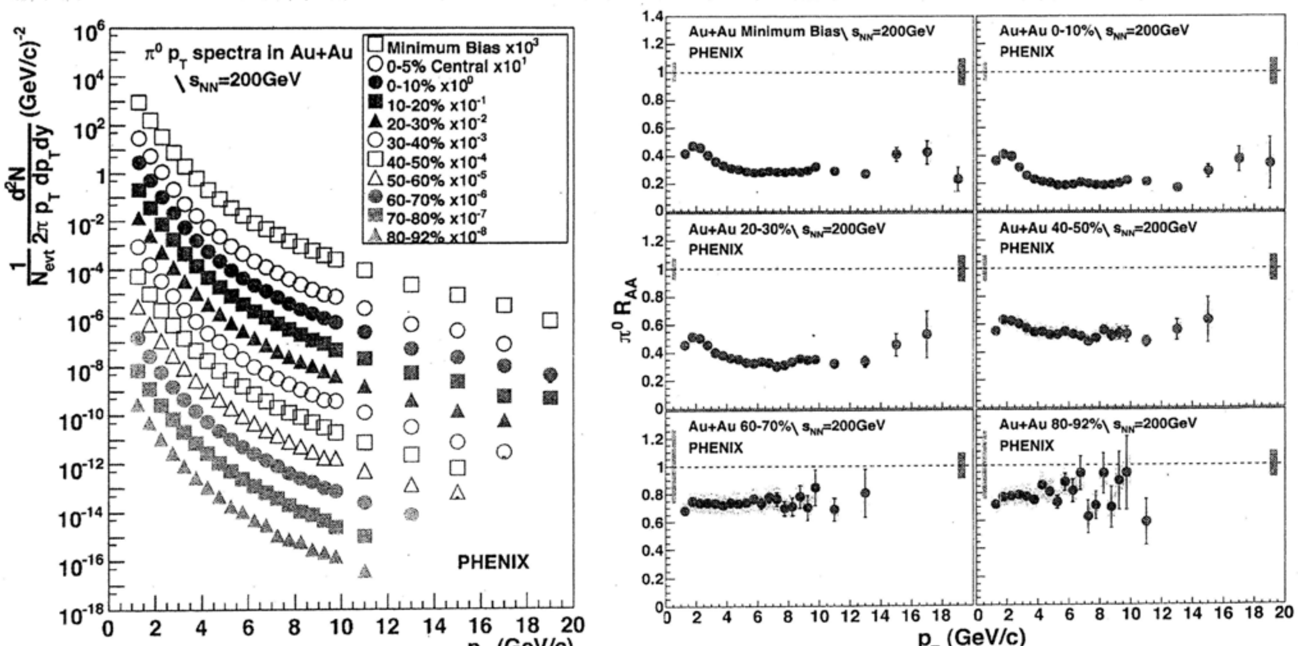
x_T scaling 62, 200, 500 GeV



√s=500/200 GeV



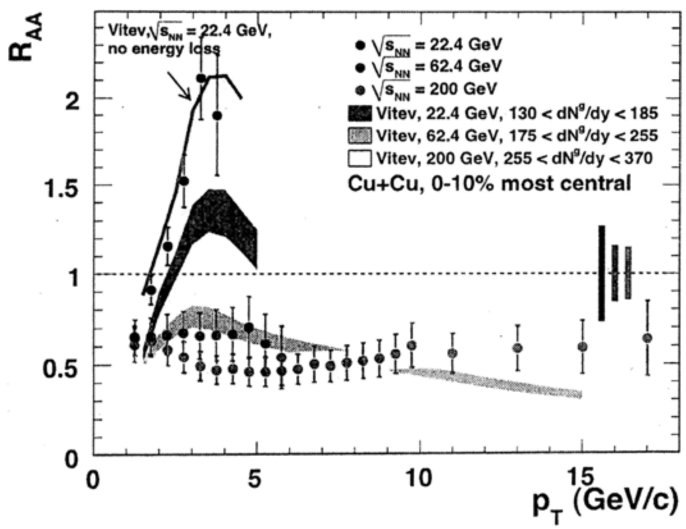
Example: π^0 Spectra in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



PHENIX, arXiv:0801.4020 [nucl-ex]

- π^0 R_{AA} measured up to p_T = 20 GeV/c (central Au+Au)
- Constant $R_{AA} \approx 0.2$ in central Au+Au up to highest p_T ($5 < p_T < 20$ GeV/c)

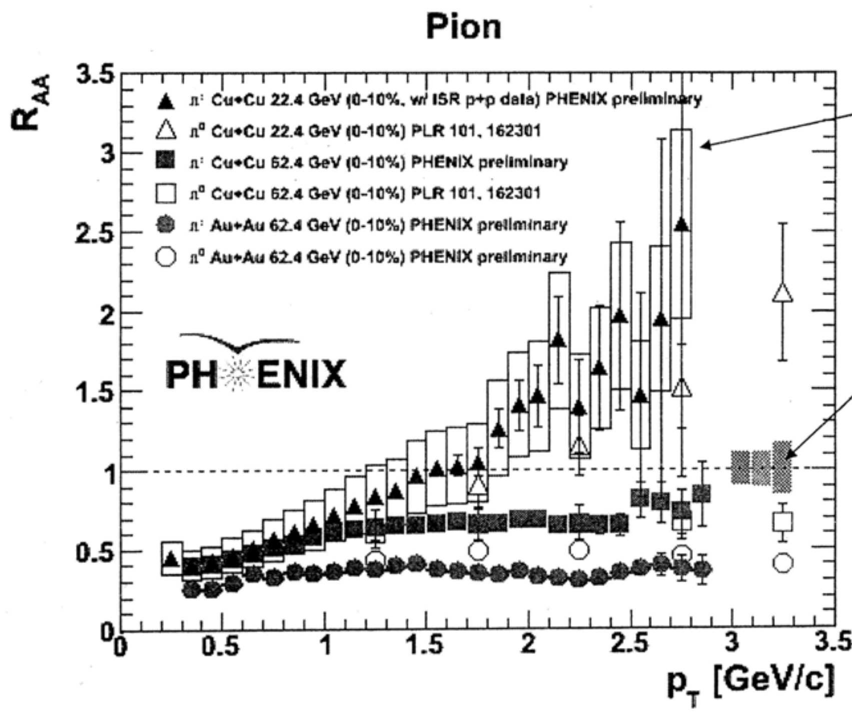
p_T Dependence of π^0 R_{AA} in Cu+Cu



PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - Suppression consistent with parton energy loss for p_T > 3 GeV/c
- 22.4 GeV:
  - No suppression
  - Enhancement consistent with calculation that describes Cronin enhancement in p+A
- Parton energy loss starts to compensate Cronin enhancement between 22.4 and 62.4 GeV

