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Formal Report

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Brookhaven Summer Program on Quarkonium Production in Elementary and Heavy Ion Collisions

June 6-17, 2011

Organizers: Adrian Dumitru, Carlos Lourenco, Péter Petreczky, Jianwei Qiu, and Lijuan Ruan

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 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 ~100 graduates of which 27 theorists and 14 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 one hundred and three 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. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the summer of 2011.

N. P. Samios, Director
June 2011

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

CONTENTS

Introduction

Understanding the structure of the hadron is of fundamental importance in subatomic physics. Production of heavy quarkonia is arguably one of the most fascinating subjects in strong interaction physics. It offers unique perspectives into the formation of QCD bound states. Heavy quarkonia are among the most studied particles both theoretically and experimentally. They have been, and continue to be, the focus of measurements in all high energy colliders around the world. Because of their distinct multiple mass scales, heavy quarkonia were suggested as a probe of the hot quark-gluon matter produced in heavy-ion collisions; and their production has been one of the main subjects of the experimental heavy-ion programs at the SPS and RHIC. However, since the discovery of J/psi at Brookhaven National Laboratory and SLAC National Accelerator Laboratory over 36 years ago, theorists still have not been able to fully understand the production mechanism of heavy quarkonia, although major progresses have been made in recent years. With this in mind, a two-week program on quarkonium production was organized at BNL on June 6-17, 2011.

Many new experimental data from LHC and from RHIC were presented during the program, including results from the LHC heavy ion run. To analyze and correctly interpret these measurements, and in order to quantify properties of the hot matter produced in heavy-ion collisions, it is necessary to improve our theoretical understanding of quarkonium production. Therefore, a wide range of theoretical aspects on the production mechanism in the vacuum as well as in cold nuclear and hot quark-gluon medium were discussed during the program from the controlled calculations in QCD and its effective theories such as NRQCD to various models, and to the first principle lattice calculation. The scientific program was divided into three major scientific parts: basic production mechanism for heavy quarkonium in vacuum or in high energy elementary collisions; the formation of quarkonium in nuclear medium as well as the strong interacting quark-gluon matter produced in heavy ion collisions; and heavy quarkonium properties from the first principle lattice calculations. The heavy quarkonium production at a future Electron-Ion Collider (EIC) was also discussed at the meeting. The highlight of the meeting was the apparent success of the NRQCD approach at next-to-leading order in the description of the quarkonium production in proton-proton, electron-proton and electron positron collisions. Still many questions remain open in lattice calculations of in-medium quarkonium properties and in the area of cold nuclear matter effects.

Upsilon Suppression at RHIC and LHC

Michael Strickland
Gettysburg College, Gettysburg, PA

RBRC Quarkonium Workshop
June 6, 2011

References:
1101.4651, 1011.3056, 1007.0889, 0903.4703, and forthcoming…

Motivation and Goals I

- Screening → quarkonium suppression in QGP
- Decrease in the real part of the binding energy (E_{bind}) as a function of temperature
- Imaginary part of E_{bind} → thermal width which increases as a function of temperature
- Real and imaginary parts of the heavy quark potential, V, are known to leading order in an isotropic and anisotropic plasma

Isotropic Potential: Laine, Philipsen, Romatschke, and Tassler, hep-ph/0611300;
Anisotropic Potential: Burnier, Laine, Vepsalainen, 0903.3467
Dumitru, Guo, and Strickland, 0903.4703
Philipsen and Tassler, 0908.1746

Motivation and Goals II

- Can solve Schrodinger equation including both Re[V] and Im[V]
- Gives Re[E_{bind}] and Im[E_{bind}] $\equiv \Gamma$ as function of typical momentum and anisotropy in momentum space
- Evolve system as a function of proper time, rapidity, and transverse coordinates for different QGP viscosities
- Use "Anisotropic Dynamics" method which can describe systems which are highly anisotropic but reduces to 2nd order viscous hydro from small anisotropy

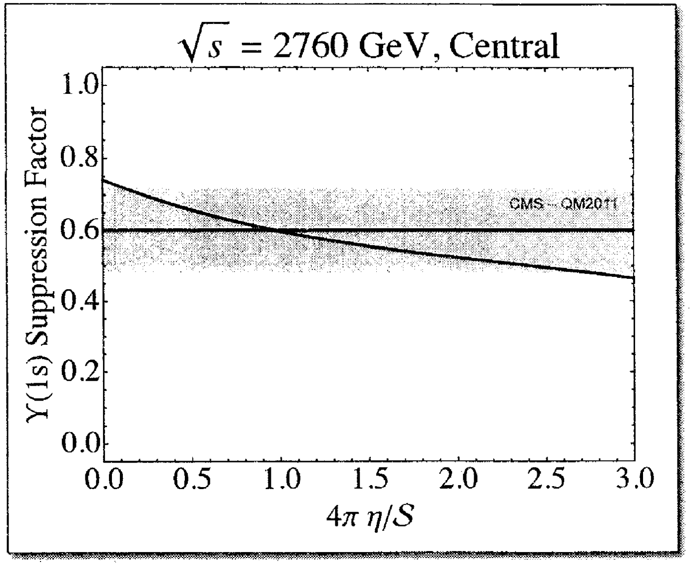
Schrodinger EQ solution: Margotta, McCarty, McGahan, Strickland, and Yager-Elorriaga, 1101.4651
Anisotropic Dynamics: Martinez and Strickland, 1007.0089, 1011.3056

Preview of Results

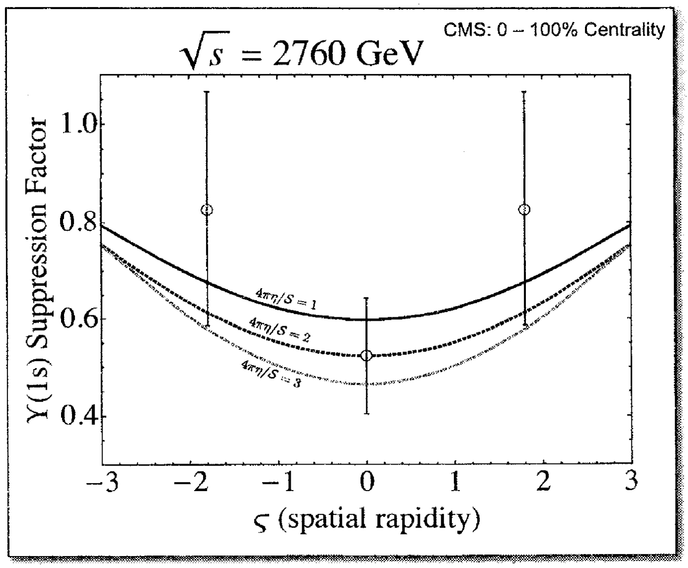
CMS says:

$\Upsilon(1S)$ R_{AA} in the most central 20%

– 0.60 ± 0.12(stat.) ± 0.10(syst.)

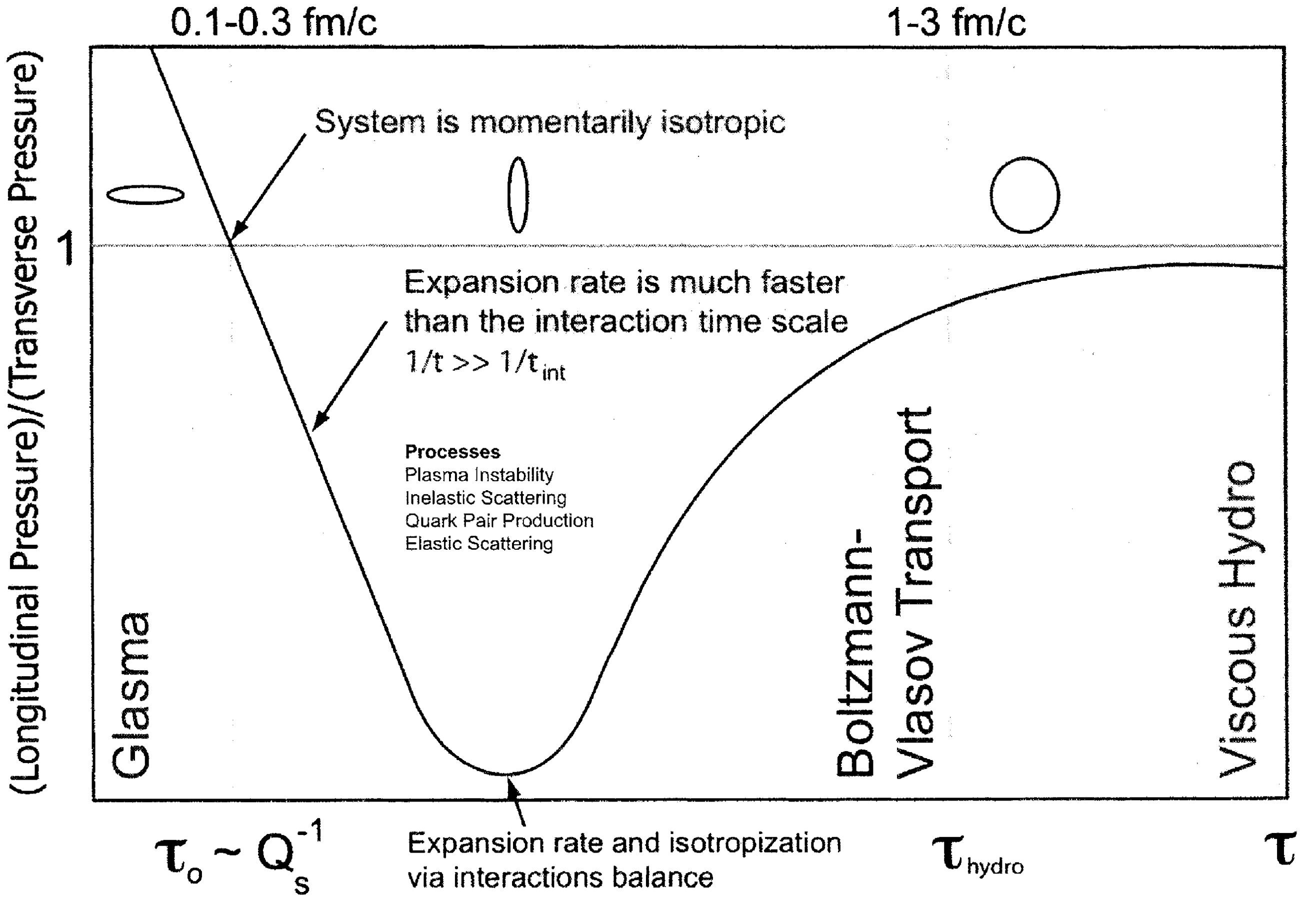


M. Strickland, forthcoming.



M. Strickland, forthcoming.

QGP momentum anisotropy



System is momentarily isotropic

Expansion rate is much faster than the interaction time scale $1/t >> 1/t_{int}$

Processes
Plasma Instability
Inelastic Scattering
Quark Pair Production
Elastic Scattering

Expansion rate and isotropization via interactions balance

Anisotropic Plasma

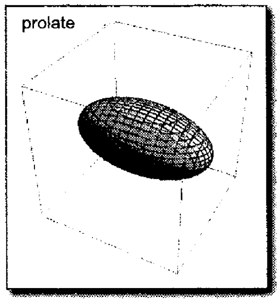
$$\begin{aligned} f(\tau,\mathbf{x},\mathbf{p}) &= f_{RS}(\mathbf{p},\xi(\tau),p_{\rm hard}(\tau)) \\ &= f_{\rm iso}\left([\mathbf{p^2}+\xi(\tau)p_z^2]/p_{\rm hard}^2(\tau)\right) \end{aligned}$$

$$\xi = \frac{\langle p_T^2\rangle}{2\langle p_L^2\rangle} - 1$$

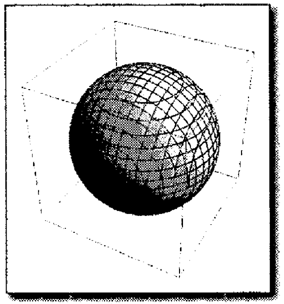
Small Anisotropy Limit (Thermal $f_{\rm iso}$)

$$f \approx f_{\rm iso}(p)\left[1-\xi\frac{p_z^2}{2\,p_{\rm hard}\,p}\left(1 \pm f_{\rm iso}(p)\right)\right]$$

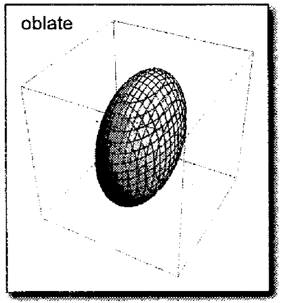
Anisotropy parameter, ξ, is related to pressure anisotropy of the system.



$-1 < \xi < 0$



$\xi = 0$



$\xi > 0$

Navier-Stokes Limit

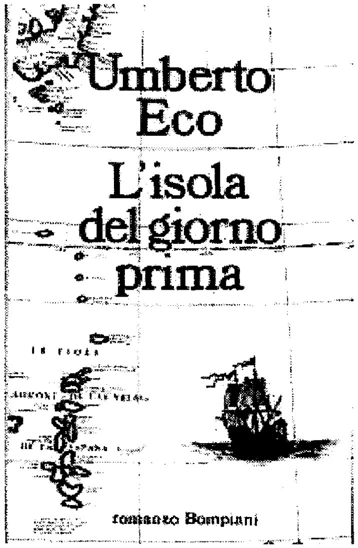
$$\xi \rightarrow \frac{10}{T\tau}\frac{\eta}{S}$$

Quarkonia
in Deconfined Matter

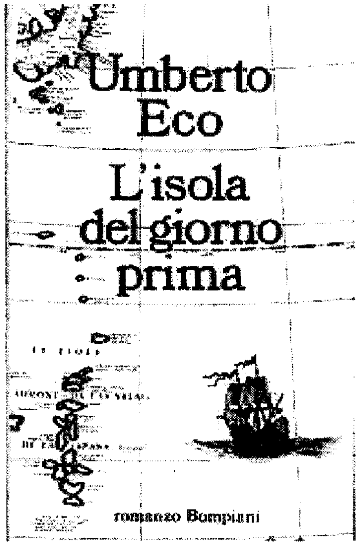
Helmut Satz

Universität Bielefeld, Germany

Quarkonium Production in Elementary and Heavy Ion Collisions
Brookhaven National Lab, June 7, 2011



The Island of the Day before



The Island of the Day before

Roberto aveva deciso di concedere solo la metá del proprio spirito alle cose in cui credeva (o credeva di credere),

per tener l'altra disponibile nel caso che fosso vero il contrario.

Roberto had decided to reserve only half of his mind for the things which he believed (or believed to believe),

so that he would have the other half free in case the opposite should turn out to be true.

Contents

1. Quarkonia are very unusual hadrons

heavy quark ($Q\bar{Q}$) bound states stable under strong decay

- heavy: $m_c \simeq 1.2 - 1.4$ GeV, $m_b \simeq 4.6 - 4.9$ GeV
- stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

What is "usual"?

- light quark ($q\bar{q}$) constituents
- hadronic size $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm, independent of mass
- loosely bound, $M_\rho - 2M_\pi \gg 0$, $M_\phi - 2M_K \simeq 0$
- relative production abundances $\sim$ energy independent, statistical: at large $\sqrt{s}$, rate $R_{i/j} \sim$ phase space at T_c
- $(dN_{\rm ch}/dy) \sim \ln s$

Quarkonia: heavy quarks ⇒ non-relativistic potential theory

Jacobs et al. 1986

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

with confining ("Cornell") potential $V(r) = \sigma\, r - \frac{\alpha}{r}$

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

Defining the heavy quark potential in perturbation theory and on the lattice

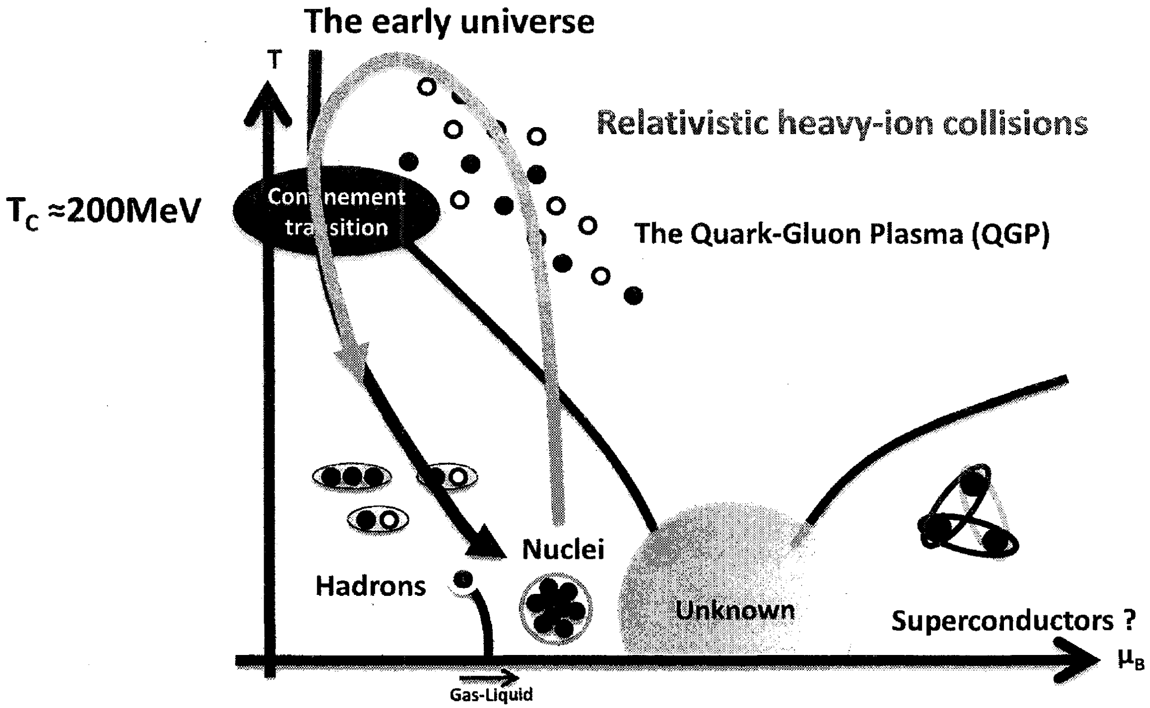
Alexander Rothkopf

Lattice part in collaboration with T. Hatsuda & S. Sasaki

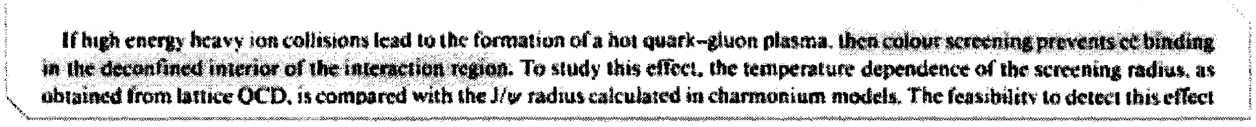
東京大学
THE UNIVERSITY OF TOKYO

Brookhaven Summer Program on
Quarkonium Production in Elementary and Heavy Ion Collision 2011

Universität Bielefeld

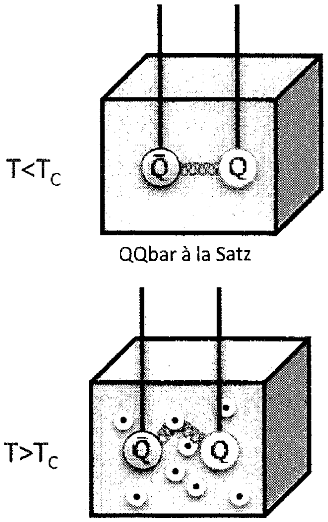


- Phase transition Quark-Gluon Plasma (**QGP**) $T>T_C$ vs. Confining phase $T<T_C$
- Recreate the QGP in the laboratory: **RHIC/LHC**
- **Heavy Quarkonium**: Clean probe for experiment and theory



If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect

PLB 178 416 (1986)



QQbar à la Satz

- Model potentials: $V(R) = -\frac{\alpha}{R} + \sigma R$ confinement

  $V(R) = -\frac{\alpha e^{-m_D R}}{R}$ Debye screening

- Static color test charges: correlations from lattice QCD Polyakov loops

- Melting sets in already below $1.2T_C$

Goal for Theory ➡ What is the proper potential to use in a non-relativistic description?

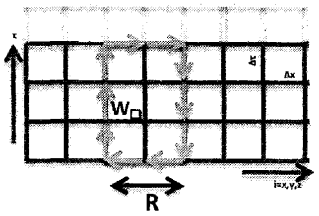
How to derive a Schrödinger equation from first principles QCD?

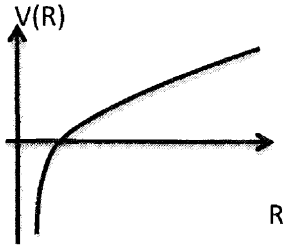
- Goal is to derive a Hamiltonian with: $H = \frac{p_1^2}{2m_Q} + \frac{p_2^2}{2m_Q} + V^{(0)}(R) + V^{(1)}(R)\frac{1}{m} + \dots$

- At **T=0** systematic framework available: NRQCD, pNRQCD Brambilla et al. 2005

Lattice QCD (LQCD): Monte Carlo

Derivation of $V^0(R)$:
Wilson Loop

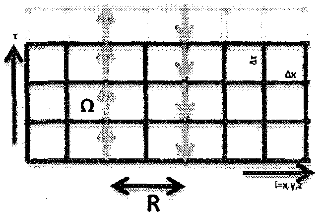


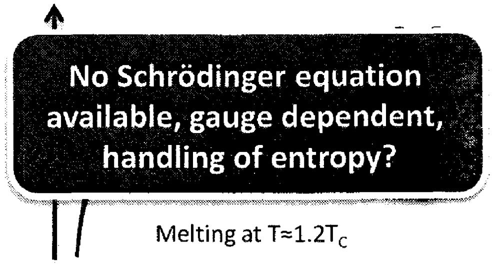


- Potential Models at T>0 Nadkarni, 1986

Lattice QCD: Monte Carlo

Ad-hoc choice:
Free Energies or
Internal Energies



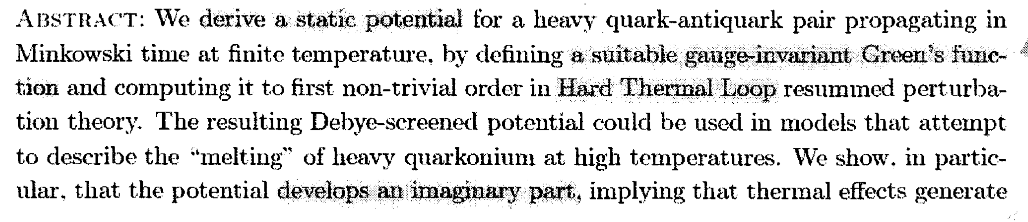


No Schrödinger equation available, gauge dependent, handling of entropy?

Melting at $T \approx 1.2T_C$

- What is a non-relativistic potential?
  - Direct answer: The non-kinetic term in a Schrödinger type E.O.M.

$$i\partial_t D^{>}(R,t) = \left(\frac{p^2}{2m_q} + V(R)\right) D^{>}(R,t)$$



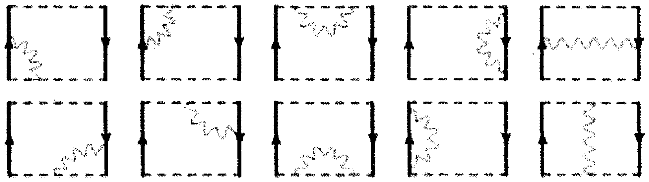
ABSTRACT: We derive a static potential for a heavy quark-antiquark pair propagating in Minkowski time at finite temperature, by defining a suitable gauge-invariant Green's function and computing it to first non-trivial order in Hard Thermal Loop resummed perturbation theory. The resulting Debye-screened potential could be used in models that attempt to describe the "melting" of heavy quarkonium at high temperatures. We show, in particular, that the potential develops an imaginary part, implying that thermal effects generate

The real-time thermal Wilson Loop

Laine et. al. JHEP03 (2007) 054; see also Beraudo et. al. NPA 806:312-338,2008

- Heavy quark propagation described by rectangular Wilson in the static limit

$$\langle \mathrm{Tr}[\exp[\oint A]]\rangle \equiv$$



〰 HTL gluon propagator

Pisarski PRL 63 (1989) 1129
Braaten, Pisarski NPB 337 (1990) 569

- Wilson Loop in the infinite time limit: Potential emerges with **real and imaginary part**

$$\lim_{t\to\infty} V^0_{rT}(t,R) = -\frac{gC_F}{4\pi}\boxed{m_D + \frac{e^{-m_D r}}{r}} - \boxed{\frac{ig^2TC_F}{4\pi}\phi(m_D r)} \qquad \phi(x) = \int_0^\infty dz \frac{z}{(z^2+1)^2}\left[1 - \frac{\sin[zx]}{zx}\right]$$

Debye screening: a cloud of quarks and gluons mitigates the interaction effects

Landau damping: collisions with the deconfined environment

Heavy quarkonium in plasma: comparison between perturbation theory and lattice

Yannis Burnier

Stony Brook

June 7, 2011

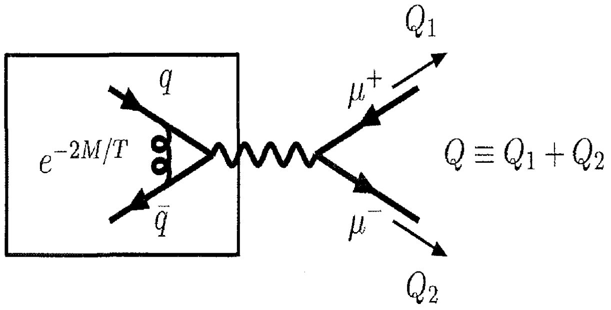
Outline

1. Introduction
2. Theoretical description of quarkonium
    - Effective field theory
    - High energy limit
3. Quarkonium on the lattice
    - Spectral function
    - Euclidean correlator
    - Euclidean definition of the potential
4. Conclusion

Heavy quarkonium as probe for QGP

Heavy quarkonium is an important probe of the properties of a quark-gluon plasma [T. Matsui, H. Satz (1986)].

- In heavy ion collisions → short lived quark-gluon plasma.
- In the primary collisions heavy quarkonium is created.
- Depending on the plasma temperature it decays (to muons for instance).
- Muon escape ↔ carry information out of the interior of the plasma.
- The frequency of the emitted muons is measured.



Different methods

Despite asymptotic freedom at the temperature of interest, the theoretical determination of the properties of heavy quarkonium is not more tractable than at $T = 0$.

Many different approaches:

1. Potential models
2. Perturbation theory
3. Lattice QCD
4. AdS/QCD

In this talk: What can we get from first principles?
→ Perturbation theory and comparison to lattice results.

Effective field theory: $T = 0$ case first

Starting form the QCD Lagrangian, we separate the light quarks (u,d,s) from the heavy quark (c):

$$\begin{aligned}\mathcal{L}_{\text{QCD}} &= \mathcal{L}_{\text{gluons}} + \mathcal{L}_{\text{light quarks}} + \mathcal{L}_{\text{heavy quark}},\\ &\mathcal{L}_{\text{gluons}} = \frac{1}{4} F^{\mu\nu\,a} F^a_{\mu\nu},\\ &\mathcal{L}_{\text{light quarks}} = \bar{\psi}_i (i\gamma^\mu D_\mu)\psi_i,\\ &\mathcal{L}_{\text{heavy quark}} = \bar{\Psi}(i\gamma^\mu D_\mu - M)\Psi.\end{aligned}$$

We want to built an effective description for the bound state of two heavy quarks.

