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Heavy Flavor Productions and Hot/Dense Quark Matter

December 12-14, 2005

Organizers:

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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 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 currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen 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 ~40 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

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

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-seven proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
October 2005

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Heavy Flavor Productions and Hot/Dense Quark Matter Workshop
December 12-14, 2005

Yasuyuki Akiba, Wei Xie, Huan Huang, Ralf Rapp and Kirill Tuchin

There are solid evidences that high temperature and high density partonic matter is formed in heavy ion collisions at RHIC. Heavy flavor production, open and hidden, is considered among the most important probes for studying QCD properties of the matter.

In 1986, T. Matsui and H. Satz predicted that the J/ψ production would be significantly suppressed in relativistic heavy-ion collisions compared to that in p+p or p+A collisions due to the Debye screening effect. They suggest that the observation of a large suppression is an unambiguous signature of the QGP formation. Recent theoretical progress has made the picture more complicated. Lattice calculations indicate that J/ψ will not disassociate until reaching the temperature a factor of two above critical temperatures. Various recombination mechanisms of J/ψ formation from charm and anti-charm pairs have been proposed recently and some even predicted enhancement of the J/ψ production when QGP is formed. It is also important to distinguish dissociation of J/ψ in a hot medium from a similar effect in the Color Glass Condensate in order to have an unambiguous argument about the QGP formation. High statistics data are therefore needed to determine the J/ψ production mechanism in the medium.

In heavy-ion collisions at RHIC, the production of high p_T particles is strongly suppressed. The suppression is considered as being due to energy loss of light quarks in the dense medium formed in the collision. There are theoretical predictions that the energy loss of heavy quarks is smaller due to "dead cone effect". The amount of charm suppression would be essential for the understanding of the medium feature via investigating how heavy quarks behave differently from light quarks using high statistics data. Open charm production provides also crucial inputs for the recombination models of the J/ψ production. Open charm can be produced in the pre-equilibrium stage of the hot dense matter. The difference of open charm at central and forward rapidity can be an important signature of the formation of Color-Glass Condensate. It would be also very interesting to learn about possible transitions and their locations in p_T from thermal to coalescence to pQCD energy loss for both open and hidden heavy flavor, similar to what appears to be emerging from light hadrons.

In year 2004, RHIC had a high luminosity Au+Au run. Very important results on heavy flavor production from PHENIX and STAR experiment were shown at Quark Matter 2005. These results inspired a lot of theoretical activities trying to understand the data in the following few months after the conference. We organized the workshop and invited top physicists in this field to discuss their latest progress in understanding heavy flavor production in the hot/dense quark matter produced at RHIC. There were many interesting new results and exciting discussions during the Workshop.

We wish to acknowledge Dr. N. Samios and the RIKEN-BNL Research Center for their support in this Workshop presentation. Our thanks also to Brookhaven National Laboratory and the Department of Energy for providing the facilities, and to the speakers and participants for attending the Workshop. Finally, our sincere appreciation goes to Pamela Esposito and Jane Lysik for their invaluable assistance in coordinating and running the Workshop.

Heavy Quarks in QCD Matter: History and the Future

D. Kharzeev

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Upton, New York 11973-5000, USA

Abstract:

The use of heavy quarks for the diagnostics of hot and dense QCD matter is reviewed. The history of the topic, recent advances, and the possible future developments are discussed, including:
1. The mechanism of heavy quark and quarkonium production in nuclear collisions, and the role of the Color Glass Condensate;
2. Dissociation of charmonium states in the Quark-Gluon Plasma: weakly and strongly-coupled regimes;
3. The mechanism of energy loss of heavy quarks in QCD matter.
Because of the recent experimental data from RHIC, both of these topics at present are profoundly puzzling. It is difficult to understand why the observed at RHIC J/ψ suppression is similar in magnitude to the one observed at a much smaller SPS energy. Two proposed at present solutions are i) charm quark recombination, in which the observation is explained by a fine tuning of the suppression and enhancement contributions; and ii) the survival of the direct J/ψ 's at both energies, suggested by the lattice QCD calculations. The tests of these solutions are discussed.
The observed energy loss of heavy quarks is perhaps even more puzzling: the present RHIC data on non-photonic electrons seem to indicate a large energy loss not only for the charm, but also for beauty quarks. This is very difficult, if not impossible, to reconcile with the radiative energy loss picture based on perturbative QCD. In my opinion, something very important is missing in the present theoretical understanding.

Why heavy quarks?

QCD matter is characterized by dimensionful parameters: saturation scale Q_S, density, transport coefficient $\hat{q}$, ...

$$M_H \leftrightarrow Q_s,\ Q_s^2/\Lambda_{\rm QCD},\ \rho^{1/3},\ T,\ \sqrt{\hat{q}L}, ...$$

depending on their values, "heavy" quarks can behave either as heavy or as light !

$\Rightarrow$Use heavy quarks to extract information about the properties of QCD matter

Why heavy quarkonia? (I)

Heavy quarkonia are characterized by the size

$$R \sim \frac{1}{\alpha_s \; M_H}$$

and the binding energy

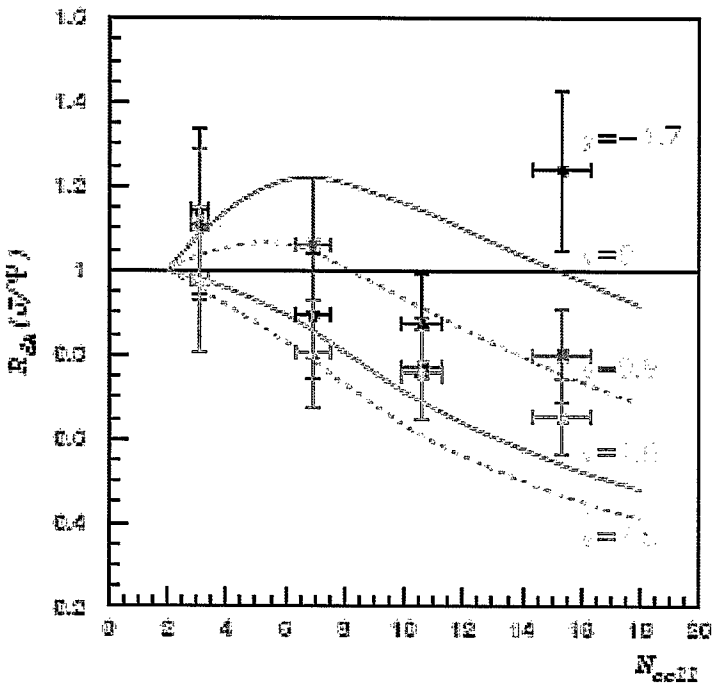
$$\epsilon \sim \alpha_s^2 \; M_H$$

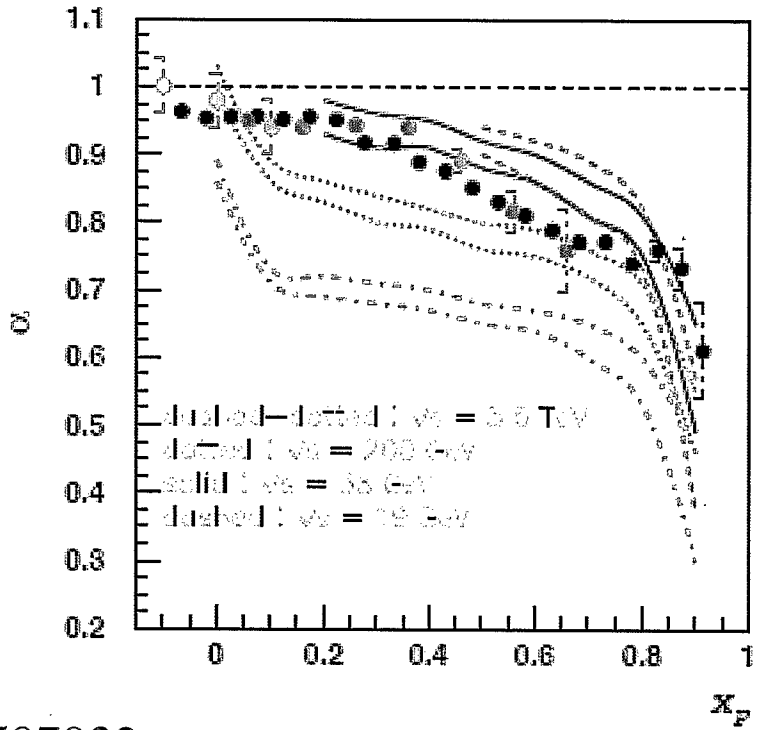
Even though $M_H >> \Lambda_{QCD}$, the inverse radius and the binding energy are not large enough to justify an entirely perturbative treatment even for bottomonium; Heavy quakonia are thus a valuable source of knowledge about non-perturbative QCD

(… and a source of trouble for the models aimed at describing their production mechanisms …)

J/Ψ production in the Color Glass Condensate

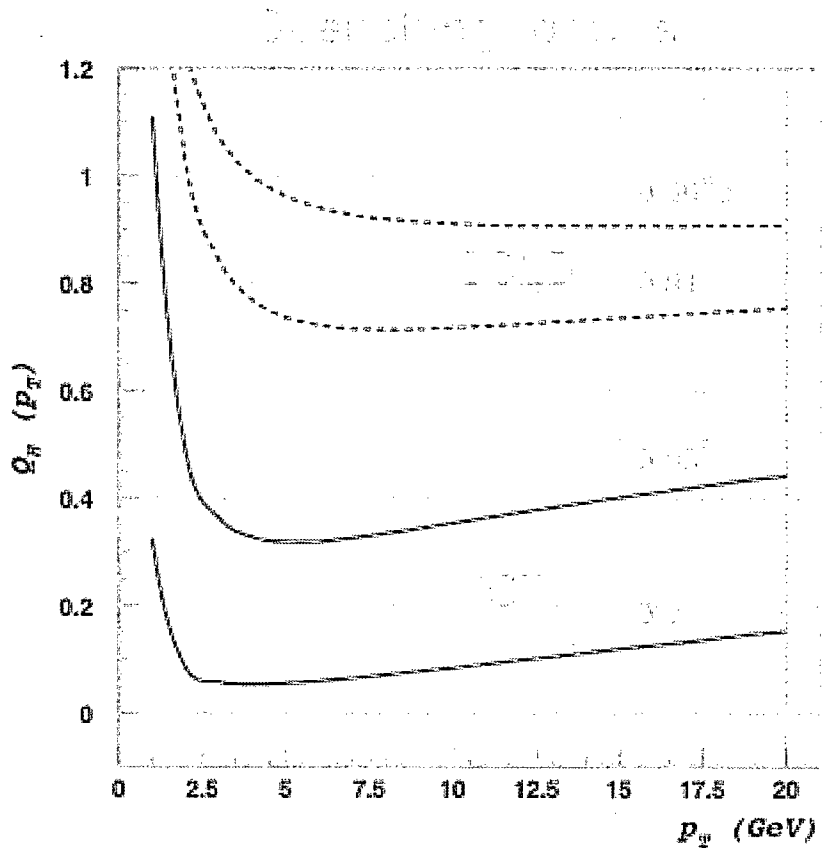
"x_F scaling"





Data: PHENIX Coll., nucl-ex/0507032
DK, K.Tuchin, hep-ph/0510358

Charm: the magnitude of suppression

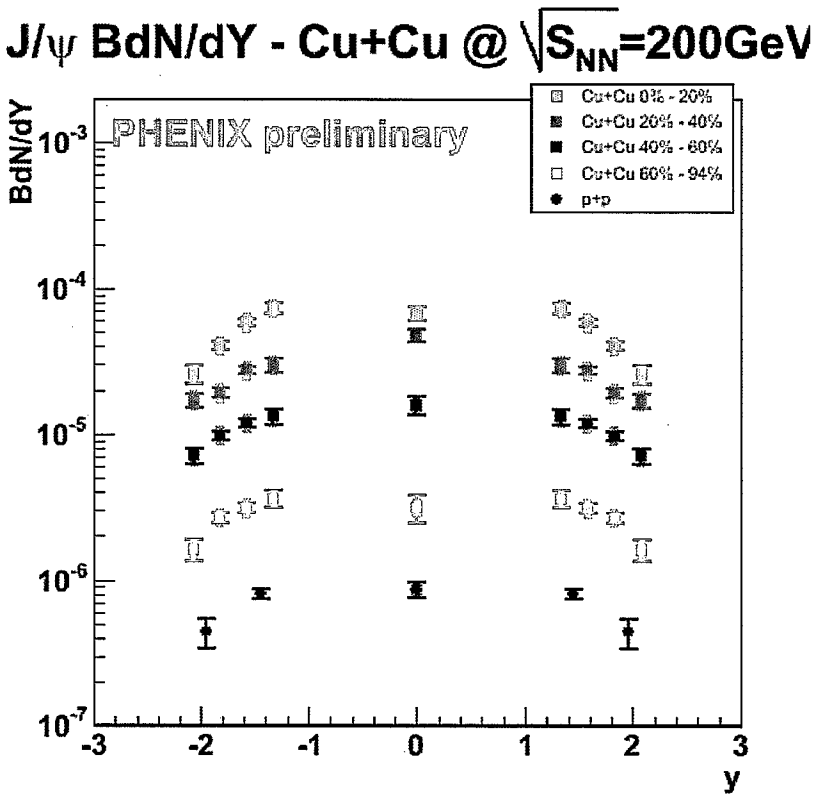


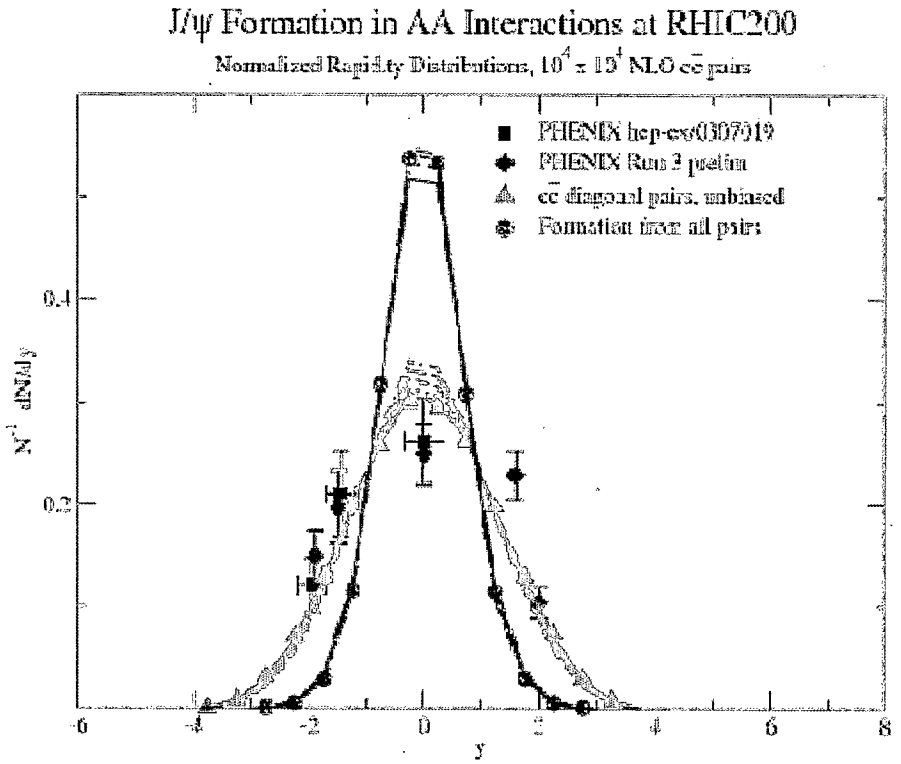
DK & K. Tuchin, hep-ph/0310358

At this Workshop, talks by M.Djordjevic, S.Wicks,…

Recombination of charm quarks?

R.Rapp, J. Rafelski, R.Thews,…





R.Thews

Recombination narrows the rapidity distribution; is this seen?
Are high p_t charmonia suppressed stronger than open charm?

PHENIX Charmonium Measurement in p+p, d+Au, Au+Au and Cu+Cu collisions

Taku Gunji for the PHENIX Collaboration

Center for Nuclear Study, Graduate School of Science, University of Tokyo, Japan

1 Summary of this talk

Results on the charm quarkonium production in p+p, d+Au, Au+Au and Cu+Cu collisions by PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) are presented.

Charmonium production in A+A collisions is not simple compared to that in p+p collisions. As the initial state effects, J/ψ yield could be modified due to gluon shadowing and/or color glass condensate in the nuclei. Cold matter effect such as nuclear absorption could lead to the suppression of J/ψ yield as observed in lower energy collisions. When the hot and dense medium is created by A+A collisions, where quarks and gluons are deconfined, J/ψ yield could be suppressed due to the color Debye screening effect. Recent lattice QCD calculations show that the suppression of J/ψ and higher charmonium states (χ_c and ψ') would be occurred above $\sim 2\ T_c$ and $\sim 1.1\ T_c$, respectively.

On the other hand, recent theoretical predictions show that the J/ψ yield would be enhanced due to the recombination of uncorrelated $c\bar{c}$ pairs created at the initial stage of collisions at RHIC energies.

Therefore, to understand the J/ψ production in A+A collisions, it is very important to study J/ψ production in different collision systems and rapidity ranges.

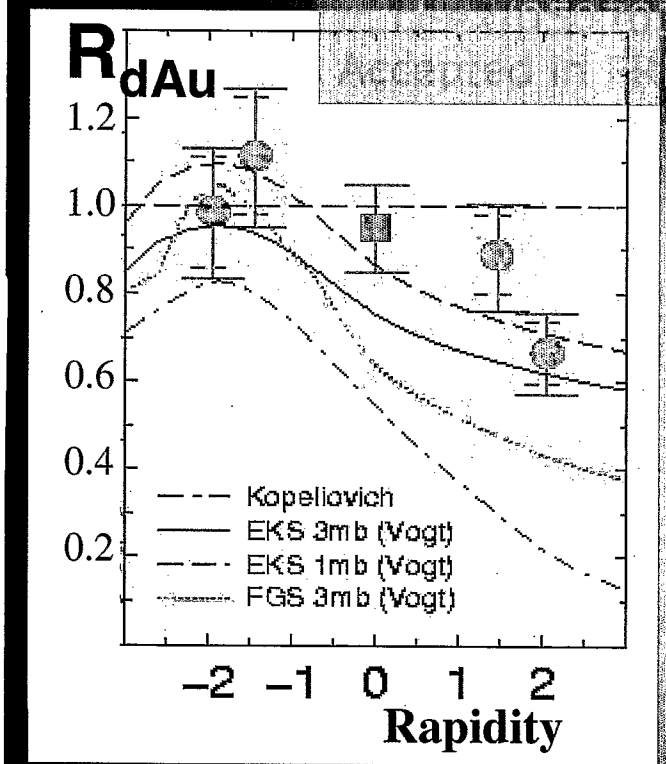
PHENIX measured J/ψ yield in p+p, d+Au, Au+Au and Cu+Cu collisions at forward-rapidity ($1.2 < |\eta| < 2.2$) using $\mu^+\mu^-$decay channel and mid-rapidity ($|\eta| < 0.35$) using e^+e^-decay channel to understand the J/ψ production at each stage of collisions.

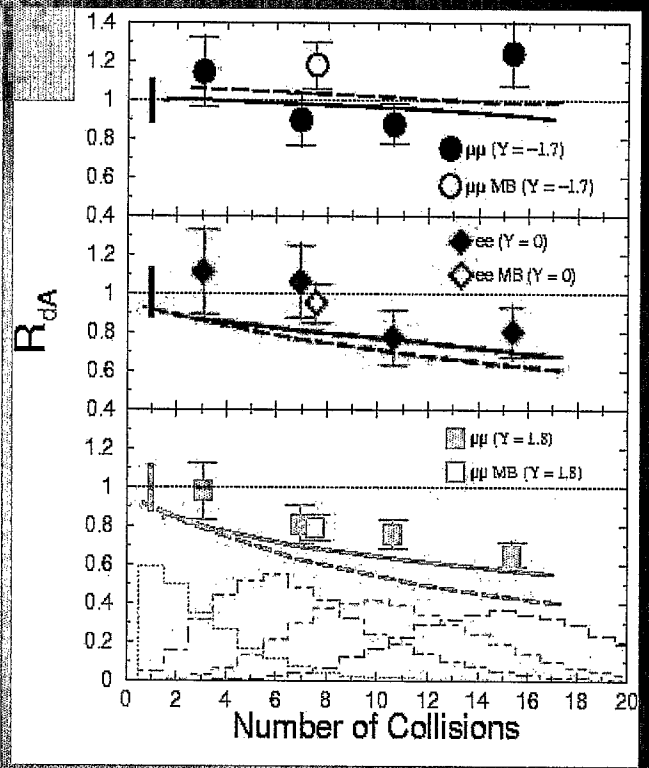
From the J/ψ measurements in d+Au collisions, nuclear absorption cross section was found to be from 1 mb to 3 mb, which is smaller compared to that at SPS energies. Gluon shadowing is also weak in small X_{Au} region. The trend of Cronin effect observed by PHENIX is consistent with the results from lower energy experiments. PHENIX d+Au results give a modest baseline for A+A collisions. Further statistics are needed for the study of the cold matter effect.

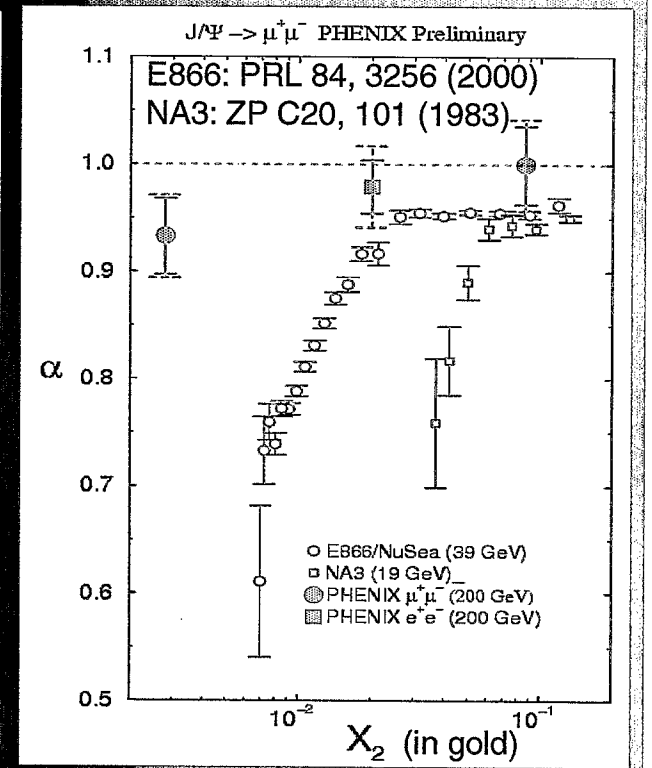
The J/ψ measurements in Au+Au collisions show that a factor of 3 suppression can be seen at the most central collisions for both forward-rapidity and mid-rapidity. The suppression pattern is same between Au+Au and Cu+Cu collisions at forward-rapidity but not at mid-rapidity. The observed suppression is beyond the cold matter effects evaluated from PHENIX d+Au results. The comparison to the theoretical models show that the suppression is over-predicted by the suppression models which described the J/ψ suppression at SPS energies successfully and that suppression and recombination models can describe the J/ψ suppression at RHIC energies much better. On the other hand, $< p_T^2 >$and rapidity shape of J/ψ cannot clarify the recombination effects due to the current large errors. Since the recombination models assume the charm p_T, rapidity distribution, radial flow and thermalization of charm and do not take into account the longitudinal flow of the medium, charm production in A+A collisions at RHIC energies and its medium modification are needed to be understood. Feed down effect is also important at RHIC energies since melting of χ_c and ψ' can explain J/ψ suppression at SPS energies. Up to mid central collisions, feed down effect can described J/ψ suppression at RHIC energies. To understand the J/ψ suppression at RHIC energies, the production of χ_c and ψ' in different collision systems are also needed to be studied.

Nuclear absorption and Shadowing

- R_{dAu} vs. rapidity, centrality, α vs. x coverage







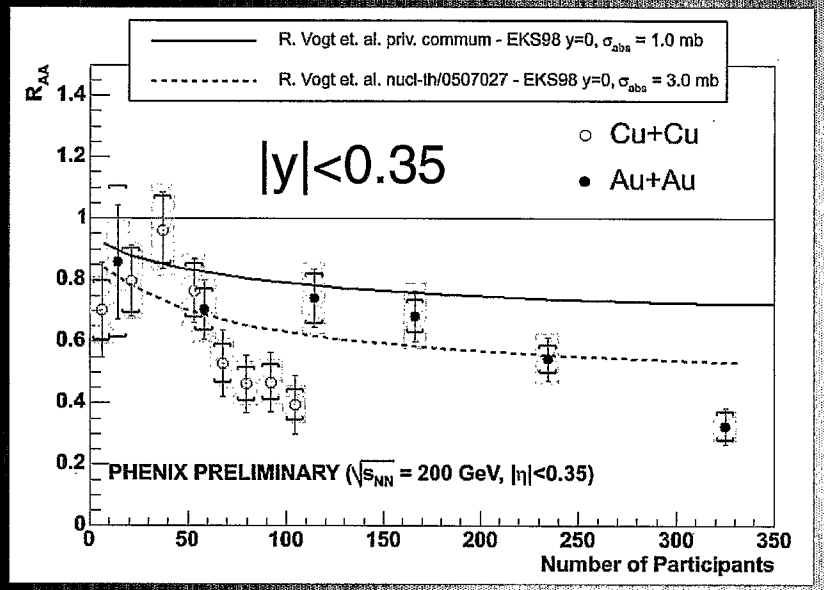
Weak nuclear absorption : σ =1–3 mb (~4.3 mb at SPS)

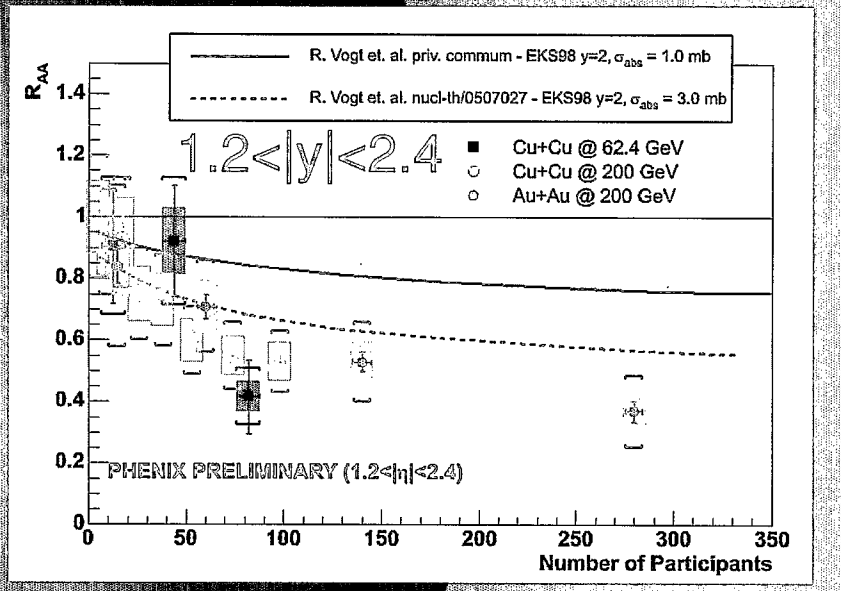
Suppression increased weakly toward the central collisions.

Weak shadowing (violation of X_{Au} scaling) : $\alpha > 0.92$

R_{AA} of J/ψ in Au+Au/Cu+Cu

- R_{AA} in Au+Au (200GeV), Cu+Cu(200GeV/62.4GeV)
- Comparison to the cold matter effects (σ_{abs} =1, 3mb)



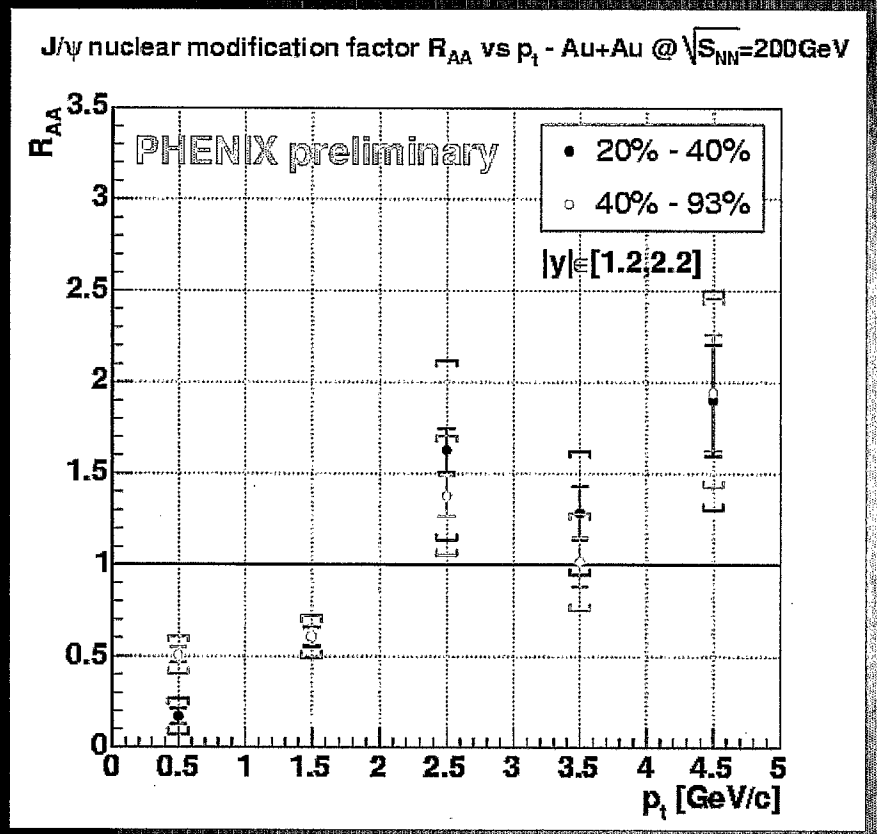


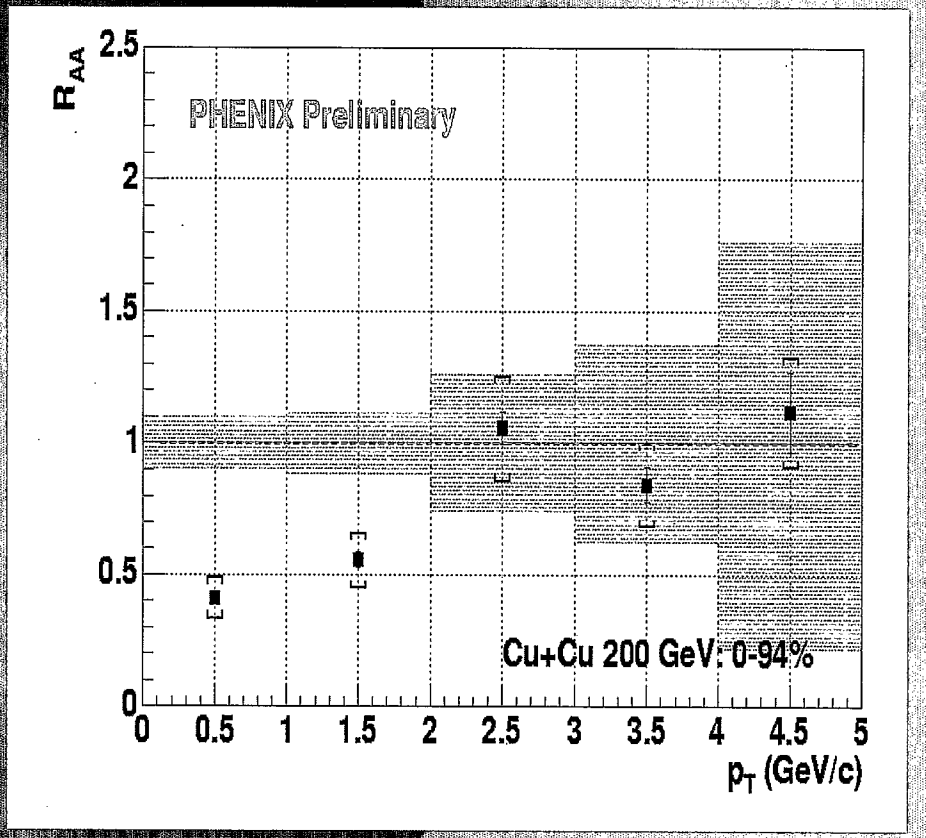
Suppression increased toward the central collisions.
Factor of 3 suppression at most central (Au+Au)
- Beyond the suppression from cold matter effect.

Same pattern between Au+Au and Cu+Cu (200GeV/62.4GeV) at forward-rapidity, but different pattern at mid-rapidity.

R_{AA} vs. p_T in Au+Au/Cu+Cu (200GeV)

- Forward-Rapidity in Au+Au and Cu+Cu (200GeV)

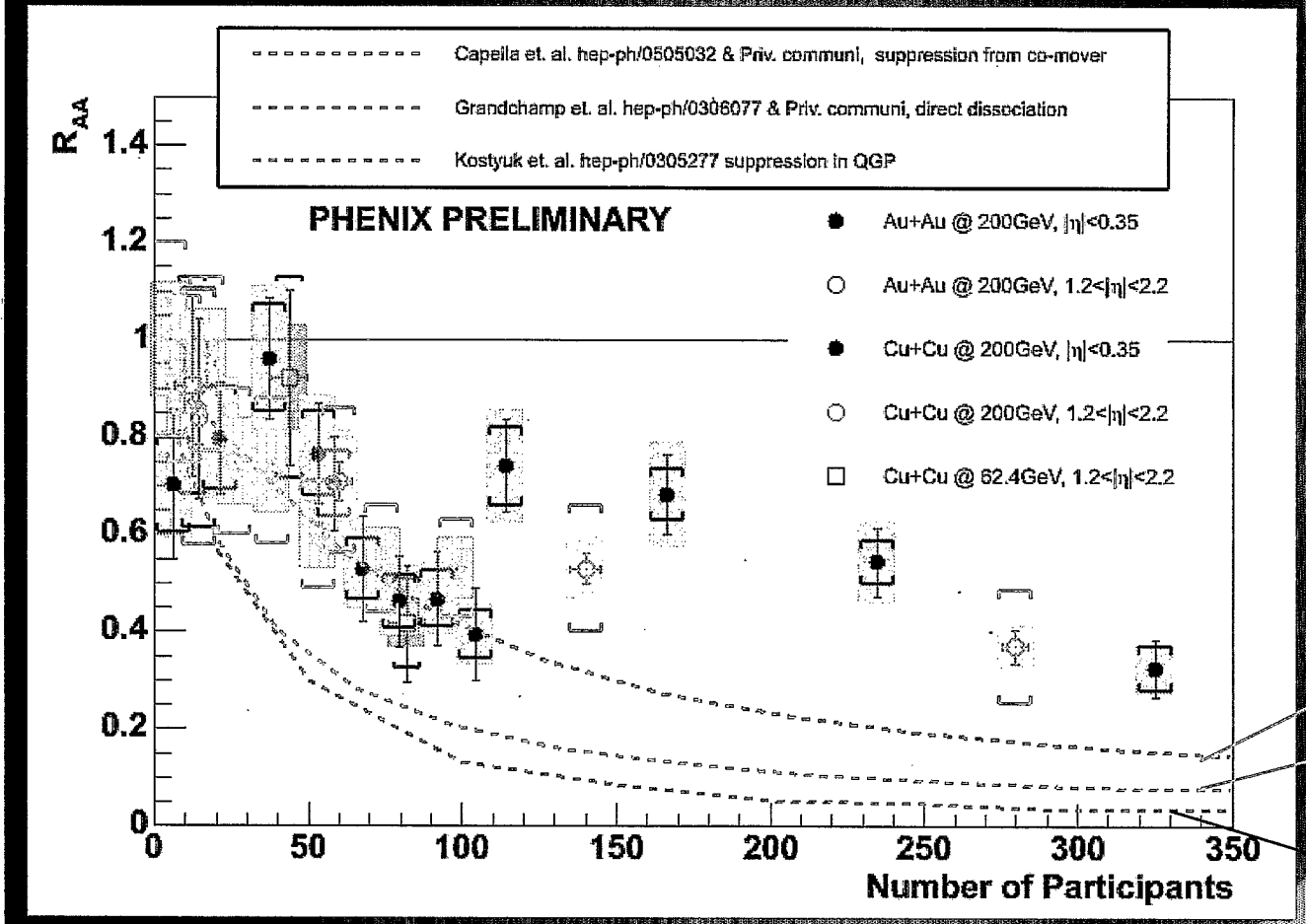




Suppression of J/ψ yield at low p_T in both Au+Au and Cu+Cu.
High p_T J/ψ escape the medium (Leakage effect)? [Phys. Lett. B 607 (2005)]

R_{AA} and suppression models

- Comparison to suppression models



J/ψ suppression at RHIC is over-predicted by the suppression models that described SPS data successfully.

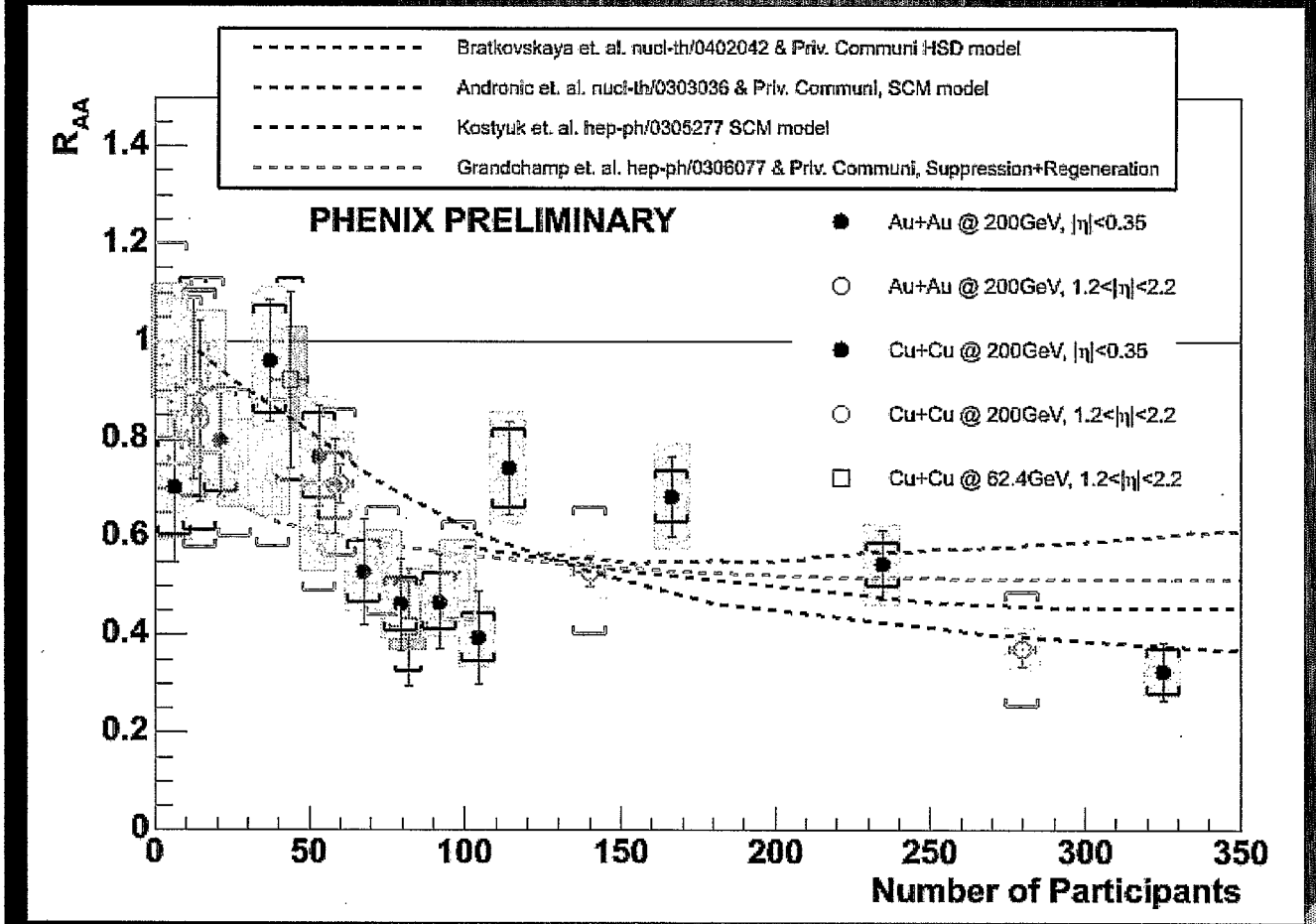
→ Co

→ Direct di

→ QGP screening (+Comover, feed down)

R_{AA} and suppression + recombination models

- Suppression + Recombination models



Better matching with results compared to the suppression models.

At RHIC (energy): Recombination compensates stronger suppression?

Non-photonic Electron v_2 and Heavy Quarkonia Measurements from STAR

W. J. Dong for the STAR Collaboration
University of California, Los Angeles

(Dated: December 13, 2005)

We present the recent non-photonic electron v_2 and J/ψ measurements from STAR.

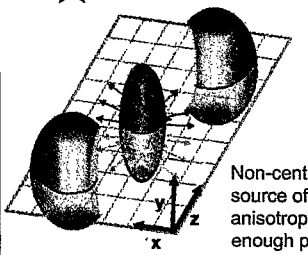
v_2 is azimuthal anisotropy of particle distribution in momentum space. In heavy-ion collisions, a particle's v_2 is built up at the early stage of the collision so it can serve as a good probe of the hot and dense medium created at RHIC energy. At RHIC, we have already observed partonic collectivity and jet quenching, the measurement of heavy quark v_2 can test the thermalization of the medium. It can also help us to understand the heavy quark energy loss in the medium. Direct v_2 measurement of the heavy quark hadrons requires large statistics that are currently not available at STAR. The measurement of the v_2 of the decay daughters from the heavy-quark hadrons allows us to gain insight into the v_2 of the heavy quarks. In this presentation, we present a method to measure the non-photonic electron v_2. Firstly, a high purity inclusive electron sample is obtained by particle identification. Then the background electrons are removed statistically from the inclusive electron sample. Finally, non-photonic electron v_2 is extracted from its event-plane-angle-adjusted ϕ distributions. The drawbacks of the method that we presented in Quark Matter 2005 will be also discussed.

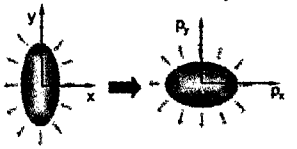
Charmonium measurements have long been of interest in the context of heavy-ion collisions. Due to their large mass, charm quarks are primarily produced via gluon fusion in the early, hard-scattering epoch of the collision. These charm quarks form charmonium bound states, namely J/ψ mesons. If the J/ψ's then find themselves in the hot and dense partonic medium, they will be subjected to dissociation—or destruction of the $c-\overline{c}$ bound state—via a number of mechanisms such as color screening or gluon scattering. This dissociation will lead to a suppression in the production of J/ψ's with respect to the production expected from pQCD and conventional suppression mechanisms. Such suppression has long been thought of as one of the characteristic signatures of the formation of a Quark-Gluon Plasma in relativistic heavy-ion collisions. Recent theoretical developments predict that another type of J/ψ production will become relevant in relativistic heavy-ion collisions: J/ψ formation via the coalescence of charm and anti-charm quarks in the final stages of the collision. One such regeneration scenario, Statistical Hadronization, maintains that there will be total J/ψ screening in the QGP and that the observed J/ψ production will be exclusively a consequence of regeneration. In STAR, we have made measurements of di-electron invariant mass spectra in Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV. Particle tracking information and electron identification was obtained using the STAR Time Projection Chamber. After imposing various event-level quality cuts, a sample of 13 million events were analyzed. Di-electron invariant mass spectra were obtained via the event mixing technique, from which a J/ψ signal of 3.5σ significance was observed. We compared the observed J/ψ signal to what the corresponding uncorrected, theoretical signal from Statistical Hadronization would look like in STAR. The yield from the Statistical Hadronization model is markedly higher than the observed raw yield, and the difference is such that we can rule out the Statistical Hadronization scenario as a dominant mechanism behind J/ψ production at RHIC.

Non-photonic Electron v2 and Heavy Quarkonia Measurements from STAR

Weijiang Dong
For STAR Collaboration

What is v2?





Non-central Au-Au collisions → azimuthally anisotropic source of matter in coordinate space → azimuthally anisotropic (isotropic) of particles in momentum space, given enough particle interactions → Non-zero (zero) v2

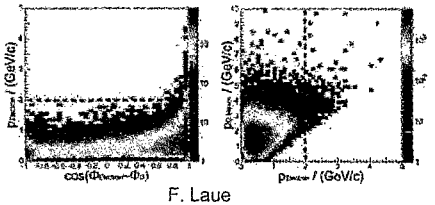
v2 is built up at the early stage of the collision so it is a nice probe of the hot and dense medium created at RHIC energy!

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\psi_r)]\right)$$

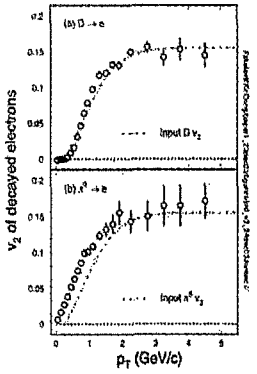
$$v_2 = <\cos[2(\phi-\psi_r)]>$$

What Is a Non-photonic Electron and Why do we measure its v2?

- A Non-photonic electron is an electron from heavy quark decay. Charm semi-leptonic decay branch ratio~9.6%, Bottom semi-leptonic decay branch ratio~10.5%
- At high pt, the v2 of the daughter electron is correlated with the parent heavy quark v2: To measure the non-photonic electron v2 is to measure the heavy quark v2 indirectly



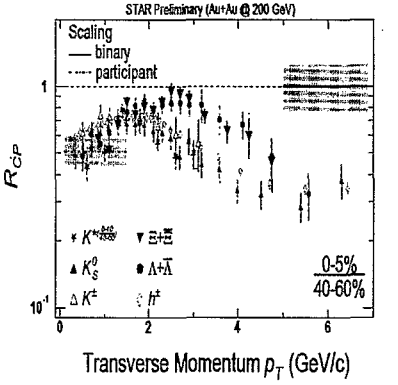
F. Laue



X. Dong et. al. *PLB597, 328(2004).*

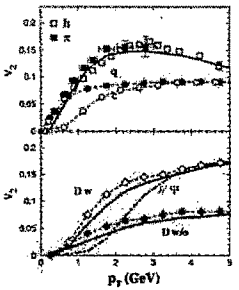
Why is heavy quark v2 interesting?

- The heavy quark v2 addresses two important physics issues
  - At RHIC we have observed partonic collectivity and jet quenching. The measurement of heavy quark v2 can test the thermalization of the medium created at RHIC energy
  - The energy loss of heavy quarks in the dense medium created in nucleus-nucleus collisions at RHIC

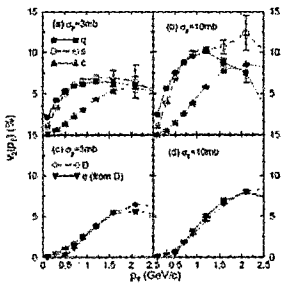


Does Heavy Quark Flow?

V. Greco et al., PLB 595(2004)202

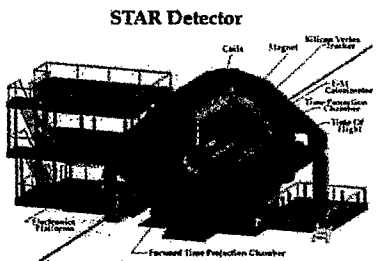


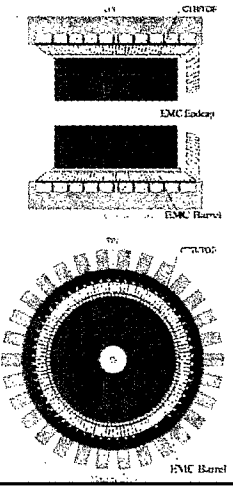
B. Zhang et al., nucl-th/0502056



- Coalescence approach: charm has same v2 as light quark or zero v2
- AMPT transportation model: mass ordering, same saturation level, cross section dependence, correlation of electron v2 and D meson v2

Major Detectors Used





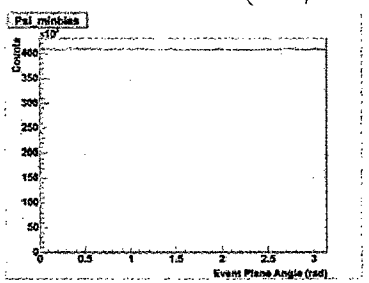
- Time Projection Chamber (TPC): dEdx v.s. P
- Electro-Magnetic Calorimeter (EMC): E
- Shower Maximum Detector (SMD): Shower size and shower position
- Signal: non-photonic electrons
- Background: hadrons and photonic electrons

Reaction Plane Angle

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[\,n(\phi-\psi_r)]\right)$$

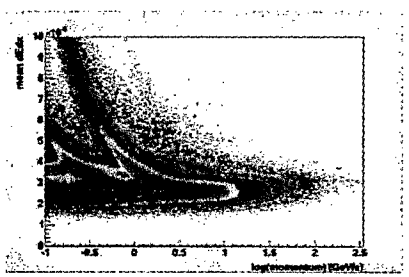
$$v_2 = <\cos[\,2(\phi-\psi_r)]>$$

$$\psi_{r(2)} = \left(\tan^{-1}\frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)/2$$



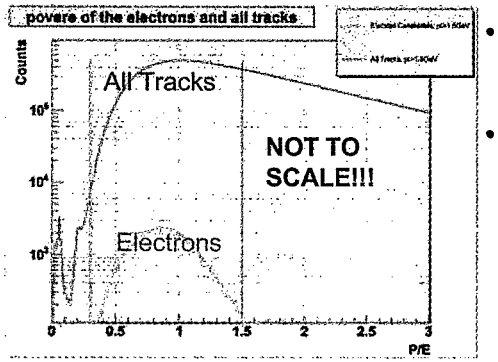
- Real reaction plane is unknown
- Event plane is the approximation of reaction plane
- Take tracks measured by TPC to get the event plane angle
- Limited resolution of event plane measurement dilutes the v2, this effect is corrected at the end

Electron ID: Cut on dEdx



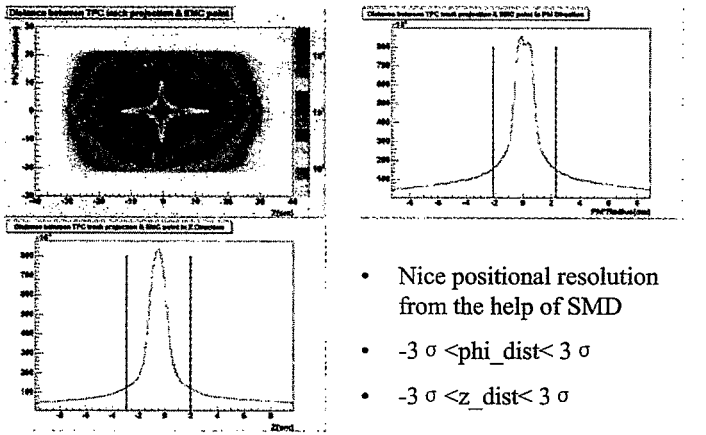
- TPC can identify charged particles to some extent
- Two orders of magnitude more hadrons than electrons
- Additional information needed to identify electrons

Electron ID: Cut on P/E



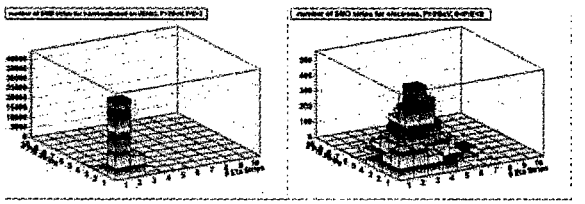
- P from TPC, E from Barrel EMC
- The P/E alone contributed hadron rejection power is not great at low pt, but becomes better at high pt

Electron ID: Cut on Projection Distance



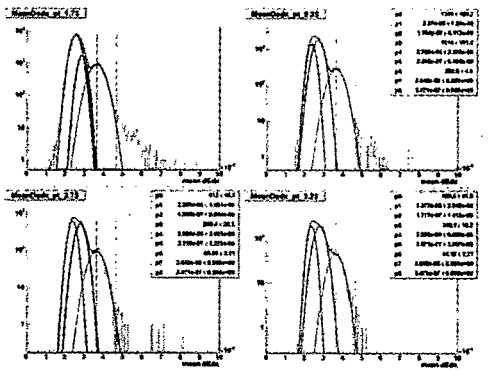
- Nice positional resolution from the help of SMD
- -3 σ <phi_dist< 3 σ
- -3 σ <z_dist< 3 σ

Electron ID: Cut on Shower Size



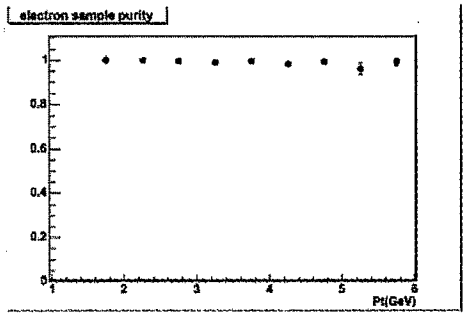
- Shower hadrons typically have small shower sizes
- Number of SMD hits per shower indicates shower size
- Number of hits on SMD larger than 1 for electrons

With All EMC Cuts Applied



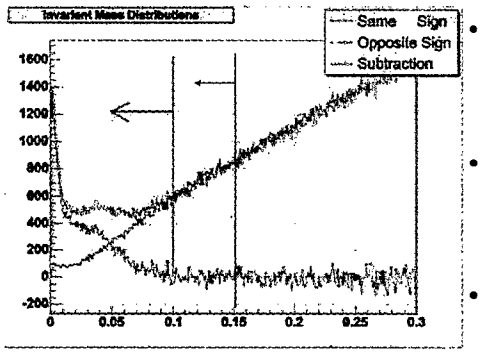
- dEdx cut: from 0 to 3 sigma on electron band

Electron Sample Purity



- Electron Purity>99% for measured pt range
- No worry about hadronic background

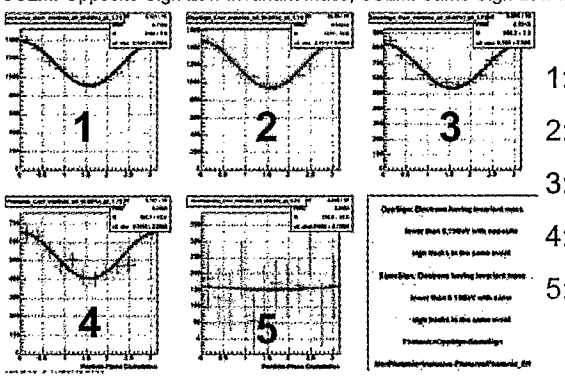
Photonic Background



- Reconstructed photonic electron is the subtraction
- Real produced photonic electron is the subtraction/eff
- eff calculated from simulation

The Removal of Background Electrons

OSLM: Opposite Sign Low Invariant Mass; SSLM: Same Sign Low Invariant Mass



1: inclusive

2: OSLM

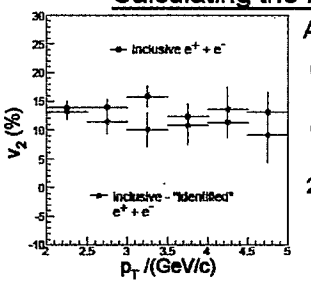
3: SSLM

4: 2-3

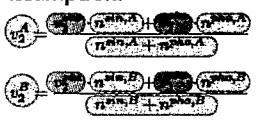
5: 1-(2-3)/eff

QM2005 Method

Calculating the non-photonic v_2



Assumption:



2 equation with 2 unknown can be solved analytically

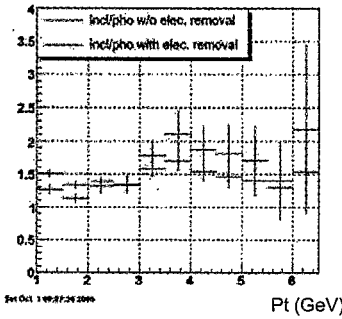
Measure the $e^{+/-}$ v_2 twice:

Sample A: without photonic electron rejection (inclusive)

Sample B: after photonic electron rejection

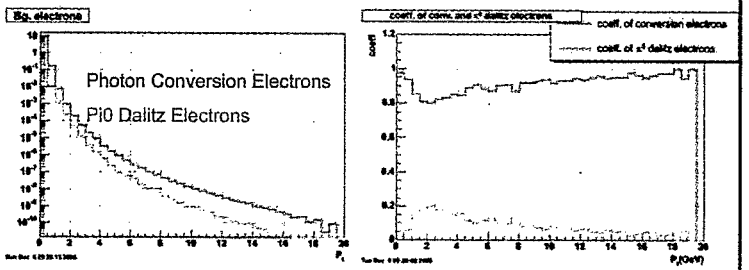
QM2005 Method: Problems

F. Laue



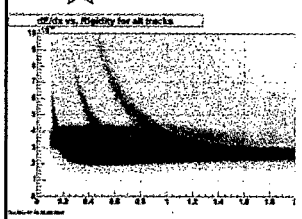
1. **Two equations are almost the same experimentally**
2. **Low invariant mass cut is essentially low opening angle cut, but v2 is just about opening angle: the v2 of non-photonic electron are not the same in two equations!**
3. **Non-flow effect**
4. **Error calculation incomplete**

Too much photon conversion electrons!

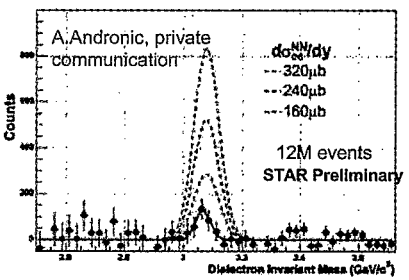


Both methods suffer from photon conversion electrons!!!

J/psi production



J. Gonzalez



- Select all possible electrons above 0.1 GeV/c, provided they don't impinge any of the hadron bands
- The di-electron invariant mass distribution is generated using the event-mixing
- Our J/psi yields are lower than statistical hadronization model predictions (red-dashed curve) ⇒ Extreme enhancement scenarios ruled out

Summary

- We have developed a new method to measure the non-photonic electron v2 in heavy ion collisions. The material in STAR detector caused too much photon conversion electrons, which make the v2 measurement very difficult. Our result is not sensitive enough to make any conclusion about heavy quark v2 so far. More work ahead!
- We have observed a J/Psi peak in our data. The magnitude of the peak seems to rule out the extreme enhancement scenarios

東京大学大学院理学系研究科附属
原子核科学研究センター
Center for Nuclear Study (CNS)

PHENIX

PHENIX Heavy Flavor Measurement by Single Leptons in p+p, d+Au and Au+Au

Fukutaro Kajihara (CNS, University of Tokyo) for the ***PHENIX*** Collaboration

Heavy Flavor Productions & Hot/Dense Quark Matter
RIKEN BNL Research Center Workshop
December 12, 2005 at Brookhaven National Laboratory

Short Summary

For p+p collisions:

Heavy flavor electron in mid-rapidity and prompt muon in forward-rapidity have a similar spectrum.

FONLL calculation are smaller than the each measured spectrum.

For d+Au collisions:

Binary scaling of heavy flavor electron works well in mid-rapidity in low p_T region.

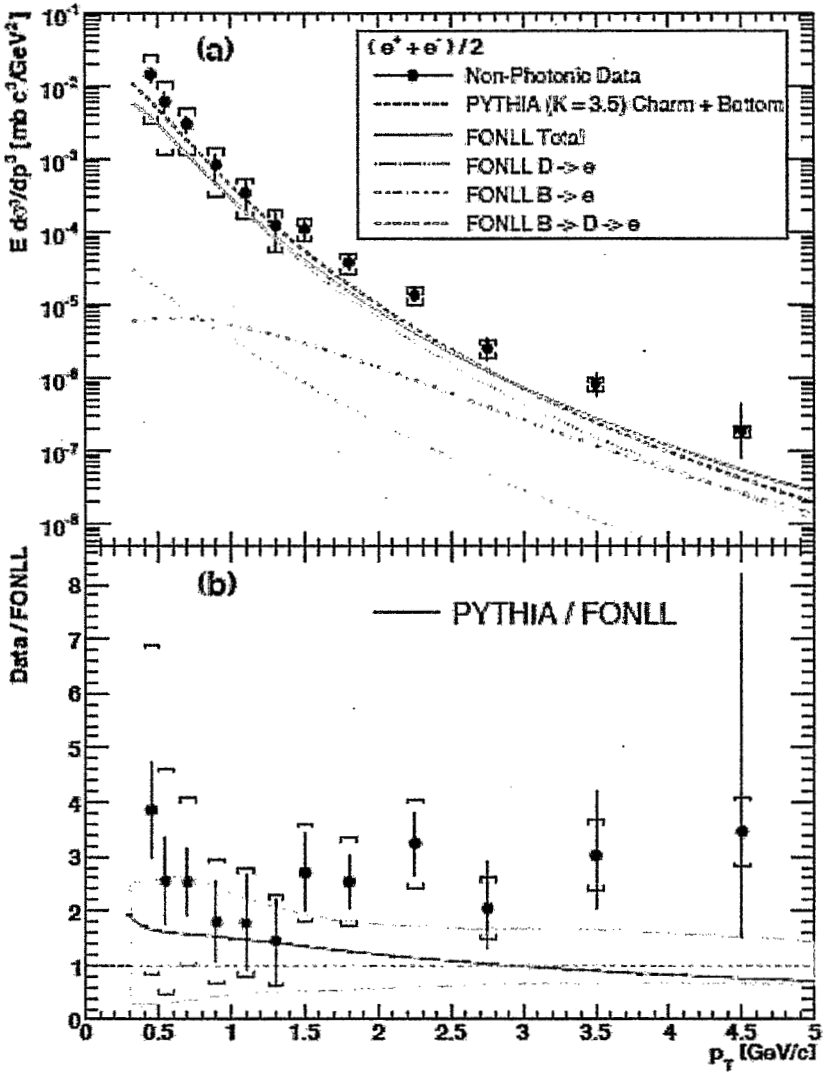
For Au+Au collisions:

Binary scaling of total charm yield works well.

Nuclear modification factor R_{AA} shows a strong suppression at high p_T region.

v2 of heavy flavor electron was found. If v2(D) = a*v2(π), a=60%.