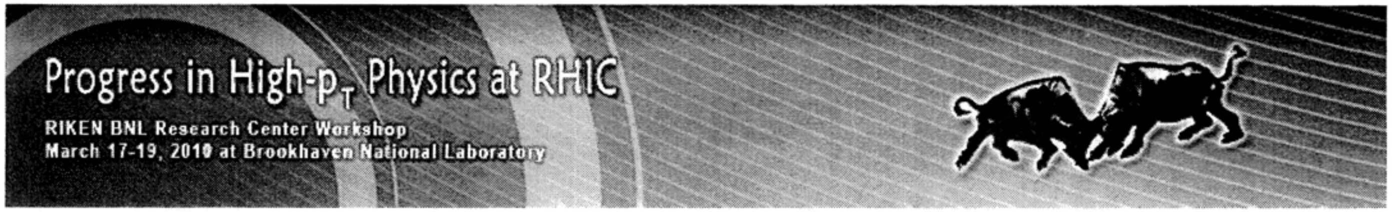
Neutral and charged pion R_{AA} in Cu+Cu



Cu+Cu 22.4 GeV:
(box) ISR p+p sys. error

Ncoll sys. error
- Cu+Cu 22.4 GeV (0-10%): black
- Cu+Cu 62.4 GeV (0-10%): blue
- Au+Au 62.4 GeV (0-10%): red

Normalization error for p+p 62.4 GeV (11%) is not shown here.



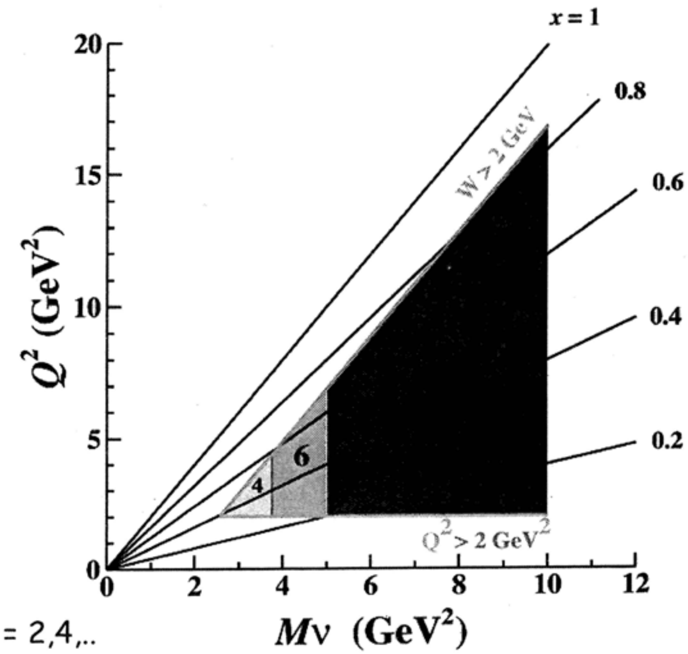
Nucleon Spin Structure Studies at JLab

Zein-Eddine Meziani
Temple University

- Longitudinal nucleon spin structure at large x
- Quark-gluon correlations and the color Lorentz force

Nucleon structure in the valence region

- Access to very large x (x > 0.4)
  - Clean region
    - No strange sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions.

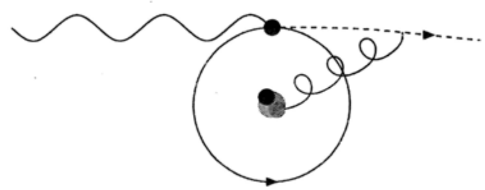


$$M_n(Q^2) = \int_0^1 dx\, x^{n-2}\, F_2(x, Q^2) \qquad n = 2,4,...$$

$$M_n(Q^2) = \int_0^1 dx\, x^{n-1}\, g_1(x, Q^2), \qquad n = 1,3,5...$$

Average Color Lorentz Force (M. Burkardt)

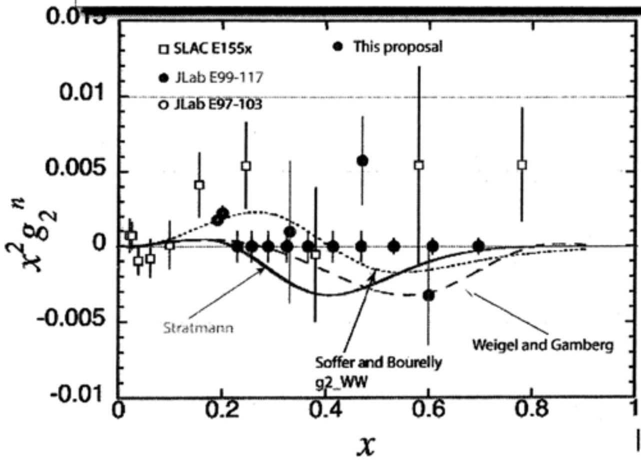
$$\int dx x^2 \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \left\langle P, S \left| \bar{q}(0) g G^{+y}(0) \gamma^+ q(0) \right| P, S \right\rangle$$



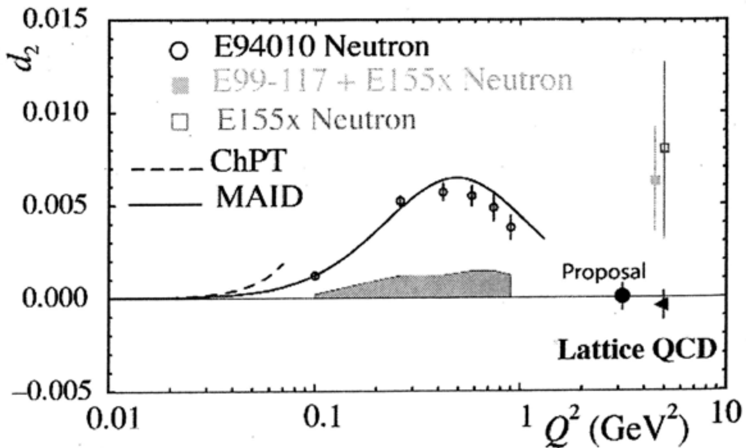
$\hookrightarrow$ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

