J/Ψ and Open Charm

Melynda Brooks
Los Alamos National Laboratory

Motivation

J/Ψ (charmonium) as probe of nuclear medium/QGP in AA collisions

- Matsui and Satz prediction of J/Ψ suppression
- NA50 confirmation (?)
- Alternative models arise and initial RHIC results
- Initial RHIC results and reaffirmation of interest in J/Ψ

Charm and J/Ψ Production in pp, pA, dA collisions:

- Charm provides important baseline to understanding J/Ψ
- Do we understand the production mechanism of charm, J/Ψ, nuclear modifications?
- Above critical to understanding if AA shows production outside bounds of expectations or not and interesting in its own right

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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

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

E_T (GeV)

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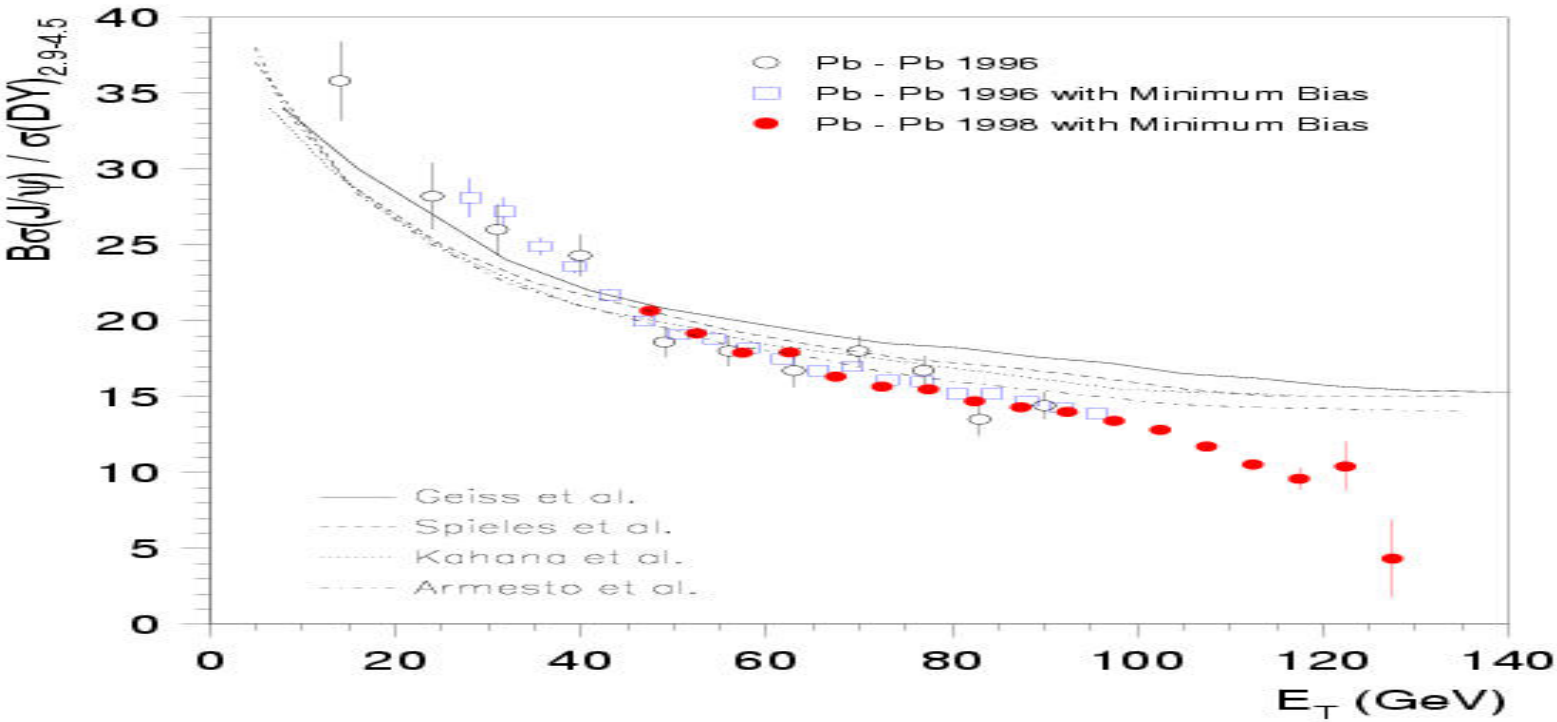

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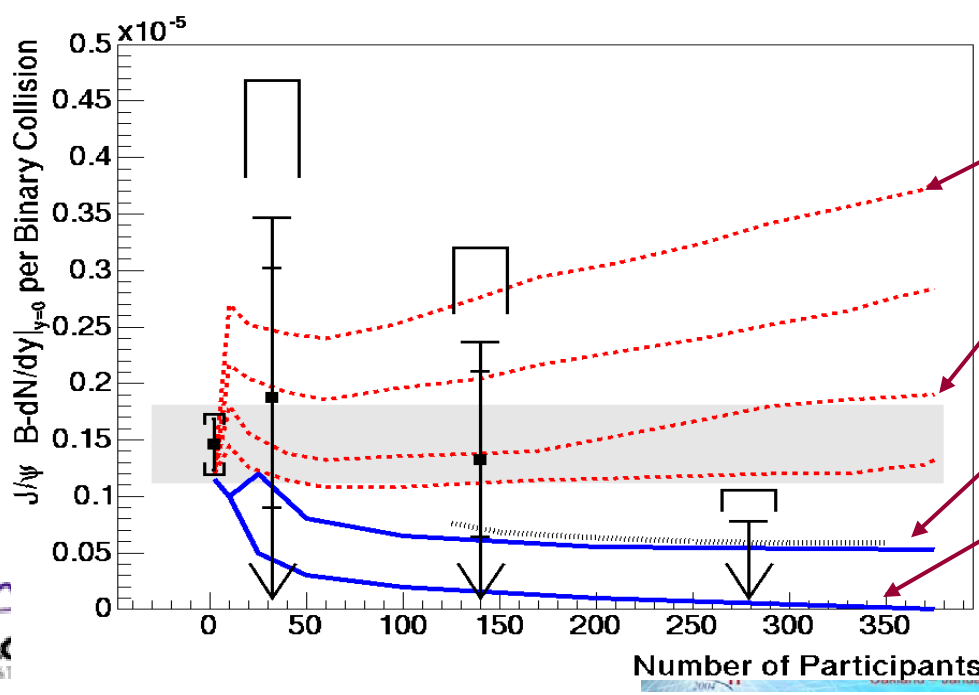

R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 054905
Plasma Coalescence Model

Binary Scaling

Absorption (Nuclear + QGP) + final-state coalescence

Absorption (Nuclear + QGP)
L. Grandchamp, R. Rapp, Nucl Phys A709, 415; Phys Lett B 523, 60

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(

Recommendations of the Brookhaven High Energy and Nuclear Physics Program Advisory Committee: RHIC Run 4

September 2003

The highest priorities for Run-4 are an extended high luminosity full energy Au-Au run ensuring a significant measurement of quarkonia production, and a polarized proton-proton machine development run. Additional priorities are a 63 A-GeV energy Au-Au