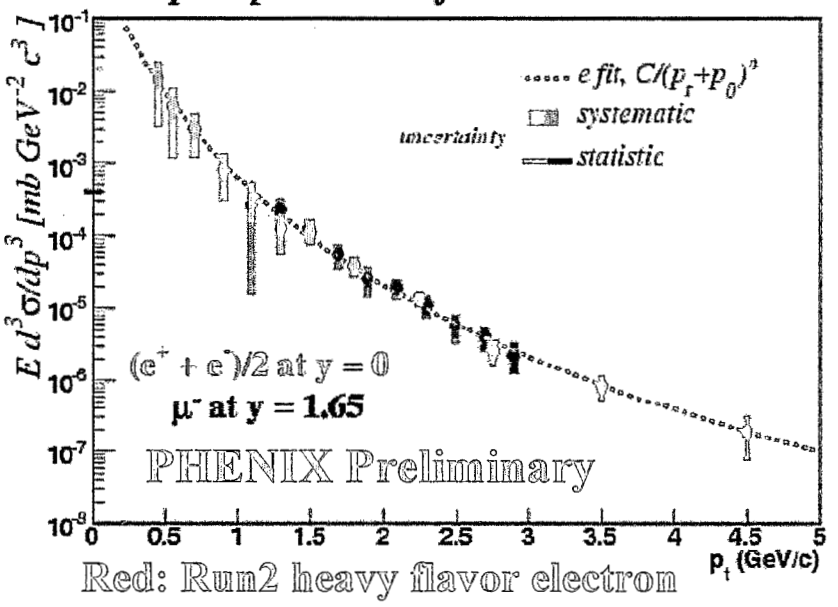
Heavy flavor electron and prompt muon in Run2 p+p at $\sqrt{s_{NN}}$ = 200 GeV



Heavy flavor electron

- **PRL accepted recently. (hepex/0508034).**
- **Data spectrum of Run 2 p+p seems to be the same or more harder than FONLL prediction.**
- **We are analyzing data of Run3 and Run5 p+p for the extension in higher p_T region.**

Lepton production from PHENIX RUN2



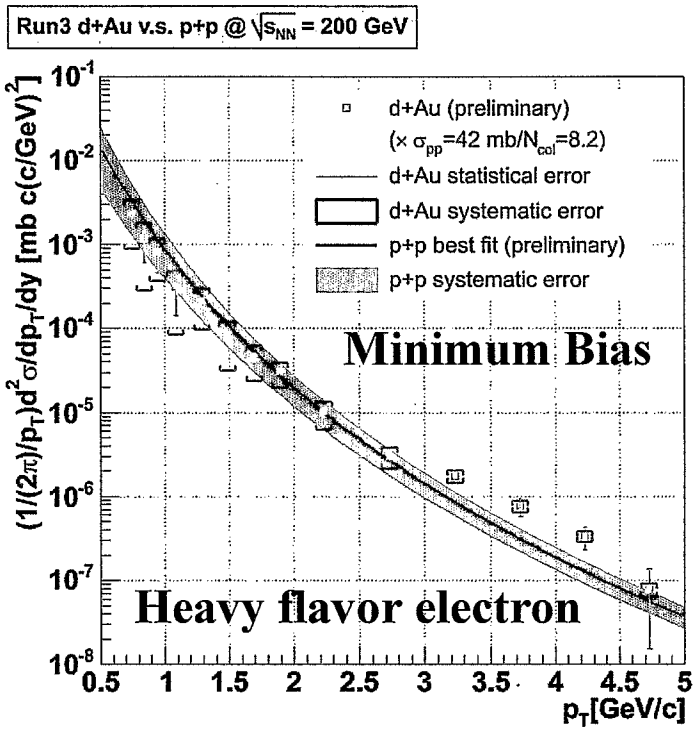
Red: Run2 heavy flavor electron

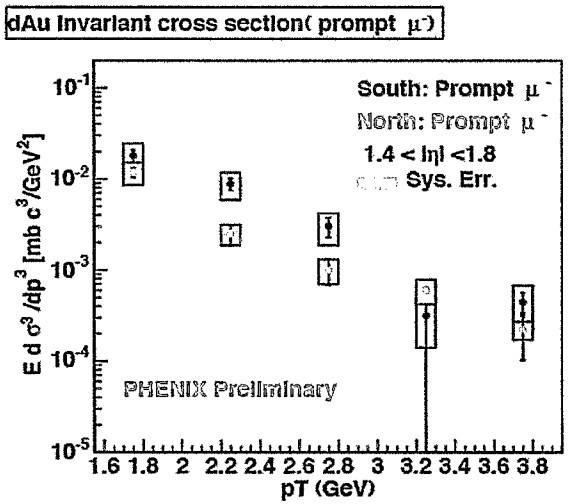
Blue: Run2 prompt muon

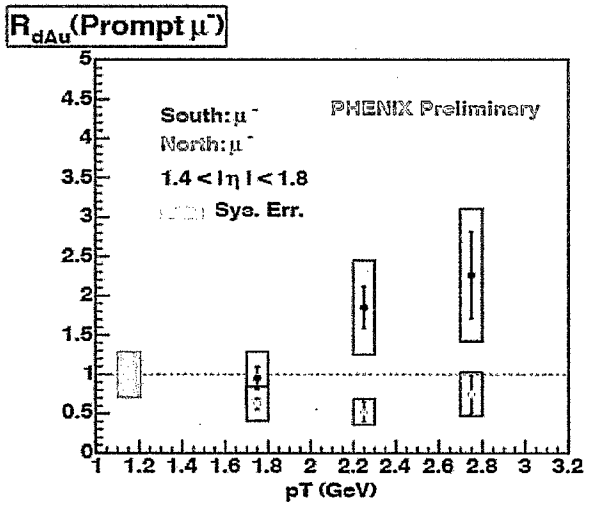
- **We obtained the same result in the central (e, $|\eta|<0.35$) and forward rapidity region (μ, $1.2<|\eta|<2.4$).**

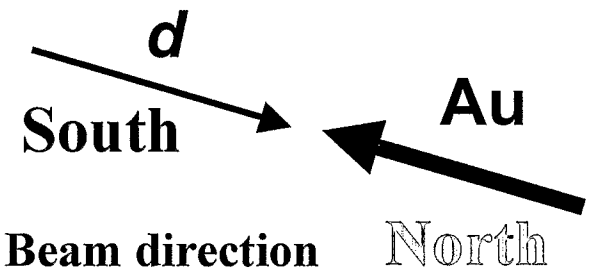
Heavy flavor electron and prompt muon in Run3 d+Au at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX









- **In low p_T region, Run3 electron data almost agrees with Run3 p+p data within error bars.**

Error is still large, but interesting μ results came

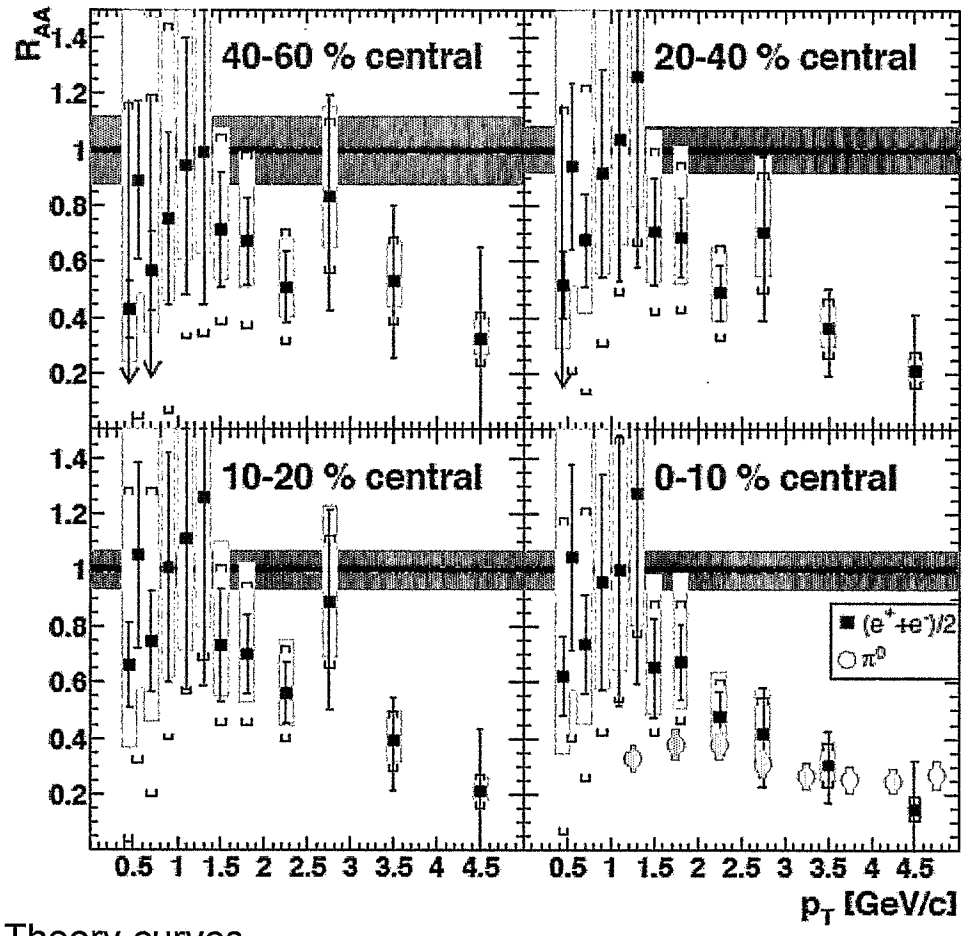
- **Suppression(?) in d going direction**
- **Enhancement(?) in Au going direction**

R_{AA} of heavy flavor electron in Run2 Au+Au at $\sqrt{s_{NN}} = 200$ GeV

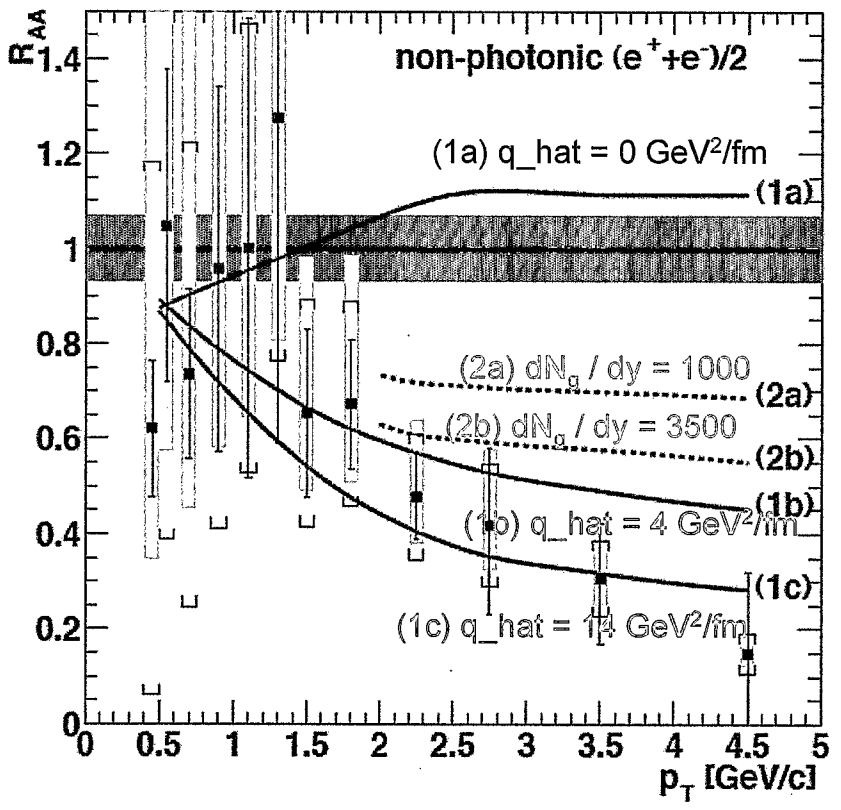
PHENIX

$$R_{AA} = \frac{dN_{AA}}{T_{AB} d\sigma_{pp}}$$

PRL accepted recently (nucl-ex/0510047).



Clear evidence for strong medium effects!

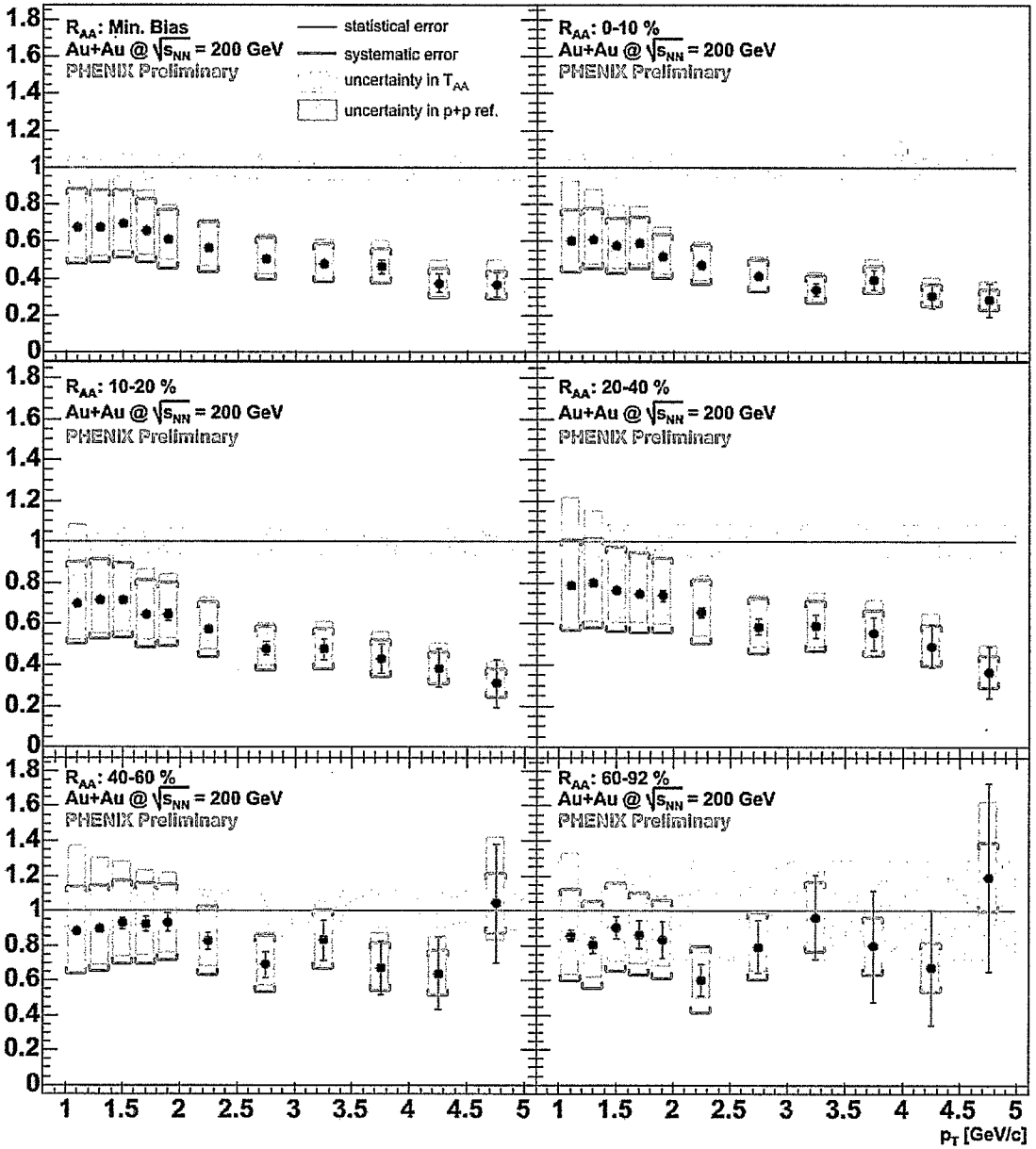


Theory curves
(1abc) from N. Armesto, *et al.*, PRD 71, 054027

(2ab) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301

R_{AA} of heavy flavor electron in Run4 Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX



$$R_{AA} = \frac{dN_{AA}}{T_{AB} d\sigma_{pp}}$$

- **We can see strong suppression even for heavy quark (charm) in high statistic Run4 data.**
- The matter is so dense that even heavy quarks are stopped.
- **We are preparing the high p_T R_{AA} (up to p_T = 10 GeV/c).**

Open Charm Flow in Run4 Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

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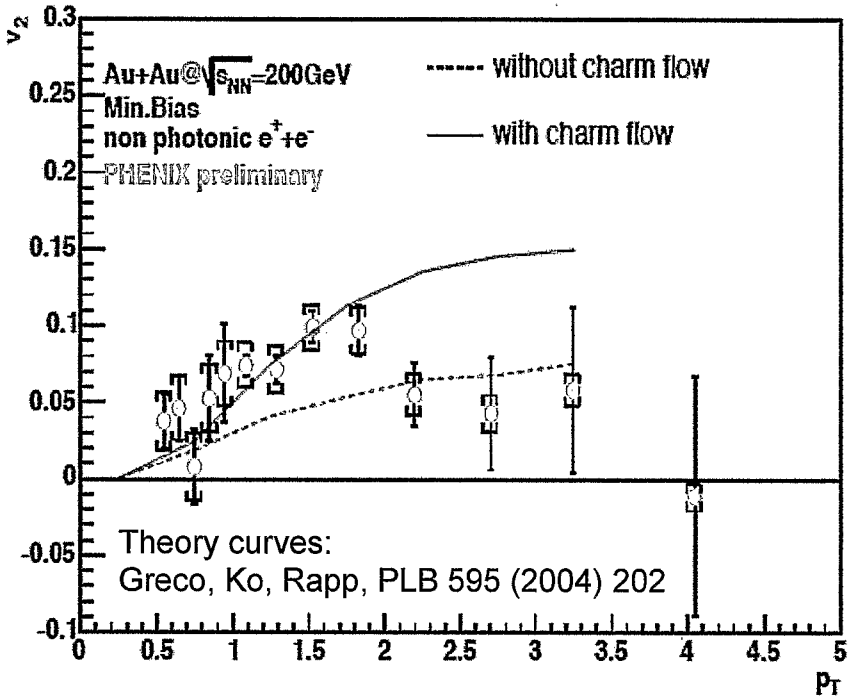

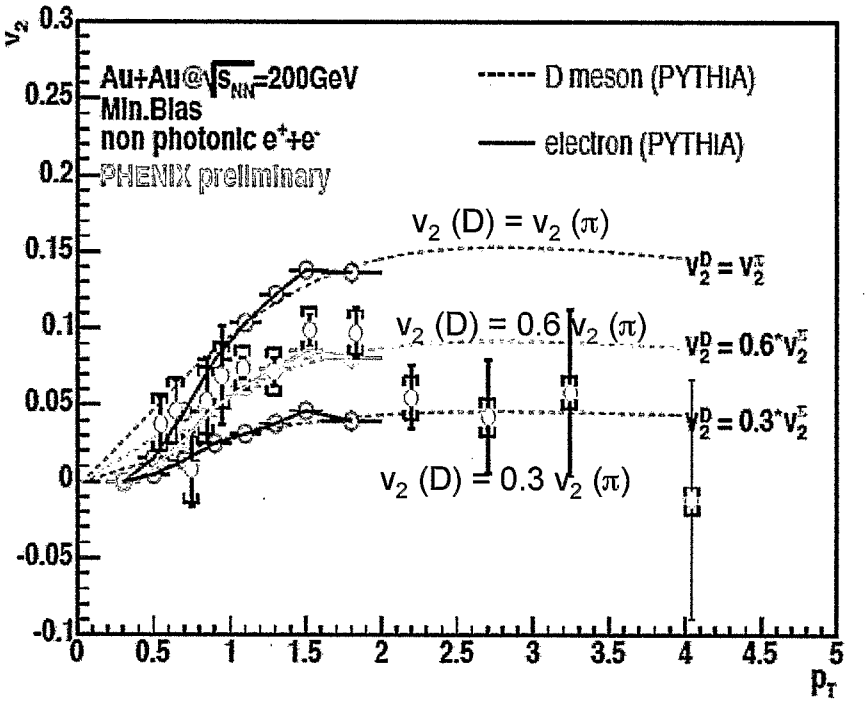

- **Significant anisotropy is observed for heavy flavor electron.**
- **v2 has good agreement of charm flow assumption below p_T < 2.0 GeV/c**
- **In high p_T region (p_T > 2 GeV/c), v2 is reduced. (b quark contribution?)**
- **If v2(D) = a*v2(π), v2(D) is non-zero value and 60% of v2(π).**

Open Charm Measurements in $\sqrt{s_{NN}}$=200 GeV p+p, d+Au and Au+Au Collisions at STAR

Haibin Zhang
Brookhaven National Laboratory
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for the STAR Collaboration

The directly reconstructed D^0 meson production via its hadronic decay channel $D^0 \rightarrow \pi K$ in minimum bias d+Au and Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV with p_T up to ~3 GeV/c is measured in STAR. By using the STAR TPC (Time Projection Chamber), TOF (Time-of-Flight) and Barrel EMC detectors, single electron/positron spectra with p_T up to ~8-10 GeV/c from the charm semi-leptonic decays are also analyzed from p+p, d+Au and Au+Au collisions. The charm production total cross-section per nucleon-nucleon collision is measured to be 1.11 ± 0.08 (stat. error) ± 0.42 (sys. error) mb in minimum bias Au+Au collisions, which roughly follows an N_{bin} scaling compared to the charm total cross-section 1.4 ± 0.2 ± 0.4 mb in d+Au collisions at the same collision energy, which indicates charm quarks might be mainly produced in initial collisions via parton fusion. The nuclear modification factors (R_{dAu} and R_{AA}) of the single electrons/positrons in d+Au and various Au+Au collision centralities are measured. The R_{dAu} is slightly above unity indicating the Cronin effect in d+Au collisions. The R_{AA} in central Au+Au collisions is suppressed as strongly as that of charged hadrons at high p_T (pT>~2 GeV/c) so that the charm transverse momentum distribution must have been modified by the hot and dense medium in central Au+Au collisions. However, the amount of bottom contributions to the single electron spectra is still unclear. In order to better understand the heavy flavor production and its interaction with hot and dense medium at RHIC, directly measured charm hadron p_T distributions are necessary.

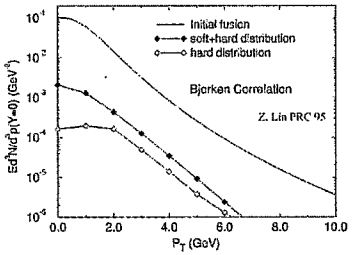
Open Charm Measurements in $\sqrt{s_{NN}}$=200 GeV p+p, d+Au and Au+Au Collisions at STAR

Haibin Zhang
Brookhaven National Laboratory
for the STAR Collaboration

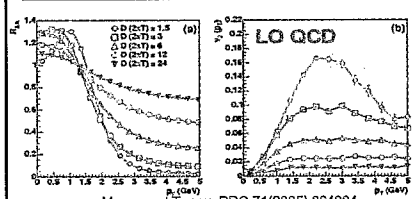
Motivation – Charm Production Mechanism

- Our final goal is to understand the properties of the hot and dense matter produced in heavy ion collisions
- Charm can provide a unique tool to study important properties of the new matter
- However, we have to understand the charm production mechanism first
- Charm is believed to be produced in initial collisions via gluon fusion ⇒ charm total cross-section should follow N_{bin} scaling from p+p to Au+Au
- It's important to measure charm total cross-section in Au+Au and compare to that in p+p and d+Au

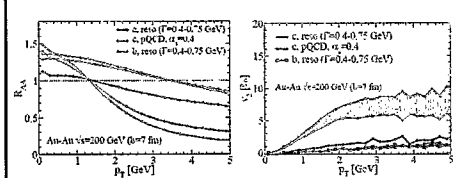
Z. Lin & M. Gyulassy, PRC 51 (1995) 2177



Motivation – Charm vs. Thermalization



Moore and Teney, PRC 71(2005) 064904

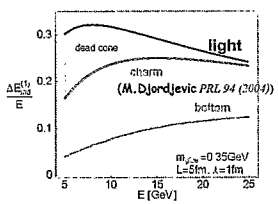


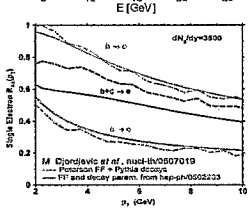
Hees and Rapp, PRC 71(2005) 034907

- Charm or "charm resonance" interact with the medium via scattering:
  - Its phase space shape may be changed at low p_T (<3-5 GeV/c)
  - Charm could pick up elliptic flow from the medium
- Measurements of charm p_T spectra and elliptic flow may give us hint that the partonic matter might be thermalized

Motivation – Charm Energy Loss

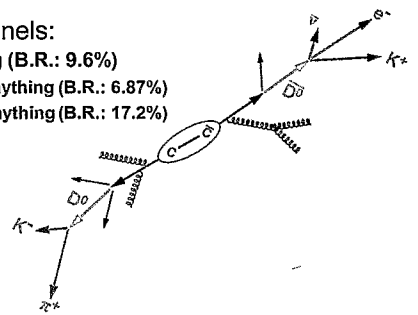
- In 2001, Dokshitzer and Kharzeev proposed "dead cone" effect ⇒ charm quark small energy loss, but in vacuum
- Recent: Heavy quark energy loss in medium, e.g.: Armesto et al, PRD 71, 054027, 2005; M. Djordjevic et al., PRL 94, 112301, 2005.
- A measurement of open charm energy loss can teach us the energy density of the partonic medium



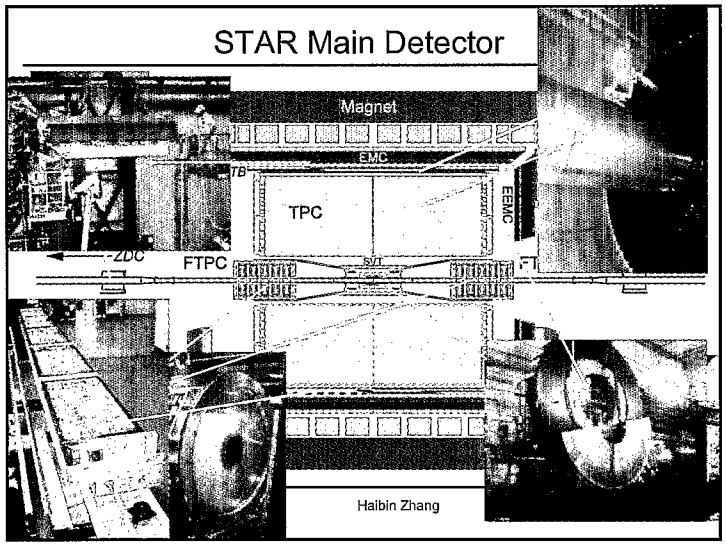


What STAR Measures

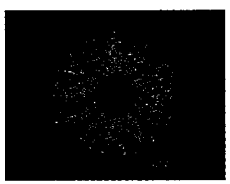
- Hadronic decay channels: $D^0 \to K\pi$, $D^* \to D^0\pi$, $D^{+/-} \to K\pi\pi$
- Semileptonic channels:
  - **$c \to e^+$ + anything (B.R.: 9.6%)**
    - **$D^0 \to e^+$ + anything (B.R.: 6.87%)**
    - **$D^\pm \to e^\pm$ + anything (B.R.: 17.2%)**



STAR Main Detector

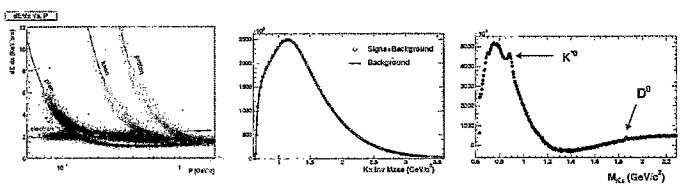


D^0 Measurement Technique

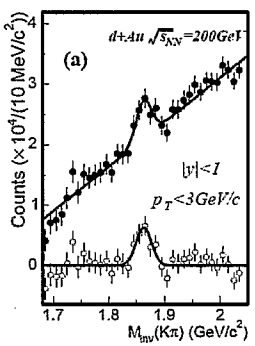


Event mixing technique

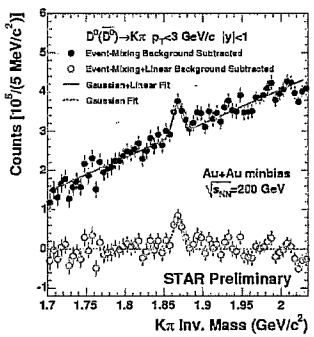
1. Select K and π tracks from PID by energy loss in TPC
2. Combine all pairs from same event ⇒ Signal+Background
3. Combine pairs from different events ⇒ Background
4. Signal = same event spectra – mixed event spectra
5. More details about this technique can be found at *PRC 71 (2005) 064902* and *PRL 94 (2005) 062301*



D^0 Signal

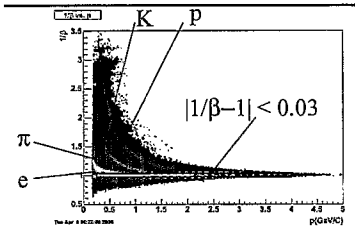


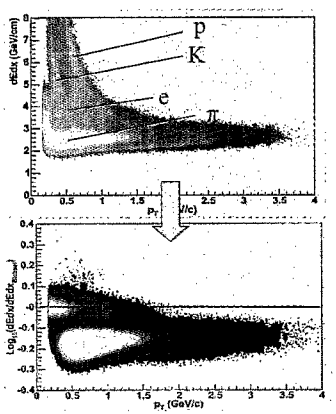
PRL 94 (2005) 062301



QM05 nucl-ex/0510063

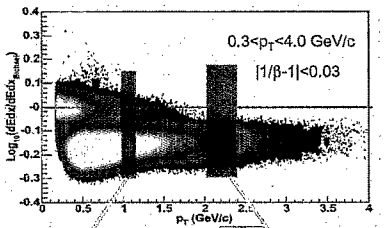
Electron ID - TOF

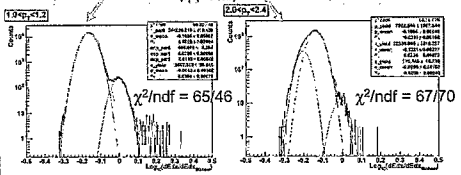




- TOF measures particle velocity
- TPC measures particle energy loss
- The cut |1/β-1|<0.03 excludes kaons and protons
- TPC dE/dx further separates the electron and pion bands

Electron ID - TOF



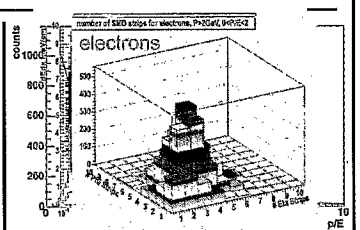


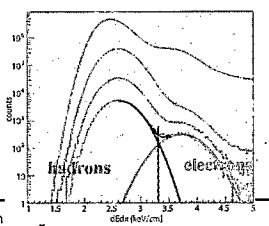
- Project the 2-D distributions into log10(dEdx/dEdxBichsel) for each pT bin
- Gaussian + Exponential fit at lower p_T and two Gaussian fit at higher p_T
- Inclusive electron yields can then be obtained for each p_T bin

Electron ID - EMC

1. TPC: dE/dx for p > 1.5 GeV/c
   - Only primary tracks
     (reduces effective radiation length)
   - Electrons can be discriminated well from hadrons up to 8 GeV/c
   - Allows to determine the remaining hadron contamination after EMC
2. EMC:
   a) Tower E ⇒ p/E
   b) Shower Max Detector (SMD)
      - Hadrons/Electron shower develop different shape
      - Use # hits cuts

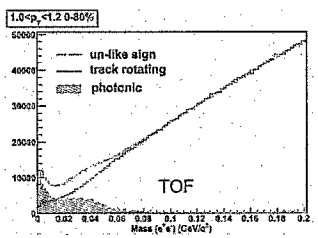
85-90% purity of electrons
(p_T dependent)
h discrimination power ~ 10^4-10^5



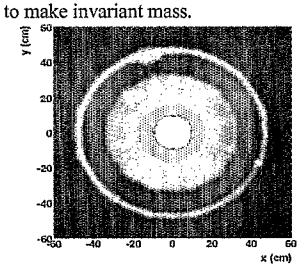


Photonic Background

γ conversion π 0 Dalitz decay η Dalitz decay Kaon decay vector meson decays	Dominant source at low p_T

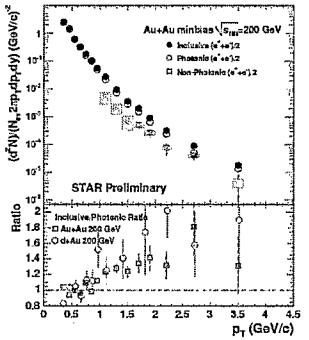


For each tagged $e^+(e^-)$, we select the partner $e^-(e^+)$ from TPC global tracks to make invariant mass.

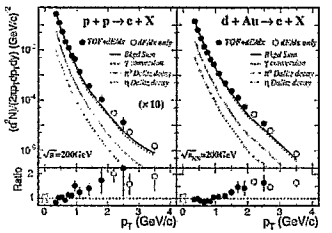


- Combinatorial background reconstructed by track rotating technique.
- Invariant mass < 0.15 for photonic background.

Inclusive Electron Spectra - TOF



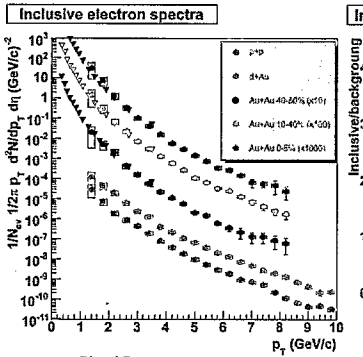
QM05 nucl-ex/0510063

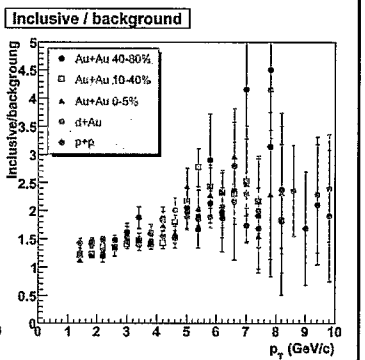


PRL 94 (2005) 062301

- Significant excess at pT>1GeV/c ⇒ contributions from heavy flavor semi-leptonic decay

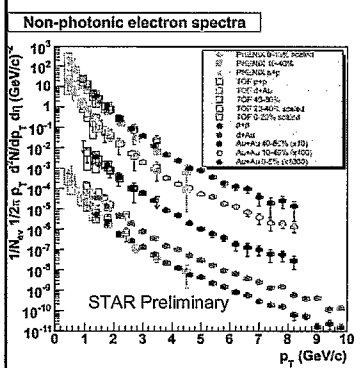
Inclusive Electron Spectra - EMC





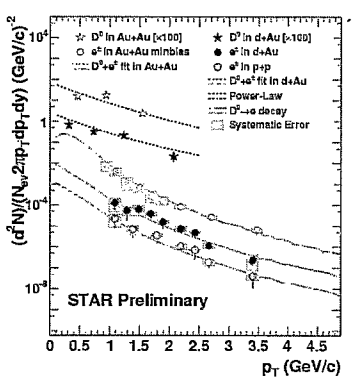
- Significant excess at pT>1GeV/c ⇒ contribution from heavy flavor semi-leptonic decay

Non-Photonic Electron Spectra



- TOF non-photonic electron spectra are measured in p+p, d+Au, Au+Au minbias, 0-20%, 20-40%, 40-80%
- EMC non-photonic electron spectra are measured in p+p, d+Au, Au+Au minbias, 0-5%, 10-40%, 40-80%
- Non-photonic electron spectra measured by TOF and EMC are consistent with each other by proper N_{bin} scaling

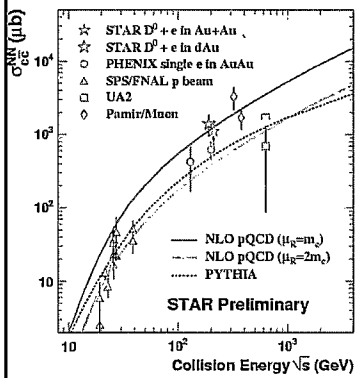
Combined Fit



D^0 and $e^{\pm}$ combined fit

- Power-law function with parameters dN/dy, $\langle p_T \rangle$ and n to describe the D^0 spectrum
- Generate $D^0 \rightarrow e$ decay kinematics according to the above parameters
- Vary (dN/dy, $\langle p_T \rangle$, n) to get the min. χ^2 by comparing power-law to D^0 data and the decayed e shape to $e^{\pm}$ data
- Advantage: D and e spectra constrain with each other

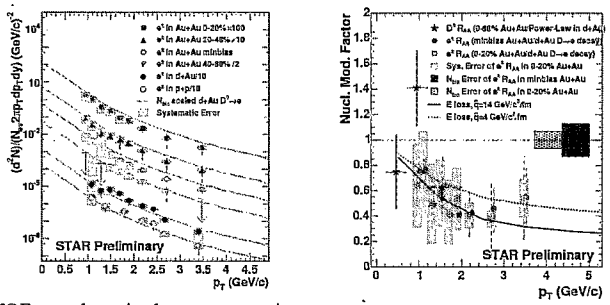
Charm Total Cross Section



Charm total cross section per NN interaction

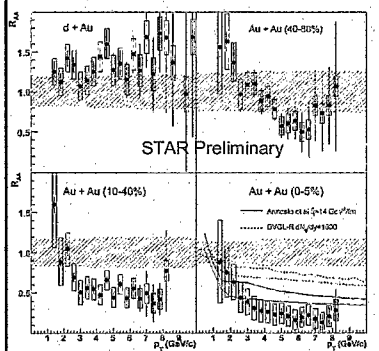
- 1.13 ± 0.09(stat.) ± 0.42(sys.) mb in 200GeV minbias Au+Au collsions
- 1.4 ± 0.2(stat.) ± 0.4(sys.) mb in 200GeV minbias d+Au collisions
- Charm total cross section follows roughly Nbin scaling from d+Au to Au+Au considering errors
- Indication of charm production in initial collisions

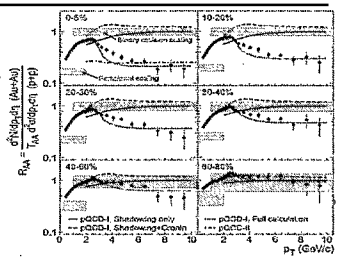
Nuclear Modification Factor - TOF



- TOF non-photonic electron spectra in central and minbias Au+Au are lower than the $D^0 \rightarrow e$ curve in d+Au scaled by N_{bin}
- TOF non-photonic electron nuclear modification factor are significantly smaller than unity at $p_T > \sim 1.5$ GeV/c

Nuclear Modification Factor - EMC





STAR: Phys. Rev. Lett. 91 (2003) 172302

- Charm high p_T suppression is as strong as light hadrons!!!
- Any beauty contributions?
- We need to measure direct D R_{AA} to clarify this

Summary

- D^0 is reconstructed via its K-π hadronic channel in d+Au and Au+Au at 200GeV
- STAR Time-of-Flight and EMC detectors provide good PID for electrons
- Non-photonic electron spectra are measured in p+p, d+Au and Au+Au at 200GeV
- Combined fit with $D^0 + e \Rightarrow$ charm total cross section per NN collision:
  - 1.4±0.2±0.4 mb in d+Au at 200GeV
  - 1.13±0.09±0.42 mb in Au+Au at 200GeV
  - Within experimental uncertainties, charm cross-section follows N_{bin} scaling from d+Au to Au+Au collisions at 200GeV!!!
- Strong suppression of non-photonic electron R_{AA} at high p_T observed in central Au+Au collisions ⇒ Challenge to existing energy loss models
- Charm transverse momentum distribution has been modified by the hot and dense medium in central Au+Au collisions!!!
- In order to better understand the heavy flavor production and its interaction with the hot and dense medium at RHIC, isolated charm from bottom, directly measured charm-hadron p_T distributions are necessary. High statistics of p+p and Au+Au data are important.

SPS Charm(onium) and Bottom(onium) measurements

E. Scomparin
INFN Torino (Italy)
Via P. Giuria 1, I-10125 Torino (Italy)

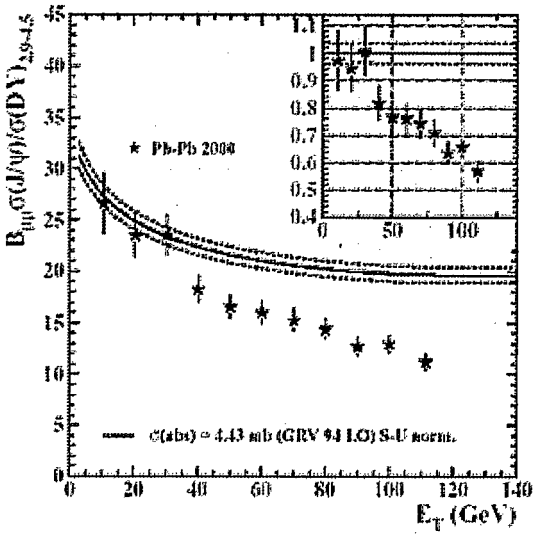
Abstract

Heavy quark and quarkonium production are an essential part of the heavy-ion program at SPS energy. In particular, quarkonium production has been studied by NA38, NA50 and, more recently, by the NA60 experiment.
The results show that in both In-In and Pb-Pb collisions an anomalous J/ψ suppression is present, i.e. suppression mechanisms different from nuclear absorption must be invoked to explain the observed J/ψ yield. The onset of the anomalous suppression occurs at around $N_{part}=100$. From the comparison of the centrality pattern of the J/ψ suppression between various systems, one can look for the physics variable, related to centrality, that drives the J/ψ suppression.
A first study of open charm production, triggered by the previous discovery (by Helios-3 and NA38/NA50) of a dimuon excess in the intermediate mass region ($m_{\phi}<m_{\mu\mu}<m_{J/\psi}$), has been recently performed by NA60. Preliminary results show that, in In-In collisions, open charm production scales, with respect to pp and pA, with the number of nucleon-nucleon collisions. This result implies that the intermediate mass excess is not due to an anomalous open charm enhancement, but rather to a "prompt" source. Further work, by theory and experiment, is needed in order to understand if thermal dimuon production can account for the observed excess.

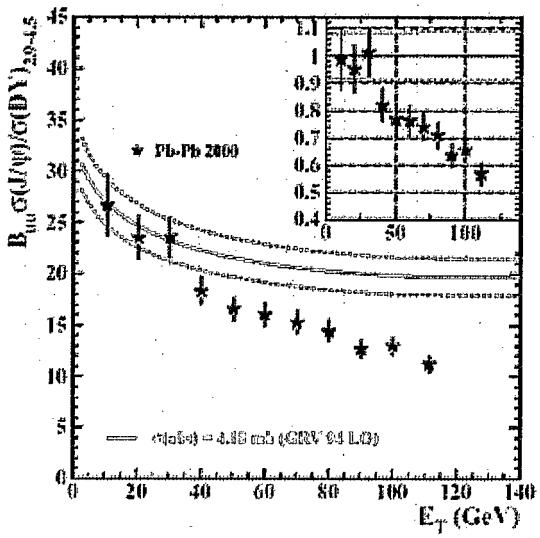
J/ψ suppression in PbPb: NA50 final results

$\sigma_{J/\psi} / \sigma_{DY}$ in Pb-Pb collisions at 158 GeV

- Final NA50 set of data

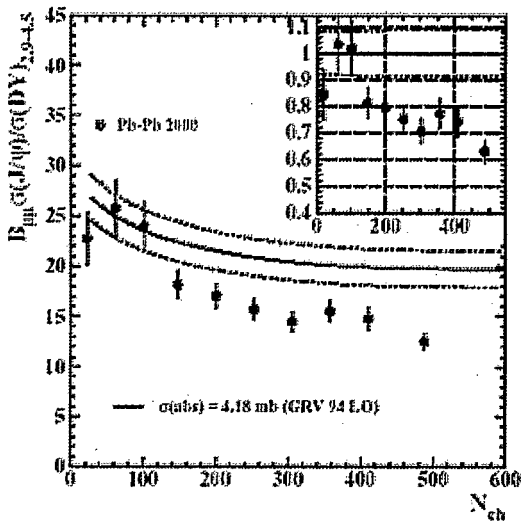


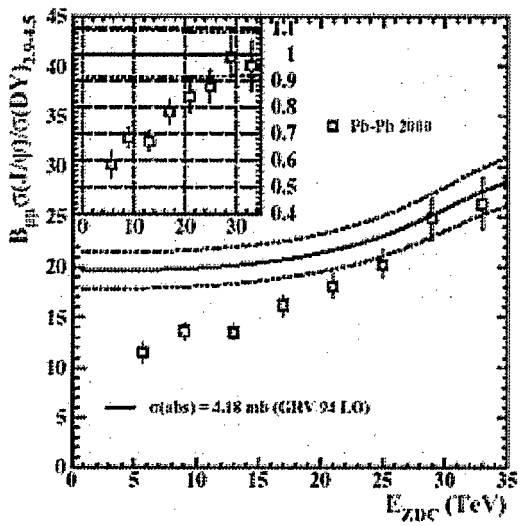
Old reference
(include S-U in the determination)



New reference
(only p-A collisions are used)

Study of various centrality estimators



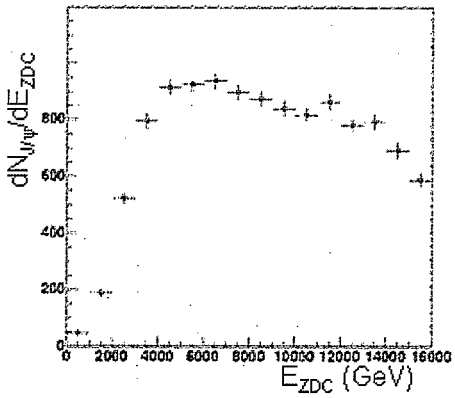


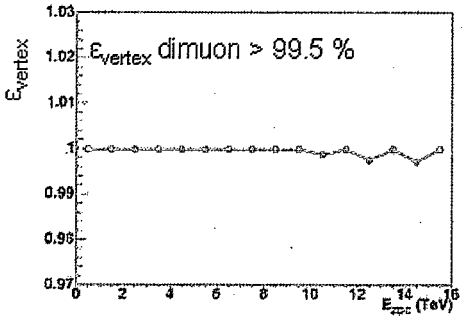
- Pattern consistent with E_T-based analysis
- Departure from normal nuclear absorption at mid-centrality
- Suppression increases with centrality

J/ψ suppression in InIn: NA60 analysis

Study of the J/ψ centrality distribution

- Compare the centrality distribution of the measured J/ψ sample with the distribution expected in case of pure nuclear absorption
- Use matched J/ψ sample
  - Inefficiencies introduced by the cuts, used in the event selection, affect in a negligible way the J/ψ sample (or are not centrality dependent)



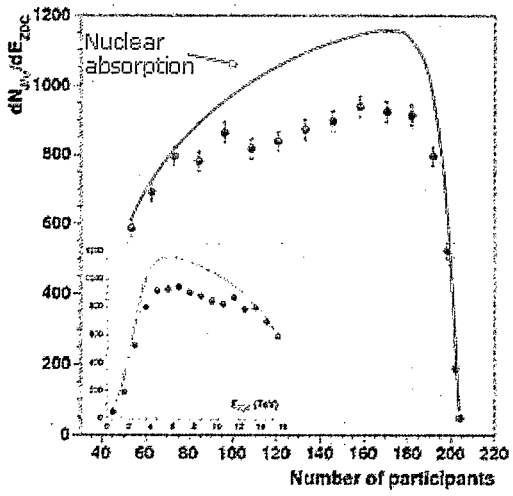


- Main advantage
  ⇒ Much smaller statistical errors
- Main drawback
  ⇒ No intrinsic normalization, if absolute cross sections are not known

Work in progress to obtain $d\sigma_{J/\psi}/dE_{ZDC}$

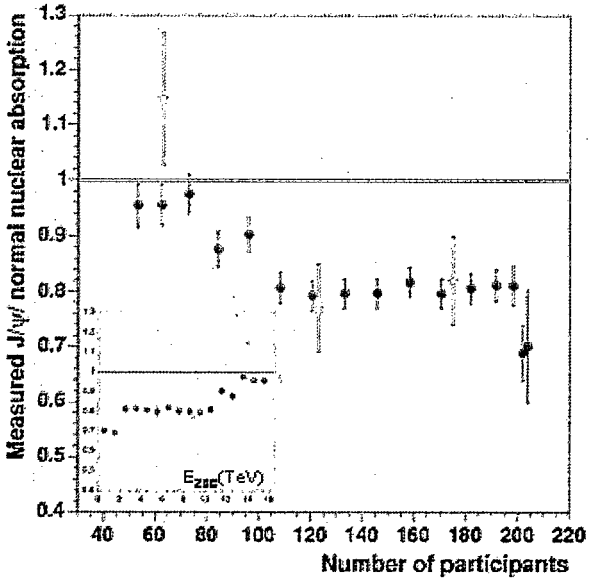
Comparison with expected yield

- Data are compared with a calculated J/ψ centrality distribution
- Use $\sigma_{J/\psi}^{abs}$ = 4.18 ± 0.35 mb



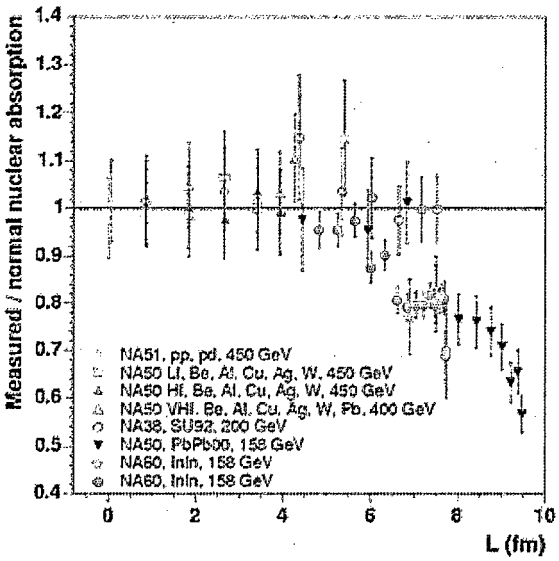
- Onset of anomalous suppression in the range 80 < N_{part} < 100
- Saturation at large N_{part}

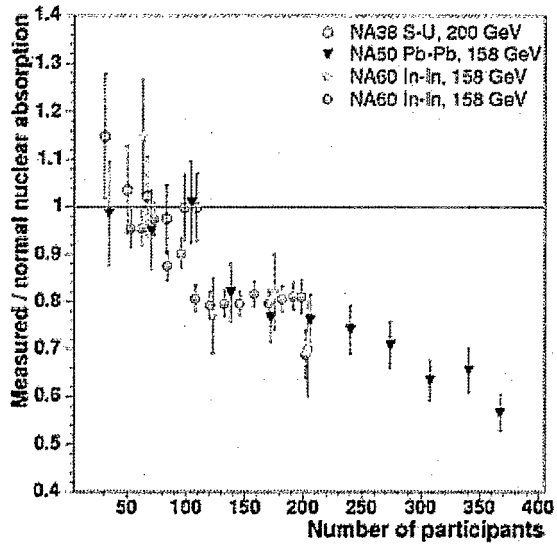
- Ratio (Measured / Expected) normalized to the standard analysis (~7% error)



J/ψ suppression in InIn: preliminary results

Comparison with previous results



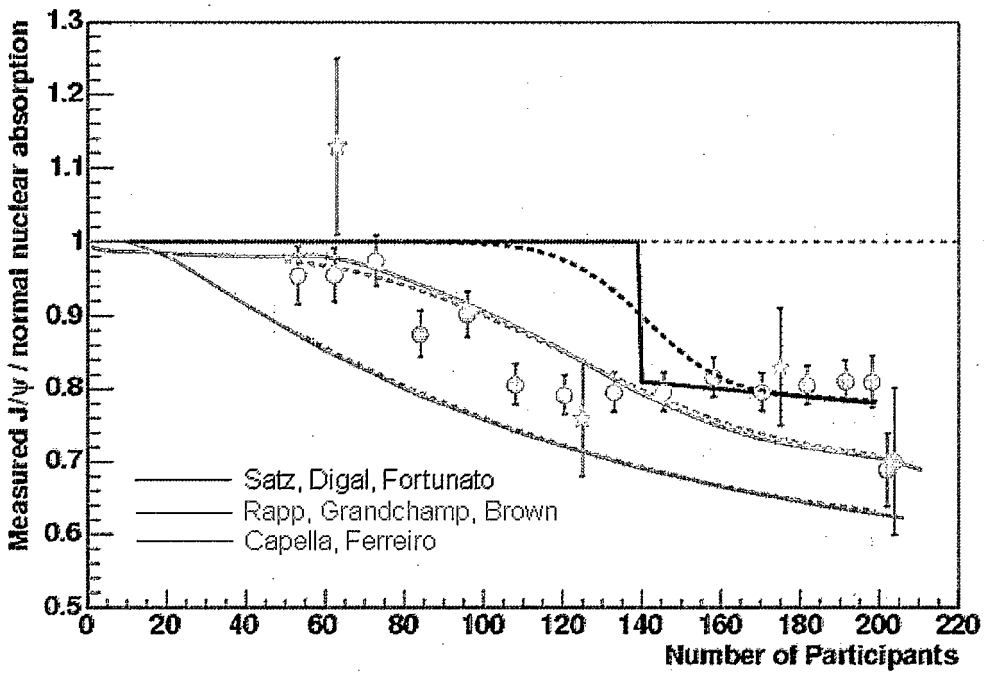


The S-U, In-In and Pb-Pb data points do not overlap in the L variable

The J/ψ suppression patterns are in fair agreement in the N_{part} variable

S-U most central point ?

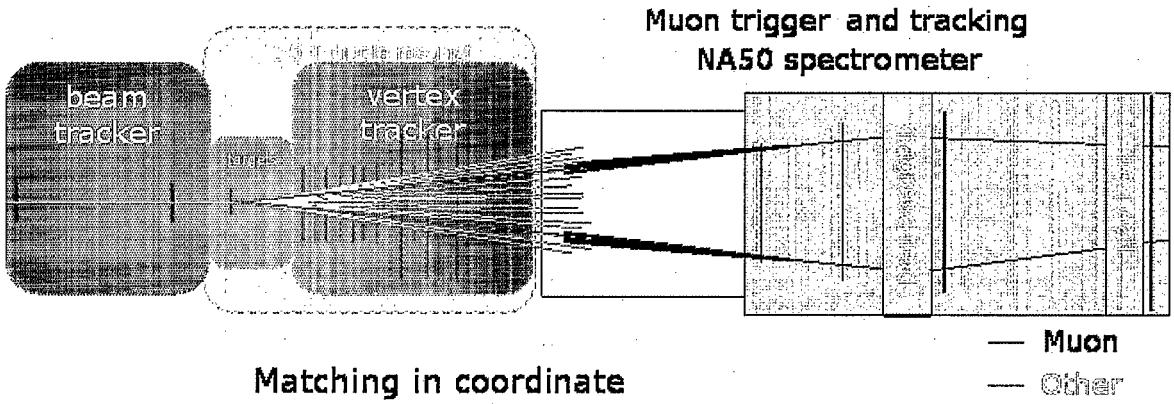
Comparison with theoretical models



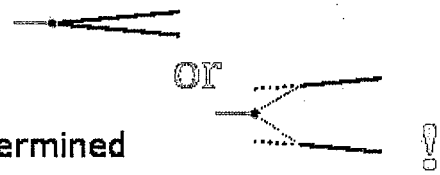
No quantitative agreement with any model

NA60: measurement of the muon impact parameter

NA60: detector concept

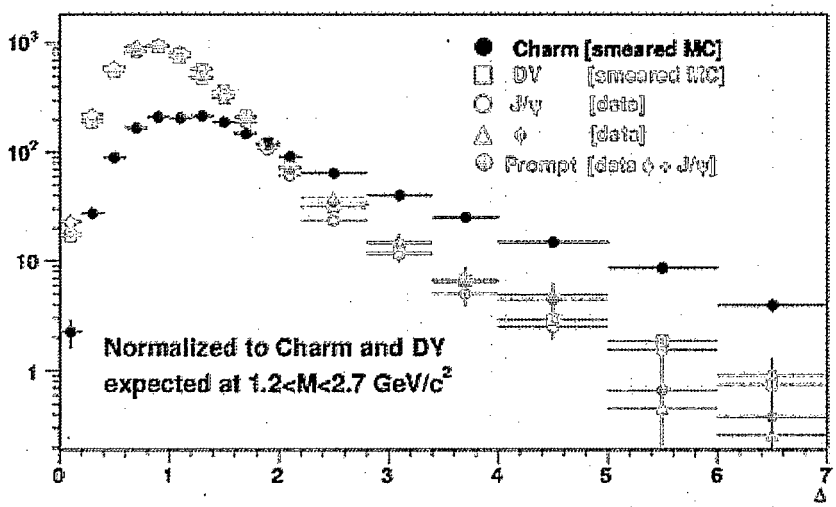


Matching in coordinate and momentum space



- Improved dimuon mass resolution
- Origin of muons can be accurately determined

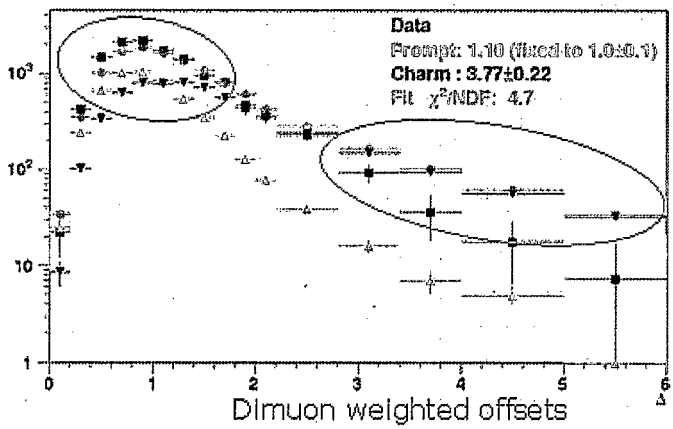
Weighted offset distribution of the expected sources



- Prompt contribution → average of the J/ψ and φ measured offsets
- Open charm contribution → MC distribution, after smearing

Check NA50 hypothesis using muon offsets

- Fix the prompt contribution to the expected DY
- Can the offset distribution be described with an enhanced charm yield?



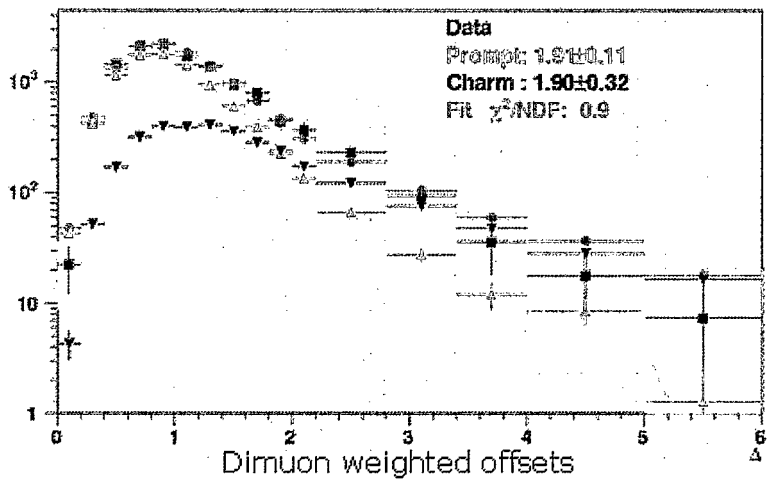
Kinematical domain
$1.2 < M < 2.7$ GeV/c^2
$0 < y_{CM} < 1$
$|\cos\theta| < 0.5$

Answer: No, the fit fails

Charm is too flat to describe the remaining spectrum...

Alternative options

- Try to describe the offset distribution leaving both contributions free



Answer: Two times more prompts than the expected Drell-Yan provides a good fit

(and the charm yield is as expected from the NA50 p-A dimuon data)

Lattice calculations on Heavy flavor
~ Open and Hidden charm states above Tc ~

Takashi Umeda (BNL)

Heavy Flavor Productions
& Hot/Dense Quark Matter

Brookhaven Natl. Lab. at 12 Dec. 2005

Subject of this talk

- In the QGP phase, heavy quarkonium states exist or not ?
- If it exists, what temperature does it dissolve at ?

where we assume the following system

- thermal equilibrium
- homogeneous in finite volume with periodic b.c.
- zero baryon chemical potential

Of course the situation is rather different from that of actual experiments

One of the most important parts of "J/ψ suppression" as a phenomenological model

Papers for charmonium SPFs at T>0

- Umeda, Matsufuru and Nomura (quenched QCD)

  T.Umeda et al, Eur.Phys.J.C37S1 (2004) 9.(hep-lat/0211003)

- Bielefeld group (quenched QCD)

  S.Datta et al., Phys.Rev.D69(2004)094507.

- Asakawa and Hatsuda (quenched QCD)

  M.Asakawa and T.Hatsuda, Phys. Rev. Lett. 92 (2004) 012001

- Trin-lat group (2-flavors QCD)

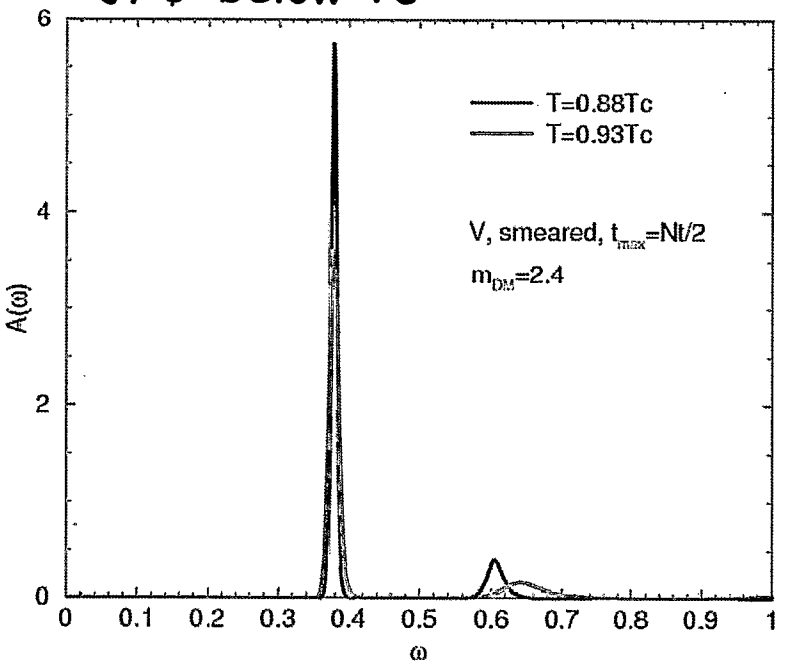
  R.Morrin et al., hep-lat/0509115 (Lattice'05)

- others

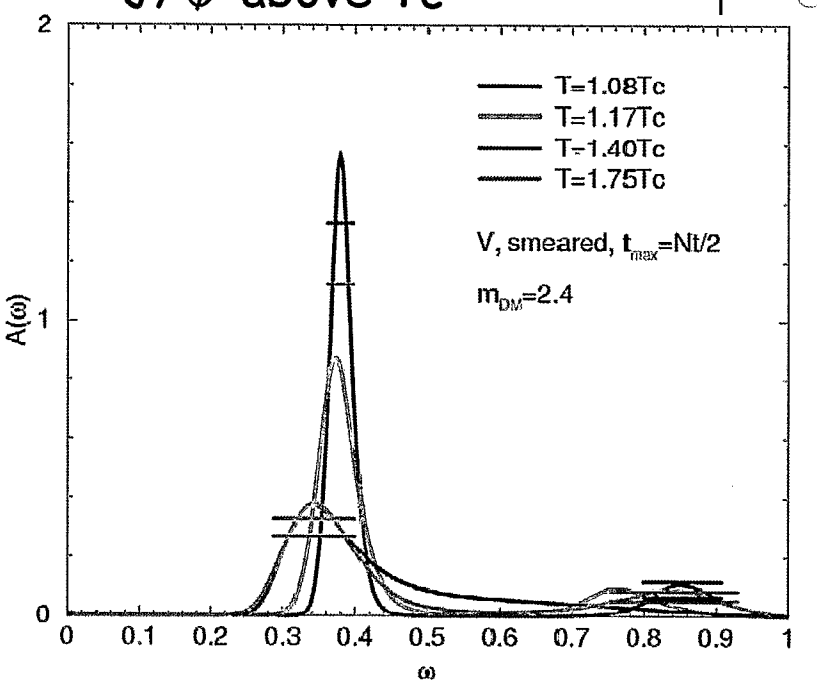
All study supports an existence of hadronic mode just above T_c

Results by T.Umeda et al.

J/ψ below Tc



J/ψ above Tc



T<Tc : no mass shift, almost same SPF as T=0
T>Tc : peak structure survives up to 1.2Tc (?)

η_c : up to 1.4Tc, J/ψ : up to 1.2Tc (at least)

Results: model dependence

- free energy : S.Digal et al. Phys.Rev.D64(2001)094015
- linear comb. of both: W.M.Alberico et al. hep-ph/0507084
- internal energy: C.Y.Wong hep-ph/0509088

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
$E_s^i[GeV]$	0.64	0.20	0.005	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1-0.2	2.31	1.13	1.1	0.83	0.75
T_d/T_c	~ 1.42	~ 1.05	unbound	~ 3.3	~ 1.22	~ 1.18	-	-
T_d/T_c	1.78-1.92	1.14-1.15	1.11-1.12	$\gtrsim 4.4$	1.60-1.65	1.4-1.5	~ 1.2	~ 1.2

Table 1: Estimated dissociation temperatures T_d in units of T_c obtained from potential models using free energies [8] (green), a linear combination of F_1 and U_1 [10] (blue) and internal energies [9] (red) as effective T-dependent potentials.

J/ψ : T_d is about $1.1T_c \sim 2\ T_c$

χ_c : T_d is less than $1.2T_c$

Summary of this talk

- From recent MEM results,
  - J/ψ, η_c states survive even in QGP phase
  - dissociation temp. may be 1.4~2 T_c (large uncertainty)
  - χ_c state may disappear just above T_c
- Recent potential model studies
  - give similar result with MEM (even large uncertainty !!)