Expected precision in Experiment E06-114



- At large Q^2, d_2 coincides with the reduced twist-3 matrix element of gluon and quark operators
- At low Q^2, d_2 is related to the spin polarizabilities



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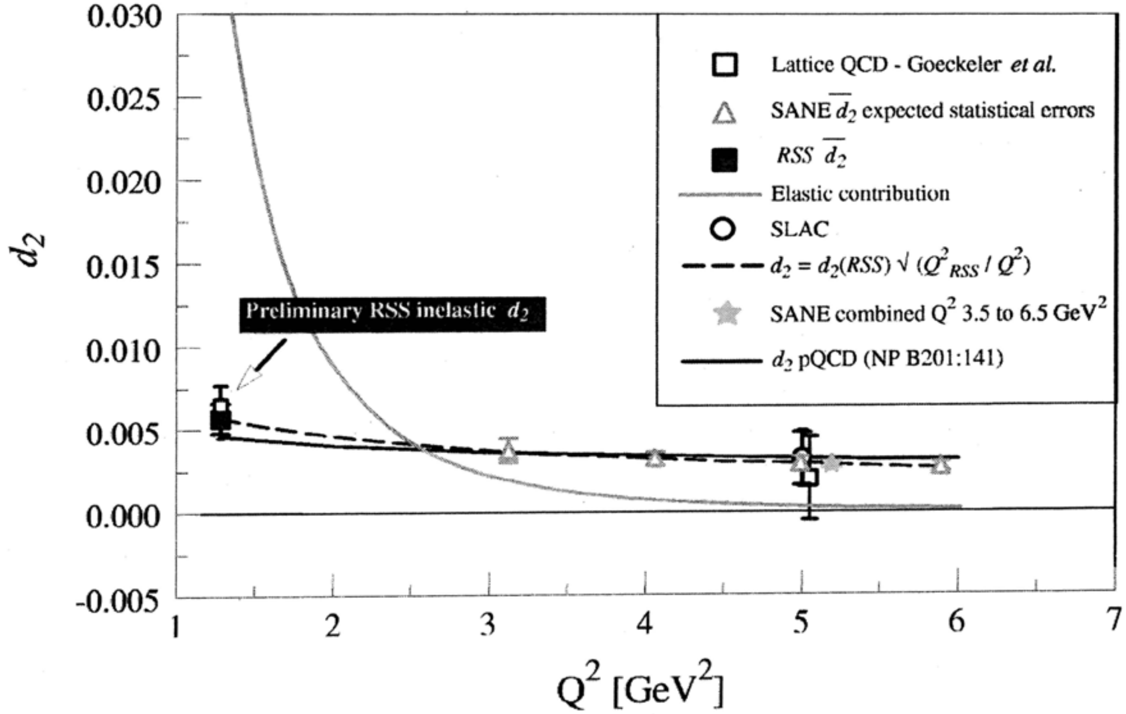
d_2^p RSS and SANE d_2^p projection in Hall C

RSS spokesperons: M. Jones, O. Rondon
SANE spokespersons: S. Choi, M. Jones, O. Rondon, Z.-E. M



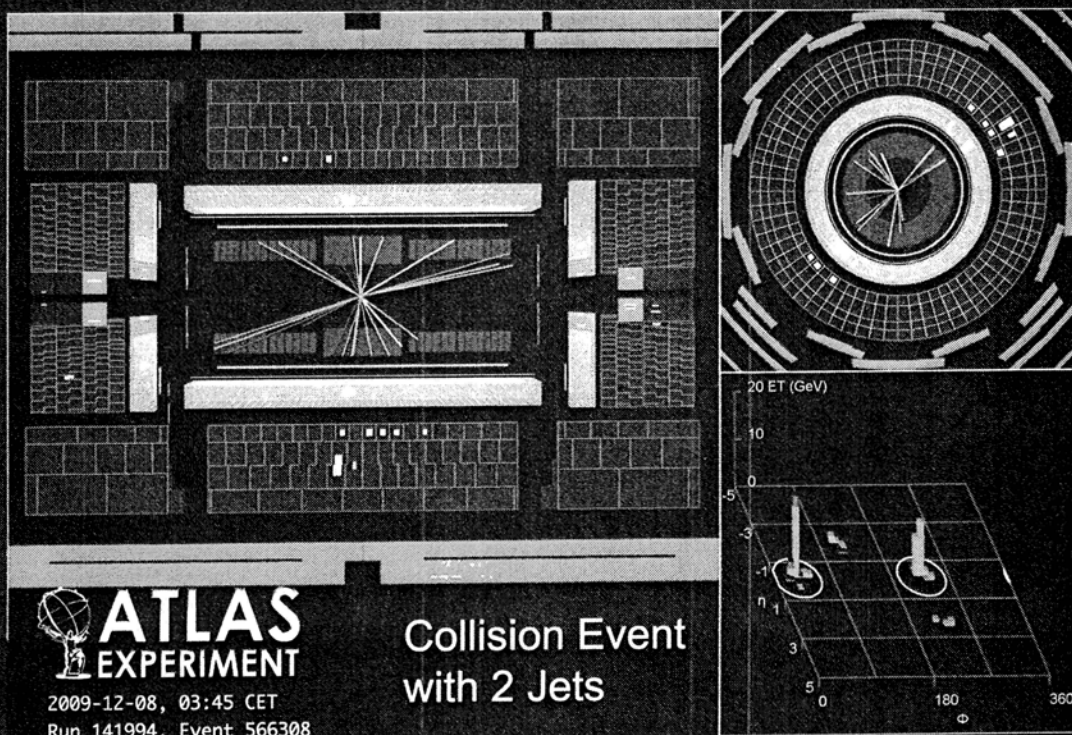
Summary

- ◎ Large x is a good ground for testing our understanding of nucleon structure
- ◎ Access to some dynamics like quark-gluon correlations is also possible using higher moments of g2 accessible at large x.
- ◎ Stay tuned for results on d2p and d2n coming soon at a workshop near you!