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Outline of Talk

Theory of Charm and J/Ψ Production

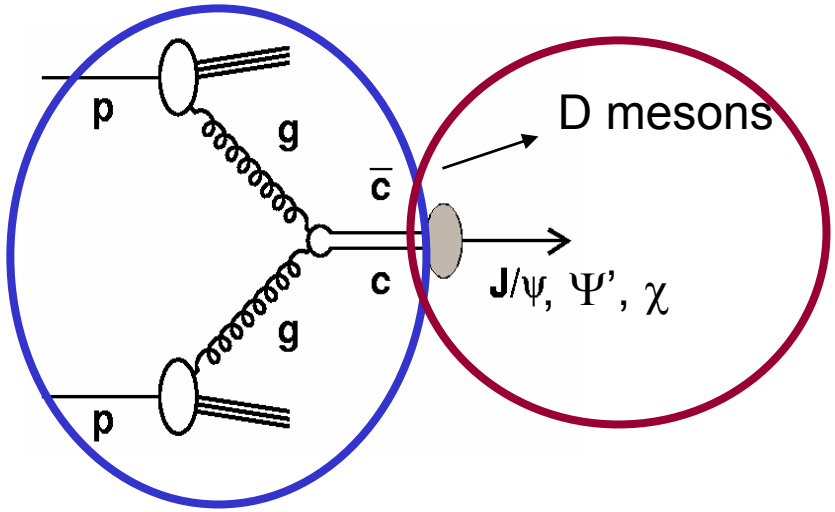
- pQCD
- $c\bar{c}$ propagation and hadronization

Existing Measurements of Open Charm and J/Ψ Production

- pp collisions
- dA, pA production
- AA production

Future Prospects and Summary

Theoretical Models of Charm and J/Ψ Production



Factorize calculations:

- pQCD to calculate $c\bar{c}$ production
- $c\bar{c}$ propagation and Hadronization

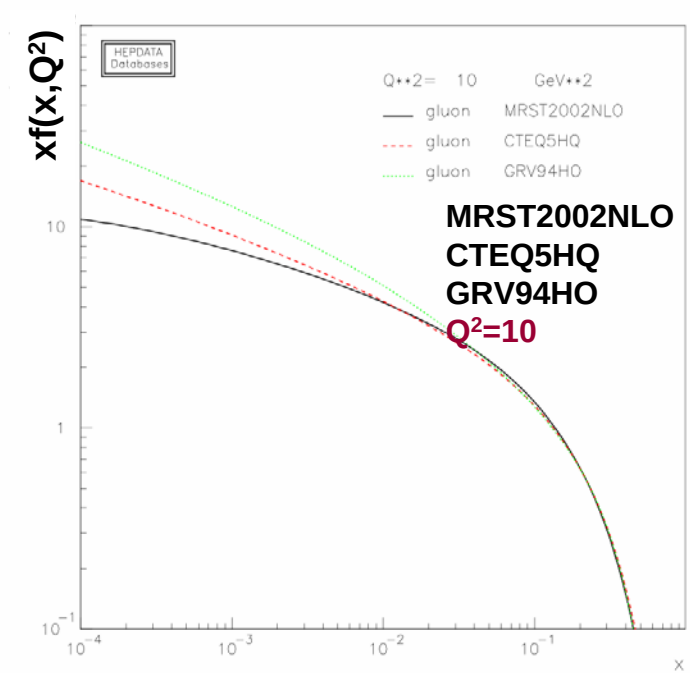
Note: much of J/Ψ production comes from feed-down from higher resonances

Input to pQCD Calculations:

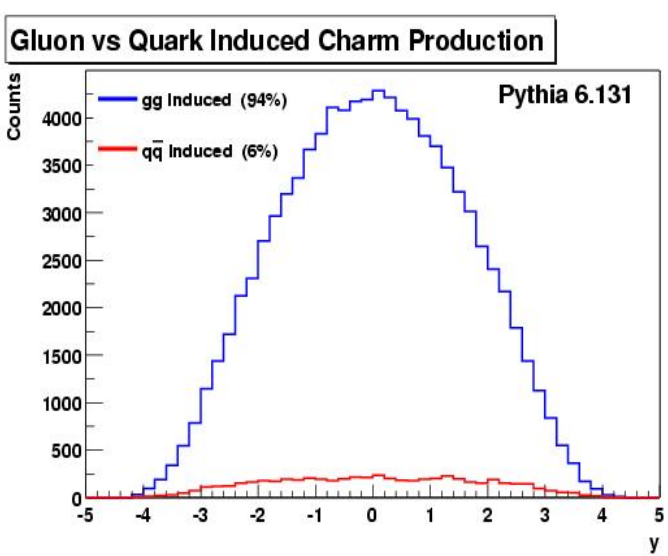
- Parton Distribution Functions→rapidity dependence , √s dependence,
  - Modified in Nucleus? , (sensitive to gluon polarization)
- LO, NLO, NNLO calculations change magnitude, shape of spectra
- Factorization, renormalization scales→total cross section
- Charm mass→total cross section
- k_T →p_T spectra

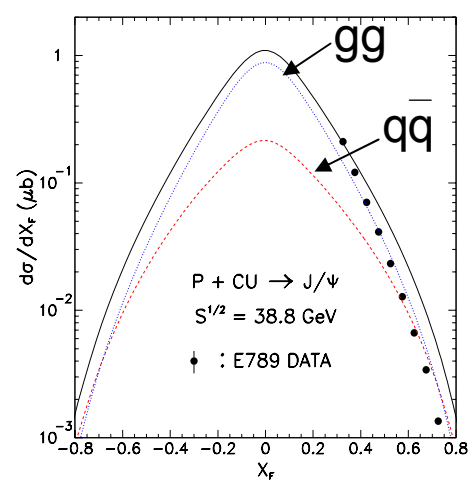
- Total cross sections and Differential vs. y, p_T, √s, etc. necessary to simultaneously constrain theoretical uncertainties
- Hadronization parameters can depend upon pQCD portion of calculation
- J/Ψ spectra dependence on Ψ', χ

Charm Production Uncertainties

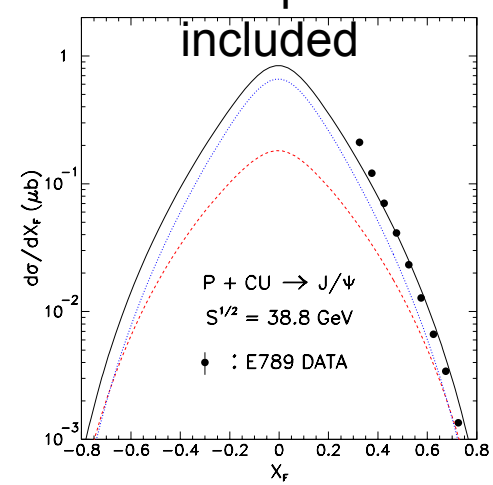


- Gluon distribution functions uncertain
- Diagrams other than gluon-gluon fusion contribute, and relative fraction changes versus rapidity, x_F
- PDFs modified in a nucleus
- Measurements versus rapidity, etc. can help constrain PDFs, uncover nuclear modifications to PDFs