Next step

- Improvement of MEM analysis
  & dynamical quark effects
- Suitable effective potential for this problem

Heavy Quarkonium Formation via Recombination in QGP

R. L. Thews

Department of Physics, University of Arizona

Tucson, AZ 85721, USA

(December 12, 2005)

Theoretical predictions and models which incorporate in-medium recombination of heavy quarks in the formation of quarkonium states are discussed in the light of the most recent RHIC results. At present the models fall into two general categories, both of which assume that the number of quark-antiquark pairs produced via the initial hard interactions of nuclei remains essentially unchanged throughout the subsequent evolution of the system. The first utilizes a statistical description of hadron abundances with temperature and baryon chemical potential fixed at the hadronization transition. These abundances are then adjusted by a heavy flavor fugacity factor to account for oversaturation due to the initial number of pairs. The second type also starts with this fixed number of pairs, and follows a time evolution of the system during which formation and dissociation of charmonium proceed via various mechanisms determined by the state of the system. The initial PHENIX measurement of $R_A A$ for J/ψ as a function of centrality favors the inclusion of in-medium formation. The measurement of $\langle {p_T}^2 \rangle$ of the J/ψ as a function of centrality, also appears to require substantial in-medium formation. The $\langle {p_T}^2 \rangle$ values are consistent with charm quark momentum distributions unchanged from their initial production predicted by pQCD calculations. At present however, the experimental uncertainties are too large to reliably exclude the possibility of some degree of charm quark thermalization.

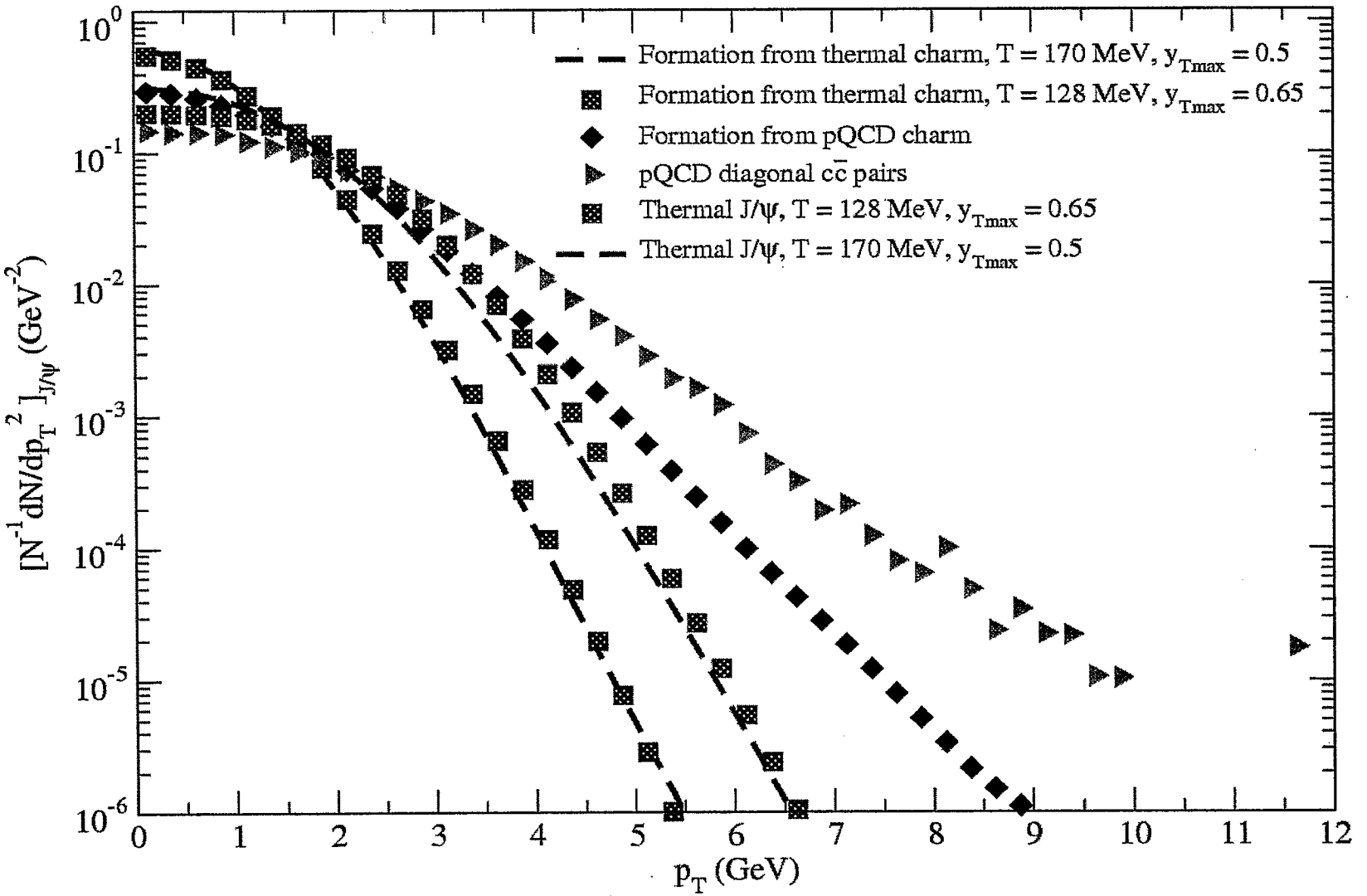
DO THE Y AND P_T SPECTRA PROVIDE A QUARK RECOMBINATION SIGNATURE?

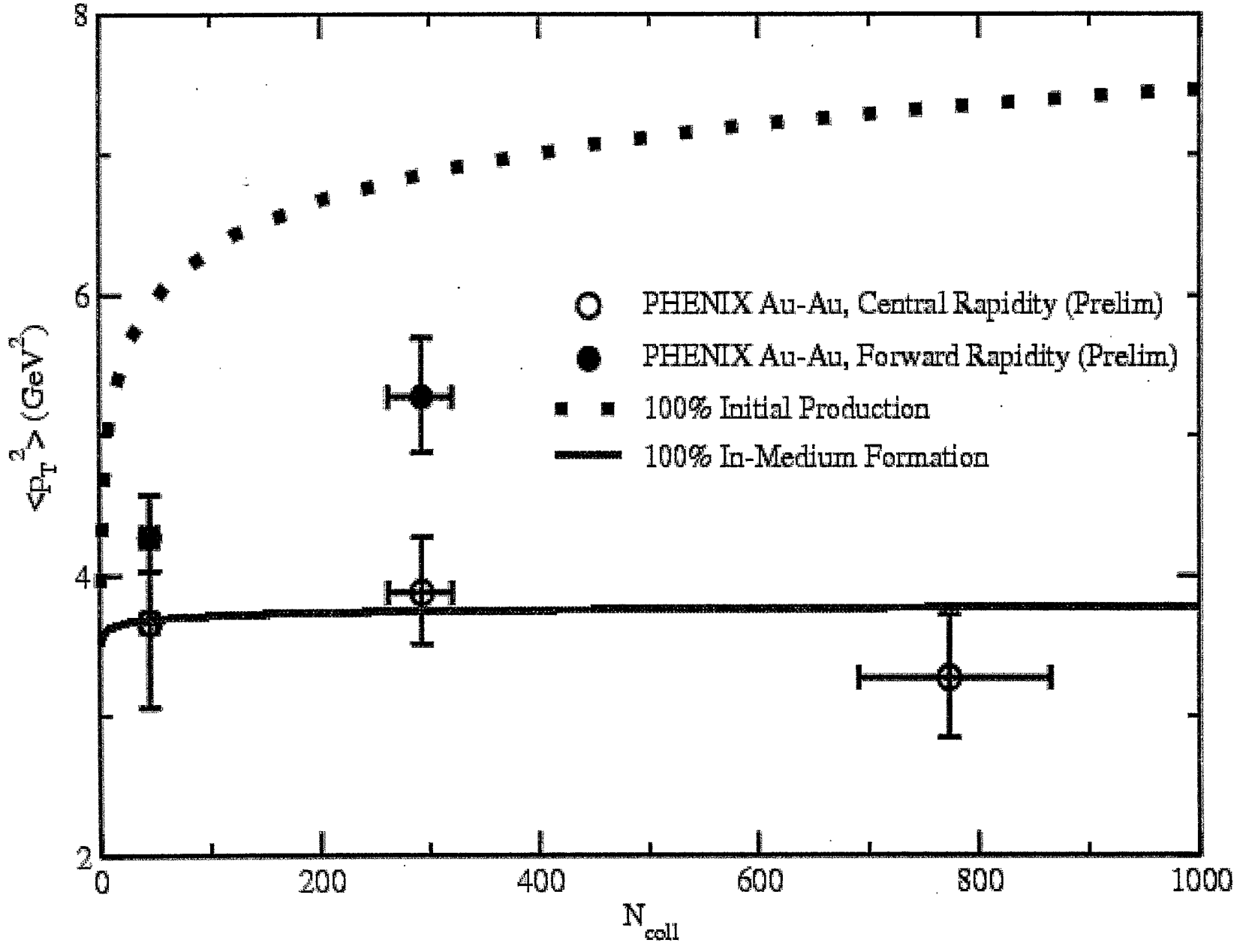
R. L. Thews and M. L. Mangano: nucl-th/0505055, PRC (in press)

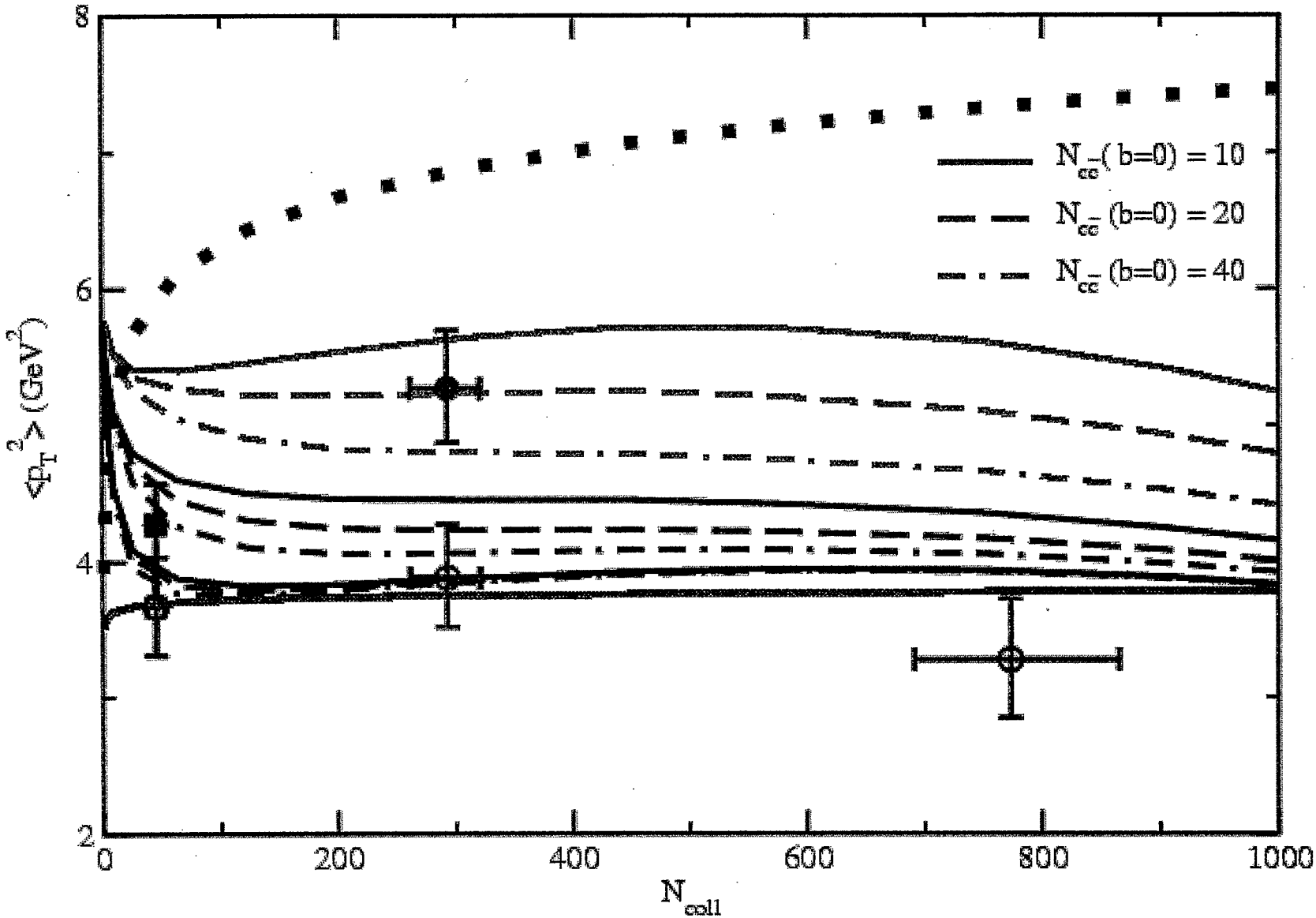
1. Generate sample of ccbar pairs from NLO pQCD (smear LO q_t)
2. Supplement with k_t to simulate initial state and confinement effects
3. Integrate formation rate using these events to define particle distributions (no cquark-medium interaction)
4. Repeat with cquark thermal+flow distribution (maximal cquark-medium interaction: thermalization?)

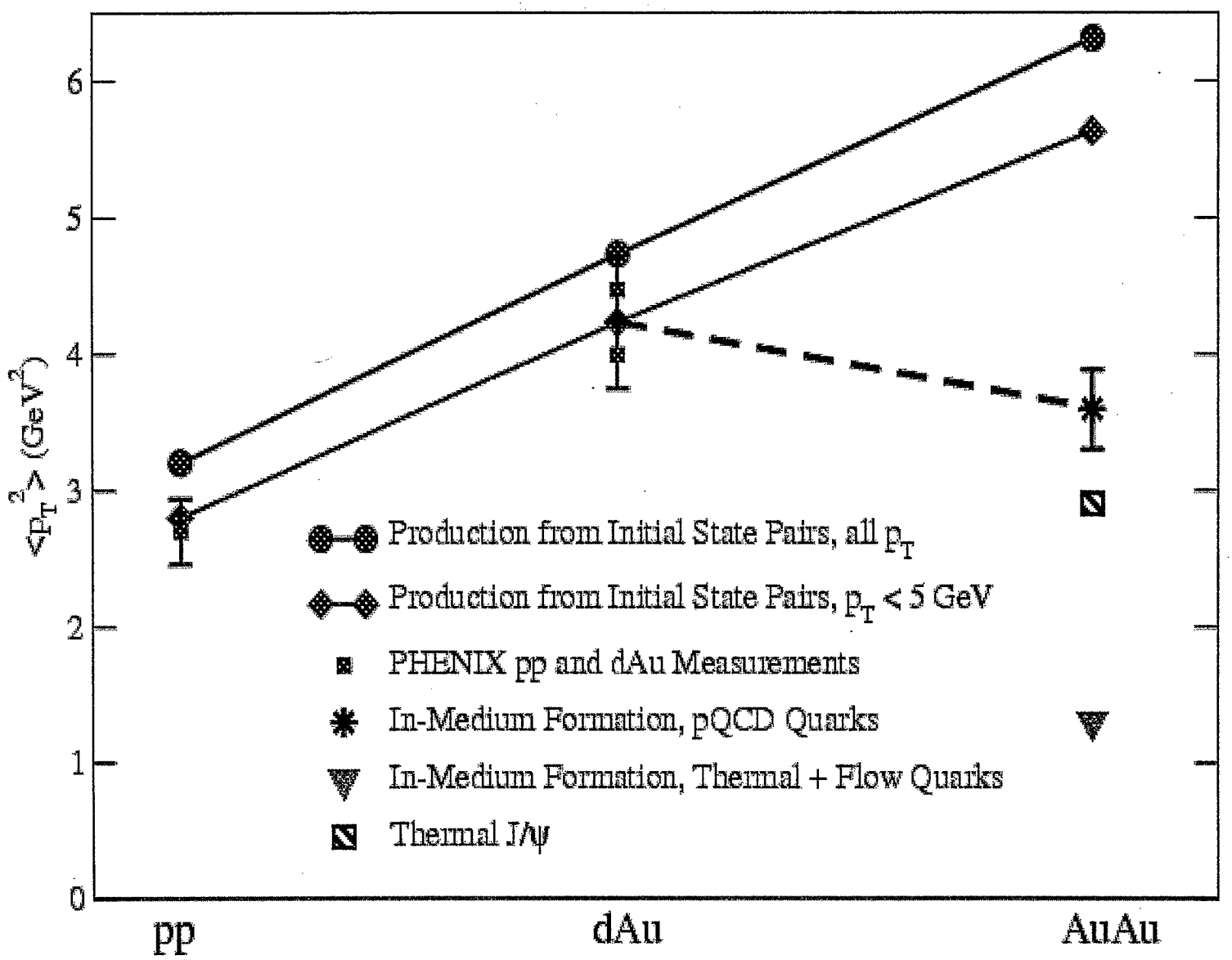
J/ψ Formation p_T Distributions

Comparison with direct Thermal Distribution




PHENIX Au-Au, Central Rapidity (Prelim)
PHENIX Au-Au, Forward Rapidity (Prelim)
100% Initial Production
100% In-Medium Formation
$<p_T^2>$ (GeV^2)
N_{coll}
8
6
4
2
0
200
400
600
800
1000


$N_{c\bar{c}}(b=0) = 10$
$N_{c\bar{c}}(b=0) = 20$
$N_{c\bar{c}}(b=0) = 40$
$\langle p_T^2 \rangle$ (GeV^2)
N_{coll}
0
200
400
600
800
1000
2
4
6
8


$<p_T^2>$ (GeV^2)
0
1
2
3
4
5
6
pp
dAu
AuAu
Production from Initial State Pairs, all p_T
Production from Initial State Pairs, $p_T < 5$ GeV
PHENIX pp and dAu Measurements
In-Medium Formation, pQCD Quarks
In-Medium Formation, Thermal + Flow Quarks
Thermal J/ψ

Collective Flow, R_{AA} and Heavy Flavor Rescattering

Hendrik van Hees[1], Vincenzo Greco[2] and Ralf Rapp[1]
[1]Cyclotron Institute and Physics Department, Texas A&M University College-Station TX, 77843-3366, USA
[2]Laboratori Nazionali del Sud INFN, via S. Sofia 62, I-95123 Catania, Italy

December 12, 2005

Abstract

Open Charm and Bottom

We evaluate thermalization and collective flow of charm (c) and bottom (b) quarks in relativistic heavy-ion collisions. Motivated by recent lattice-QCD results, we assume the existence of D- and B-meson like resonance states in the strongly interacting quark-gluon plasma (sQGP) for temperatures $T \lesssim 2T_c$ to study heavy-quark thermalization via resonant elastic heavy-light quark scattering. We calculate drag and diffusion coefficients within a Fokker-Planck approach which we use in a Langevin simulation to compute transverse-momentum (p_T) spectra and elliptic flow (v_2) of c- and b-quarks in the quark-gluon plasma (QGP), while the flow profile of the expanding QGP is parameterized by an elliptic fireball model adapted to describe findings from hydrodynamic models. We find large suppression factors and v_2 for c-quarks without further upscaling of cross sections as is necessary in perturbative-QCD calculations for both elastic scattering and radiative energy loss. We use a combined heavy-light quark coalescence and fragmentation model for the hadronization of the heavy quarks to D- and B-mesons. We find that the R_{AA} and v_2 of the associated decay electrons is in approximate agreement with recent experimental results from the Relativistic Heavy Ion Collider (RHIC) for non-photonic single electrons ($e^{\pm}$). Thus, the existence of resonances in the sQGP is a viable non-perturbative mechanism for early charm-quark thermalization as suggested by the $e^{\pm}$ data from RHIC.

Bottomonia at RHIC

We investigate the properties of bottomonium states, Υ, Υ', and χ_b (Y) in the QGP by evaluating dissociation rates, taking into account in-medium modifications of b-quarks and color screening. The latter renders bottomonia less bound in the QGP, and the usually applied dipole approximation for the gluo-dissociation process ($Y + g \to b + \bar{b}$) becomes inefficient. Therefore, we introduce quasi-free inelastic scattering, i.e., $g, q + Y \to g, q + b + \bar{b}$, as the most relevant breakup mechanism for bottomonia in the QGP. We apply corresponding dissociation rates in a rate equation to calculate the time evolution and centrality dependence of bottomonium yields under RHIC conditions. While in a similar approach for charmonia it was shown that a large fraction of the final J/ψ yield at RHIC is due to secondary regeneration in the quark-gluon plasma, for the Υ we find a large suppression. This finding depends sensitively on the color-screening effects for the Υ in the QGP. If this scenario is valid, it may lead to a larger (net) suppression for bottomonia than for charmonia which would be an intriguing new signature for the formation of a strongly interacting QGP in heavy-ion collisions at collider energies.

I. Open Charm and Bottom

Motivation

Measured p_T spectra and v_2 of non-photonic single electrons

coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium

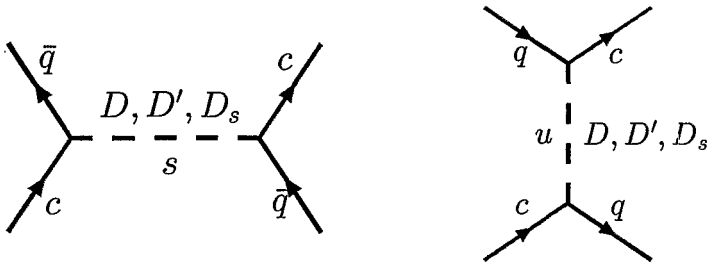
What is the underlying microscopic mechanism for thermalization?

- pQCD elastic HQ scattering: need unrealistically large α_s [Moore, Teaney '04]
- Gluon-radiative energy loss: need to enhance transport coefficient $\hat{q}$ by large factor [Armesto et al '05]

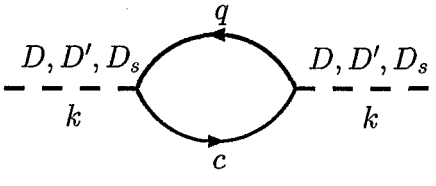
Assumption: survival of D- and B-meson resonances in the sQGP facilitates elastic heavy-quark rescattering

Elastic Resonance Scattering

elastic heavy-light-(anti-)quark scattering: Dress propagators with



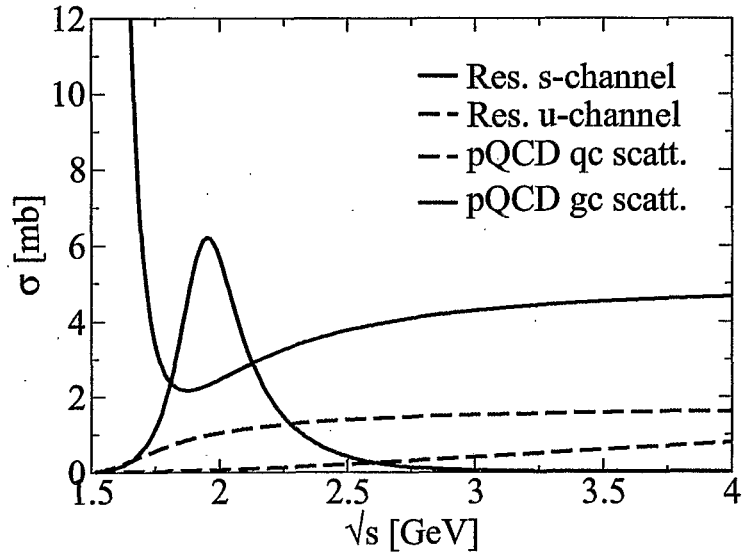
D- and B-meson like resonances in sQGP



parameters

$m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
$m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV

Cross sections



Use LO pQCD with Debye-screened t-channel gluons ($\mu_D = gT$)

total pQCD and resonance cross sections: comparable in size

BUT pQCD forward peaked $\leftrightarrow$ resonance isotropic

resonance scattering more effective for friction and diffusion

Heavy-quark rescattering in QGP

Calculate drag and diffusion coefficients in Fokker-Planck approach from elastic resonance scattering cross sections

$A(t,p)$ friction (drag) coefficient $= 1/\tau_{\text{eq}}$

B_{ij}: time scale for momentum fluctuations

to ensure correct equilibrium limit: $B_1(t,p) = T(t)E_p A(t,p)$ (Einstein dissipation-fluctuation relation)

Resonance scattering $\Rightarrow$ enhancing FP coefficients by factor ~ 4 compared to pQCD

describe bulk QGP medium by elliptic fire-ball parameterization fitted to hydrodynamical flow pattern [Kolb '00]

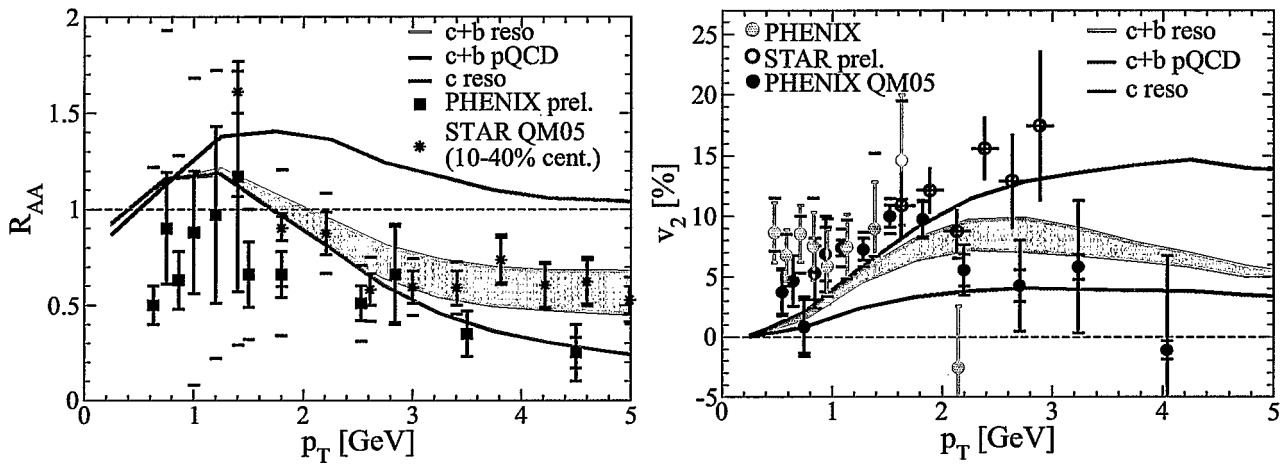
Isentropic expansion: $S =$ const (fixed from N_{ch}) $\Rightarrow T(t)$

simulate FP equation as relativistic Langevin process

initial conditions from exp. p_T-spectra for D-mesons and non-phot. electrons $\Rightarrow$ initial b, c spectra

Observables: p_T-spectra (R_{AA}), v_2

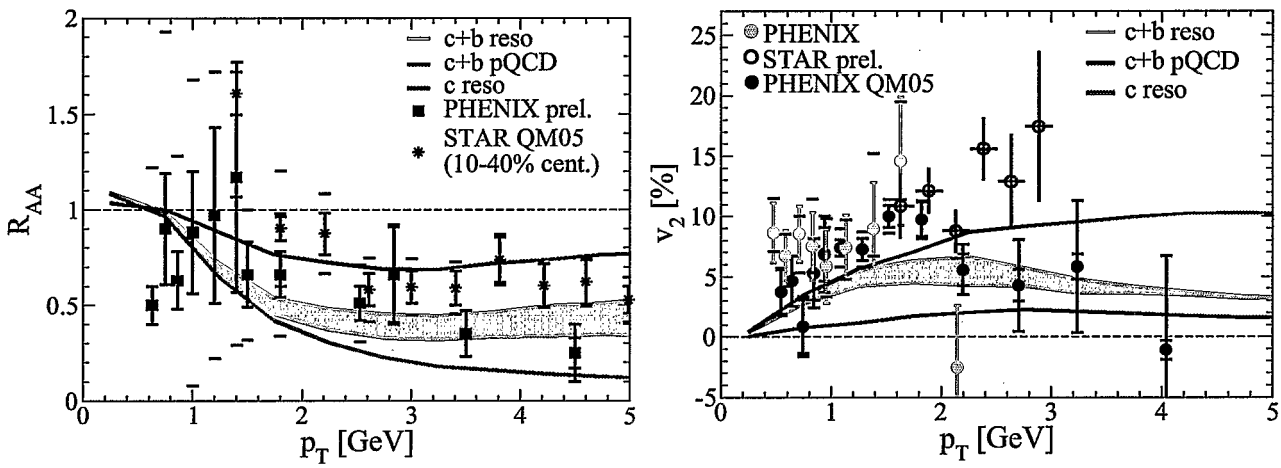
Hadronization: Coalescence with light quarks
(fixed before [Greco et al 03]) + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)
input for c- and b-quarks from Langevin simulation
single electrons from decay of D- and B-mesons



Rough agreement with data from elastic resonance scattering without further upscaling of cross sections!

Observables: p_T-spectra (R_{AA}), v_2

Hadronization: Fragmentation only
single electrons from decay of D- and B-mesons



need to readdress question of coalescence to fragmentation ratio!

Conclusions and Outlook I

Assumption: survival of resonances in the (s)QGP
nonperturbative re-interactions of heavy quarks in QGP
Observables via Langevin approach and coalescence+fragmentation

- Elastic resonance scattering $\Rightarrow R_{AA}^{(c)} \simeq 0.2$, $v_2^{(c)} \simeq 0.1$
  without upscaling of cross sections
  small effects on bottom quarks
  Heavy-light quark coalescence enhances $v_2^{(e)}$ and R_{AA} for $p_T \simeq 2$ GeV
  bottom dominates for $p_T > 3.5$ GeV $\Rightarrow$ reduced suppression, $v_2^{(e)}$

For details, see: HvH, R. Rapp, Phys. Rev. C 71, 034907 (2005) [nucl-th/0412015],
HvH, V. Greco, R. Rapp [nucl-th/0508055,hep-ph/0510050]

Further investigations

- improved (softer) fragmentation
- better control of coalescence/fragmentation ratio
- implementation of gluon-radiation processes
- quantitative consequences for quarkonia

Bottomonia at RHIC

Motivation

Matsui & Satz (1986):
Quarkonia suppression due to color screening as signature of QGP in heavy-ion collisions
sQGP: from lQCD $Q\bar{Q}$ resonances survive at $T > T_c$

- J/ψ and η_c "melt" at $T_{\text{diss}}^{(J/\psi)} \simeq 2T_c$
- Υ: $T_{\text{diss}}^{\Upsilon} \simeq 4T_c$

Resonances facilitate secondary regeneration of quarkonia in QGP

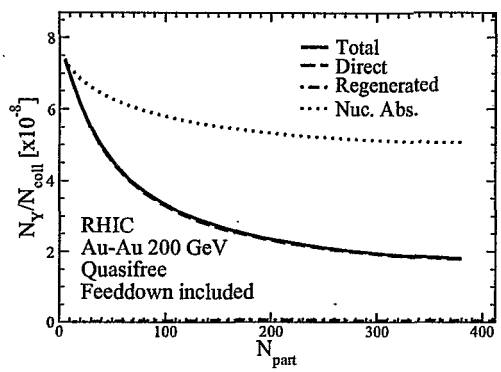
$c\bar{c}$ recombination substantial part of final J/ψ yield at RHIC
[Braun-Munzinger et al 01, Thews et al 01, Grandchamp, Rapp 01]

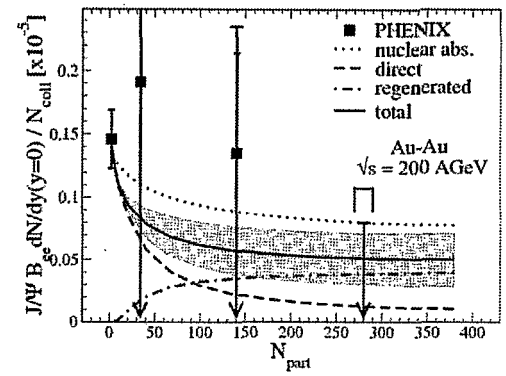
J/ψ suppression dominant at SPS

Bottomonium at RHIC?
similar to Charmonium at SPS?

Υ vs. J/ψ at RHIC

gluo-dissociation becomes inefficient for loosely bound states
$\Rightarrow$ destruction by quasifree scattering of bound c(or $\bar{c}$) with q and g





[Grandchamp et al 03]

Suppression prevalent effect

color screening in QGP [Karsch, Mehr, Satz 88]

suppression of higher bottomonia and feeddown to Υ

with vacuum Υ masses: thermal suppression for Υ negligible

magnitude of suppression sensitive to color screening

J/ψ: yield dominated by regeneration

Conclusions and Outlook II

rate-equation approach to evaluate Υ abundances

Dissociation rates from quasi-free destruction process

Suppression predominant effect at RHIC (and LHC)

At LHC: substantial fraction of total Υ yield due to regeneration

Color screening main microscopic mechanism for suppression

Υ may be more suppressed than J/ψ

intriguing new signature for QGP formation in ultra-relativistic heavy-ion collisions!

For details see: L. Grandchamp, , S. Lumpkins, D. Sun, HvH., R. Rapp [hep-ph/0507314]

Future work

more microscopic approach for dissociation-regeneration processes

p_T spectra (v_2) for bottomonia

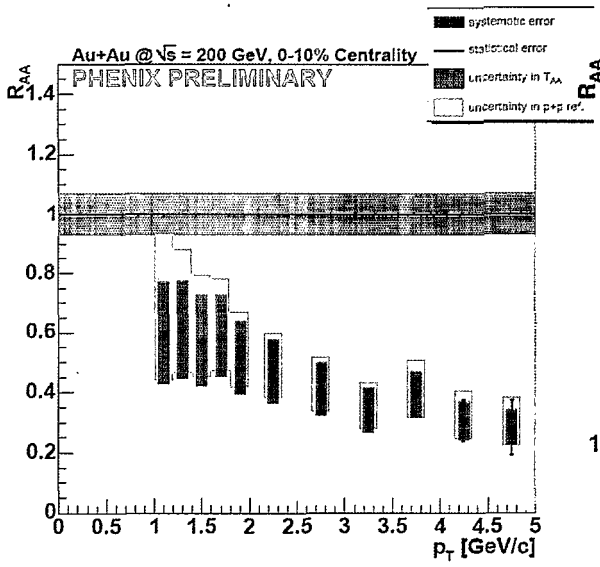
Heavy Quark Energy Loss Nucleus-Nucleus Collisions

Magdalena Djordjevic

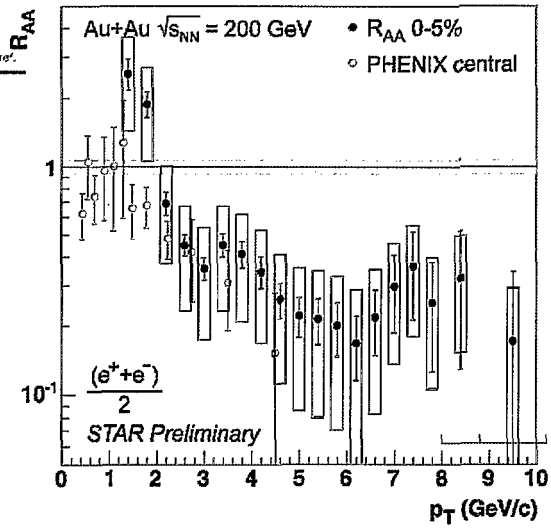
The Ohio State University

Quark Gluon Plasma is the new form of matter expected to be created in Ultrarelativistic Heavy Ion Collisions. Heavy quark production and attenuation will provide unique tomographic probes of that matter. To compute nonphotonic single electron spectra we apply the radiative energy loss. We show that both charm and bottom contributions have to be taken into account. Surprisingly, recent data on nonphotonic electron quenching in central Au+Au collisions at 200 AGeV at RHIC show significant discrepancies with theoretical predictions (that are based on radiative energy loss mechanisms) as long as realistic values for multiplicity are used. We discuss whether the inclusion of the elastic energy loss can lead to the agreement with the experimental results.

Single electron suppression measurements at RHIC



V. Greene, S. Butsyk, QM2005 talks



J. Dunlop, J. Bielcik; QM2005 talks

Significant reduction at high pT suggest sizable energy loss!

Can this be explained by the energy loss in QGP?

Outline

1) Radiative energy loss mechanisms.

2) **Heavy meson (D and B) and single electron suppression.**

3) **B mesons can not be neglected in the computation of single electron spectra.**

4) Radiative energy loss alone can not explain the experimental data.

5) **Inclusion of elastic energy loss as a solution?**

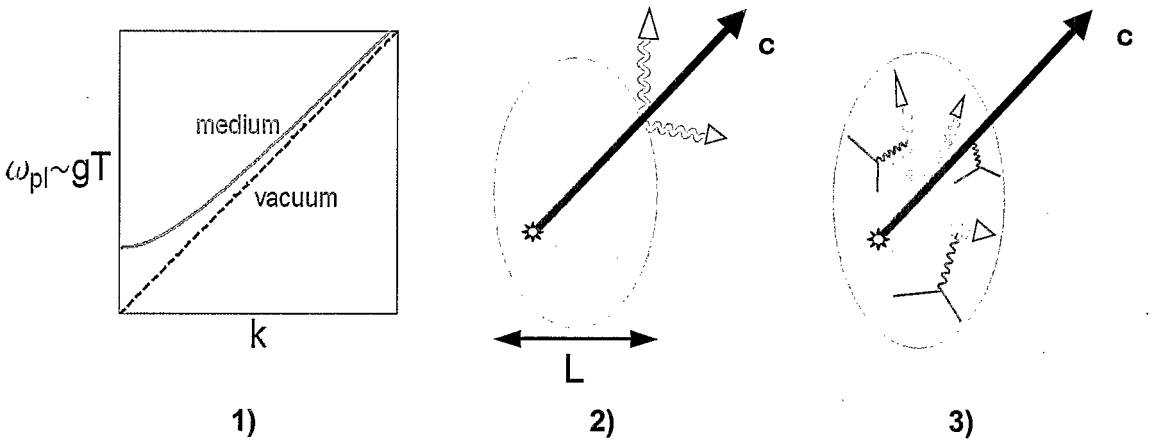
Radiative heavy quark energy loss

Three important medium effects **control the radiative energy loss:**

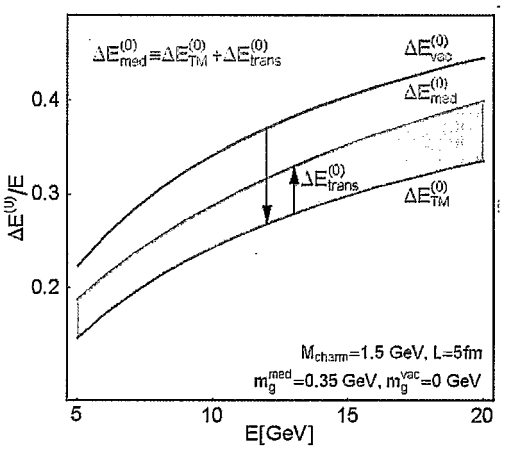
1) Ter-Mikayelian effect (M. D. and M. Gyulassy, Phys. Rev. C 68, 034914 (2003))

2) Transition radiation (M. D., to be published).

3) Energy loss due to the interaction with the medium
(M. D. and M. Gyulassy, Phys. Lett. B 560, 37 (2003); Nucl. Phys. A 733, 265 (2004))



Transition & Ter-Mikayelian for charm



Transition radiation lowers Ter-Mikayelian effect from 30% to 15%.

Two effects approximately cancel each other for heavy quarks.

What about light quarks?

Problem:

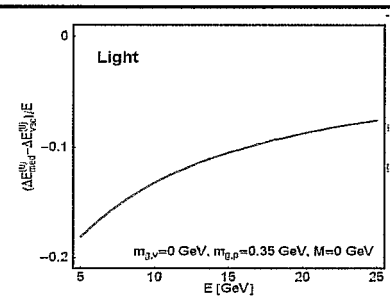
$$\frac{dI^{(0)}_{vac}}{dx\, d^2\mathrm{k}} = \frac{C_R \alpha_S}{\pi^2}\frac{1}{\mathrm{k}^2} \to \infty$$

$$\frac{dI^{(0)}_{TM}}{dx\, d^2\mathrm{k}} = \frac{C_R \alpha_S}{\pi^2}\frac{\mathrm{k}^2}{(\mathrm{k}^2+m^2_{g,p})^2} \to \text{finite}$$

Infinite discontinuity

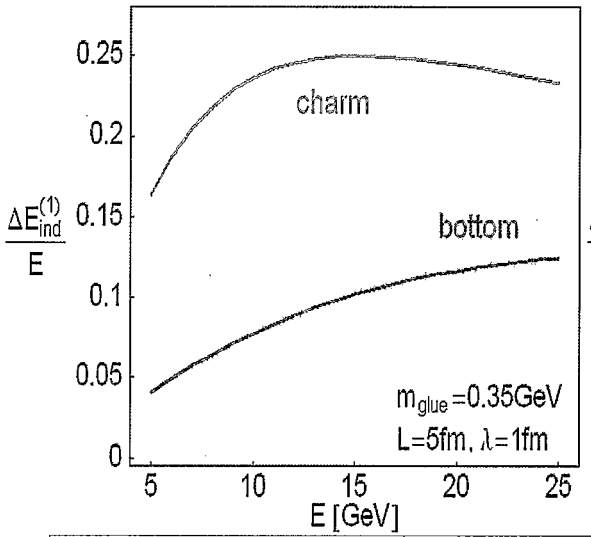
Transition radiation as a solution:

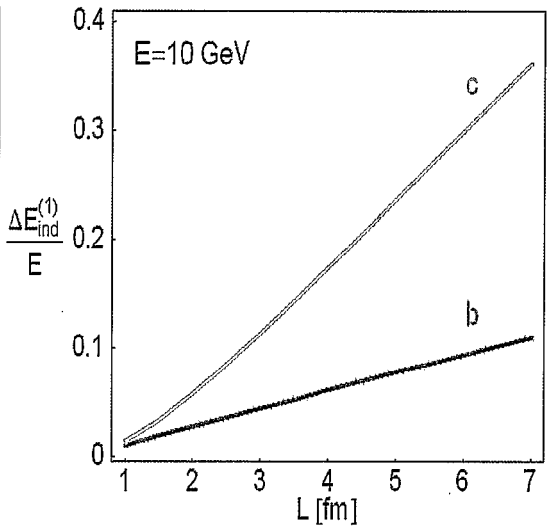
$$\frac{d(I^{(0)}_{med} - I^{(0)}_{vac})}{dx\, d^2\mathrm{k}} = -2\frac{C_R \alpha_S}{\pi^2}\frac{m^2_{g,p}}{(\mathrm{k}^2+m^2_{g,p})^2}\left(1-\cos\left(\frac{(\mathrm{k}^2+m^2_{g,p})L}{2Ex}\right)\right)$$



Transition radiation provides natural regularization of m=0 light quark energy loss.

Medium induced energy loss for charm and bottom

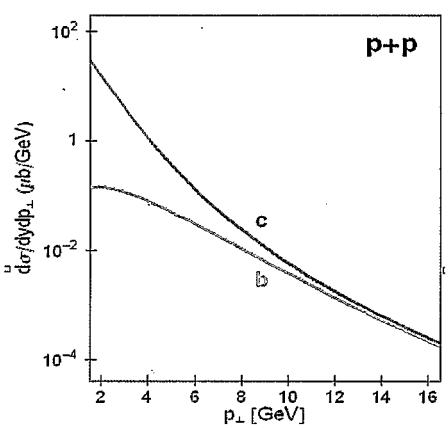


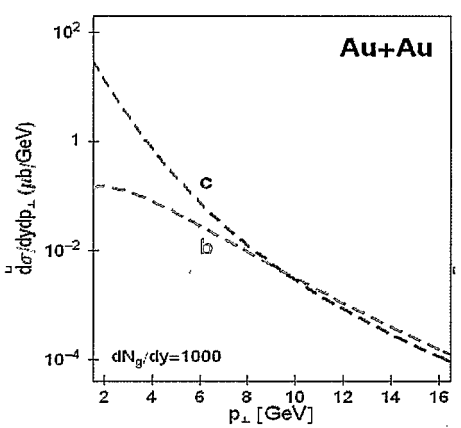


For 10 GeV heavy quark (c, b) jet, thickness dependence is closer to linear Bethe-Heitler like form L^1. This is different than the asymptotic energy quadratic form characteristic for light quarks.

Pt distributions of charm and bottom before and after quenching at RHIC

To compute the jet quenching we generalized the GLV method (PLB538:282,2002).

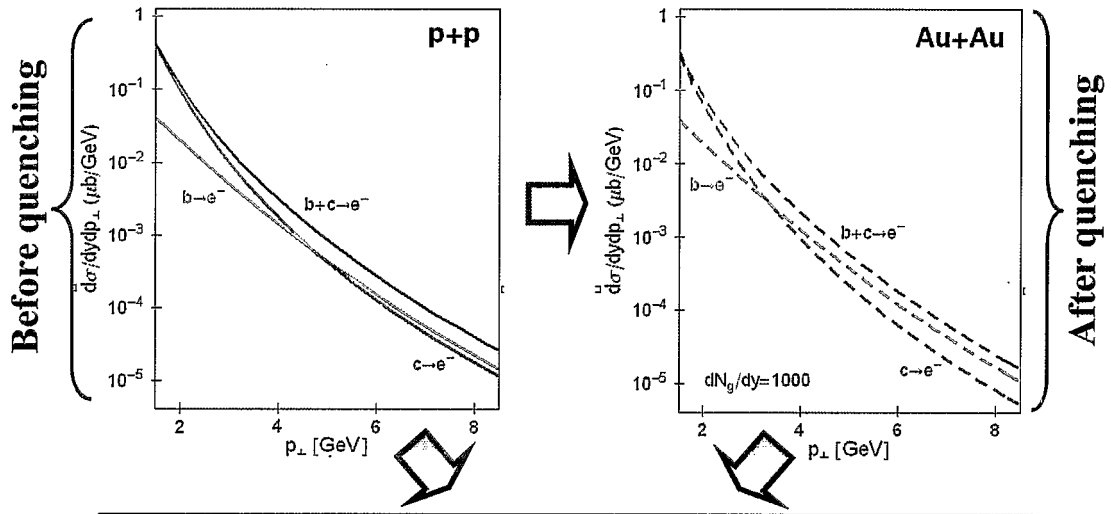




Before quenching **After quenching**

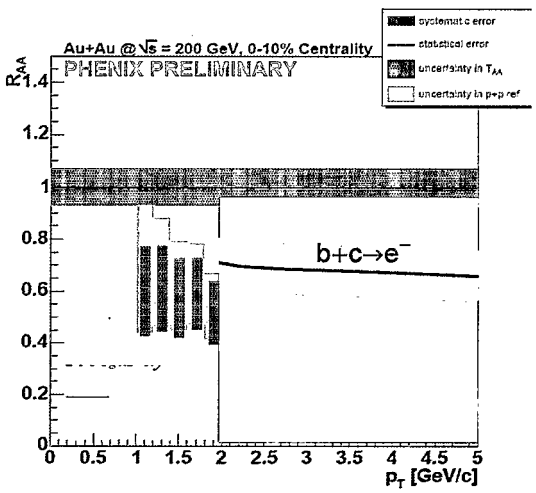
Single electrons pt distributions before and after quenching at RHIC

Panels show single e^- from FONLL (done by R. Vogt).
(M. D., M. Gyulassy, R. Vogt and S. Wicks, nucl-th/0507019, to appear Phys. Lett. B (2005))



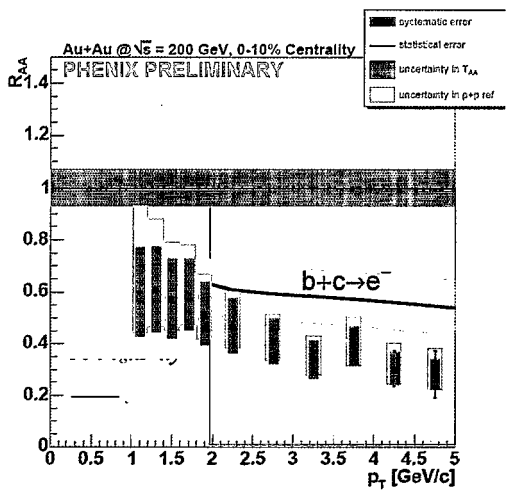
Bottom dominate the single e^- spectrum after 4.5 GeV!

Comparison with single electron data



Disagreement with PHENIX preliminary data!

Practical solution is to increase the gluon rapidity density



Reasonable agreement, but the $dN_g/dy=3500$ is not physical!

Is elastic energy loss important?

Early work:

E. Braaten and M. H. Thoma, Phys. Rev. D 44, 2625 (1991).
M. H. Thoma and M. Gyulassy, Nucl. Phys. B 351, 491 (1991).

↓

Elastic energy loss is negligible!

↓

Conclusion was based on wrong assumptions (i.e. they used α =0.2).

Recent work:

M. G. Mustafa, Phys.Rev.C72:014905,2005)

↓

Used correct $\alpha = 0.3$

↓

Elastic and radiative energy losses are comparable!

First results indicate that the elastic energy loss may be important (see talk by Simon Wicks)

Available elastic energy loss calculations can give only rough estimates to jet quenching. ⇒ More work is needed!

Conclusions

We applied the theory of heavy quark energy loss to compute heavy meson and single electron suppression.

We show that bottom quark contribution can not be neglected in the computation of single electron spectra.

The recent single electron data show significant discrepancies with theoretical predictions based only on radiative energy loss.

However, the elastic energy loss may have an important contribution to jet quenching.

Influence of Elastic Energy Loss on Heavy Flavor Quenching

Simon Wicks
Columbia University

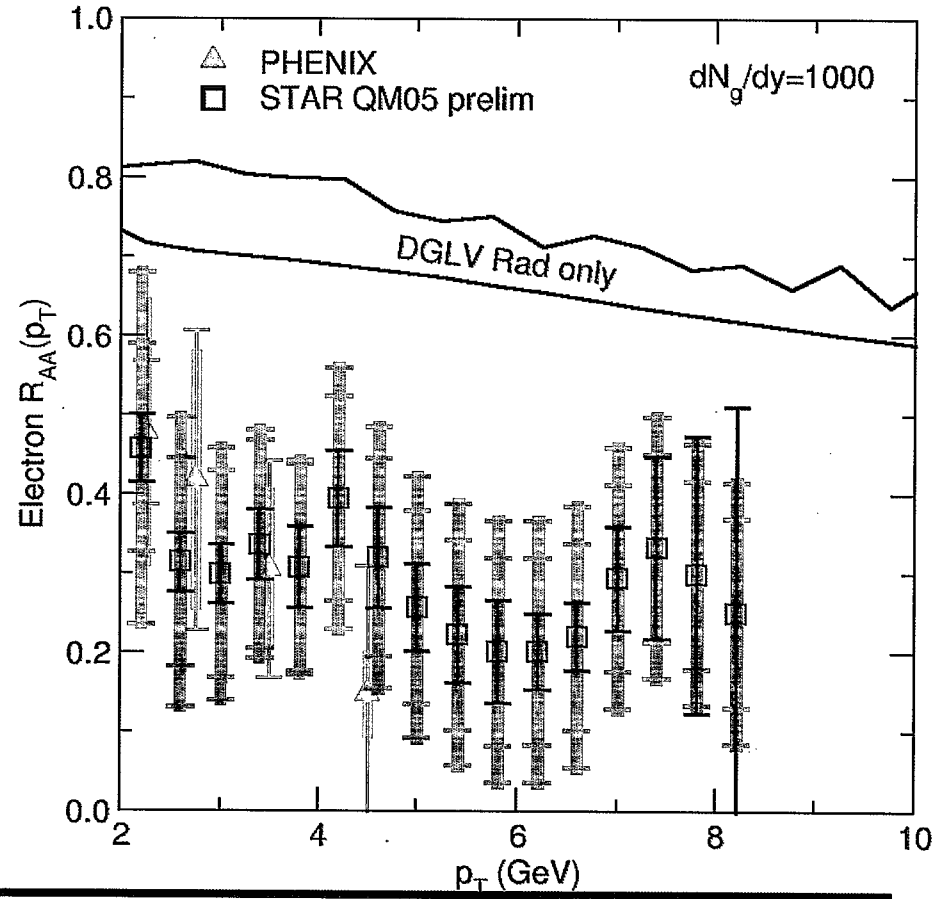
Work done with William Horowitz, Magdalena Djordjevic and Miklos Gyulassy
with input from Azfar Adil

- Collisional energy loss must be included to account for all perturbative physical effects
- Important theoretical issues remain to be resolved
  - Retardation effects
  - Collisional - radiative interference
  - Running coupling
- Fixed L predictions get closer to single electron RAA data
- Fixed L predictions move away from the π^0 RAA data

BNL Heavy Flavor Workshop, 12th December 2005

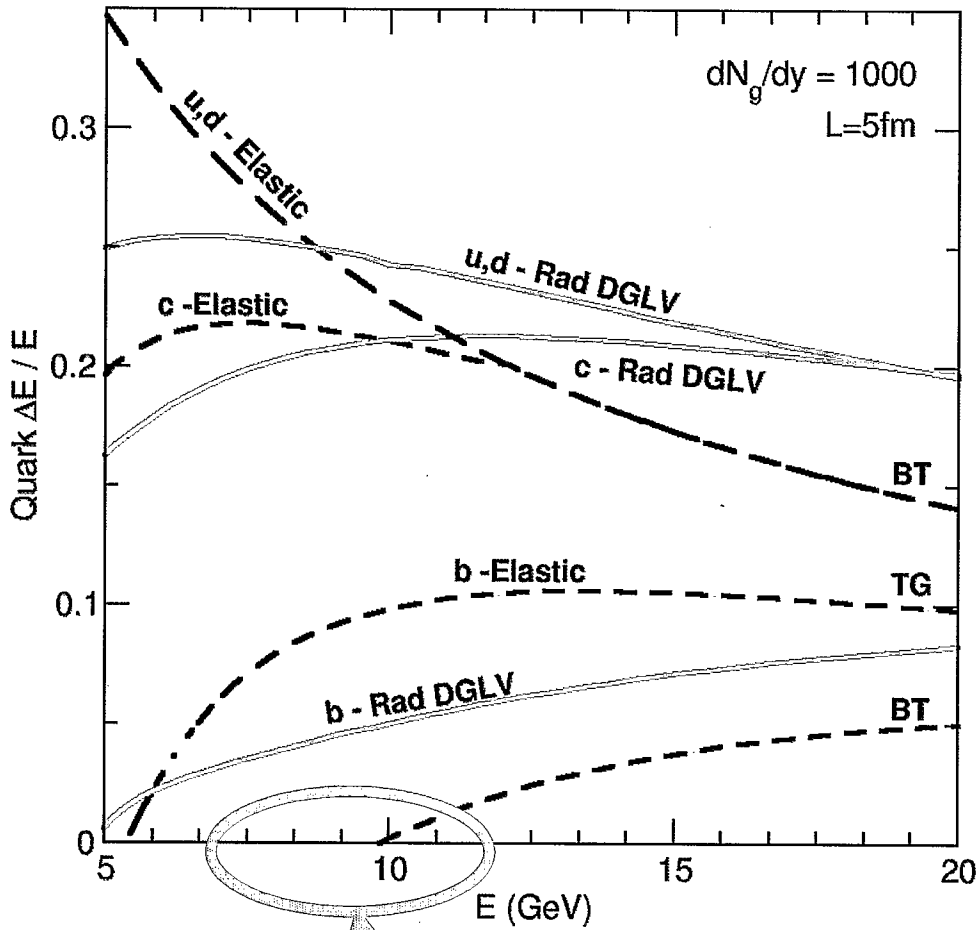
Radiative energy loss

- Radiative energy loss insufficient to explain electron data.
- Constraint on dN_g/dy: bulk entropy density from total pion rapidity density.
  - Cannot just 'dial in' dN_g/dy = ~3500
- Non-perturbative effects?
  - Stay with pQCD, where falsifiable predictions are possible
  - Include collisional energy loss in addition to radiative.
    (as suggested in M. Djordjevic thesis)



AIM: To establish experimental limits on the kinematic range in (p_T,y) where **perturbative QCD** can be accurately used to predict jet dynamics in dense QCD media.

Models of elastic energy loss



- Collisional energy loss is of the same magnitude as radiative in the kinematic region of interest (see M. G. Mustafa, Phys.Rev.C72:014905,2005)
- First estimate: Bjorken kinematic estimate of magnitude (FERMILAB-PUB-82-059-THY, unpublished), then over time, improved treatment of IR and UV.
- Further possible improvement: input from evolving medium simulations by Molnar and Hirano.

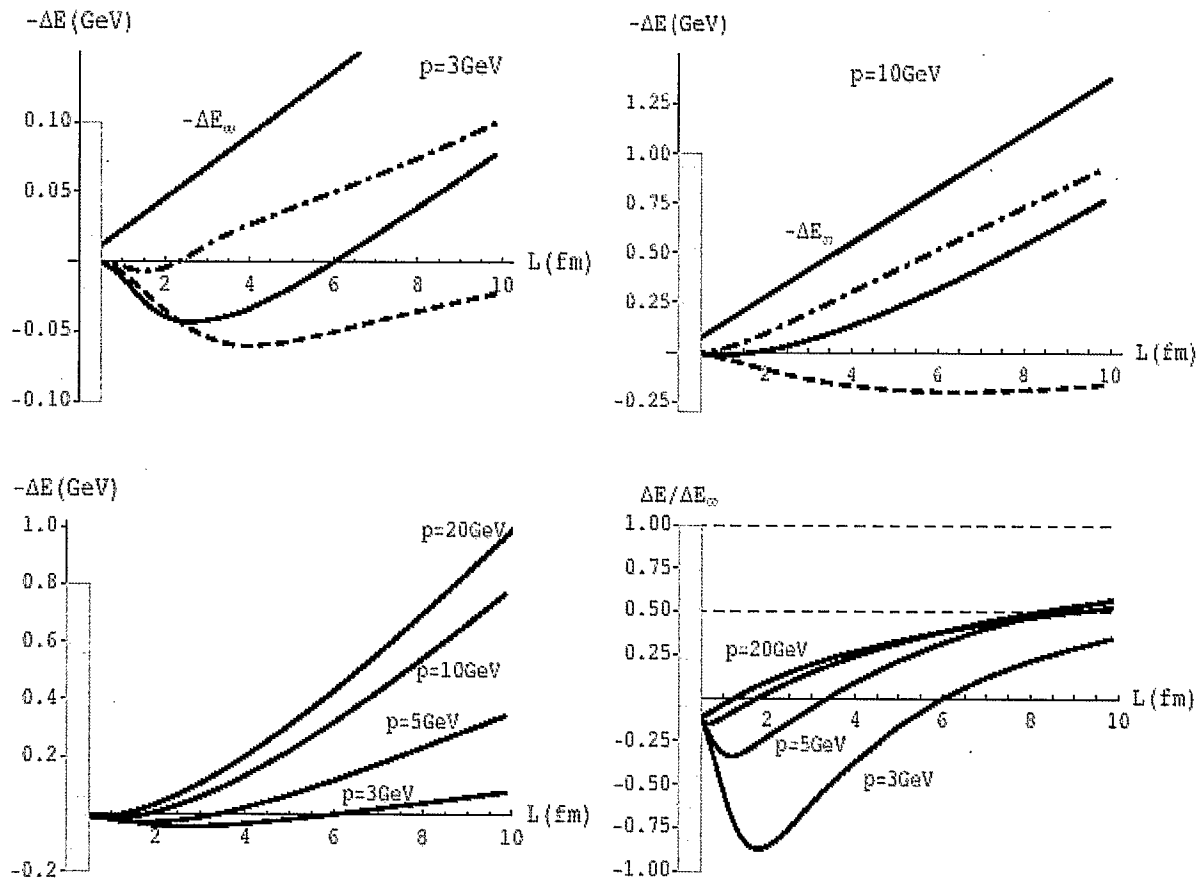
BT: unphysical energy gain for bottom due to a failure of the extrapolation from the weak-coupling limit **(Romatschke, Strickland)**.

Open problem: Retardation effects?

Peigné et al claim: strong suppression of elastic due to transient field and retardation effects

(unexpected positive energy gain due to transverse response function)

Peigné, Gossiaux, Gousset (hep-ph/0509185)

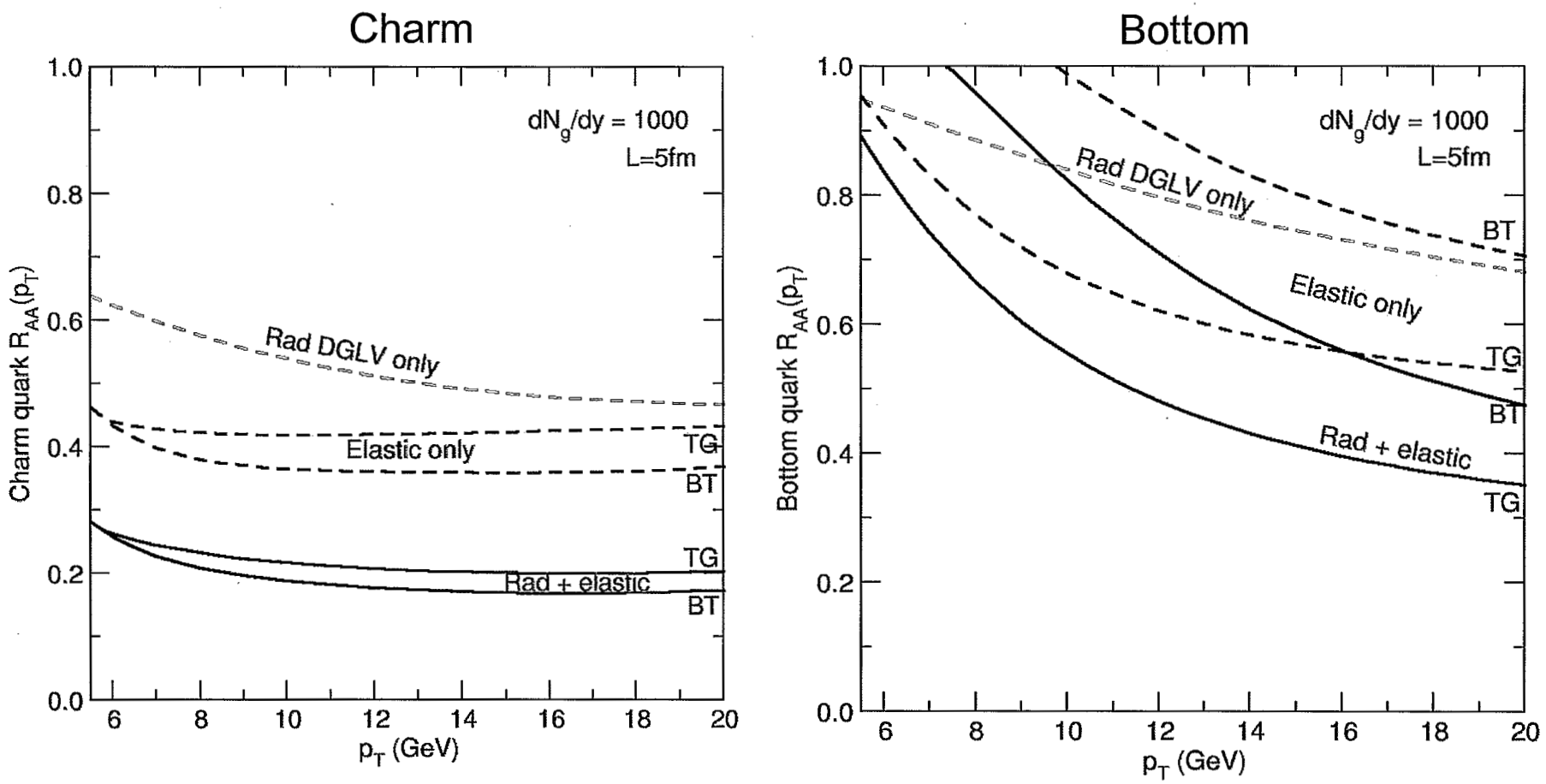


BUT: formalism used *mixes* radiative (zerorth order) and elastic mechanisms

Part of medium induced energy ***gain*** is due to Ter-Mekilian (see M. Djordjevic) that is **cancelled** by Transition Radiation (not included by Peigne).