High p_T Physics: LHC Prospects

Brian A. Cole, Columbia University

March 19, 2010

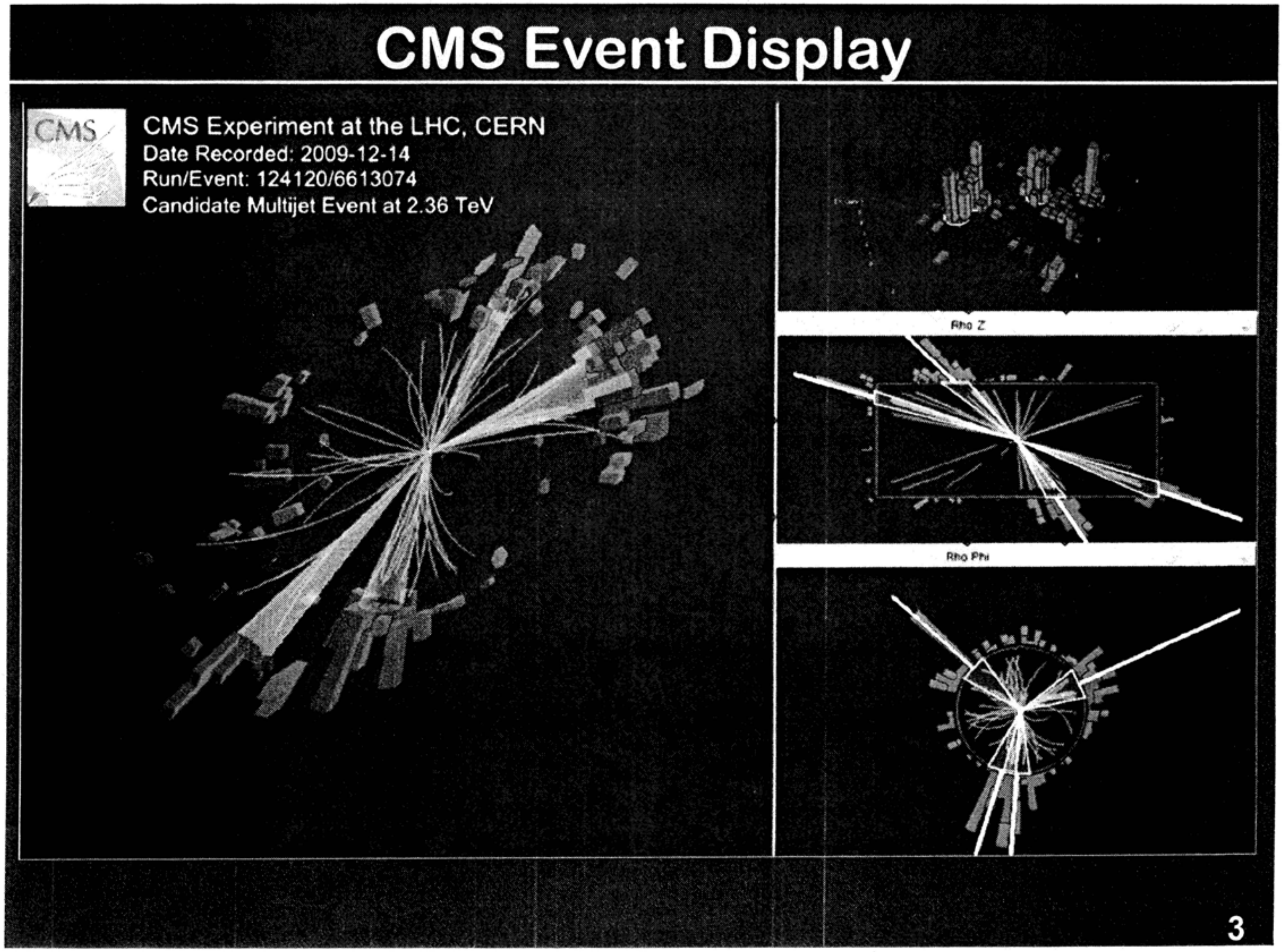


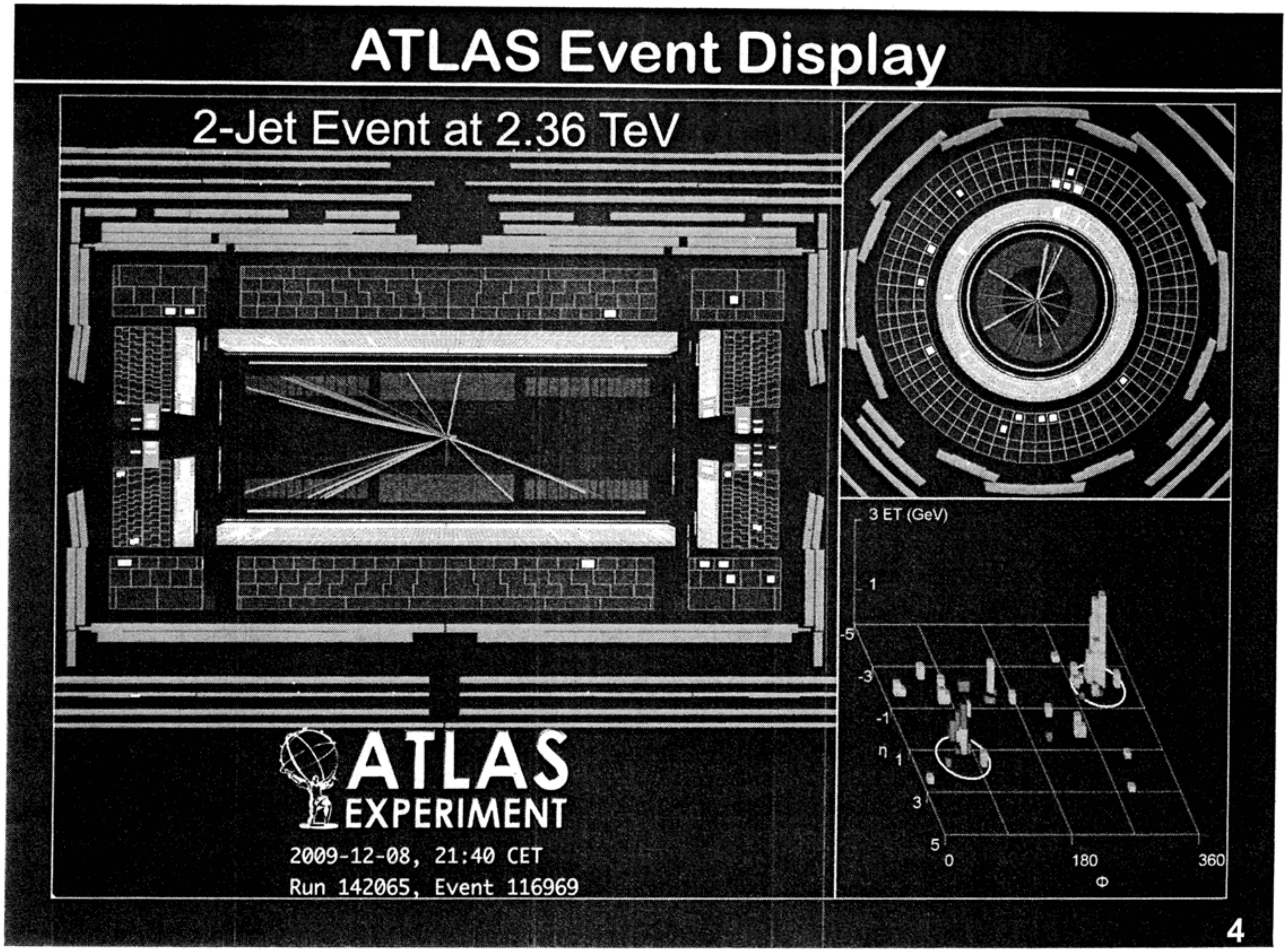
LHC High-p_T Physics (Relevant to this meeting)

While the primary focus of the LHC is on electro-weak and BSM physics, the LHC will be a powerful tool for studying QCD

- **Very high Q2 hard scattering processes**
  - Production of many-jet final states, heavy flavor
    - ⇒ Tests of understanding of parton showers
- **Hard processes involving low-x partons**
  - In p+p, tests for BFLK physics, diffractive hard physics(?)
  - In p+A, A+A, shadowing measurements, saturation tests
    - ⇒ (semi?)-hard QCD @ large parton densities
- **Jet quenching in A+A**
  - Extended jet p_T range , higher jet yields
  - Jet measurements at very large Q^2
    - ⇒ Modification of extended parton showers in medium

2


CMS Event Display
CMS
CMS Experiment at the LHC, CERN
Date Recorded: 2009-12-14
Run/Event: 124120/6613074
Candidate Multijet Event at 2.36 TeV