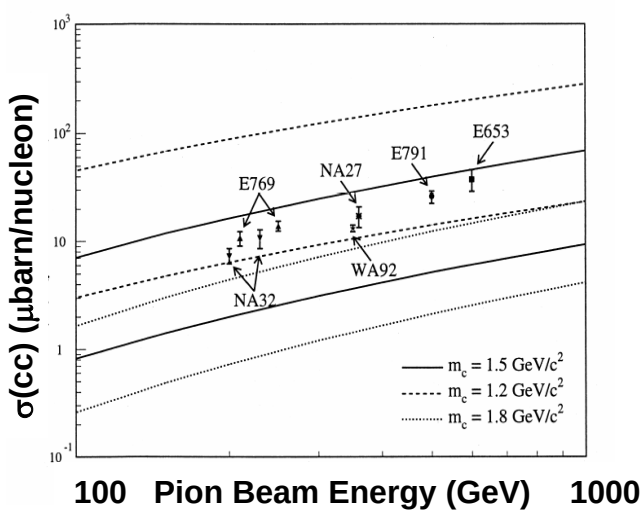


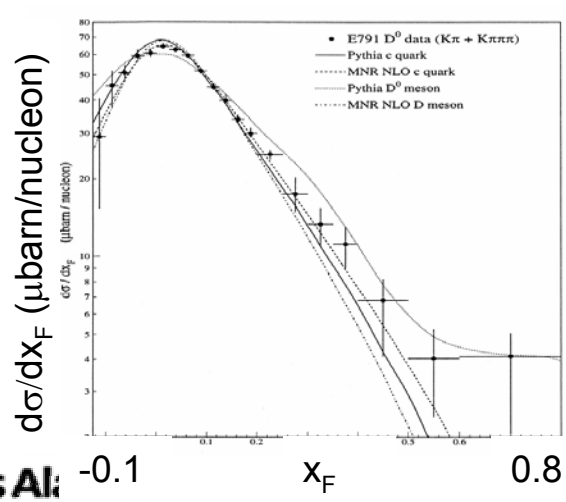
Nuclear dependence included

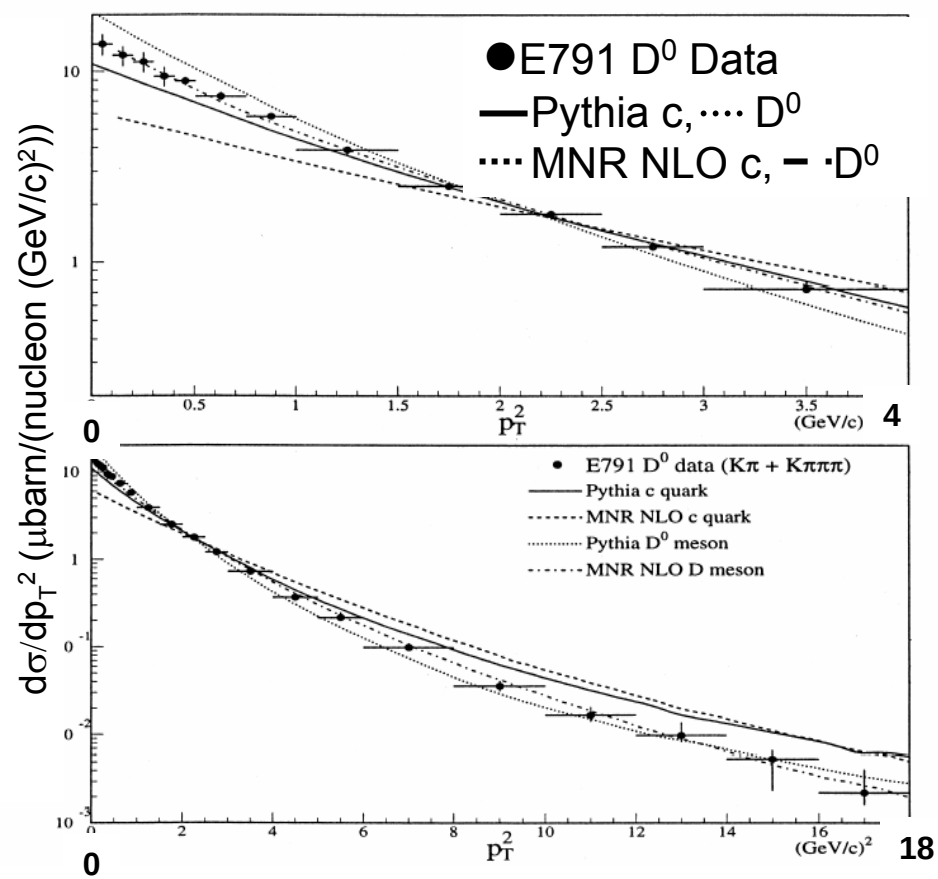


Open Charm Production Cross Sections—Theory vs. Data

- Charm hadro-production over a large energy range predicted reasonably well by theory
- Large error bands due to m_c, scale uncertainties; theoretical parameters that fit data not unique

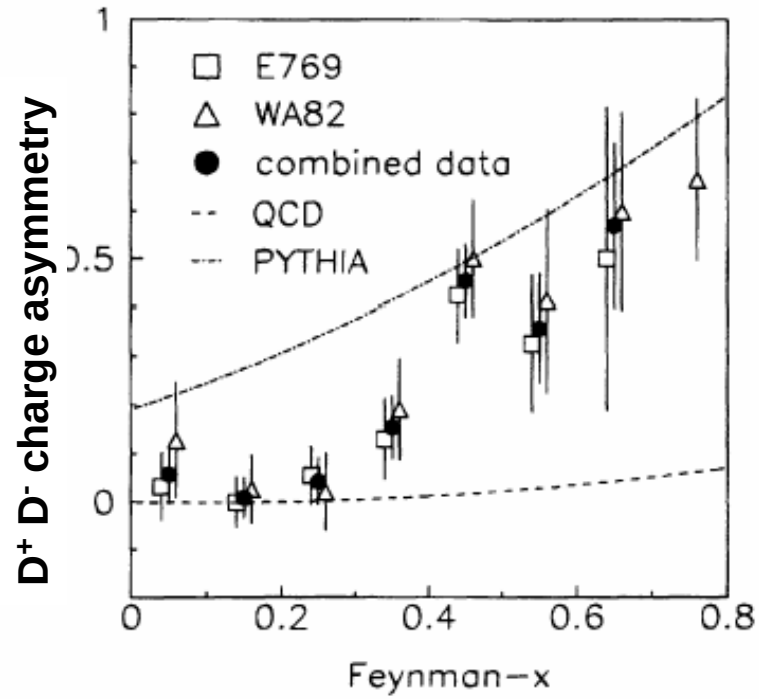






*Aitala et al, Phys Lett B, 462 (1999) 225-236

Charm Production Asymmetries at large X_F



π^+ beam ($u\bar{d}$)

$D^+(c\bar{d})$ favored over D^- $(\bar{c}d)$

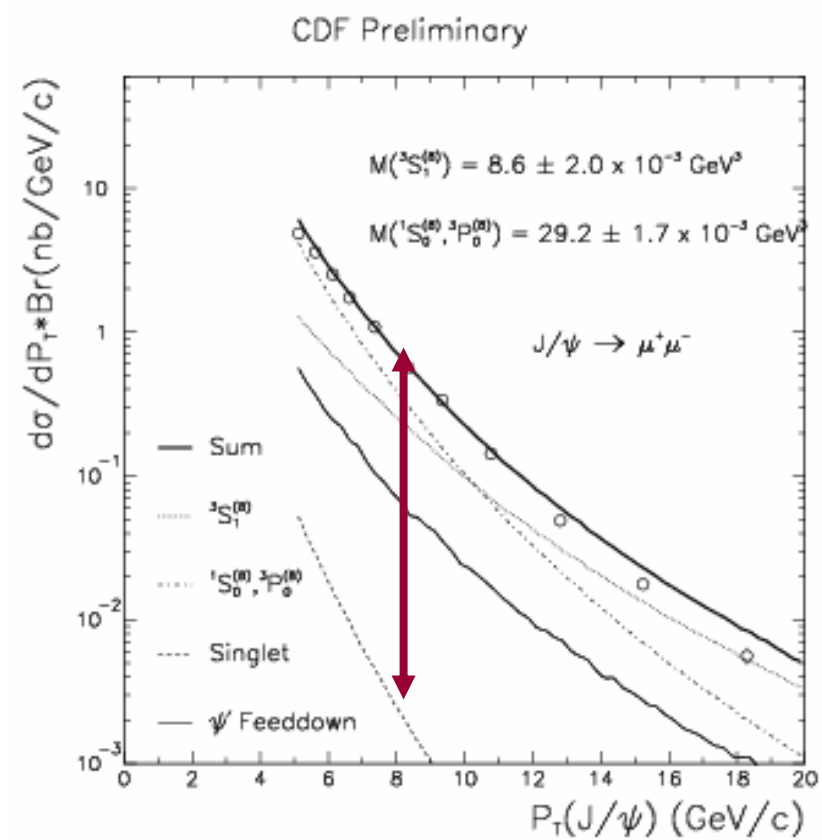
Alves et al, *Phys Rev Lett 72 (1994) 812