- Heavy quarks have a small binding energy $E_b \ll M$.

⇒ We have the following hierarchy of scales:

$$M \gg p \sim Mv \sim 1/r_b \gg E_b \sim Mv^2$$

⇒ The velocities v of the heavy quarks are small.

⇒ Use the Non-Relativistic QCD for the heavy quarks.

NRQCD

NRQCD is an effective low energy $E \sim Mv$ description for the heavy quark

- Relativistic spinors are decomposed in non-relativistic components $\Psi = \binom{\phi}{\chi}$.
- The Lagrangian of NRQCD reads

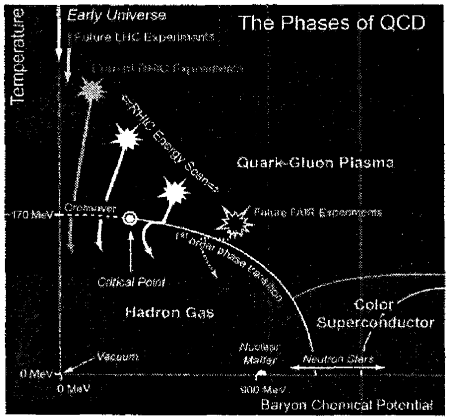
$$\mathcal{L}^{\mathrm{NRQCD}}_{\mathrm{heavy\ quark}} = \phi^\dagger (iD_0 + \frac{\mathbf{D}^2}{2M})\phi + \chi^\dagger (iD_0 - \frac{\mathbf{D}^2}{2M})\chi + \mathcal{O}\left(\frac{1}{M^2}\right)$$

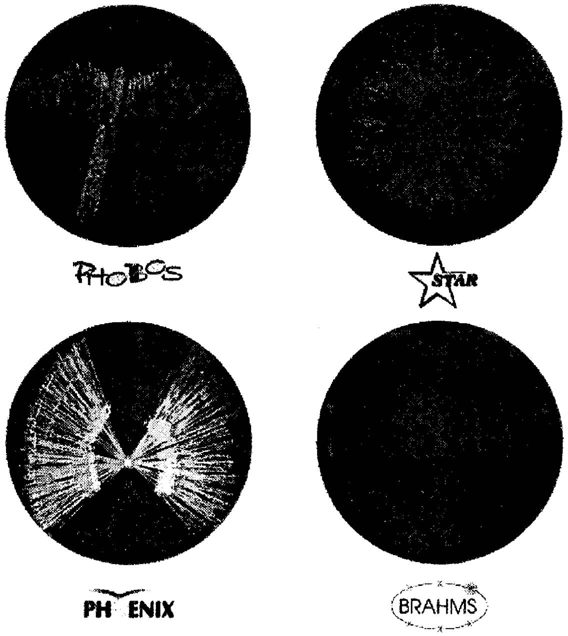
- In NRQCD terms are arranged in inverse powers of M.
- It can be obtained from QCD by a Foldy-Wouthuysen transformation.

With NRQCD we integrated the hard scale M, but we can do better:
$\Rightarrow$ Integrate the soft scale $p \sim Mv \sim 1/r_b$. $\Rightarrow$ New effective field theory: potential NRQCD.

Helmut Satz and the Formative Days of RHIC

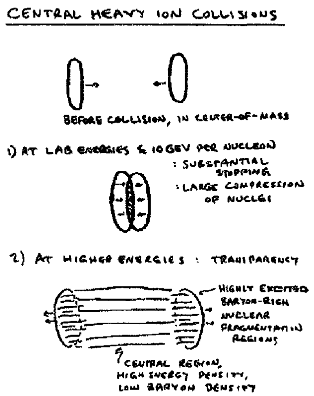
T. Ludlam
June 9, 2011

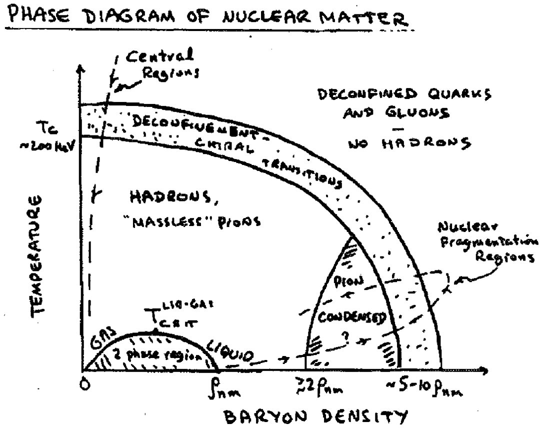




In the Beginning: Making the Case for RHIC

1983 NSAC Long Range Plan for Nuclear Physics





Concepts and ideas that called for a new breed of Nuclear Physics, with High Energy Physics tools.

A time of change, and some turmoil for HEP:

QCD was still rather new; J/ψ had recently been discovered, as had jets.

Isabelle had just been killed.

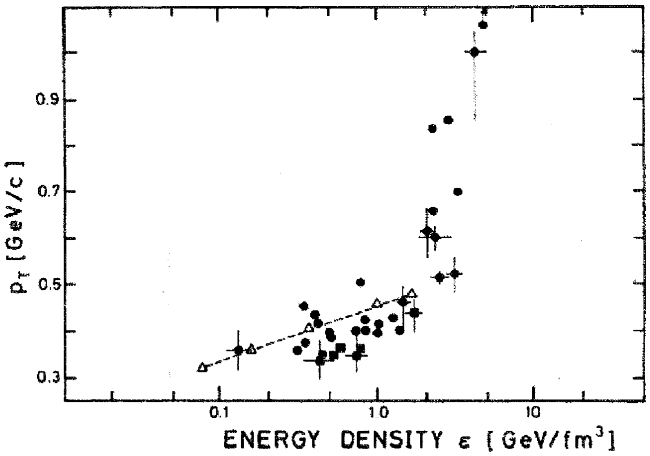
At "Quark Matter '83", at BNL, Alan Bromley spoke of long-standing *"artificial barriers that have separated nuclear and particle physicists".*

General skepticism that in such complicated collisions, any real physics could be separated from "nuclear effects".

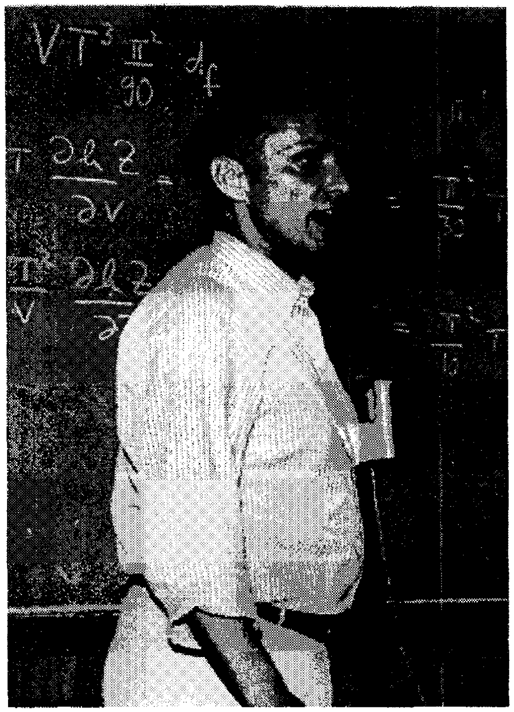
Collective Effects in nuclear collisions?

At the time, there was scant evidence that high energy collisions with nuclei produced more than just a superposition of single particle interactions...

- **Cronin effect (enhanced large p_T production in p-A)**
- **EMC effect (quarks are softer in nuclei)**
- **Collective flow (projectile “bounce-off”, “side splash” in A-A)**
- **Cosmic ray effects (JACEE experiment)**



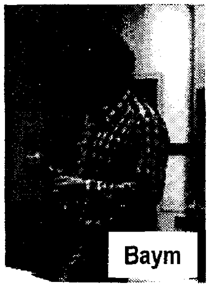
Helmut (and friends) stepped in and led us on the long road to RHIC



In the 1970's Helmut had established the renowned High energy theory group at Bielefeld, approaching particle physics with statistical and thermodynamic methods.

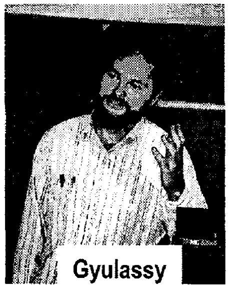
In 1985 he joined the BNL Physics Department, and for the next decade he divided his time between BNL, Bielefeld, and CERN.

He spoke eloquently to both the NP and HEP camps here in the U.S., and made many trips across the ocean during the critical period prior to RHIC approval in 1990, speaking with scientists and bureaucrats at all levels with a clarity that made the physics crisp and convincing.



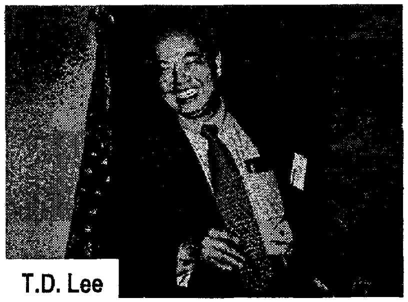
Baym

McLerran



Gyulassy

Willis



T.D. Lee

Presentation to NSAC, May 1986

H. SATZ:

HIGH ENERGY PHYSICS WITH HEAVY IONS

WHY ? HEP with hadrons → strong interaction dynamics
HEP with nuclei → strong interaction thermodynamics

NB: critical (collective) phenomena
= new physics, beyond dynamics

HOW ? Theory: statistical QCD
lattice formulation
computer simulation
→ prediction of thermodynamic observables

Exp't: collisions of sufficiently heavy nuclei
at sufficiently high energies
observe photon & dilepton spectra, p_T-
distributions of hadrons, ...

WHERE? BNL & CERN

WHEN? First studies CERN SPS (200 GeV/A) Nov. 86 $\}$ O^{16}, S^{32}
BNL AGS (15 GeV/A) Fall 86
heavy ions -"- + Booster 1990 A^{197}

dedicated machine RHIC 100+100 GeV/A
heavy ions

Statistical QCD

"Energetic nuclear collisions are our only tool to study in the laboratory the condensed state of matter in strong interaction physics." H.S. QM '84 summary

Deconfinement as the Mott transition of QCD

Debye screening of a given color charge due to the presence of many other such charges...

Mott transition in QCD,

from colour insulator (hadronic matter)

to colour conductor (quark-gluon plasma)

From the 1986 presentation to NSAC:
Phase transition from a color insulator (hadrons) to a color conductor (QGP).

atomic solids:

conductivity (indicates phase) $\sigma = \begin{cases} O(e^{-E_{ioniz.}/T}) & \text{insulator} \\ n/T & \text{conductor} \end{cases}$

QCD:

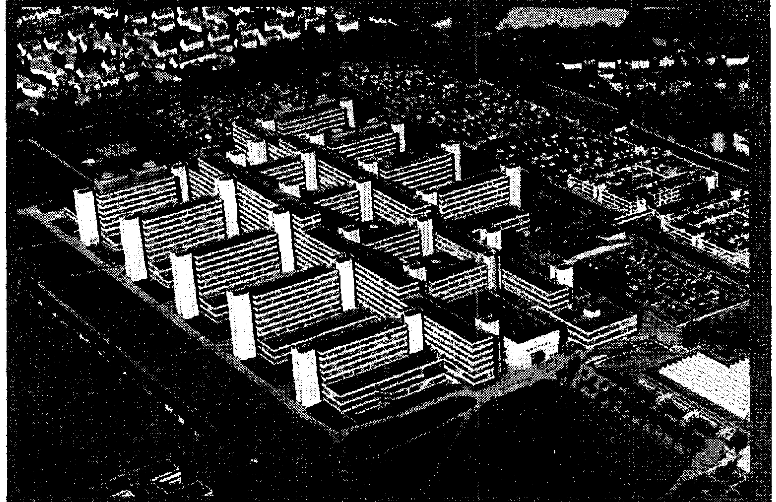
Polyakov loop $\bar{L} \sim e^{-V/T} = \begin{cases} O(e^{-m_H/T}) & \text{hadronic matter} \\ \to 1 & \text{quark plasma} \end{cases}$

$V \sim \lim_{r\to\infty} V(r)$

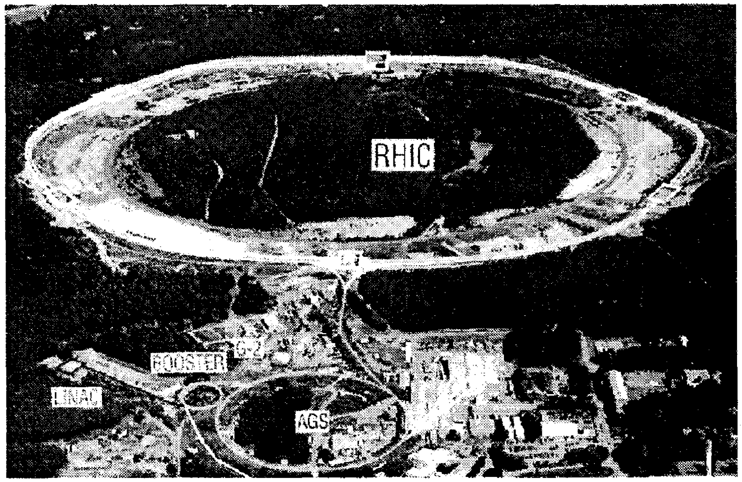
as phase indicator

Helmut's other side: Physics in Bielefeld

Bielefeld

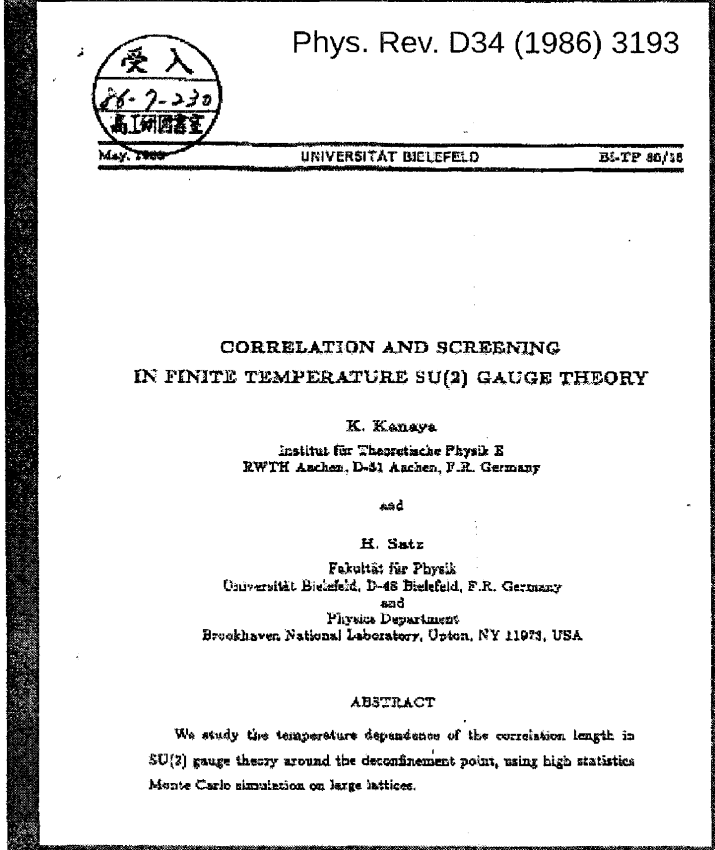


Brookhaven



25 years @ BNL

Lattice QCD Thermodynamics & J/psi suppression



Phys. Rev. D34 (1986) 3193

May, [illegible] UNIVERSITÄT BIELEFELD BI-TP 86/16

CORRELATION AND SCREENING IN FINITE TEMPERATURE SU(2) GAUGE THEORY

K. Kanaya
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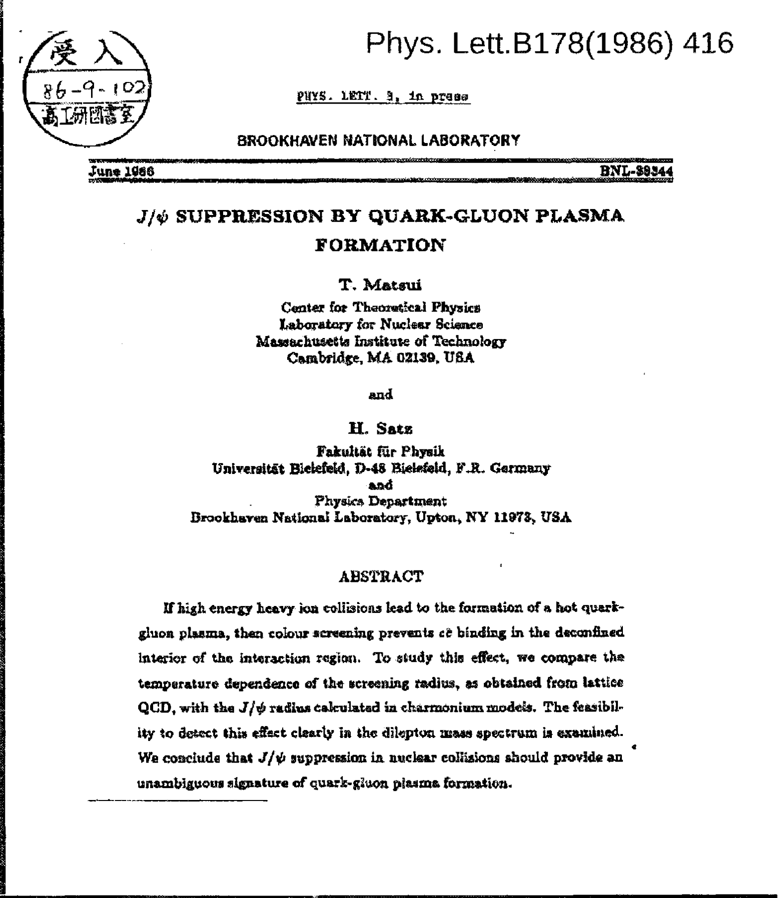
and

H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

We study the temperature dependence of the correlation length in SU(2) gauge theory around the deconfinement point, using high statistics Monte Carlo simulation on large lattices.



Phys. Lett.B178(1986) 416

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

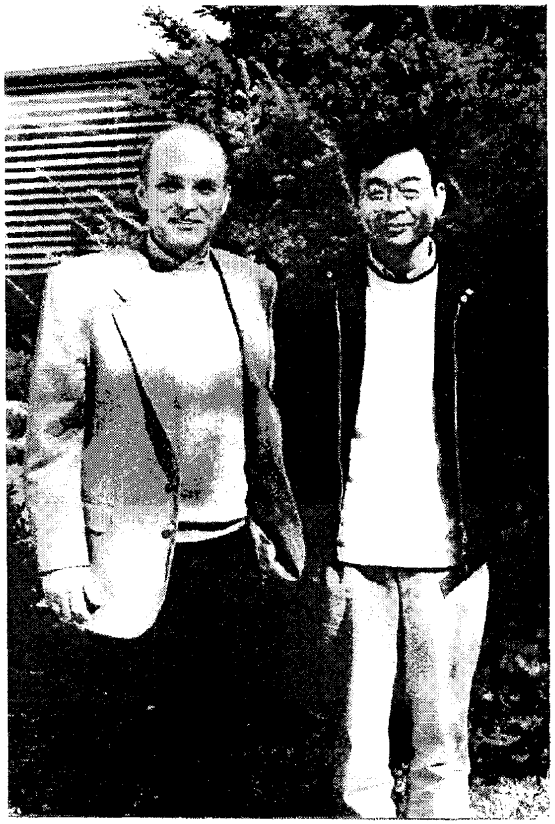
H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

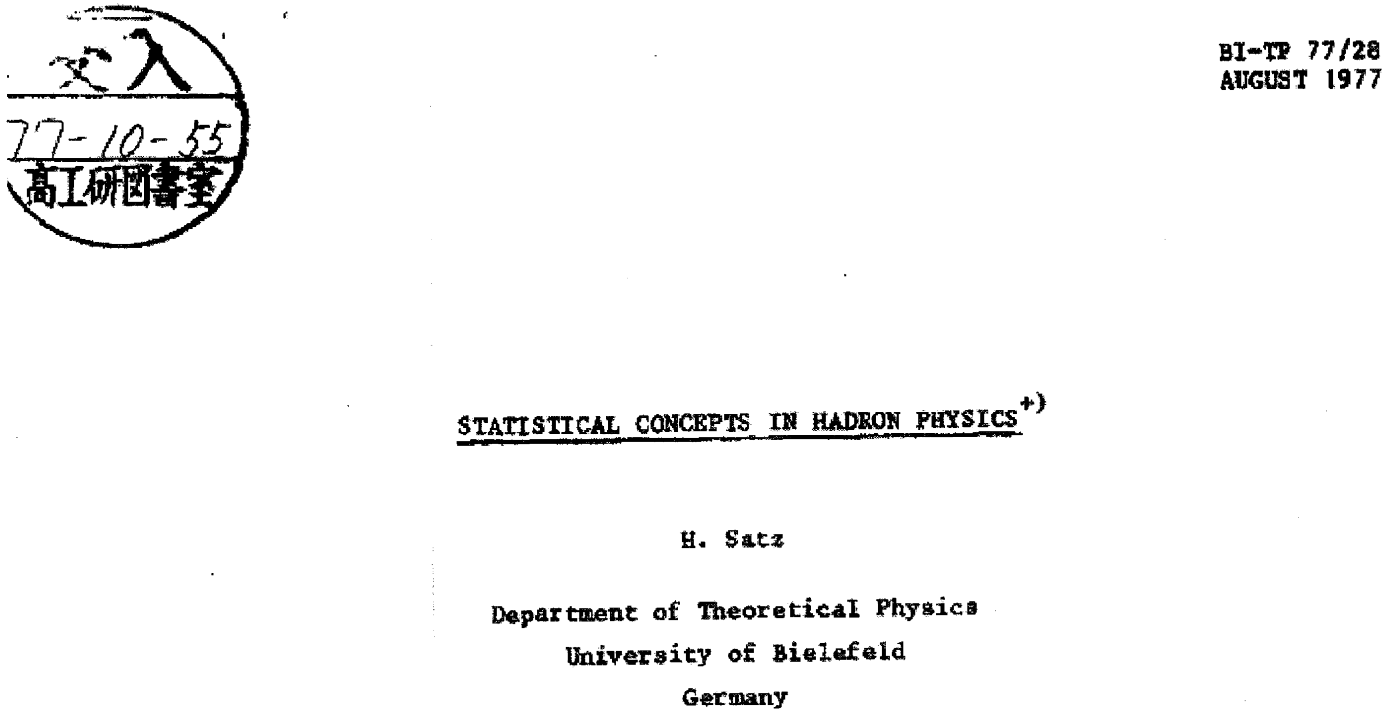
25 years @ BNL

Lattice QCD Thermodynamics & J/psi suppression



Helmut Satz & Tetsuo Matsui

back to the roots....1977



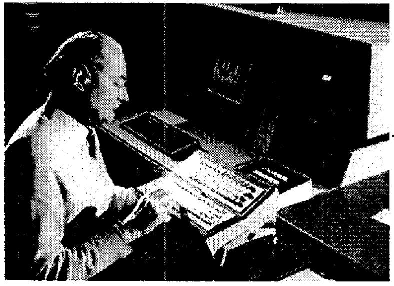
BI-TP 77/28
AUGUST 1977

STATISTICAL CONCEPTS IN HADRON PHYSICS+)

H. Satz

Department of Theoretical Physics
University of Bielefeld
Germany

back to the roots....1977



Rolf Hagedorn

BI-TP 77/28
AUGUST 1977

On a more general level, it is of course also still open if all hadronic systems indeed obey the temperature bound (27), making that relation something of a "fourth law of thermodynamics", or if at sufficiently high energy density a phase transition sets in, from a hadron gas to one of hadronic constituents ("quark gas")^{22,23,24}, whose interaction is not governed by the dynamics we have considered here.

IV. PHASE TRANSITIONS IN HADRONIC SYSTEMS

The transformation of a hadron gas into a quark gas would in many ways correspond to a conventional phase transition. Since hadrons and their

Larry McLerran

22) N. Cabbibo,G. Parisi, Phys. Lett. 59B (1974) 67
23) J.C. Perry, M.J. Collins, Phys. Rev .Lett. 34 (1975) 1353
24) B.A. Freedman, L.P. McLerran, MIT preprint 541 (1976)

Percolation and Lattice QCD

Volume 97B, number 1 PHYSICS LETTERS 17 November 1980

A PERCOLATION APPROACH TO STRONGLY INTERACTING MATTER

T. ÇELIK, F. KARSCH and H. SATZ
Department of Theoretical Physics, University of Bielefeld, Germany

Received 5 September 1980

Using percolation theory to determine transition points, we show that strongly interacting bulk systems exhibit hadronic matter behaviour for densities $0.48\ n_0 \leqslant n \leqslant 14.0\ n_0$ and quark matter behavior for $n \geqslant 3.84\ n_0$, where $n_0 = 0.17\ \text{fm}^{-3}$ is nuclear density. For $3.84\ n_0 \leqslant n \leqslant 14.0\ n_0$, we find a coexistence region of the two phases.

Volume 101B, number 1,2 PHYSICS LETTERS 30 April 1981

HIGH TEMPERATURE SU(2) GLUON MATTER ON THE LATTICE

J. ENGELS, F. KARSCH and H. SATZ
Department of Theoretical Physics, University of Bielefeld, Germany
and
I. MONTVAY
II. Institut für Theoretische Physik der Universität Hamburg [1], *Germany*

Received 21 January 1981

We calculate by Monte Carlo simulation on the lattice the energy density ϵ of an SU(2) Yang–Mills system at finite physical temperature. First, we study the high temperature form of ϵ, showing that the conventional euclidean lattice formulation converges to the parameter-free Stefan–Boltzmann limit of a free gluon gas in the continuum. Secondly, we show that the specific heat of gluon matter exhibits a sharp peak at the transition point from the confined phase to the color-screened gluon gas. The resulting transition temperature is found to be 210 ± 10 MeV.

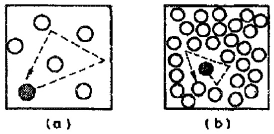


FIG. 4. Particle mobility in a dilute (a) and in a dense (b) system.

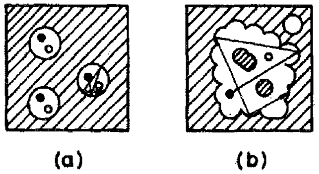


FIG. 2. Quark mobility at (a) low and at (b) high density.

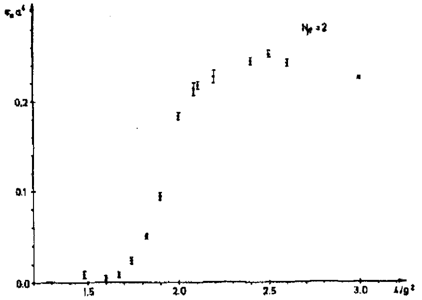


Fig. 3. Energy density of gluon matter versus $4/g^2$, at fixed lattice size $N_\beta = 2$, after about 500 iterations.