Results - Partonic Raa (fixed L=5fm)

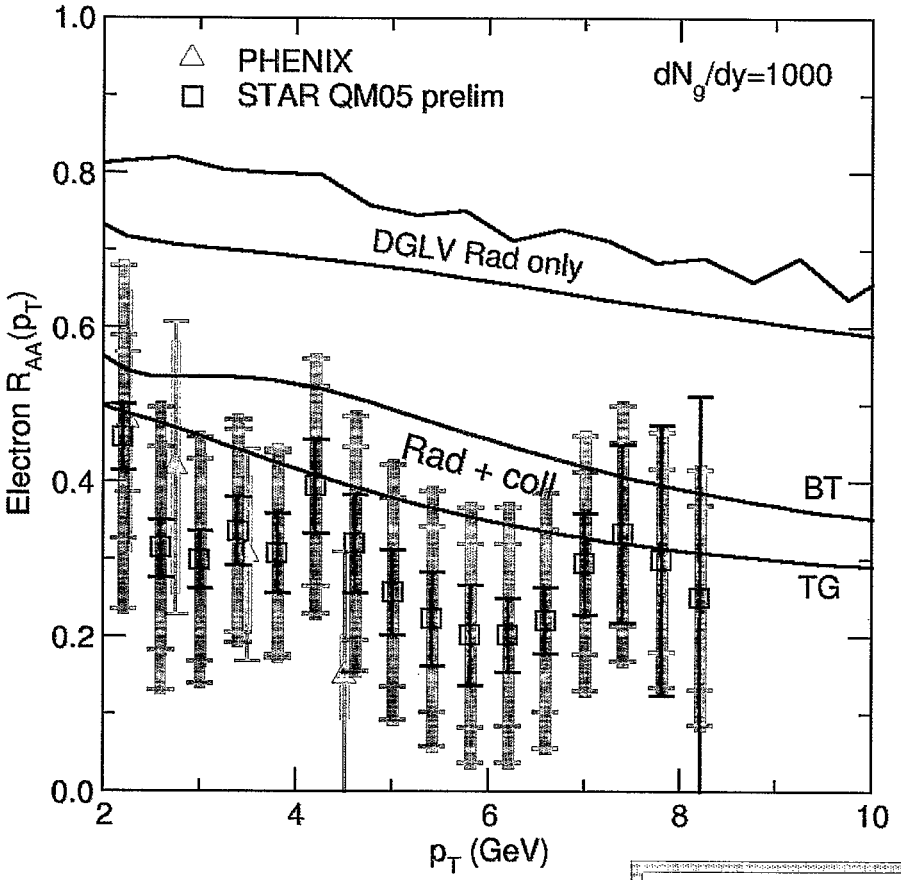
Fixed L=5fm; α=0.3; dN_g/dy=1000

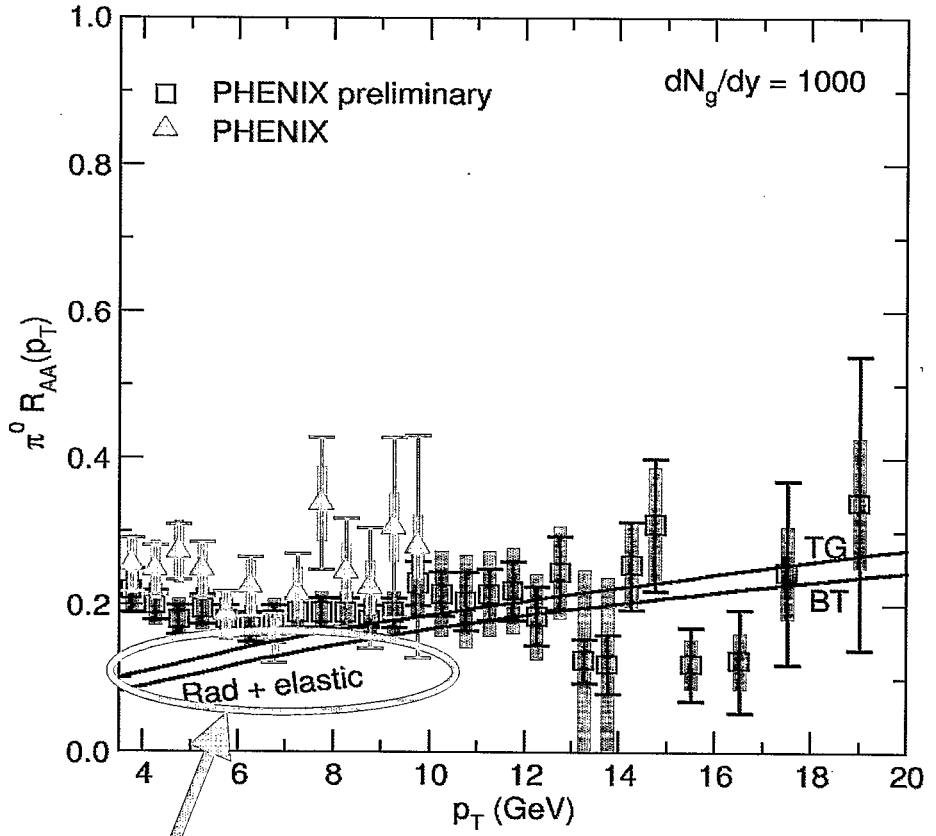


- Radiative + collisional ~2x suppression of radiative alone
- Large difference between BT and TG for bottom quark quenching

Results - Electron and Pion Raa (fixed L=5fm)

Fixed L=5fm; α=0.3; dN_g/dy=1000





Pions overquenched at low pT (for fixed L=5fm)

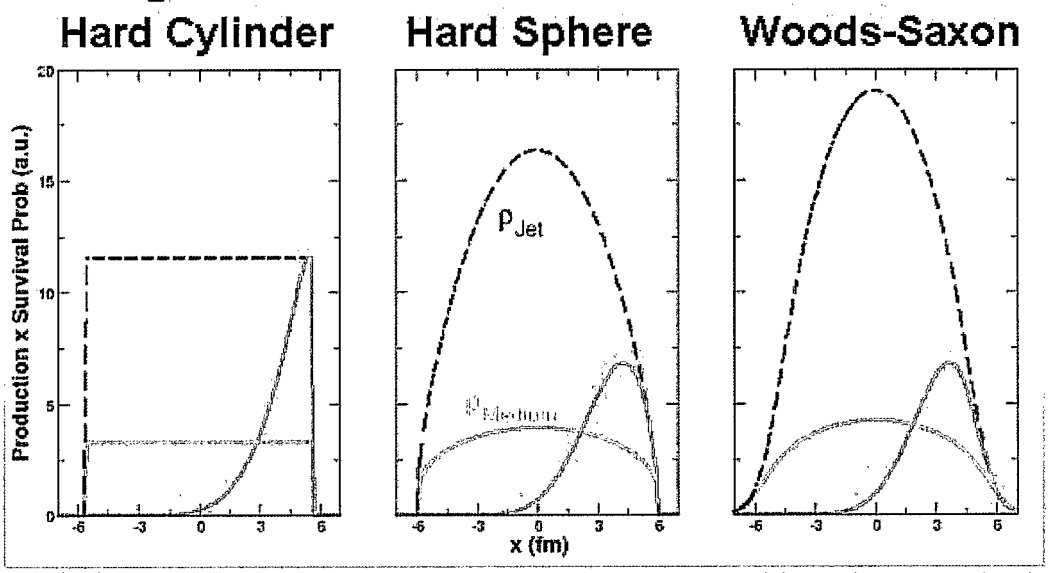
Role of Dynamic Geometry in Heavy Quark Tomography

William Horowitz
Columbia University

We show that models based on simplified nuclear geometries lead to surface emission bias. As a result, we use the more realistic Woods-Saxon distribution; unfortunately, natural definitions for the edge and for the length a parton propagates in the medium are lost. Defining the length as a line integral through the participant density divided by the density's average value, we calculate the incoherently convolved DGLV inelastic loss (with multigluon fluctuations) with the infinite time elastic loss for fixed strong coupling. We see that the partons probe a significant portion of the medium, and that the average partonic lengths of emission do not evolve intuitively as a function of parton species and transverse momentum. Using pQCD production (with bottom) and fragmentation, inclusion of both energy loss mechanisms, allowing path lengths to fluctuate, and varying the coupling all lead to large effects on the theoretical RAA values, which may be seen as simultaneously fitting the non-photonic electron RAA and the pion RAA within error.

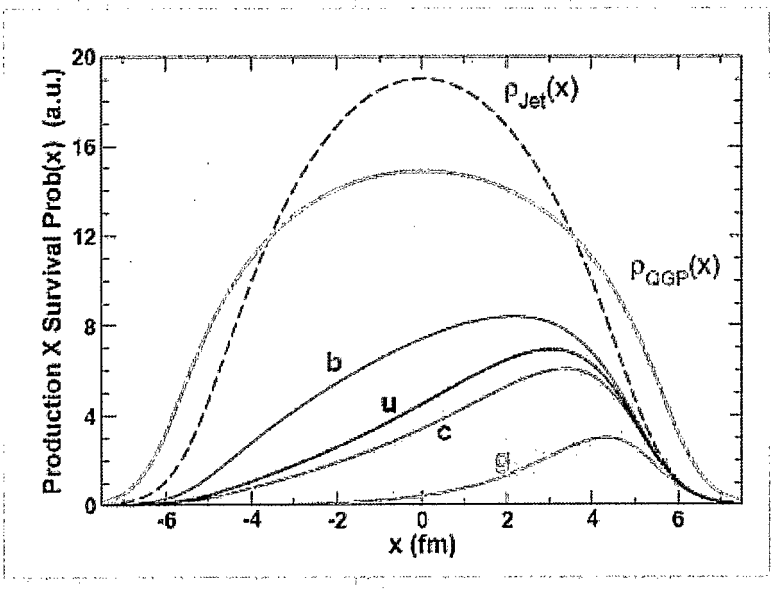
Significance of Nuclear Profile

- Simpler densities create a surface bias



Toy model for purely geometric radiative loss from Drees, Feng, Jia, Phys. Rev. C.71:034909

Volume Emission of Partons



- fixed $p_T = 15$ GeV, $y = \phi = 0$, and $\alpha_s = .3$

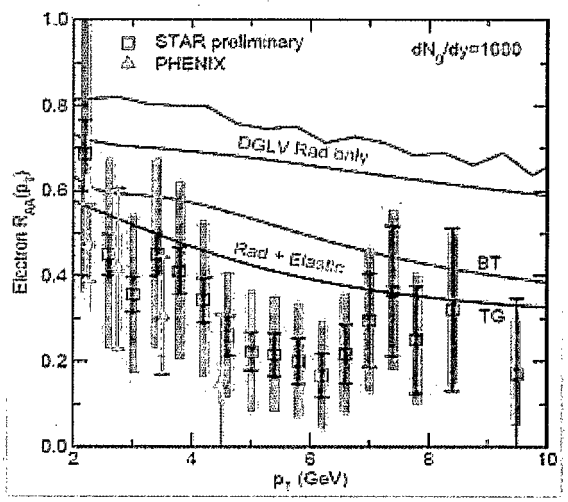
Average Lengths of Emission

- Dynamic volume depends on partonic species and p_T
  - For p_T = 5, 10, 15, 20 GeV, α_s = .3
  - $\langle L_g \rangle$ = 1.74, 1.93, 2.16, 2.41 fm
  - $\langle L_u \rangle$ = 3.83, 4.21, 4.47, 4.62 fm
  - $\langle L_c \rangle$ = 4.65, 4.43, 4.48, 4.50 fm
  - $\langle L_b \rangle$ = 6.17, 5.69, 5.43, 5.29 fm

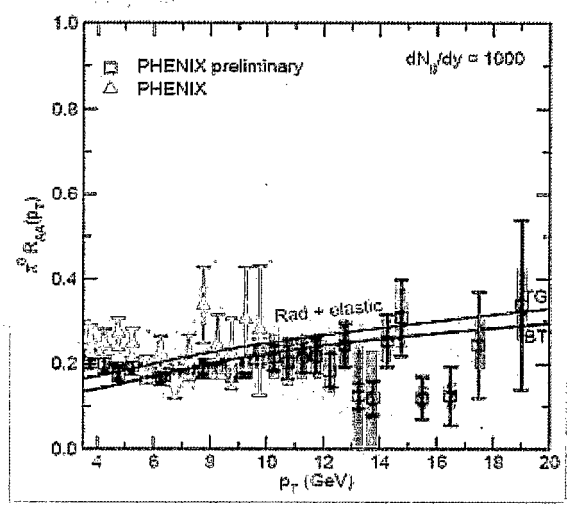
The Results

$\alpha_s = .3$

- Electrons



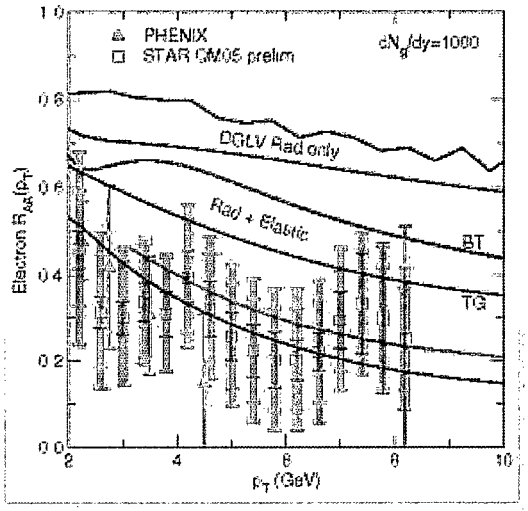
- Pions



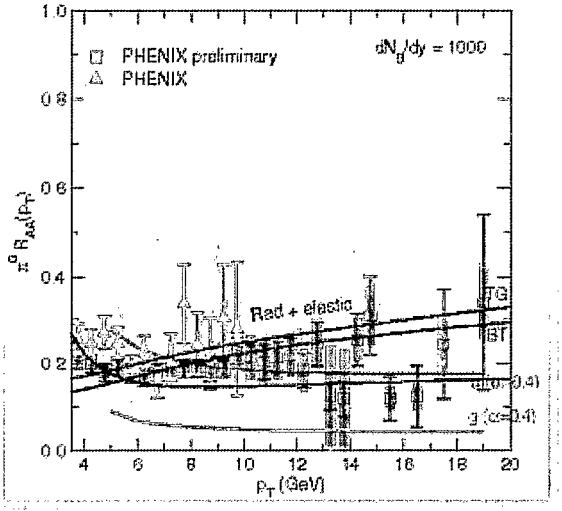
The Results

$\alpha_s = .4$

- Electrons



- Pions



P.-B. Gossiaux (gossiaux@subatech.in2p3.fr)

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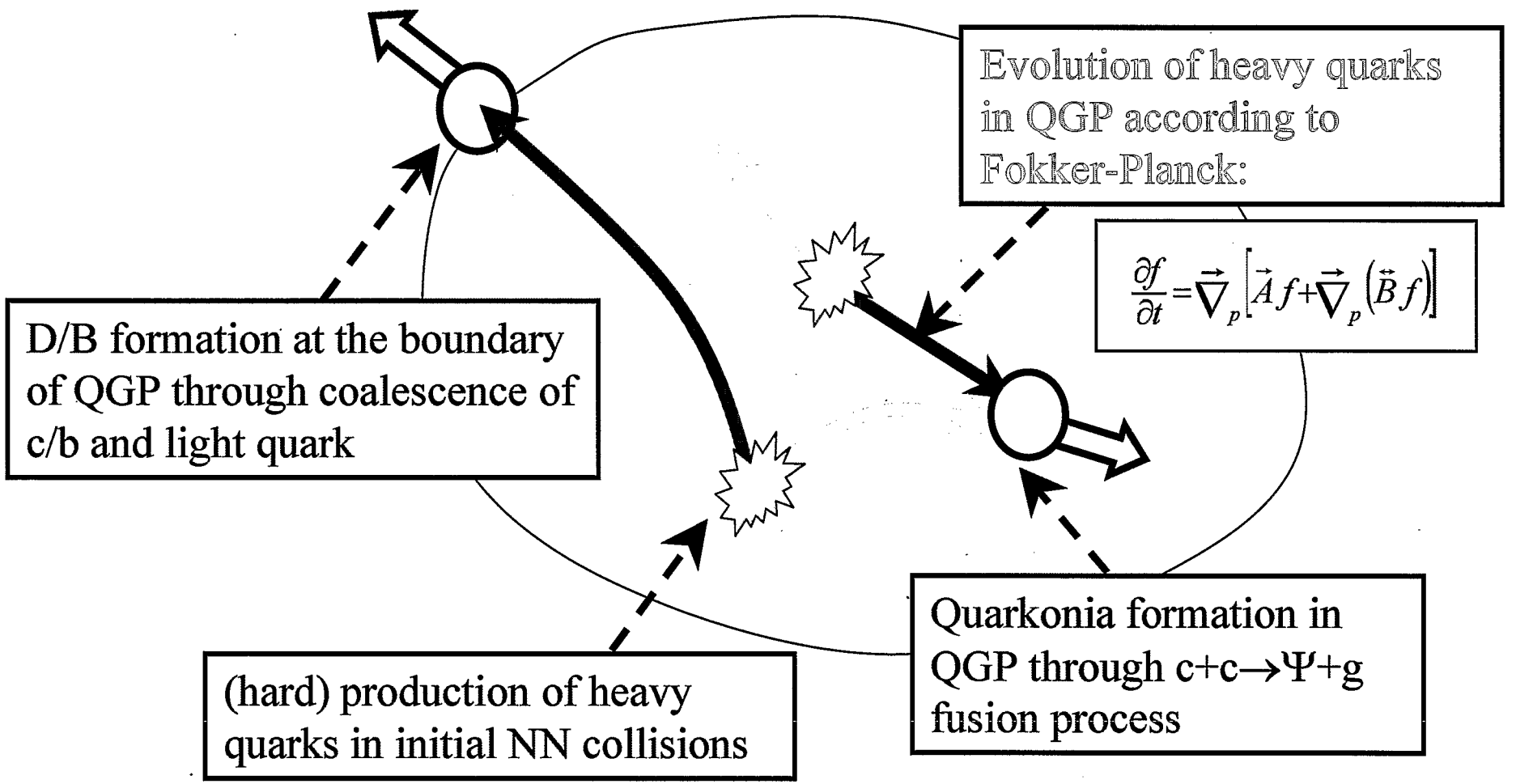
Thermalization of heavy quarks and consequences on charmonia production

Summary:

We study the time evolution of the phase space distribution of charm quarks during QGP expansion within the frame of the Fokker-Planck equation. This permits to include mechanisms such as energy loss and fluctuations in a very natural and flexible fashion, without resorting to a microscopic description of the surrounding medium. As a first application of this formalism, we study the R_{AA} of the decay-electrons of outgoing D mesons, which permits to calibrate the transport coefficients. From this observable, we deduce that experimental data point towards a significant although not complete thermalization of c quarks in QGP. As for the elliptic flow of those D mesons, first results of our model seem to indicate that a significant part of it would be produced after the end of QGP.

Having gained a better control on the evolution of the charm quarks during QGP, we turn to the study of the c+cbar → J/Psi+g reaction within this phase, i.e. to the « delayed » J/Psi production. We present integrated as well as differential (as a function of its transverse mass and rapidity) rates and discuss the impact of QGP parameters as well as the dissociation temperature on these observables. It is found that the absence of charmonia enhancement at RHIC puts strong constrains on the dissociation temperature (and thus on lattice results) as well as on the initial number of charmed quarks produced in incoherent hadronic collisions.

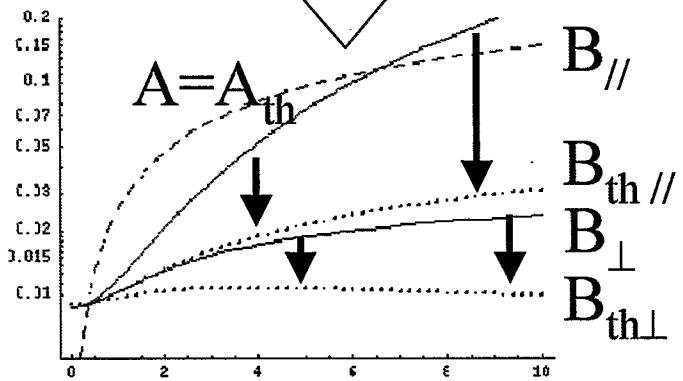
Schematic view of our model for hidden and open heavy flavors production in AA collision at RHIC and LHC

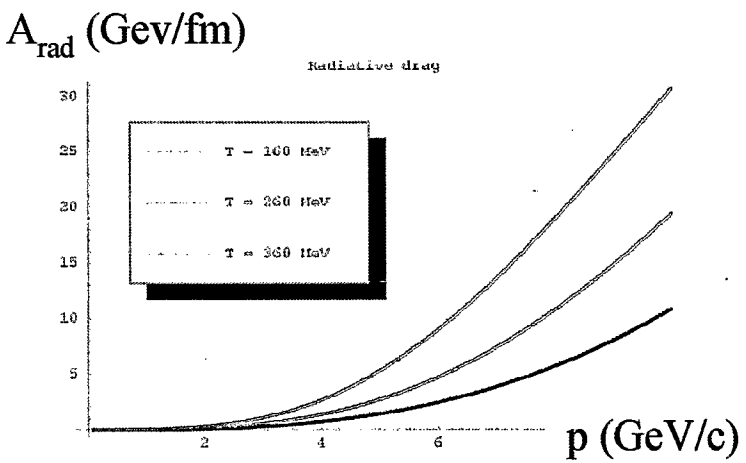


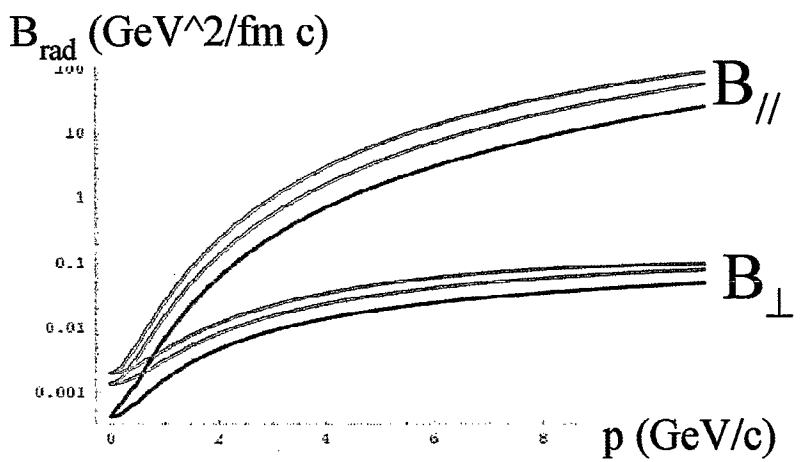
Transport coefficients

Four sets:

1. FP coefficients (A,B)≡(drag,diffus) deduced by Mustafa, Pal and Srivastava (MPS)
2. Adapt (A,B) → (A_{th} =A,B_{th}) such then the associated f_{asympt} is a Boltzmann distribution, and then → ($\kappa_{col} A_{th}$, $\kappa_{col} B_{th}$) with κ_{col} varying from 0 → ∞ in order to span from free streaming → instantaneous thermalization.
3. MPS + « radiative » coefficients deduced using the Gunion and Bertsch elementary cross section for qQ →qQ+g and its equivalent for gQ →gQ+g in t-channel (u & s-channels are suppressed at high energy).
4. No LPM for the time ⇒ MPS + κ_{rad} x RAD

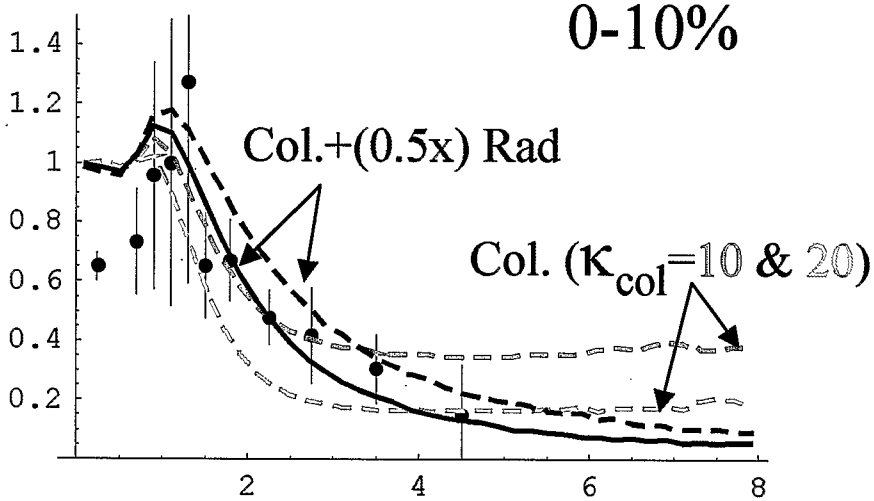


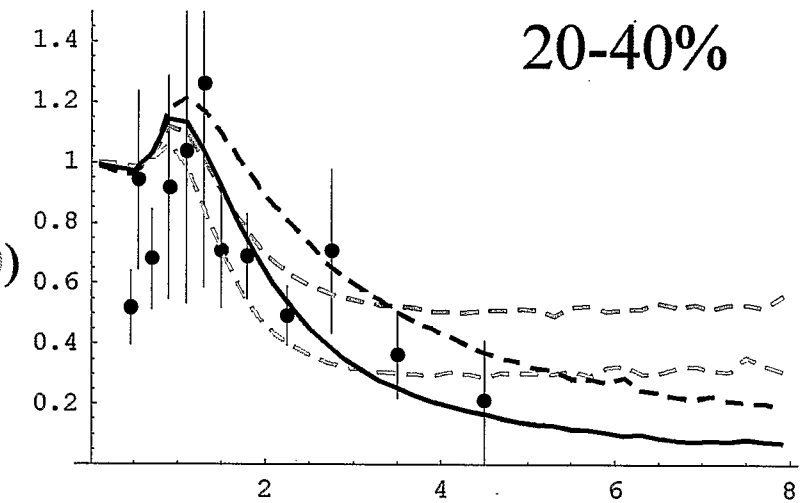


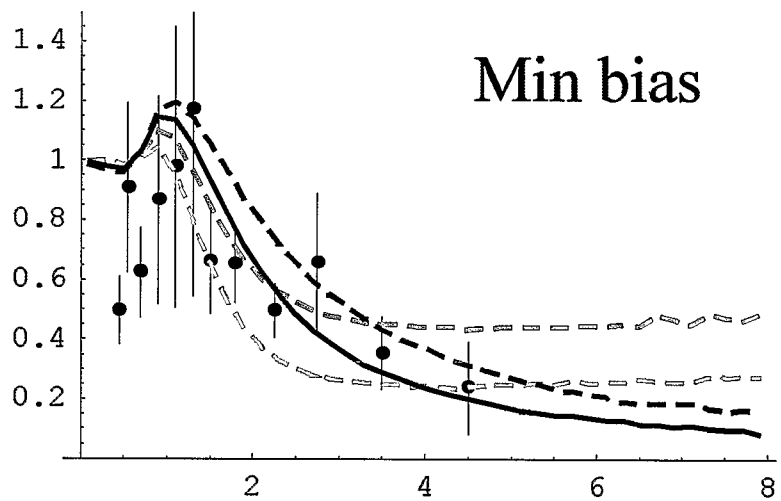


Leptons (← D decay) transverse momentum distribution (y=0)

R_{AA}





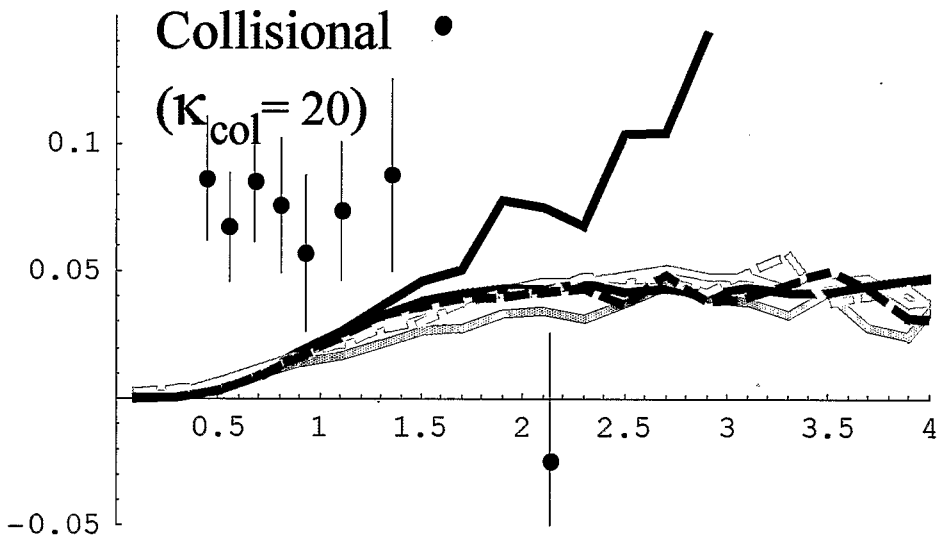


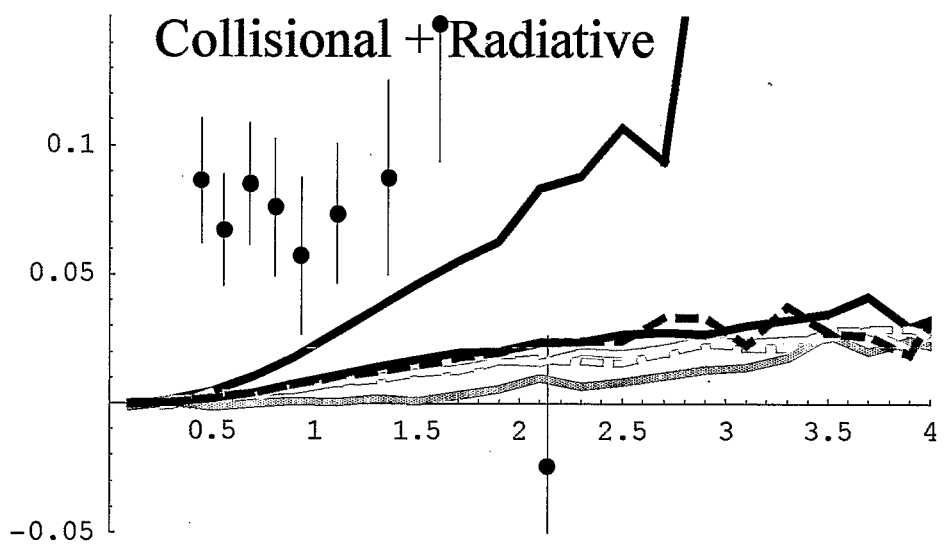
<u>Conclusion I:</u>

One can reproduce the R_{AA} either :

- With cranked up collisional processes
- With « reasonnable » (κ_{rad} not far away from unity) use of radiative processes.

NP-Electron elliptic flow at RHIC: comparison with experimental results





c-quarks

D

Decay electrons

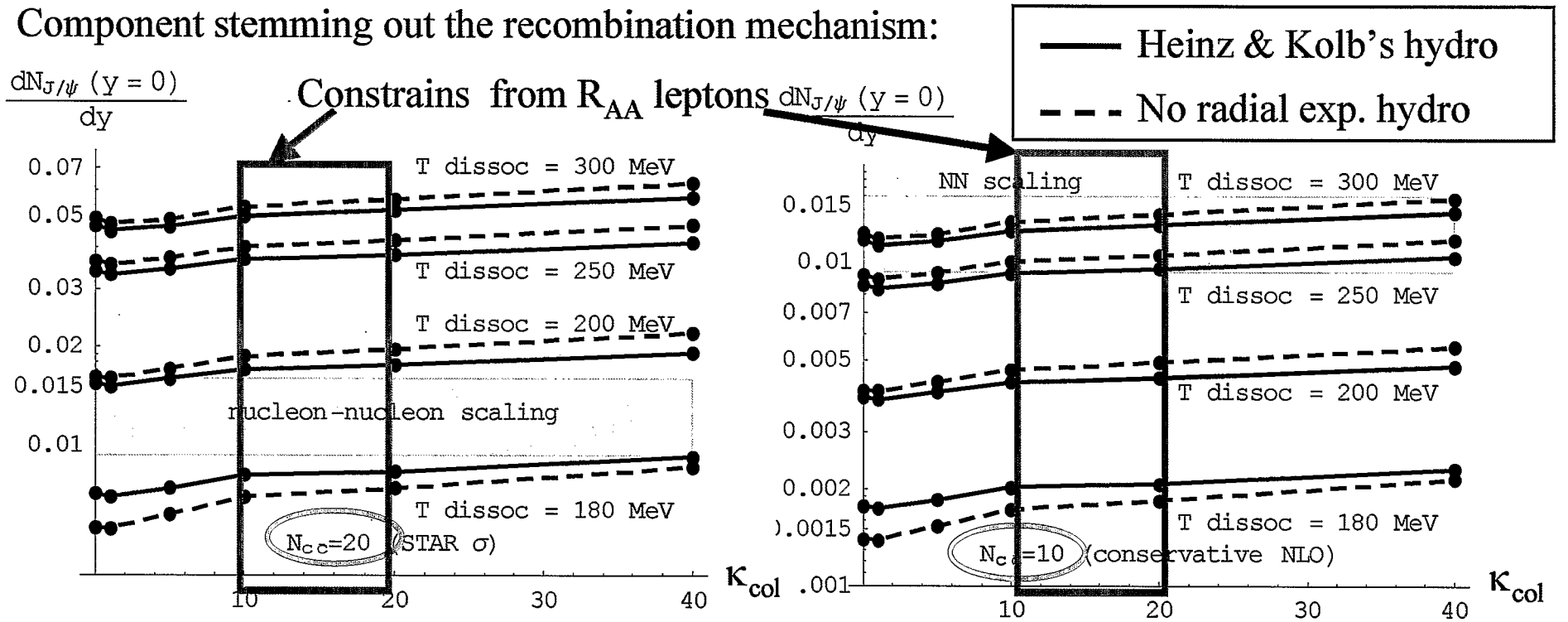
Tagged const quarks

Conclusion III:

One cannot reproduce the v_2 consistently with the R_{AA}!!!
Contribution of light quarks to the elliptic flow of D mesons is small

Results for J/ψ production at mid-rapidity, central

Component stemming out the recombination mechanism:



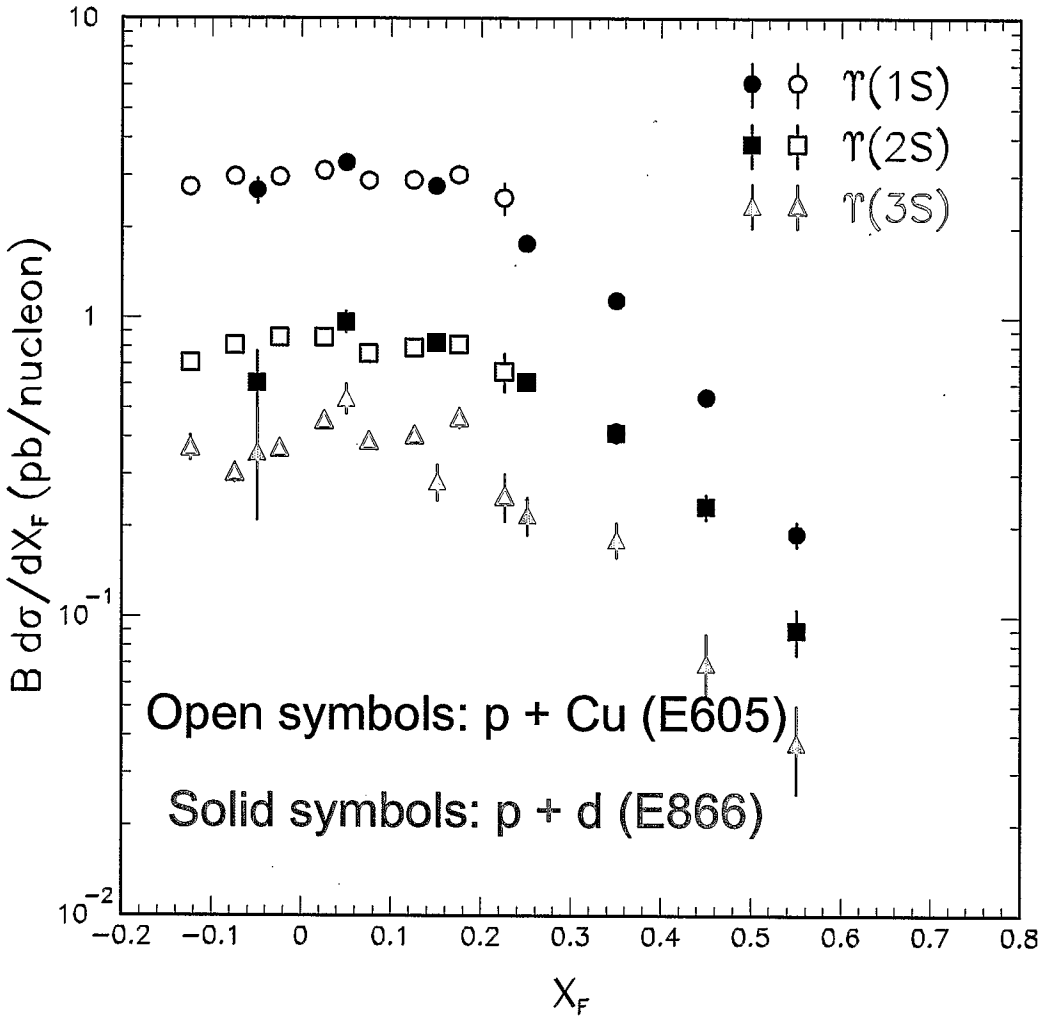
- N_c and T_{dissoc} : key parameters as far as the total numbers are considered
- Thermalization increases production rates, but only mildly.
- Radial expansion of QGP has some influence for a very specific set of parameters
- Firm conclusions can only be drawn when the initial number of c-cbar pairs is known more precisely.

Heavy Flavor Production in p-A Collisions

Jen-Chieh Peng, Univ. of Illinois at Urbana-Champaign

- A-dependence of quarkonium production has been reasonably well studied in p-A. Negative x_F data are becoming available from HERA-B
- Open-charm A-dependence data at a wide range of rapidity is needed for understanding the RHIC A+A open-charm data
- Polarization of quarkonium remains a mystery. Additional information from E866 on Ψ' and upsilon polarization will become available.
- New results on heavy quark production are obtained at HERA-B

Upsilon cross sections for p+d at 800 GeV

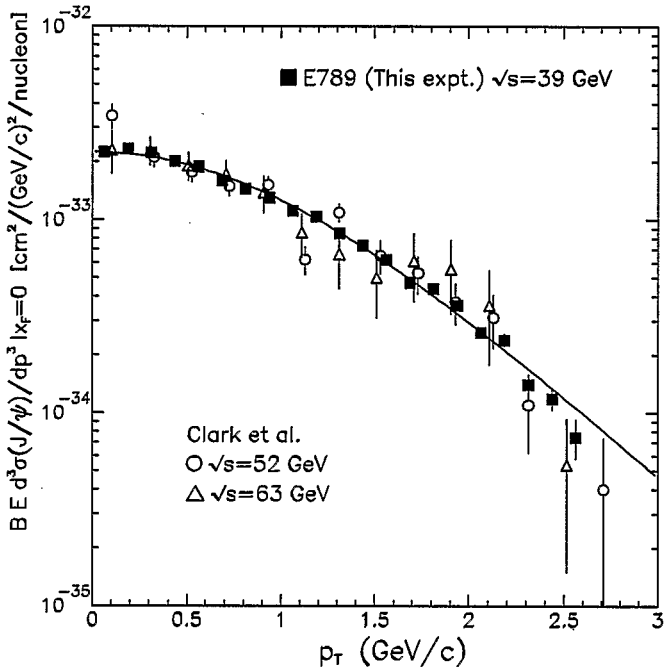


$\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ ratios are A-independent

$p_T -$ distributions for J/Ψ and Υ

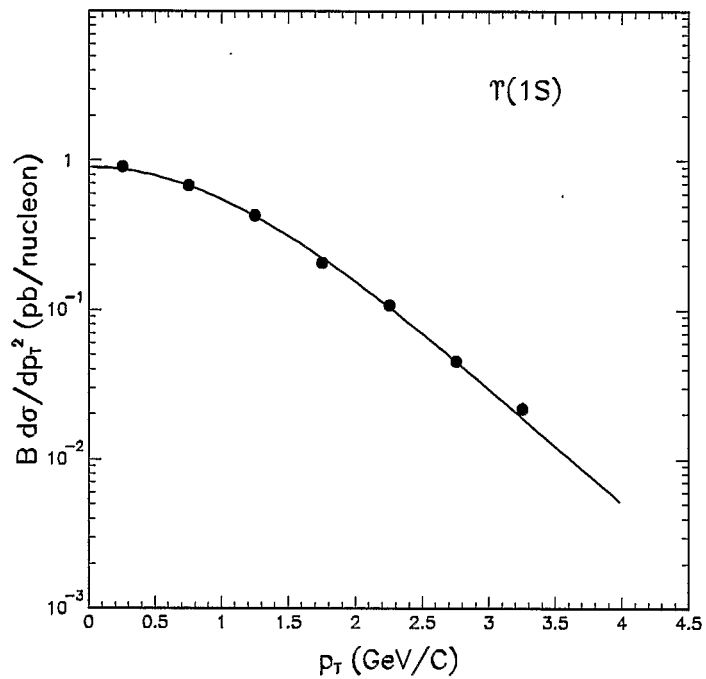
$p + Au \rightarrow J/\Psi$

800 GeV



$p + d \rightarrow \Upsilon(1S)$

800 GeV



$\langle p_T{}^2 \rangle = 2.48\,\mathrm{GeV}^2/\mathrm{c}^2$ $\langle p_T{}^2 \rangle = 2.92\,\mathrm{GeV}^2/\mathrm{c}^2$

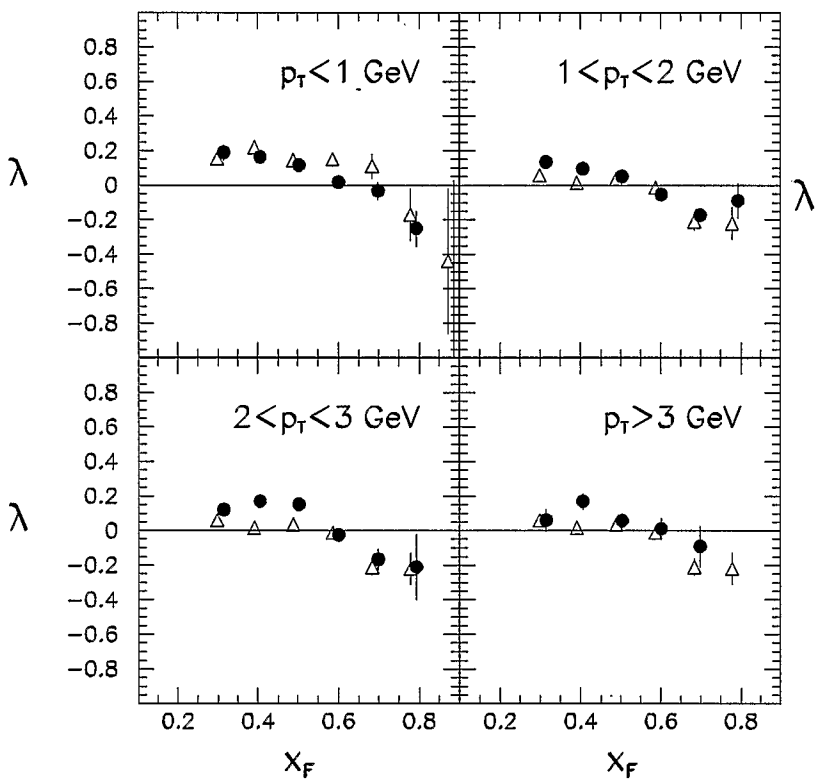
$\langle p_T{}^2 \rangle = 3.45\,\mathrm{GeV}^2/\mathrm{c}^2$ for $p + Cu \rightarrow \Upsilon(1S)$ (E605)

Polarization of J/Ψ in p + Cu Collision

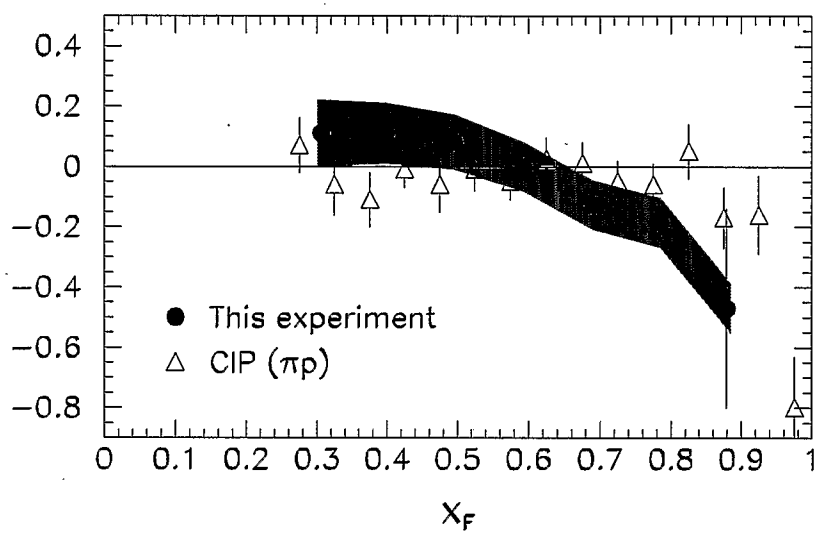
$$d\sigma/d\Omega \sim 1 + \lambda \cos^2\theta$$

(λ=1: transversely polarized, λ = -1: longitudinally polarized
λ = 0, unpolarized)

E866 data



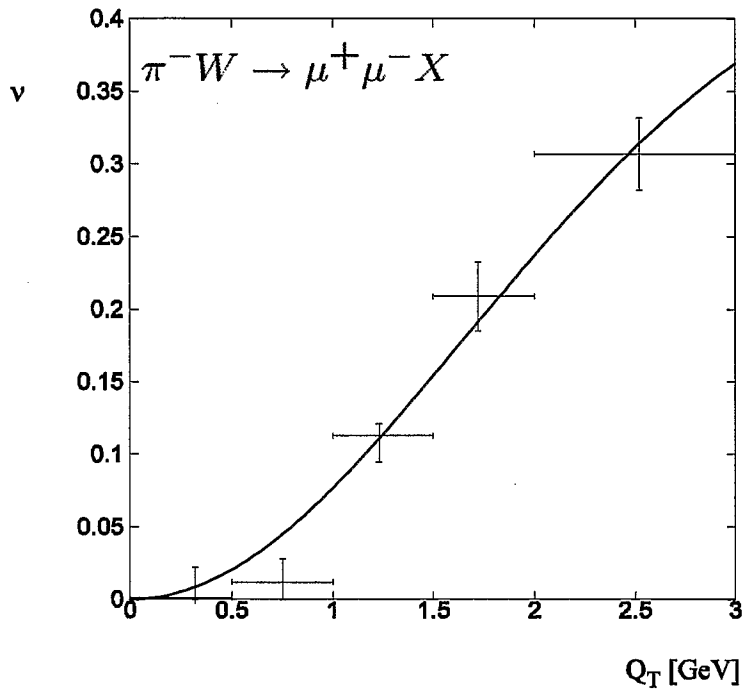
hep-ex/030801

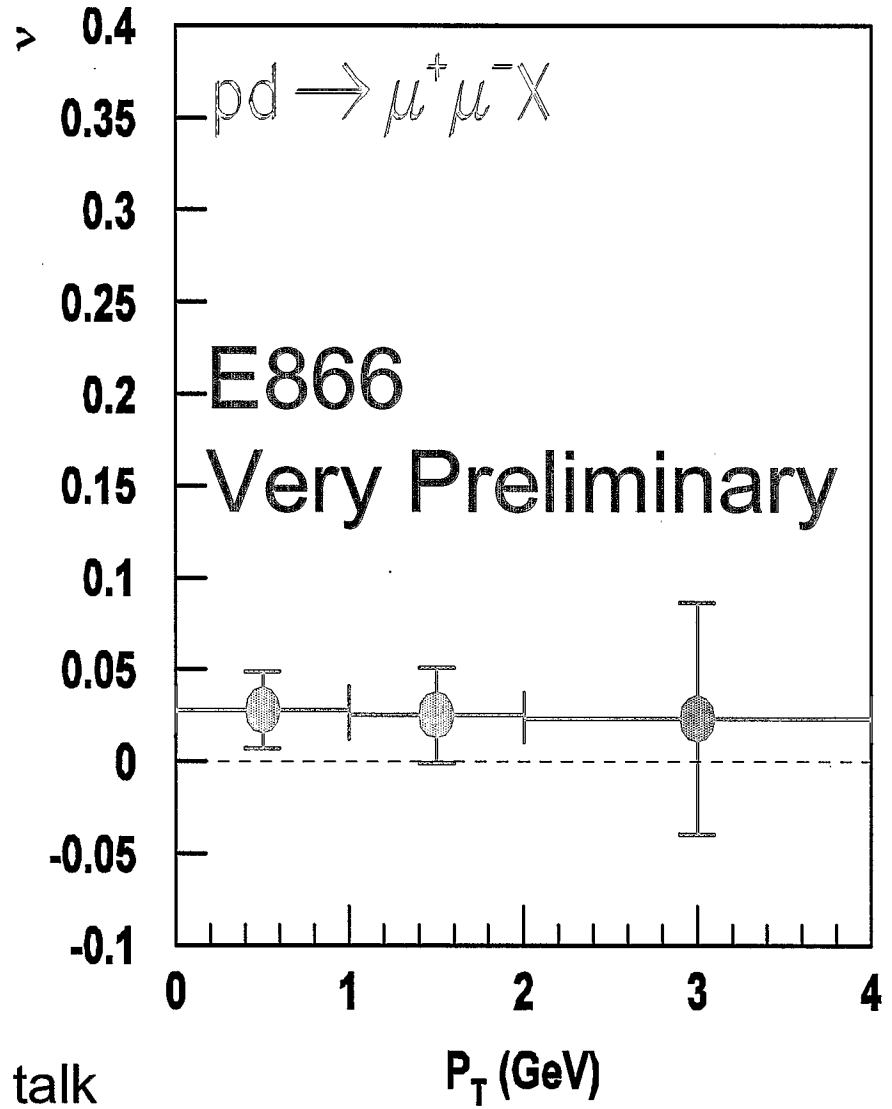


- λ is small, but nonzero
- λ becomes negative at large x_F
- No strong p_T dependence for λ

Polarization of Ψ' is being analyzed

Azimuthal cos2ϕ distribution for Drell-Yan processes





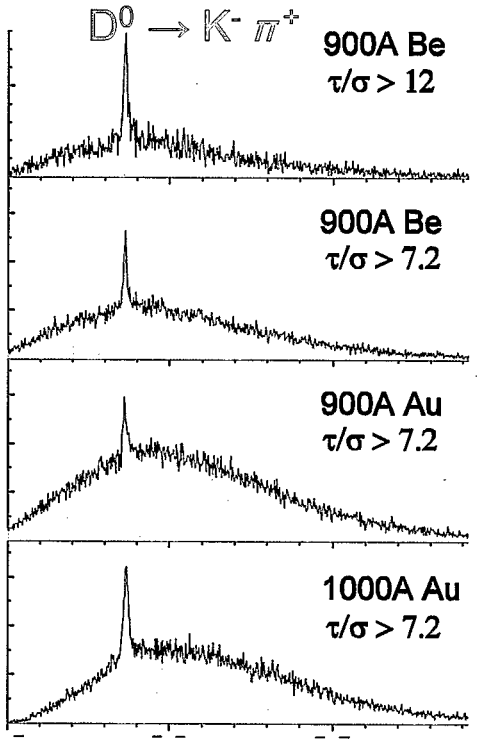
Lingyan Zhu, DNP05 talk

Nuclear effects of open-charm production

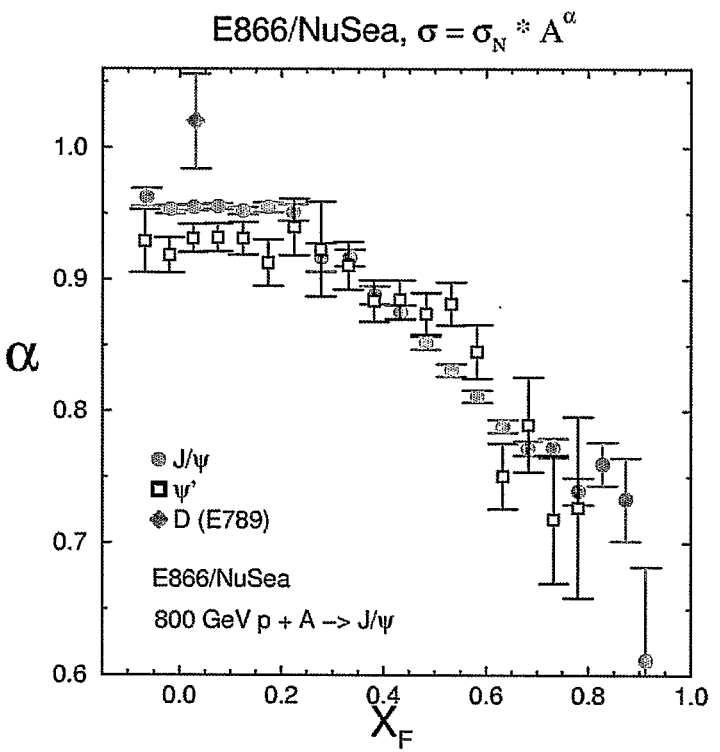
$p + A \rightarrow D + x$ at $s^{1/2} = 38.8$ GeV

E789 open-aperture, silicon vertex + dihadron detection

h^+h^- mass spectrum (after vertex cut)



No nuclear effect for D production (at xF ~ 0)



Need to extend the measurements to large x_F region

Quarkonium Production and Cold Matter Effects in pp, dA and AA Interactions

R. Vogt

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
Physics Department, University of California, Davis, CA 95616, USA

We describe hadroproduction of quarkonium in the color evaporation model (CEM). We show that the data is in qualitative agreement with the predictions of the model: ratios of χ_c/ψ and ψ'/ψ are independent of $\sqrt{S}$. We describe the parameter choice of m_Q and $\mu_F = \mu_R$ for several sets of parton densities. The agreement between the CEM and the Tevatron Run I and Run II data is relatively good [1]. Measurements of the relative chi_c to J/ψ production rates in pp and $p\overline{p}$ as well as of their A dependence should provide more complete information about the production method [2].

Currently, the J/ψ program at PHENIX is making progress, with data taken in pp, d+Au, Au+Au and Cu+Cu collisions at $\sqrt{S_{NN}} = 200$ GeV and Cu+Cu data at $\sqrt{S_{NN}} = 62$ GeV. The CEM agrees well with the shape and magnitude of the pp data. Initial-state shadowing and final-state absorption have been compared to the d+Au data as a function of rapidity and centrality [3]. The shadowing parameterizations (EKS98 and nDSg) and absorption cross sections ($\sigma_{\rm abs} < 3$ mb) that best agree with fits to the d+Au data [4] are calculated for the AA case to determine the baseline from cold nuclear matter effects [5]. These predictions are compared to the AA data to determine the strength of possible dense matter effects [4]. Predictions for cold matter effects on J/ψ and Υ production at the LHC in pPb and Pb+Pb collisions at 8.8 and 5.5 TeV respectively are also shown.

[1] M. Bedjidian *et al.*, arXiv:hep-ph/0311048; N. Brambilla *et al.*, arXiv:hep-ph/0412158.

[2] R. Vogt, Nucl. Phys. A **700** (2002) 539.

[3] R. Vogt, Phys. Rev. C **71** (2005) 054902.

[4] M. Leitch and R. Vogt, in progress.

[5] R. Vogt, Heavy Ion Phys., in press [arXiv:nucl-th/0507027].

Prediction of J/ψ Rapidity Distributions at RHIC

Agreement of CEM with overall normalization of Run 3 data good
Shape has right trend for d+Au with EKS98 shadowing

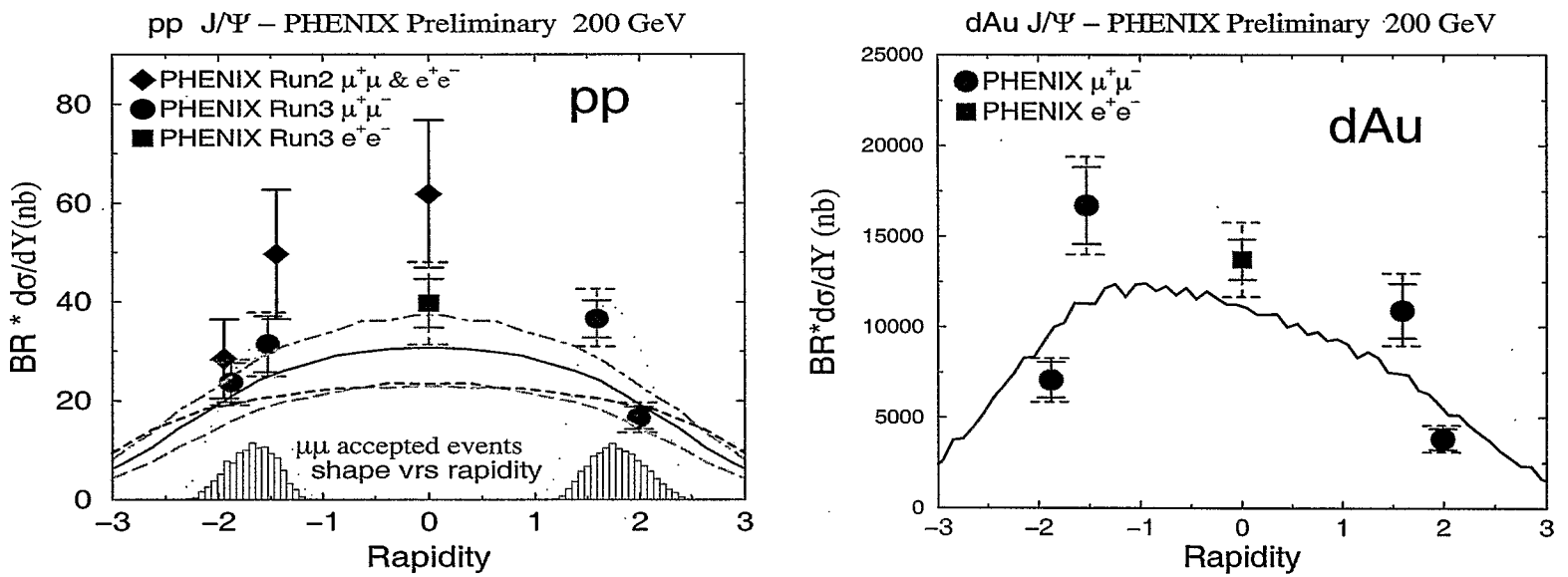


Figure 10: The inclusive J/ψ y distributions in $\sqrt{S} = 200$ pp (left-hand side for $\psi 1$ (solid), $\psi 2$ (dashed), $\psi 3$ (dot-dashed) and $\psi 4$ (dotted)) and d+Au (right-hand side with $\psi 1$ and EKS98) interactions. Plots courtesy of Mike Leitch.

Setting Baseline Cold Nuclear Matter Effects at RHIC: In Collaboration with Mike Leitch

Determine balance of shadowing and absorption from RHIC data

Compare combinations of shadowing parameterizations and absorption cross sections to RHIC d+Au data

Make χ^2 fits to $R_{\mathrm{dAu}}(y)$, $R_{\mathrm{dAu}}(N_{\mathrm{coll}})$ for all combinations – are some parameterizations more favored than others?

Take results with relative best agreement to determine the maximum range of cold nuclear matter effects in AA collisions

This becomes baseline onto which hot matter effects of color screening and recombination can be added

Results shown here for EKS98 and nDSg shadowing since their shapes are most compatible with the data

Absorption and Shadowing at RHIC: $R_{\mathrm{dAu}}(y)$

EKS98 and nDSg compared to d+Au data with $0 < \sigma_{\mathrm{abs}} < 3$ mb and MRST parton densities with $m = 1.2$ GeV, $\mu = 2m_T$

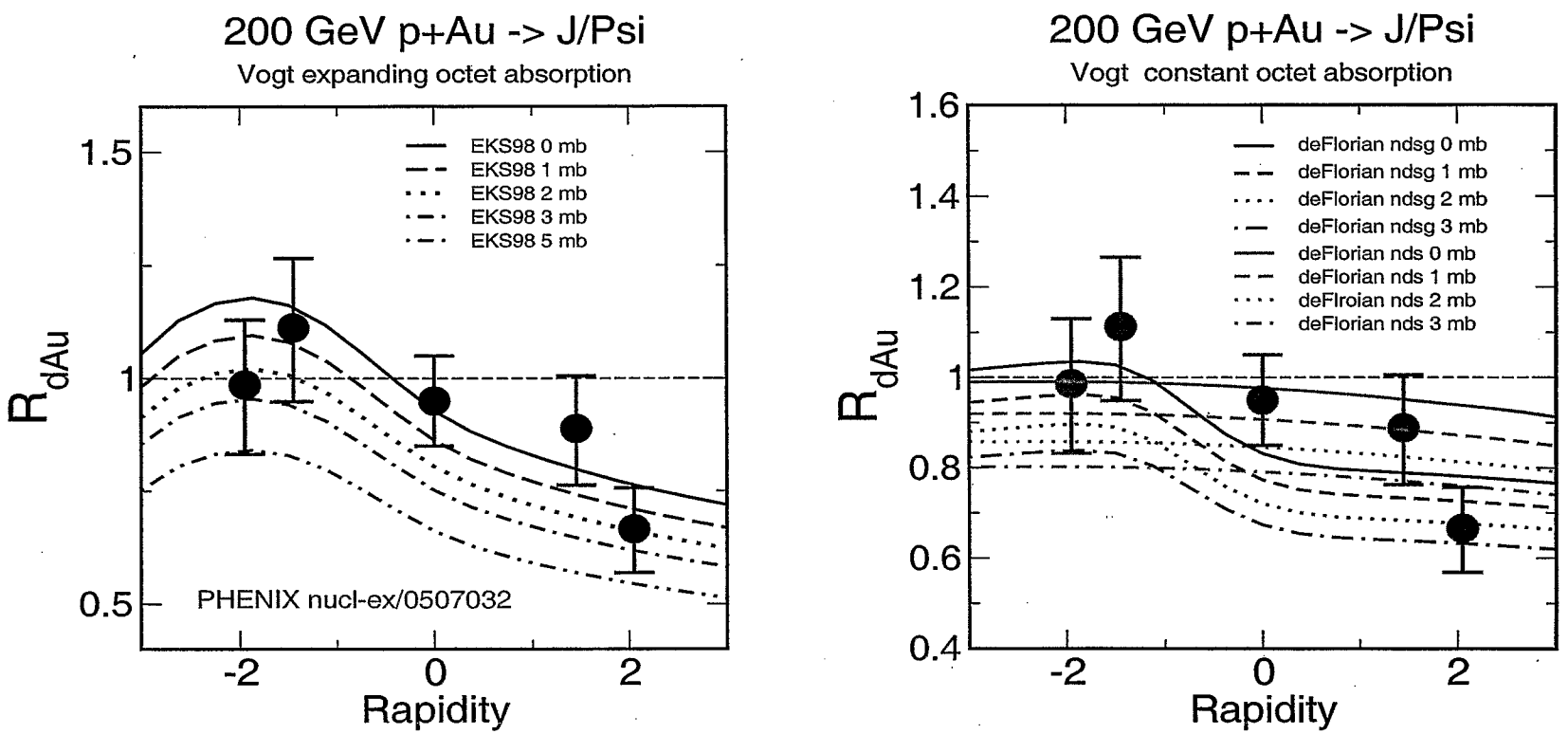


Figure 14: Octet absorption for $0 \leq \sigma_{\mathrm{abs}} \leq 3$ mb calculated with EKS98 (left) and nDSg (right) using the MRST PDFs and $m = 1.2$ GeV, $\mu = 2m_T$ compared to PHENIX data. (An additional overall normalization error of 12% is not shown.) RV and Mike Leitch, in progress.