Rho Z
Rho Phi
3


ATLAS Event Display
2-Jet Event at 2.36 TeV
ATLAS
EXPERIMENT
2009-12-08, 21:40 CET
Run 142065, Event 116969
3 ET (GeV)
1
-5
-3
-1
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1
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5
0
180
360
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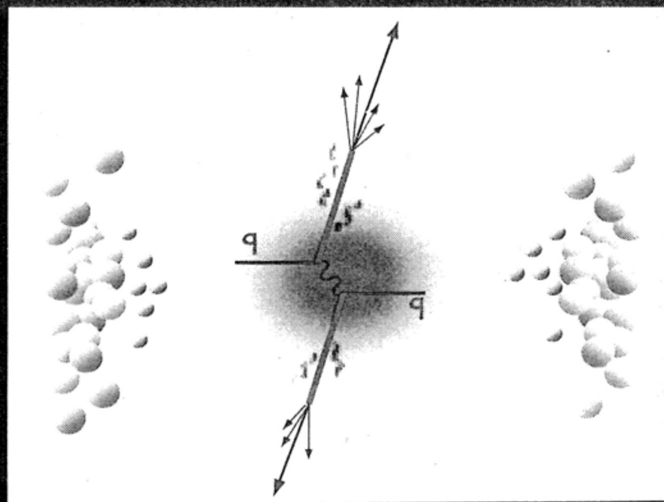
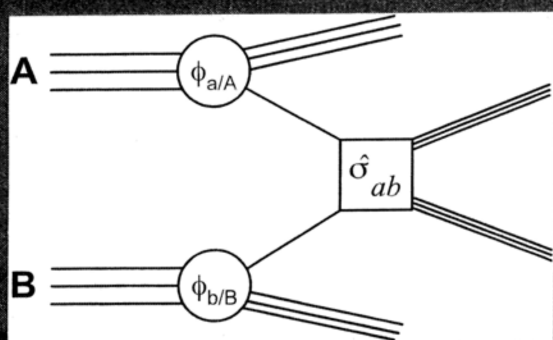
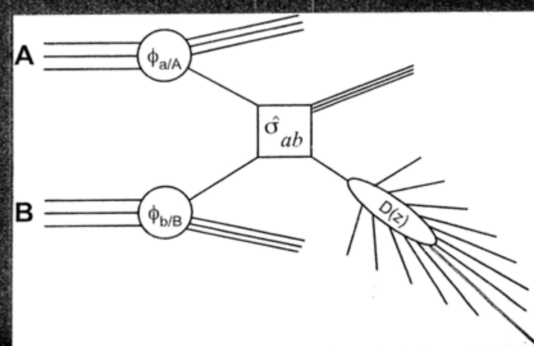
4

Picturing (and understanding) high-p_T physics



- RHIC community has been conditioned by exposure to cartoons or schematics of physics applicable only at LO
  - ⇒Mea Culpa
  - Even in hard processes QCD is more complicated





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Prospects

- 7 TeV p-p
  - LHC magnets already being ramped to 3.5 TeV
  - 7 TeV operation on few week time-scale
  - Goal for 2010-2011, 1 fb-1

    ⇒Unprecedented sample of jets out to ~ TeV
- 2.6 TeV Pb+Pb
  - Few weeks of low-luminosity ~10^{-25} fall 2010.