Quarkonium Production at Hadron-Hadron Colliders

Geoffrey Bodwin
Argonne National Lab

- Factorization of the Inclusive Production Cross Section
  - Status of a Proof of Factorization
- Comparisons of NRQCD Factorization with Hadron-Hadron Experiments
  - Quarkonium Production and Polarization at the Tevatron
  - J/ψ production at RHIC
  - J/ψ production at the LHC
- Summary

Factorization of the Inclusive Quarkonium Production Cross Section

- In heavy-quarkonium hard-scattering production, high-momentum scales appear: m and p_T.
- We would like to use NRQCD to separate the perturbative physics at these high-momentum scales from the low-momentum, nonperturbative effects in the heavy-quarkonium dynamics.
- The probability for a $Q\bar{Q}$ pair to evolve into a heavy quarkonium can be calculated as a vacuum-matrix element in NRQCD:

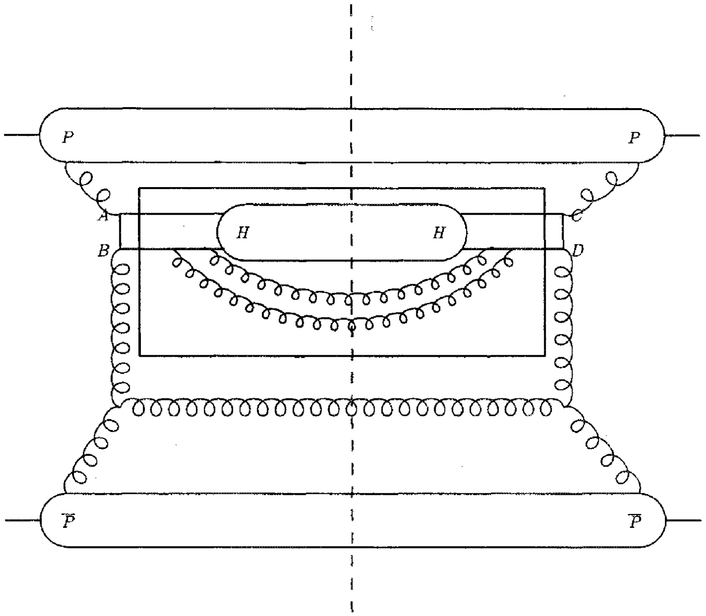
$$\mathcal{O}_n^H(\Lambda) = \langle 0|\chi^\dagger \kappa_n \psi \Big(\sum_X |H + X\rangle\langle H + X|\Big)\psi^\dagger \kappa'_n \chi|0\rangle .$$

- This is the matrix element of a four-fermion operator, but with a projection onto an intermediate state of the quarkonium H plus anything.
  - κ_n and κ'_n are combinations of Pauli and Color matrices.

- Conjecture (GTB, Braaten, Lepage (1995)):
  The inclusive cross section for producing a quarkonium at large momentum transfer (p_T) can be written as a sum of "short-distance" coefficients times NRQCD matrix elements.

$$\sigma(H) = \sum_n F_n(\Lambda)\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle .$$

- The part of the diagram inside the box corresponds to an NRQCD matrix element.



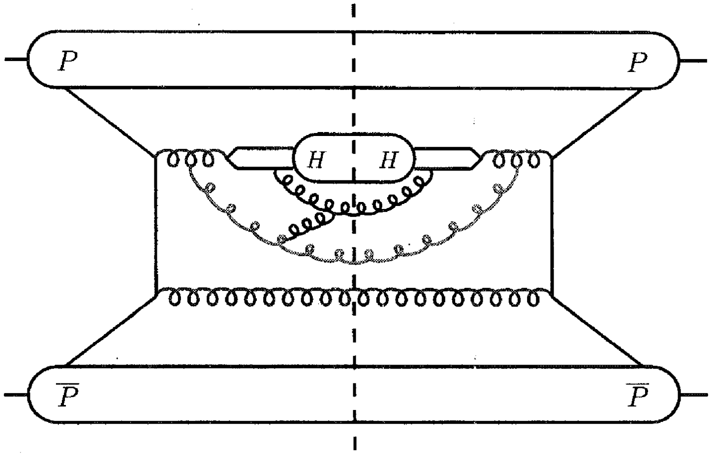
- The points $A(C)$ and $B(D)$ are within $\sim 1/m$ of each other.
  - Kinematics implies that the virtual Q is off shell by order m.
- The points $A(B)$ and $C(D)$ are within $1/p_T$ of each other.
  - The part of the diagram outside the box is insensitive to changes of momentum flow from $A(B)$ to $C(D)$ of order p_T.

- The "short-distance" coefficients $F_n(\Lambda)$ are essentially the process-dependent partonic cross sections to make a $Q\bar{Q}$ pair convolved with the parton distributions.
  - They have an expansion in powers of α_s.
- The operator matrix elements are universal (process independent).
  - Only the color-singlet production and decay matrix elements are simply related.
- The matrix elements have a known scaling with v.
- The NRQCD factorization formula is a double expansion in powers of α_s and v.
- A key feature of NRQCD factorization:
  Quarkonium production can occur through color-octet, as well as color-singlet, $Q\bar{Q}$ states.
- If we drop all of the color-octet contributions and retain only the leading color-singlet contribution, then we have the color-singlet model (CSM).
  - Inconsistent for P-wave production: IR divergent.

Status of a Proof of Factorization

- A proof is complicated because gluons can dress the basic production process in ways that apparently violate factorization.
- A proof of factorization would involve a demonstration that diagrams in each order in α_s can be re-organized so that
  - All soft singularities cancel or can be absorbed into NRQCD matrix elements,
  - All collinear singularities and spectator interactions can be absorbed into parton distributions.
- Nayak, Qiu, Sterman (2005, 2006): The color-octet NRQCD matrix elements must be modified by the inclusion of eikonal lines to make them gauge invariant.
  - The eikonal lines are path integrals of the gauge field running from the creation and annihilation points to infinity.
  - Essential at two-loop order to allow certain soft contributions to be absorbed into the matrix elements.
  - Does not affect existing phenomenology, which is at tree order or one-loop order in the color-octet contributions.

- Nayak, Qiu, Sterman (2005, 2006): A key difficulty in proving factorization to all orders is the treatment of gluons with momenta of order m in the quarkonium rest frame.



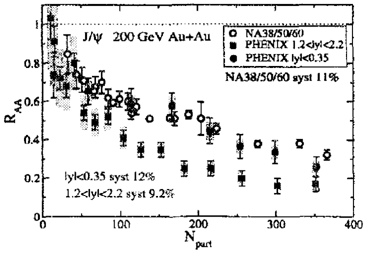
- If the orange gluon has momentum of order m, it can't be absorbed into the NRQCD matrix element as a quarkonium constituent.
- But the orange gluon can have non-vanishing soft exchanges with the quarkonium constituents.
- The orange gluon can be treated as the eikonal-line part of the NRQCD matrix element, provided that the answer does not depend on the direction of the eikonal line (universality of the matrix elements).

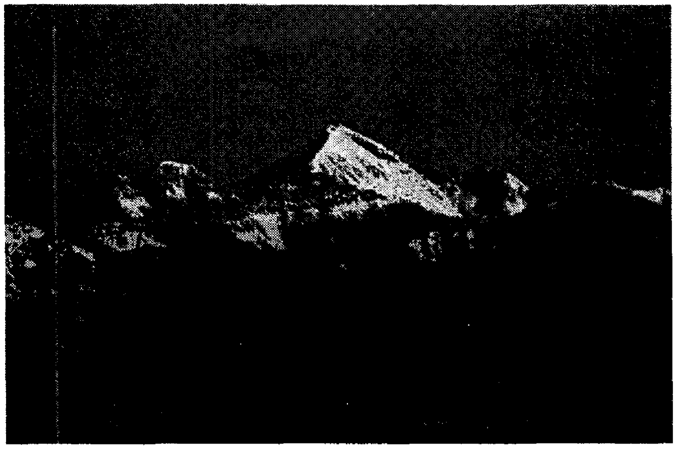
- Nayak, Qiu, Sterman (2005, 2006): At two-loop order, the eikonal lines contribute but a “miracle” occurs: The dependence on the direction of the eikonal line cancels.
- In general, factorization of the inclusive cross section beyond two-loop order is still an open question.
- An all-orders proof is essential because the α_s associated with soft gluons is not small.

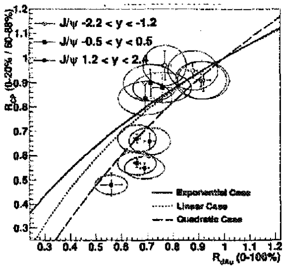
Landscape of the Quarkonia Puzzle

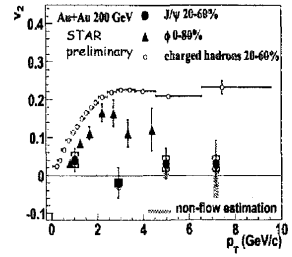
QWG at BNL - June 6-18, 2011

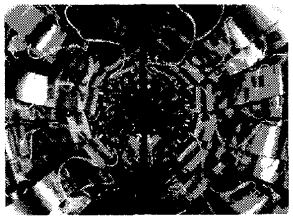
Mike Leitch, LANL



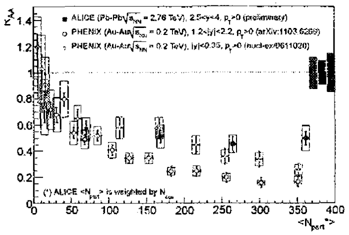


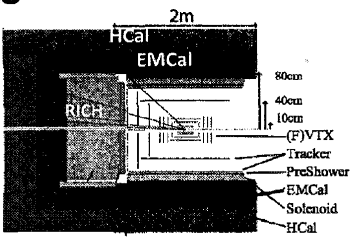






- Charmonia Suppression in A+A Collisions
- (Strong) CNM effects
- Production uncertainties
- Heavier Quarkonia
- Future





Quarkonia Suppression in A+A Collisions - Debye Screening

For the hot-dense medium (QGP) created in A+A collisions at RHIC

- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks
- Is there deconfinement? → look for Quarkonia screening

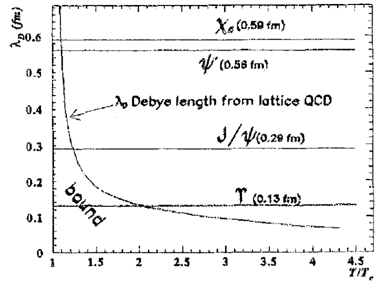
> Matsui and Satz, Phys. Lett. B 178 (1986) 416:
> *"If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents ccbar binding in the deconfined interior of the interaction region ... ... It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation."*

Debye screening predicted to destroy J/ψ's in a QGP with other states "melting" at different temperatures due to different sizes or binding energies.

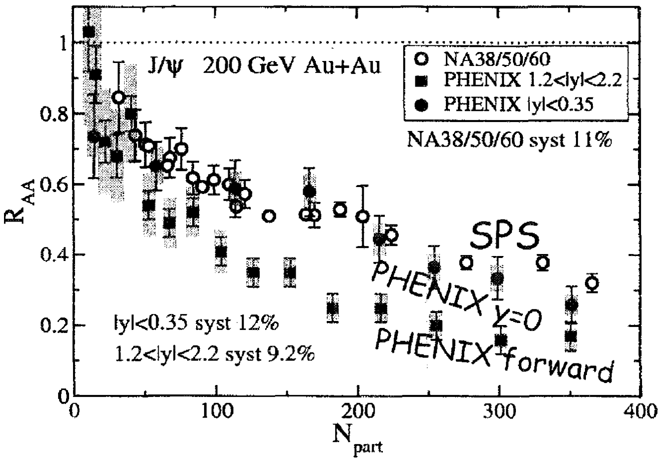
Different lattice calculations do not agree on whether the J/ψ is screened or not - measurements will have to tell!

Satz, hep-ph/0512217

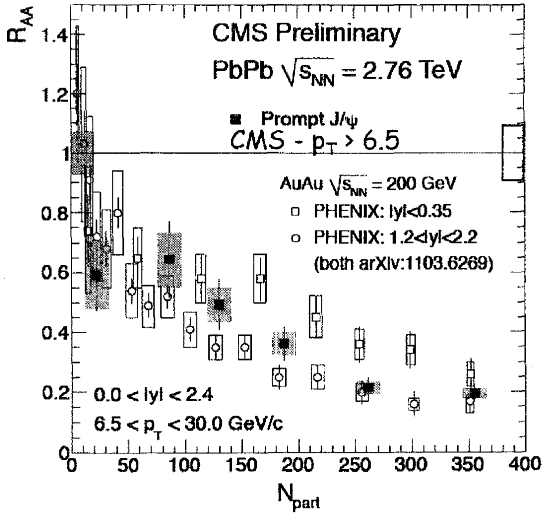
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

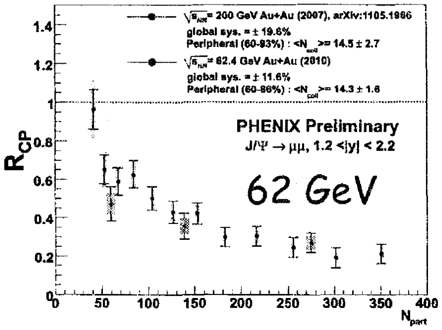


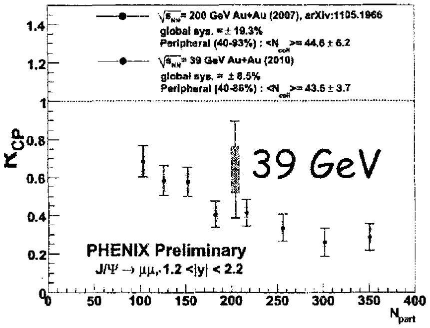
Quarkonia Suppression in A+A Collisions - key observations and questions



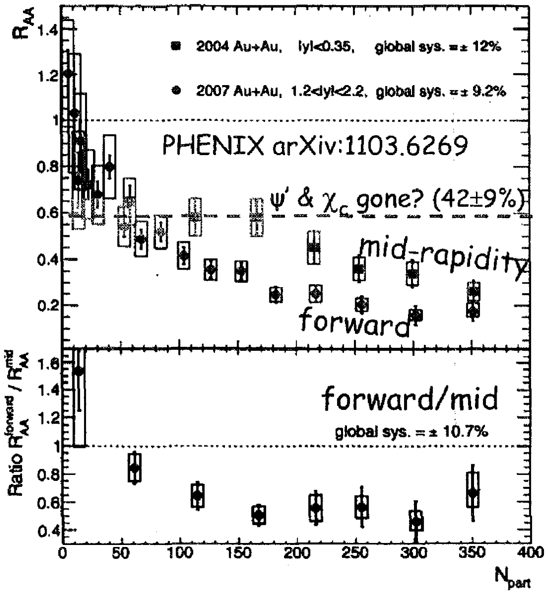
Overall suppression of J/ψ is nearly identical between RHIC, SPS, & LHC







Quarkonia Suppression in A+A Collisions - key observations and questions



PHENIX arXiv:1103.6269

ψ' & χ_c gone? (42±9%)

mid-rapidity

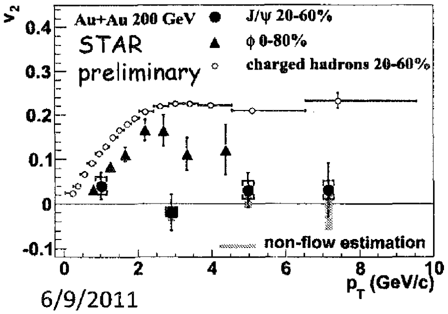
forward

forward/mid

Forward-rapidity is suppressed more than Mid-rapidity

Stronger forward rapidity suppression due to CNM effects?

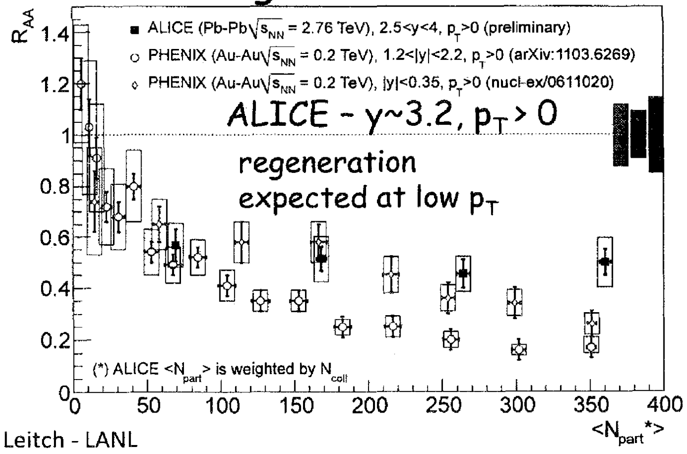
Regeneration at mid-rapidity reduces suppression relative to forward (and gives net suppression similar to SPS)?



STAR preliminary

no J/ψ flow at RHIC!

Hint of regeneration at ALICE?

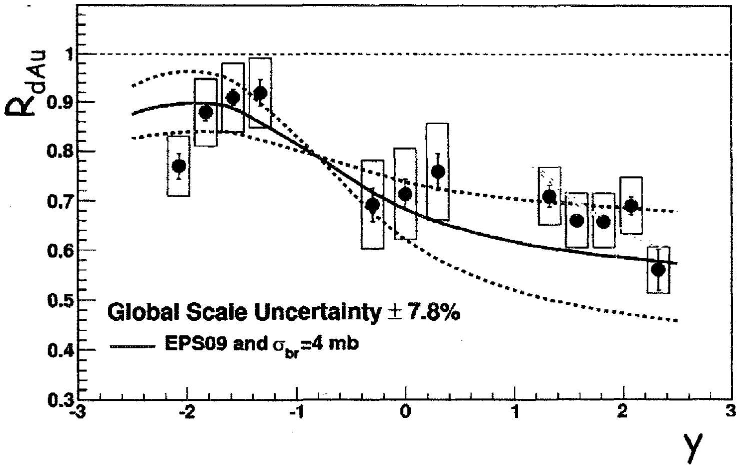


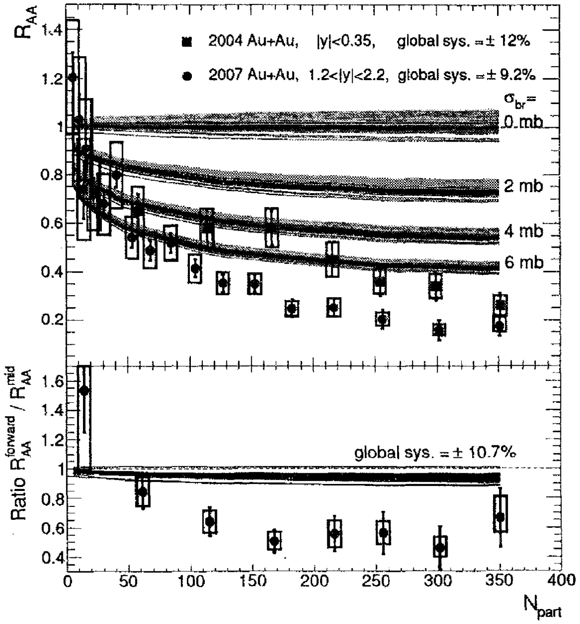
ALICE - y~3.2, p_T> 0

regeneration expected at low p_T

Quarkonia Suppression in A+A Collisions - key observations and questions

CNM effects appear to provide a large fraction of the observed suppression; so difficult to conclude much w/o a thorough understanding of CNM and its extrapolation to A+A from d+A

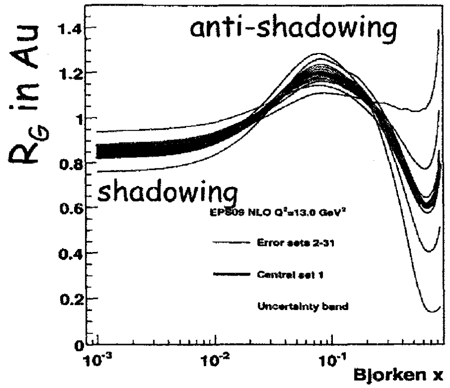


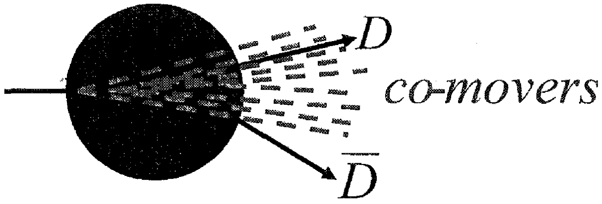


- Probably have to understand CNM in a fundamental way in order to obtain reliable/quantitative extrapolations to A+A
- Only then can we be quantitative about the suppression effects of the QGP

What are the CNM effects that are so strong in quarkonia production?

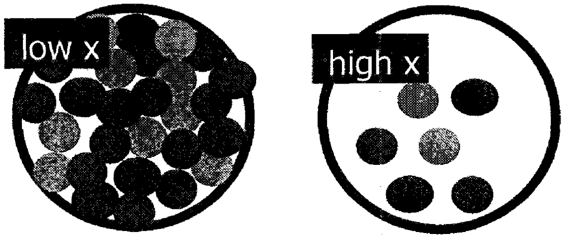
Traditional shadowing from fits to DIS or from coherence models



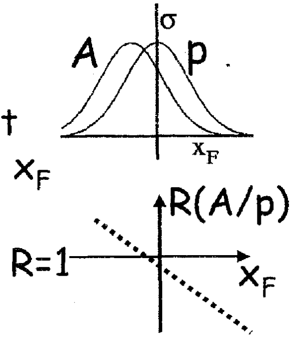


Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

Gluon saturation from non-linear gluon interactions for the high density at small x; amplified in a nucleus.



Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F

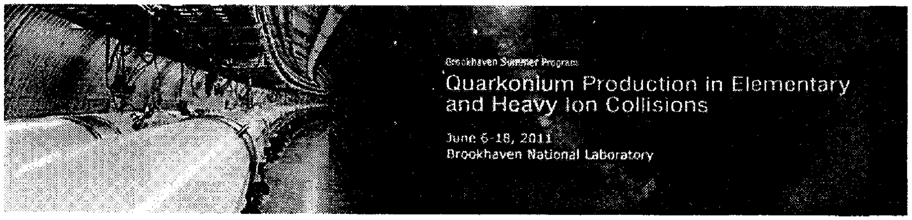


Quarkonium Production in Hot Medium

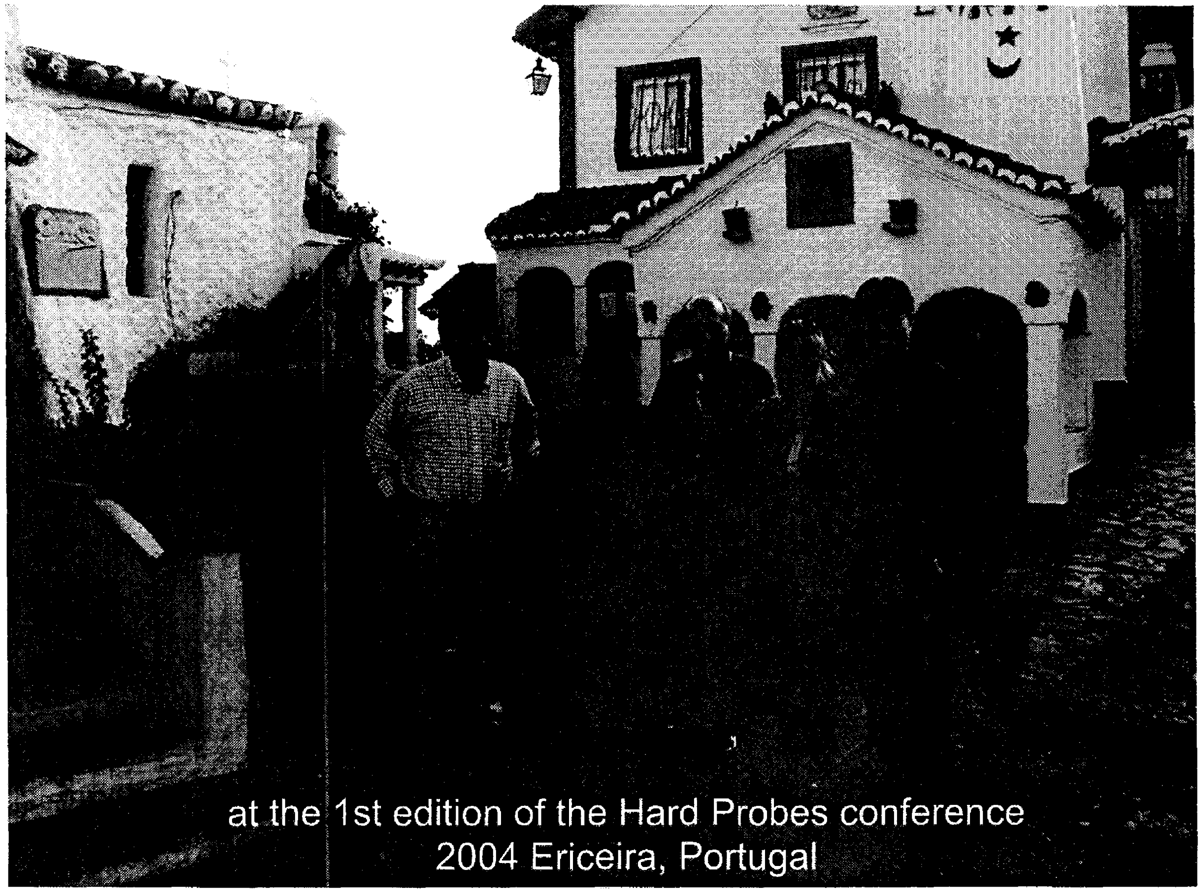
Ágnes Mócsy

Pratt Institute, Brooklyn, New York

Pratt

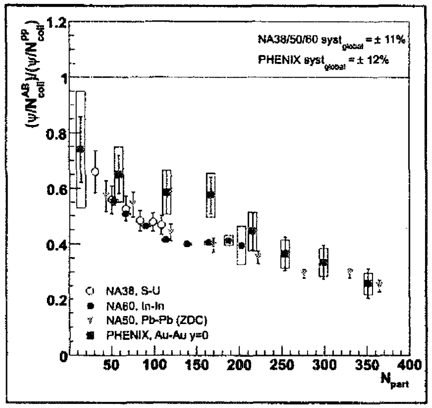


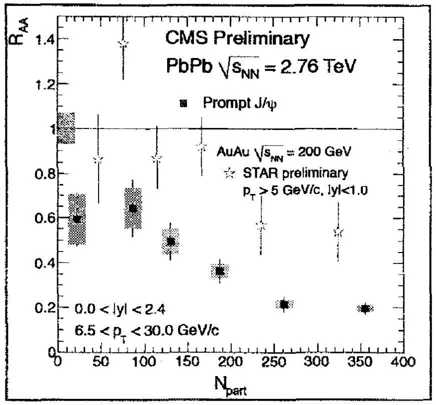
Herzliche Glückwünsche, Helmut!