Absorption and Shadowing at RHIC: $R_{\mathrm{dAu}}(N_{\mathrm{coll}})$

Centrality dependence of shadowing alone generally stronger for nDSg at $y = -1.7$, 0, similar for $y = 1.7$

Data do not help distinguish between different σ_{abs}

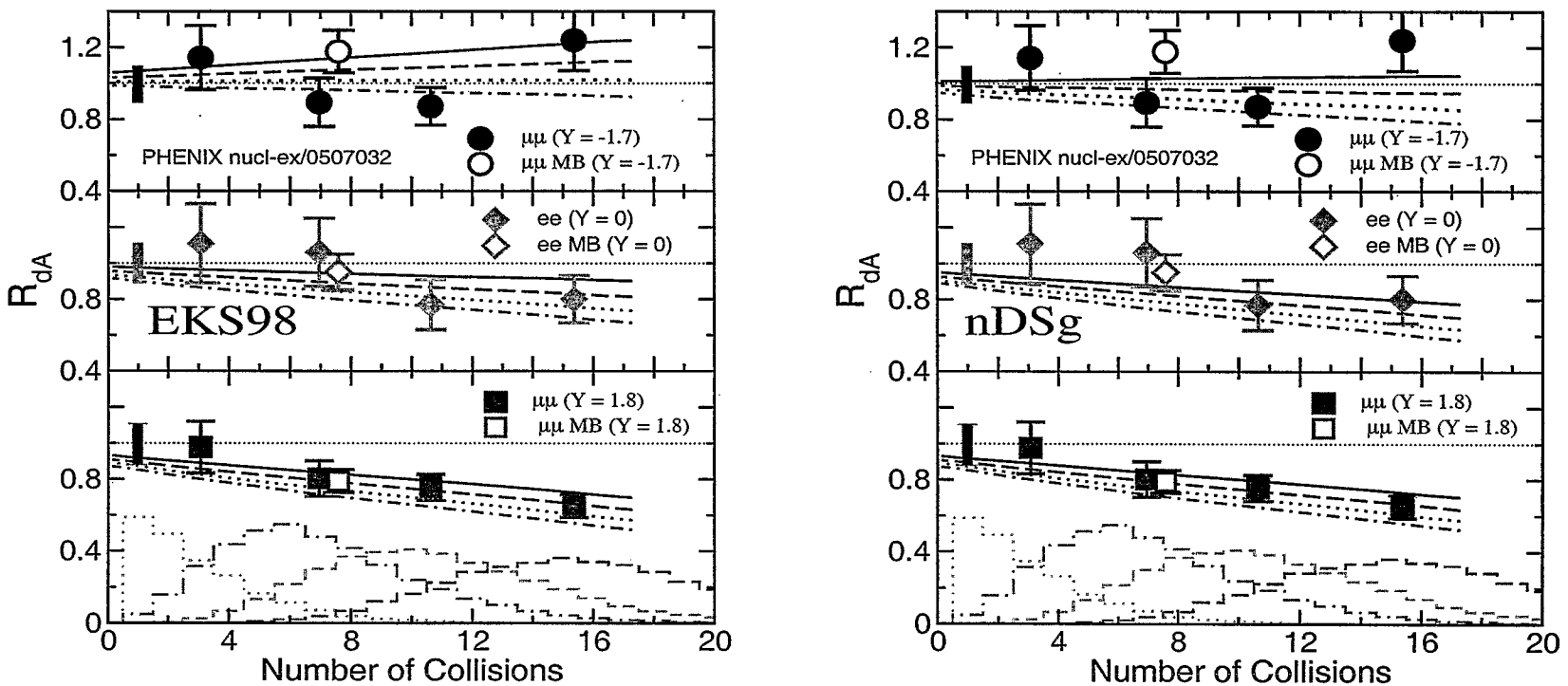


Figure 16: Octet absorption for $0 \leq \sigma_{\mathrm{abs}} \leq 3$ mb (upper to lower) calculated with EKS98 (left) and nDSg (right) with the MRST PDFs and $m = 1.2$ GeV, $\mu = 2m_T$. PHENIX data are shown for d+Au collisions at 200 GeV for $y = -1.7$ (top), 0 (middle) and 1.7 (bottom). (An additional 12% overall normalization error is not shown.) RV and Mike Leitch, in progress.

Absorption and Shadowing at RHIC: $R_{\mathrm{AA}}(N_{\mathrm{part}})$

Cold matter effects with $\sigma_{\mathrm{abs}} \sim 2-3$ mb in relatively good agreement with all but most central data

Room left for some dense matter effects

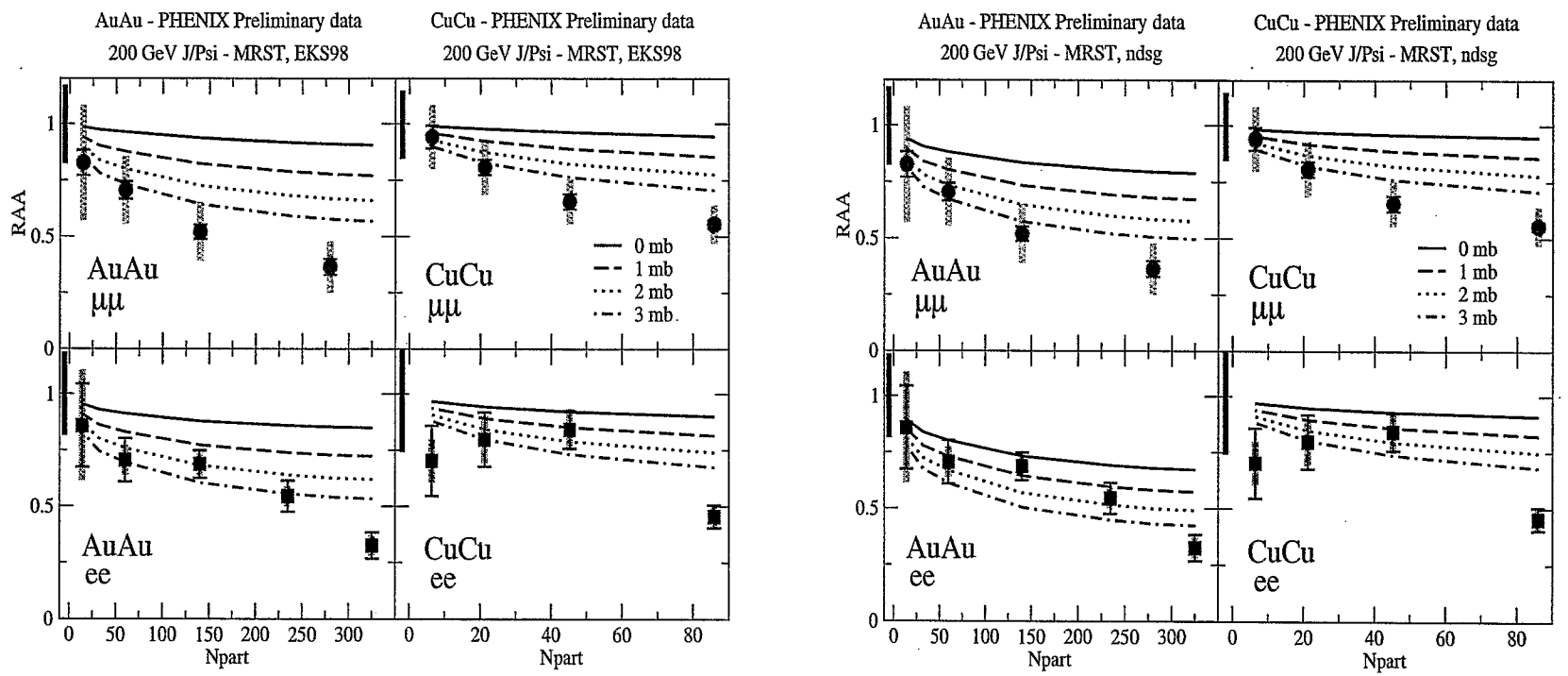


Figure 17: Octet absorption for $0 \leq \sigma_{\mathrm{abs}} \leq 3$ mb (top to bottom) calculated with EKS98 (left) and nDSg (right) with the MRST PDFs and $m = 1.2$ GeV, $\mu = 2m_T$. PHENIX data are shown for Au+Au and Cu+Cu collisions at 200 GeV in the forward $\mu\mu$ (upper) and central ee detectors. RV and Mike Leitch, in progress.

Heavy Quarkonia in a Hot Medium

Cheuk-Yin Wong
Oak Ridge National Laboratory
& University of Tennessee

- Successes of the phenomenological recombination model suggest the possibility that heavy and light quarkonia may be bound in quark-gluon plasma

- Two new surprising results from lattice gauge calculations
  - Lattice spectral function analyses in quenched QCD show that J/ψ is stable up to 1.6Tc
  - Lattice static Q-Q "potential" appears to be very strong between 1 and 2 Tc
  - Shuryak, Zahed, Brown, Lee, and Rho suggested that even light quarkonia may be bound in quark-gluon plasma
- We need
  - to confirm these lattice gauge results
  - to study effects of dynamical quarks on J/ψ stability
  - to assess the strength of the Q-Q potential
  - to examine the stability of heavy and light quarkonia in quark-gluon plasma to provide useful support to the recombination model and the thermal model of chemical yields

How to get the potential for a Q-Qbar pair?

1. Consider a static color-singlet Q and Qbar separated by a distance r in a gluon medium at temperature T in quenched QCD. Get F_1, U_1, and $TS_1 = U_1 - F_1$
2. Study a dynamical Q-Qbar in motion in the gluon medium. For a fixed temperature and volume, the equilibrium of the Q-Qbar and gluons is reached when the grand potential A is a minimum.

Grand potential $A = \mathcal{F} + \text{Langrange multiplier terms}$

$$= \mathcal{U} - TS + \text{Langrange multiplier terms}$$

$\delta A / \delta \psi_i^+ = 0$ leads to the Schroeding er equation for ψ_i :

$$\left\{ \frac{\hbar^2 p^2}{2\mu} + U_{Q\bar{Q}}^{(1)}(r) - \varepsilon_i(Q\bar{Q}) \right\} \psi_i(r) = 0$$

$$U_{Q\bar{Q}}^{(1)}(r) = V_{Q\bar{Q}}(r) + \sum_j n_j(g) \int dr' \phi_j^+(r') \left[V_{Qg}(r' + \frac{r}{2}) + V_{\bar{Q}g}(r' - \frac{r}{2}) \right] \phi_j(r')$$

$$= V_{Q\bar{Q}}(r) + \int dr' \rho_g(r') \left[V_{Qg}(r' + \frac{r}{2}) + V_{\bar{Q}g}(r' - \frac{r}{2}) \right]$$

$$= U_{Q\bar{Q}} + U_{Qg} + U_{\bar{Q}g}$$

But, $U_1 = U_{Q\bar{Q}} + U_{Qg} + U_{\bar{Q}g} + U_g$. Therefore, $U_{Q\bar{Q}}^{(1)}(r) = U_1 - U_g$

By the first law of thermodynamics,

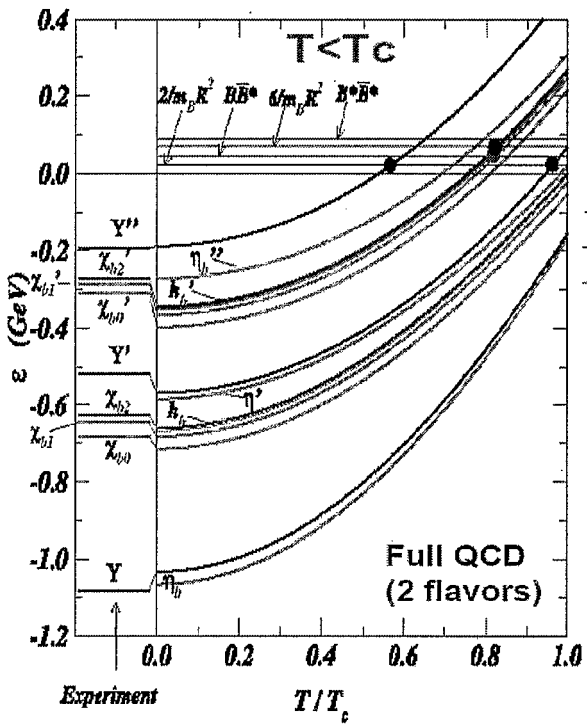
$$\frac{dU_g}{dV} = \varepsilon = T\frac{dS_g}{dV} - p \quad (S_g \text{ is the gluon entropy})$$

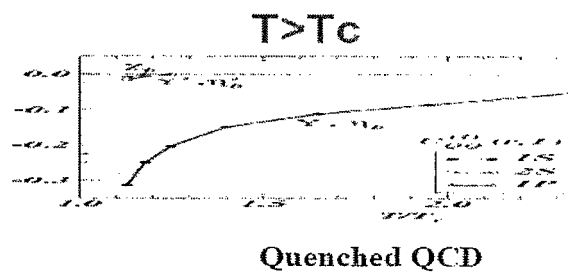
$a(T) = 3p/\varepsilon$ is known from the equation of state

So, $U_g = \frac{3}{3+a} TS_g$. But $TS_g = U_1 - F_1$

Hence, $U_{Q\bar{Q}}^{(1)} = U_1 - U_g = U_1 - \frac{3}{3+a}(U_1 - F_1)$

The potential for between Q and $\bar{Q}$ is $U_{Q\bar{Q}}^{(1)} = \frac{3}{3+a} F_1 + \frac{a}{3+a} U_1$





Spontaneous dissociation temperatures in quenched QCD

Heavy Quarkonium	Spectral Analysis	$U^{(1)}_{\varrho\bar{\varrho}}$ Potential	F_1 Potential	U_1 Potential
J/ψ	1.62-1.70T_c	1.62T_c	1.40T_c	2.60T_c
χ_c , ψ '	below 1.1 T_c	unbound	unbound	1.18T_c
Y		4.10T_c	3.50 T_c	~5.0 T_c
χ_b	1.15-1.54 T_c	1.19T_c	1.10T_c	1.73T_c

Spontaneous dissociation temperatures in quenched QCD & full QCD

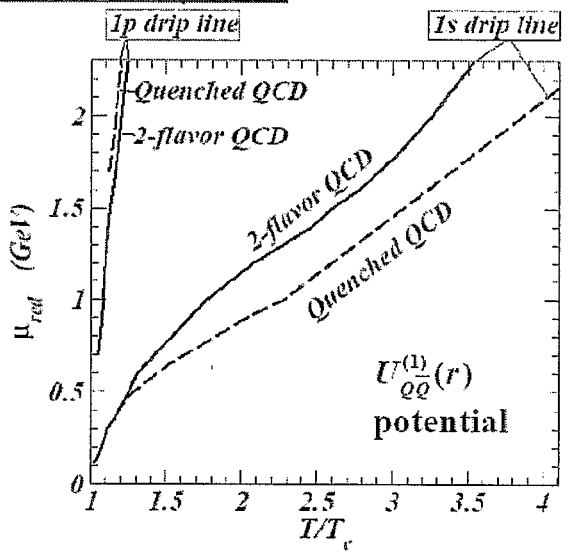
Heavy Quarkonium	Quenched QCD $U^{(1)}_{Q\bar{Q}}$	2-flavor QCD $U^{(1)}_{Q\bar{Q}}$	Spectral Analysis Quenched QCD
J/ψ	$1.62T_c$	$1.42T_c$	~ $1.6\ T_c$
χ_c , ψ'	unbound	unbound	below $1.1\ T_c$
Υ	$4.10T_c$	$3.30\ T_c$	
χ_b	$1.18T_c$	$1.22T_c$	1.15-1.54

The quark drip line

- The quark drip line is the line in the (μ_{red},T) space above which a Q-Qbar is unbound.
- It can be characterized by the nature of the Q-Qbar state: 1s drip line, 1p drip line,..
- Given the Q-Qbar potential, the drip line can be determined by locating the spontaneous dissociation temperature as a function of the reduced mass.

Stability of quarkonia in quark-gluon plasma in full QCD

Dynamical quarks modifies the 1s drip line but only slightly the 1p drip line.



Conclusions

- The potential model is consistent with the lattice gauge spectral function analysis, if the Q-Qbar potential is a linear combination of F_1 and U_1,with coefficients that depend on the equation of state.
- The effects of the dynamical quarks modify only slightly the stability of J/ψ. J/ψ dissociates spontaneously at about 1.62 Tc in quenched QCD and at 1.42 Tc in 2-flavor QCD.
- The interaction between a static quark and antiquark is such that the quark drip lines limit possible quarkonium states with light quarks to temperatures close to Tc.

Heavy flavor production in nuclear collisions

Jörg Raufeisen
Institut f. Theoretische Physik, Philosophenweg 19, 69120 Heidelberg, Germany

At high center of mass energies, hadroproduction of heavy quarks can be expressed in terms of the same color dipole cross section as low Bjorken-x DIS. The corresponding formula is given on transparency one: the cross section for heavy quark pair production can be written as convolution of a light-cone wavefunction $\Psi_{G\to Q\bar{Q}}$ describing the transition $G \to Q\bar{Q}$ and the cross section $\sigma_{q\bar{q}G}$ for scattering a color neutral quark-antiquark-gluon system on a nucleon. The latter can be expressed in terms of the same dipole cross section as low x DIS, for which we employ a phenomenological parameterization. The light-cone wavefunction is calculable in perturbative QCD. This dipole formulation has first been introduced in 1995 by Nikolaev, Piller and Zakharov with the intention of developing a theoretical framework for the description of nuclear effects.

Since the heavy quark cross section varies $\propto 1/m_Q^2$ (modulo logs), most of the theoretical uncertainties arise from the choice of the heavy quark mass m_Q. This is shown for the case of open charm pair production on the second transparency. Of course, the same uncertainty is also present in the NLO parton model. Once free parameters are fixed to describe existing total cross section data, dipole approach and NLO parton model calculations agree numerically well.

Simple eikonalization of the dipole cross section accounts only for part of the initial-state effects. Since the heavy quark pair has a small transverse size, $\rho \sim 1/m_Q$, double scattering gives a higher twist contribution to shadowing. The leading twist contribution to shadowing for heavy quarks originates from rescattering of higher Fock states, containing gluons. This is accounted for by multiplying the nuclear thickness $T(b)$ is the eikonal formula by the gluon shadowing ratio $R_G(b) < 1$. However, in the case of charm the suppression from higher twist rescattering is comparable to the leading twist gluon shadowing, because the former will be enhanced by a power of the saturation scale Q_s^2, which is of order of the charm quark mass. Numerical results are shown on the fourth transparency.

Additional suppression may be caused by energy loss. The energies of the initial state partons are always in a regime where the Landau-Pomeranchuk suppression of bremsstrahlung makes radiative energy loss independent of the projectile energy. Hence, initial-state radiative energy loss is negligible at collider energies. The magnitude of final state energy loss depends on the value of the transport coefficient $\hat{q}$, which is related to the density of the medium and to the dipole cross section. I employ a successful parameterization of the dipole cross section (KST) and use Bjorken's estimate of the energy density to obtain a value for $\hat{q}$ (fifth transparency). The time averaged transport coefficient turns out to be at least one order of magnitude below the value that needed to reproduce the measured quenching of light and of heavy flavored hadrons.

The Dipole Approach to Heavy Quark Production

- The result for the $Q\overline{Q}$ cross section is, (Nikolaev, Piller, Zakharov, JETP **81**, 851, 1995):

$$\frac{d\sigma(pp \to Q\overline{Q} + X)}{dy_{Q\overline{Q}}} = x_1 G(x_1, \mu_F) \int_0^1 d\alpha d^2\rho \left|\Psi_{G\to Q\overline{Q}}(\alpha,\rho)\right|^2 \sigma_{q\bar{q}G}(x_2,\alpha,\rho)$$

  - α: Light-Cone momentum fraction of the heavy quark Q
  - ρ: transverse size of the $Q\overline{Q}$ pair
  - $\left|\Psi_{G\to Q\overline{Q}}(\alpha,\rho)\right|^2 = \alpha_s(\mu_R)/(4\pi^2)\left\{\left[\alpha^2 + (1-\alpha)^2\right] m_Q^2 K_1^2(m_Q\rho) + m_Q^2 K_0^2(m_Q\rho)\right\}$
  - and

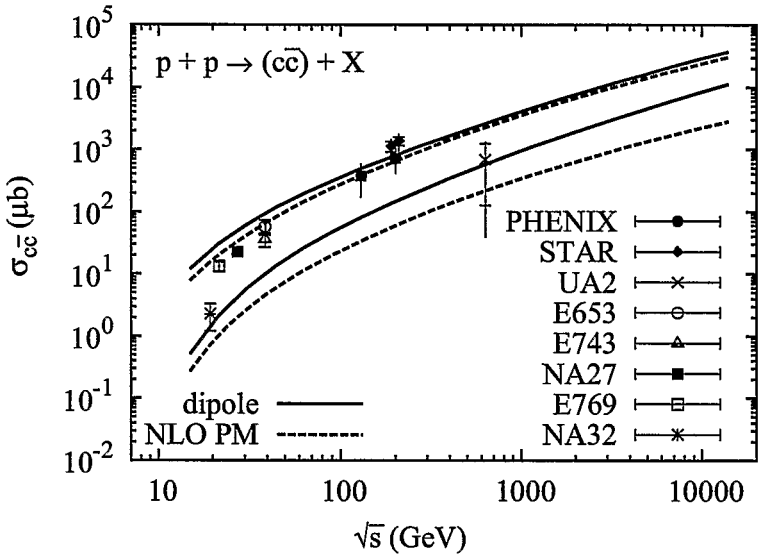
$$\sigma_{q\bar{q}G}(x_2,\alpha,\rho) = \frac{9}{8}\left[\sigma_{q\bar{q}}(x_2,\alpha\rho) + \sigma_{q\bar{q}}(x_2,(1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(x_2,\rho).$$

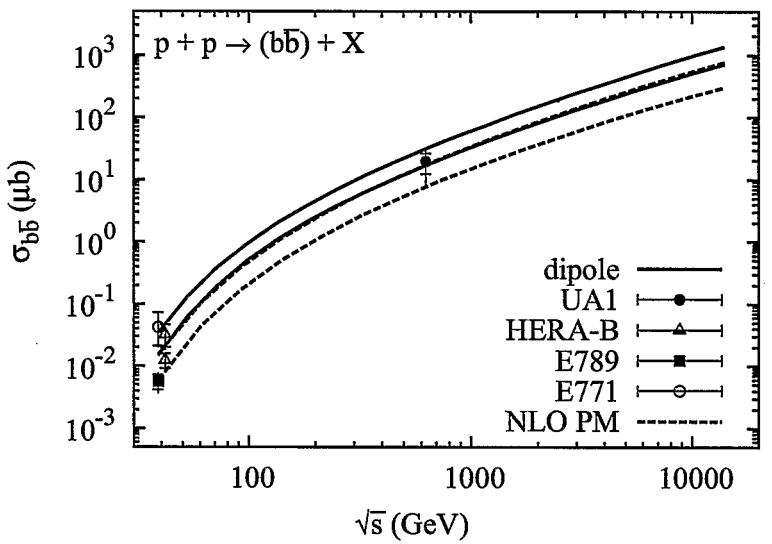
- General rule:

$$\sigma(a + N \to bcX) = \int d\Gamma \left|\Psi_{a\to bc}(\Gamma)\right|^2 \sigma^N_{bc\bar{a}}(\Gamma)$$

  - Γ: set of all internal variables of the (bc)-system
  - $\Psi_{a\to bc}$: Light-Cone wavefunction for the transition $a \to bc$
  - $\sigma^N_{bc\bar{a}}$: cross section for scattering the $bc\bar{a}$-system off a nucleon

Theoretical Uncertainties





JR, J.C. Peng, Phys. Rev. D**67**, 054008, 2003

- Large uncertainties for open charm production from choice of m_c

$$1.2\,\text{GeV} \leq m_c \leq 1.8\,\text{GeV},\ m_c \leq \mu_R \leq 2m_c,\ \mu_F = 2m_c$$
$$4.5\,\text{GeV} \leq m_b \leq 5.0\,\text{GeV},\ m_b \leq \mu_R, \mu_F \leq 2m_b$$

- Dipole Approach valid only at high energies (HERA-B energy too low)

Inclusion of Higher Fock States

- Higher Fock states are included in the parametrization of $\sigma_{q\bar{q}}^N(x,\rho)$.
- However, the rescattering of these higher Fock states is neglected in the eikonal approximation.
- This can be cured by the following recipe:

$$\sigma_{q\bar{q}}^A(x,\rho) = 2\int d^2b \left\{1 - \exp\left(-\frac{\sigma_{q\bar{q}}^N(x,\rho)\widetilde{T}(b)}{2}\right)\right\},$$

where

$$\widetilde{T}(b) = T(b)R_G(x,b)$$

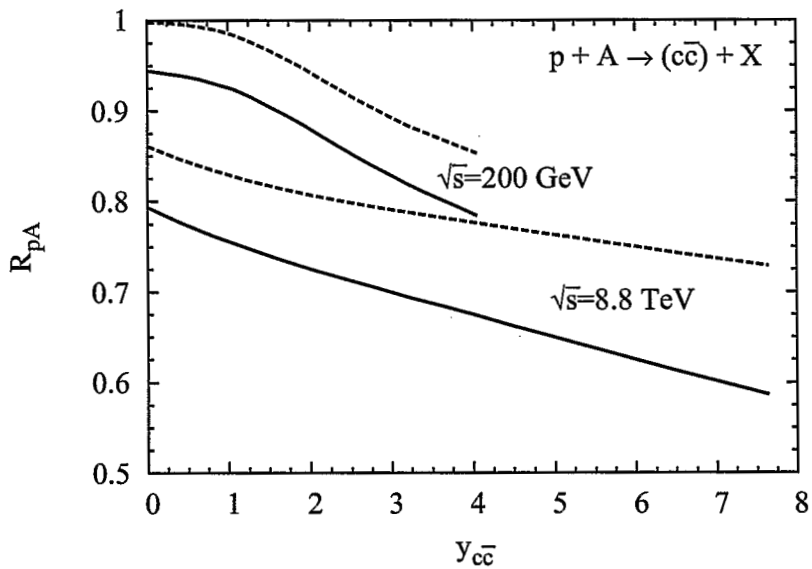
and $R_G(x,b)$ is the leading twist gluon shadowing, calculated from the propagation of a GG dipole through a nucleus.

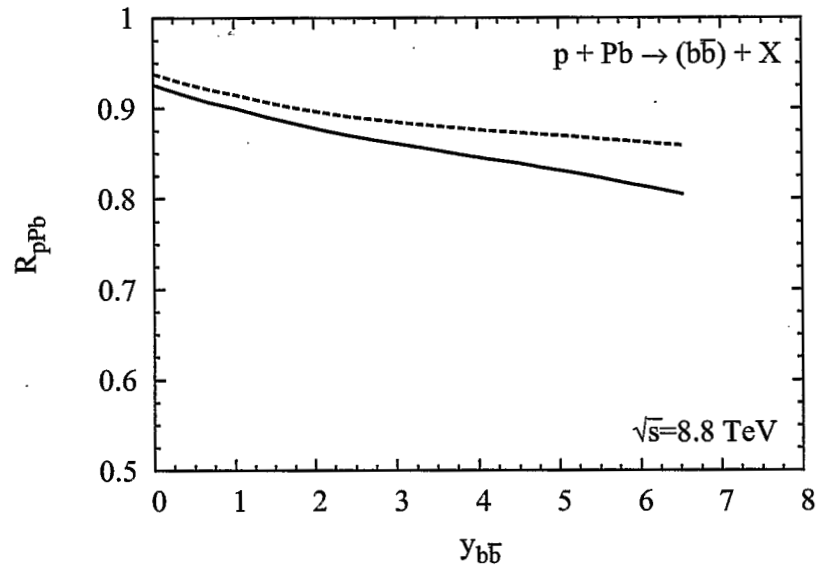
- Expansion of the nuclear dipole cross section:

$$\sigma_{q\bar{q}}^A(x,\rho) = \frac{\pi^2}{3}\alpha_s\rho^2 \int d^2b T(b)R_G(x,b)xG_N(x) - \frac{\pi^2\alpha_s^2}{36}\rho^4 \int d^2b\,[T(b)R_G(x,b)xG_N(x)]^2 + \ldots$$

Already the single scattering term is suppressed due to gluon shadowing.

Suppression of Open Charm and Bottom in pA Collisions





JR, J. Phys. G**30**(2004)S1159

- Dashed curves: Gluon Shadowing only
- Solid curves: Total suppression (including $Q\overline{Q}$ rescattering and Gluon Shadowing)
- Gluon Shadowing reduces the probability for $Q\overline{Q}$ rescattering.

The transport coefficient in heavy ion collisions

- In HIC, a medium with high energy density is created. Bjorken's estimate of the initial energy density at RHIC yields

$$\epsilon_{Bj} = \frac{\langle m_T \rangle}{\pi R_A^2 \tau_0} \left(\frac{dN}{dy} \right)_{y=0} \approx 10\,\text{GeV/ fm}^3 \approx 60\epsilon_{cold} \tag{1}$$

at initial time $\tau_0 = 0.5$ fm.

- Because of the expansion of the medium, the hard parton sees an averaged transport coefficient,

$$\hat{q}^{med} = \frac{2\hat{q}}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau (\tau - \tau_0) \frac{\tau_0}{\tau}. \tag{2}$$

Salgado, Wiedemann, PRL89,092303(2002)

- The averaged transport coefficient is then

$$\hat{q}^{med} \approx 10\hat{q}^{cold} \approx 2\,\text{GeV/ fm}^2. \tag{3}$$

$\hat{q} \gtrsim 20\,\text{GeV/ fm}^2$ is needed to reproduce pion quenching at RHIC.
(Armesto et al, hep-ph/0511257)

Quark Pair Production in the Color Glass Condensate

Raju Venugopalan
Brookhaven National Laboratory

RBRC Heavy Flavor Workshop, Dec. 12th-14th, 2005

Work done in collaboration with J.-P. Blaizot, H. Fujii and F. Gelis.

Based on,

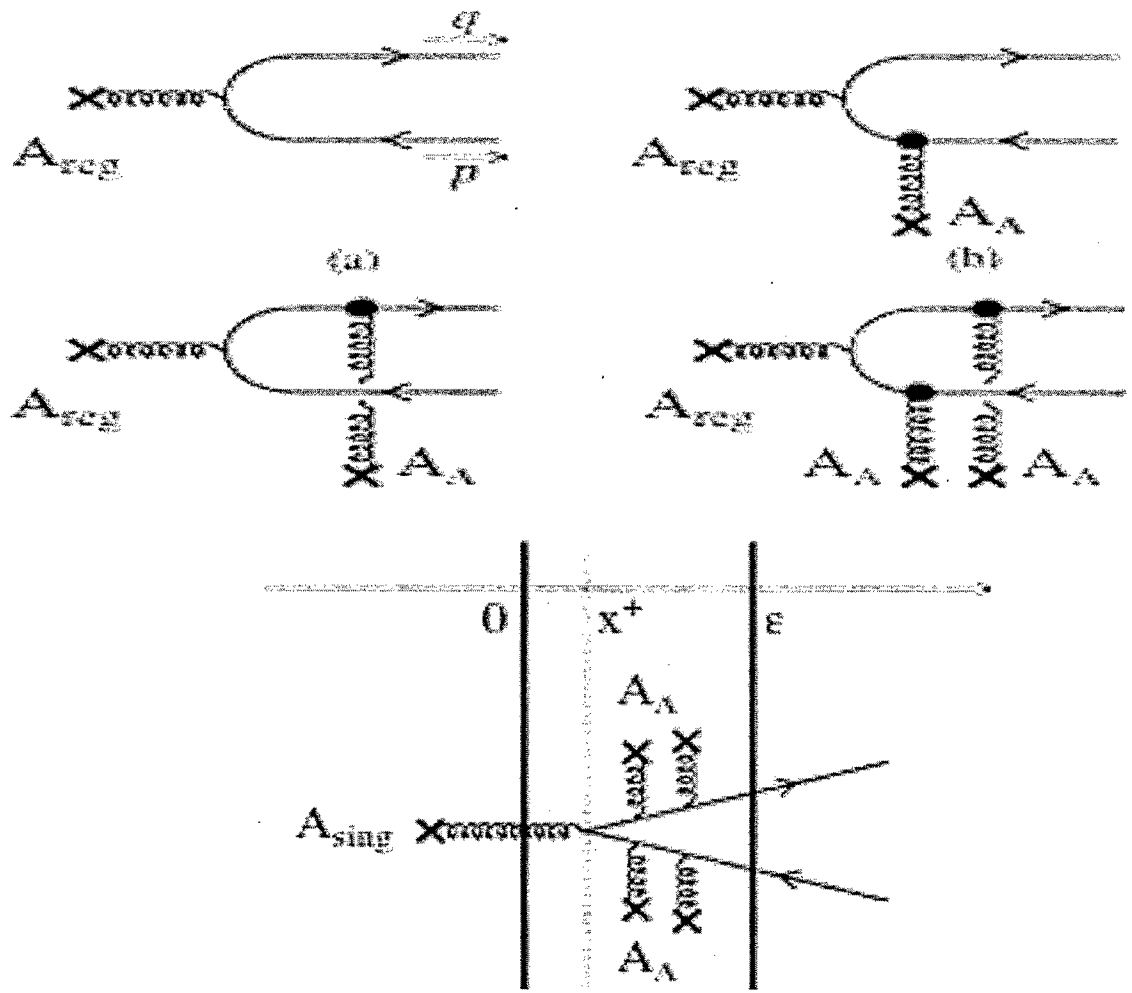
a) F. Gelis and RV, PRD **69**: 014019, (2004)
b) J.-P. Blaizot, F. Gelis and RV, NPA **743**:57, (2004)
c) H. Fujii, F. Gelis and RV, PRL **95**:162002 (2005)
d) H. Fujii, F. Gelis, and RV, in preparation.

Also discuss related work of

Kharzeev & Tuchin; Tuchin;
Gelis, Kajantie and Lappi

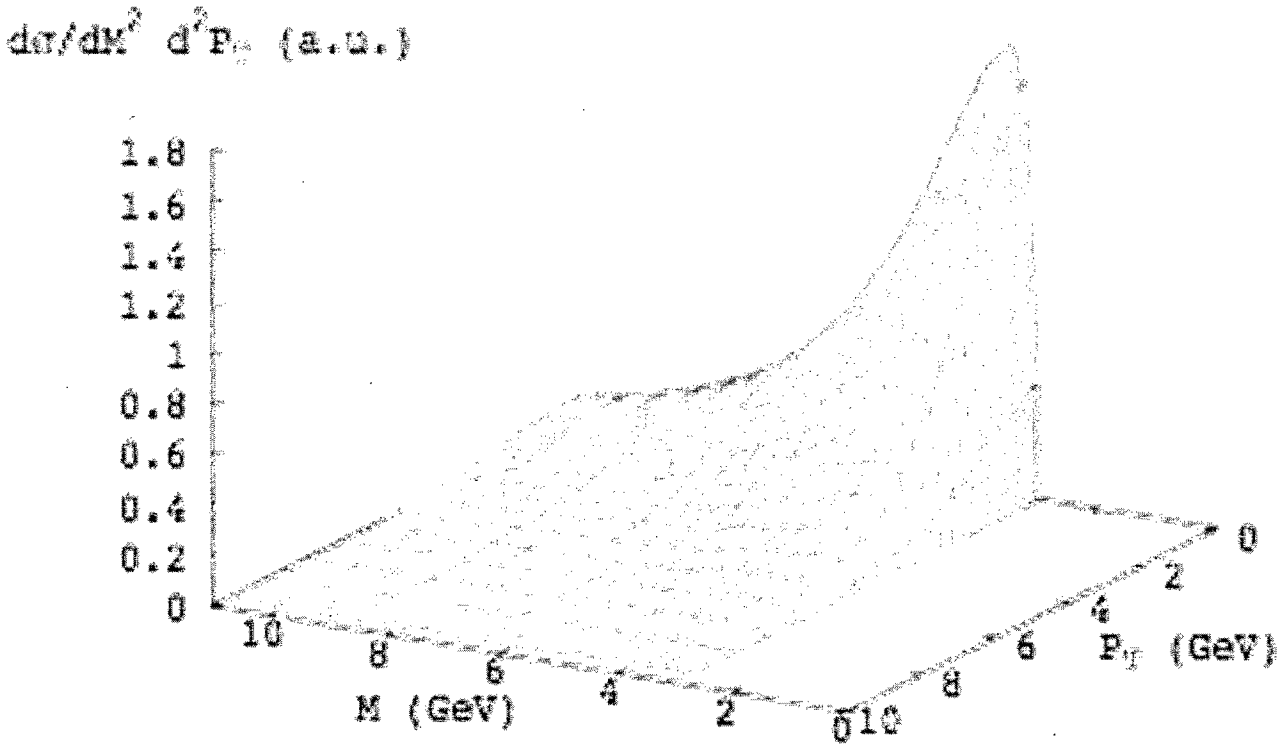
QUARK PRODUCTION TO ALL ORDERS IN pA

Blaizot, Gelis, RV

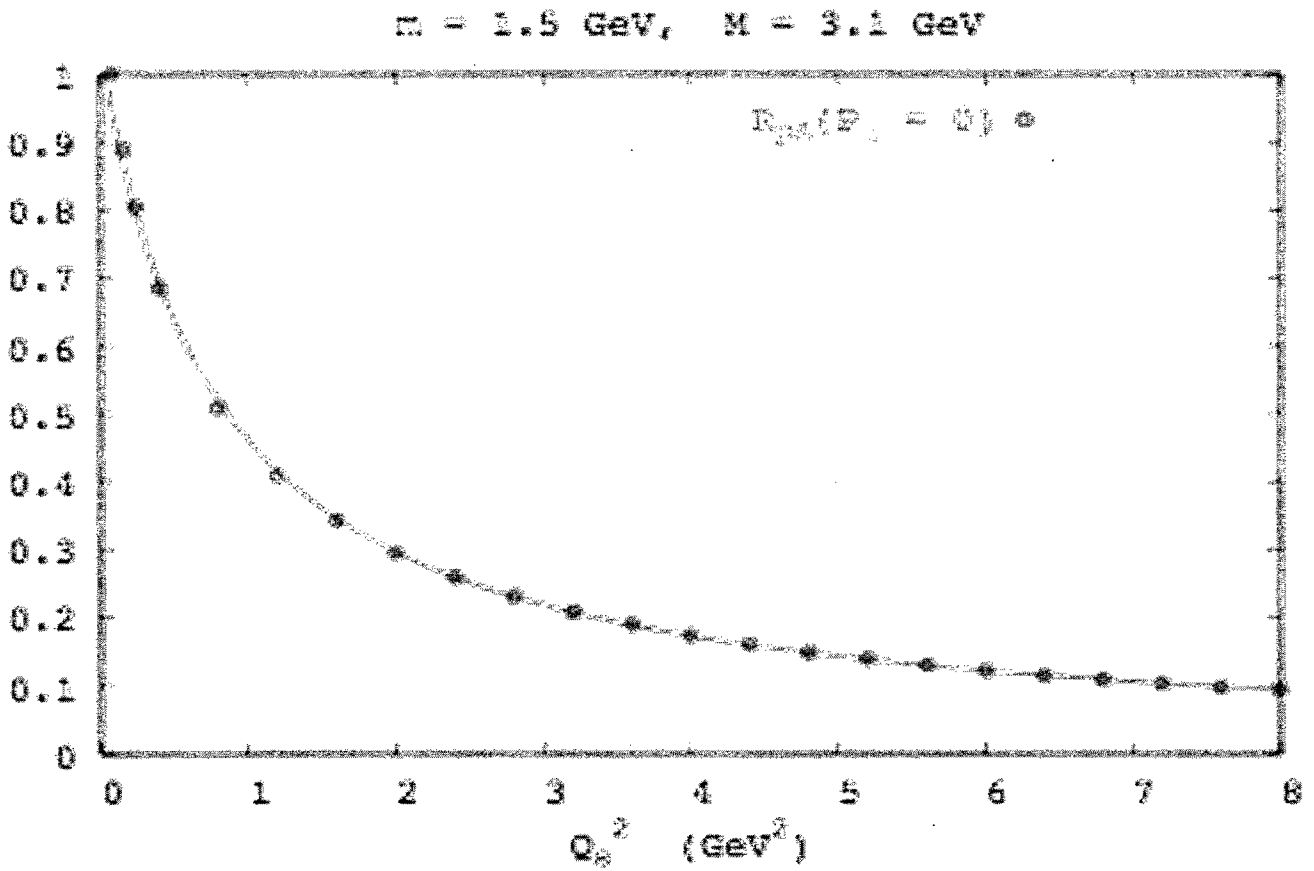


☆ Neither quark pair production nor single quark production is kt-factorizable

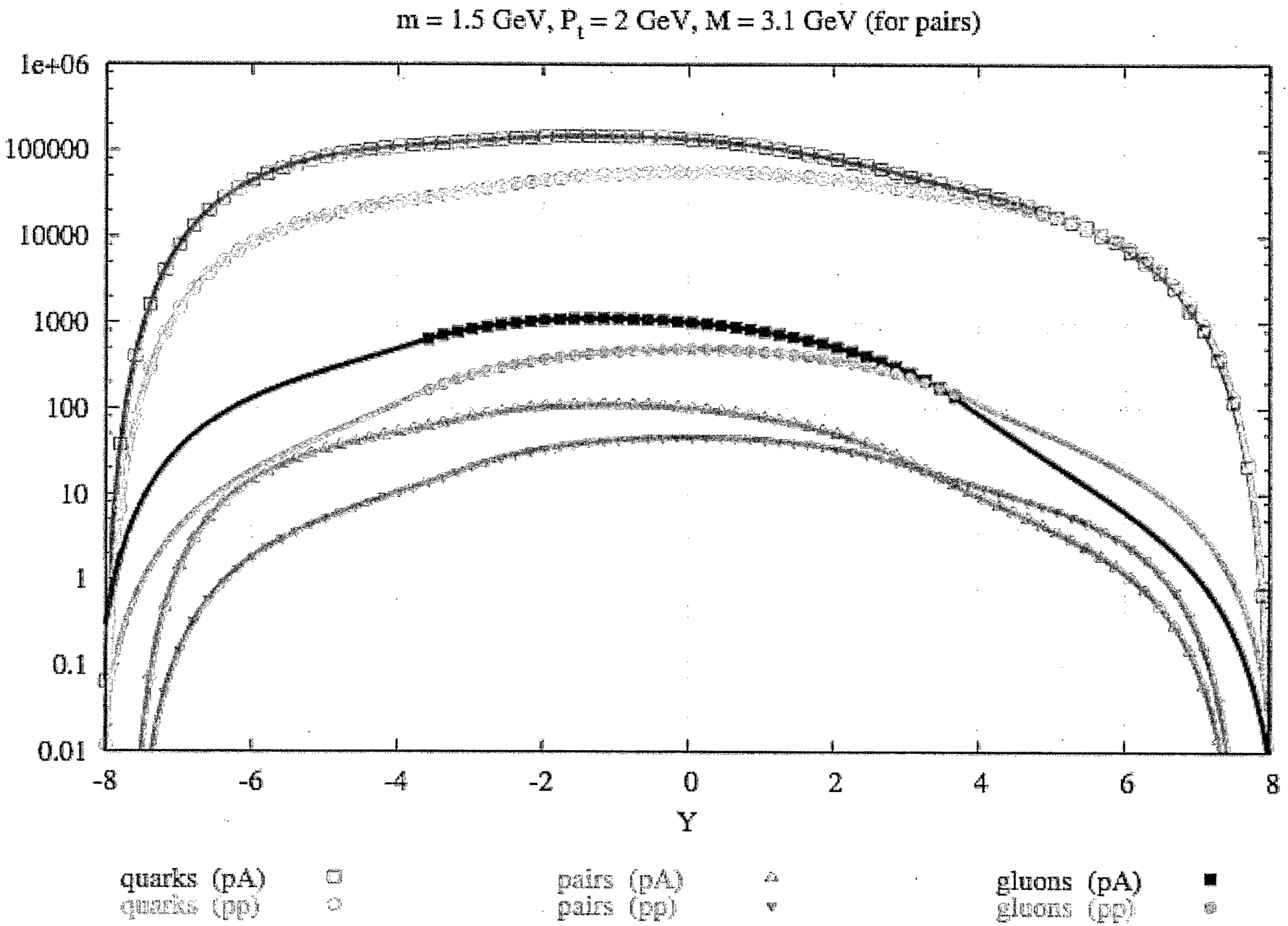
Pair cross-sections:



R_pA: suppression $R_{pA} \propto 1/Q_s^2 \; ; \; Q_s^2 \sim A^{1/3}$



Frankfurt, Strikman; Matsui, Fujii


m = 1.5 GeV, P_t = 2 GeV, M = 3.1 GeV (for pairs)
1e+06
100000
10000
1000
100
10
1
0.1
0.01
-8
-6
-4
-2
0
2
4
6
8
Y
quarks (pA)
quarks (pp)
pairs (pA)
pairs (pp)
gluons (pA)
gluons (pp)

Outlook

We can compute both small x evolution (shadowing) and multiple scattering effects in quark production on same footing. More detailed
studies in progress for D-Au collisions

Quark production in AA collisions can be computed at the earliest stages.

Energy loss? Is NLO in this picture but recent theoretical developments suggest it can be computed consistently.

Heavy Flavour Production at HERA (H1/ZEUS)

Achim Geiser, DESY Hamburg

Heavy Flavor Productions and Hot/Dense Quark matter,
BNL, USA, 13. Dec. 05

This is an excerpt only. For full talk, see workshop web pages

- open heavy flavour production
  - photoproduction
  - Deep Inelastic Scattering (F_2)
- inelastic quarkonium production (J/ψ)
- conclusions

thanks to O. Behnke for some slides

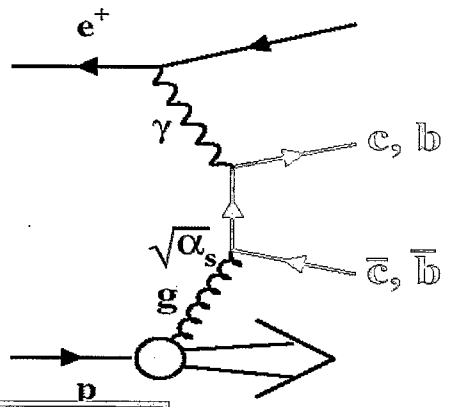
pQCD approximations

assume one dominant hard scale:

Massive scheme: $\rightarrow m_b$

- **b massive**
- **neglects** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **Perturbative production:**

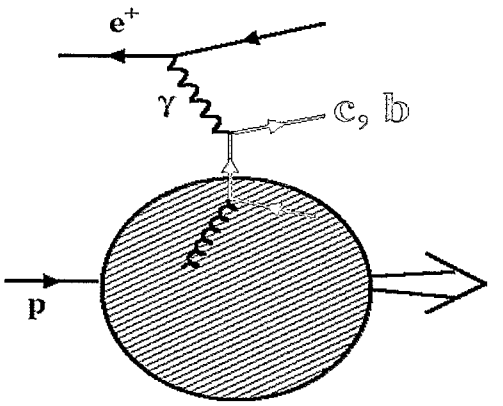


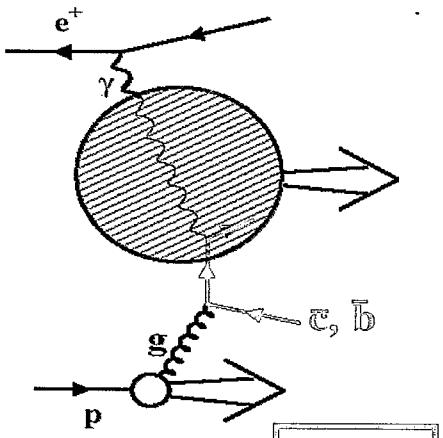
(FO) NLO

Massless scheme: $\rightarrow p_T, Q^2$

- **b massless!!!**
- **Resums** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **b also in Proton and Photon!**





NLL

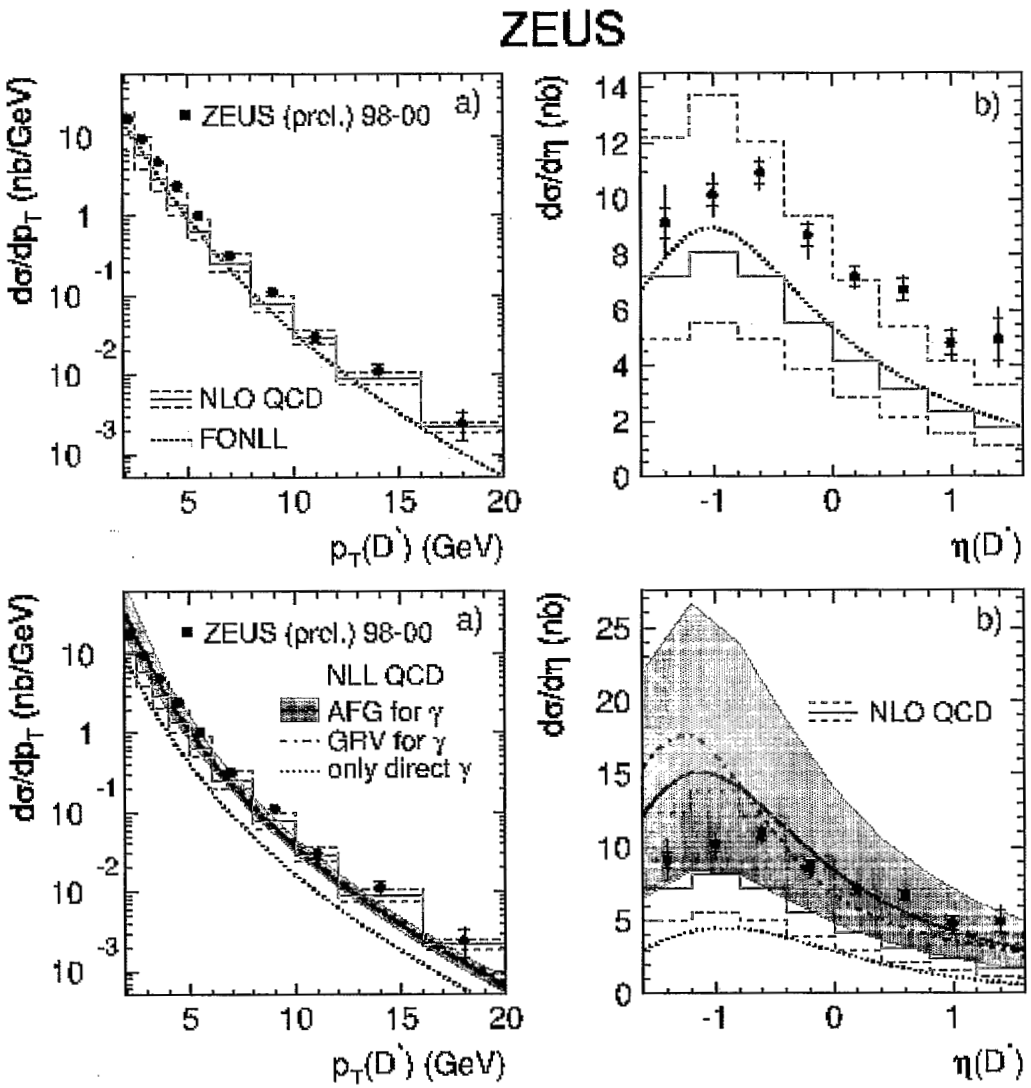
Variable schemes (VFNS):

$\rightarrow$ **at small** Q^2 **massive, at large** Q^2 **massless**

FONLL

which describes HERA data best?

Charm in photoproduction



QCD calculations using

CTEQ5M1 + AFG structure functions

$m_c = 1.5 +- 0.2$ GeV, $\mu_0^2 = m_c^2 + p_T^2$,

$\mu_r = \mu_f = \mu$, $\mu_0/2 < \mu < 2\mu_0$

$f(c \to D^*) \approx 0.235$

$e_{Peterson} = 0.035$ (FO NLO), 0.02 (FONLL)

NLO (FMNR)

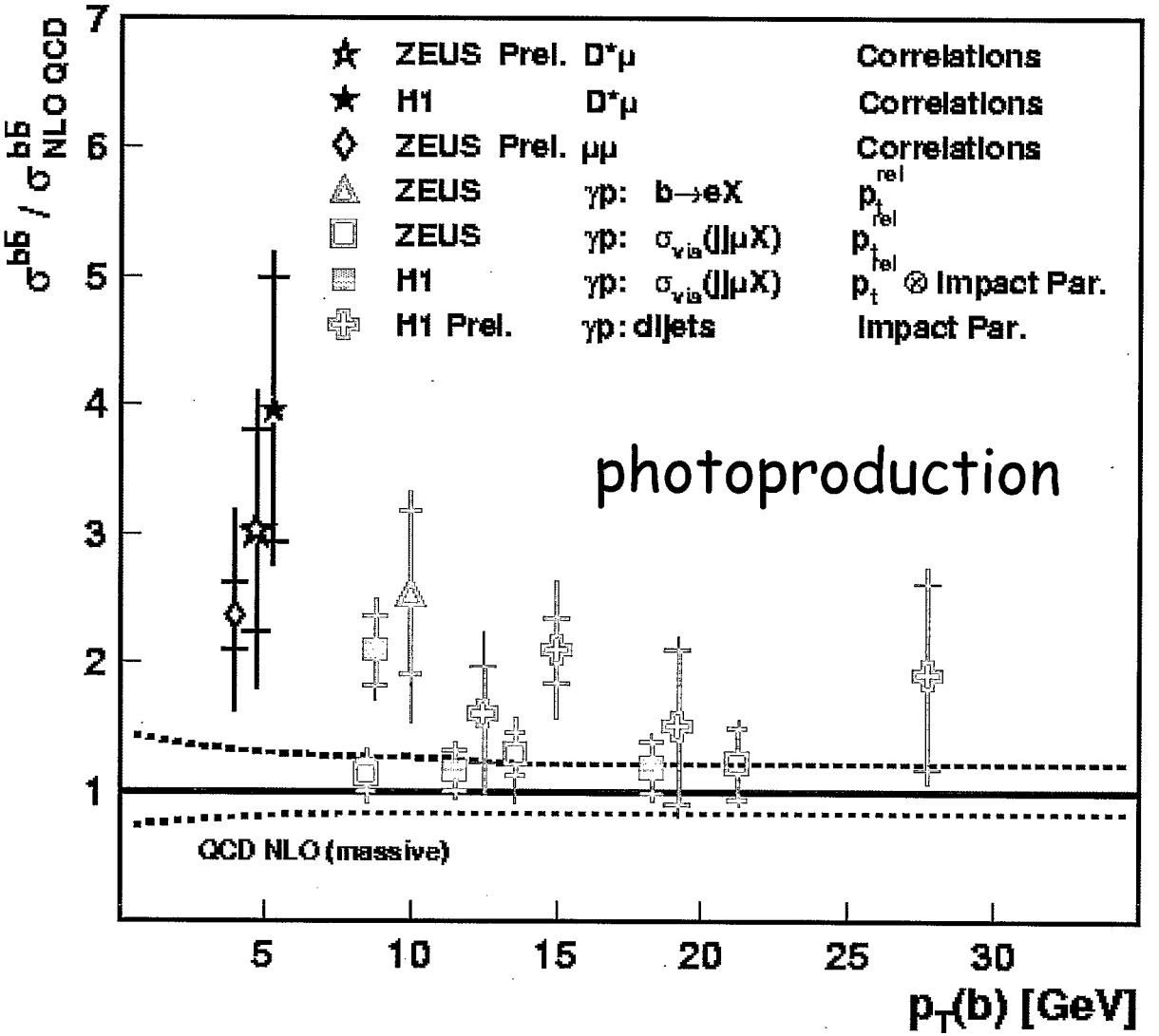
reasonable agreement
some deviations at forward η

FONNL (Cacciari et al.)
similar, not better at large p_T

NLL (Kniehl et al.)
larger norm., shape not better

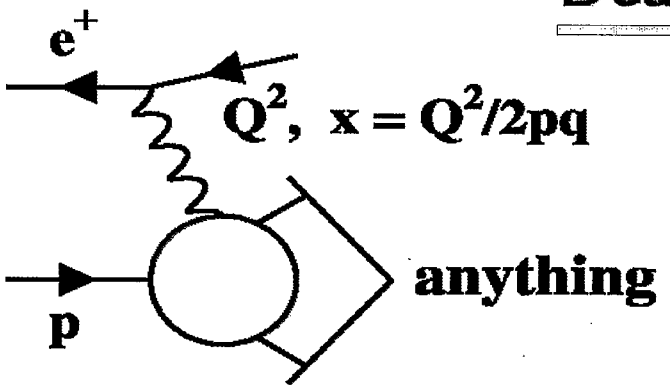
Beauty cross sections vs. p_{Tb}

$p_{Tb} \gg m_b$
better
described
than
$p_{Tb} \sim m_b$?

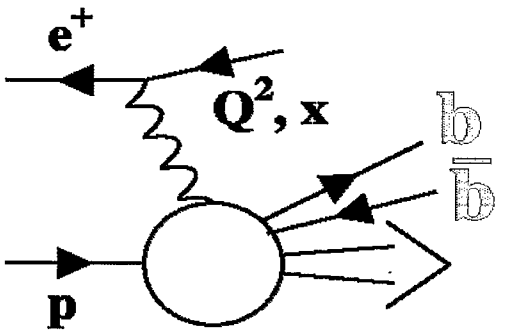


Beauty contribution to F_2

Beauty contribution to inclusive DIS



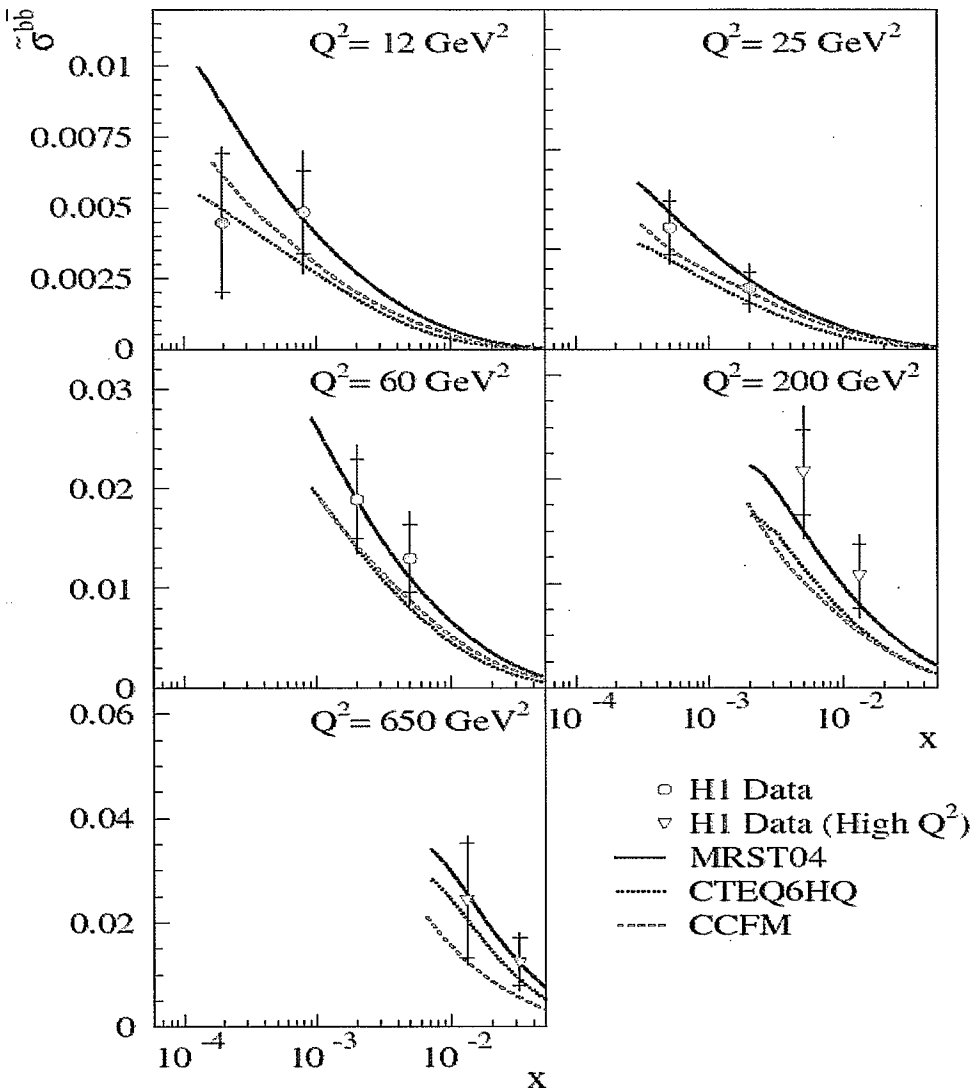
$$\frac{d^2\sigma^{ep}}{dQ^2dx} \propto F_2(x, Q^2)$$



$$\frac{d^2\sigma^{ep\to b\bar{b}x}}{dQ^2dx} \propto F_2^{b\bar{b}}(x, Q^2)$$

Use inclusive lifetime tagging to determine fraction of b quark events $\rightarrow F_2^{b\bar{b}}$

Beauty contribution to F_2



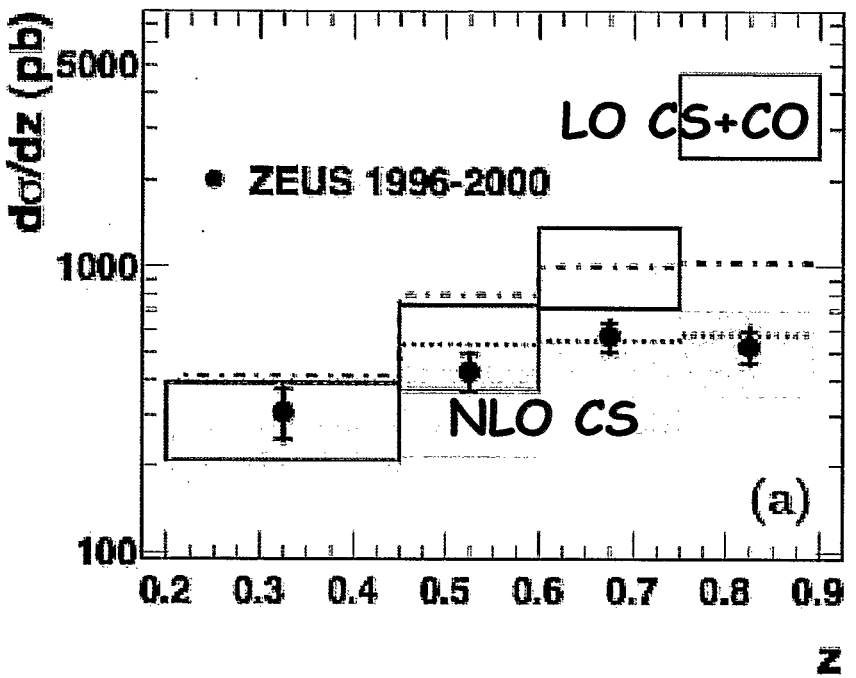
$F_2^{b\bar{b}}$ vs x in bins of Q^2

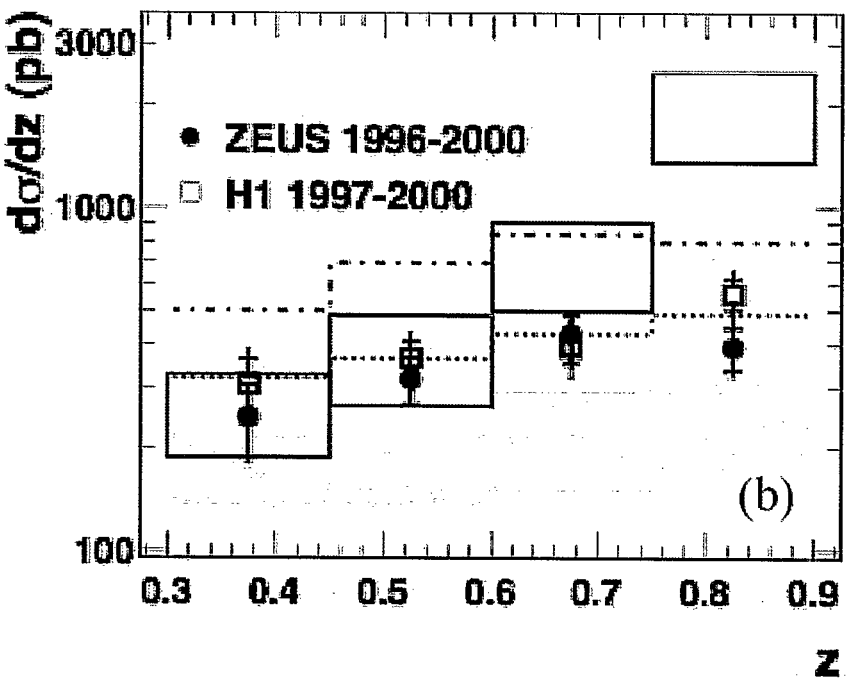
- **First measurements at all!**
- **Rise towards smaller x and larger Q^2 $\leftrightarrow$ gluon density**
- **MRST04 and CTEQ6HQ differ up to factor two!**
- **Data described well by calculations**

inelastic J/ψ electroproduction

CS + kt-factorization

$p_T^*(J/\psi) > 1$ GeV





Color Octet contribution not really needed to describe HERA data

Summary and Conclusions

- Heavy Flavour production in e-p collisions is good testing ground for perturbative QCD
- charm production: reasonably described, no clear preference between "massive" NLO and "massless" NLL calculations. NNLO or NLO+PS needed for some regions of phase space. charm fragmentation measurements competitive with e^+e^-.
- beauty production: reasonable description at high p_{Tb}
  getting worse (but still acceptable) at low p_{Tb}?
  problem with threshold region?
- DIS (F_2): both charm and beauty well described
  first measurement of $F_2^{b\bar{b}}$
- inelastic J/ψ production: data acceptably described by both LO CS+CO, and NLO CS only. CO not really needed.
- HERA II performing well. Expect improved results soon!