- At large x_F $c\bar{c}$ more likely to pair up with valence quarks of beam→D^+ favored over D^- when π+ beam, for example
- Production in different kinematic regions often uncovers different physics
- Charm production spectra also sensitive to hadronization model

Hadronization into J/Ψ

Various J/Ψ hadronization models:

- Color-singlet model (CSM)
  - $c\bar{c}$ pair in color-singlet state, with same quantum numbers as J/Ψ forms into J/Ψ
  - Predicts no polarization
- Color-octet model (COM)
  - J/Ψ formed from $c\bar{c}$ color-octet state with one or more soft gluons emitted
  - Color octet matrix elements expected to be universal
  - Predicts transverse polarization at high p_T of J/Ψ
- Color-evaporation model (CEM)
  - Assumes a certain fraction of $c\bar{c}$ (determined from experimental data) form J/Ψ by emission of several soft gluons
  - Predicts no polarization

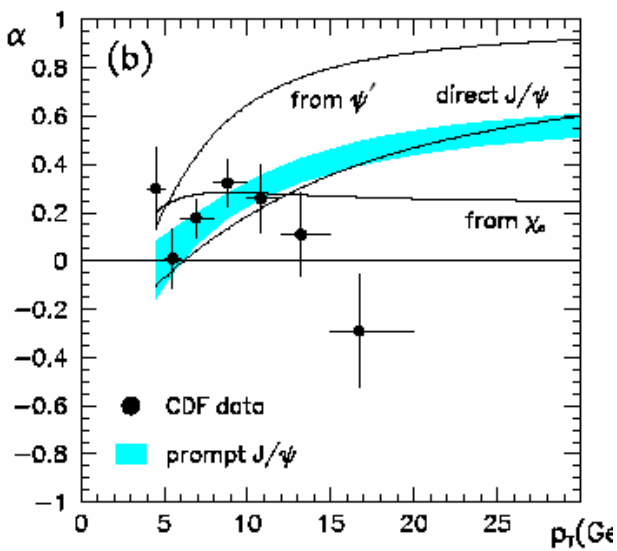


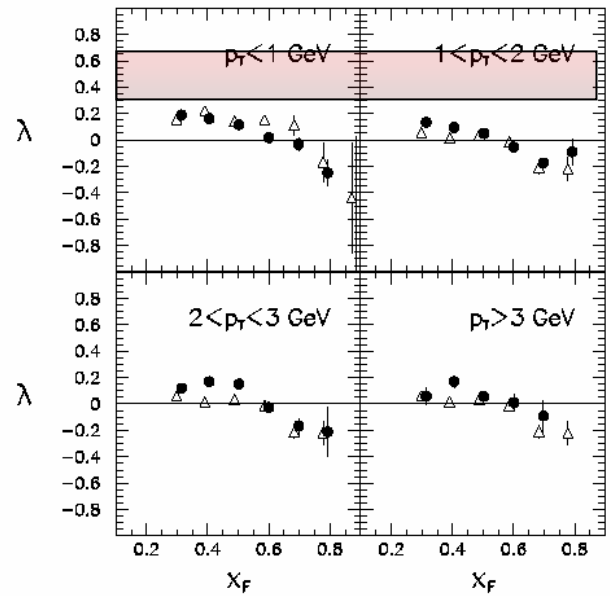
CDF Data first uncovered short-comings of CSM

- Would polarization measurements solidify COM?