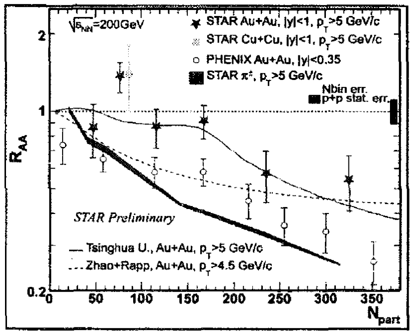


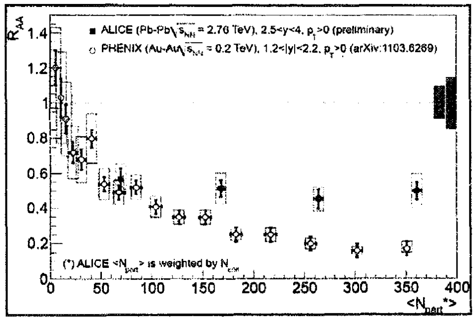
at the 1st edition of the Hard Probes conference
2004 Ericeira, Portugal

Starting Point : R_{AA}









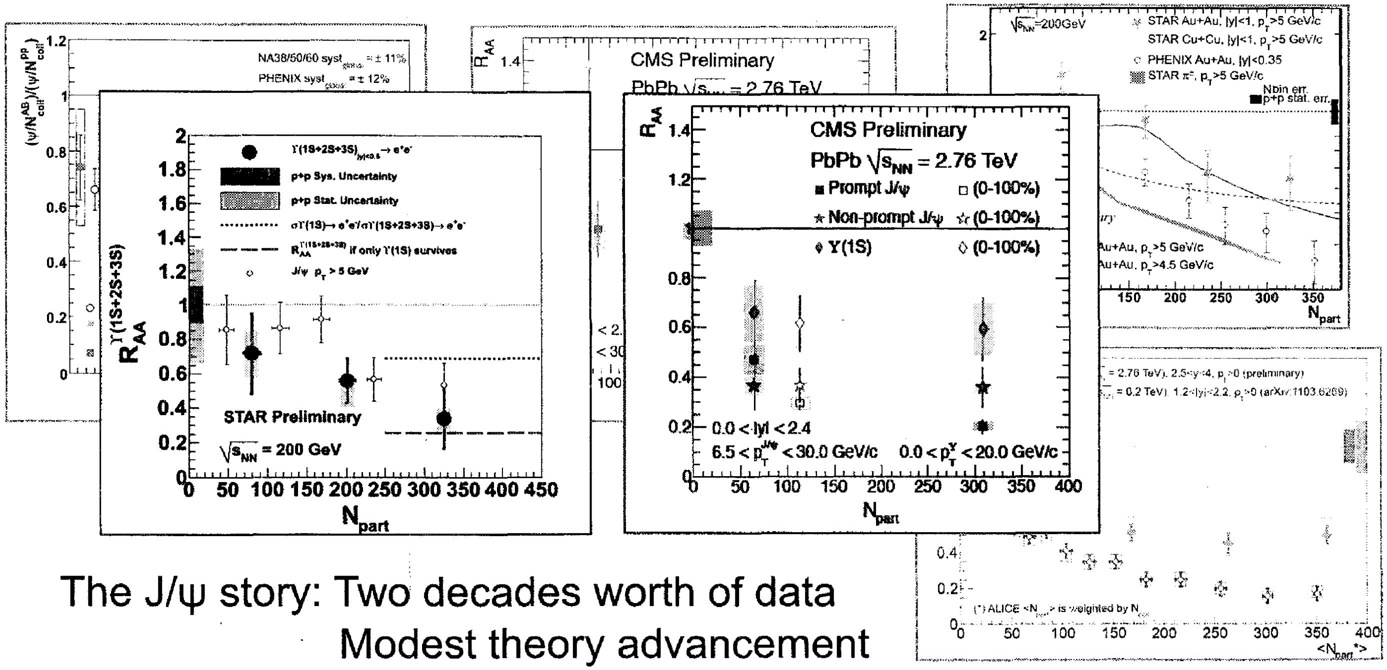
The J/ψ story: Two decades worth of data

Modest theory advancement

Lots of ad-hoc phenomenological modeling

It is difficult to unambiguously interpret - we are still not there

Starting Point : R_{AA}



The J/ψ story: Two decades worth of data

Modest theory advancement

Lots of ad-hoc phenomenological modeling

It is difficult to unambiguously interpret - we are still not there

The Υ story just started !

Main Outline

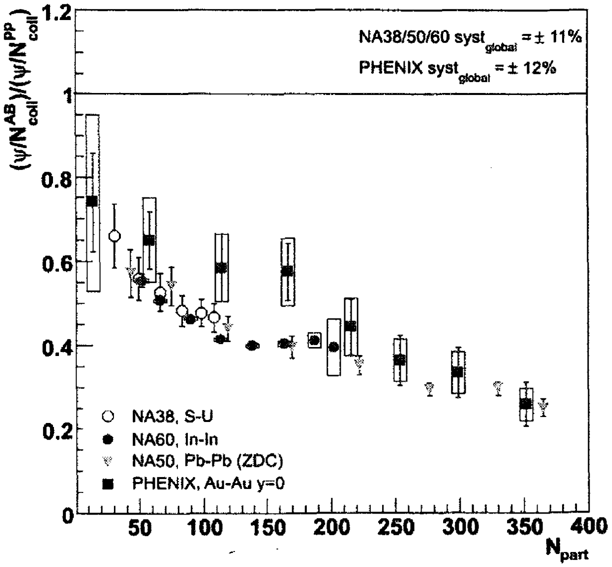
- What we know theoretically about quarkonium in deconfined medium

- Bridging between theory and experimental data

- Some cross-checks: in attempt to isolate pure hot medium effects

The R_{AA}

- J/ψ nuclear modification factor:
  yield in AA collisions relative to yield in pp (where no QGP formation expected) scaled with number of binary NN collisions



$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N^{AuAu}_{J/\psi}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N^{pp}_{J/\psi}/\mathrm{d}y}$$

- If AA is superposition of pp then R_{AA}=1
- Deviation from 1 indicates medium effects
- If no J/ψ measured then R_{AA}=0

- A J/ψ-suppression pattern observed at SPS and RHIC and LHC

Heavy quarkonium in a weakly-coupled QGP using EFTs

Miguel A. Escobedo

Physik-Department T30f. Technische Universität München

9th of June, 2011

Work done in collaboration with N. Brambilla, J. Ghiglieri, J. Soto and A. Vairo.

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Outline

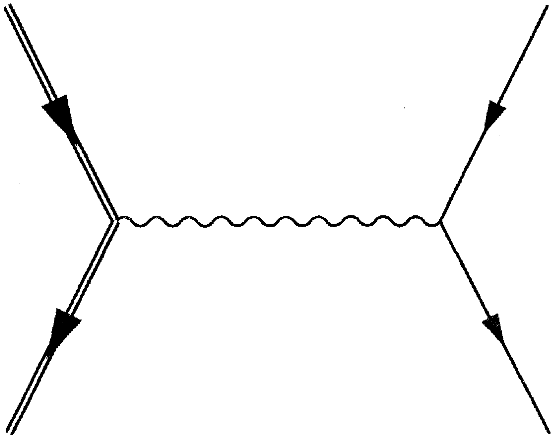
1. Motivation
2. The $\frac{1}{r} \gg T \gg \Delta E \gg gT$ regime
3. $m \gg T \gg \frac{1}{r} \sim gT$. Dissociation temperature.

Energy scales for zero temperature heavy quarkonium

Heavy quarkonium at $T = 0$ is a system with a lot of different energy scales.

For example, for computing the decay of J/Ψ to electrons...

- We need annihilation cross section of the quark and the anti-quark to electrons. The energies involved are of the order of m_c.



Energy scales for zero temperature heavy quarkonium

Heavy quarkonium at $T = 0$ is a system with a lot of different energy scales.
For example, for computing the decay of J/Ψ to electrons...

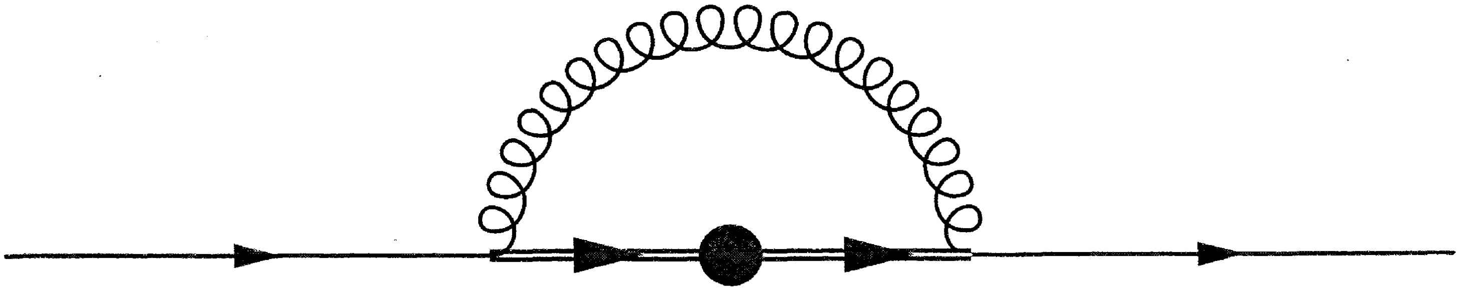
- We also need the probability that the quark and the anti-quark are at the same point, this is given by the wave-functions. The energies involved are of the order of $1/r$.

$$\Psi_{ab}(\mathbf{r})$$

Energy scales for zero temperature heavy quarkonium

Heavy quarkonium at $T = 0$ is a system with a lot of different energy scales.
For example, for computing the decay of J/Ψ to electrons...

- If we want to make a precision computation, we need to include the effects of the color octet component of J/Ψ. The energy involved here is of order of the binding energy.



Energy scales for zero temperature heavy quarkonium

Heavy quarkonium at $T = 0$ is a system with a lot of different energy scales.

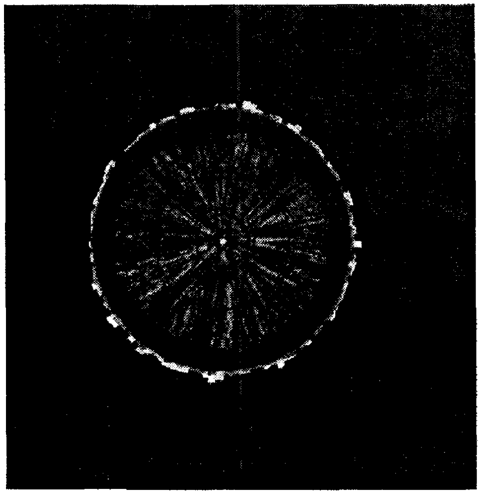
For example, for computing the decay of J/Ψ to electrons...

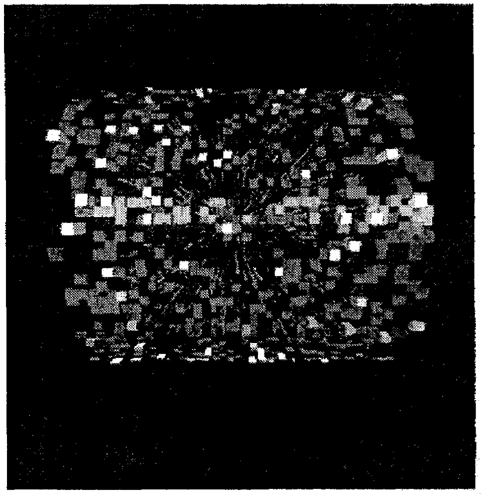
- We need annihilation cross section of the quark and the anti-quark to electrons. The energies involved are of the order of m_c.
- We also need the probability that the quark and the anti-quark are at the same point, this is given by the wave-functions. The energies involved are of the order of $1/r$.
- If we want to make a precision computation, we need to include the effects of the color octet component of J/Ψ. The energy involved here is of order of the binding energy.

Measuring the Υ Nuclear Modification Factor at STAR

Rosi Reed (UC Davis)

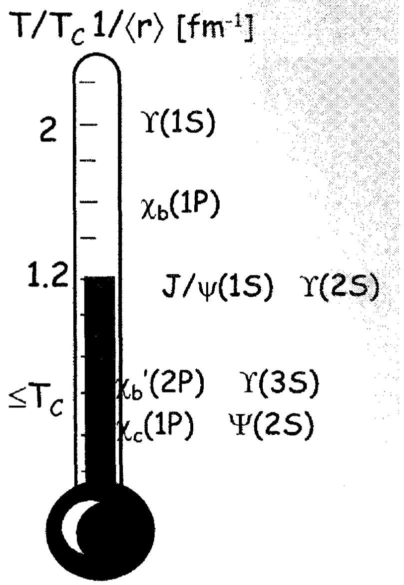
for the STAR Collaboration



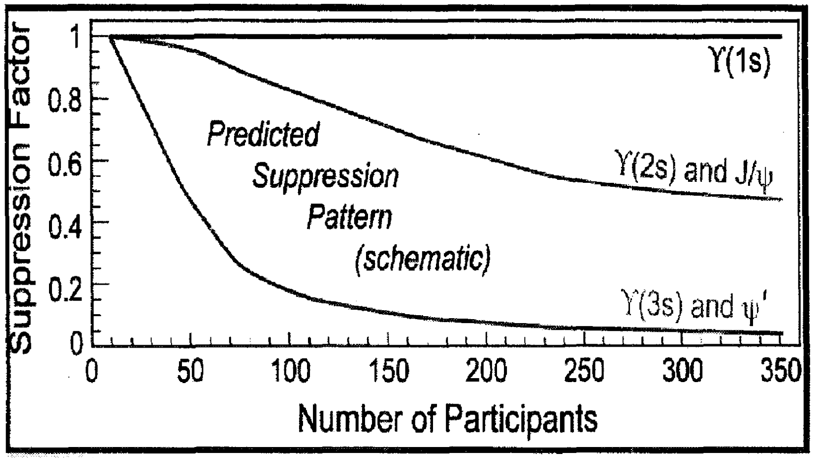


Motivations

Sequential suppression of Quarkonium mesons acts as a QGP thermometer.



] A. Mocsy and P.Petreczky, PRL 99, 211602 (2007)



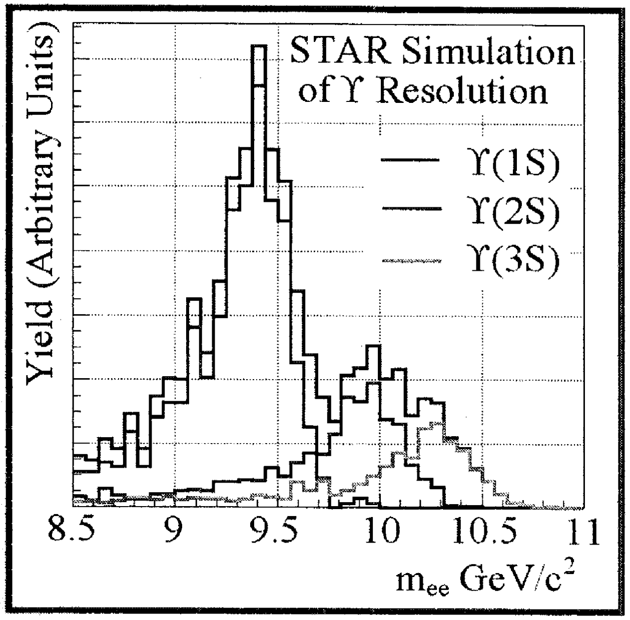
Expectation at 200 GeV

$\Upsilon(1S)$ does not melt

$\Upsilon(2S)$ is likely to melt

$\Upsilon(3S)$ will melt

ϒ at STAR



- Decay channel: $\Upsilon \rightarrow e^{+}e^{-}$

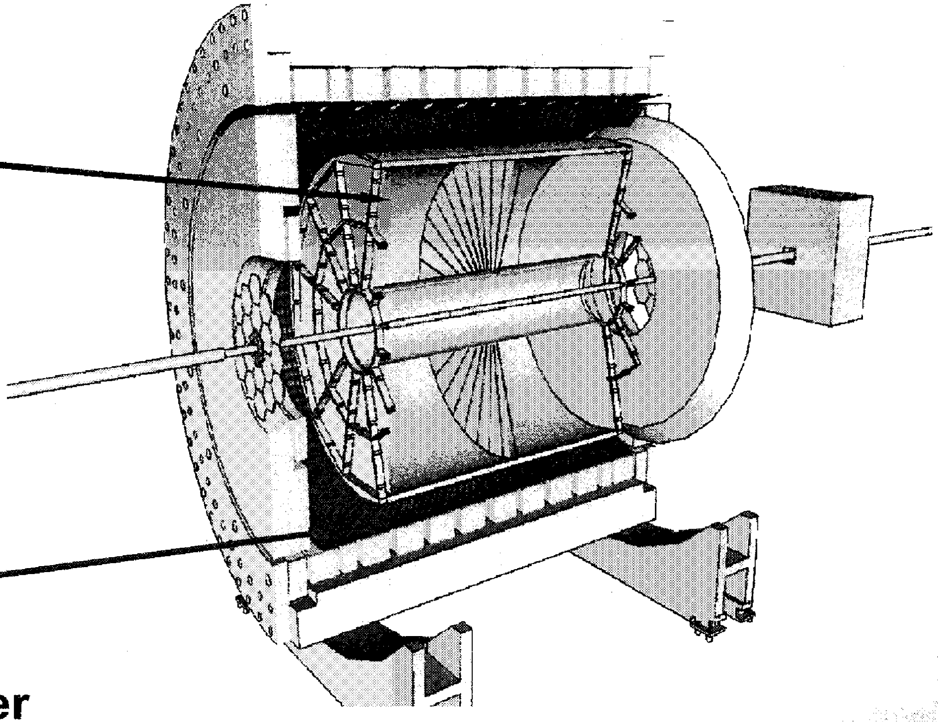
Pros

- Small background at M~10 GeV/c^2
- Co-mover absorption is small at 200 GeV
- Recombination negligible at 200 GeV
- Large Acceptance
- Fast Trigger

Cons

- Low rate of 10^{-9} per minbias pp interaction
- Good resolution needed to separate 3 S-states

Υ at STAR



TPC

$|\eta| < 1$, $0 < \phi < 2\pi$

Tracking → momentum

dE/dx → electron ID

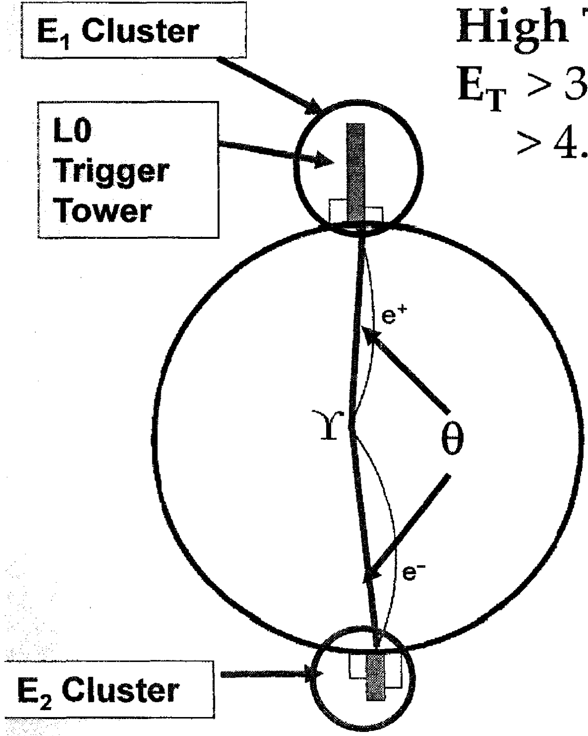
BEMC

$|\eta| < 1$, $0 < \phi < 2\pi$

E/p → electron ID

High-energy tower trigger

Trigger and Analysis



High Tower

E_T > 3.5 GeV (pp)

> 4.0 GeV (AuAu)

L2 Parameters

(pp only)

E$_1$ Cluster,

E$_2$ Cluster,

Cos(θ),

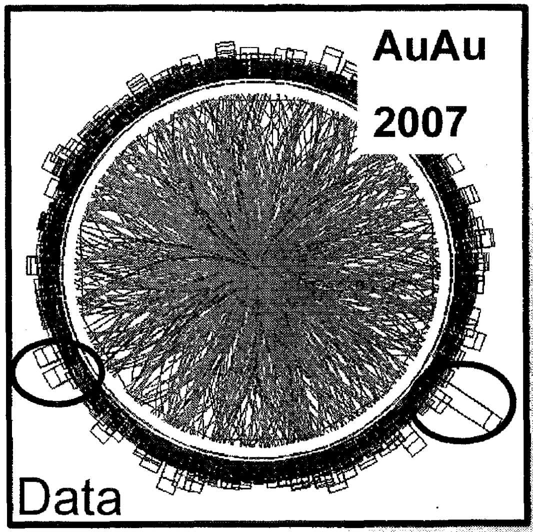
Invariant Mass

Rejection

~10^5 in pp

Can sample

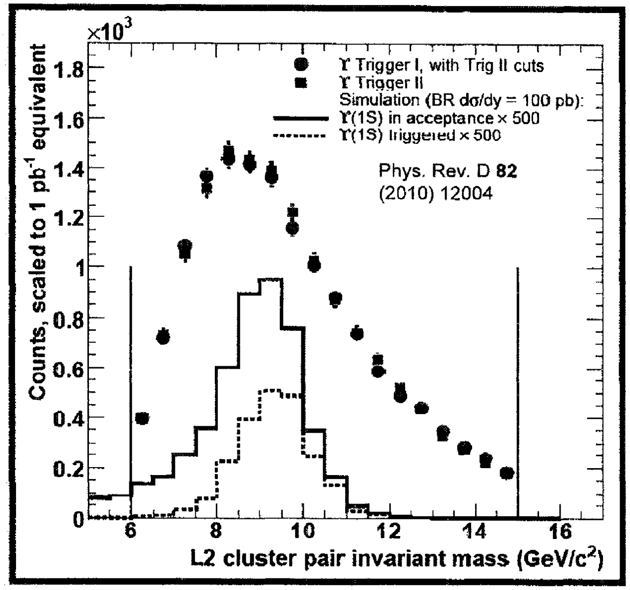
full luminosity



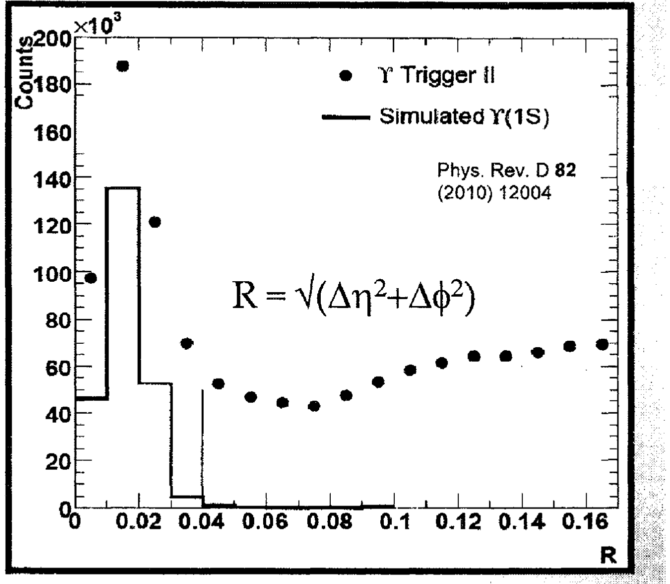
STAR

Analysis Techniques

Triggered candidates exceed number of Υ by a factor of ~700 (p+p)



TPC tracks that extrapolate to R=0.04 in η–ϕ to trigger clusters are "matched"



Estimating the Uncertainty on J/ψ Production

R. Vogt (LLNL and UC Davis)

Outline

- **Production in pp – Color Evaporation**
- **Fraction of J/ψ from B Decays**
- **Brief Discussion of Cold Matter Effects**

Color Evaporation

All quarkonium states are treated like $Q\overline{Q}$ $(Q = c, b)$ below $H\overline{H}$ $(H = D, B)$ threshold

Distributions for all quarkonium family members similar, modulo decay feed down, production ratios should be independent of $\sqrt{s}$

At LO, $gg \to Q\overline{Q}$ and $q\overline{q} \to Q\overline{Q}$; NLO add $gq \to Q\overline{Q}q$

$$\sigma_Q^{\rm CEM} = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 \; f_{i/p}(x_1, \mu^2) \; f_{j/p}(x_2, \mu^2) \; \hat{\sigma}_{ij}(\hat{s}) \; \delta(\hat{s} - x_1 x_2 s)$$

Values of m_Q and Q^2 fixed from NLO calculation of $Q\overline{Q}$ production

Main uncertainties arise from choice of PDFs, heavy quark mass, renormalization (α_s) and factorization (evolution of PDFs) scales

Inclusive F_Q fixed by comparison of NLO calculation of $\sigma_Q^{\rm CEM}$ to $\sqrt{s}$ dependence of J/ψ and Υ cross sections, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for J/ψ, $Bd\sigma/dy|_{y=0}$ for Υ

Data and branching ratios used to separate the F_Q's for each quarkonium state

Resonance	J/ψ	ψ'	χ_{c1}	χ_{c2}	Υ	Υ'	Υ''	$\chi_b(1P)$	$\chi_b(2P)$
$\sigma_i^{\rm dir}/\sigma_H$	0.62	0.14	0.6	0.99	0.52	0.33	0.20	1.08	0.84
f_i	0.62	0.08	0.16	0.14	0.52	0.10	0.02	0.26	0.10

Table 1: The ratios of the direct quarkonium production cross sections, $\sigma_i^{\rm dir}$, to the inclusive J/ψ and Υ cross sections, denoted σ_H, and the feed down contributions of all states to the J/ψ and Υ cross sections, f_i, Digal *et al.*.

Why Still CEM?

Open and hidden charm photo- and hadroproduction show similar energy dependence

High p_T Tevatron Run I data show that, within uncertainties of the data, the prompt J/ψ, the ψ' and χ_c p_T dependencies are the same

Amundsen *et al.* calculated p_T distribution (only partial real part) harder than data at high p_T, undershoots at low p_T – likely because they do not include any k_T smearing

Gavai *et al.* calculated complete J/ψ p_T distribution starting from exclusive NLO $Q\overline{Q}$ production code by Mangano *et al.*

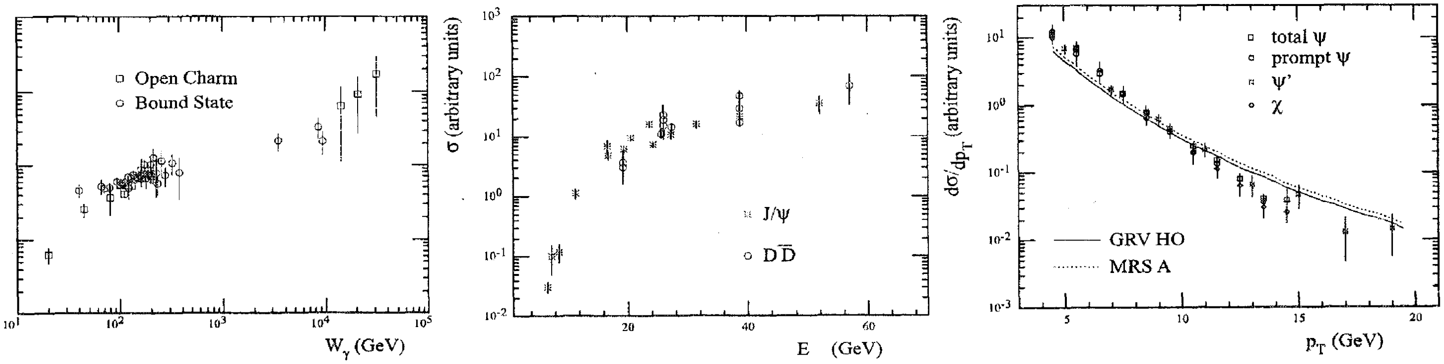


Figure 1: (Left) Photoproduction data as a function of the photon energy in the hadron rest frame, W_γ. (Center) Hadroproduction data as a function of the center-of-mass energy, E_{cm}. In both cases, the normalization has been adjusted to show the similar shapes of the data. (Right) Run I data from the CDF Collaboration, shown with arbitrary normalization. The curves are the predictions of the color evaporation model at tree level, also shown with arbitrary normalization. [Amundson *et al.*]

How to Fix the Uncertainty on the CEM Result?