Surprises and Anomalies in Heavy Quarkonium Production

Jianwei Qiu

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Ames, Iowa 50011, U.S.A.

Quantum Chromodynamics (QCD) as a theory for strong interaction is a very solid building block of Standard Model. It has an exact SU(3) color gauge symmetry and the asymptotic freedom at short-distance. QCD perturbation theory has shown a tremendous success in interpreting phenomena in high energy collisions.

How QCD behaves outside the asymptotic region? How QCD bound states were formed? And many many questions about QCD and strong interactions have not been answered or not yet asked. Although lattice QCD calculations have been providing new insights to the non-perturbative regime of QCD, its full potential is still limited by the power of modern computers. In this talk, I will demonstrate why production of heavy quarkonia is arguably one of the most fascinating subjects in strong interaction physics and it might offer unique perspectives into the formation of QCD bound states.

Because of the heavy quark mass, heavy quarkonium has two intrinsic scales: the scale to binding the heavy quark pair together, a non-perturbative scale; and the scale to produce it, a perturbative scale of the order of heavy quark mass. Heavy quarkonium provides a non-relativistic system of strong interaction, which naturally allows us to use the non-relativistic approximation of QCD (NRQCD) to study the formation of heavy quarkonium while the strong coupling constant is small enough for calculating the production of the heavy quark pair. NRQCD model for calculating heavy quarkonium production has been very successful in interpreting many data, in particular, the high p_T data from Tevatron at Fermilab.

On the other hand, there are still many surprises both experimentally and theoretically. For example, NRQCD failed to explain the data on J/ψ polarization measured at the Tevatron while it is very consistent with the unpolarized data. The prediction of NRQCD is about one order of magnitude smaller than the data on production of double charmonia at Belle. It is fair to say that after 30 years, since the discovery of J/ψ, theorists still have not been able to fully understand the production mechanism of heavy quarkonia.

RHIC with its capability to accelerate different particles could offer an excellent opportunity to learn and exam the formation of heavy quarkonium, and in general, QCD bound states. Nuclear matter could be an effective filter to distinguish the differences between various production models.

Heavy quarkonium production

- Quarkonium has two intrinsic scales:

  Heavy quark mass:

  $$m_Q > \text{GeV} \quad \Rightarrow \quad \alpha_s\left(2m_Q\right) < 0.3$$

  A perturbative scale

  Heavy quark binding:

  $$M_{J/\psi} - 2m_c \sim fm^{-1} \quad \Rightarrow \quad \alpha_s\left(fm^{-1}\right) > 1$$

  A non-perturbative scale

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

- Non-perturbative physics in "production" is different from "decay"

  A heavy quark pair with invariant mass less than the threshold of a pair of open flavor mesons will become a bound quarkonium

  Charm: $\frac{v^2}{c^2} \sim \frac{k_Q^2}{m_Q^2} \sim \frac{M_D^2 - m_c^2}{m_c^2} \sim 0.8 > 0.3$ Bottom: $\frac{v^2}{c^2} \sim 0.4 > 0.1$

  Depend on choice of heavy quark mass

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Hidden heavy flavors - Quarkonia

- Heavy quark pairs are produced locally:

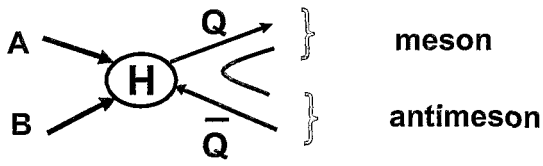
  $$\Delta r \sim \frac{1}{2m_Q} \leq 0.1 \text{ fm (for a charm-quark pair)}$$

  $$\leq 0.025 \text{ fm (for a b-quark pair)}$$

  Heavy quark pairs are produced at a distance scale much less than fm

  A heavy quark pair needs to be coherently self-interacted and expanded before a heavy quarkonium can be formed

- A heavy quark pair is likely to become two open flavor heavy mesons if the invariant mass of the pair is larger than the total mass of the two mesons:



Open flavor threshold for the quarkonium production

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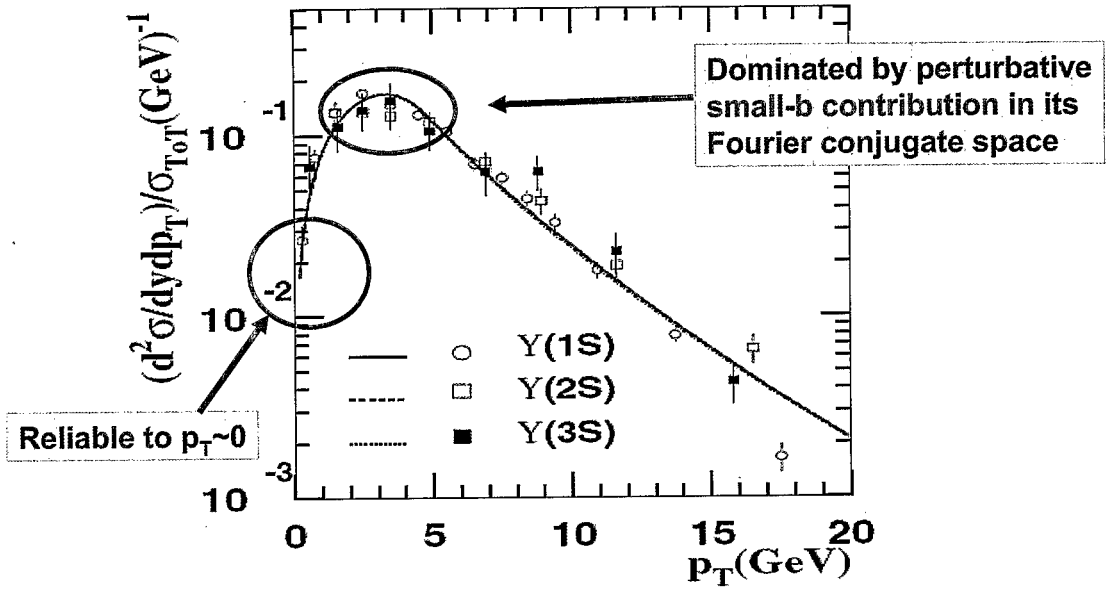
CDF Run – I Upsilon data



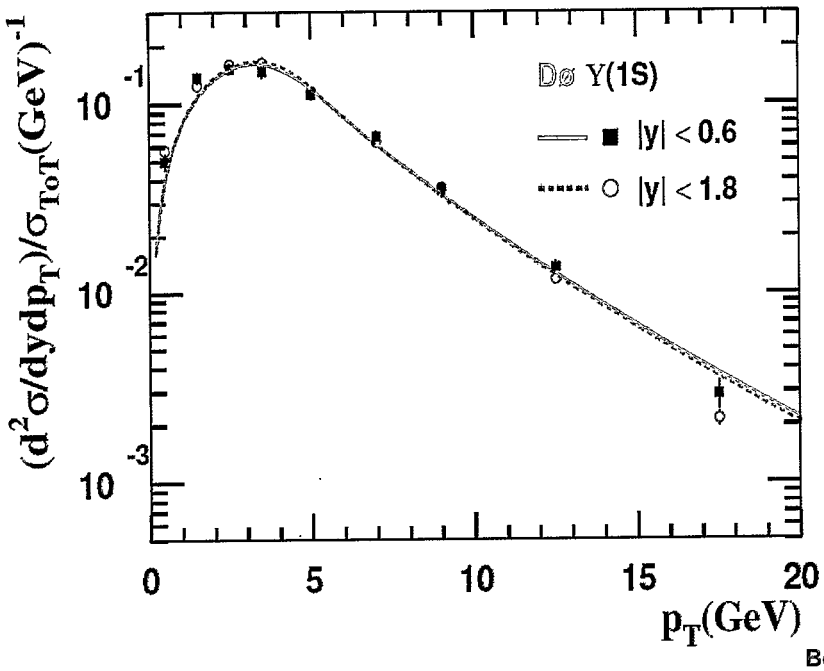
With all order resummation of soft gluon shower

Berger, Qiu, Wang

Jianwei Qiu, ISU

D0 Run – II Upsilon data

(a prediction)

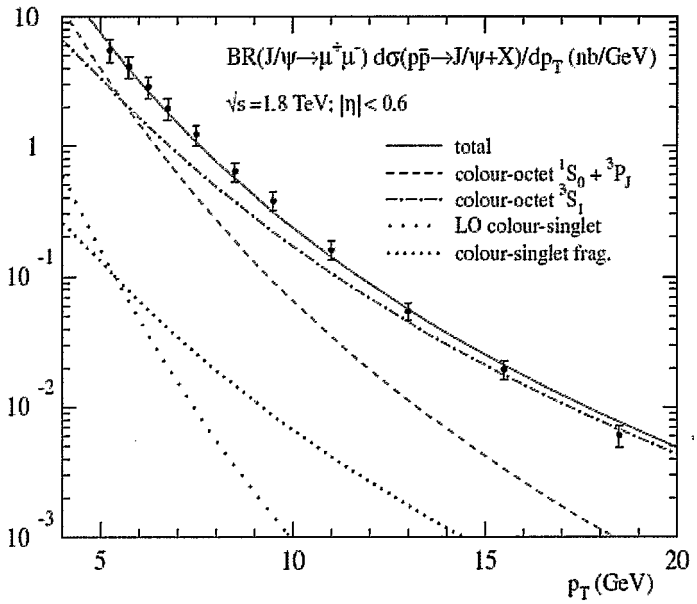


Berger, Qiu, Wang

Jianwei Qiu, ISU

NRQCD model vs CDF data

- Tevatron data for J/ψ, ψ', Υ production

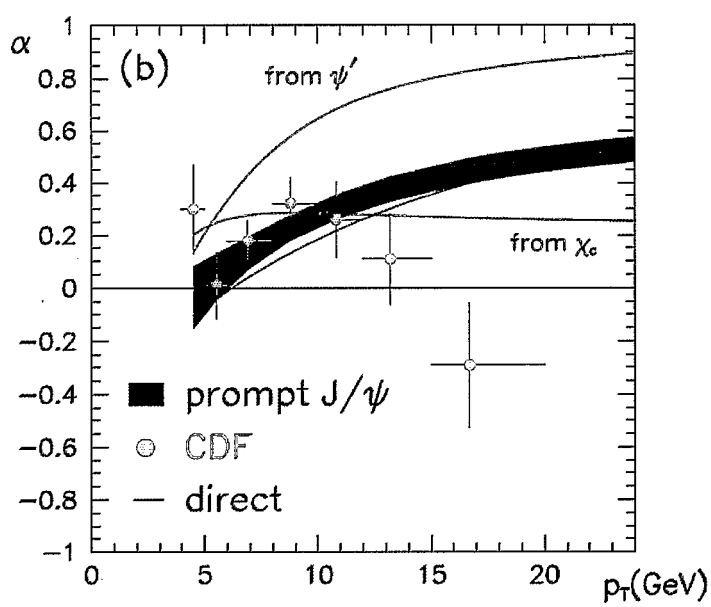


- Data are more than an order of magnitude larger than the predictions of the color-singlet model.
- Color-octet matrix elements are determined from fits to the data.
- p_T distributions are consistent with NRQCD, but not with the color-singlet model.

Bodwin's talk

Jianwei Qiu, ISU

Surprises – experimentally



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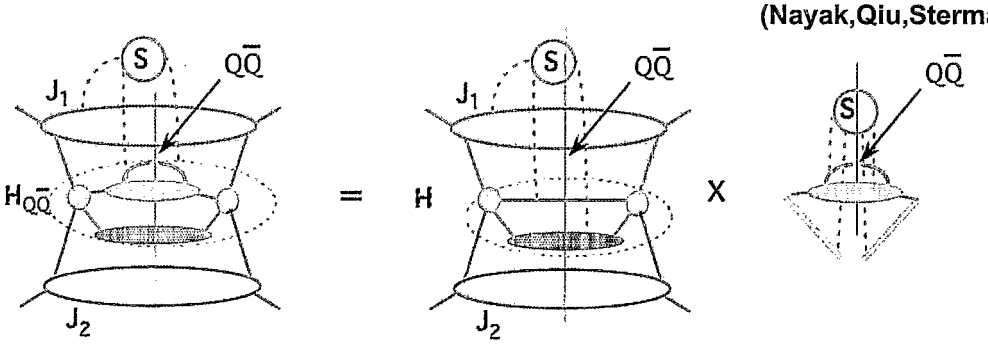
Surprises – theoretically

- No proof for NRQCD factorization for production for $p_T \leq m_Q$
- When $p_T >> m_Q$, single hadron inclusive cross section factorizes

(Nayak,Qiu,Sterman)



- Further factorization: $D_{H/g}(z, m_c, \mu) = \sum_n d_{g\to c\bar{c}[n]}(z, \mu, m_c)\,\langle \mathcal{O}_n^H \rangle$

  succeeds up to two-loop level, after a redefinition of NRQCD matrix elements – No all order proof for the production!

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Anomalies

Double $c\bar{c}$ Production at Belle and BaBar

$$e^+e^- \to J/\psi + \eta_c$$

- Belle: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.
- BaBar: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 17.6 \pm 2.8 \pm 2.1$ fb
- NRQCD: $\sigma(e^+e^- \to J/\psi + \eta_c) = 2.31 \pm 1.09$ fb

Comparison to Belle & Theory

$J/\psi\, c\bar{c}$	η_c	χ_{c0}	$\eta_c(2S)$
Nevt, BaBar ($124.4\, fb^{-1}$)	127 ± 20	81 ± 16	121 ± 20
Nevt, Belle ($155\, fb^{-1}$)(*)	235 ± 26	89 ± 24	164 ± 30
(+) $\sigma_{Born} \times \mathcal{B}_{>2}$, BaBar (*)	$17.6 \pm 2.8 \pm 2.1$	$10.3 \pm 2.5 \pm 1.8$	$16.4 \pm 3.7 \pm 3.0$
(+) $\sigma_{Born} \times \mathcal{B}_{>2}$, Belle (*)	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
(+) NRQCD by Braaten and Lee [1]	2.31 ± 1.09	2.28 ± 1.03	0.96 ± 0.45
(+) NRQCD by Liu, He and Chao [2]	5.5	6.9	3.7

See Bodwin's talk for updated numbers

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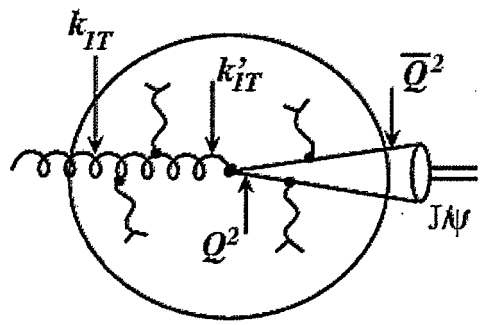
Multiple parton rescattering model

- J/ψ is unlikely to produce at the production point
- Final-state:
  Increases the relative momentum of the pair
  $\bar{Q}^2 > Q^2$
  leads to suppression of J/ψ
- Threshold effect leads to different effective σ_{abs}
- Leads to curved line for the suppression factor.



- Initial-state:
  Broadening in k_T
  $k_T' > k_T$
  leads to x_F-dependence of the suppression in pA

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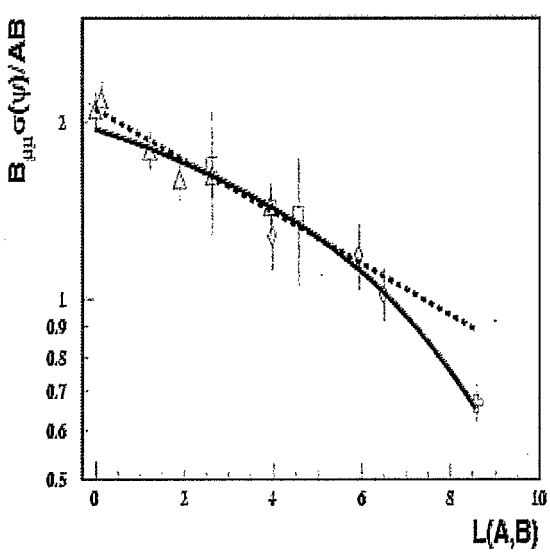
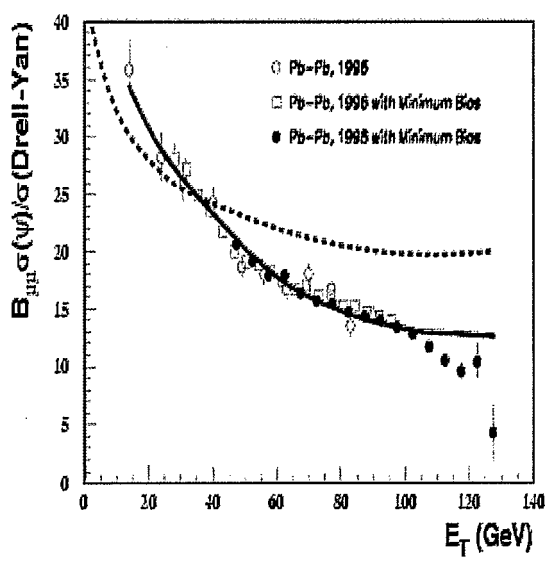
Comparison with SPS data

Qiu, Vary, Zhang, PRL 2002





Calculation for RHIC kinematics is underway

Accardi and Qiu

Jianwei Qiu, ISU

Heavy Flavour Production at Fermilab Tevatron

Mary Bishai
Brookhaven National Lab

In summer 2001, Run II of the Fermilab Tevatron began. As of December, 2005 more than 1fb^{-1} of $p\bar{p}$ data at $\sqrt{s} = 1.96$ TeV has been collected by both the CDF and D0 detectors. There have been several notable new results in heavy flavour production:

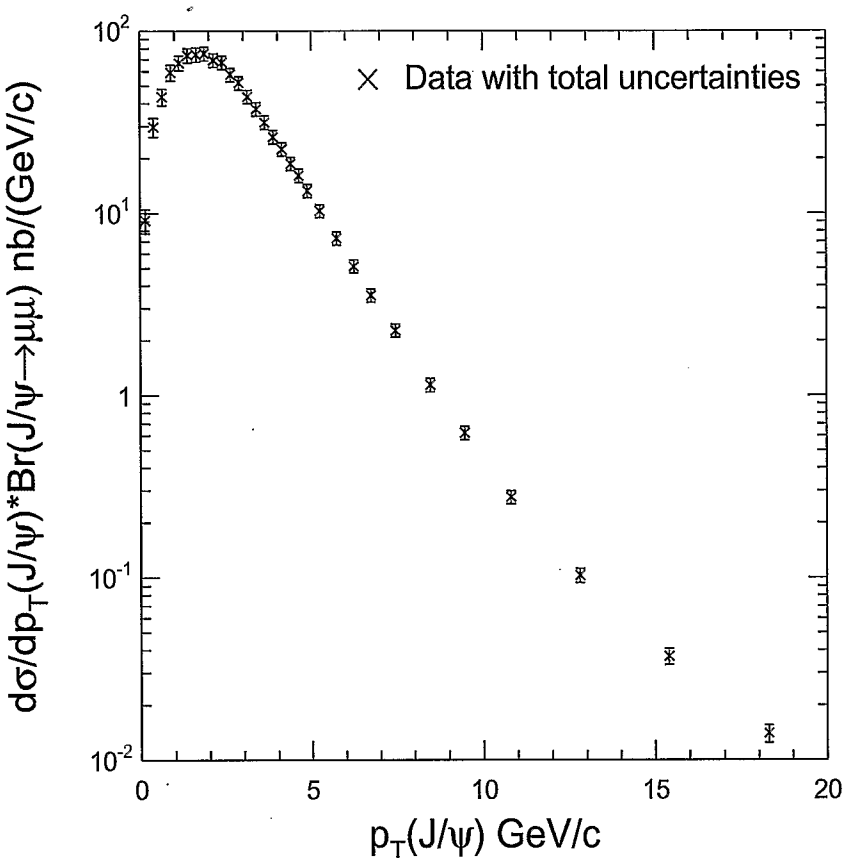
Quarkonia: New measurements of the inclusive J/ψ cross-sections down to $p_T = 0$ GeV/c (CDF) and $|y| < 2.0$ (D0). The new measurement of $\Upsilon(1S)$ cross-sections at $\sqrt{(s)} = 1.96$ TeV (D0) is found to be in good agreement with the Run I measurements from CDF. The measurement of J/ψ polarization at $\sqrt{(s)} = 1.96$ TeV by CDF is found to follow the same general trend of increasing longitudinal polarization at high p_T as the Run I measurement and is still in conflict with the COM predictions. Evidence for diffractive production of exclusive $\mu\mu\gamma$ candidates has been observed by CDF.

Charm and Bottom production: The measurement of the central ($|y| < 0.6$) b-hadron cross-sections over all p_T has been performed by CDF and is found to be in good agreement with FONLL calculations. The b-jet cross-sections at $\sqrt{(s)} = 1.96$ TeV have been measured by CDF and D0 and found to be in good agreement with Pythia LO MC. The $D^{+,0,*}$, D_s differential cross-sections have been measured by CDF and found to be consistent with FONLL calculations.

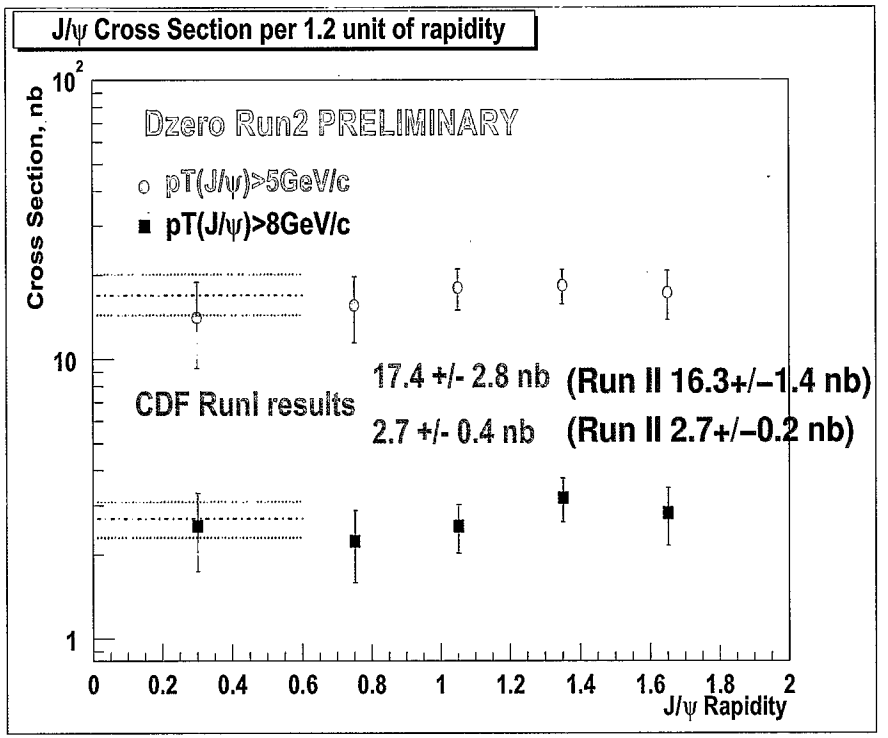
J/ψ Cross-sections - Run II

$$\frac{d\sigma(p\bar{p}\rightarrow J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity}\times\text{acceptance}\times\text{efficiency}\times\Delta p_T}$$

$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6)$ vs $p_T(J/\psi)$



$\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5,8GeV/c)$ vs $y(J/\psi)$



$$\sigma(p\bar{p} \rightarrow J/\psi X, \mid y(J/\psi) \mid < 0.6) = 4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\ \mu b$$

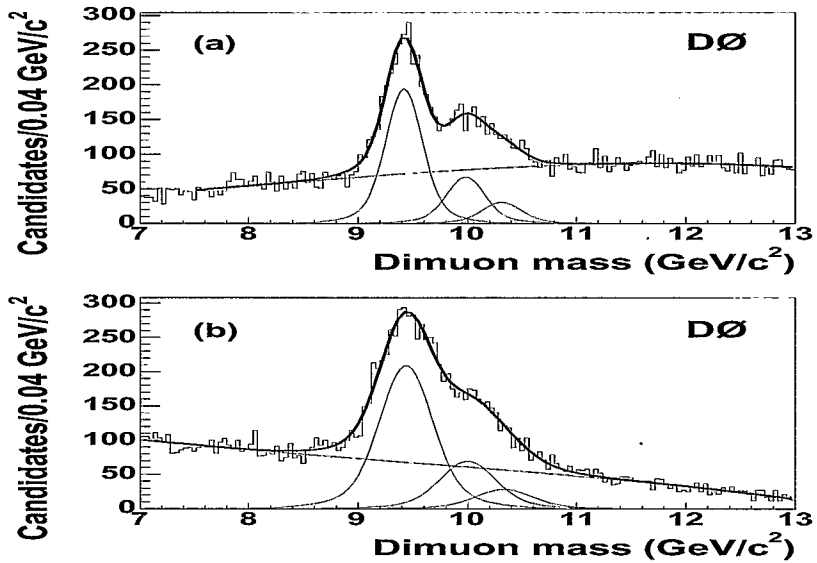
Υ production at $\sqrt{s} = 1.96$ TeV

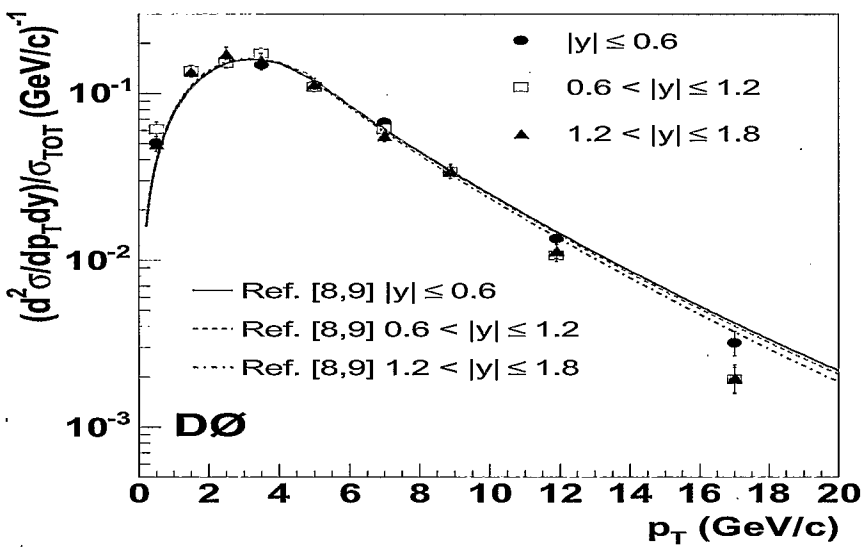
D0 Run II measurements of the Υ cross-sections from 160 pb^{-1}.

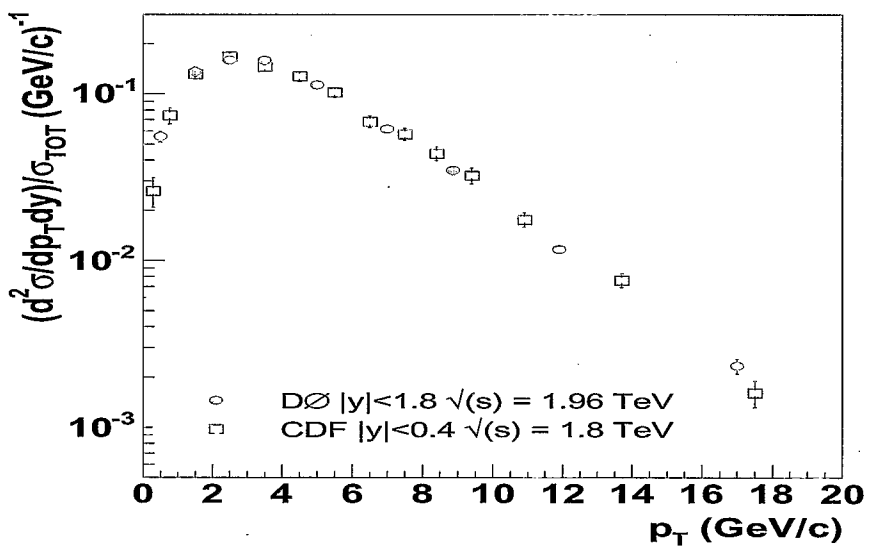
PRL 94, 232001 (2005).

(a) $|y^{\Upsilon}| \leq 0.6$

(b) 1.2 < $|y^{\Upsilon}| \leq 0.6$ < 1.8

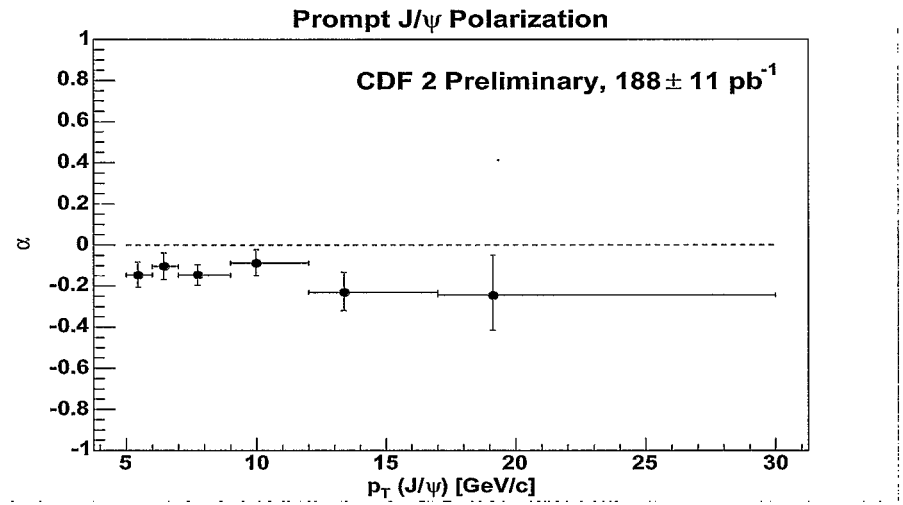






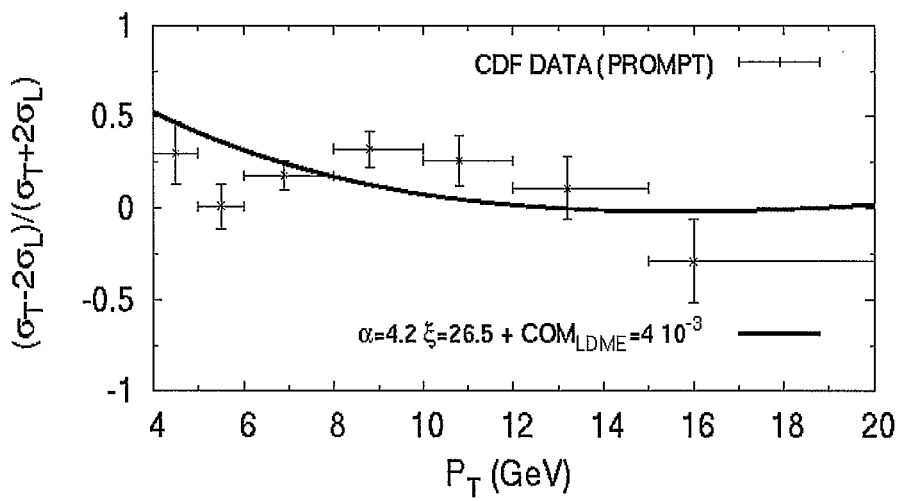
Polarization: new data, theory

CDF Run II measurement of the prompt J/ψ polarization at $\sqrt{s} = 1.96$ TeV. 188 ± 11 pb^{-1}. Both Run I and Run II show increasing longitudinal polarization at higher p_T.



CDF Run II

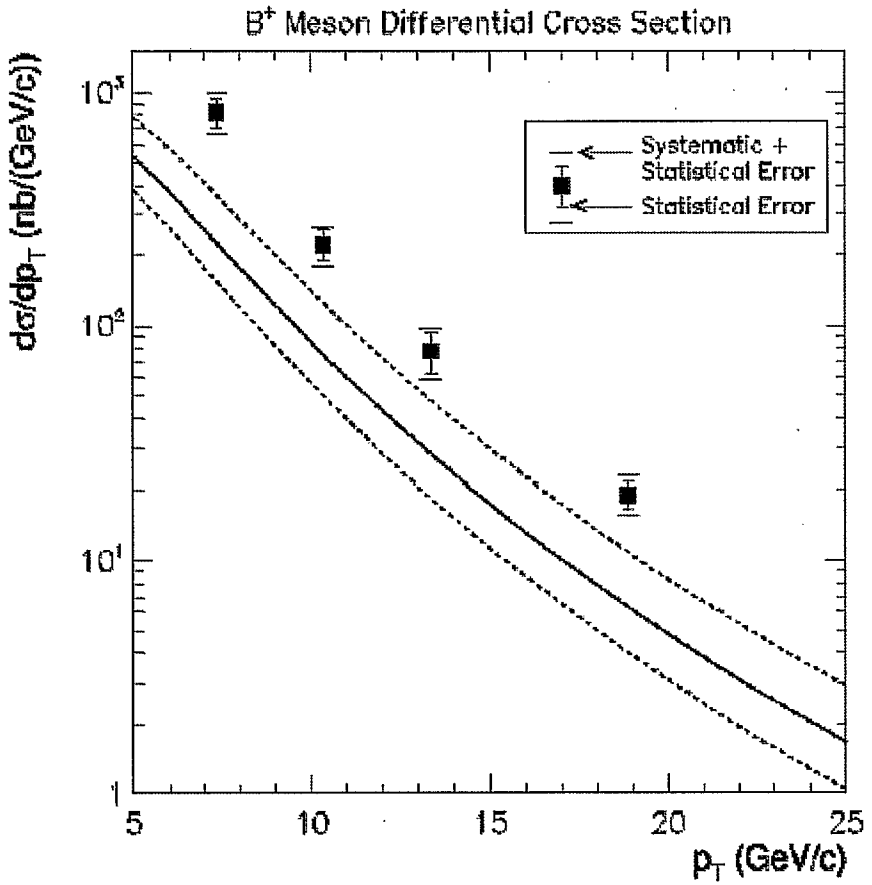
Lansberg, hep-ph/0507175 (July 2005). *Introduced non-static relativistic effects to the hadroproduction of quarkonia ⇒ contributions which produce only longitudanlly polarized quarkonia.*



CDF Run I

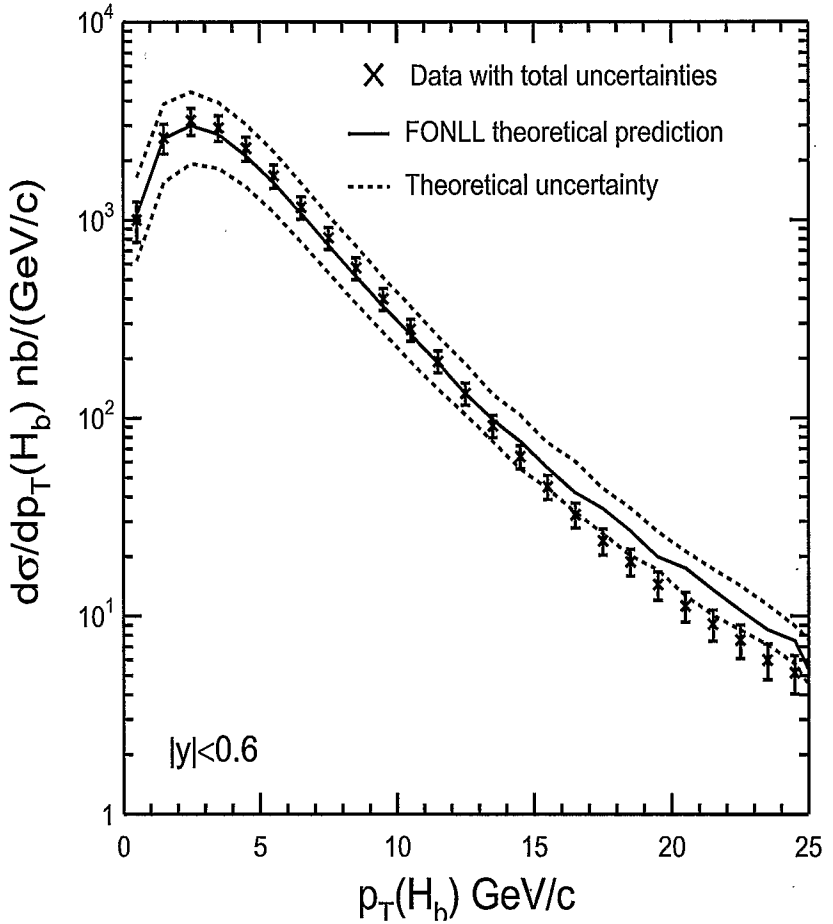
b-Production cross-section

$\sigma(p\bar{p} \to B^+X)$ vs $(p_T(B^+))$



1997

$\sigma(p\bar{p} \to bx)$ versus $(p_T(H_b))$

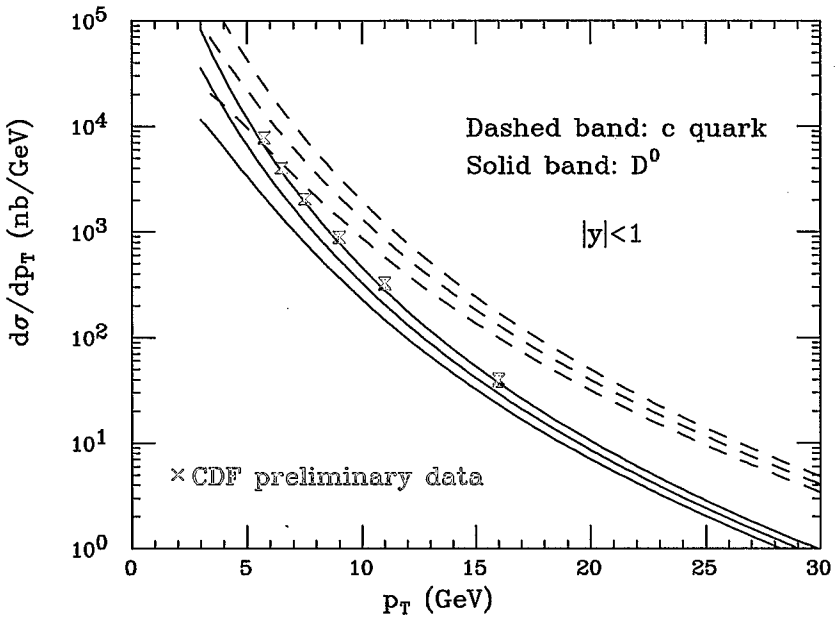


2003

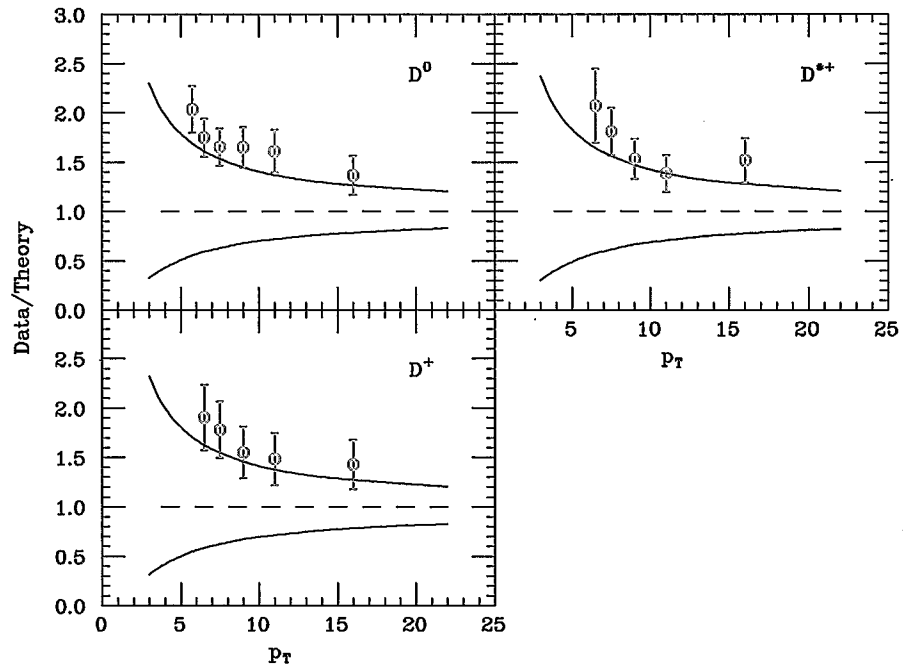
$\sigma_{\rm CDF} = 17.6 \pm 2.5\mu$b, $\sigma_{\rm FONLL} = 16.8^{+7.0}_{-5.0}\mu$b (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

Charm cross-sections

D^0 Meson Differential Cross-section



D Meson Cross-sections Data/Theory



M. Cacciari, P. Nason. hep-ph/0306212.

$$\sigma(p\bar{p} \to D^0 X, |\, y \,| < 1.0, p_T > 5.5\ \mathrm{GeV/c}) = 13.3 \pm 0.2(stat) \pm 1.5(syst)\ \mu\mathrm{b}$$

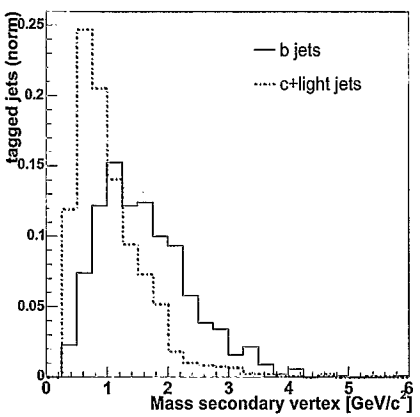
$$\sigma(p\bar{p} \to D^+ X, |\, y \,| < 1.0, p_T > 6.0\ \mathrm{GeV/c}) = 4.3 \pm 0.1(stat) \pm 0.7(syst)\ \mu\mathrm{b}$$

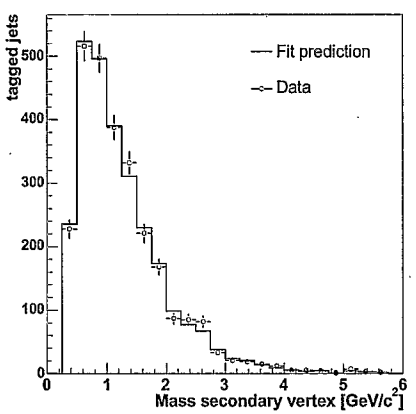
$$\sigma(p\bar{p} \to D^{*+} X, |\, y \,| < 1.0, p_T > 6.0\ \mathrm{GeV/c}) = 5.2 \pm 0.1(stat) \pm 0.8(syst)\ \mu\mathrm{b}$$

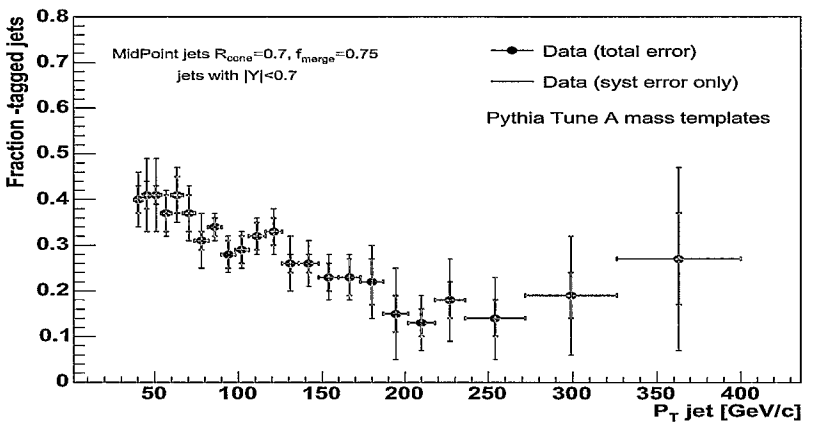
$$\sigma(p\bar{p} \to D_s X, |\, y \,| < 1.0, p_T > 8.0\ \mathrm{GeV/c}) = 0.75 \pm 0.05(stat) \pm 0.22(syst)\ \mu\mathrm{b}$$

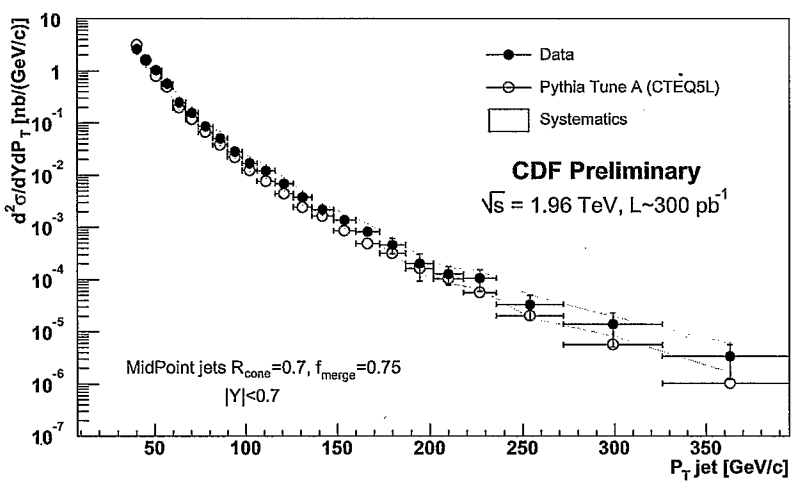
High p_T b-Jet Production (CDF)

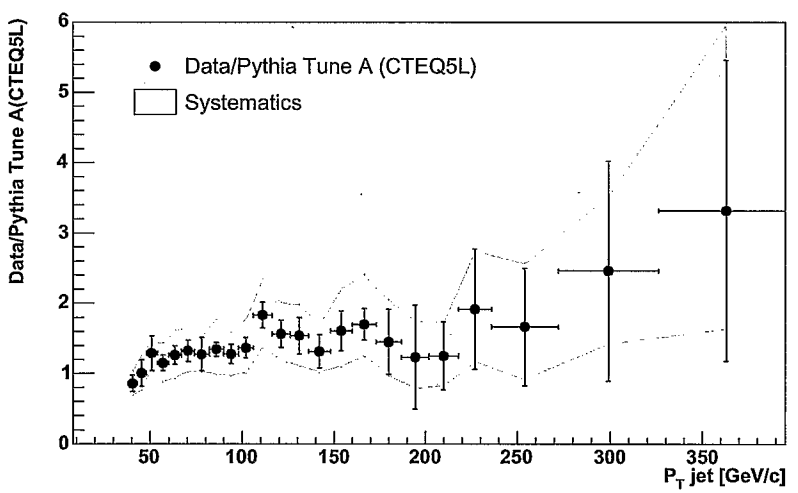
- b/c jet? = fit to the secondary vertex mass:











b-jet xsecs: good agreement with Pythia (LO QCD) at high p_T.

Heavy Quark Fragmentation Functions in e^+e^- annihilation

Rolf Seuster
University of Hawaii

Heavy Flavor Productions &
Hot/Dense Quark Matter '05, BNL

A new determination of the charm fragmentation function at an energy of 10.6 GeV is presented. Comparisons between several fragmentation functions and the measurement are performed, the best agreement is found for models by Bowler and the Lund group.
Older measurements at the Z^0 for charm and beauty quarks are reviewed. A similar conclusion for beauty quarks is found, the Bowler model shows the best agreement. Comparing the charm fragmentation function at two different energies shows discrepancies, which are not yet resolved.

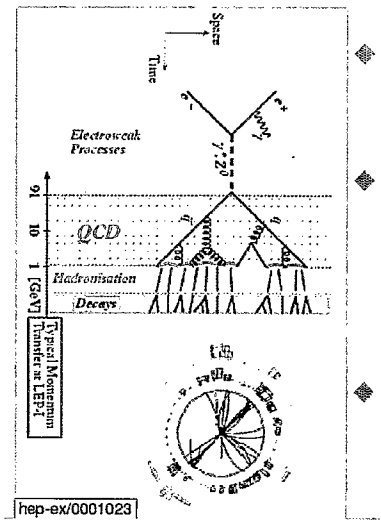
Heavy Quark Fragmentation Functions in e^+e^- annihilation

Rolf Seuster
Univ. of Hawaii

Heavy Flavor Productions &
Hot/Dense Quark Matter '05, BNL

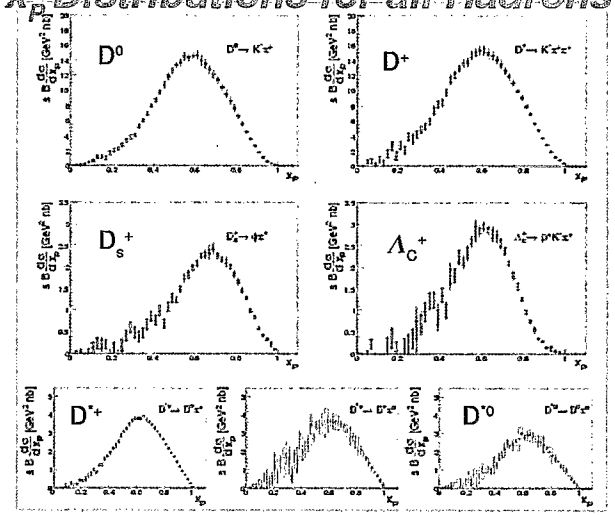
-Introduction
-Charm Fragmentation Functions @ 10.6 GeV
  $c \rightarrow D^0, D^+, D_s^+, \Lambda_c^+, D^{*+}$ and D^{*0}
-Beauty Fragmentation Function @ 91.2 GeV
  $b \rightarrow$ weakly decaying B's
  D^{*+} from $Z_0 \rightarrow cc$ decays
-Discussion
-Summary

Introduction: typical e^+e^- event



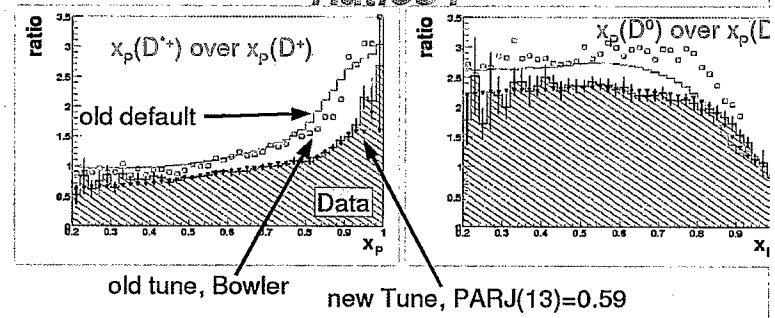
- different states of a typical e^+e^- annihilation event
- QCD:
  parton shower, gluon splitting, hadronization
  "fragmentation function"
- electroweak phase:
  decay of most resonances

x_p Distributions for all Hadrons



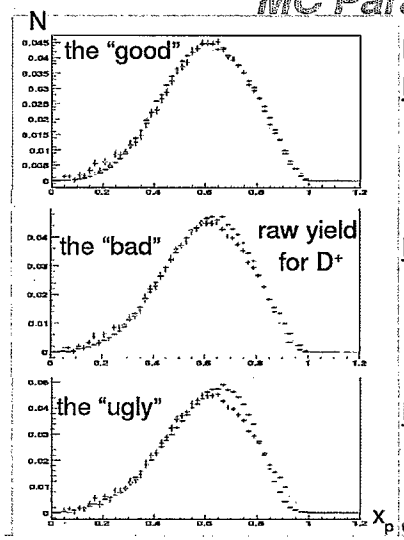
⇒ precise and detailed spectrum !

Ratios I



With new tune ("probability of producing a charmed meson with spin=1
excellent agreement btw. data and MC

MC Parameter



Function	Parameter in Minimum
Bowler	(a|b)=(0.12|0.58) χ^2/d.o.f.=188/60
Kartvelishvili	α_c=4.0 χ^2/d.o.f.=861/60
Peterson	ϵ_c=0.039 χ^2/d.o.f.=2230/60

other two btw. Bowler and Kartvel.

Status @ ICHEP '02

... but not much changed sinc

Overview: model test χ^2/d.o.f.

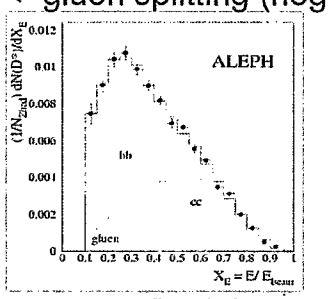
	ALEPH	DELPHI (prelim.)			OPAL	SLD
		x_{vd}	x_L	z		
Bowler	—	35/8	43/8	1/2	67/44	17/15
Lund	—	42/8	53/8	2/2	75/44	17/15
UCLA	—	—	—	—	—	27/17
Kartvelishvili et al.	107/94	—	—	36/3	99/45	32/16
Peterson et al.	117/94	287/9	245/9	187/3	159/45	70/16
BCFY	—	—	—	—	—	105/16
Collins/Spiller	181/94	—	—	536/3	407/45	142/16
Herwig 6 cldir=1	—	—	—	—	540/46	—
Herwig 5 cldir=1	—	—	—	—	4279/46	149/17
Herwig 5 cldir=0	—	—	—	—	—	1015/17

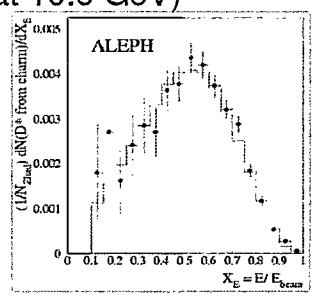
same ranking observed by all experiments!
(fragm. function parameters: rough agreement)

D^{*+} @ 91.2 GeV (ALEPH)

EPJ C16(2000) 597

- $D^{*+} \rightarrow D^0 \pi^+$ (same decay chain as @ 10.6 GeV)
- most D^{*+} at 91.2 GeV are from B decays
- gluon splitting (negl. at 10.6 GeV)



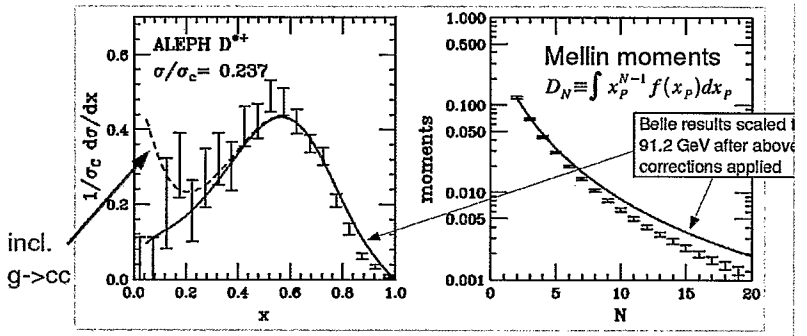


3 parameter fit: relative contributions from bb and gluon and ϵ_c parameter of Peterson frag.fcn. $\epsilon_c = (33.9 \pm 3.7) \cdot 10^{-3}$

for comparison: Belle @ 10.6 GeV $\epsilon_c = 54 \cdot 10^{-3}$

Comparisons between different Energies, cont'd

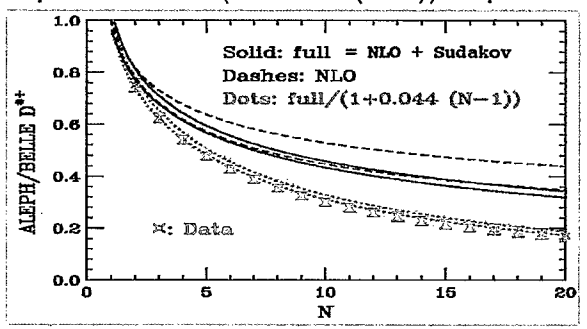
- previous corrections applied:



after all → remaining difference !

Difference between 91.2 GeV and 10.6 GeV

- empirical fit: 1/(1+0.044(N-1)) dependence



source unclear, data inbetween 10.6 and 91.2 needed to resolve 1/E or $1/E^2$ corrections

Summary

- new, precise measurement of charm fragmentation function at $\sqrt{s}$ = 10.6 GeV
- conclusions for charm @ 10.6 GeV and beauty @ 91.2 GeV in good agreement:
  - -Bowler or Lund frag.fcns. prefered
  - -Peterson disfavoured
- differences between charm @ 10.6 GeV and charm @ 91.2, yet unresolved

NRQCD and Heavy-Quarkonium Production

Geoffrey T. Bodwin

High Energy Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

The effective field theory NRQCD is a convenient formalism for separating physics at the scale of the heavy-quark mass from physics at the scale of quarkonium bound-state dynamics. The NRQCD factorization approach provides a systematic method for calculating inclusive quarkonium production (and decay) rates as a double expansion in powers of α_s and v, where v is the heavy-quark or antiquark velocity in the quarkonium rest frame. NRQCD factorization for production rates relies upon hard-scattering factorization and has not yet been established.

The NRQCD factorization approach for quarkonium production has enjoyed a number of successes [1]. These include quarkonium production at the Tevatron, $\gamma\gamma \to J/\psi + X$ at LEP, quarkonium production at DIS at HERA, and quarkonium production in pp collisions at RHIC. For other processes, the agreement between theory and experiment is less than satisfactory. Examples include production of polarized quarkonium at the Tevatron, inelastic quarkonium photoproduction at HERA, and double $c\bar{c}$ production at Belle and BaBar. The Belle and BaBar results on exclusive double-$c\bar{c}$ production and the Belle results on inclusive double-$c\bar{c}$ production present particularly severe challenges to pQCD. A check by BaBar of the inclusive results would be very useful.

In many cases, inclusion of corrections of higher order in α_s and v and soft-gluon resummation should help to bring theory into agreement with experiment. More precise theoretical predictions are hampered by uncertainties in the NRQCD matrix elements. Lattice calculations can help to pin down the decay matrix elements. However, it is not yet known how to formulate the calculation of production matrix elements on the lattice.

Although a great deal of progress has been made in the last decay in understanding heavy-quarkonium production at a fundamental level, there are many challenging problems that remain to be solved.

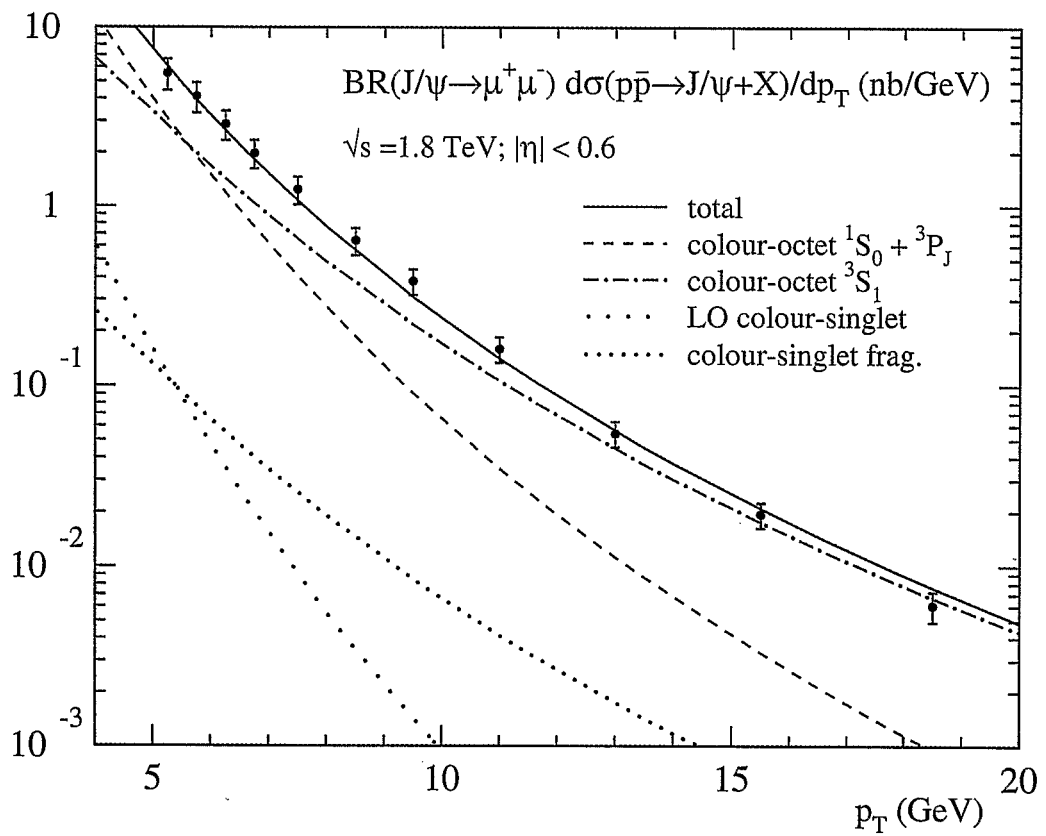
References

[1] For a comprehensive review of the status of theory and experiment in quarkonium production, see N. Brambilla *et al.*, arXiv:hep-ph/0412158.

Some Successes of the NRQCD Factorization Method

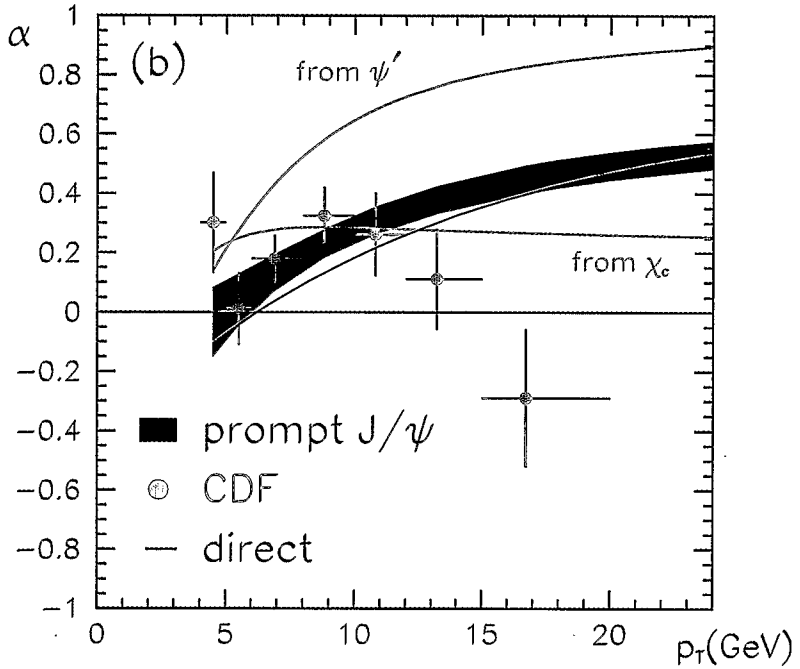
Quarkonium Production at the Tevatron

- Explanation (color-octet mechanism) of Tevatron data for J/ψ, ψ', Υ production.