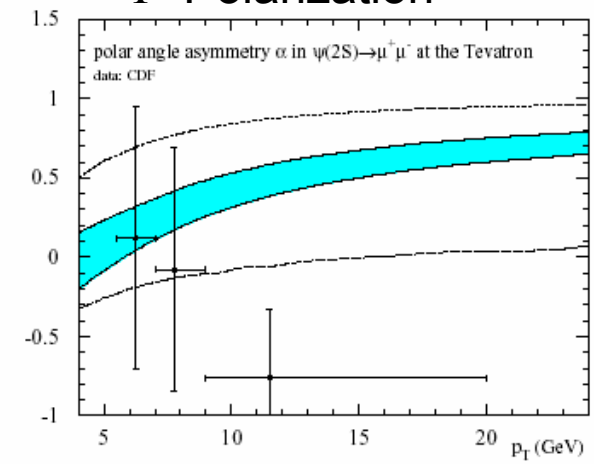
J/Ψ Production—Polarization

Color Octet Model predicts J/Ψ polarization at large p_T NOT SEEN in data



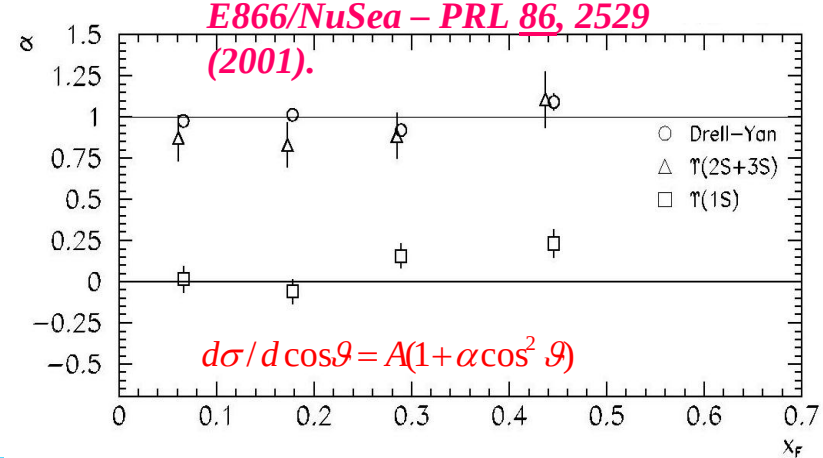


Ψ' Polarization



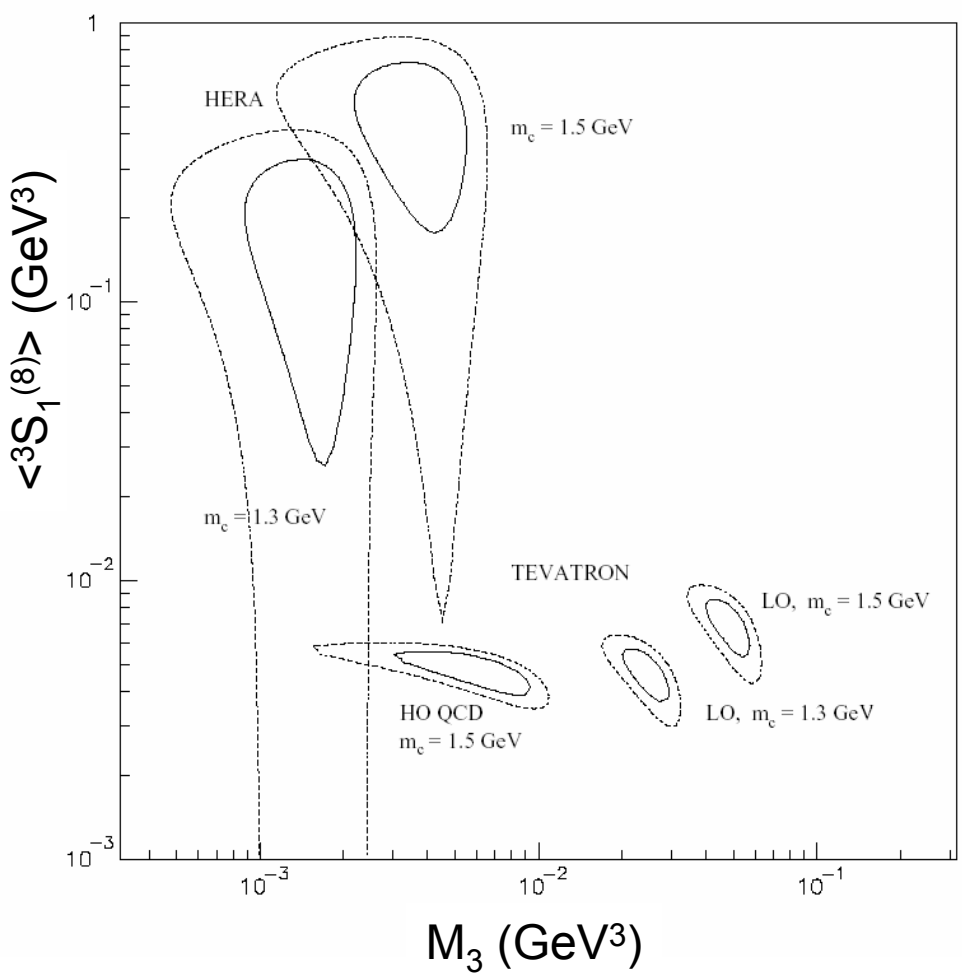
- CDF and Fermilab E866 data show little polarization of J/Ψ and opposite trend of predictions
- Υ polarized for (2S+3S) but not (1S)
- Is feed-down washing out polarization or something more?

E866/NuSea – PRL 86, 2529 (2001).



$$d\sigma/d\cos\vartheta = A(1+\alpha\cos^2\vartheta)$$

Matrix Element Extraction for photo, hadro-production



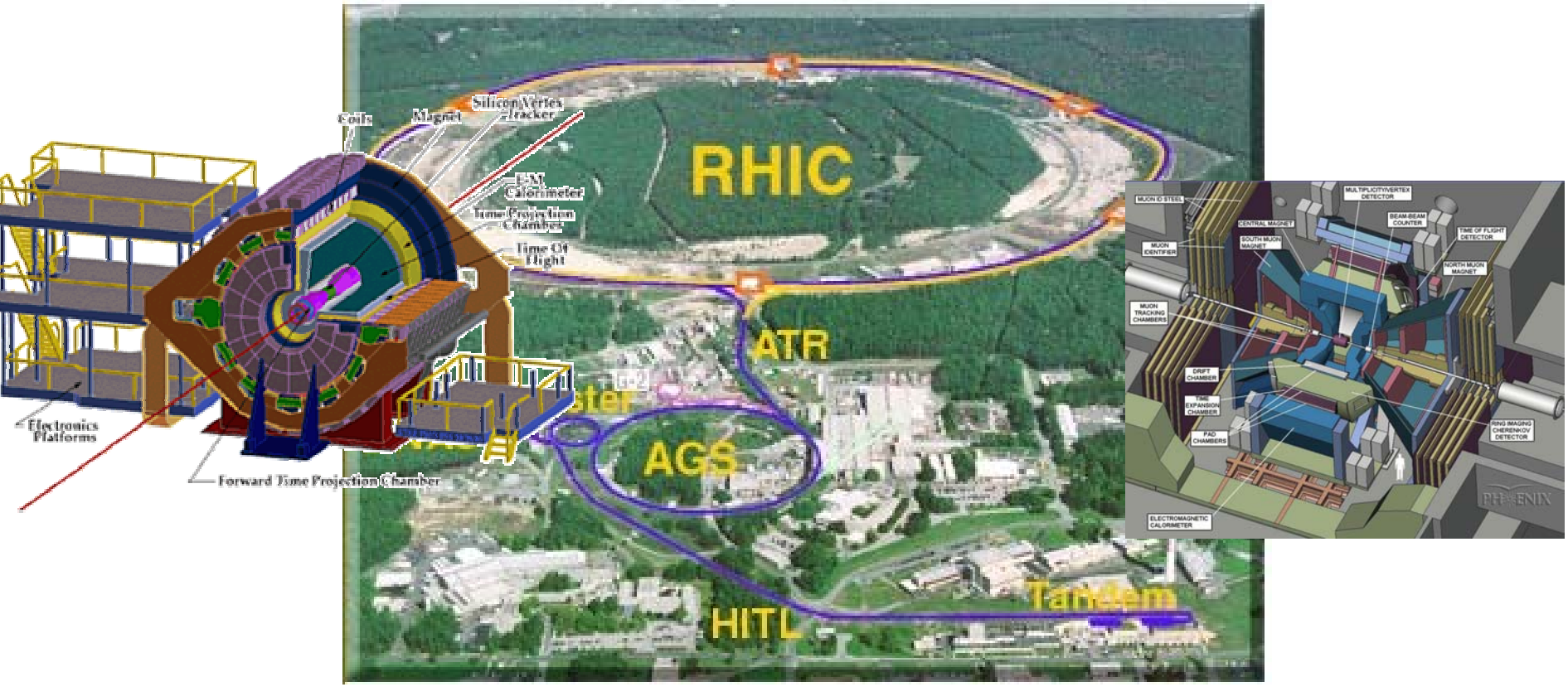
Extracted values of matrix elements from photo-production and hadro-production J/Ψ dependent upon pQCD calculation part

Is this agreement?

Is factorization picture not valid?

*Mizukoshi, hep-ph/99111384v2

Charm and J/Ψ Data from RHIC



Run I, 2001 Au-Au beams at $\sqrt{s}$=130 GeV

- Open charm from PHENIX

Run II, 2002 Au-Au beams and p-p at $\sqrt{s}$=200 GeV

- Open charm and J/Ψ from PHENIX

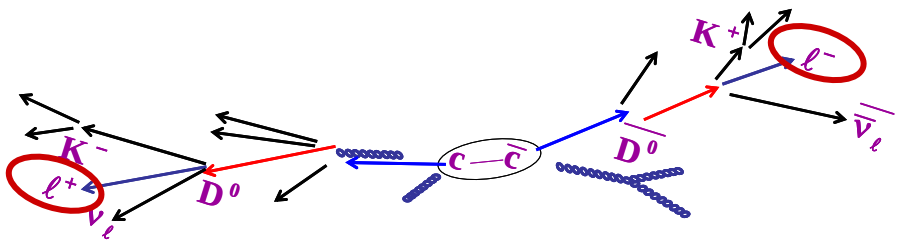
Run III, 2003 d-Au, p-p at $\sqrt{s}$=200 GeV