Previously took 'by eye' fit to $Q\overline{Q}$ total cross section

Dates back to original Hard Probes Collaboration report in 1995 – only PDF changed over time

Since I've been asked what the uncertainty on the cross section is, I have to try to invent some, work in progress

Choosing J/ψ Parameters I: FONLL-based

Main sources of uncertainty:

Mass: $1.3 < m < 1.7$ GeV for charm (central value, 1.5 GeV)

Scale: renormalization, μ_R, and factorization, μ_F, scales governing α_s and PDF behavior respectively

Parton Density: evolution of gluon density

With a given PDF set define a fiducial region of mass and scale that should encompass the true value:

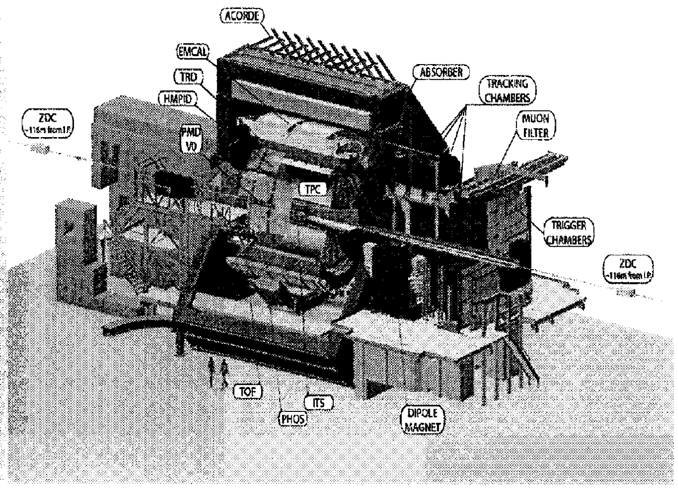
- For $\mu_F = \mu_R = m$, vary mass between upper and lower end of range;
- For central mass value, vary scales independently within a factor of two: $(\mu_F/m, \mu_R/m) = (1,1)$, (2,2), (0.5,0.5), (0.5,1), (1,0.5), (1,2), (2,1).

Define upper and lower bounds of theoretical values; the maximum and minimum may not come from the same set of parameters at a given energy or p_T

The uncertainty band comes from the upper and lower limits of mass and scale uncertainties added in quadrature:

$$\begin{aligned}\sigma_{\rm max} &= \sigma_{\rm cent} + \sqrt{(\sigma_{\mu,{\rm max}} - \sigma_{\rm cent})^2 + (\sigma_{m,{\rm max}} - \sigma_{\rm cent})^2} \\ \sigma_{\rm min} &= \sigma_{\rm cent} - \sqrt{(\sigma_{\mu,{\rm min}} - \sigma_{\rm cent})^2 + (\sigma_{m,{\rm min}} - \sigma_{\rm cent})^2}\end{aligned}$$

J/ψ production in pp collisions with ALICE



Ionut Cristian Arsene
for the ALICE Collaboration

GSI

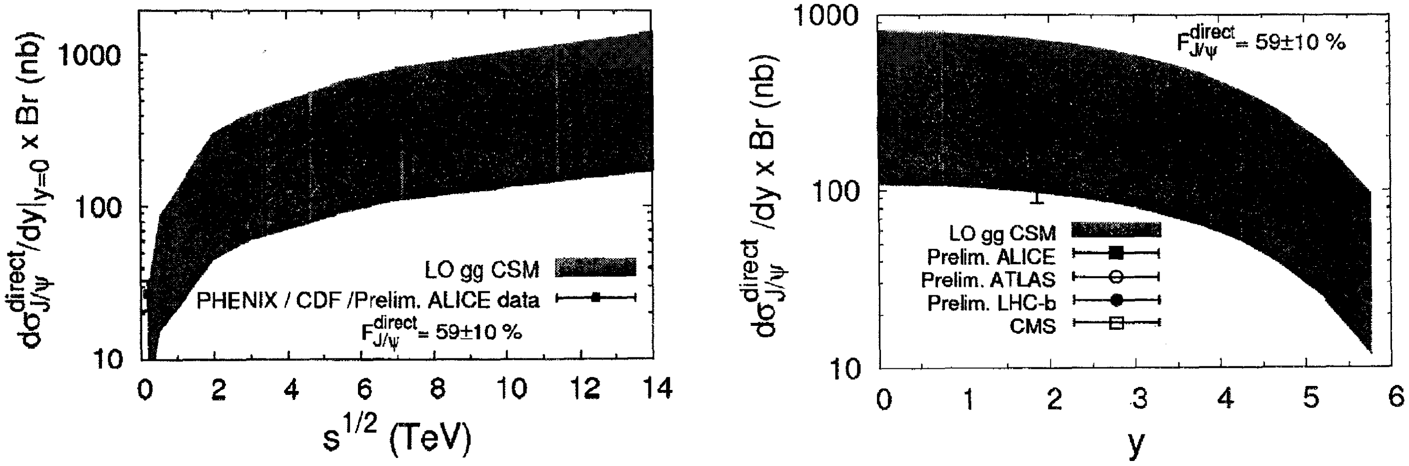
FIAS Frankfurt Institute
for Advanced Studies

EMMI

Quarkonium Production in Elementary and Heavy Ion Collisions,
Brookhaven National Laboratory, June 9 2011

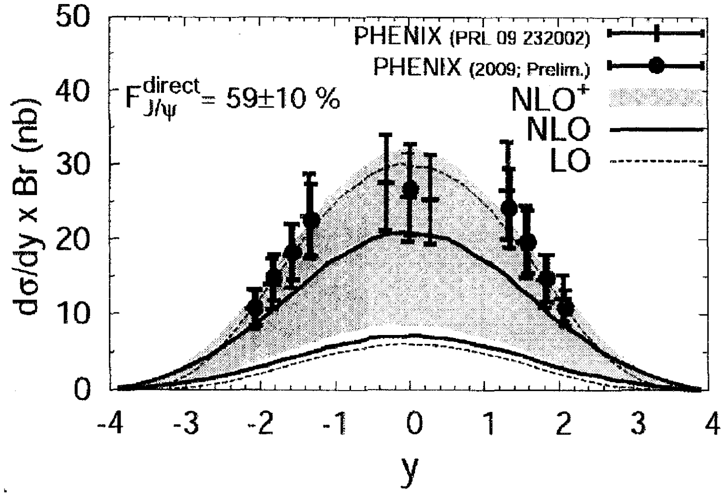
Motivation

- Quarkonium production is an important observable in both elementary and heavy ion collisions.
- The production mechanisms in pp collisions are not fully understood but recent theoretical developments can account for the yields:

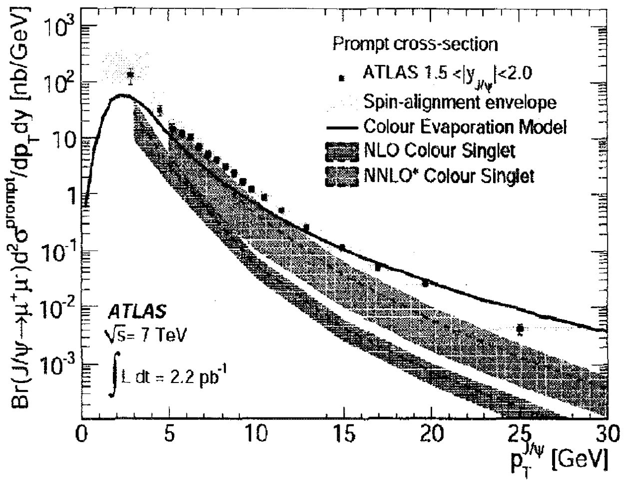


J.P.Lansberg, PoS(ICHEP 2010), 206

Motivation



S.J.Brodsky, J.P.Lansberg, PRD81 (2010) 051502



ATLAS Collaboration, arXiv:1104.3038

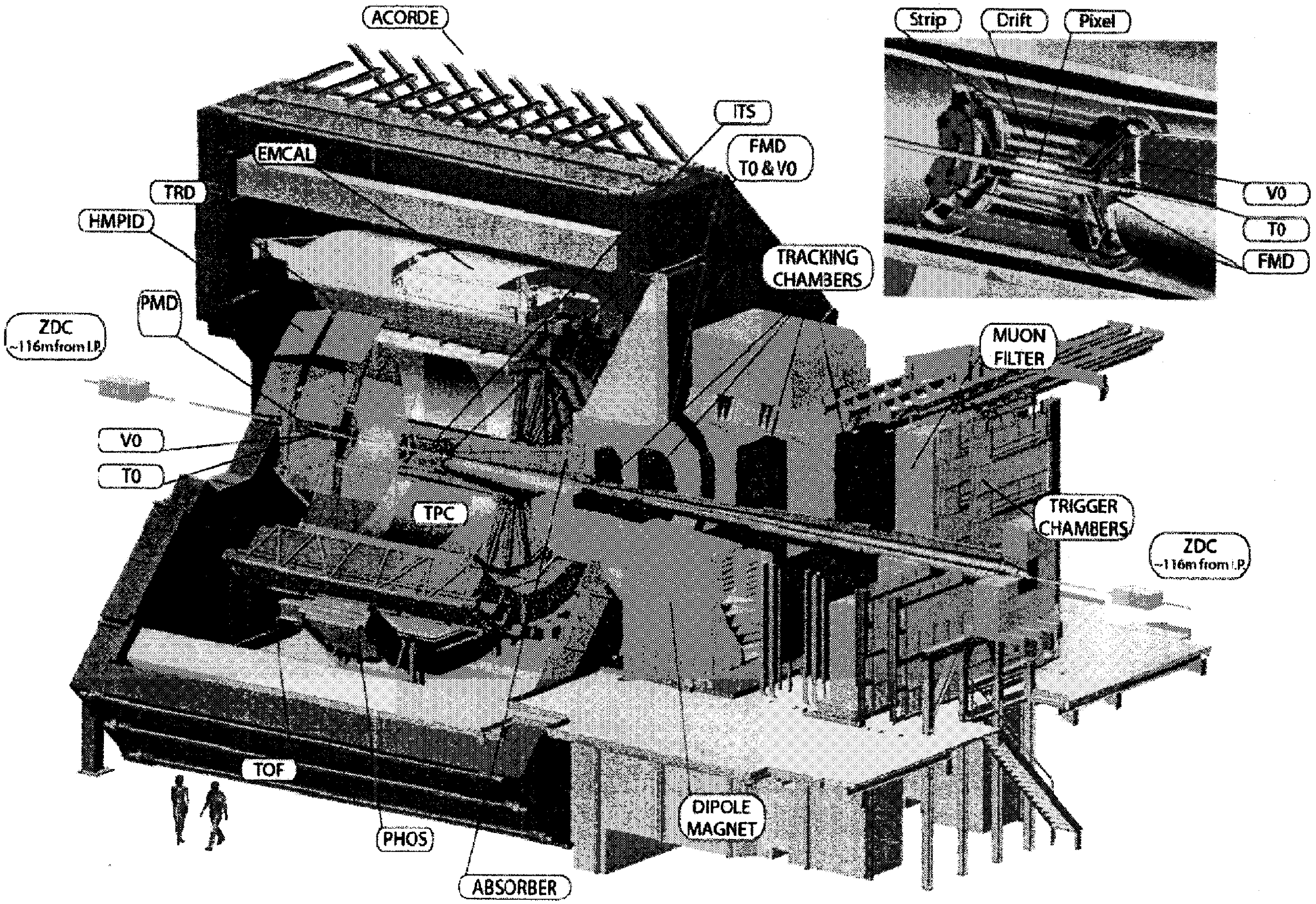
- Theoretical uncertainties are big
- NNLO* corrections in the CSM model give a good description of the pt spectrum at intermediate pt.
- More observables from experiment should be employed to constrain theory?

Experimentally accessible information

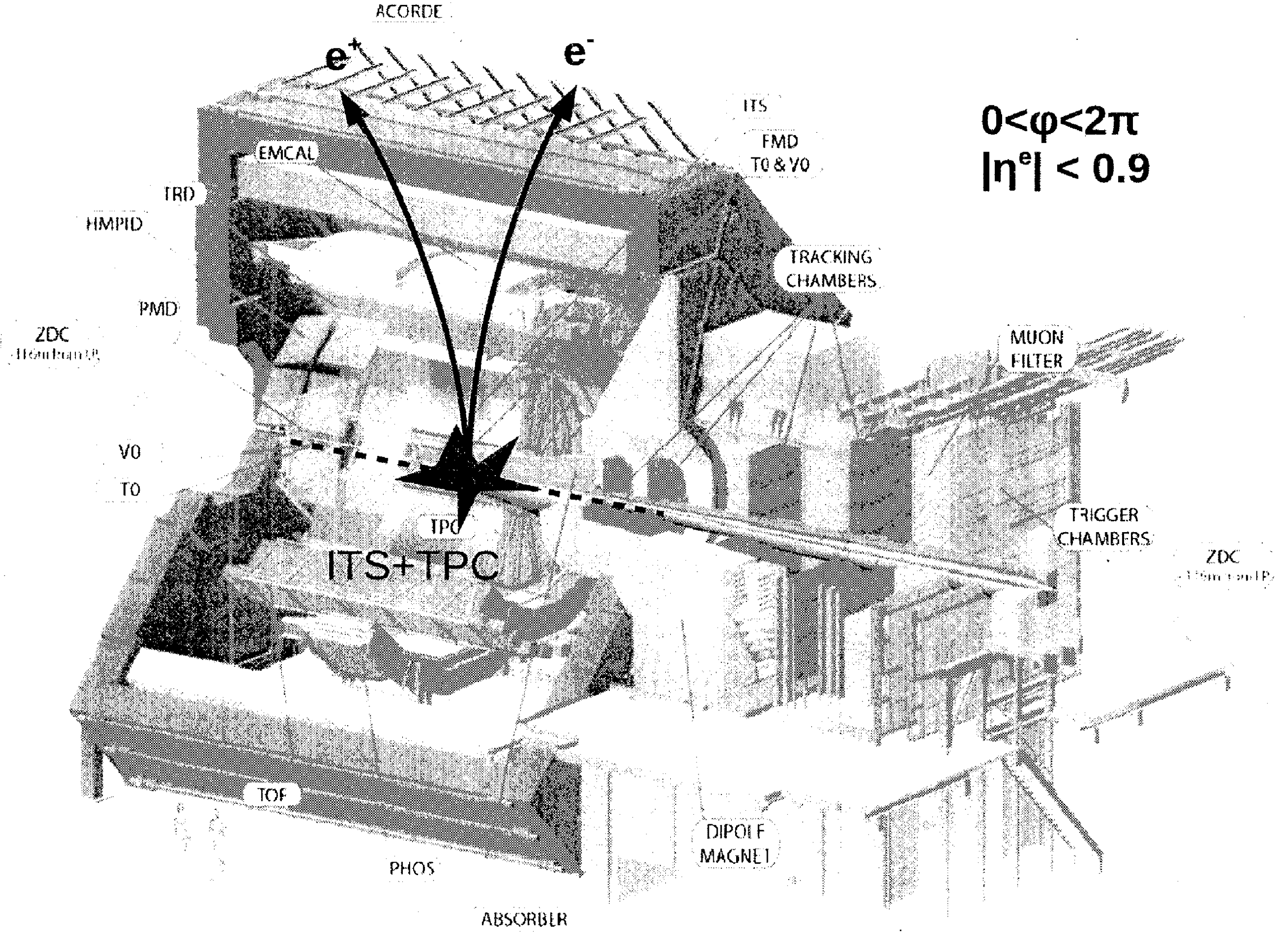
- Production rates (cross-section)
  - Inclusive and exclusive channels:
    direct, feed-down from beauty and higher charmonium states
  - differential vs. rapidity, transverse momentum

- Correlations
  - J/ψ correlations with hadrons, leptons, photons,
  - understand the production context
    - event multiplicity
    - underlying event, jet fragmentation cone
- Polarization measurements
  - Collins-Soper, Helicity

ALICE setup


ACORDE
Strip
Drift
Pixel
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
V0
T0
FMD
TRACKING CHAMBERS
PMD
ZDC
~116m from I.P.
MUON FILTER
V0
T0
TPC
TRIGGER CHAMBERS
ZDC
~116m from I.P.
TOF
DIPOLE MAGNET
PHOS
ABSORBER

ALICE setup



$0<\varphi<2\pi$
$|\eta^e| < 0.9$

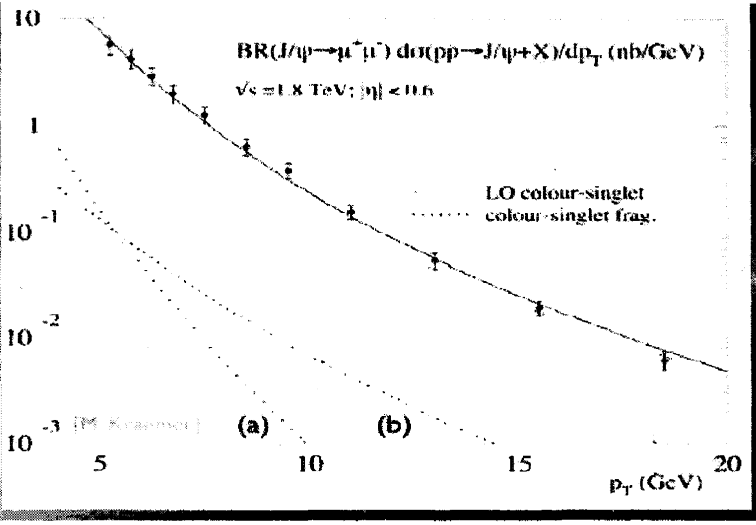
Quarkonium Production in Elementary and Heavy Ion Collisions
Brookhaven National Lab, June 10, 2011

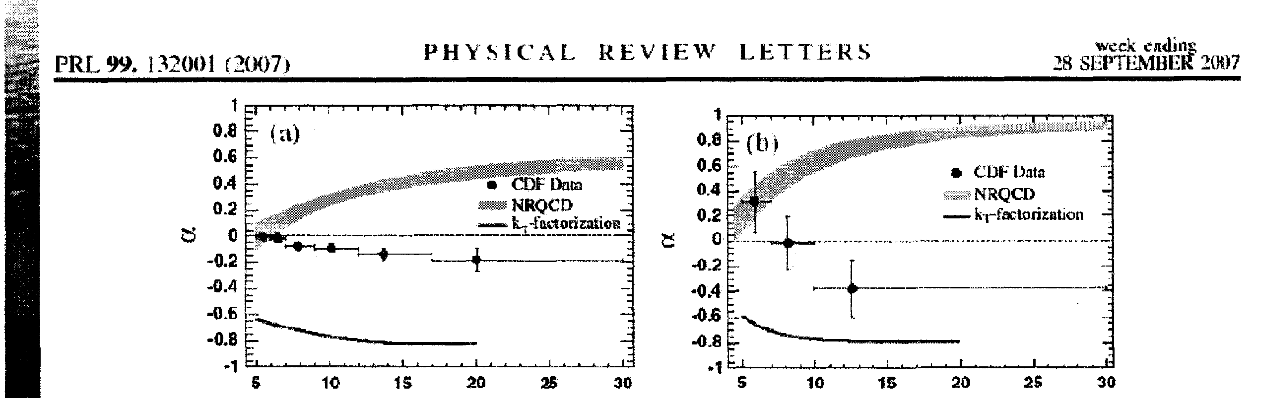
The prediction of the J/psi polarization at hadron colliders

Jian-Xiong Wang
Institute of High Energy Physics, Chinese Academy of Science, Beijing

Based on our recently wrok with: B. Gong, R. Li, L. P. Wan

Introduction





PRL **99**, 132001 (2007) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect J/ψ.
- heavy quarkonium production is a good place to testify these theoretical framework.
- But there are still many difficulties.
  - J/ψ photoproduction at HERA
  - J/ψ production at the B factories
  - J/ψ polarization at the Tevatron
- NLO corrections are important.
  - Double charmonium production at the B factories

- The predication for J/Ψ Polarization at LO was done by

  Color-singlet and Octect: E. Braaten, B. A. Kniehl and J. Lee, 2000,
  others ……
- The predication for J/Ψ Polarization at NLO was done by

  Color-singlet: B. Gong, J. X. Wang, 2007
  Color-octet (${}^3S_1^8,\ {}^1S_0^8$) : B. Gong, X. Q. Li and J. X. Wang, 2008

- How about ${}^3P_J^8$ color-octet contribution to J/Ψ polarization?

  **** Very difficult and not available yet.

To go through the problem to obtain the predication for LHC measurement:

- One possible way: New Factorization scheme for Heavy Quarkonium Production, Z. B. Kang G. Sterman, J. W. Qiu

- Another way: Try to give a estimate under some reasonable approximation with uncertainty.

polarization of quarkonium

$$\frac{d\sigma}{d\Omega dy} \propto 1 + \lambda(y)\cos^2\theta + \mu(y)\sin 2\theta\cos\phi + \frac{\nu(y)}{2}\sin^2\theta\cos 2\phi,$$

where y stands for a suitable variable (such as transverse momentum p_t) and the θ and ϕ are the polar an

azimuthal angles of the outgoing l^+ respectively. The polarization parameters, λ, μ and ν, are related to tl

density matrix of quarkonium production as

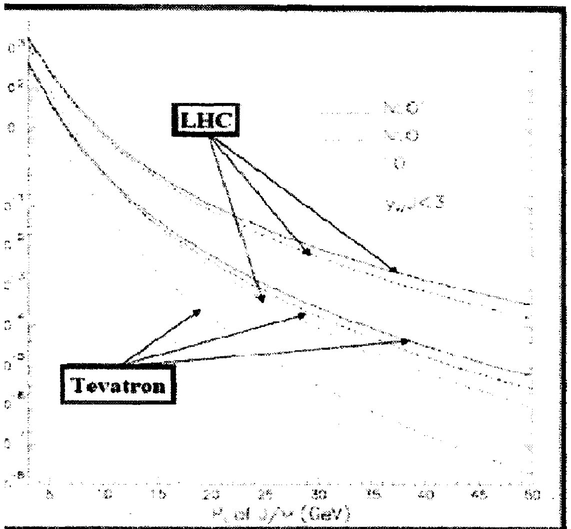
$$\lambda(y) = \frac{\frac{d\sigma_{11}}{dy} - \frac{d\sigma_{00}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}, \quad \mu(y) = \frac{\sqrt{2}Re\frac{d\sigma_{10}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}, \quad \nu(y) = \frac{2\frac{d\sigma_{1-1}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}$$

Here $d\sigma_{\lambda\lambda'}/dy$ are the 'differential density matrix elements' and defined as

$$\frac{d\sigma_{\lambda\lambda'}}{dy} = \frac{1}{F}\int\prod_{i=1}^{n}\frac{d^3p_i}{2E_i}\delta^4(p_a + p_b - \sum_{i=1}^{n} p_i)\delta(y - y(p_{J/\psi}))M(\lambda)M^*(\lambda'),$$

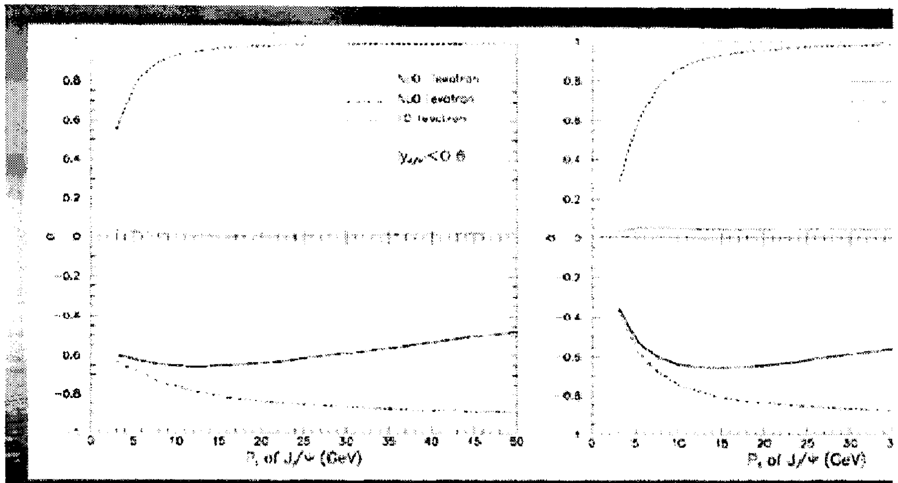
where $M(\lambda)$ is the matrix element of polarized J/ψ production, λ and λ' stand for the polarization,

orrection to color-singlet J/ψ production



Transverse momentum distribution of J/ψ production

NLO* contribution from $J/\psi+c\bar{c}$ is included



Transverse momentum distribution of J/ψ polarization paramete

J/ψ polarization status drastically changes from transverse polariza

dominant at LO into longitudinal polarization dominant at NLO

P_t distribution of J/ψ production at QCD NLO was calculated in PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano

Some technique problems must be solved to calculate J/ψ polarization

P_t distribution of J/ψ polarization at QCD NLO was calculated in PRL100,232001 (2008), B. Gong and J. X. Wang

INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

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Les deux infinis

Color singlet contribution and the quarkonium production puzzle

J.P. Lansberg
IPN Orsay – Paris-Sud 11

Brookhaven Summer Program, Quarkonium Production in Elementary and Heavy Ion Collisions
June 9, 2011
Brookhaven National Laboratory, USA

Outline

Introduction

1. Basic pQCD approach: Colour Singlet Model → Puzzle

Solution to the puzzle ... which puzzle ?