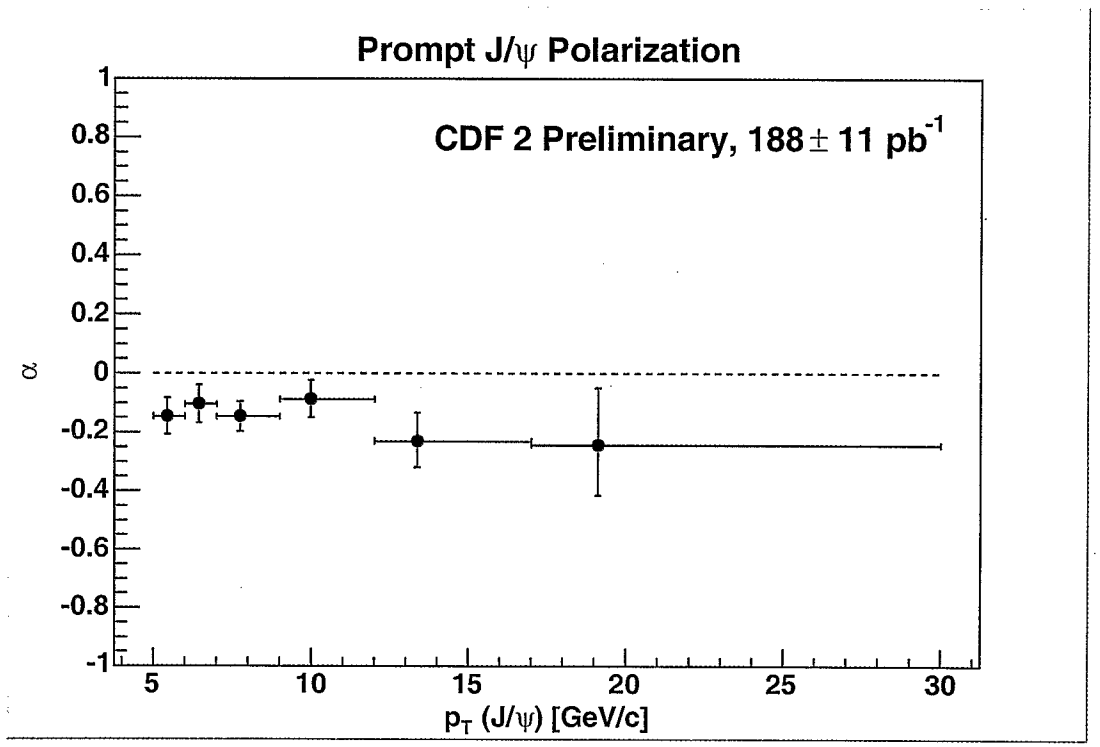


- Data are more than an order of magnitude larger than the predictions of the color-singlet model.
- Color-octet matrix elements are determined from fits to the data.
- p_T distributions are consistent with NRQCD.

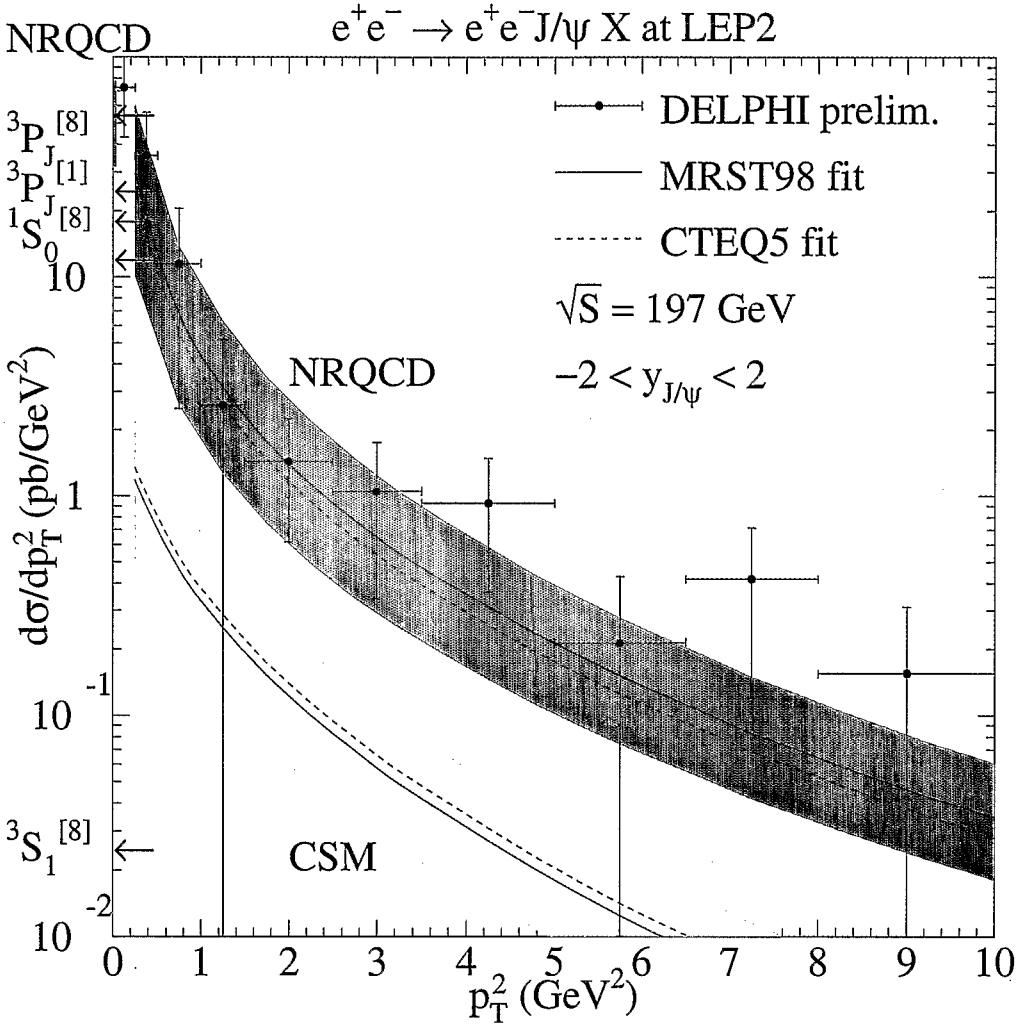
Run I data:



Run II data:



$\gamma\gamma \to J/\psi + X$ at LEP



- Comparison of theory (Klasen, Kniehl, Mihaila, Steinhauser) with Delphi data clearly favors NRQCD over the color-singlet model.
- Theory uses Braaten-Kniehl-Lee matrix elements from Tevatron data and MRST98LO (solid) and CTEQ5L (dashed) PDF's.
- Theoretical uncertainties from
  - Renormalization and factorization scales (varied by a factor 2),
  - NRQCD color-octet matrix elements.
- Different linear combination of matrix elements than in Tevatron cross sections.

Double $c\bar{c}$ Production at Belle and BaBar

$$e^+e^- \to J/\psi + \eta_c \text{ (exclusive)}$$

Situation in 2003

Belle: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>4} = 33^{+7}_{-6} \pm 9$ fb.

NRQCD: $\sigma(e^+e^- \to J/\psi + \eta_c) = 2.31 \pm 1.09$ fb.

- Order-of-magnitude discrepancy between theory and experiment.
- NRQCD factorization calculation by Braaten, Lee.
- The uncertainty from m_c is shown.
- There are also large uncertainties from corrections of higher order in α_s, v, and uncertainties in matrix elements.
- Exclusive process: the color-octet contribution is suppressed by v^4, so only color-singlet matrix elements are needed.

Present Situation

Belle: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.

BaBar: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 17.6 \pm 2.8 \pm 2.1$ fb.

NRQCD: $\sigma(e^+e^- \to J/\psi + \eta_c) = 3.78 \pm 1.26$ fb.

- Belle cross section has moved down.
- BaBar cross section is somewhat lower.
- Braaten and Lee corrected a sign error in the QED interference term, raising the prediction.
- QCD part confirmed by Liu, He, Chao: $\sigma(e^+e^- \to J/\psi + \eta_c) = 5.5$ fb. (Different choice of m_c, NRQCD matrix elements, α_s.)
- QCD calculation confirmed by Brodsky, Ji, and Lee in light-front QCD in the quarkonium nonrelativistic limit.
- Zhang, Gao, Chao: A new calculation of corrections at NLO in α_s shows that the K factor may be as large as 1.8.
  - Not sufficient to remove the discrepancy between theory and experiment by itself.

Heavy Flavour Productions &
Hot/Dense Quark Matter
BNL 14/12/2005

(Theoretical) review of heavy quark production

Matteo Cacciari
LPTHE - Paris 6

Outline

- What can be calculated
- How accurately we can/do calculate it? What tools are available?
- Does it work? Comparisons with data
- Implications for RHIC

We review the calculation in perturbative QCD of open heavy quarks in the vacuum. The limits of pQCD predictions, the state-of-the-art of the calculations, their phenomenological implementations and the comparisons with the experimental data are addressed.

We also consider the theoretical uncertainties of a baseline calculation of heavy quark production in pp collisions at RHIC. We show how the limited knowledge of the charm and bottom relative contributions reflects into an uncertainty for a prediction of the quenching ratio R_AA.

NLO implementation of factorization theorem

Hadroproduction

Nason, Dawson, Ellis, NP B327 (1989) 49, NP B303 (1988) 607
Beenakker, van Neerven, Meng, Schuler, Smith, NP B351 (1991) 507

Photoproduction

Nason, Ellis, NP B312 (1989) 551
Smith, van Neerven, NP B374 (1992) 36

This is still the state of the art for fixed order perturbative calculations, and should be the building block of all phenomenological predictions:

- it incorporates in a rigorous manner production "channels" like flavour excitation and gluon splitting which Monte Carlo calculations have to include by hand (beware MC tunes and recipes!!)
- it allows a **rough estimate of the theoretical uncertainty**

NNLO is perhaps in the works, but it's not for tomorrow

The rule of thumb on uncertainties

- A LO calculation gives you a **rough estimate** of the cross section

- A NLO calculation gives you a **good estimate** of the cross section and a **rough estimate** of the uncertainty

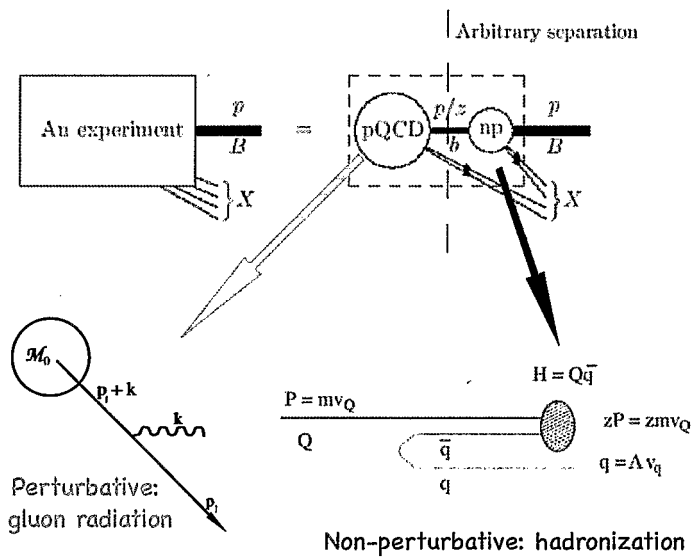
- A NNLO calculation gives you a **good estimate** of the uncertainty

Believe it or not, this is one of the motivations for embarking in years-long NNLO calculations (I'm serious.....)

Of course, when the NLO calculation still suffers from large uncertainties an NNLO one can also bring real improvements in the determination of the cross section

Non-perturbative Fragmentation

When extracting the **heavy quark → heavy meson non-perturbative fragmentation function** from data, one must consider the **unavoidable interplay with perturbative physics**



Not being the c/b quark a physical particle, **the non-perturbative fragmentation function cannot be a physical observable**: its details depend on the perturbative calculation it is interfaced with.

A single fragmentation function cannot do for all calculations

One more word of caution

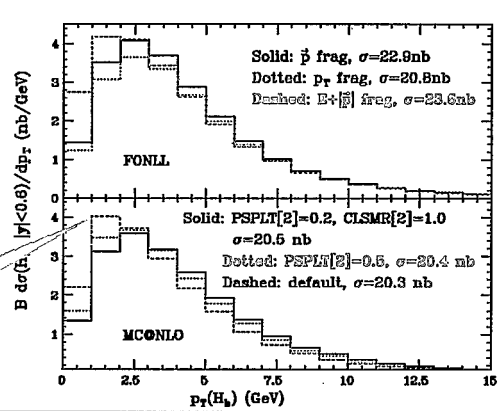
The non-perturbative FF is usually employed in hadronic collisions by writing

$$E_H \frac{d^3\sigma_H(p_H)}{dp_H^3} = E_Q \frac{d^3\sigma_Q(p_Q)}{dp_Q^3} \otimes D^{np}_{Q\to H}$$

Bear in mind that when the transverse momentum is small two things happen:

1. The "independent fragmentation" picture fails, as factorization-breaking higher twists grow large. So, whatever the result of the convolution above, there will be further uncertainties looming over it

2. Scaling a massive particle's 4-momentum is an ambiguous operation. One can scale the transverse momentum at constant rapidity, the 3-momentum at constant angle in a given frame, etc.



Different fragmentation choices

Putting things together

A modern tool for producing phenomenological predictions for heavy quark at the differential level will

1- properly **resum** (say to next-to-leading log accuracy) the large logarithms

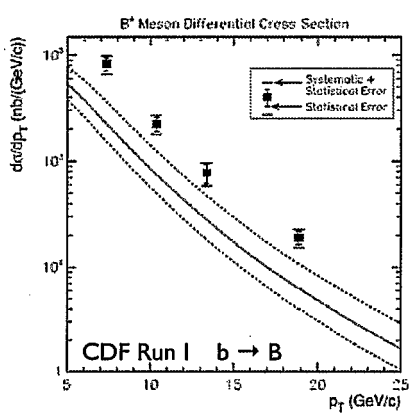
2- **match** the resummation to a full NLO fixed order calculation

3- properly **extract** from data (and **use** for predictions) **non-perturbative** fragmentation functions describing the hadronization of the heavy quarks

NB. Whether you need all this or not depends, of course, on your accuracy goal. If you are happy with a factor of two uncertainties or more none of this is probably necessary: take the 15 years old NLO calculation and go ahead (but then don't come to me complaining of discrepancies with QCD!)

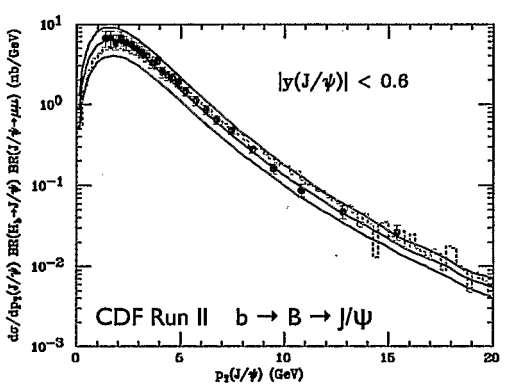
On the other hand, if you aim at a few 10% accuracy then you need this stuff.

'Before'



'Factor of 3' excess

'After'



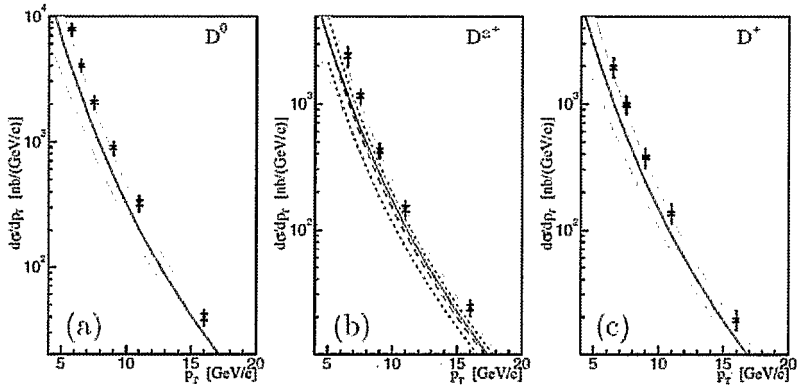
Perfect agreement

Key improvement:
b → B non-perturbative fragmentation properly extracted from LEP data within the FONLL framework

Does it work? Charm production @ Tevatron Run 2

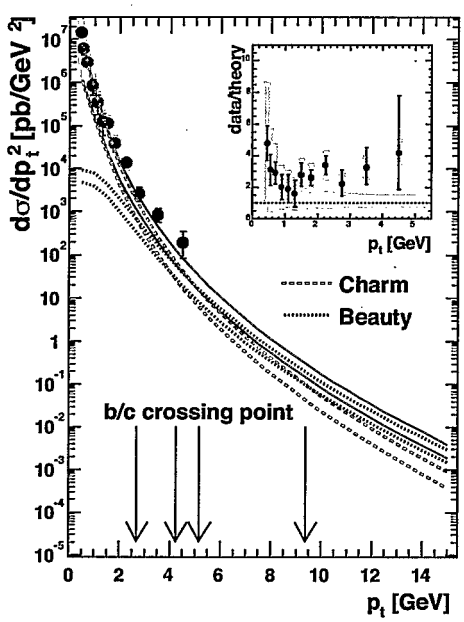
The same FONLL framework also provides a good description of charm production at the Tevatron:

CDF Run II c->D data [PRL 91:241804,2003]



The non-perturbative charm fragmentation needed to describe the c → D hadronization has been extracted from moments of ALEPH data at LEP. Now even better fragmentation data from CLEO and BELLE are available:

Charm and bottom production @ RHIC

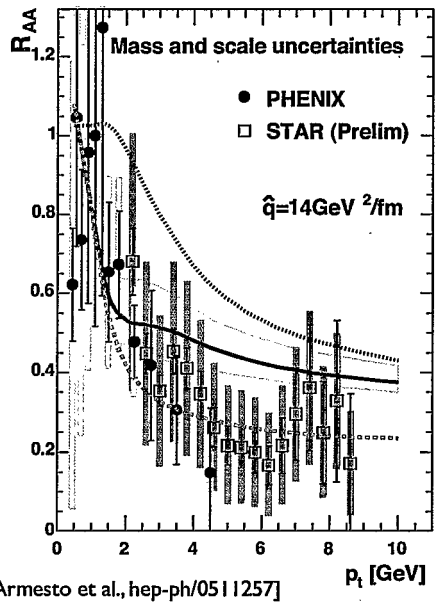


The slope of the charm and bottom contribution is fairly similar: the crossing point easily moves, though the relative contributions are less affected by uncertainties

NB. Especially for bottom the transverse momentum is small: all the further uncertainties previously mentioned can apply

R_AA for Charm and bottom @ RHIC

The charm and bottom spectra easily translate into R_AA via the application of quenching weights



[Armesto et al., hep-ph/0511257]

The uncertainty on the charm and bottom relative contribution reflects on an uncertainty of order 0.1 on R_AA

R_AA looks too high. However, remember the very large perturbative uncertainty on charm: the NNLO prediction could be quite larger. Observation: if you normalize charm to the data R_AA comes out about right

Conclusions

- Heavy quark phenomenology is mature and has the tools to produce predictions in many realistic situations. These predictions can include all the available knowledge for calculating heavy quark production in QCD. Since they are implemented in a rigorous framework, it is usually possible to also provide a (more or less reliable) estimate of the theoretical uncertainty
- Most predictions seem to agree well with Tevatron and HERA data for charm and bottom production. For Heavy Ions collisions they should provide a solid benchmark against which to compare in the search for nuclear effects
- Final note: given the size of intrinsic pQCD uncertainty, it is very unlikely that effects of the order of a few (tens of) percent will ever be visible just by comparing to the absolute value of the cross sections

Quarkonium Recombination In Presence of Strangeness Rich Expanding QGP

BNL, December 14, 2005

Presented by Johann Rafelski, with: Jean Letessier, and Inga Kouznetsova
Department of Physics, University of Arizona, Tucson, AZ 85721

OBJECTIVES:

1. Understanding the strangeness RHIC results;
2. Dynamics of thermal s and c production at RHIC-200 (and extrapolate to LHC);
3. Strangeness/expansion impact on redistribution of charm/bottom into hadrons.

ABSTRACT: Kinetic strangeness production is compared to the available strangeness yield measurements at RHIC. QGP yield saturation as function of initial conditions and evolution scenarios are considered. Insights gained allow to narrow down the expectations for strangeness production at LHC and to evaluate thermal charm production yields at RHIC and LHC. Implications for yields of Charmonium, D_s meson, and B_c are presented.

Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318

Strangeness / Entropy: A measure of strangeness content in QGP

Relative s/S yield measures the number of active degrees of freedom and degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3 + (g_s n_f/6)\mu_q^2 T} \simeq 0.028$$

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out

Allow for chemical non-equilibrium of strangeness $\gamma_s^{\rm QGP}$, and possible quark-gluon pre-equilibrium – gradual increase to the limit expected:

$$\frac{s}{S} = \frac{0.03\gamma_s^{\rm QGP}}{0.4\gamma_{\rm G} + 0.1\gamma_s^{\rm QGP} + 0.5\gamma_q^{\rm QGP} + 0.05\gamma_q^{\rm QGP}(\ln\lambda_q)^2} \to 0.028.$$

We expect the yield of gluons and light quarks to approach chemical equilibrium fast and first: $\gamma_{\rm G} \to 1$ and $\gamma_q^{\rm QGP} \to 1$, thus $s/S \simeq 0.028\gamma_s^{\rm QGP}$.

Thermal average rate of strangeness and charm production

Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p}_1, T)$ to obtain average rate A per unit time and volume:

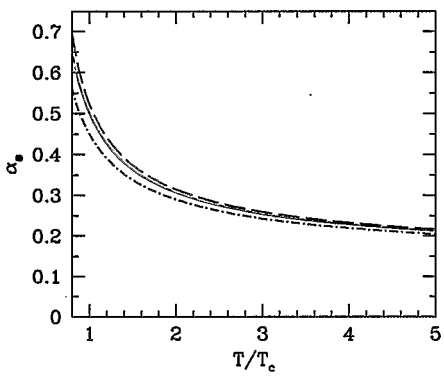
$$A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}}\gamma_1\gamma_2\rho_1^\infty\rho_2^\infty\langle\sigma_{s,c}v_{12}\rangle_T^{12\to 34} \quad \langle\sigma v_{\rm rel}\rangle_T \equiv \frac{\int d^3p_1\int d^3p_2\sigma_{12}v_{12}f(\vec{p}_1,T)f(\vec{p}_2,T)}{\int d^3p_1\int d^3p_2 f(\vec{p}_1,T)f(\vec{p}_2,T)}.$$

The generic angle averaged cross sections for (heavy) flavor s, $\bar{s}$ production processes $g+g\to s+\bar{s}$ and $q+\bar{q}\to s+\bar{s}$, are:

$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_s^2}{3s}\left[\left(1+\frac{4m_{s,c}^2}{s}+\frac{m_{s,c}^4}{s^2}\right)\tanh^{-1}W(s) - \left(\frac{7}{8}+\frac{31m_{s,c}^2}{8s}\right)W(s)\right],$$

$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_s^2}{27s}\left(1+\frac{2m_{s,c}^2}{s}\right)W(s). \qquad W(s)=\sqrt{1-4m_{s,c}^2/s}$$

RESUMMATION



The relatively small experimental value $\alpha_s(M_Z)\simeq 0.118$, established in recent years helps to achieve QCD resummation with running α_s and m_s taken at the energy scale $\mu\equiv\sqrt{s}$. Effective T-dependence:

$$\alpha_s(\mu=2\pi T)\equiv\alpha_s(T)\simeq\frac{\alpha_s(T_c)}{1+(0.760\pm 0.002)\ln(T/T_c)}$$

with $\alpha_s(T_c)=0.50\pm 0.04$ and $T_c=0.16$ GeV.
α_s^2 varies by factor 10; we also use running $m_{s,c}$.

STRANGENESS, CHARM IN ENTROPY CONSERVING EXPANSION

QGP expansion is adiabatic i.e. $(g_G = 2_s 8_c = 16, g_q = 2_s 3_c n_f)$

$$S=\frac{4\pi^2}{90}g(T)VT^3 = \textbf{Const.} \quad g = g_G\left(1-\frac{15\alpha_s(T)}{4\pi}+\ldots\right)+\frac{7}{4}g_q\left(1-\frac{50\alpha_s(T)}{21\pi}+\ldots\right).$$

The volume, temperature change such that $\delta(gT^3V)=0$. Strangeness phase space occupancy, $g_s = 2_s 3_c\left(1-\frac{k\alpha_s(T)}{\pi}+\ldots\right), k=2$ for $m_s/T\to 0$:

$$\gamma_{s,c}(\tau)\equiv\frac{n_{s,c}(\tau)}{n_{s,c}^\infty(T(\tau))}, \quad n_{s,c}(\tau)=\gamma_{s,c}(\tau)T(\tau)^3\frac{g_s(T)}{2\pi^2}z^2K_2(z), \quad z=\frac{m_{s,c}}{T(t)}, \quad K_i: \text{Bessel f.}$$

evolves due to production and dilution, keeping entropy fixed:

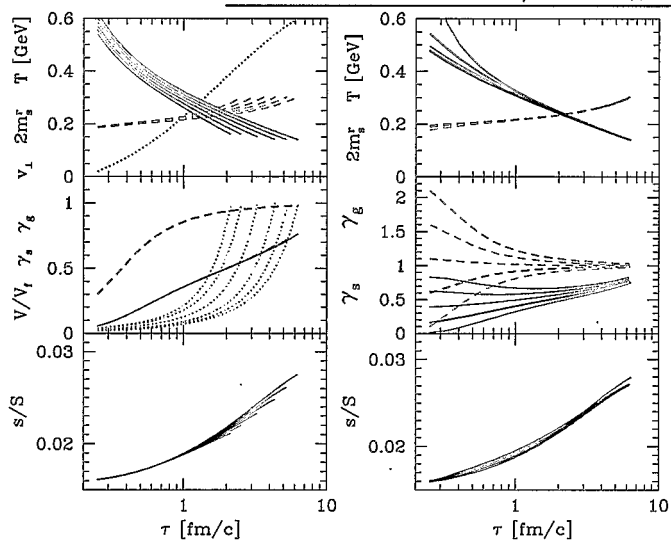
$$\frac{d}{d\tau}\frac{s,c}{S} = \frac{A_G}{S/V}\left[\gamma_G^2-\gamma_{s,c}{}^2\right]+\frac{A_q}{S/V}\left[\gamma_q^2-\gamma_{s,c}{}^2\right]$$

Which for $\gamma_{s,c}$ assumes the form that makes dilution explicit:

$$\frac{d\gamma_{s,c}}{d\tau}+\gamma_{s,c}\frac{d\ln[g_s z^2K_2(z)/g]}{d\tau} = \frac{A_G}{n_s^\infty}\left[\gamma_G^2-\gamma_{s,c}{}^2\right]+\frac{A_q}{n_s^\infty}\left[\gamma_q^2-\gamma_{s,c}{}^2\right]$$

For $m_s\to 0$ dilution effect decreases, disappears, and $\gamma_s\le\gamma_{G,q}$, importance grows with mass of the quark: $z=m_{s,c}(T)/T$ grows rapidly near phase transition.

Evolution in time of s/S and γ_s at RHIC



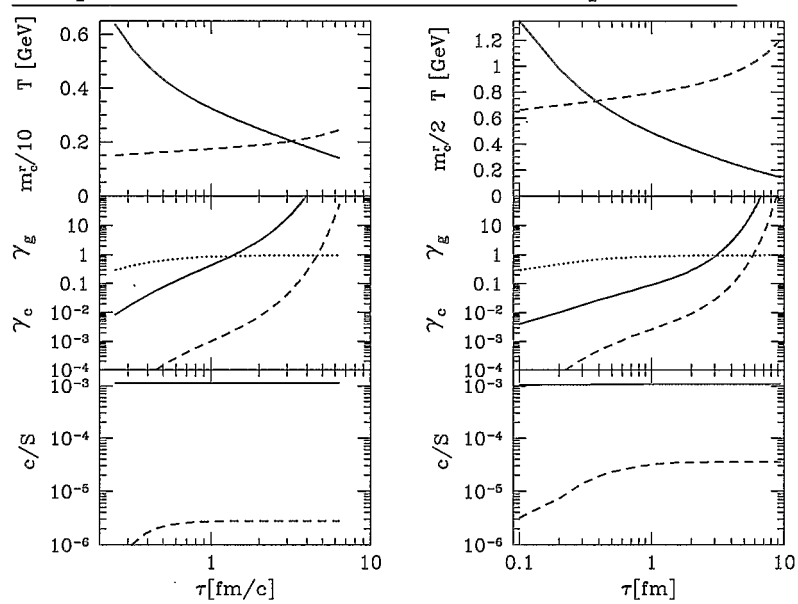
On right: study of the influence of the initial density of partons.

Implications for Charm at RHIC and LHC

Similar for thermal charm yield: guaranteed to be thermalized distribution at central rapidity And look at statistical hadronization on rapidly expanding strangeness oversaturated system, evaluating all specific

$$\frac{\text{charmed hadron yields}}{\text{all charm (bottom) yield}}$$

Comparison of thermal with direct charm production



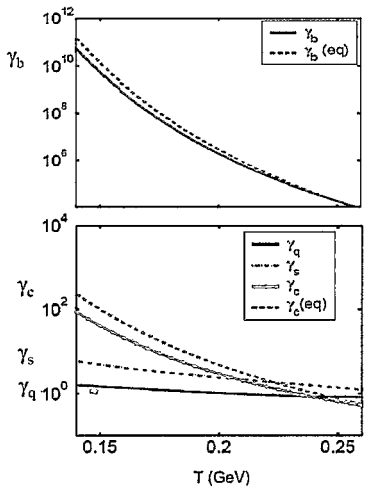
Left RHIC and right LHC: lid lines total charm γ_c, dashed lines γ_c corresponding to thermal charm production; and bottom panel: specific charm yield per entropy, solid lines for all charm, and dashed lines for thermally produced charm. Thermal charm production alone exceeds significantly chemical equilibrium! Direct production yield (to see assumed values multiply with $dS/dy = 5000$ on left (RHIC) and =20,000 on right (LHC)) remains significantly (300 at RHIC and 60 times at LHC) above thermal production (compare lines in bottom panel).

Charm chemistry in presence of high s/S

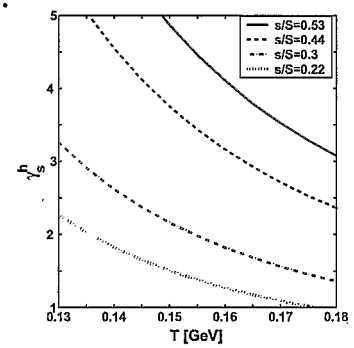
Recombination hadronization of charm has to be considered at a given s and S created in the dynamics of RHIC collision rather than for prescribed statistical yields. Charm distribution among particles according to:

$$\frac{dN_c}{dy} = \frac{dV}{dy}\left[\gamma_c^{\rm h} n^c_{\rm open} + \gamma_c^{\rm h\,2}(n^c_{\rm hidden} + 2\gamma_q^{\rm h} n^{\rm eq}_{ccq} + 2\gamma_s^{\rm h} n^{\rm eq}_{ccs})\right];$$

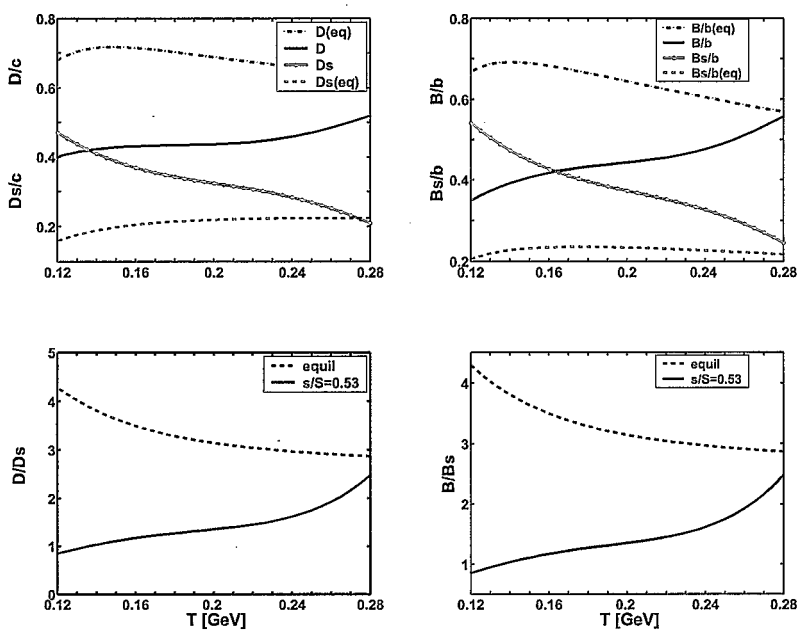
$$n^c_{\rm open} = \gamma_q^{\rm h} n^{\rm eq}_D + \gamma_s^h n^{\rm eq}_{Ds} + \gamma_q^{\rm h\,2} n^{\rm eq}_{qqc} + \gamma_s^{\rm h}\gamma_q^h n^{\rm eq}_{sqc} + \gamma_s^{\rm h\,2} n^{\rm eq}_{ssc}; \qquad n^c_{\rm hidden} = \gamma_c^{\rm h\,2} n^{\rm eq}_{c\bar{c}}$$



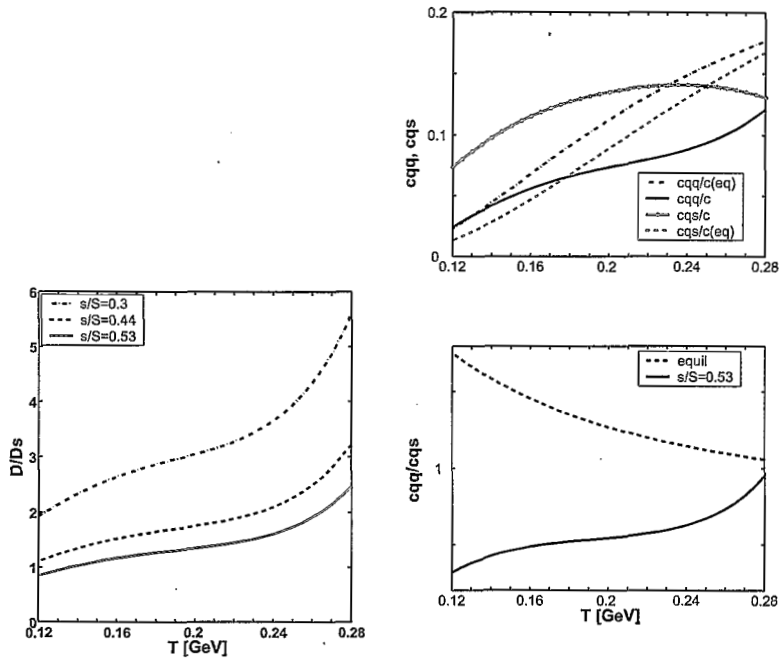
For $db/dy = 1$, $dc/dy = 10$, $ds/dy = 650$ and $dS/dy = 12,000$ (only 2.5 times RHIC) the hadron occupancies were obtained (equilibrium values for $\gamma_i^{\rm QGP} = 1$ for freeze-out at T).



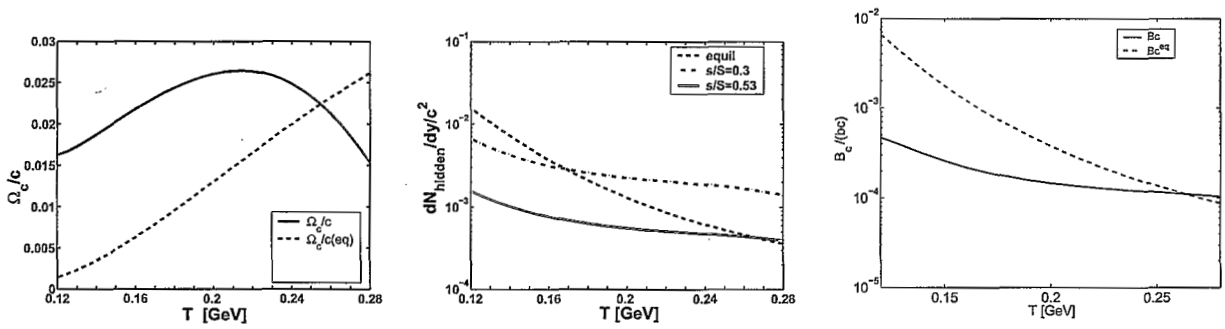
Yields of D, D_s and B, B_s at $s/S = 0.053$



Yields of D, D_s and c-baryons at variable $\dot{s}/S$



Yields of charmonium, css-baryons and B_c



Further work on heavy flavor chemistry on the way. Return now to discuss relevance of understanding of strangeness at LHC and phase transition dynamics.

Conclusions

1) We understand the CHEMICAL conditions of the QGP at freezeout at RHIC and in presence of fast hadronization. Hadron abundances are controled by prevailing valance quark yields and are not in chemical equilibrium;

2) Thermal charm (aside of direct charm) is present, produced in thermal glue fusion;

3)Charmed strange baryons enhanced, impact multicharm hadron yields, charmonium reduced.

Gluon Polarization from Heavy-Flavor Production

Werner Vogelsang

Physics Department and RIKEN-BNL Research Center,
Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

To measure the so far largely unknown polarization of gluons, Δg, in the nucleon is a key goal of several current experiments in high-energy nuclear physics. The successful start of polarized proton-proton collisions at the BNL Relativistic Heavy Ion Collider (RHIC) has opened up new, unequaled possibilities. Gluon polarization can be accessed by a variety of probes, such as single-inclusive hadron, jet, prompt photon, or heavy quark production. In the COMPASS experiment at CERN, instead, a beam of longitudinally polarized muons is scattered off a polarized fixed target. Here, high-p_T hadron pairs, both in photoproduction and in deep-inelastic electroproduction, and heavy-flavor photoproduction have been identified as promising tools for gaining knowledge about Δg. The RHIC and COMPASS experiments have presented their first data at the recent PANIC '05 conference in Santa Fe, New Mexico.

A meaningful extraction of parton densities from experiment requires a reliable interpretation of the underlying data in the framework of perturbative QCD. Factorization theorems assure that in the presence of a large scale, for instance, a heavy-quark mass m, the cross section can be written as a convolution of partonic hard scattering cross sections, which depend on the process under consideration, and certain combinations of the *universal* parton densities. The partonic cross sections are amenable to QCD perturbation theory. For a reliable theoretical framework, knowledge of higher-order corrections is in many cases crucial.

In the present talk we first give an introduction to gluon polarization and describe what is currently known about Δg. We then turn to photoproduction of heavy flavors, as studied by COMPASS. We find that next-to-leading order corrections to the spin-dependent charm cross section may be very large in the COMPASS kinematic regime. QCD "threshold" resummation, even though showing some success in the unpolarized case, does not seem to be able to bring the theoretical calculation under better control. We next discuss the spin asymmetry for heavy-flavor production at RHIC. At RHIC's rather high energy, the spin asymmetries for the total charm and bottom cross sections are rather small, but cuts on the transverse momenta of the produced charm or bottom quarks make the asymmetries more favorable. Measurements of a lepton-signal will contain a mix of charm and bottom events; future vertex detection capabilities at the RHIC experiments PHENIX and STAR should prove very useful here. We finally also briefly discuss spin asymmetries in charmonium production.

Outline:

- Introduction to $\Delta g(x,Q^2)$
- Phenomenology of Δg in high-energy scatt.
- Δg from $\gamma p \to Q\bar{Q}\, X$
- Δg from $pp \to Q\bar{Q}\, X$
- Conclusions

Many results shown are due to I. Bojak & M. Stratmann
PLB 433 (1998) 411; NP B540 (1999) 345; PR D67 (2003) 034010
Some results H. Yokoya & WV

Why interest in Δg ?

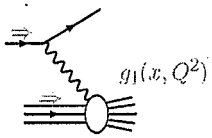
- appears in high-energy scattering of polarized protons
- moments become local operators.
  1st moment of Δg is local in $A^+ = 0$ gauge:

$$\Delta G(Q^2) = \int_0^1 dx\, \Delta g(x,Q^2) = \frac{1}{2P^+} \langle P,S \,|\, A^1 F^{+2} - A^2 F^{+1} \,|\, P,S \rangle_{Q^2}$$

Jaffe, Manohar '90

- the quantity that appears in the proton helicity sum rule :

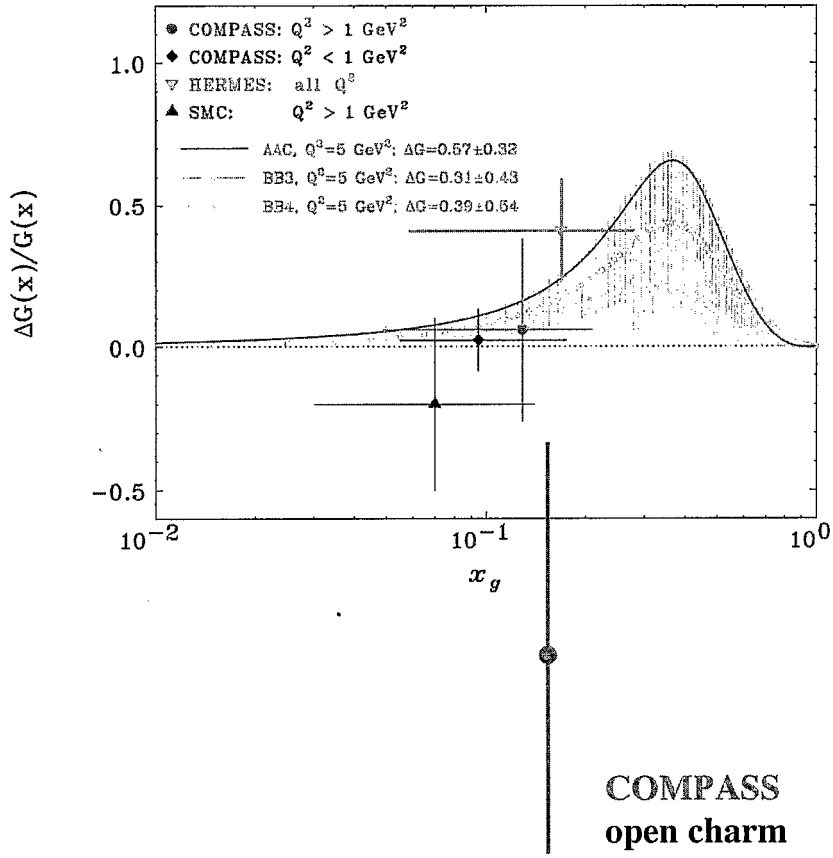
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



Jaffe, Manohar; Ratcliffe; Ji; Teryaev; Jaffe, Bashinskii; Ji, Hoodbhoy, Lu; ...

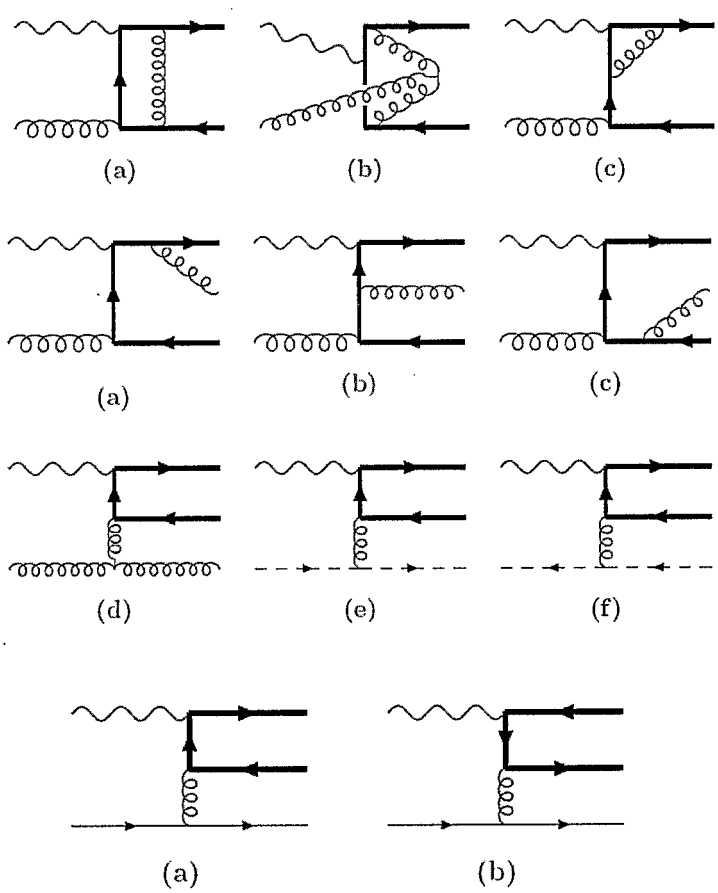
Quark spin
(ax. charge) ≈ 0.1

EMC, SMC, E142-155, HERMES



COMPASS
open charm

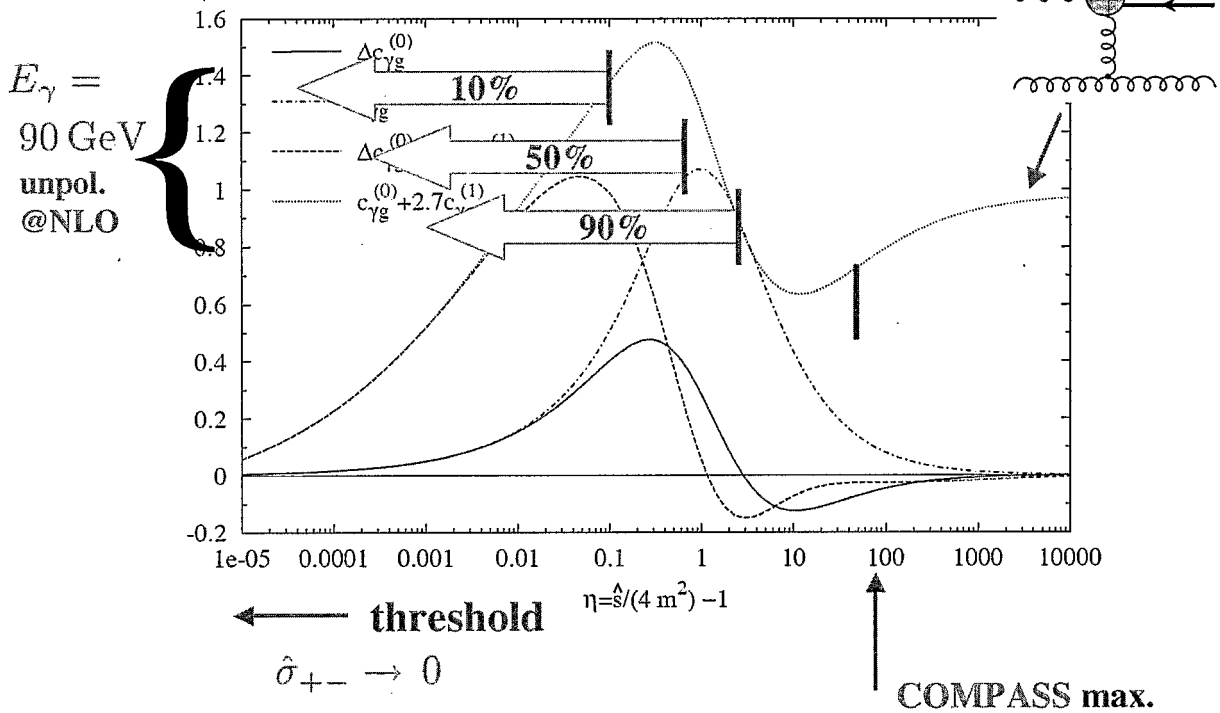
NLO :



Ellis, Nason
Smith, van Neerven

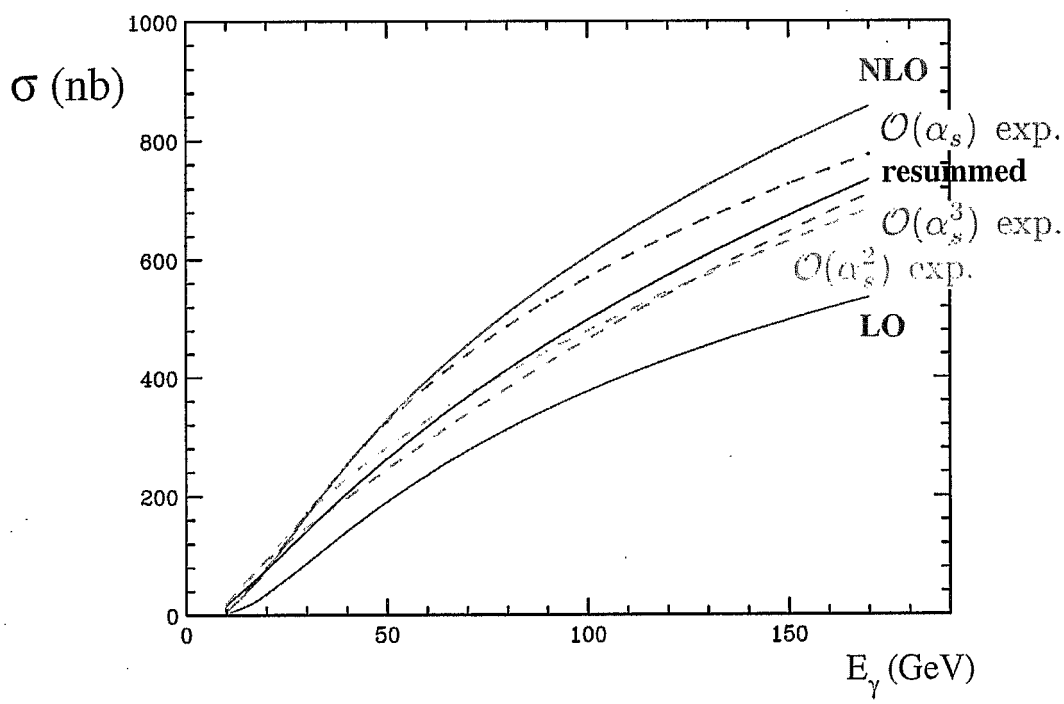
Bojak, Stratmann
Contogouris et al.

Bojak, Stratmann



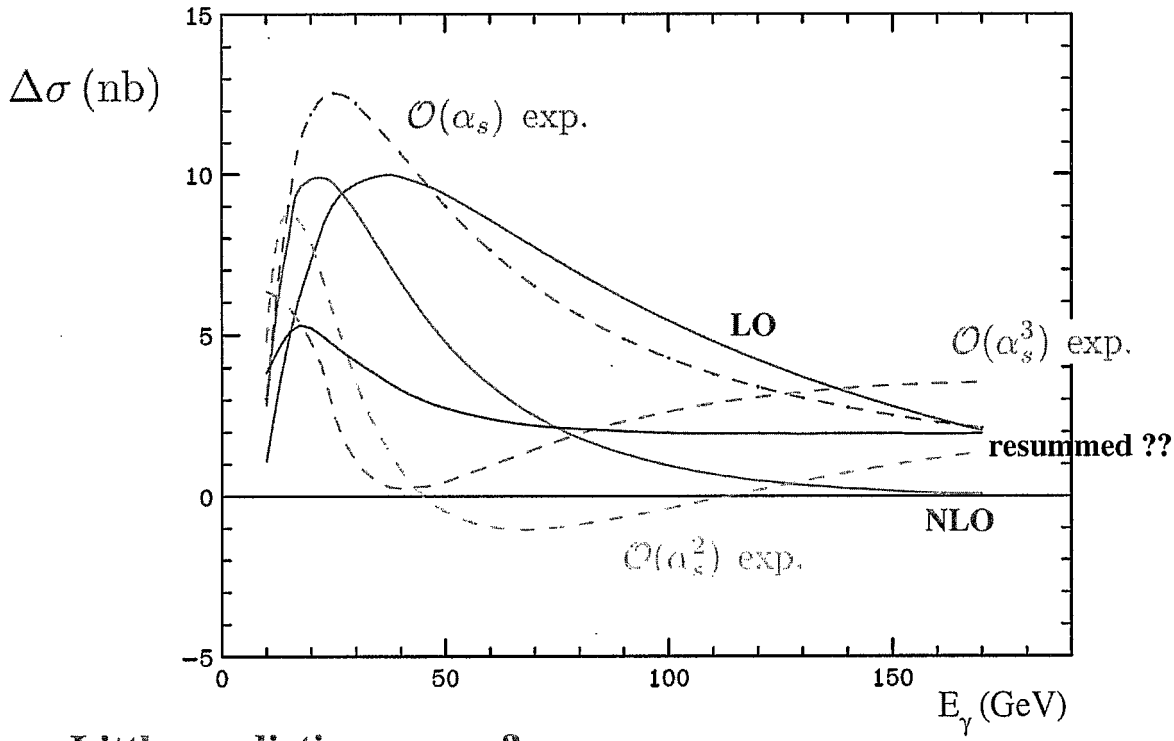
$$\Delta\sigma_{\gamma p}(S, m^2) = \frac{e_Q^2 \alpha \alpha_s(\mu^2)}{m^2} \int_{4m^2/S}^{1} dx \;\; \Delta g(x, \mu^2) \;\; \Delta c_{\gamma g}\left(\frac{4m^2}{xS}, \alpha_s(\mu^2), \frac{\mu^2}{m^2}\right)$$

H. Yokoya & WV



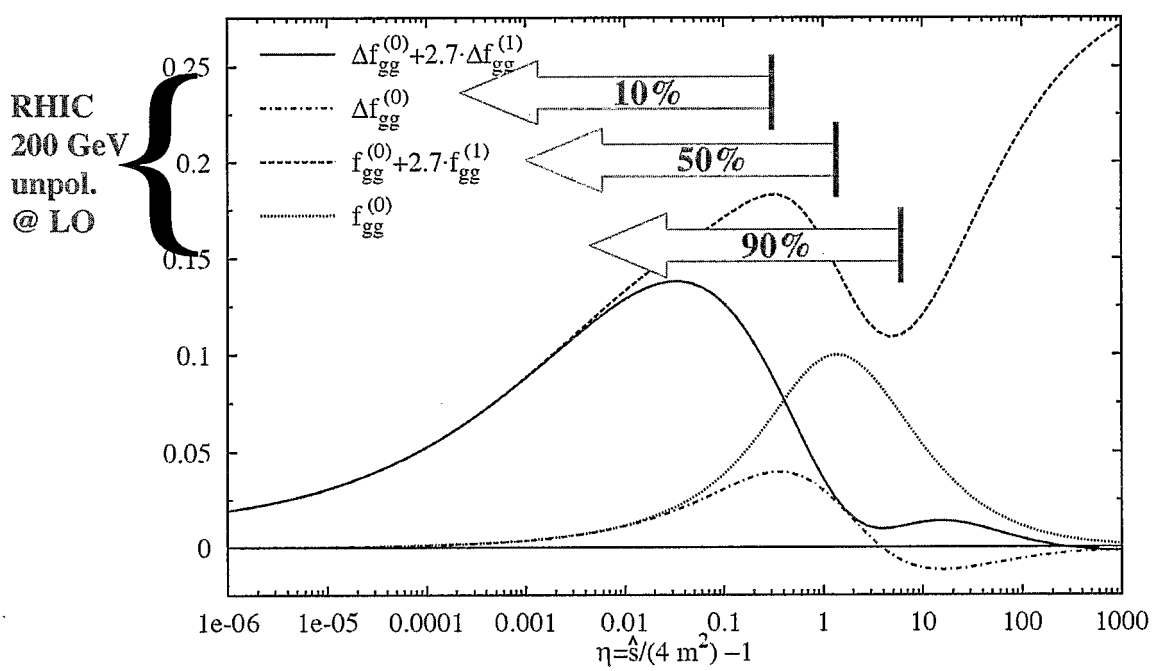
Pol. case for GRSV std.

H. Yokoya & WV



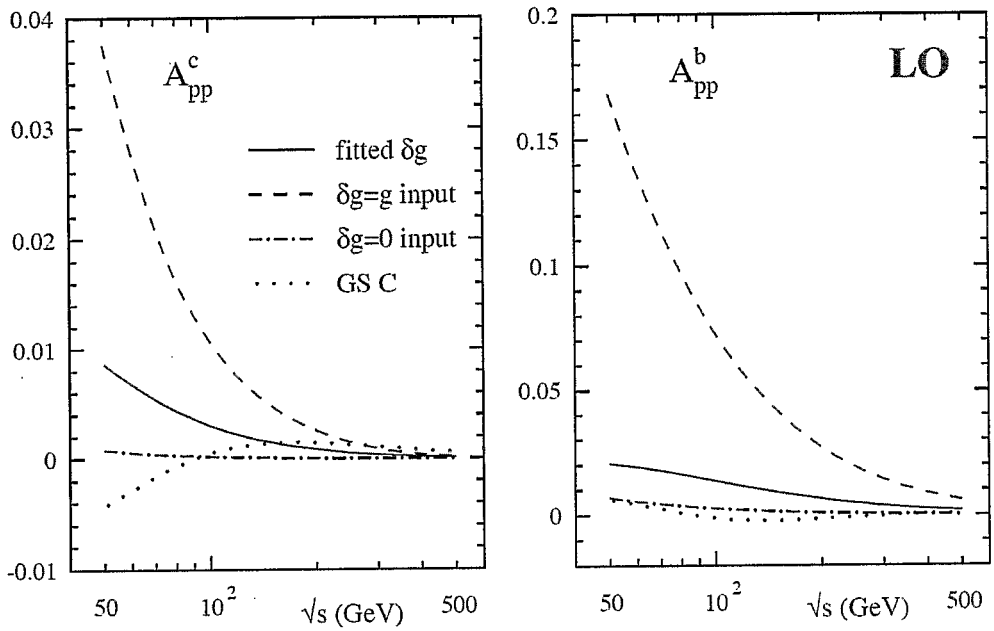
- **Little predictive power ?**

Bojak, Stratmann



$$\sigma_{pp} = \frac{\alpha_s^2(\mu^2)}{m^2}\int_{4m^2/S}^1 dx_a \int_{4m^2/x_aS}^1 dx_b\, g(x_a,\mu^2)\, g(x_b,\mu^2)\, f_{gg}\left(\frac{4m^2}{x_a x_b S}, \alpha_s(\mu^2), \frac{\mu^2}{m^2}\right)$$

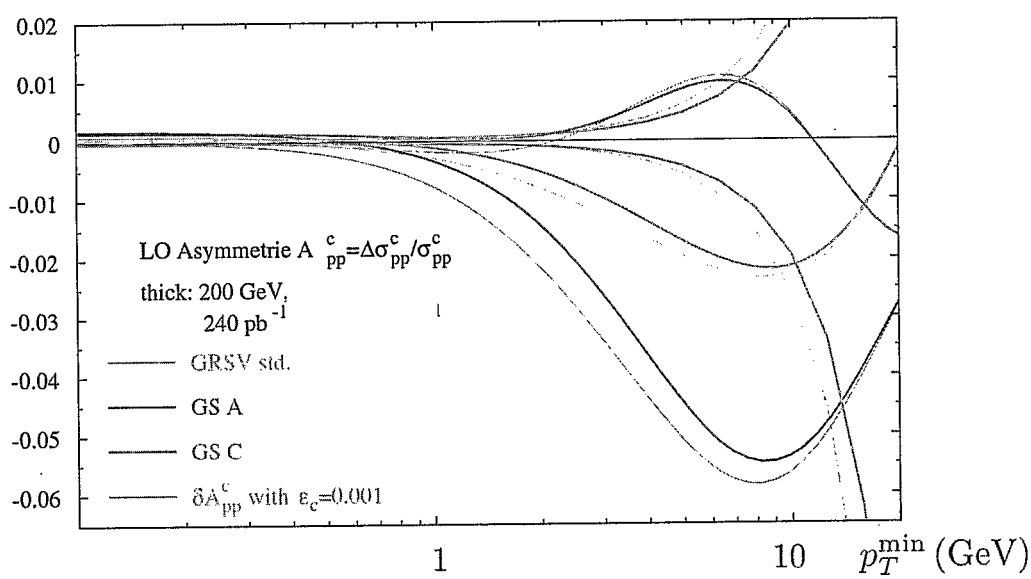
→ **total cross section has small spin asymmetry :**



Stratmann / Lampe, Reya

Bojak, Stratmann

- **Better prospects as function of p_T^{min}:**



- **NLO available**
- **Convolution with efficiencies for electron detection**
- **a mix of c and b**

Future of heavy flavor Measurements in PHENIX

Tony Frawley
Florida State University

For the PHENIX Collaboration

RBRC Heavy Flavor Workshop
BNL, December 14, 2005

The Upgraded PHENIX Detector

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel (Pixel + Strips)
- Si Vertex Endcap (mini-strips)

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Resistive Plate Chamber Time of Flight
- Hadron Blind Detector

Calorimetry:

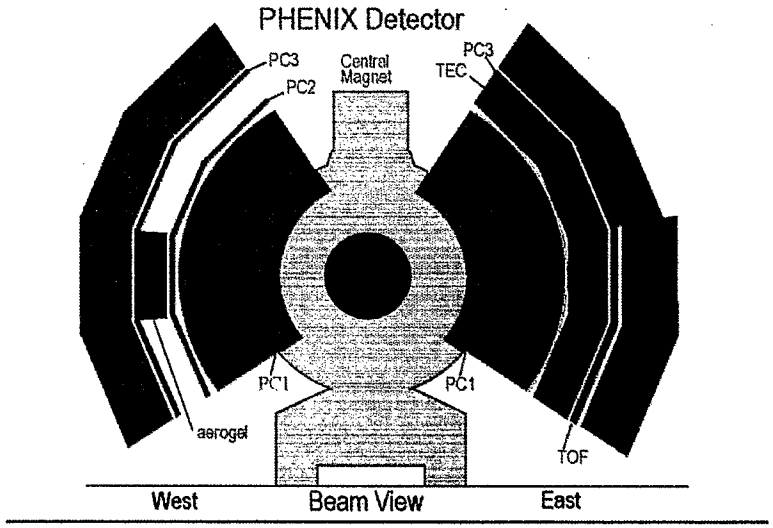
- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter

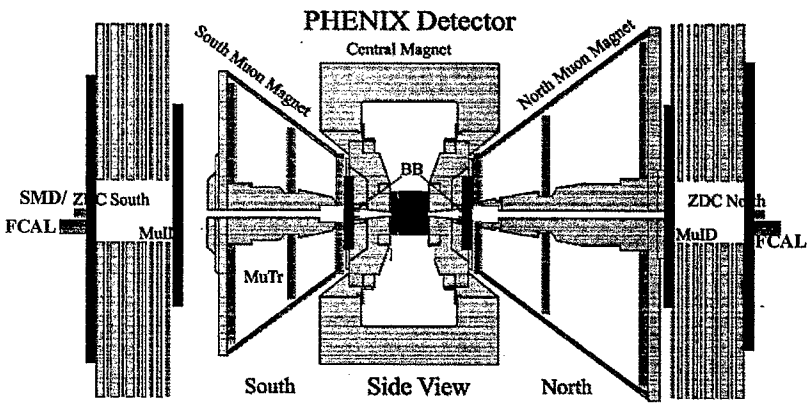
Event Characterization:

- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

Data Acquisition:

- DAQ Upgrade





Summary for VTX detector

Open heavy flavor from tight displaced vertex cuts.

- Much cleaner c+b $\rightarrow$ e measurement.
- Separate c $\rightarrow$ e and b $\rightarrow$ e statistically.
- Separate B $\rightarrow$ J/ψ $\rightarrow$ ee from prompt J/ψ.

Background reduction from loose vertex cuts to reduce light meson decays.

- Reduces background in open charm measurements
- Reduces combinatorial background in quarkonium measurements.

Improved momentum resolution $\rightarrow$ improved invariant mass resolution.

- J/ψ and ψ' separation
- Upsilon states separation

pA program improvements

Jet reconstruction in central barrel?

Summary for NCC

π^0 separation from γ and electrons to 30 GeV/c allows χ_c measurement via $\chi_c \rightarrow J/\psi \rightarrow \mu\mu\ \gamma$.

This measurement will be hard in central AuAu because of the combinatorial background. We are presently trying to quantify the expected signal/background and signal significance.

Even a measurement at Npart ~ 100 would be very useful, since J/ψ suppression is almost fully turned on by then.

The improvement in reaction plane resolution provided by the NCC enhances the J/ψ v_2 precision by ~ 2.5.

Heavy flavor yields for PHENIX

200 GeV Au+Au for a 12 week physics run. Other species comparable.

Signal	$\lvert\eta\rvert$	Obtained	RHIC I (> 2008)	RHIC II
$J/\psi \rightarrow e^+e^-$	< 0.35	~ 800	3,300	45,000
$J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4	~ 7000	29,000	395,000
$\psi' \rightarrow e^+e^-$	< 0.35		60	800
$\psi' \rightarrow \mu^+\mu^-$	1.2-2.4		520	7,100
$\chi_c \rightarrow e^+e^-\gamma$	< 0.35		220	2,900*
$\chi_c \rightarrow \mu^+\mu^-\gamma$	1.2-2.4		8,600	117,000*
$\Upsilon \rightarrow e^+e^-$	< 0.35		30	400
$\Upsilon \rightarrow \mu^+\mu^-$	1.2-2.4		80	1,040
$B \rightarrow J/\psi \rightarrow e^+e^-$	< 0.35		40	570
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4		420	5,700

* Large backgrounds, quality uncertain as yet.

Conclusions

RHIC II and the detector upgrades bring us dramatically expanded capabilities in heavy ion collisions, including:

- Separated **open charm and beauty**, R_{AA} and v_2 measurements to high p_T. Clean measurements of heavy quark energy loss.
- **J/ψ R_{AA}** to high p_T. **J/ψ v_2** versus p_T. **J/ψ $\langle p_T^2 \rangle$** vs centrality. Precise J/ψ rapidity dependence. All are strong tests of production models.
- Excited charmonium: $\chi_c \rightarrow$ **J/ψ+γ** and **ψ' R_{AA}**.
- Y **R_{AA}**. Which Upsilons are suppressed at RHIC?
- **B → J/ψ**. Independent B yield measurement, background to prompt J/ψ.
- **Jets tagged** with J/ψ, b, c, bb, cc - many clean handles on jet properties.