Physics

- High-statistics studies of parton showers generated by high-Q^2 processes
- Unique studies of jet quenching in Pb+Pb

  ⇒ New physics of radiating color charge in medium

  ⇒ Crucial probe of quark-gluon plasma for $T/T_c > 2$
- Low-x physics (which I didn't have time to discuss)

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The Science of Future Electron Ion Collider

Connections to Existing Facilities

Abhay Deshpande
Stony Brook University & RBRC

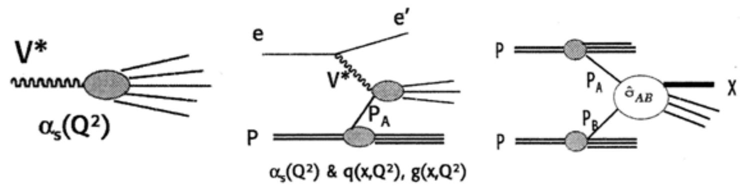
In the first part of this talk, I emphasized the historical precedence and the importance of the complementary methods to understand the laws of physics. Electron-electron (e-e), electron-hadron (e-h or DIS) and hadron-hadron (h-h) scattering have historically played a crucial role in our knowledge of the Standard Model. There is no reason to anticipate any thing different in future for QCD studies, which include spin & heavy nuclei as controlled experimental variables. Recent attempts to elevate, one technique against the other, i.e. the importance of DIS vs. h-h scattering for understanding the nucleon spin, miss the essential point that they allowing independent confirmation of the object of interest. Further, results obtained in h-h scattering include input from e-e and e-h scattering experiments. On the other hand, it can also be argued that only the measurements made in h-h scattering are a true test of QCD as they by employing results from e-e, e-h scattering, and state-of-the-art theory of pQCD along with the underlying assumptions of universality and (where appropriate) factorization.

In the second half of the talk, I reviewed the two polarized-electron-ion-collider proposals under consideration at BNL (eRHIC) and Jefferson Laboratory (ELIC ELectron Ion Collider). The eventual machine parameters planned for the proposals are similar, but the path and time scale to achieve may be different. The luminosities are planned between 10^{32}– ~ few x 10^{34} $cm^{-2}sec^{-1}$ (10 - few x1000 times HERA). Electron, proton and deuteron (in ELIC) and ^{3}He (in eRHIC) are expected to be polarized. eRHIC proposal uses one of the existing hadron/nuclear beams of RHIC. The staged realization proposes starting with a ~4 GeV energy electron beam, employing a race-track layout of ERLs with multiple passes. This could then be expanded in to the full eRHIC, which would involve electron beams in the existing RHIC tunnel, also with multiple passes. Up to 20 GeV electron beams are possible. ELIC plans to use the upgraded CEBAF 12 GeV electron beam and proposes to build a hadron/nuclear beam complex next to it. Electron from 3-11 GeV may be used for collisions. In the initial stage, the proton beam energies are expected to be around 30-60 GeV, to be later increased to about 250 GeV by adding additional hadron ring.

The science drivers (the golden measurements) for the electron ion collider are being studied and formulated in detail by the EIC Collaboration. The nucleon spin study will be driven by precision measurements of the gluon's contribution to the nucleon spin and aspects of 3D structure of the nucleon through measurements of Transverse Momentum Distributions (TMDs) and Generalized Parton Distributions (GPDs). The nuclei at high energy in the EIC will allow a precision study of QCD at extremely high gluon densities (Color Glass Condensate). A new possibility and preliminary studies in precision electroweak physics with the highest possible energy and luminosity is now being explored.

Experimental tools of (particle) physics

Collisions of e-e, e-p and p-p scattering



Progress in our understanding of nature needs continuous interplay amongst different tools…

Only by doing that can we make full use of their diversity & complementary

G. Altarelli, DIS09

To see if we understand SSA completely: ee, ep, pp essential!

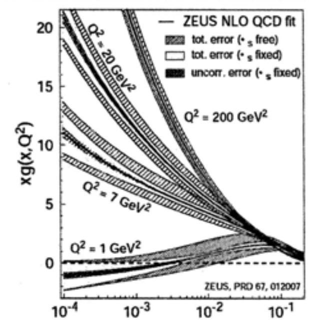
Example:

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to \pi^+ X\right)}{dx_1 dx_2 dz} \propto f_i^{\uparrow}(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

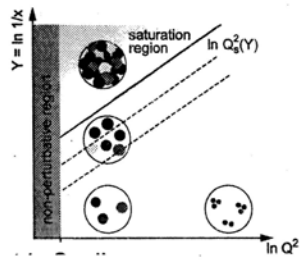
SSA in pp — Proton structure (ep) — Theory input — Fragmentation (ee)

- Another view (***not*** at odds with the previous):
  - ep, ee experiments measure objects
  - Theorists use them and (**techniques + assumptions**) in (p)QCD to calculate/predict outcomes in pp scattering
  - pp experiments the ideal **(the only)** place **<u>to test our understanding of QCD</u>**

Gluons still not well understood!



- Rise at high Q^2, low x
  - **Infinite rise, infinite cross section?**
  - Is this due to use of **linear** DGLAP?
  - Direct consequence to high energy hadron cross sections
- **Negative g(x) at low Q^2?**



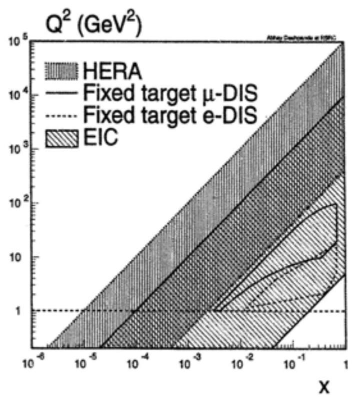
- What is the effect of including **non-linear** effects in DGLAP equation?
  - BK, JIMWLK
- A possible scenario: Color Glass Condensate
- Characteristic scale $Q_s(x,A)$
- **Experiment with high densities of gluons → Nuclei!**

Nucleon Spin ~~Crisis~~ Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G \qquad (?)$$