2. The CSM predictions and the total yield

Recent progresses: QCD corrections

3. Describing the mid- and high-P_T's: QCD corrections
4. Colour Octet Dominance is challenged at low/mid P_T in pp
5. QCD corrections and feed-down do matter for the polarisation
6. ψ production at very large P_T

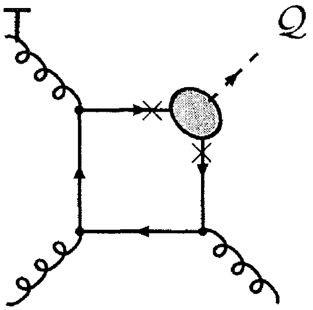
Part I

Introduction

Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

- Perturbative creation of 2 quarks Q and $\bar{Q}$ BUT



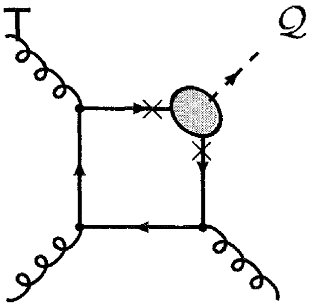
LO

$$\alpha_s^3 \frac{(2m_Q)^4}{P_T^8}$$

Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

- Perturbative creation of 2 quarks Q and $\bar{Q}$ BUT
  - on-shell ($\times$)
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a $^3S_1$ state (for J/ψ, ψ' and Υ)



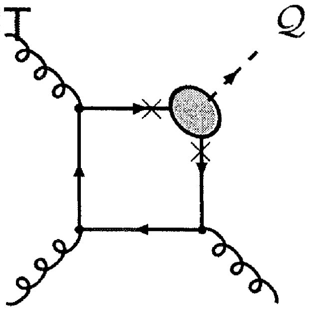
LO

$$\alpha_s^3 \frac{(2m_Q)^4}{P_T^8}$$

Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

- Perturbative creation of 2 quarks Q and $\bar{Q}$ BUT
  - on-shell ($\times$)
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a $^3S_1$ state (for J/ψ, ψ' and Υ)



LO

$\alpha_s^3 \frac{(2m_Q)^4}{P_T^8}$

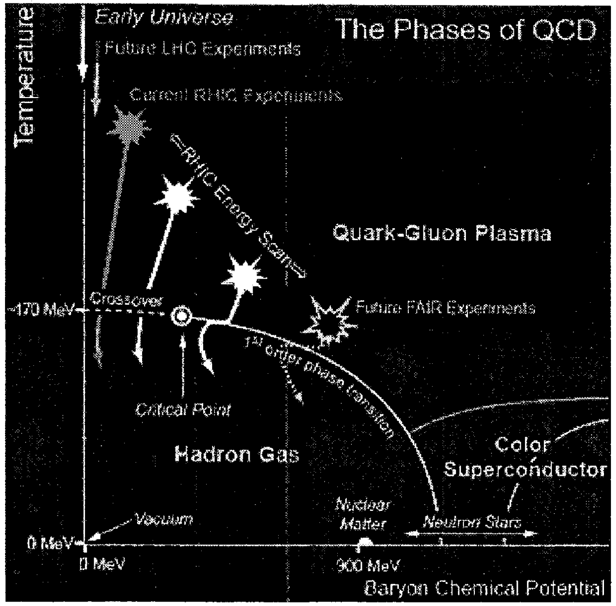
- Non-perturbative binding of quarks → Schrödinger wave function

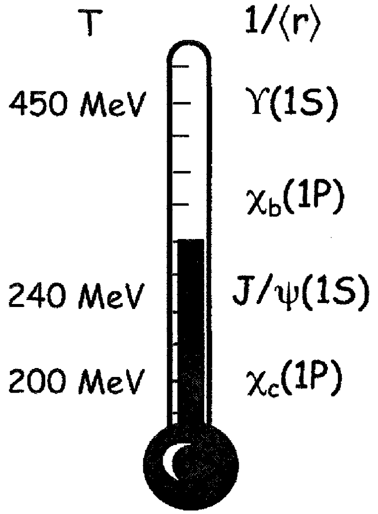
Measurement of Upsilon production cross section in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV

Anthony Kesich
STAR Collaboration
University of California, Davis

Summer Quarkonium Workshop
June 13, 2011

Quarkonia as a Temperature Probe



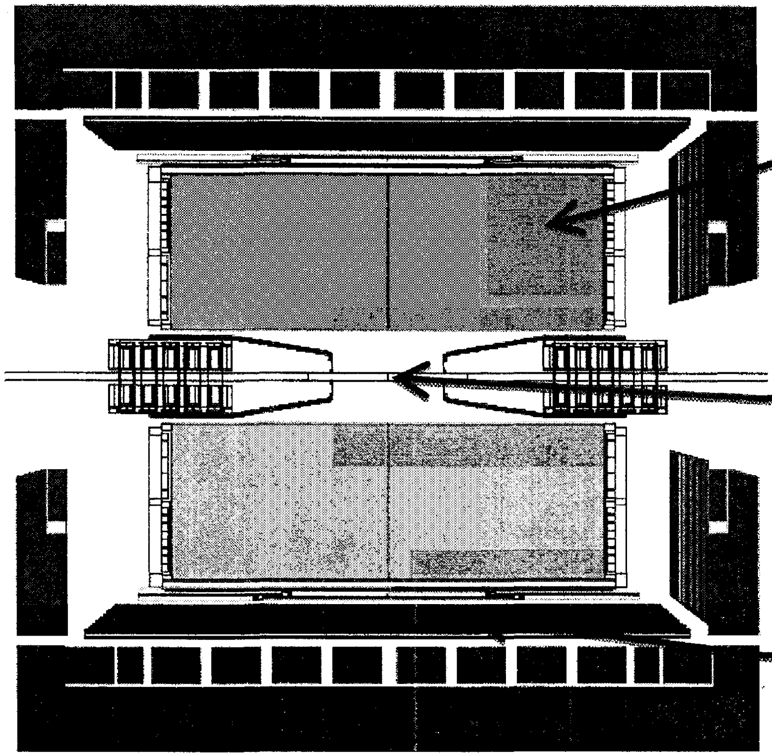


T	$1/\langle r \rangle$
450 MeV	$\Upsilon(1S)$
	$\chi_b(1P)$
240 MeV	$J/\psi(1S)$
200 MeV	$\chi_c(1P)$

A .Mocsy, BNL Quarkonia Workshop, June 2011

- Quarkonia suppression is a proposed signature of QGP formation
- Degree of suppression is a probe of initial QGP temperature
- Need d+Au measurements to constrain cold nuclear matter effects
  - e.g. Shadowing, Cronin effect

STAR Detector



Time Projection Chamber

- Gas Ionization Tracker
- Used for eID
- Full coverage in ϕ
- $|\eta|<1$

No Silicon Tracker!

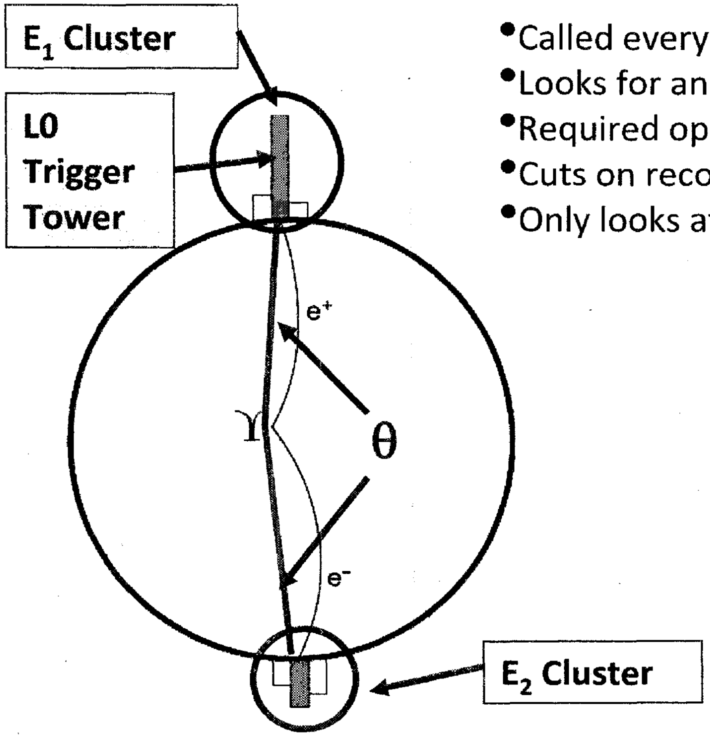
Reduces EM material budget from 0.06 to 0.01 radiation lengths. Removed in Run 8 and beyond.

Electromagnetic Calorimeter

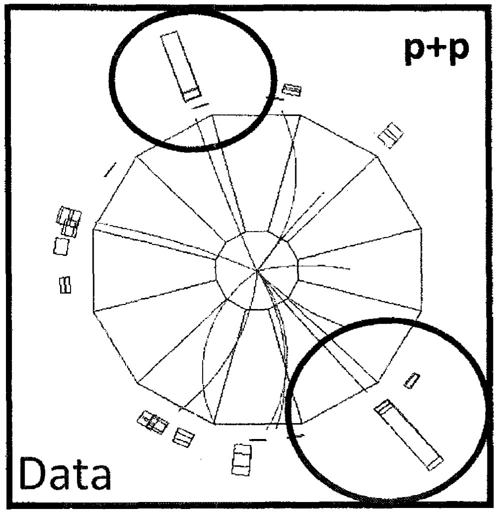
- Fast detector
- Used for triggering and eID
- Full coverage in ϕ
- $|\eta|<1$

STAR

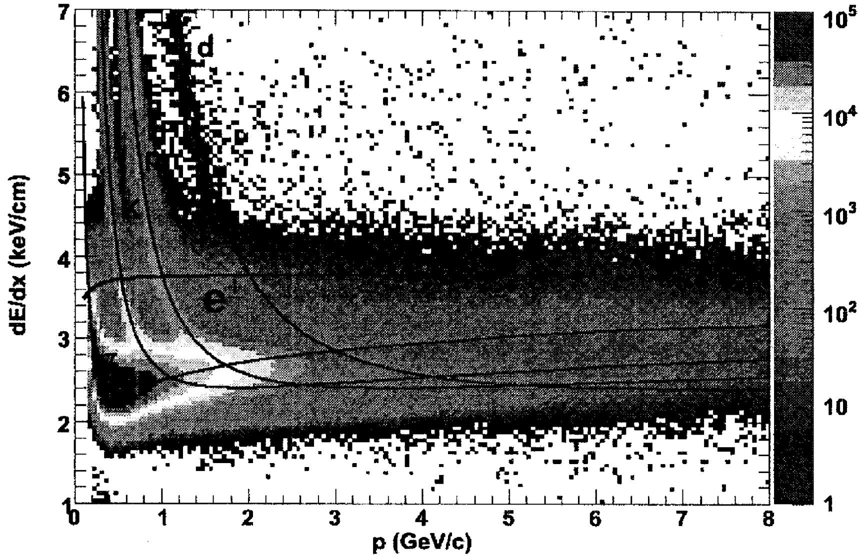
Upsilon Trigger



- Called every time we see a high energy tower (>4.2 GeV)
- Looks for an associated high energy cluster
- Required opening angle larger than 90°
- Cuts on reconstructed mass
- Only looks at the electromagnetic calorimeters

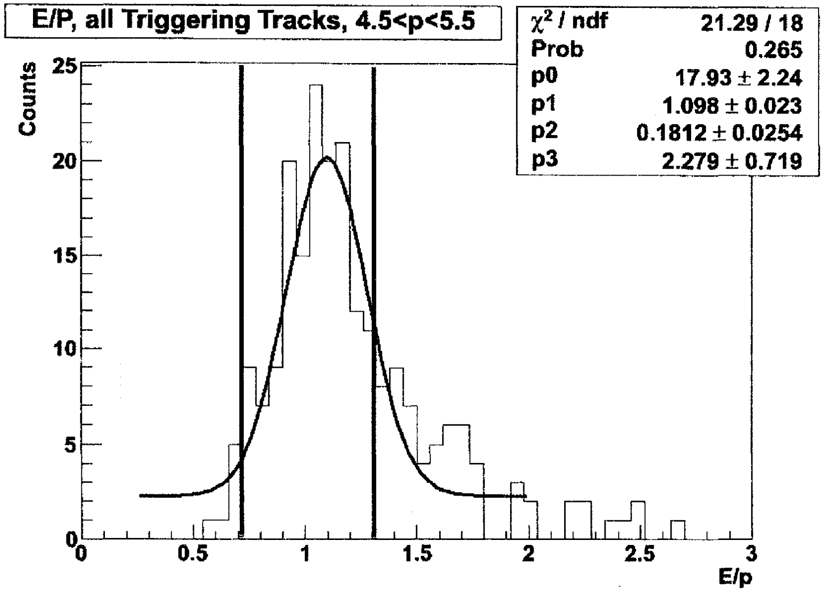


eID via Energy Loss



- •Identify electrons via energy loss in the TPC
- •Some contamination from hadrons
  - •Contamination is less at higher momenta

Track Matching and E/p



- •We can reject out-of-time tracks by matching to the EMC
    - •EMC is a fast detector as opposed to the TPC
- •Once matched, we can compute E/p for the track
    - •"Over-cut" on dE/dx to get a more pure sample (but smaller)
    - •Due to their low mass, electrons will have E/p ≈ 1
    - •Some variation from 1 due to background and E loss

Quarkonium Workshop, Brookhaven National Laboratory, 6-18 June 2011

Cold nuclear matter effects on quarkonium production @ RHIC and LHC

Elena G. Ferreiro
Universidade de Santiago de Compostela, Spain

Work done in collaboration with
F. Fleuret, J-P. Lansberg , N. Matagne and A. Rakotozafindrabe
EPJC61 (2009), PLB680 (2009), PRC81 (2010), NPA855 (2011)

Introduction: motivation

- A lot of work trying to understand **A+A** data (since J/ψ ≡ QGP signal)

Quarkonium as a hint of deconfinement

QGP probe

- If we focalise on **p+A** data (where no QGP is possible) only cold nuclear matter (CNM) effects are in play here:

shadowing and nuclear absorption

Quarkonium as a hint of coherence

nPDF probe

- In fact, the question is even more fundamental: **p+p** data we do not know the specific production kinematics at a partonic level:

$(2 \rightarrow 2,3,4)$ vs $(2 \rightarrow 1)$

Quarkonium as a hint of QCD

QCD probe

Introduction : contents

Our goal:

To investigate the **CNM effects** and the impact of the specific **partonic production** kinematics

3 ingredients:

•J/ψ partonic production mechanism

•Shadowing

•Nuclear absorption

- Results on J/ψ production @ RHIC and LHC
- Extend our study to ϒ CNM effects : *fractional energy loss*

Quarkonium as a tool of COLD and HOT effects

- **cold effects:** **wo thermalisation NO QGP**

gluon shadowing
gribov shadowing
nuclear structure functions in nuclei ≠ superposition of constituents nucleons
NI@SPS, IMP@RHIC

nuclear absorption
multiple scattering of a pre-resonance c-cbar pair within the nucleons of the nucleus
IMP@SPS, RHIC?

CGC
percolation
parton saturation
non-lineal effects favoured by the high density of partons become important and lead to eventual saturation of the parton densities
non thermal
colour connection

partonic comovers
hadronic comovers
dissociation of the c-cbar pair with the dense medium produced in the collision **partonic or hadronic**
suppression by a dense medium, not thermalized

Others: Cronin effect
EMC effect, energy loss

- **hot effects:** **w thermalisation QGP**

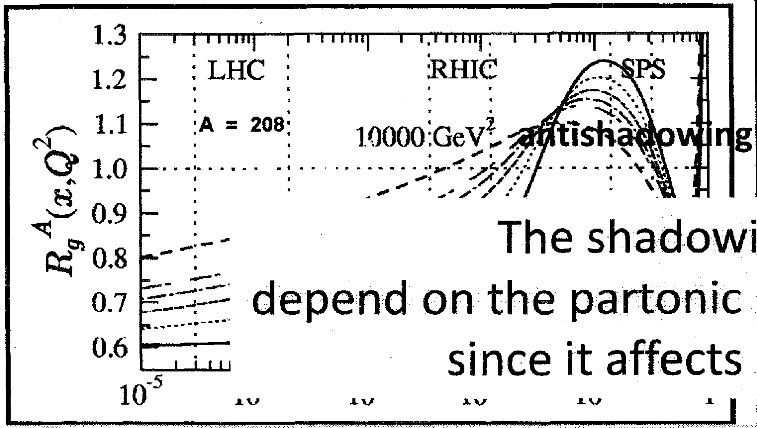
QGP sequential suppression recombination

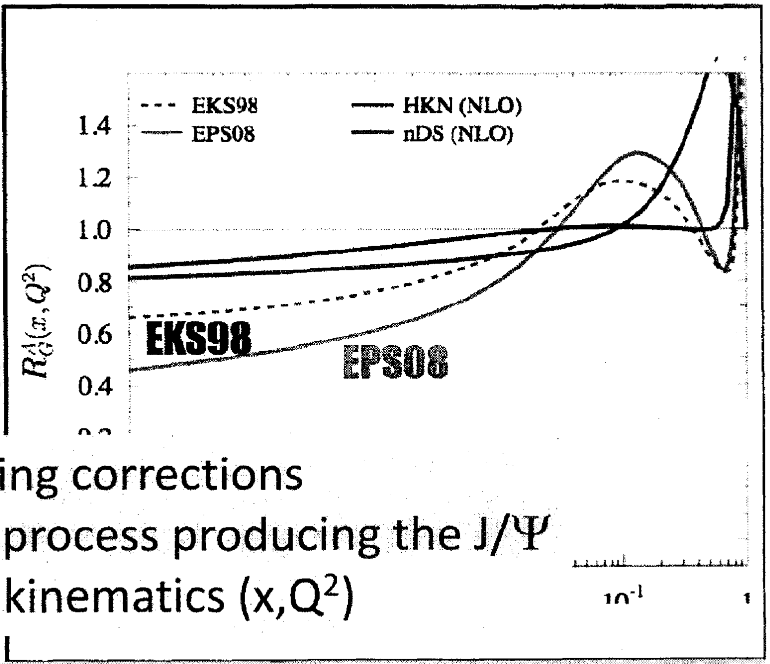
Shadowing: an initial cold nuclear matter effect

- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

Shadowing effects increases with energy (1/x) and decrease with Q^2 (m_T)

$$R_i^A(x,\mu_f) = \frac{f_i^A(x,\mu_f)}{A f_i^{nucleon}(x,\mu_f)}\,, \quad f_i = q, \bar{q}, g$$





The shadowing corrections
depend on the partonic process producing the J/Ψ
since it affects kinematics (x,Q^2)

Nuclear absorption: a final **cold nuclear matter** effect

Particle spectrum altered by interactions with the nuclear matter they traverse
=> J/Ψ suppression due to final state interactions with spectator nucleons

- Usual parameterisation:
  (Glauber model)

$$\boxed{\text{Sabs} = \exp(-\rho\ \sigma\text{abs}\ L)}$$

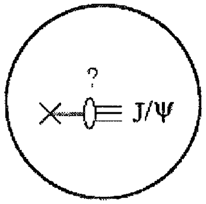
nuclear matter density   break-up cross section   path length

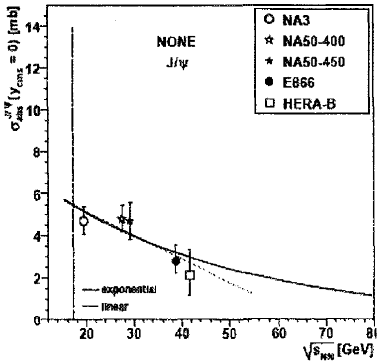
Energy dependence

- At low energy: the heavy system undergoes successive interactions with nucleons in its path and has to survive all of them => Strong nuclear absorption
- At high energy: the coherence length is large and the projectile interacts with the nucleus as a whole => Smaller nuclear absorption

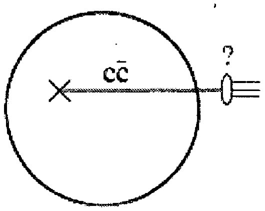
In terms of formation time:

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$

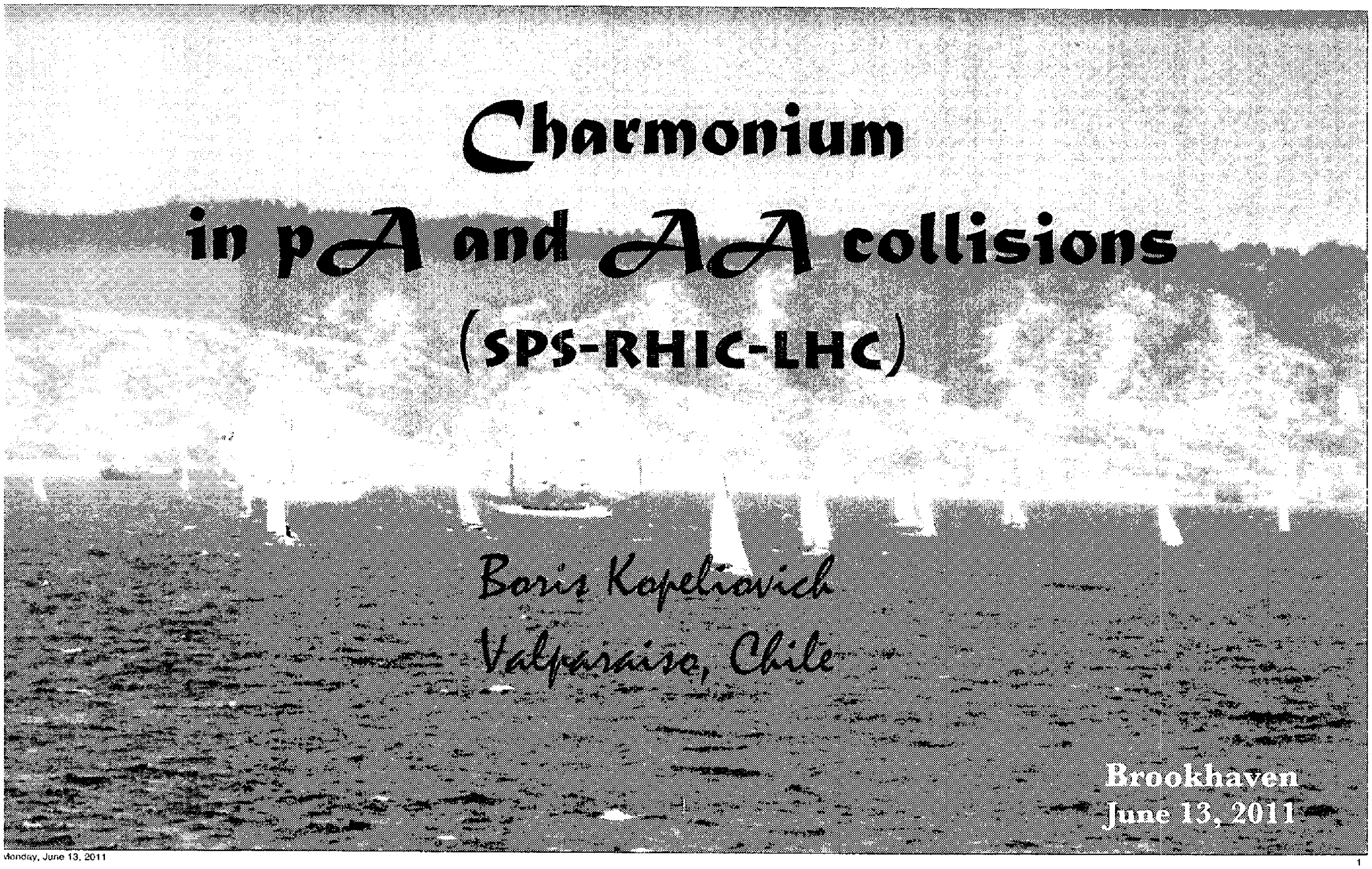




High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



Rapidity dependence of nuclear absorption? σabs @ mid y < σabs @ forward y?



Charmonium
in pA and AA collisions
(SPS-RHIC-LHC)

Boris Kopeliovich
Valparaiso, Chile

Brookhaven
June 13, 2011

Outline

- **pA:** J/ψ suppression in pA
  Leading/higher twist shadowing,
  absorption, color transparency, etc.

- **pA->AA:** Nontrivial transition.
  Double color filtering, "Cold nuclear matter" is not cold, etc.

- **AA:** Charmonium survival in a dense medium
  Probing the transport coefficient

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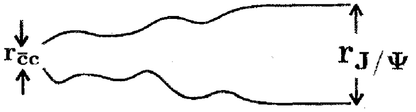
B. Kopeliovich, BNL, June 13, 2011

pA: J/Ψ formation and color transparency

A $\bar{c}c$ dipole is produced with a small separation $\boxed{r_{\bar{c}c} \sim \frac{1}{m_c} \sim 0.1\text{fm}}$
and then evolves into a J/Ψ mean size $r_{J/\Psi} \sim 0.5$ fm
during formation time $t_f = \frac{2E_{J/\Psi}}{m^2_{\Psi'} - m^2_{J/\Psi}} = 0.1\,\text{fm}\left(\frac{E_{J/\Psi}}{1\,\text{GeV}}\right)$

Perturbative expansion



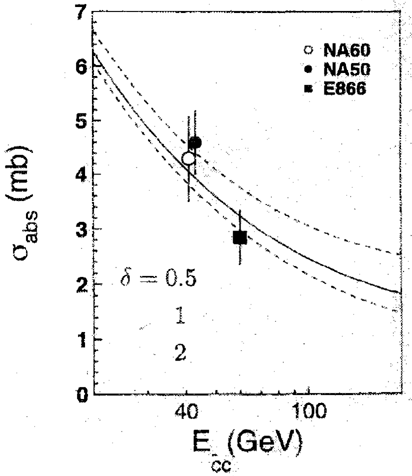
$$\frac{dr_T}{dt} = \frac{4p_T}{E_{\bar{c}c}}$$

$$r_T^2(t) = \frac{8t}{E_{\bar{c}c}} + \frac{\delta}{m_c^2}$$

The mean cross section is L-dependent

$$\bar{\sigma}_{abs}(L, E_{\bar{c}c}) = \frac{1}{L}\int_0^L dl\,\sigma_{abs}(l) = C(E_{\bar{c}c})\left(\frac{4L}{E_{\bar{c}c}} + \frac{\delta}{m_c^2}\right)$$

$$R_{pA} = \frac{1}{A\sigma_{abs}}\int d^2b\left[1 - e^{-\sigma_{abs}T_A(b)}\right]$$



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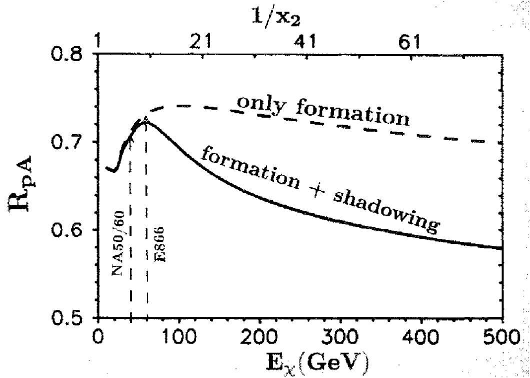
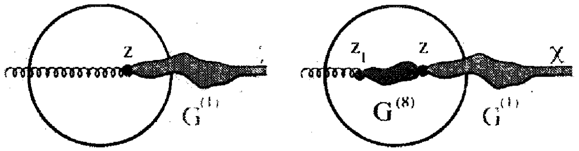
pA: Higher twist c-quark shadowing

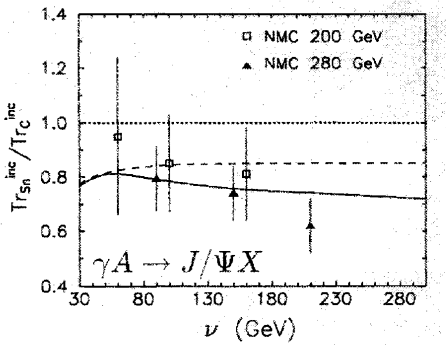
At higher energies $\bar{\sigma}_{abs}$ is affected by another time scale, the lifetime of a $c\bar{c}$ fluctuation

$$t_p = \frac{2E_{J/\Psi}}{m^2_{J/\Psi}} = \frac{1}{x_2 m_N}$$ (5 times shorter than t_f)



If $t_p \gtrsim R_A$ the initial state fluctuation $g \to \bar{q}q$ leads to shadowing corrections related to a non-zero $\bar{c}c$ separation.