Future of STAR Measurements in the Heavy Quark Sector

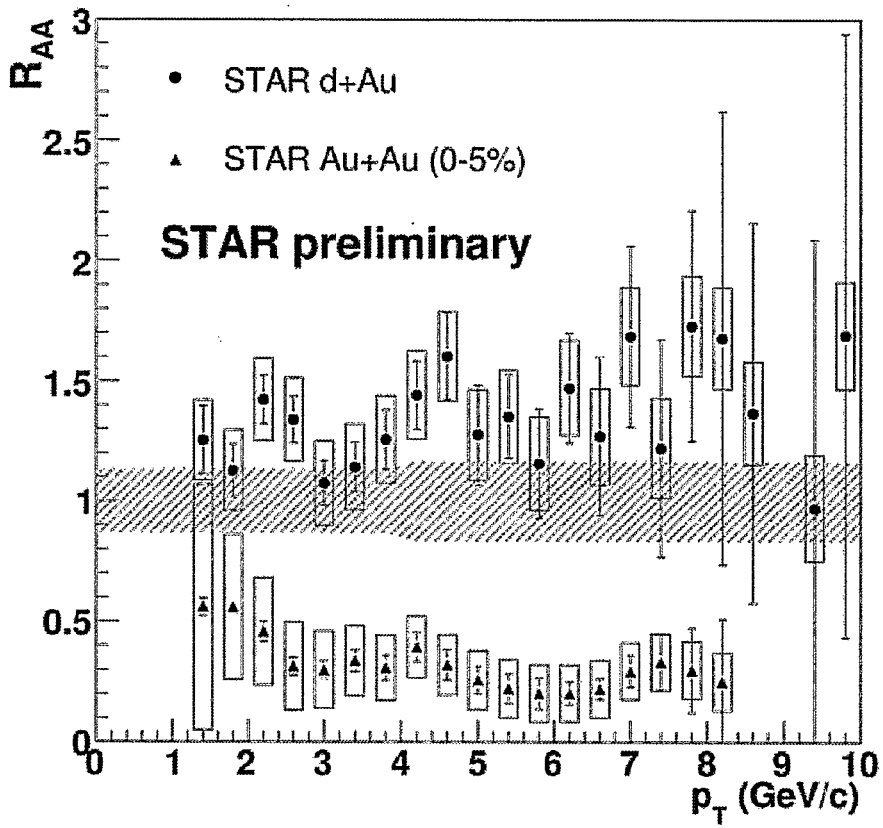
James C. Dunlop
Brookhaven National Laboratory

Summary

- STAR has proven capabilities for heavy flavor measurements at RHIC
  - Electron identification using three detector systems (TPC, TOF, EMC) from 1 to >10 GeV/c
  - Photonic background rejection using topological methods
  - Triggering capabilities to utilize full luminosity for rare probes
  - Direct reconstruction of charmed mesons
- STAR has a clear path for improving its capabilities
  - Completion and extension of calorimetric coverage
  - Extension of TOF coverage to full azimuth for electrons and combinatoric background rejection in direct reconstruction
  - Upgrade of Data Acquisition to increase effective luminosity and untriggered data samples
  - Installation of the heavy flavor tracker for displaced vertices

Outline

- Physics motivation: what remains to be learned in the heavy quark sector?
- Current detector and upgrade strategy/timeline
- Limitations of current detector and how upgrades remove these



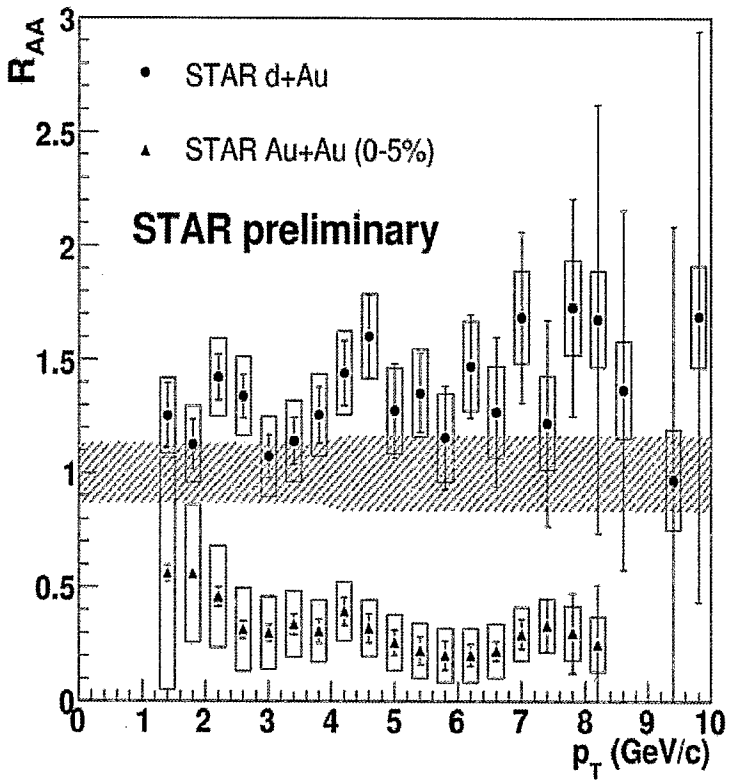
STAR: nucl-ex/0511005, nucl-ex/0510073, nucl-ex/0510063

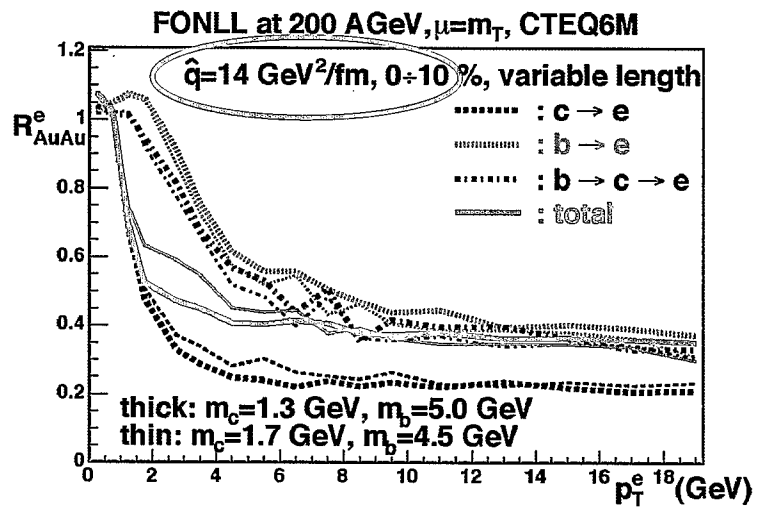
A central question: the relative yield of c and b

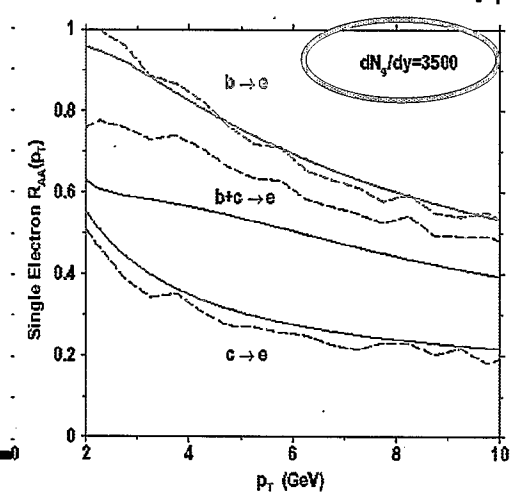
The observed suppression of non-photonic electons (NPEs) is not presently understood!

Attempts to reproduce it have completely changed the paradigm for the energy loss of light and heavy quarks

Armesto et al, private comm.



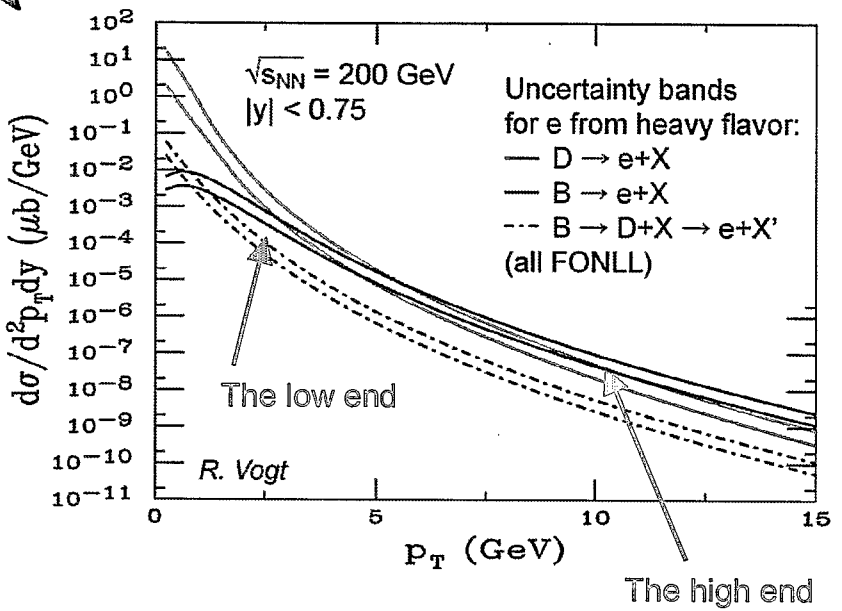




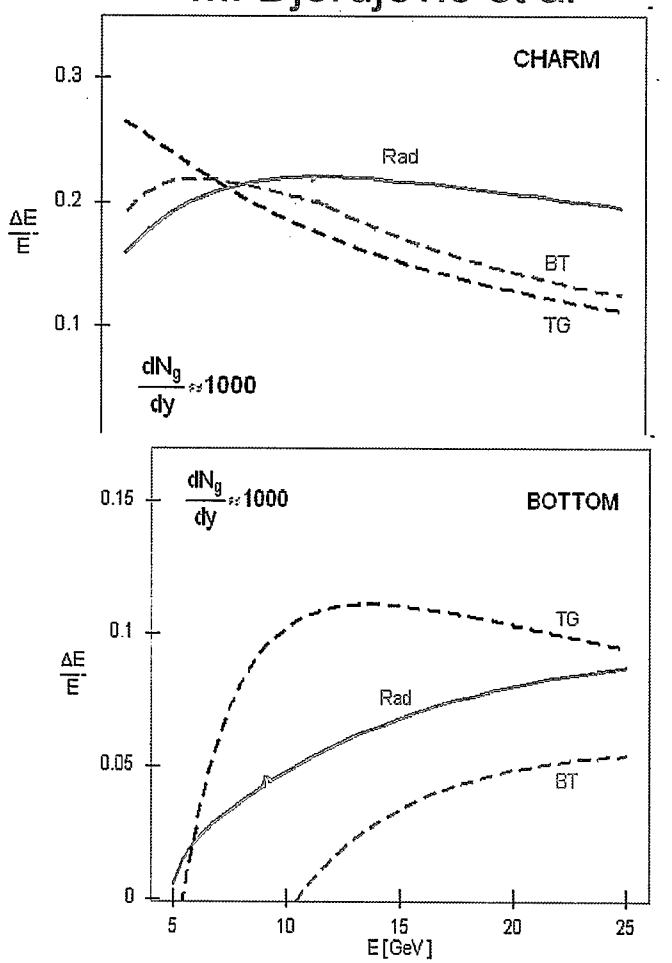
Resolving this is a crucial next step

Djordjevic et al, nucl-th/0507019

Further measurements of NPEs alone won't solve the problem



M. Djordjevic et al



The relative yield of charm and bottom is highly uncertain

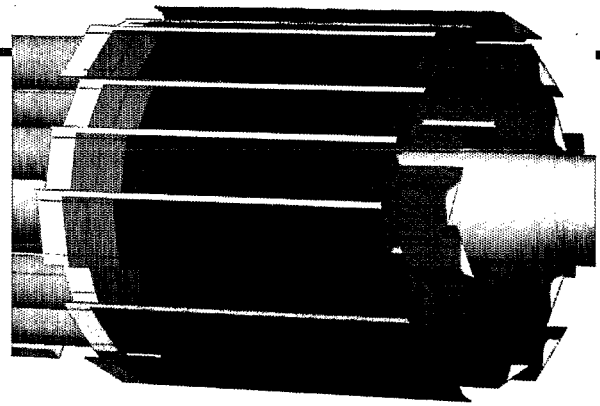
The collisional and radiative energy loss for the two is predicted to be different

The charm spectra must be measured directly to untangle the two contributions (Bears on the interpretation of the suppression for light quarks as well)

Upgrades relevant to heavy flavor

- Barrel Electromagnetic Calorimeter (EMC): High pt e
  - ¾ barrel of run 5 has been instrumented to full azimuthal coverage, $-1 < \eta < 1$, for next RHIC run: COMPLETE
- Barrel Time of Flight (TOF): Particle ID (e, hadrons)
  - Current prototype patches to be upgraded to full azimuth, $-1 < \eta < 1$.
  - Project is funded and proceeding
- Forward Meson Spectrometer (FMS): CGC studies
  - Full azimuthal EM Calorimetry $2.5 < \eta < 4.0$
  - Possibility of charm measurements in this region
  - Project is proceeding: complete by next d+Au run
- Data acquisition upgrade (DAQ1000): Data rate 10x
  - Upgrade TPC readout an order of magnitude, ~double effective Luminosity
  - Target for completion: RHIC run in 2008
- Heavy Flavor Tracker (HFT): Displaced vertices
  - High precision (<10 um) measurements for displaced vertices
  - Goal: standalone detector in place for RHIC run in 2009

An enabling technology for event-by-event charm measurement in STAR: the Heavy Flavor Tracker



- **Heavy flavor collectivity**
- **Charm quark kinetic equilibration**
- **Heavy flavor (c,b) energy loss**
- **Vector mesons → e^+e^-**

Two layers of Active Pixel Sensors (APS) around a new thin (0.5mm) small radius (14 mm) beam pipe

- 10^8 pixels, $(30\ \mu m)^2$
- Crucial for low p_T: thin
  - 50 μm thick
- 10 μm point resolution

Significant progress on:

- Simulations
- Mechanical design
  - integration and installation
  - support
  - alignment
  - calibration
- Sensor prototyping
- Readout design

The LHC heavy flavor program (from ALICE point of view)

P. Crochet for the ALICE collaboration

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Université Blaise Pascal, 24 Av. des Landais
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Philippe.Crochet@clermont.in2p3.fr

With a nucleus-nucleus center-of-mass energy nearly 30 times larger than the one reached at RHIC, the LHC will open a new era for studying the properties of strongly interacting matter at extreme energy density. One of the most exciting aspects of this new regime is the abundant production rate of hard probes which can be used, for the first time, as high statistics probes of the medium. Furthermore, heavy flavor measurements at LHC should provide a comprehensive understanding of open and hidden heavy flavor production at unprecedented low x where strong nuclear gluon shadowing is expected. The heavy flavor sector at LHC is subject to other significant differences with respect to SPS and RHIC energies. First, the large production rate offers the possibility to use new and large variety of observables. Then, the magnitude of most of the in-medium effects is dramatically enhanced. Physics perspectives with heavy flavors with the ALICE detector at the LHC are reviewed

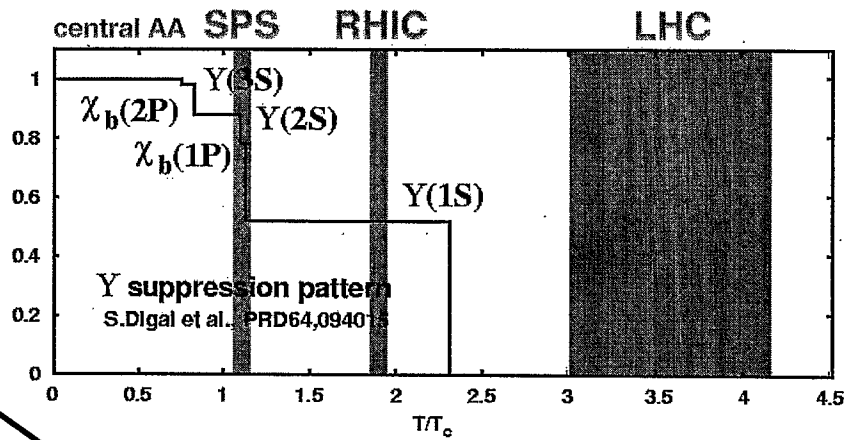
Heavy flavors: what is different @ the LHC

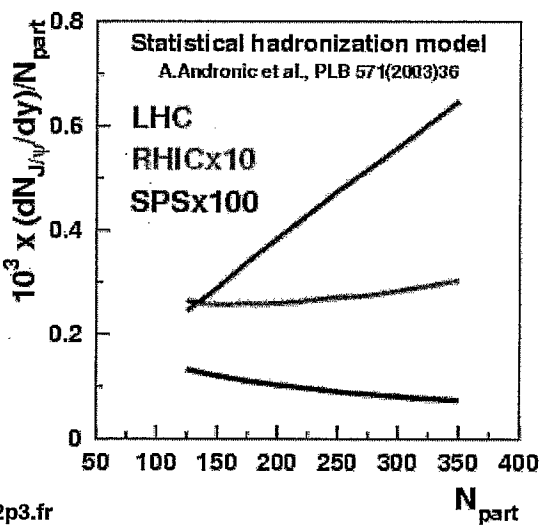
N($q\bar{q}$) per central AA (b=0)

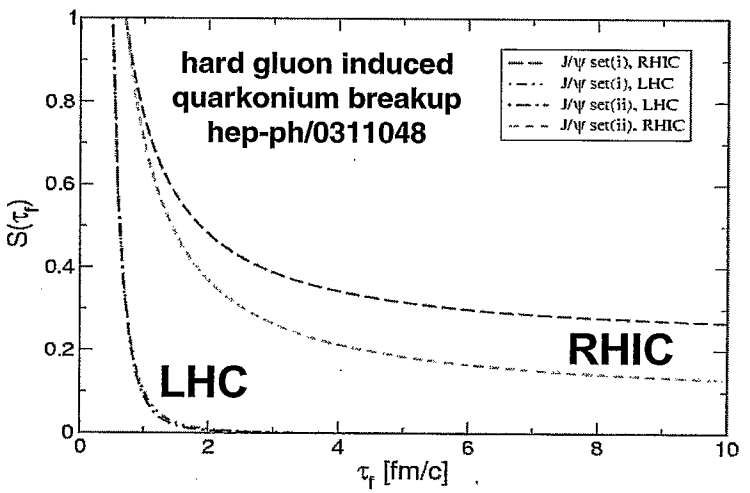
	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5

- large primary production
- melting of $\Upsilon(1S)$ by color screening
- none of the primary J/ψ survives the (PbPb)QGP
- a lot of charmonia from b hadron decay
- large secondary production of charmonia

statistical hadronization, kinetic recombination, DD annhililation







Philippe.Crochet@clermont.in2p3.fr

(di)leptons: what is different @ the LHC

B-chain:

$X \leftarrow B\bar{B} \rightarrow \mu^- + D + X$
$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \mu^+ + X$

BB-diff:

$X + \mu^+ \leftarrow B\bar{B} \rightarrow \mu^- + X$

charm pure NLO

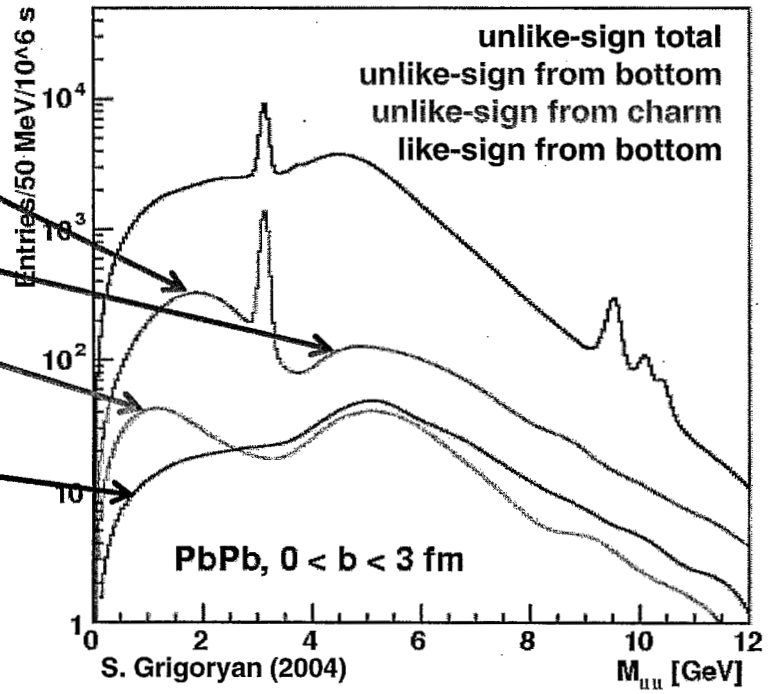
$B \rightarrow D$ decay:

$X + \mu^- \leftarrow B^-B^+ \rightarrow \pi^+ + \bar{D}^0$
$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \mu^- + X$

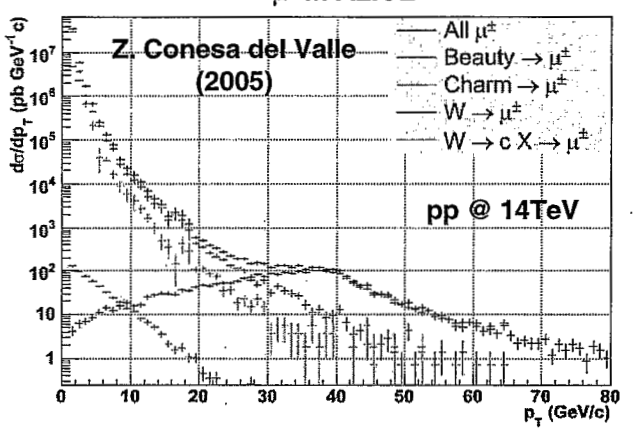
B^0 oscillations:

$X + \mu^- \leftarrow \bar{B}^0B^0 \rightarrow \bar{B}^0 \rightarrow \mu^- + X$

dimuons in ALICE, $p^{\mu}_t > 2$ GeV/c



$\mu^{\pm}$ in ALICE



- large combinatorial background
- dileptons from b decay dominate the spectrum below Υ & J/ψ
- large yield of secondary J/ψ from b decay
- dileptons from b decay have different origin at low & high mass
- sizeable yield of like-sign correlated dileptons from b decay
- $W^{\pm}$ stick out from single lepton spectra with large statistics

Centrality dependence of quarkonium yields in ALICE-muon

cross-sections from R. Vogt in hep-ph/0311048,

with shadowing & feed-down, w/o nuclear-absorption/suppression/enhancement

- J/ψ: large stat., good sign.
  (allows much narrower centrality bins)
- ψ': small S/B
- ϒ: good stat., S/B > 1, good sign.
- ϒ': good stat., S/B > 1, good sign.
- ϒ'': low statistics

similar rates for ϒ in the dielectron channel

Pb-Pb, $\sqrt{s}$ = 5.5 TeV, L = 5.10^{26} $cm^{-2}s^{-1}$, T = 10^6 s
2σ mass cut, ε assumes dN_{ch}/dy = 4000 @ y = 0 in central

	b (fm)	0-3	3-6	6-9	9-12	12-16	min-bias
	ε (GeV/fm³)	32	30	28	16	5	
J/ψ	S (×10³)	132.6	234.6	198.2	94.75	21.66	681.4
	S/B	0.2	0.27	0.48	1.08	3.13	0.33
	S/√S+B	148	224	254	222	128	413
ψ'	S (×10³)	3.69	6.53	5.5	2.61	0.59	18.92
	S/B	0.012	0.017	0.03	0.063	0.172	0.02
	S/√S+B	6.7	10.4	12.6	12.4	9.3	19.53
ϒ	S (×10³)	1.349	2.38	1.991	0.932	0.204	6.33
	S/B	1.66	2.31	3.6	6.06	9.12	2.46
	S/√S+B	29	40.8	39.5	28.3	13.6	67.14
ϒ'	S (×10³)	0.353	0.623	0.522	0.244	0.054	1.8
	S/B	0.65	0.9	1.36	2.25	3.46	1.03
	S/√S+B	11.8	17.2	17.3	13	6.4	30.19
ϒ''	S (×10³)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	S/B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	S/√S+B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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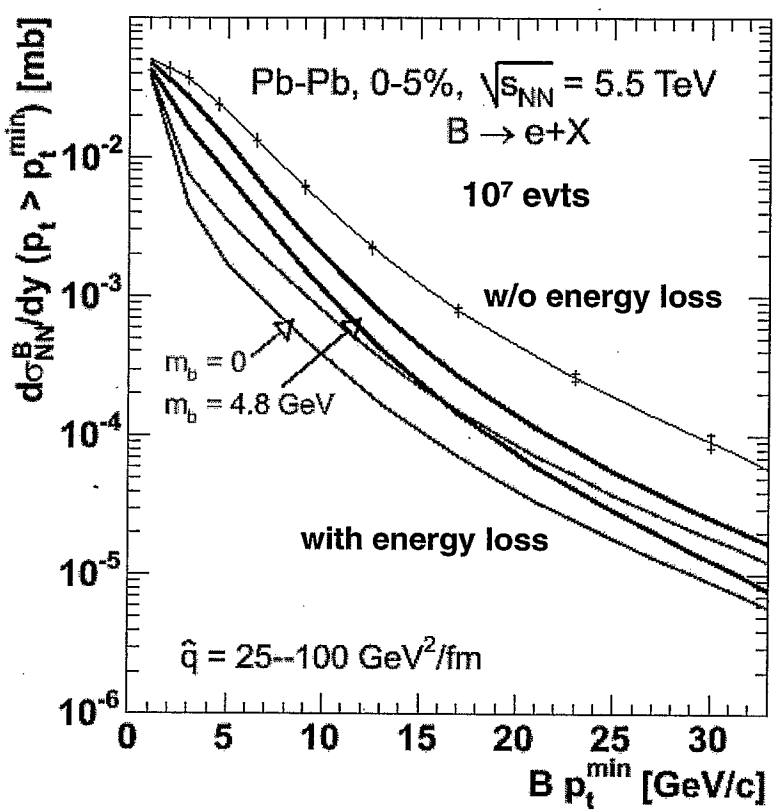
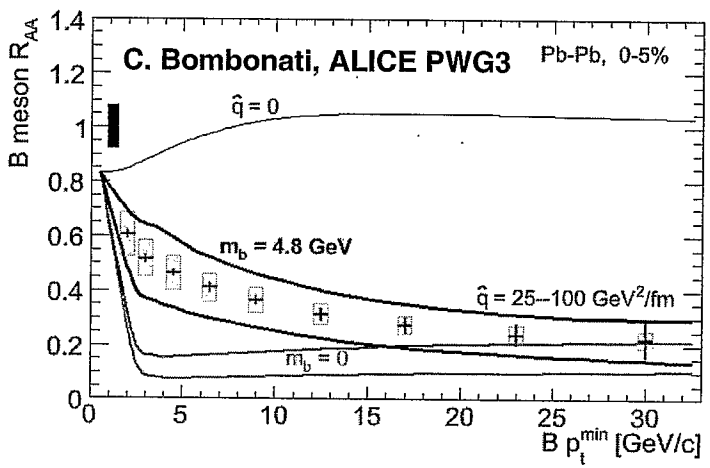
b-hadron inclusive differential cross-section from single electrons



same method as the one used with muons plus scenario for b-quark energy loss

- electrons with $2 < p_t < 20$ GeV/c → b-hadrons with $2 < p_t^{min} < 30$ GeV/c
- clear sensitivity to energy loss
- gives direct access to $R_{AA}^{b\text{-hadrons}}$
- R_{AA}^{h}, R_{AA}^{D0} & $R_{AA}^{b\text{-hadrons}}$ can be measured simultaneously



F. Antinori, C. Bombonati, A. Dainese, M. Lunardon & R. Turrisi (2005), ALICE PPRVII
E-loss: N. Armesto, A. Dainese, C.A.Salgado & U.A. Wiedemann, Phys. Rev. D 71 (2005) 054027

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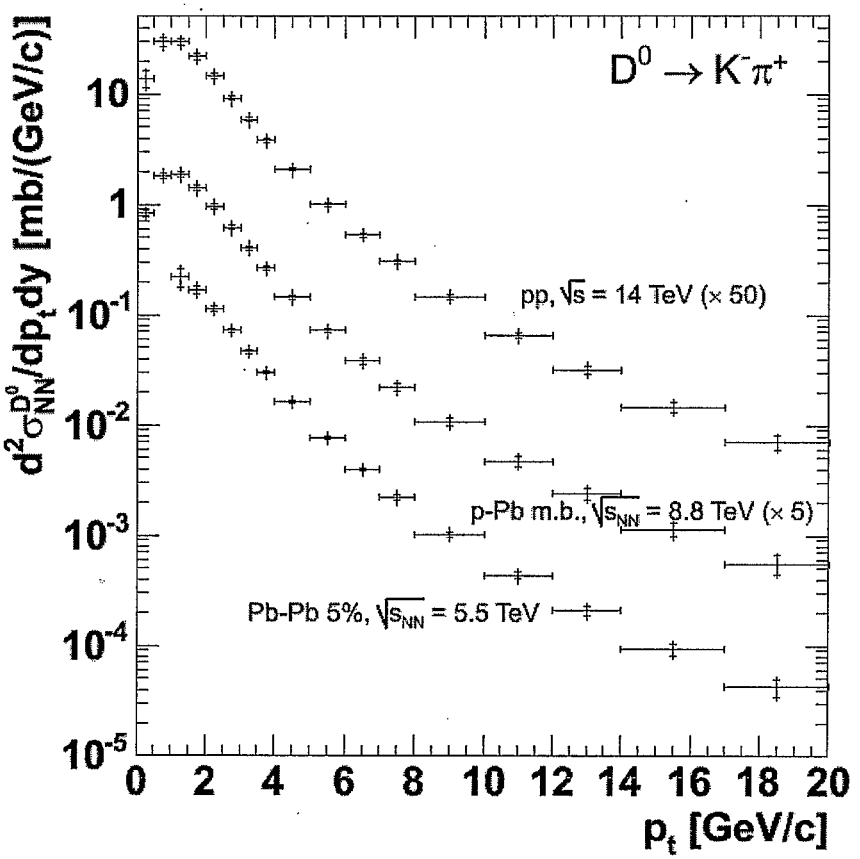
Hadronic charm differential x-section

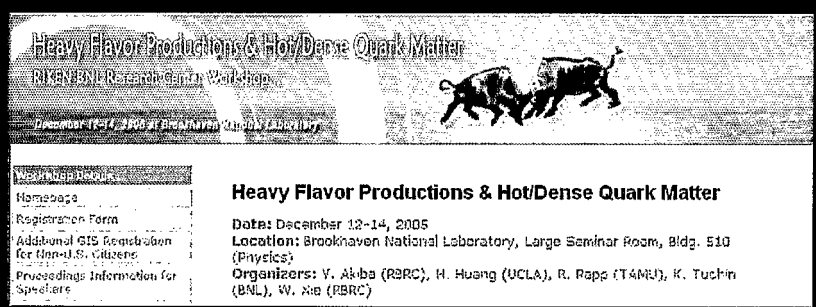


system	pp	pPb	PbPb
$\sqrt{s}$ (TeV)	14	8.8	5.5
trig	MB	MB	CC
N_{evt}	10^9	10^8	10^7
time (months)	8	1	1
p_t^{min} (GeV/c)	0.5	0.5	1
E_{stat} (%)	3	2	7
E_{syst} (%)	14	16	17

the most precise measurement of the total charm x-section in pp collisions @ LHC

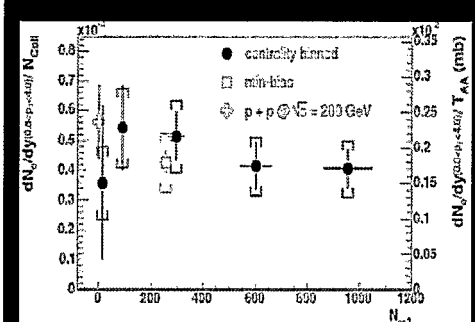
Philippe.Crochet@clermont.in2p3.fr

Summary of Experimental Results



Jamie Nagle
University of Colorado at Boulder

Total Charm Scaling at RHIC



Binary scaling of total open charm yield

STAR Charm total cross section per NN interaction

1.13 ± 0.09(stat.) ± 0.42(sys.) mb in 200GeV minbias Au+Au collsions

1.4 ± 0.2(stat.) ± 0.4(sys.) mb in 200GeV minbias d+Au collisions

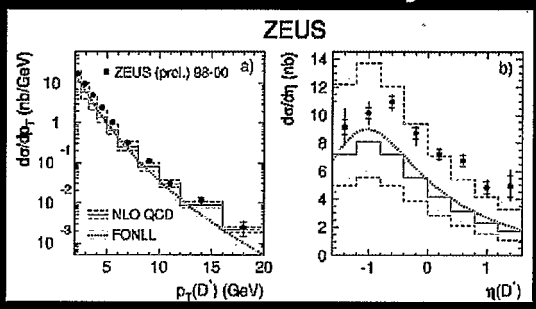
Charm total cross section follows roughly Nbin scaling from d+Au to Au+Au considering errors

Indication of charm production in initial collisions

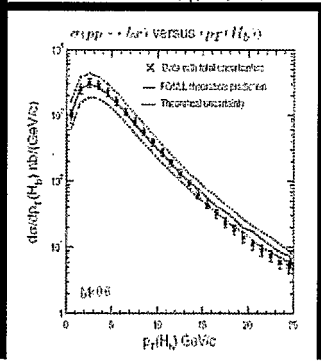
Quiz: What fraction of the charm cross section is represented by electrons above pT > 0.8 GeV?
(a) 0.85, (b) 0.50, (c) 0.15

2

Charm/Beauty and pQCD NLO

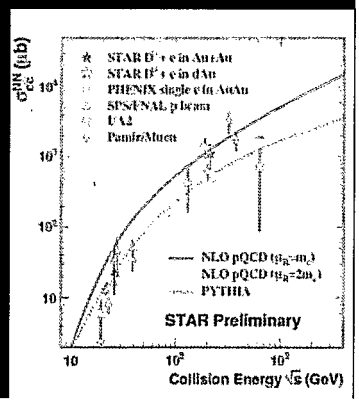


Charm / Beauty in Photoproduction

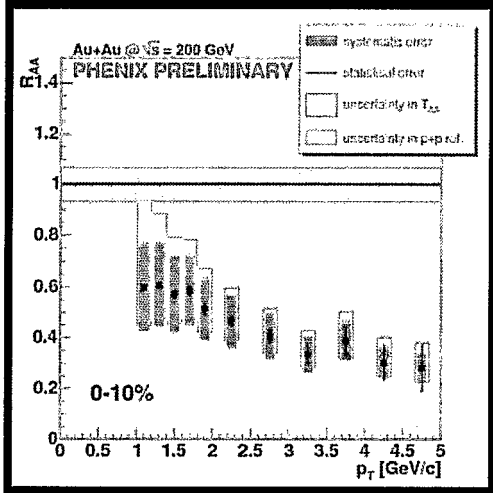


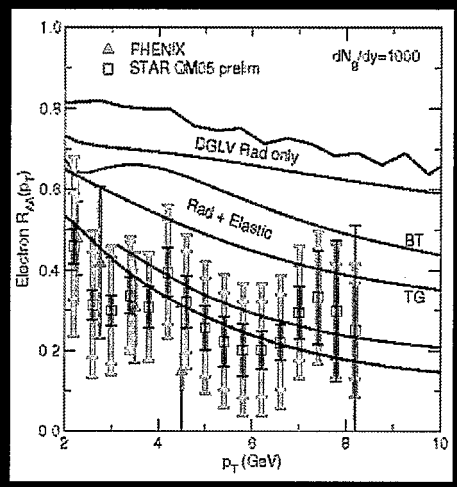
Tevatron

RHIC



Suppression of High p_T Charm

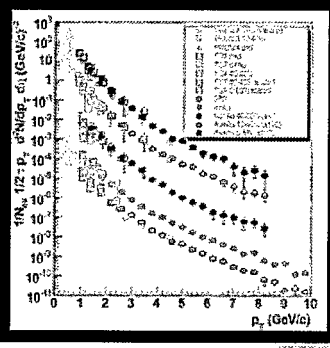




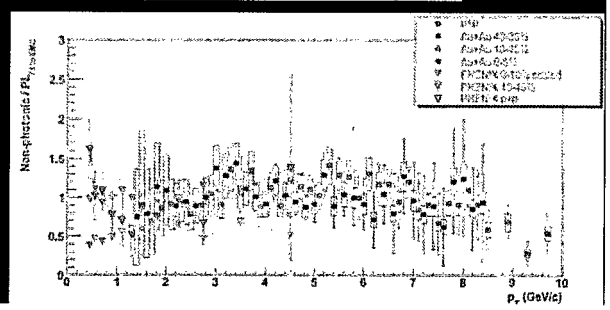
4

Post QM - Direct Comparison

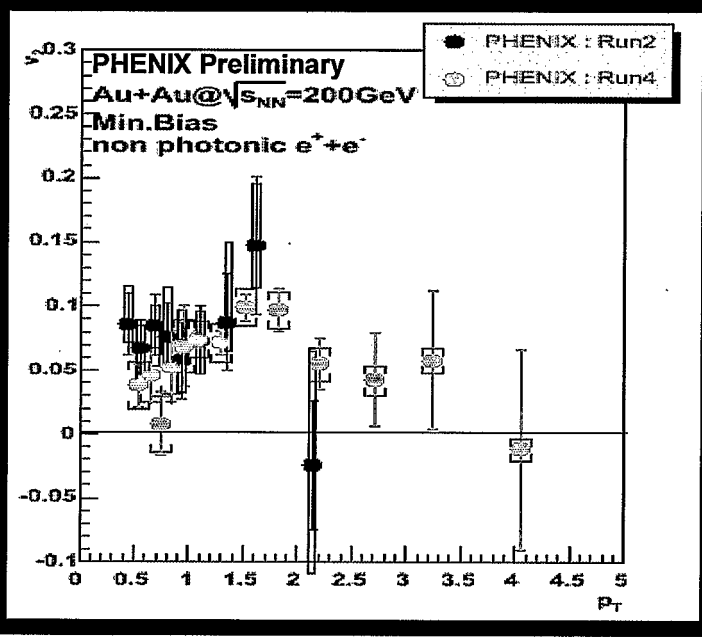
"STAR TOF, BEMC and PHENIX agree reasonably well. Systematic uncertainties are under evaluation"



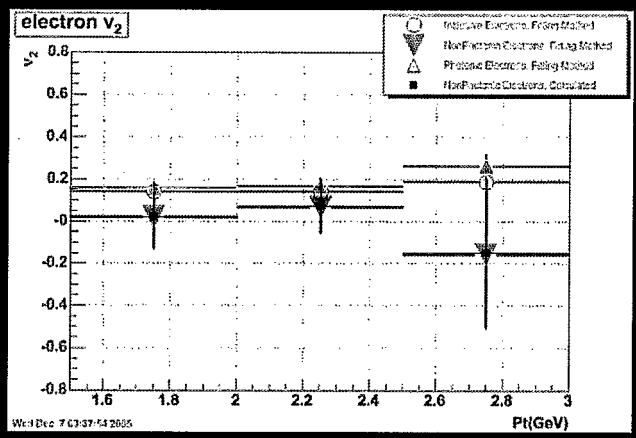
STAR high pT data has decreased significantly in both pp and AuAu, and the PHENIX results are somewhat higher.



Non-Photonic Electron Flow

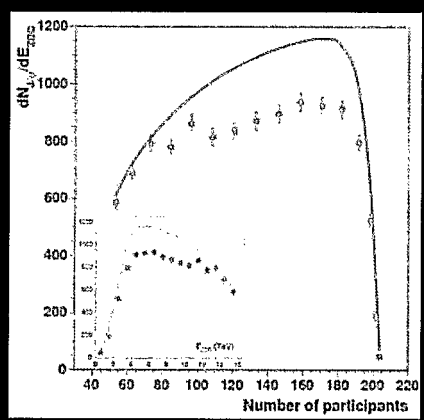


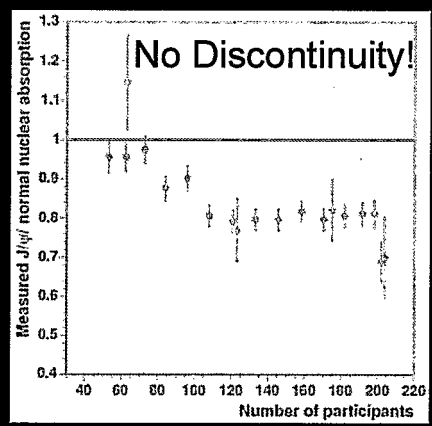
STAR Workshop Report



"The detector material in STAR caused too much photonic background, which caused huge systematic and statistical uncertainties. Our result is not sensitive enough to make any conclusion about heavy quark v2 so far. More work ahead!" [7]

NA60 Data



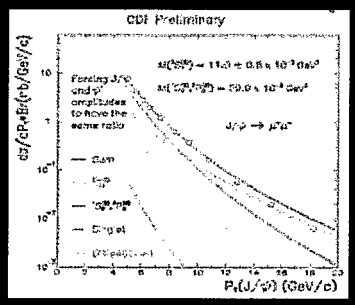


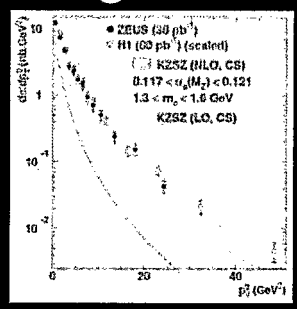
Quiz: What is the most central bin for which one can reliably quote Glauber parameters with "no systematic error"?

(a) 20%, (b) 10%, (c) 5%, (d) 1%, (e) 0.1%

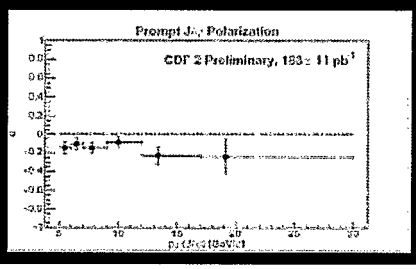
8

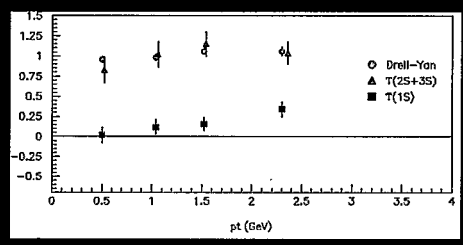
Color Singlet/Octet?



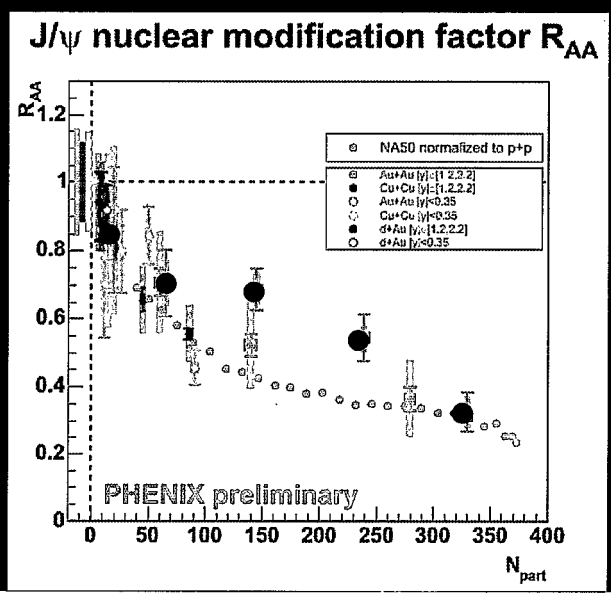


Polarization as a key test-





Looks Like CERN Suppression



10

Heavy quarks BNL workshop, theoretical summary

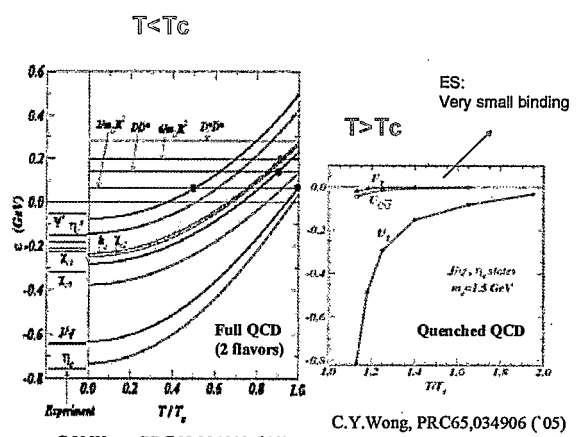
Edward Shuryak
Department of Physics and Astronomy
State University of New York
Stony Brook NY 11794 USA

outlook

- Heavy quark bound states at T>Tc ? (F or U or a combination?)
- Evolving theory of J/psi in QGP (diagonal O(Nc) re-creation or non-diagonal O(N_c^2) recombination?)
- Phenomenology of charm diffusion and flow: Dc, FP coefficients
- Theory of the charm/bottom energy loss (radiative, collisional,ionization...)
- My apology for not covering other things such as heavy quark production in pp or pA

T.Umeda (BNL) Lattice Heavy flavor

- MEM spectral densities hep-lat/0509115 new lighter at 1.75 Tc, also in Bielefeld chi_c goes to the left with rising T (not eta_c but chi_c)
- Potential model analysis: Miyamura et al PRL 57 (1986) suppression from the screening
- Color averaged free energy was used before
- Timing: F or U?
- several new papers Wong hep-ph/0507084, Alberico 0509088
- Potential model studies are in agreement with MEM



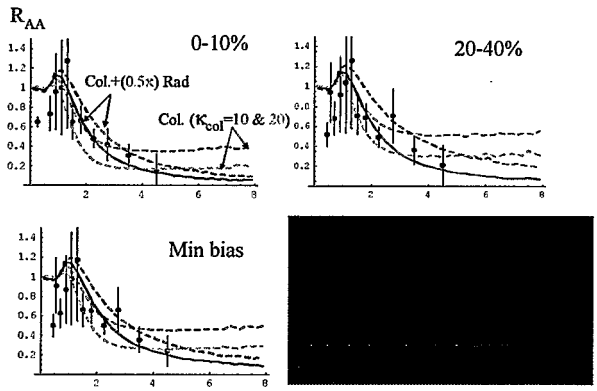
R.Thews

- New scenario with recombination
- 20-40 cbar c pairs (phenix-star) in central AuAu
- Statistical hadronization for J/psi works but Ncc^2 different in models
- cbar c should find each other in QGP before deconfinement...
- J/psi is quadratic in Nc in this scenario: (not in mine,see below) and should be quite large at LHC
- Non-diagonal give smaller pt (flow can distort) and narrower y (the latter do not seem to agree with data...)

Pol-Bernard Gossiaux

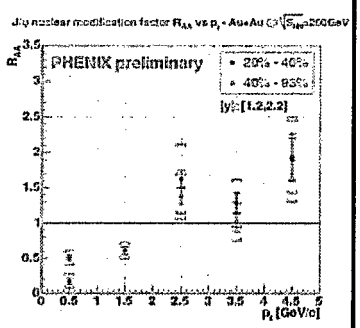
- Fokker-Plank and NOT Boltzmann
- Measure transport coefficients, not calculate
- A and B, Diffusion coefficient in p space: mean kicks etc,
- Mustafa et al Srivastava 97 gave FP coefficients
- Relaxation time larger than collision time
- Asymptotic distribution is Tsallis distr (?) Rafelski 99
- Large coefficient on top of pqcd like Molnar, Both for collisional and radiational
- No force on c after QGP
- Small broadening of y distribution
- Vs pt distribution: kappa_collisional=10-20 or radiational+coll
- V2: 20 kappa_coll is not enough, nor is coll+rad. All give too little:
- light quarks contribute very little to v2 of D, way below
- J/psi= alpha N_c^2, how large is alpha?
- Ncc=20 depends on kappa_coll and depend on Tdiss
- Ratio of jpsi(y)/nC^2(y) is due to diffusion

Leptons (← D decay) transverse momentum distribution (y=0)



Cbar c pair flies till it meets the hydro cell moving with the same speed, and then get stuck in it

- Possible if v(Jpsi)< v(flow)<.7
- Agrees with the idea that suppression is seen below pt=3GeV*.7=2 GeV
- (fig. at right from Gunji (PHENIX))



Potentials: free energies F, U=F-TS, and exp(-(hbar^2/Mr^2+U)/T) I ignore octet, see below

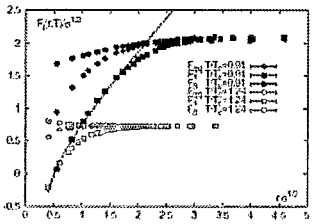


FIG. 1. Heavy quark free energies for 2-flavors of dynamical quarks at a quark mass of $m/T = 0.40$ on $16^3 \times 4$ lattices shown are the different color channels, the singlet (F_1), octet (F_8) and color averaged ($F_{\langle q\bar{q}\rangle}$) renormalized to the zero-T potential (solid line)

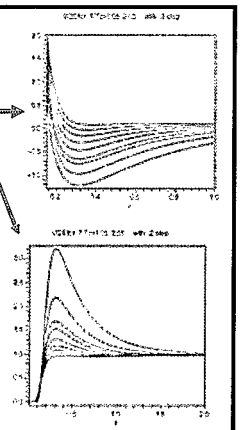


FIG. 2. The [illegible] distributions [illegible] for the total [illegible] for $T/T_c = 1.0/m$

Fokker-Plank with interaction keeps cbar and c correlated for long time: note small flux outward

VQE for T/Tc=1.05,2.65 with .2 step

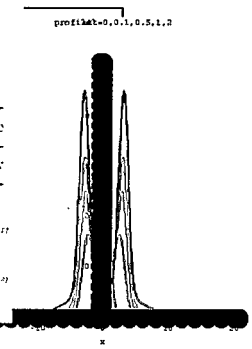
$$\frac{\partial P}{\partial t} + D\frac{\partial}{\partial r} f_0 \frac{\partial}{\partial r}(P/f_0) = 0$$

$$f_0 = exp(-V_{eff}/T)$$

Finally, we included the mixing between the color singlet and color octet channels. Its form is fixed by the condition that no changes should occur if the distributions are in equilibrium, and that the total probability $P_1 + P_8$ be conserved in time. The corresponding coupled system of equations reads

$$\dot{P}_1 = -w\left(\frac{P_1}{f_1} - \frac{P_8}{f_8}\right) + (f_1' - 2f_1/2)\left(\frac{P_1}{f_1}\right)' + f_1\left(\frac{P_1}{f_1}\right)''$$

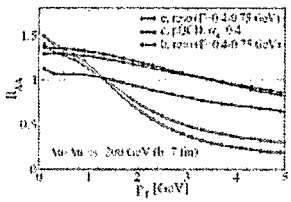
$$\dot{P}_8 = +w\left(\frac{P_1}{f_1} - \frac{P_8}{f_8}\right) + (f_8' - 2f_8/2)\left(\frac{P_8}{f_8}\right)' + f_8\left(\frac{P_8}{f_8}\right)''$$

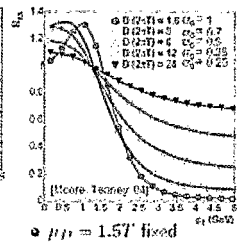


H. Van Hees (HH+RR), TAMU

- Why charm Diffusion const. is so small? (sigma© is so large?)
- => Survival of Resonances (heavy-light) to enhance scattering in sQGP, above the threshold: several time larger than pQCD trasport x.s. by factor 3 (because the res. sigma is isotropic)
  - Fokker-Plank : drag and diffusion
  - Relat.Langevin =>RAA, v2
- Coalescence with light q (which brings in its v2)
- b dominates for pt>3.5 GeV (?)
- Bottomonium lifetimes calculated vs T (fig) including quasifree dissociation reduce lifetime, but again it can happen many times....
- rate eqn: suppression of Upsilon and find suppression larger
- That for psi and equal about factor 2 (from nuclear absorption)
- Ralf said feed down from other Ys was very important for that

Spectra and elliptic flow for heavy quarks

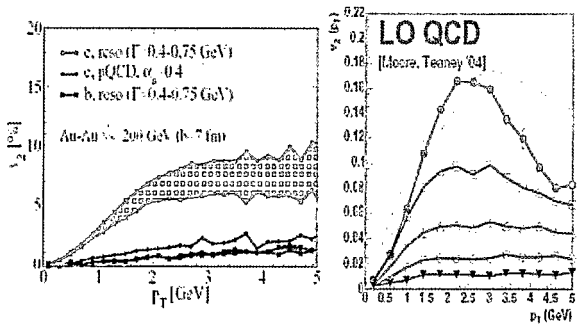




- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances => c-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

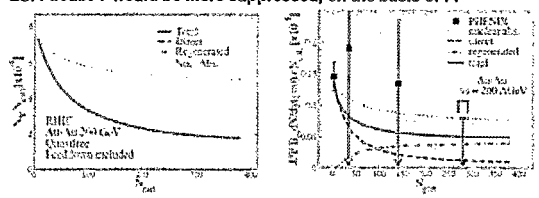
- $\mu_D = 1.5T$ fixed
- $2\pi TD \simeq \frac{3}{2\pi T}$

Spectra and elliptic flow for heavy quarks



Υ vs. J/ψ at

ES: I doubt Υ would be more suppressed, on the basis of FP



[Grandchamp et al 03]

- Suppression prevalent effect
  - color screening in QGP
  - suppression of higher bottomonia and feeddown to Υ
- with vacuum Υ thermal suppression for Υ negligible magnitude of suppression sensitive to color screening
- J/ψ yield dominated by regeneration

M.Djordjevic (Ohio S)

- Heavy quark: larger losses that light or not? DK- dead cone, but this is only if radiation. Other processes can be the opposite at same pt (ES 97).
- Ter-Mikaelyan effect (medium modif. of gluons=>no soft massless gluons) enhance yield of c (reduces radiation)
- Transition radiation at the boundary:TM effect reduced from 30% to 15%, so nearly cancel each other
- Now we ignore those two effets and look at radiation
- Charm looses about 25% and bottom only 10% or so, linear in energy and not quadratic as light quark
- For 5 gev charm delta E is 50% lower than for light, but at 25 GeV both are about the same, but bottom much less (good fig)
- Prediction for suppr is for charm .5 pm.1. After quneching b

starts to dominates after 3 GeV pt, not 5

Single electron from both c and b: RAA=.7 or so at pt=10 GeV disagrees with data by large factor!

1 OPTION: INCREASE DN/DY OF GLUONS

2 option: elastic energy loss (?) to be calculated

Conclusion: b is important, and c is not that much suppressed as light q/g jets:

Radiative energy loss not enough!

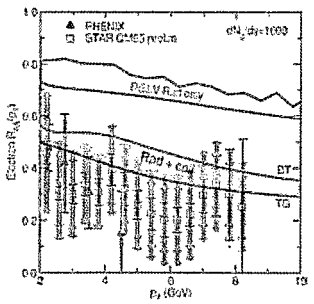
S.Wicks Columbia

- Elastic and radiative dEdx (ES: not enhanced by resonances like for RR+HH)
- Improved elastic in UV and IR,
- (fig) same order as radiative
- But Romatschke+Strickland –improved
- Finite time effects? Formation? Energy ``gain" at lower pt compared to vacuum radiation?
- Combining the two, twice the suppression
- But what about Casimir scaling and pions? Those would be overquenched!

Playing with L since light prop.to L^2 and elastic to L.

Results - Electron Raa (fixed L=5fm)

Fixed L=5fm; α=0.3; dN_g/dy=1000



Simon Wicks, Columbia University
(Heavy Flavor Workshop, 12th

17

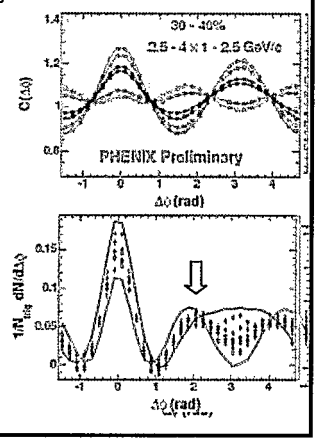
PHENIX: Reaction Plane Angle Dependence
(from B.Cole)

My comments on that:

⇒What is radiated is not gluons, which do not propagate in sQGP, but sound (Casalderrey, Teaney,ES 04), and dE/dx can be calculated like a drag for a fighter jet... from hydro

⇒Has the sonic boom been already seen?

Mean Cs=.33 time average over 3 stages=> $\phi=\pi$ +/-1.23=1.91



Strength of dE/dx

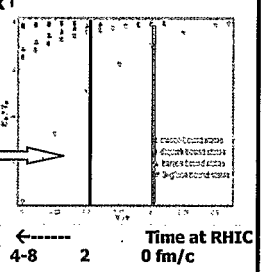
- BDMPS, Gyulassy+..., all assumed QGP is made of uncorrelated charges
- But when they are correlated

(e.g. + and – alternated) local electric field is larger => $\hat{q} \propto \int dz\vec{E}(z)$^2

No contradiction between large DE/dx and entropy

chain (qgg...gq) network or crytalline order must be important for dE/dx!

- Timing of dEdx
- |Binding|>T only at T<1.5Tc
- a ``latent time" delta tau at RHIC before local order settles? (T_max=2Tc)



Plus about 4 fm/c at T=Tc in the so called mixed phase!

My questions: (instead of conclusions)

- Stability domain of J/psi in T is about fixed. But not the Lifetime of J/psi in QGP (Gamma). What about a correlation exp(-U/T) which is there even if the state is gone? What is its role?
- What is actually observed in J/psi RHIVC data:

  (i) original J/psi survived, (ii) Diagonal (twins)`` re-created" J/psi or (iii) nondiagonal (unrelated) J/psi ?
- Is J/psi quadratic in Nc really seen? (Thews,Rapp et al) test the depth of the minimum at 62 GeV , if true one should be able to locate min. in y

- What is the value of the [illegible]
- **In pQCD the radiative or collisional dEdx have the same Casimir scaling, g vs c =>9/4 which we don't see. What is the mechanism? Resonances for charm? Why we have such large v2?**
- Jets: tomography in space and time=> matter changes, possibly dE/dx is not just proportional to density of matter, but depends on the effective coupling=closeness to Tc
- Why we don't see a dominance of dEdx at the very early time when we have strong color glass fields?

(R.Venugopalan)

Heavy Flavor Productions and Hot/Dense Quark Matter

December 12-14, 2005
Physics Department Large Seminar Room

Registered Participants as of November 21, 2005

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Heavy Flavor Productions and Hot/Dense Quark Matter

Physics Department Large Seminar Room

Agenda

Monday Morning, December 12 (Chair: M. Tannenbaum)

08:00 - 09:00		Registration
09:00 - 09:10		Welcome
09:10 - 09:55	*D. Kharzeev*	Historic Review of Probing Quark Matter via Heavy Flavor Measurement
09:55 - 10:25	*T. Gunji*	PHENIX Charmonium Measurement in p-p, d-Au and Au-Au
10:25 - 10:55	*W. Dong*	Non-photonic Electron v2 and Heavy Quarkonia Measurements from STAR
10:55 - 11:05		**COFFEE BREAK**
11:05 - 11:35	*F. Kajihara*	PHENIX Open Charm Measurement in p-p, d-Au and Au-Au
11:35 - 12:05	*H. Zhang*	Star Open Charm Measurement in p-p, d-Au and Au-Au
12:05 - 13:30		**LUNCH** (only served at the Berkner Hall Cafeteria until 13:00)

Monday Afternoon, December 12 (Chair: R. Rapp)

13:30 - 14:10	*E. Scomparin*	SPS Charm and Bottom Measurements
14:10 - 14:50	*T. Umeda*	Lattice Calculations on Heavy Flavor: Open and Hidden Charm States Above T_c
14:50 - 15:30	*R. Thews*	Heavy-Quarkonium Formation in QGP via Recombination
15:30 - 15:40		**COFFEE BREAK**
15:40 - 16:30	*H. van Hees*	Collective Flow, R_AA and Heavy Flavor Rescattering
16:30 - 17:10	*M. Djordjevic*	Heavy Quark Energy Loss in Nucleus-Nucleus Collision
17:10 - 17:30	*S. Wicks*	Heavy Quark Elastic Energy Loss
17:30 - 17:50	*W. Horowitz*	Role of Dynamic Geometry in Heavy Quark Tomography

Tuesday Morning, December 13 (Chair: N. Xu)

09:00.- 09:40	*P.-B. Gossiaux*	Thermalization of Heavy Quarks and Consequences on the Charmonia Production
09:40.- 10:20	*J.-C. Peng*	Heavy Flavor Production in p-A Collisions
10:20 - 10:30		**COFFEE BREAK**
10:30 - 11:10	*R. Vogt*	Heavy Quarkonium Production and Color Evaporation Model
11:10 - 11:50	*C.-Y. Wong*	Heavy Quarkonium Dissociation Cross Sections and in-Medium Effects
11:50 - 13:10		**LUNCH** (only served at the Berkner Hall Cafeteria until 13:00)

Tuesday Afternoon, December 13 (Chair: M. Leitch)

13:10 - 13:50	*J. Raufeisen*	Effect of Shadowing and Initial State Energy Loss on Heavy Flavor Production
13:50 - 14:30	*R. Venugopalan*	Heavy Flavor Production and Color Glass Condensate
14:30 - 15:10	*A. Geiser*	HERA: H1-Zeus Heavy Flavor Measurements
15:10 - 15:30		**COFFEE BREAK**
15:30 - 16:30	*J. Qiu*	Heavy Quark Physics and QCD (BNL Colloquium in Conjunction w/Workshop)
16:40 - 17:20	*M. Bishai*	Tevatron Heavy Flavor Measurement
17:20 - 18:00	*R. Seuster*	Heavy Quark Fragmentation Functions from e-e Collisions
19:30 - 22:30		**DINNER**

Wednesday Morning, December 14 (Chair: G. Bunce)

09:00 - 09:40	*G. Bodwin*	NRQCD and Heavy Quarkonium Production
09:40 - 10:20	*M. Cacciari*	Theoretical Review of Heavy Quark Production
10:20 - 10:30		**COFFEE BREAK**
10:30 - 11:10	*J. Rafelski*	Quarkonium Recombination In Presence of Strangeness Rich Expanding QGP
11:10 - 11:50	*W. Vogelsang*	Heavy Flavor Measurements from Polarized p-p Collisions for the Gluon Spin Structure Function
11:50-13:20		**LUNCH** (only served at the Berkner Hall Cafeteria until 13:00)

Wednesday Afternoon, December 14 (Chair: F. Antinori)

13:20 - 14:00	*T. Frawley*	Future of Heavy Flavor Measurement at PHENIX
14:00 - 14:40	*J. Dunlop*	Future of Heavy Flavor Measurement at STAR
14:40 - 14:50		**COFFEE BREAK**
14:50 - 15:30	*P. Crochet*	LHC Heavy Flavor Program
15:30 - 16:30	*J. Nagle*	Summary of Experimental Results
16:30 - 17:30	*E. Shuryak*	Summary of Theory Results

Additional RIKEN BNL Research Center Proceedings:

Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
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

Additional RIKEN BNL Research Center Proceedings:

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

Additional RIKEN BNL Research Center Proceedings:

Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299

Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559

Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116

Volume 10 – Physics of Polarimetry at RHIC – BNL-65926

Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762

Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634

Volume 7 – RHIC Spin Physics – BNL-65615

Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234

Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105

Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912

Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724

Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723

Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

Heavy Flavor Productions and Hot/Dense Quark Matter

December 12-14, 2005

Li Keran

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

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Speakers:

F. Antinori	M. Bishai	G. Bodwin	P. Crochet	M. Djordjevic
A. Frawley	A. Geiser	J. Gonzalez	P. Gossiaux	V. Greco
T. Gunji	H. van Hees	F. Kajihara	D. Kharzeev	J. Nagle
J. Peng	J. Qiu	J. Raufeisen	E. Scomparin	R. Seuster
E. Shuryak	R. Thews	T. Umeda	R. Vogt	R. Venugopalan
C. Wong	H. Zhang	W. Vogelsang		

Organizers: Y. Akiba, H. Huang, R. Rapp, K. Tuchin and W. Xie