- We **know** how to measure $\Delta\Sigma$ and ΔG precisely using pQCD in a **model independent** way
  - ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG ***not large* as anticipated in the 1990s, but *measurements incomplete, precision at low x?***
- Orbital angular momenta: L_Q (L_G?) Z.E. Meziani's talk
  - Through **GPDs: 3D tomographic images of the proton**
  - Significant model dependence…
  - A lot to learn from the 6 GeV and the 12 GeV Jlab program & an ongoing theoretical development

EIC in the US: Basic Parameters



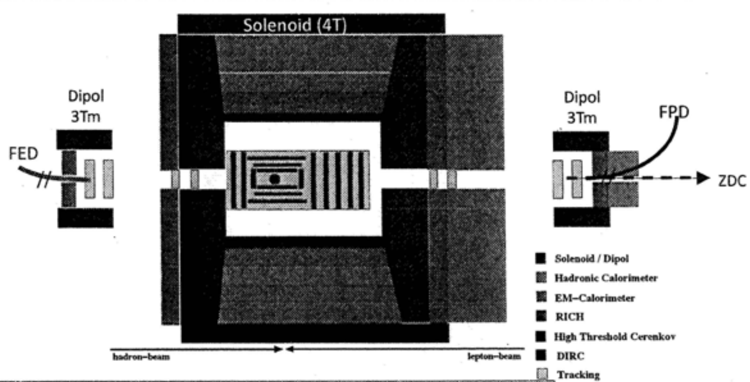
- E_e=**10** GeV (5-20 GeV variable)
- E_p=**250** GeV (50-250 GeV Variable)
- **Sqrt(S_{ep}) = 30-100 GeV**
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam polarization ~ 70% for e,p
- **Luminosity $L_{ep} = 10^{33\text{-}34}$ cm^{-2}s^{-1}**
- **Aimed Integrated luminosity:**
  - **50 fb^{-1} in 10 yrs (100 x HERA)**
  - **Possible with 10^{33} cm^{-2}s^{-1}**

Nuclei:

- **p->U; E_A=20-100 GeV**
- **Sqrt(S_{eA}) = 12-63 GeV**
- **L_{eA}/N = 10^{33} cm^{-2}s^{-1}**

6/26/09 EIC: Physics Opportunities & Accelerator Challenges 25

First ideas for a detector concept



- ❑ Dipoles needed to have good forward momentum resolution
  - ➢ Solenoid no magnetic field @ r ~ 0
- ❑ DIRC, RICH hadron identification → π, K, p
- ❑ high-threshold Cerenkov → fast trigger for scattered lepton
- ❑ radiation length very critical → low lepton energies

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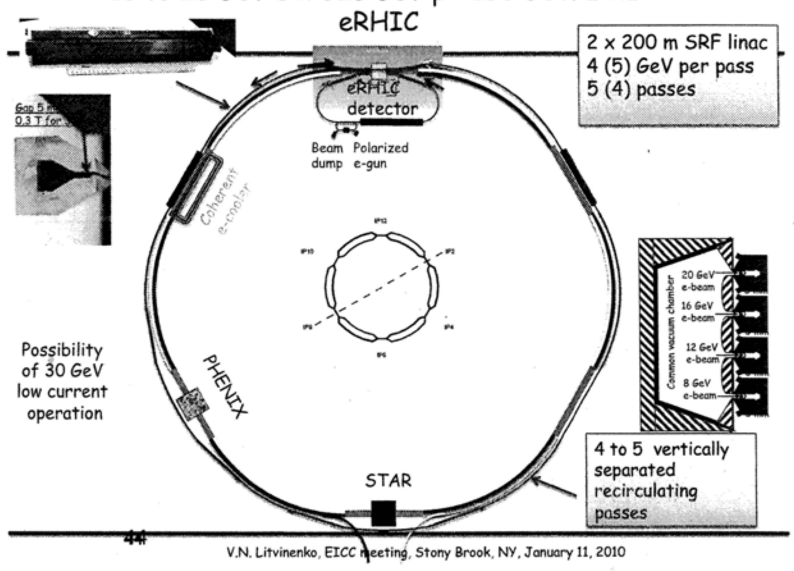
Machine/Detector (→Physics)

- Inclusive
  - Nucleon
    - Polarized PDFs (g1 → ΔG, F_2 & F_L →G) — <u>Nucleon Spin</u>
    - Parity experiments — Beyond SM
  - Nucleus: Nuclear PDFs, EMC Effect, Low-x →G — Extreme QCD
- Semi-Inclusive
  - Nucleon:
    - Polarized PDFs (g1 →ΔQ,ΔQbar, Δg_{jets}) — <u>Nucleon Spin</u>
    - Transverse Momentum Dependent (TMDs) — ***<u>Nucleon Spin</u>***
  - Nucleus: Diffraction → Low-x → G — Extreme QCD
- Exclusive
  - Nucleon:
    - 3D structure → GPDs →L_z — ***<u>Nucleon Spin</u>***
    - EW physics — EW & BSM
  - Nucleus: 3D structure of Nuclei(?) — **<u>QCD of nuclei</u>**

10 to 20 GeV e x 325 GeV p - 130 GeV/u Au

eRHIC



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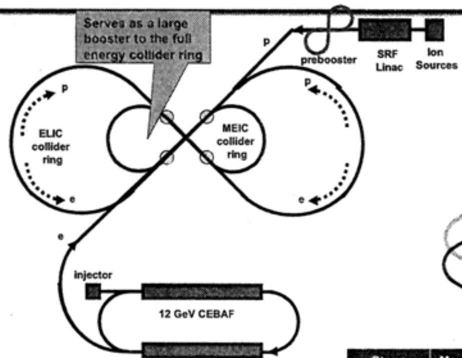
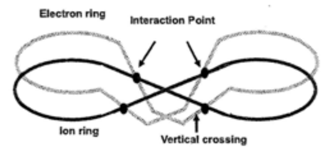
V.N. Litvinenko, EICC meeting, Stony Brook, NY, January 11, 2010

ELIC: High Energy Upgrade



Circumference	m	1800
Radius	m	140
Width	m	280
Length	m	695
Straight	m	306



Stage	Max. Energy (GeV/c)		Ring Size (m)		Ring Type		IP #
	p	e	p	e	p	e	
Low	12	5 (11)	630		Warm	Warm	1
Medium	60	5 (11)	630		Cold	Warm	2
High	250	10	1800		Cold	Warm	4