Path integral technique: all possible paths of the quarks are summed up; $\sigma_{abs}(r_T, E_{\bar{c}c})$ gives the imaginary part of the light-cone potential.

pA: Leading twist gluon shadowing

The coherence length for gluon shadowing is much shorter than for quarks

$$\boxed{l_c^g = \frac{P^g\ s}{m_{J/\Psi}^2 m_N}\, x_1(1-x_1)} \qquad \boxed{P^g \approx 0.1}$$ is independent of the scale.

This is why there is no shadowing above $\tilde{x}_2 \gtrsim 0.01$ where $\tilde{x}_2 = x_2/(1-x_1)$

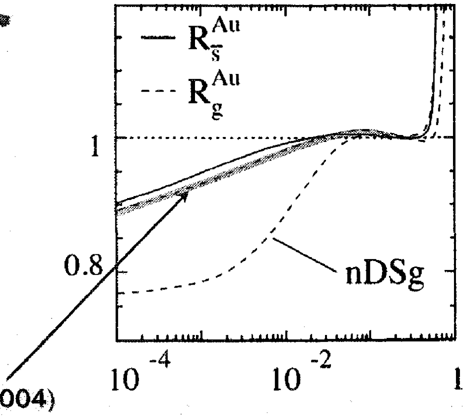
in particular, gluon shadowing should not affect any of the fixed-target experiments $l_c^g < 1\ \mathrm{fm}$

No gluon shadowing at RHIC at $x_F = 0$, since $x_2 \geq 0.018$ is too large.

At forward rapidities x_2 is falling as

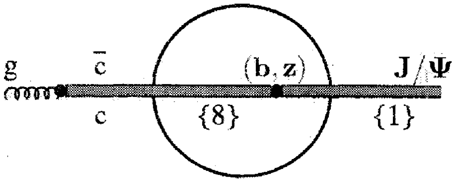
$$x_2 \geq e^{-\eta}\sqrt{(m_{J/\Psi}^2 + \langle p_T^2 \rangle)/s}$$

Still gluon shadowing is very weak



NLO: D. de Florian&R. Sassot(2004)

pA: Charmonium suppression at RHIC/LHC



The $\bar{c}c$ pair attenuates not only in final state (breakup), but also in initial state (shadowing)

$$\mathbf{S_{pA}(b,z)} = \int \mathbf{d^2 r_T\, K_0(m_c r_T)\, r_T^2\, \Psi_{J/\Psi}(r_T) e^{-\frac{1}{2}\sigma_{\bar{c}cg}(r_T) T_-(b,z) - \frac{1}{2}\sigma_{\bar{c}c}(r_T) T_+(b,z)}}$$

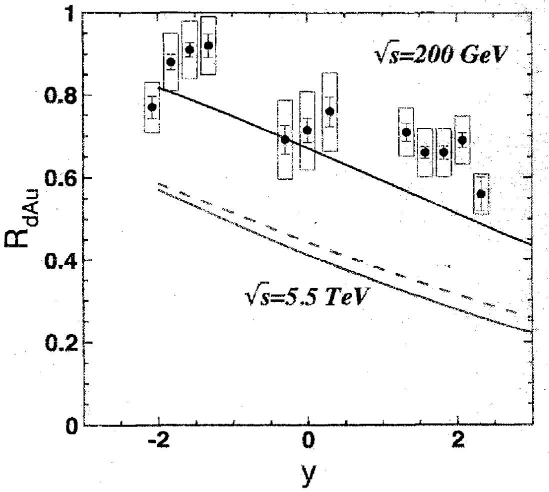
$$\mathbf{T_-(b,z)} = \int_{-\infty}^{z} \mathbf{dz' \rho_A(b,z')}$$

$$\mathbf{T_+(b,z) = T_A(b) - T_-(b,z)}$$

$$\mathbf{T_A(b) = T_-(b,\infty)}$$

$$\sigma_{\bar{c}cg}(\mathbf{r_T}) = \frac{9}{4}\sigma_{\bar{c}c}(\mathbf{r_T}/2) - \frac{1}{8}\sigma_{\bar{c}c}(\mathbf{r_T})$$

Both cross sections $\sigma_{\bar{c}cg}$ and $\sigma_{\bar{c}c}$ steeply rise with rapidity $\sigma_{\bar{c}c} \propto Q_s^2(x_2) \propto e^{0.288\eta}$ as dictated by DIS data from HERA.



B. Kopeliovich, BNL, June 13, 2011

Thermal Kinetic Equation Approach to Charmonium Production in Heavy-Ion Collision

Xingbo Zhao
with Ralf Rapp

Department of Physics and Astronomy
Iowa State University
Ames, USA

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

Brookhaven National Lab, Upton, NY, Jun. 14th 2011

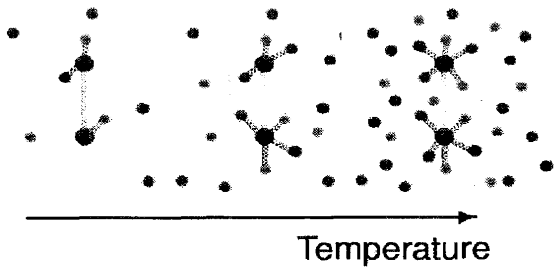
Outline

- Thermal rate-equation approach
  - Dissociation rate in quasi-free approximation
  - Regeneration rate from detailed balance
  - Connection with lattice QCD

- Numerical results compared to exp. data
  - Collision energy dependence (SPS->RHIC->LHC)
  - Transverse momentum dependence (RHIC)
  - Rapidity dependence (RHIC)

Motivation: Probe for Deconfinement

- Charmonium (Ψ): a probe for deconfinement
  - Color-Debye screening reduces binding energy -> Ψ dissolve



[Matsui and Satz, '86]

- Reduced yield expected in AA collisions relative to superposition of individual NN collisions

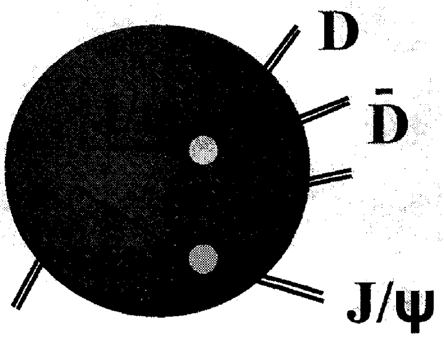
- Other factors may also suppress Ψ yield in AA collision
  - Quantitative calculation is needed

Motivation: Eq. Properties ↔ Heavy-Ion Coll.

- Equilibrium properties obtained from lattice QCD
  - free energy between two static quarks ($\xrightarrow{?}$ heavy quark potential)
  - Ψ current-current correlator ($\xrightarrow{?}$ spectral function)
- Kinetic approach needed to translate static Ψ eq. properties into production in the dynamically evolving hot and dense medium

Picture of Ψ production in Heavy-Ion Coll.

- 3 stages: 1->2->3
  1. Initial production in hard collisions
  2. Pre-equilibrium stage (CNM effects)
  3. Thermalized medium
- 2 processes in thermal medium:
  1. Dissociation by screening & collision
  2. Regeneration from coalescence



- Fireball life is too short for equilibration
  - Kinetic approach needed for off-equilibrium system

Thermal Rate-Equation

- Thermal rate-equation is employed to describe production in thermal medium (stage 3)

$$\frac{dN_\Psi}{d\tau} = \underline{-\Gamma N_\Psi} + \underline{\Gamma N_\Psi^{eq}} \qquad (\Psi = J/\psi,\ \chi_c,\ \psi')$$

  - Loss term for dissociation Gain term for regeneration
  - Γ: dissociation rate N_ψ^{eq}: eq. limit of Ψ
  - Detailed balance is satisfied by sharing common Γ in the loss and gain term
  - Main microscopic inputs: Γ and N_ψ^{eq}

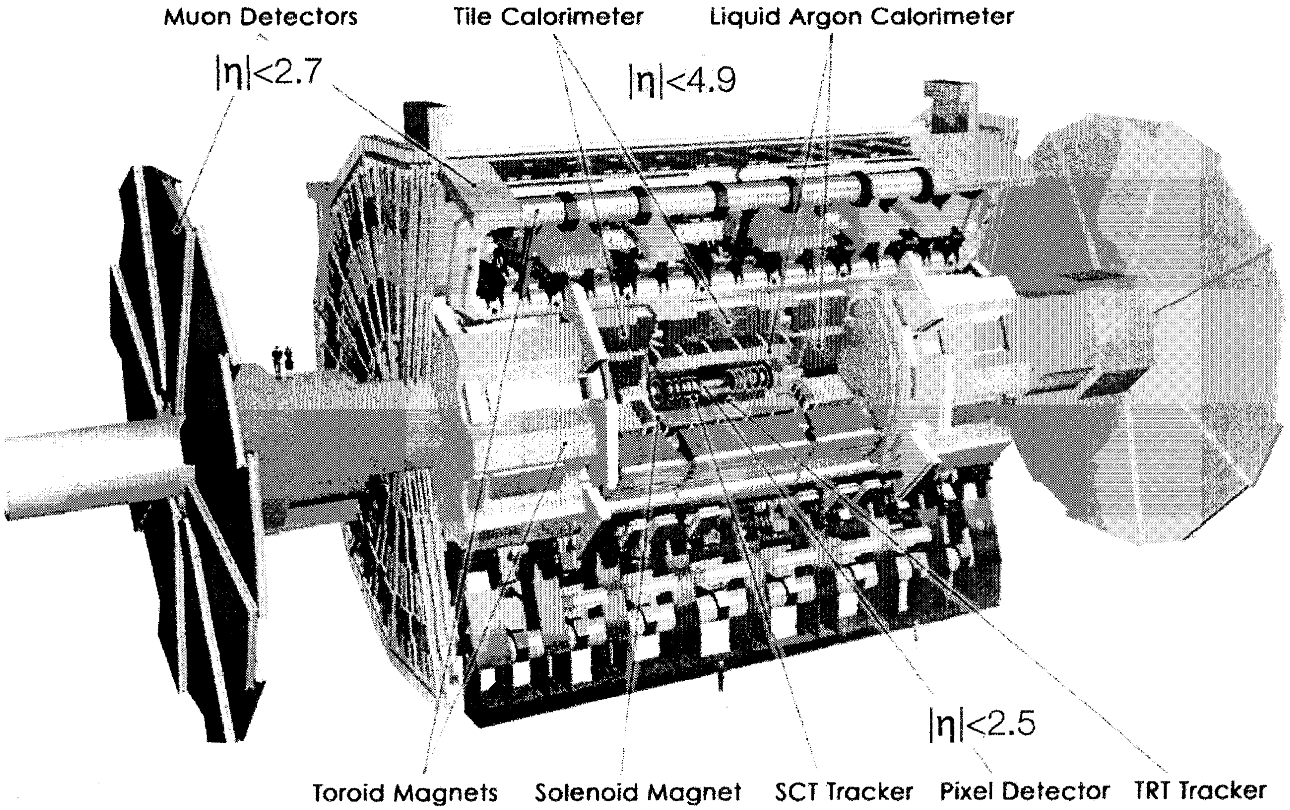
Quarkonia and Vector Bosons measured with the ATLAS detector at the LHC

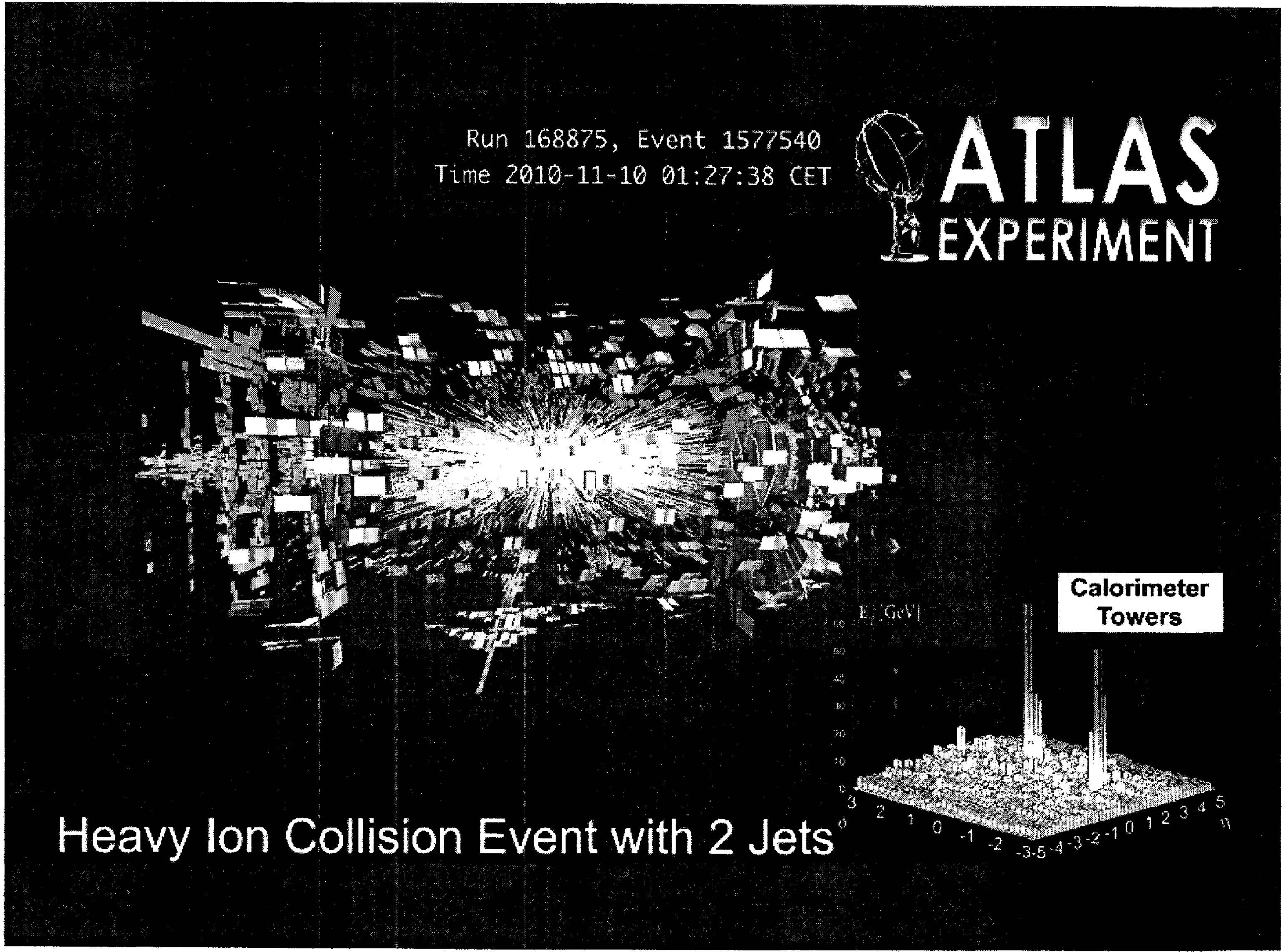
Peter Steinberg, for the ATLAS Collaboration
Brookhaven National Laboratory
June 15, 2011
BNL Quarkonia Workshop

J/psi and Z results: **Phys.Lett. B697:294-312,2011**
W results: **http://cdsweb.cern.ch/record/1353227**

Special thanks to Helio Takai & Rikard Sandstrom

The ATLAS Detector





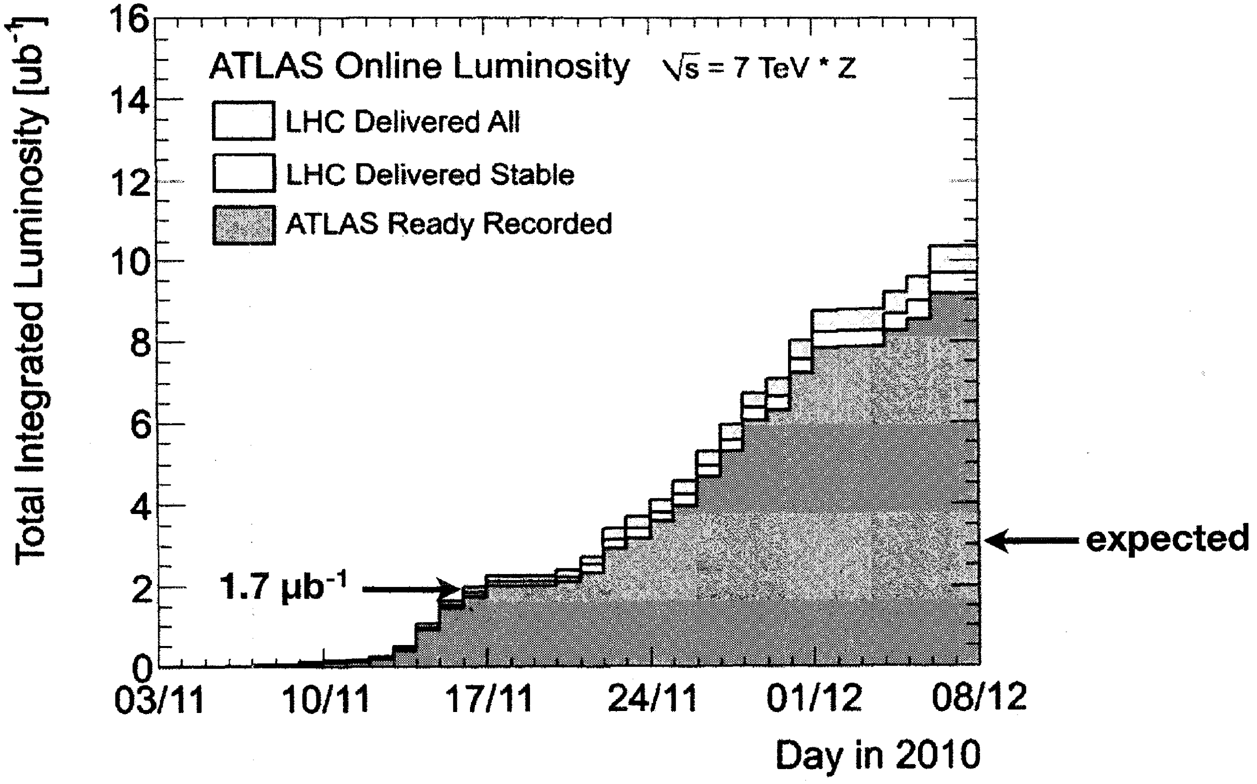
Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET

ATLAS EXPERIMENT

Calorimeter Towers

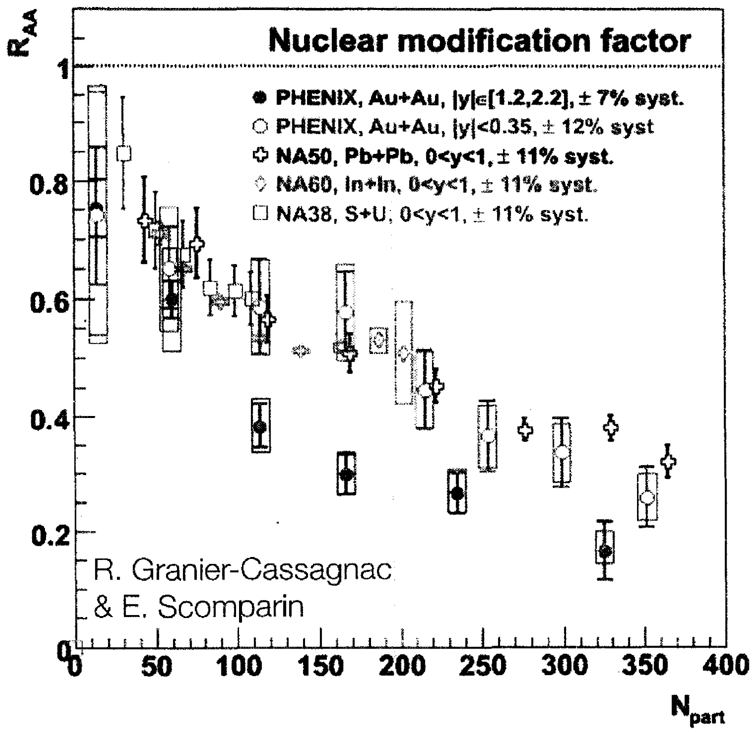
Heavy Ion Collision Event with 2 Jets

Integrated luminosity



9.7 μb^{-1} delivered, 9.2 μb^{-1} recorded by ATLAS

J/ψ suppression



R. Granier-Cassagnac
& E. Scomparin

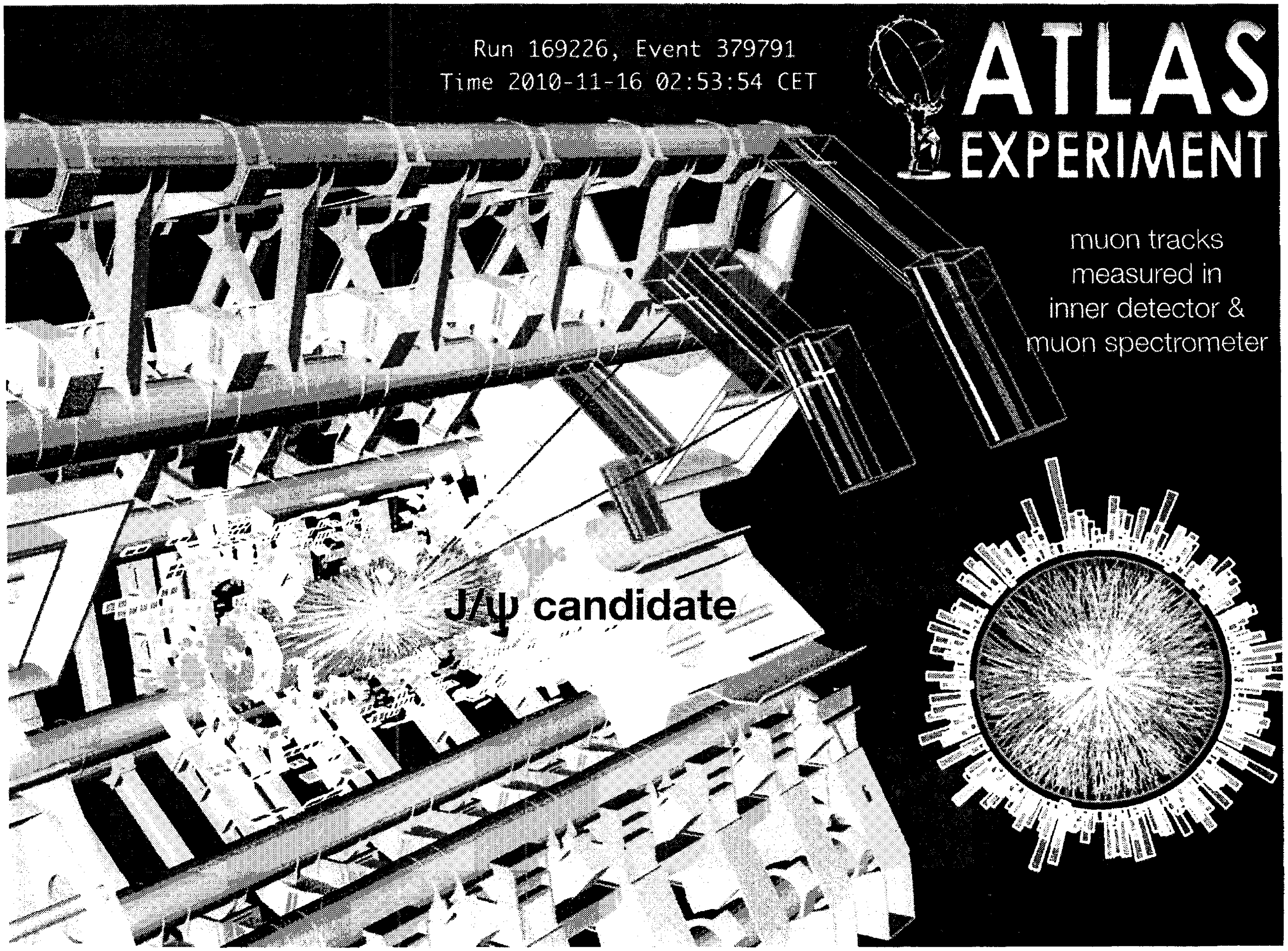
Mocsy & Petreczky (2007)

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Color screening predicts quarkonia states to melt at different temperatures,

At high densities, also expect some J/ψ regeneration (at low p_T)

Suppression factor observed to drop by ~2 between peripheral and central events: similar over x10 in $\sqrt{s_{NN}}$



muon tracks
measured in
inner detector &
muon spectrometer

J/ψ candidate

Non-relativistic bound states in a moving thermal bath

Miguel A. Escobedo

Physik-Department T30f. Technische Universität München

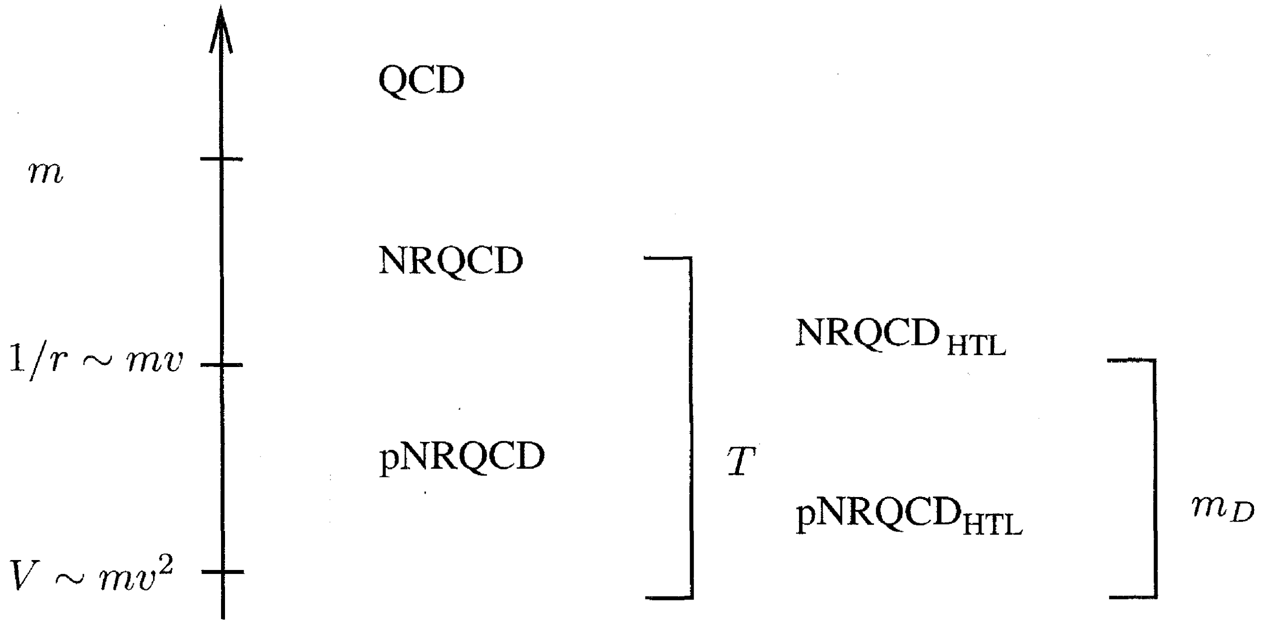
15th of June, 2011

arXiv [1105.1249]. Work done in collaboration with Massimo Mannarrelli and Joan Soto.