- Open charm from PHENIX and STAR, J/Ψ from PHENIX

Run IV, 2004 Au-Au, $\sqrt{s}$=200 GeV

- More measurements to come

Open Charm Production from Single Leptons from PHENIX



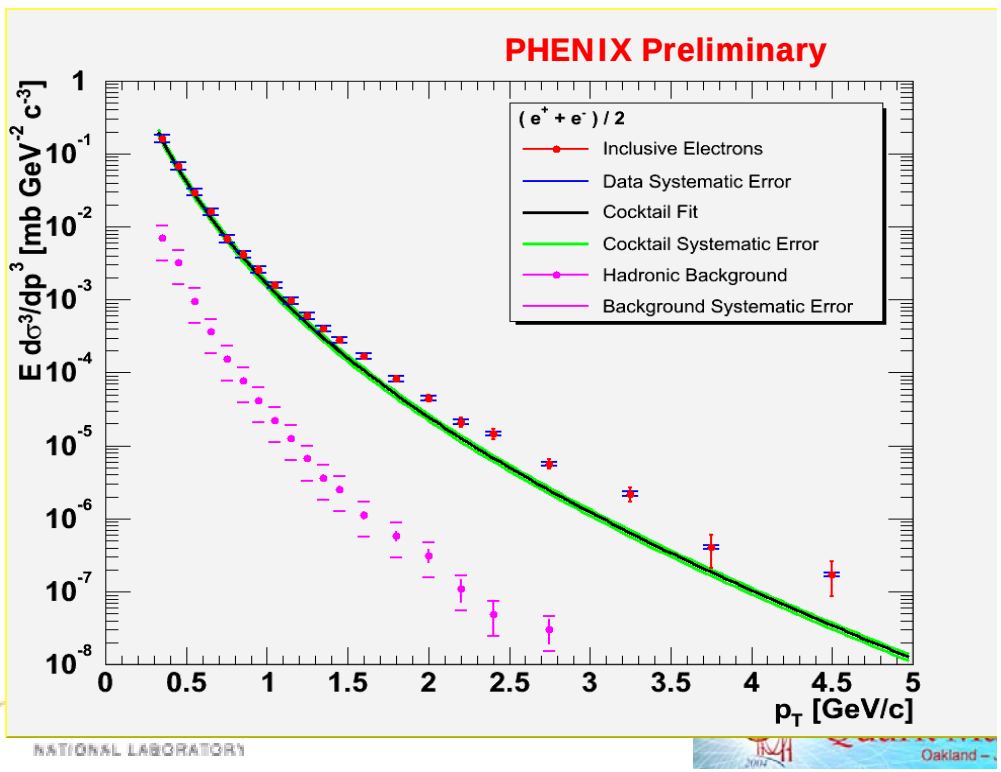
Electrons at Central Rapidity:

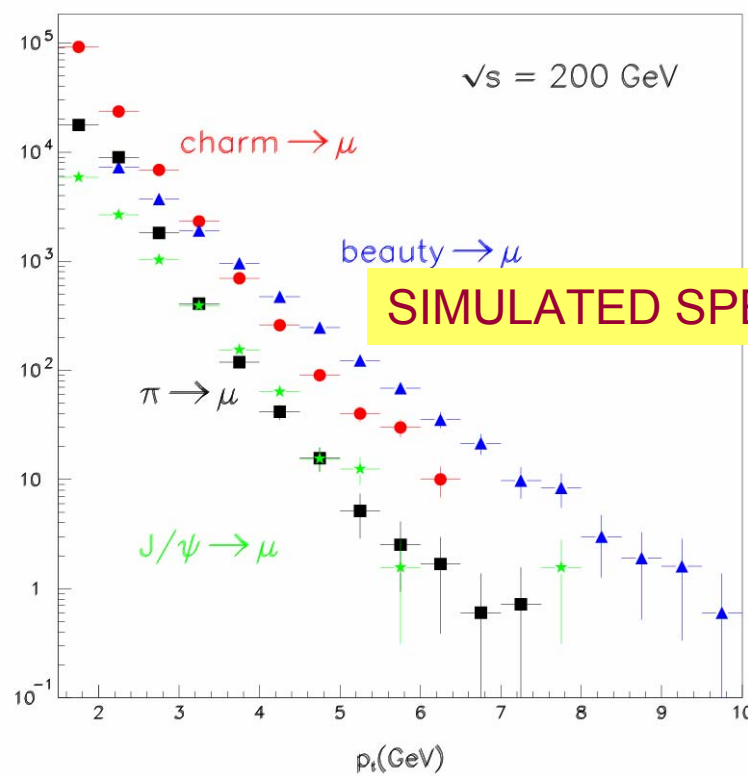
Cocktail = π^0 Dalitz + γ Conversions, etc.

Excess over cocktail = charm + bottom

Muons at |y|=(1.2-2.4):

Cocktail = π, K decay muons and punch-through, etc.





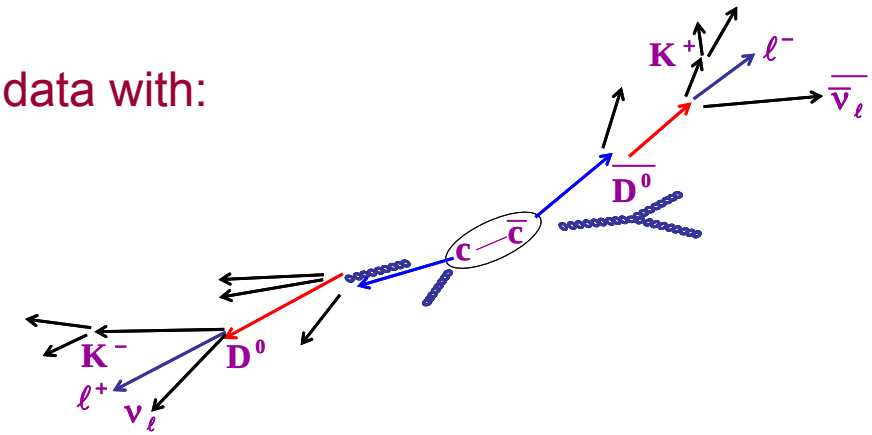
SIMULATED SPECTRA

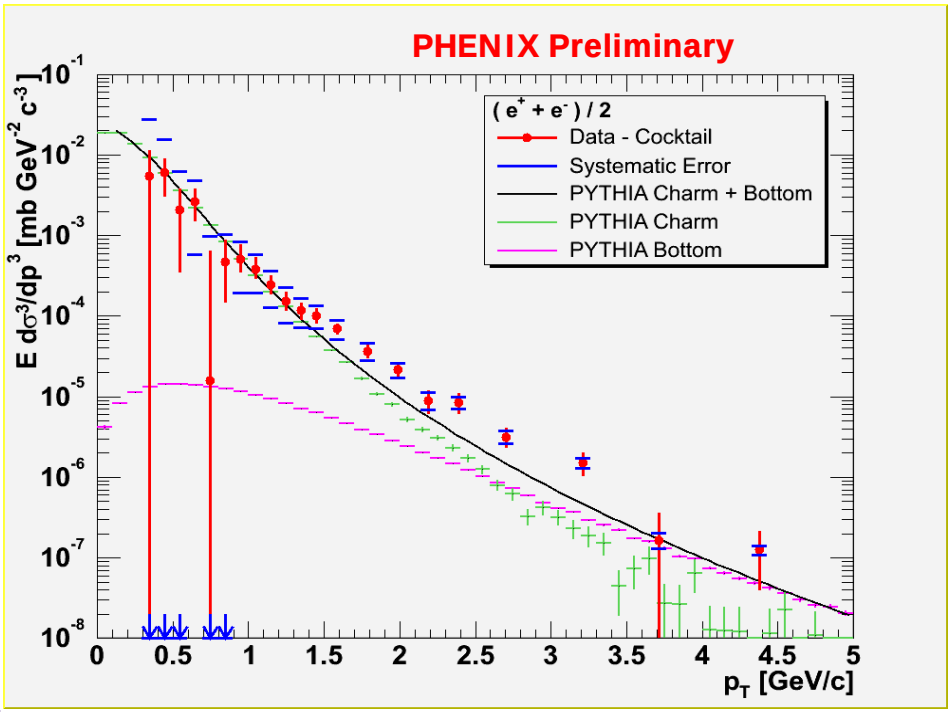
Brooks

PHENIX: Charm at |y|=0 from pp

PHENIX single electron:

- PYTHIA pp charm cross section agrees with data with:
  - PDF=CTEQ5L
  - m_c = 1.25 GeV/c^2
  - K = 3.5
  - $\langle k_T \rangle$ = 1.5 GeV/c



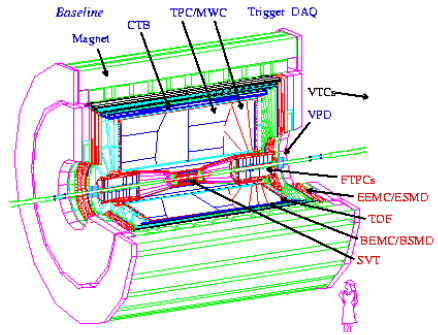


- PYTHIA tuned for QM02 under predict data at p_T>1.5 GeV/c
- Forward rapidity analysis underway

*S. Kelly "Charm Production in AuAu, dAu and pp Reactions at PHENIX"

STAR: Charm at |y|<1.0 from pp*

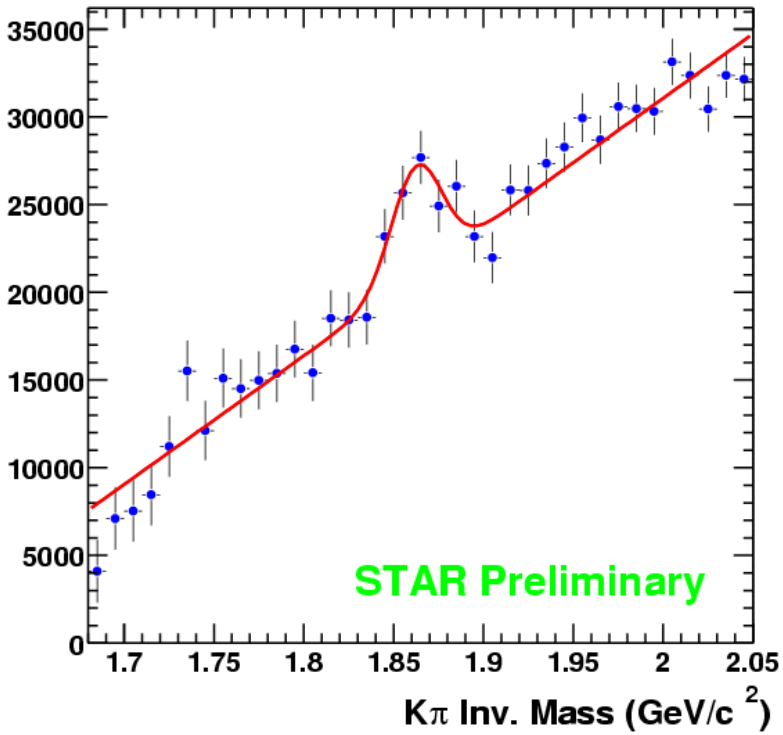
STAR D meson and single electron measurements:



- $D^0 \rightarrow K\pi$ $p_T=(0,3)$ $|y|<1.0$
- $D^{*\pm} \rightarrow D^0\pi$ $p_T=(1.3,6.0)$
- $D^+ \rightarrow K\pi p$ $p_T=(6.7,11)$
- Single electrons $p_T=(0,3)$

First direct open charm measurement at RHIC!

Results shown with dAu a little later

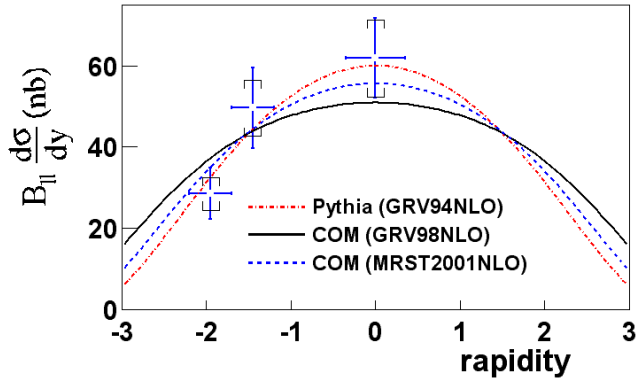


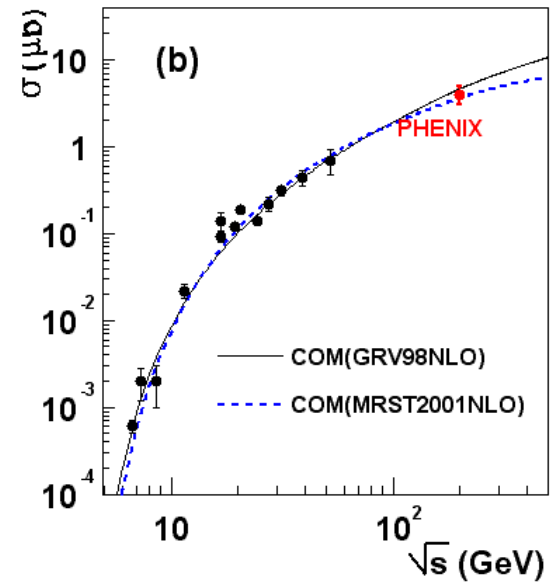
A. Tai, "Measurements of high pt D and D+ production in d+Au collisions at 200 GeV"

*L. Ruan, "Open charm production and Cronin Effect of leptons and identified hadrons in p+p an d+Au collisions at 200 GeV at STAR"

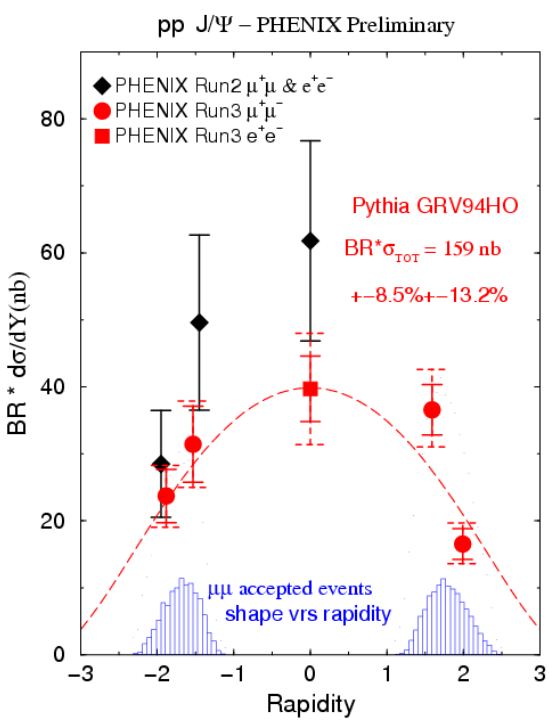
PHENIX: J/Ψ→e+e- and μ+μ- from pp

R. Granier "J/Psi Production and Nuclear Effects for dAu and pp Collisions at RHIC"





σ= 3.99 +/- 0.61(stat) +/- 0.58(sys) +/- 0.40(abs) μb
(BR*σ_{tot} = 239 nb)