Overarching goals of EIC

- **Nucleon Spin Structure**
  - **Longitudinal spin structure: ΔG, ΔQ, ΔQbar**
    - *Mostly inclusive & semi-inclusive measurements*
  - **Nucleon spatial structure**
    - **TMDs & GPDs (→L_z?)**
    - ***Mostly semi-inclusive & exclusive measurements***
- **QCD at extreme condition & spatial structure of nuclei**
  - **Low x gluon distribution & GPDs in nuclei**
  - ***Inclusive & semi-inclusive (diffractive & other) off nuclei***
- Parity & Precision EW Physics (Emergent ?)
  - *Inclusive, semi-inclusive/exclusive physics*

Progress in High-p_T Physics at RHIC

March 17 – 19, 2010

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Progress in High-P_T Physics at RHIC

Physics Large Seminar Room
March 17-19, 2010

Wednesday, March 17th

8:30 – 9:00	***REGISTRATION***	
Session Chair: Gerry Bunce		
9:00 – 9:05	*Nick Samios*	Welcome
9:05 – 9:35	*George Sterman*	High p_T Physics at RHIC
9:35 – 10:05	*Mike Tannenbaum*	High p_T Physics from the AGS to the ISR to RHIC
10:05 – 10:35	*Jacques Soffer*	A Few Relevant Cases for Studying High-p_T Physics at the RHIC pp Collider
10:35 – 11:00	***COFFEE BREAK***	
11:00 – 11:30	*Daniel de Florian*	CHE: W Production at NLO and the Polarized Sea Distributions
11:30 – 12:00	*Harold Spinka*	First W Production Results From STAR
12:00 – 12:30	*Kenichi Karatsu*	W Boson Production and Spin Asymmetry Measurements at PHENIX
12:30 – 14:00	**LUNCH**	
Session Chair: Abhay Deshpande		
14:00 – 14:30	*Pavel Nadolsky via EVO*	Spin Asymmetry in W Boson Production -- Hadron Decay Modes
14:30 – 15:00	*Christian Schill*	Spin Physics Results from COMPASS
15:00 – 15:30	*Bernd Surrow*	Status and Future Prospects of the STAR W Program
15:30 – 16:00	***COFFEE BREAK***	
16:00 – 16:30	*Marco Stratmann*	Heavy Quark Correlations in Polarized pp Collisions
16:30 – 17:00	*Scott Wissink*	Status of Delta G Measurements at STAR
17:00 – 17:30	*Swadhin Taneja*	Gluon Polarization: Status and Plans for Measurements at PHENIX

Thursday, March 18th

Session Chair: Jacques Soffer		
9:00 – 9:30	*Mauro Anselmino*	SSAs in Hadron-Hadron Collisions and TMDs
9:30 – 10:00	*John Koster*	Transverse Spin Physics at PHENIX
10:00 – 10:30	*Robert Fersch*	Measurement of the Collins Asymmetry in Mid-Rapidity Jets at STAR
10:30 – 11:00	***COFFEE BREAK***	
11:00 – 11:30	*Andreas Metz*	Nontrivial Relations Between GPDs and TMDs
11:30 – 12:00	*Jen-Chieh Peng*	Recent Results and Future Prospects for Drell-Yan Experiments
12:00 – 12:30	*Ming Liu*	New Probes for Future Transverse Spin Physics
12:30 – 14:00	***LUNCH***	

Thursday, March 18th (continued)

Session Chair: Mauro Anselmino		
14:00 – 14:30	*Feng Yuan*	Looking Forward at RHIC
14:30 – 15:00	*Ralf Seidl*	Experimental Results and Future Prospects on Spin-Dependent Fragmentation
15:00 – 15:30	*Delia Hasch*	Latest Results from HERMES
15:30 – 16:00	***COFFEE BREAK***	
16:00 – 16:30	*Adrian Dumitru*	Two-Particle Correlations and the Small-x Gluon Four-Point Function
16:30 – 17:00	*Wilco den Dunnen*	Double Transverse Spin Asymmetries as a Probe for New Physics
18:00 – 20:00	***DINNER, BROOKHAVEN CENTER SOUTH ROOM***	

Friday, March 19th

Session Chair: Jen-Chieh Peng		
9:00 – 9:30	*Jianwei Qiu*	Low Mass Dilepton Production at High-p_T
9:30 – 10:00	*Zvi Citron*	Probing Low x in d+Au and p+p Collisions in PHENIX
10:00 – 10:30	*Hank Crawford*	Low x Physics at STAR
10:30 – 11:00	***COFFEE BREAK***	
11:00 – 11:30	*Jamal Jalilian-Marian*	Photon-Hadron Correlations in dA Collisions as a Probe of Saturation Physics
11:30 – 12:00	*Daniel Boer*	Lambda Polarization and Low-x Physics
12:00 – 12:30	*Mark Schlegel*	TMDs in Two-Photon Production
12:30 – 14:00	***LUNCH***	
Session Chair: Jianwei Qiu		
14:00 – 14:30	*Rodolfo Sassot*	Medium Modified Fragmentation Functions and PDFs
14:30 – 15:00	*Mateusz Ploskon*	Jet Measurements in p-p and A-A Collisions by STAR
15:00 – 15:30	*Martin Purschke*	$\sqrt{s}$ Dependence of Pion Production Cross Sections
15:30 – 16:00	***COFFEE BREAK***	
16:00 – 16:30	*Zein-Eddine Meziani*	Nucleon Spin Structure Studies at JLab
16:30 – 17:00	*Brian Cole*	Status and Plans at the LHC
17:00 – 17:30	*Abhay Deshpande*	RHIC-to-EIC Transition: Connections and Complementarities

Additional RIKEN BNL Research Center Proceedings:

Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009 – BNL
Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1 -31, 2009. BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30-July 4, 2008, Beijing, China, BNL-81685-2008
Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 - BNL-81478-2008
Volume 89 – Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 – BNL-81318-2008
Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, Dec 12-14, 2005 – BNL-76915-2006
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003

Additional RIKEN BNL Research Center Proceedings:

Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics –BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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Progress in High-p_T Physics at RHIC

March 17-19, 2010

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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