Outline

1. Introduction
2. Heavy quarkonium potential in a moving thermal bath
    - The real part of the potential
    - The imaginary part of the potential
    - The relativistic case
3. Non-relativistic EFT in a moving thermal bath
4. Conclusions

EFT for bound states at finite temperature



QCD

m

NRQCD

$1/r \sim mv$

pNRQCD

$V \sim mv^2$

T

$\text{NRQCD}_{\text{HTL}}$

$\text{pNRQCD}_{\text{HTL}}$

m_D

Imaginary part of the potential

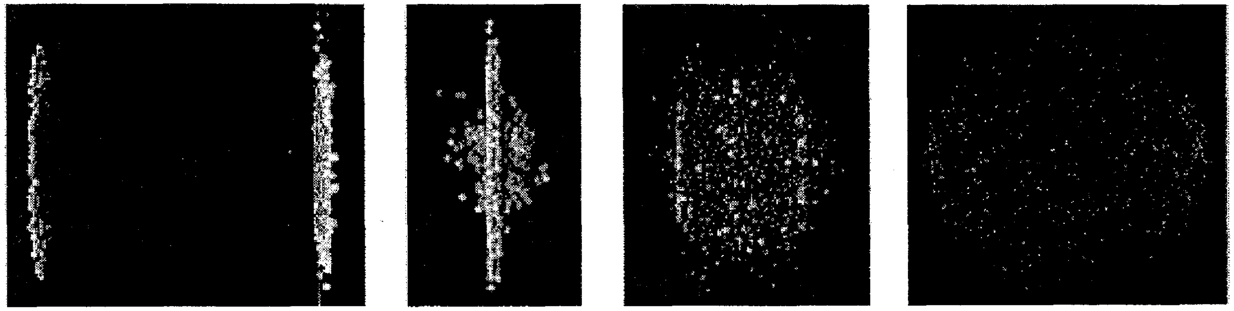
For $T \gg \frac{1}{r} \sim gT$

$$V(r) = -\frac{4\alpha_{\rm s} e^{-m_D r}}{3r} - i\frac{4\alpha_{\rm s} C_F T \phi(m_D r)}{3},$$

- This imaginary part of the potential was found by Laine, Philipsen, Romatschke and Tassler.
- It was confirmed by EFT techniques [Escobedo and Soto—Brambilla, Ghiglieri, Petreczky and Vairo].
- It was found that in the $g \to 0$ limit this provides the dominant dissociation mechanism.
- This temperature is smaller than the one obtained just with screening.

Ideal conditions

- The EFTs for HQ at finite temperature and the imaginary part of the potential were obtained assuming thermal equilibrium and that the bound state is at rest.
- This is not what happens in heavy-ion collisions.



Relax this conditions

- Anisotropic plasma
  Burnier, Laine and Vepsäläinen. Dumitru, Guo and Strickland. Philipsen and Tassler.
- Quarkonium is moving
- ...

Quarkonium Production at ep and e^+e^- Colliders

Geoffrey Bodwin
Argonne National Lab

- Highlights from Last Week's Episode
- $\gamma\gamma \to J/\psi + X$ at LEP
- Inelastic J/ψ Photoproduction Cross Section at HERA
- Polarization in Inelastic J/ψ Photoproduction at HERA
- J/ψ Production in DIS at HERA
- Factorization in Exclusive Quarkonium Production
- Exclusive Double-Charmonium Production at Belle and BaBar
- Inclusive Double $c\bar{c}$ Production at Belle
- Summary

Highlights from Last Week's Episode

NRQCD Factorization Formula

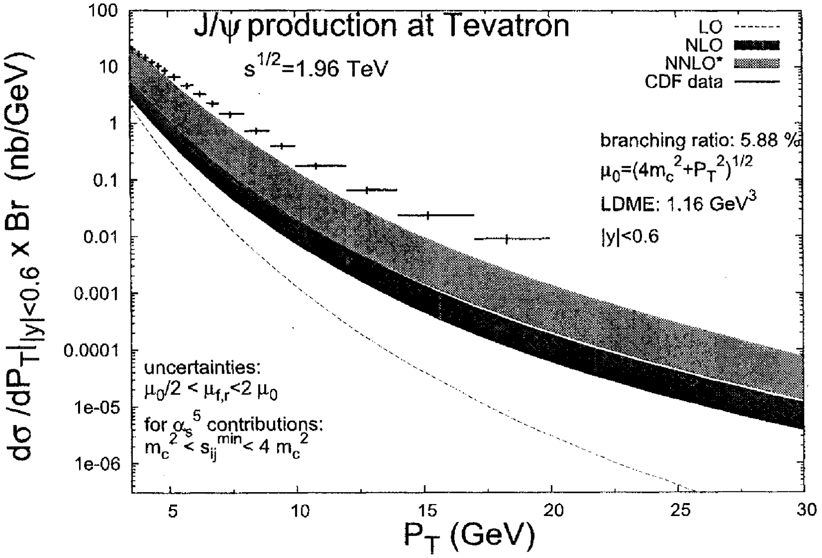
- Conjecture (GTB, Braaten, Lepage (1995)):
  The inclusive cross section for producing a quarkonium at large momentum transfer (p_T) can be written as a sum of "short-distance" coefficients times NRQCD matrix elements.

$$\sigma(H) = \sum_n F_n(\Lambda) \langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle .$$

- The "short-distance" coefficients $F_n(\Lambda)$ have an expansion in powers of α_s.
- The operator matrix elements $\langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle$ are universal (process independent).
  - Only the color-singlet production and decay matrix elements are simply related.
- The matrix elements have a known scaling with v.
- The NRQCD factorization formula is a double expansion in powers of α_s and v.
- Quarkonium production can occur through color-octet, as well as color-singlet, $Q\bar{Q}$ states.
- If we drop all of the color-octet contributions and retain only the leading color-singlet contribution, then we have the color-singlet model (CSM).
  - Inconsistent for P-wave production: IR divergent.

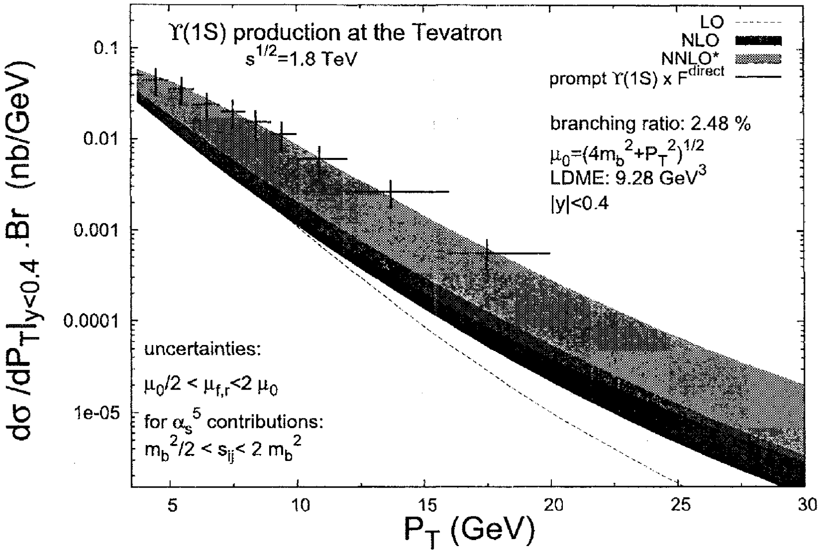
NLO and NNLO* Contributions to Color-Singlet Production

- Large corrections are caused by slower fall-off with p_T as new channels open up.
- The perturbation expansion might be brought under better control by making use of the fragmentation approach of Kang, Qiu, and Sterman (2010).
- Even if one includes NNLO* corrections to the color-singlet contribution, there is still room for a large color-octet contribution.



- Plot from Pierre Artoisenet, based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano.
- The NNLO* calculation is an estimate based on real-emission contributions only.

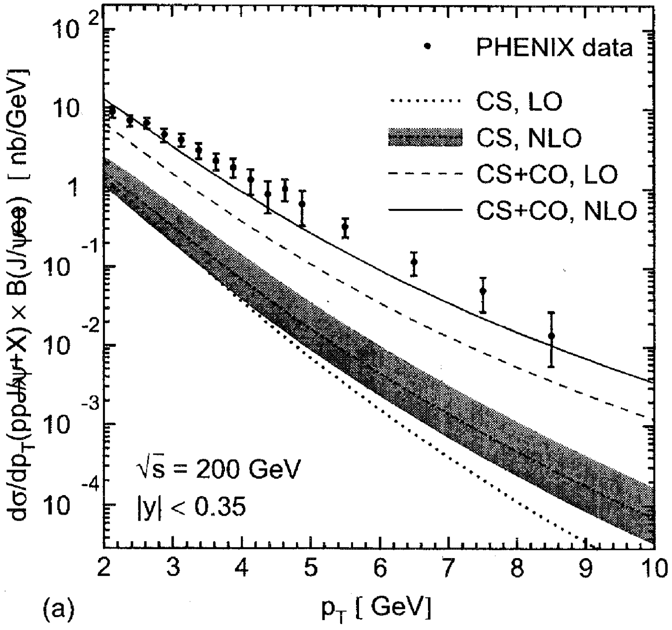
- The NNLO* color-singlet contribution to Υ production could explain the data by itself, but it does not rule out a large, or even dominant, color-octet contribution.



- Plot from Pierre Artoisenet, based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano (2008)
- NLO results confirmed by Gong and Wang (2007).

NLO Contributions to Color-Octet Production

- The first complete NLO calculations of the color-octet contributions through order v^4 have been completed recently.
- Corrections to S-wave production are small.
  Corrections to P-wave production are large.
- Color-octet matrix elements that were obtained from fits to the Tevatron data lead to predictions for J/ψ production at RHIC and the LHC that are in good agreement with the data.



- NLO NRQCD calculation of Kniehl and Butenschön (2010).
- Feeddown ($\approx 36\%$) is not included in the theoretical prediction.
- The NLO color-singlet contribution is well below the PHENIX data.

Gluon fragmentation into charmonium at NLO

Pierre Artoisenet
The Ohio State University

In collaboration with Eric Braaten

Brookhaven Summer Program
Quarkonium Production in Elementary and Heavy Ion Collisions

17 June 2011

Outline

Part I. Fragmentation into heavy quarkonium

from early predictions to latest developments

Part II. Gluon fragmentation into charmonium at NLO

work in progress

Reference

Eric Braaten

Quarkonium Production via Fragmentation Revisited

talk given at the workshop

"Quarkonium production, Probing QCD at the LHC"

17-21 April 2011, *Vienna University of Technology*

I. Fragmentation into heavy quarkonium

from early predictions to latest developments

Quarkonium production

1. Creation of heavy quark and antiquark
   - what are the relevant parton processes?
   - can they be calculated

     using perturbative QCD

     in terms of α_s and m_Q?

2. Binding of $Q\overline{Q}$ to form quarkonium
   - can it be parametrized by a few functions

     or (better yet) by a few constants?

Quarkonium production

1. Creation of heavy quark and antiquark
   - what are the relevant parton processes?
   - can they be calculated using perturbative QCD in terms of α_s and m_Q?

related Q:
fragmentation
or
complete fixed-order ?

2. Binding of $Q\overline{Q}$ to form quarkonium
   - can it be parametrized by a few functions or (better yet) by a few constants?

The France-Stanford Center for
Interdisciplinary Studies

Quarkonium physics at a fixed-target experiment with the proton and lead LHC beams

Jean-Philippe Lansberg
IPNO, Paris-Sud XI U.

Brookhaven Summer Program, Quarkonium Production in Elementary and Heavy Ion Collisions
June 17, 2011
Brookhaven National Laboratory, USA

with F. Fleuret (LLR), S.J. Brodsky (SLAC), . . .

Part I

A fixed-target experiment using the LHC beam(s): generalities

A Fixed Target ExperRiment

Generalities

- *pp* or *pA* with a 7 TeV *p* beam : $\sqrt{s} \simeq 115$ GeV (+Fermi motion for *pA*)
- Same ballpark as electron-ion colliders → **complementary**
- For *pA*, a Fermi motion of 0.2 GeV would induce a spread of 10 % of $\sqrt{s}$

S.Fredriksson, NPB 94 (1975) 337

- The beam may be extracted using "Strong cristalline field"

E. Huggerhøj, U.I Huggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131 (+ next page)

- Expected luminosities with 5×10^8 *p*/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\mathcal{L}$ (pb^{-1}.y^{-1})
Liq. H_2	0.07	1	21	210
Liq. D_2	0.16	2	24	240
Be	1.85	9	60	600
Cu	8.96	64	40	400
W	19.1	185	30	300
Pb	11.35	207	16	160

(preliminary !)

- Using **NA51**-like 1.2m-long liquid H_2 & D_2 targets, $\mathcal{L}_{H_2/D_2} \simeq 20$ fb$^{-1}y^{-1}$
- For comparison, PHENIX recorded lumi for Run9 pp at 200 GeV: 16 pb^{-1} & Run8 *d*Au at 200 GeV : 0.08 pb^{-1}

A Fixed **T**arget **E**xper**R**iment

Generalities

- *Pbp* or *PbA* with a 2.75 TeV Pb beam : $\sqrt{s} \simeq 72$ GeV
- Cristal channeling is also possible (to extract a few per cent of the beam)
- Requires cristals highly resistant to radiations: progress with diamonds

P. Ballin ***et al.*****, NIMB 267 (2009) 2952**

- Expected luminosities with 7×10^5 Pb/s extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Liq. H_2	0.07	1	**28**
Liq. D_2	0.16	2	**34**
Be	1.85	9	**84**
Cu	8.96	64	**56**
W	19.1	185	**42**
Pb	11.35	207	**22**

(Preliminary !)

- For comparison, Phenix recorded lumi for Run10
  AuAu at 200 GeV: 1.3 nb^{-1} & AuAu at 62 GeV: 0.11 nb^{-1}

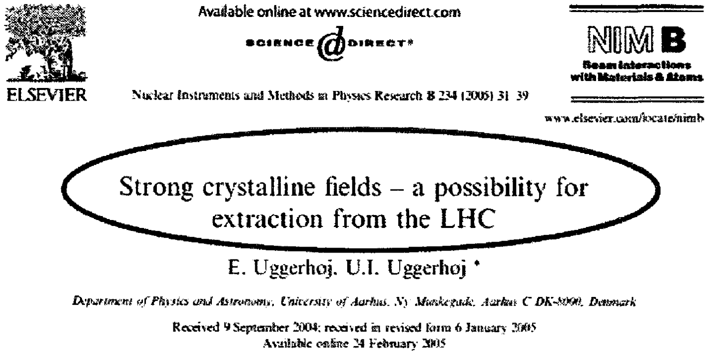
Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies



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Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Strong crystalline fields – a possibility for extraction from the LHC

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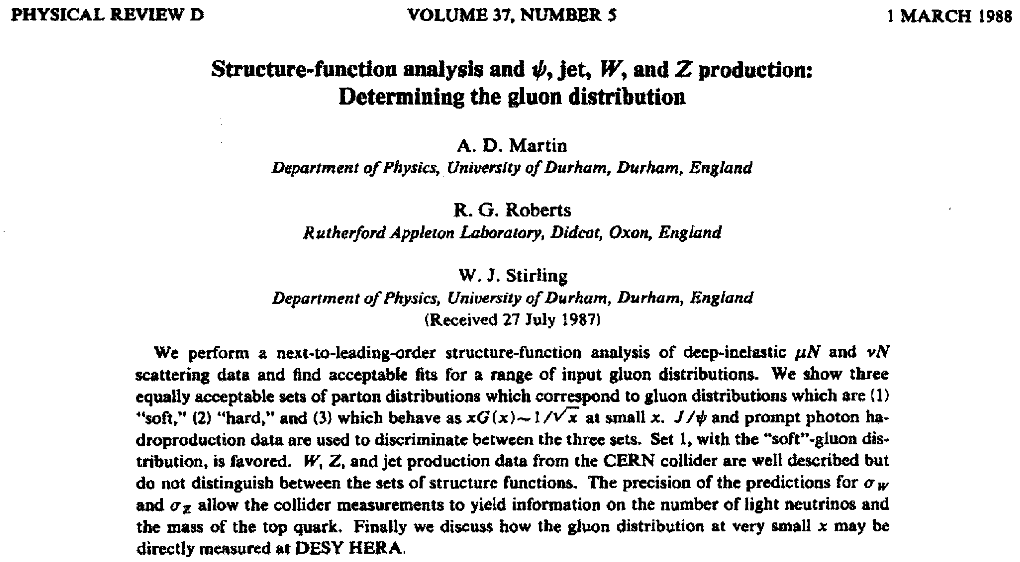
Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

Need for a quarkonium observatory

- Many hopes were put in quarkonium studies to extract gluon PDF
  - in photo/lepto production (DIS)
  - but also in $g-g$-fusion process
  - mainly because of the presence of a natural “hard” scale: m_Q
  - and the good detectability of a dimuon pair



PHYSICAL REVIEW D VOLUME 37, NUMBER 5 1 MARCH 1988

Structure-function analysis and ψ, jet, W, and Z production: Determining the gluon distribution

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Department of Physics, University of Durham, Durham, England

(Received 27 July 1987)

We perform a next-to-leading-order structure-function analysis of deep-inelastic μN and νN scattering data and find acceptable fits for a range of input gluon distributions. We show three equally acceptable sets of parton distributions which correspond to gluon distributions which are (1) “soft,” (2) “hard,” and (3) which behave as $xG(x)\sim 1/\sqrt{x}$ at small x. J/ψ and prompt photon hadroproduction data are used to discriminate between the three sets. Set 1, with the “soft”-gluon distribution, is favored. W, Z, and jet production data from the CERN collider are well described but do not distinguish between the sets of structure functions. The precision of the predictions for σ_W and σ_Z allow the collider measurements to yield information on the number of light neutrinos and the mass of the top quark. Finally we discuss how the gluon distribution at very small x may be directly measured at DESY HERA.

Brookhaven Summer Program: Quarkonium Production in Elementary and Heavy Ion Collisions

Attendees

First Name	Last Name	Affiliation
Ionut	Arsene	GSI Helmholtzzentrum fur Schwerionenforschung
Elke-Caroline	Aschenauer	Brookhaven National Laboratory
Pierre	Astoisenet	Ohio State University
Geoffrey	Bodwin	Argonne National Laboratory
Guillermo	Breto	UC Davis
Yannis	Burnier	Stony Brook University
Heng-Tong	Ding	Brookhaven National Laboratory
Adrian	Dumitru	Baruch College (CUNY) and RBRC
Ferreiro	Elena	University of Santiago de Compostela, Spain
Miguel Ángel	Escobedo	Technische Universität München
Amthony	Frawley	Florida State University
Philipp	Gubler	Tokyo Institute of Technology
Yu	Jia	Institute of High Energy Physics, CAS
Zhongbo	Kang	RBRC
Frithjof	Karsch	University of Bielefeld, Germany
Anthony	Kesich	University of California - Davis
Boris	Kopeliovich	UTFSM, Valparaiso, Chile
Jean-Philippe	Lansberg	IPN Orsay
Michael	Leitch	Los Alamos National Laboratory
Carlos	Lourenco	CERN
Agnes	Mocsy	Pratt Institute
Swagato	Mukherjee	Brookhaven National Laboratory
Yonathan	Munwes	Tel Aviv University
Michael	Murray	University of Kansas

Hiroshi	Ohno	University of Tsukuba, Japan
Peter	Petreczky	Brookhaven National Laboratory
Rob	Pisarski	Brookhaven National Laboratory
Jianwei	Qiu	Brookhaven National Laboratory
Ralf	Rapp	Texas A&M University
Rosi	Reed	University of California, Davis
Jorge	Robles	Brookhaven National Laboratory
Alexander	Rothkopf	University of Bielefeld
Lijuan	Ruan	Brookhaven National Laboratory
Matthew	Rudolph	Massachusetts Institute of Technology
Nicholas	Samios	RBRC / Brookhaven National Laboratory
Helmut	Satz	Univ. Bielefeld
Enrico	Scomparin	INFN - Laboratori Nazionali di Frascati
George	Sterman	Stony Brook University
Marco	Stratmann	Brookhaven National Laboratory
Michael	Strickland	Gettysburg College
Karolis	Tamosiunas	Vilnius University, Vanderbilt University
Zebo	Tang	University of Science and Technology of China
Michael	Tannenbaum	Brookhaven National Laboratory
Thomas	Ullrich	Brookhaven National Laboratory
Ramona	Vogt	Lawrence Livermore National Laboratory
Jianxiong	Wang	Institute of High Energy Physics, Chinese Academy of Sciences
Nu	Xu	Lawrence Berkeley National Laboratory
Zhangbu	Xu	Brookhaven National Laboratory
Ho-Ung	Yee	Stony Brook University
Clint	Young	McGill University
Xingbo	Zhao	Iowa State University

Brookhaven Summer Program on Quarkonium Production in Elementary and Heavy Ion Collisions

Agenda

Monday, June 6

Small seminar room

10.00-11.00 M. Strickland: Upsilon Suppression at RHIC and LHC

Tuesday, June 7

Small seminar room

10.00-11.00 H. Satz : Quarkonia in Deconfined Matter

Wednesday, June 8

Small seminar room

9.30-10.30 A. Rothkopf : Defining the heavy quark potential in perturbation theory and on the lattice

10.30-11.00 Coffee break

11.00-12.00 Y. Burnier : Static quark correlators in perturbative finite temperature QCD

Thursday, June 9

Large seminar room

9.00 Organizers : Opening Remarks
9.05 S. Vigdor : Welcome
9.15 N. Samios : Helmut Satz and heavy ion physics in BNL
9.30 T. Ludlam : Helmut Satz and early days of RHIC
10.00 F. Karsch : Helmut's other side: Physics in Bielefeld

10.30-11.00 Coffee break

11.00 G. Bodwin : Quarkonium production in hadron-hadron collisions
11.30 M. Leitch : Landscape of the Quarkonia Puzzle
12.00 M. Murray : Quarkonium suppression in Pb-Pb collisions at LHC

12.30-14.00 Lunch Break

14.00 A. Mocsy : Quarkonium production in hot medium
14.30 Z. Tang : J/psi measurements at STAR
15.00 M.A. Escobedo : EFT approach for quarkonium at finite temperature

15.30-16.00 Coffee Break

16.00 R. Reed : Measuring the Upsilon Nuclear Modification Factor at STAR
16.30 R. Vogt : Uncertainties on the J/psi Cross Section
17.00 I. Arsene : J/psi production in pp collisions in ALICE

18.00 Workshop Dinner (Berkner Hall)

Friday, June 10

Large seminar room

9.00 P. Gubbler : Sum rule approach to quarkonium at finite temperature
9.30 A. Frawley: Experimentally determining cold nuclear matter effects on J/psi
10.00 E. Scomparin : J/psi production in Pb-Pb collisions in the ALICE experiment

10.30-11.00 Coffee Break

10.00 C. Young : Quarkonium production in sQGP
11.30 R. Rapp : Theory of heavy quarks in medium
12.00 M. Rudolph : Quarkonium production in pp collisions at the LHC

12.30-14.00 Lunch Break

14.00 G. Sterman : PQCD factorization for heavy quarkonium production
14.30 J. Wang : The prediction of the J/psi polarization at hadron colliders
15.00 J.-P. Lansberg : Color singlet contribution to the problem of heavy quarkonium

15.30-16.00 Coffee Break

16.00-17.00 Round table discussion : what can we learn about properties of the matter created in heavy ion collisions from quarkonium measurements ?
conveners : A. Mocsy and N. Xu

Monday, June 13

Large seminar room

13.30-14.00 A. Kesich : Upsilon measurements in d+Au collisions at STAR
14.00-15.00 E. Ferreiro : Cold Nuclear Matter Effects on quarkonium production at RHIC and LHC energies

15.00-15.30 Coffee Break

15.30-16.30 B. Kopeliovich : Charmonium in pA and AA collisions
16.30-17.30 Discussion on initial state effects (convener : A.Dumitru)
Comments by G. Bodwin

Tuesday, June 14

Large seminar room

10.00-10.45 L. Ruan : Future heavy flavor measurements from STAR
10.45-11.30 D. Morison : Future heavy flavor measurements in PHENIX
14.00-15.00 X. Zhao : A thermal kinetic approach for charmonium production in HI collisions

Wednesday, June 15

Large seminar room

14.00-14.30 P. Steinberg : Quarkonium results from ATLAS
14.30-15.30 H. Ohno : charmonium spectrum at T>0 from lattice QCD
15.30-16.30 M.A. Escobedo : Non-relativistic bound states in a moving thermal bath

Thursday, June 16

Large seminar room

11.00-12.00 R. Pisarski : The transition to deconfinement
14.00-15.00 H.-T. Ding : Fate of quarkonia at T>0 and heavy quark diffusion from lattice QCD
15.30-16.00 S. Mukherjee : Charmonium correlators in lattice QCD

Friday, June 17

Large seminar room

9.00-10.00 G. Bodwin : Quarkonium production in ep and e+e- collisions

10.00-10.30 Coffee Break

10.30-11.30 P. Artoisenet : Gluon fragmentation into charmonium at NLO
11.30-12.30 J.-P. Lansberg : Quarkonium physics at a fixed target experiment with the proton and lead LHC beams

12.30-14.00 Lunch Break 78

14.00-15.00 Y. Jia : Linking NRQCD and light-cone approaches for exclusive quarkonium production

15.00-15.30 Coffee Break

15.30-16.30 Discussion on quarkonium production in elementary collisions and in the medium (convener: D. Kharzeev)

Additional RIKEN BNL Research Center Proceedings:

Volume 103 – Opportunities for Drell-Yan Physics at RHIC, BNL, May 11-13, 2011 – BNL-95236-2011-2011
Volume 102 – Initial State Fluctuations and Final-State Particle Correlations, BNL, February 2-4, 2011 – BNL-94704-2011
Volume 101 – RBRC Scientific Review Committee Meeting, October 27-29, 2010 – BNL-94589-2011
Volume 100 – Summer Program on Nucleon Spin Physics, BNL, July 14-27, 2010 – BNL-96163-2011
Volume 99 – The Physics of W and Z Bosons, BNL, June 24-25, 2010 – BNL-94287-2010
Volume 98 – Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC?, BNL – May 10-12, 2010 – BNL-94271-2010
Volume 97 – RBRC Scientific Review Committee Meeting, October 21-22, 2009 – BNL-90674-2009
Volume 96 – P- and CP-Odd Effects in Hot and Dense Matter, April 26-30, 2010 – BNL-94237-2010
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Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009
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
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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
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

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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
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

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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
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