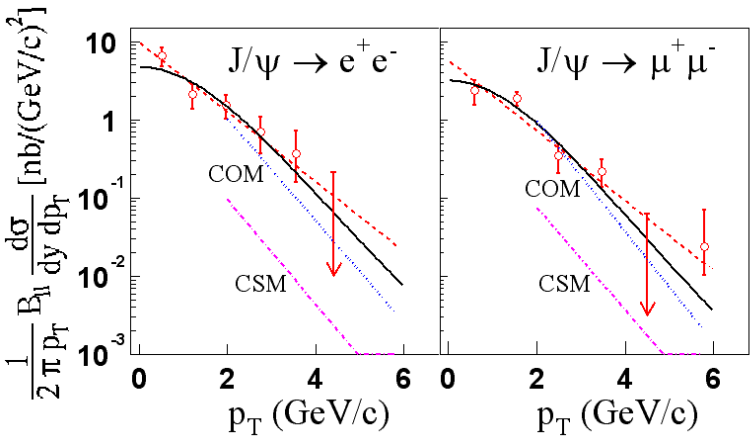


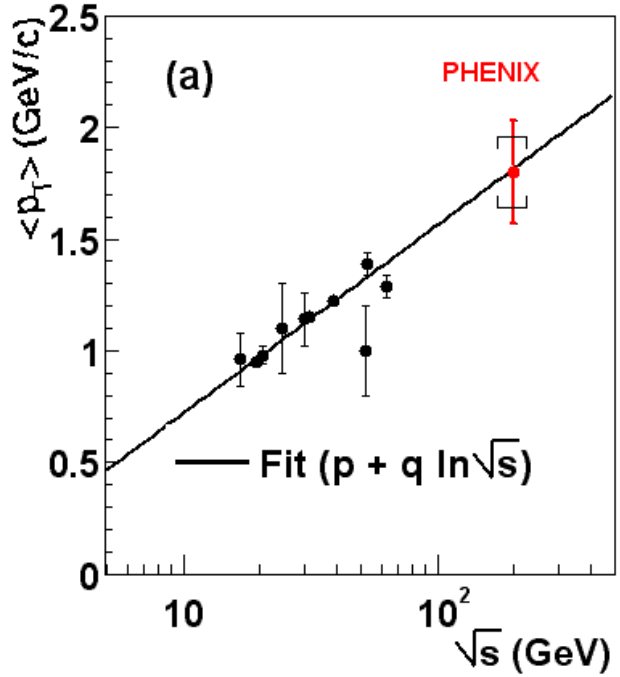
Central and forward rapidity measurements from Central and Muon Arms:

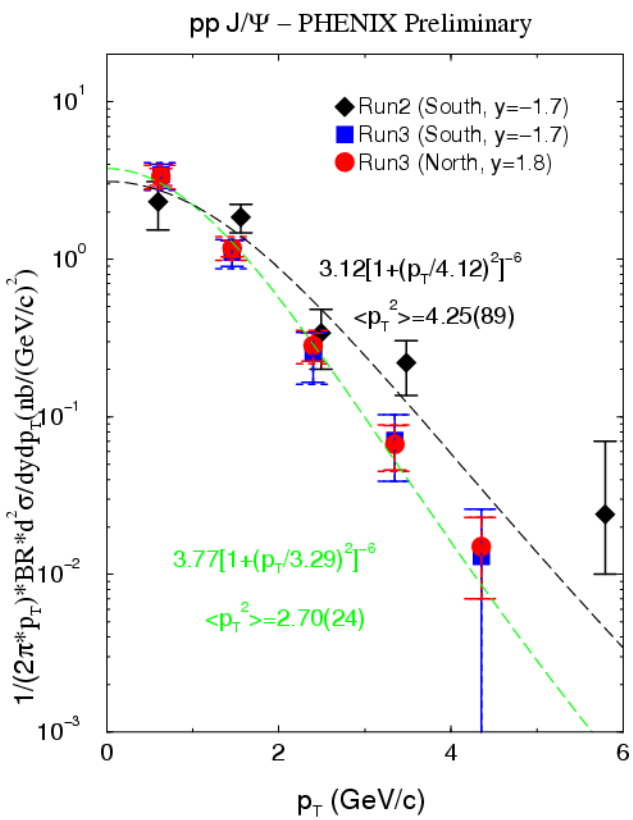
- Rapidity shape consistent with various PDFs
- √s dependence consistent with various PDFs with factorization and renormalization scales chosen to match data

Higher statistics needed to constrain PDFs

PHENIX: J/Ψ→e+e- and μ+μ- from pp







- p_T shape consistent with COM over our p_T range
- Higher statistics needed to constrain models at high p_T
- Polarization measurement limited

Summary of Nucleon-Nucleon Charm and J/Ψ Production

Our Understanding of Production:

- Cross sections from pQCD match open charm real data reasonably well but
- Difficult to simultaneously constrain PDFs, m_C, k_T, normalization and factorization scale. LARGE changes in parameters can still match data.
- CEM and COM can also match J/Ψ data well but some resolution required between COM predictions and data
- More theoretical work to reconcile production calculations and data, more data covering large kinematic regions with smaller error bars desireable?

What we have coming, what we might like:

- Forward rapidity charm production to come
- Smaller error bars versus rapidity and at high p_T might be nice to further constrain models

Nuclear Effects on Charm, J/Ψ Production in dA

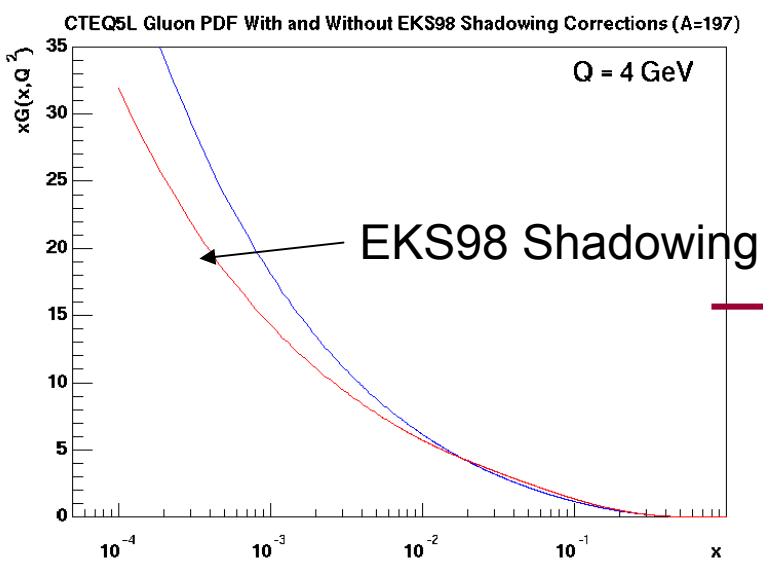
Initial state/final state interactions with medium

- Multiple scattering→broadening of p_T spectra
- Energy loss→shift of x_F distribution, reduction in cross section as partons effectively shifted to lower $\sqrt{s}$
  - Not expected to be significant effect at RHIC
- Absorption reduces J/Ψ as $c\bar{c}$, J/Ψ propagate through nucleus

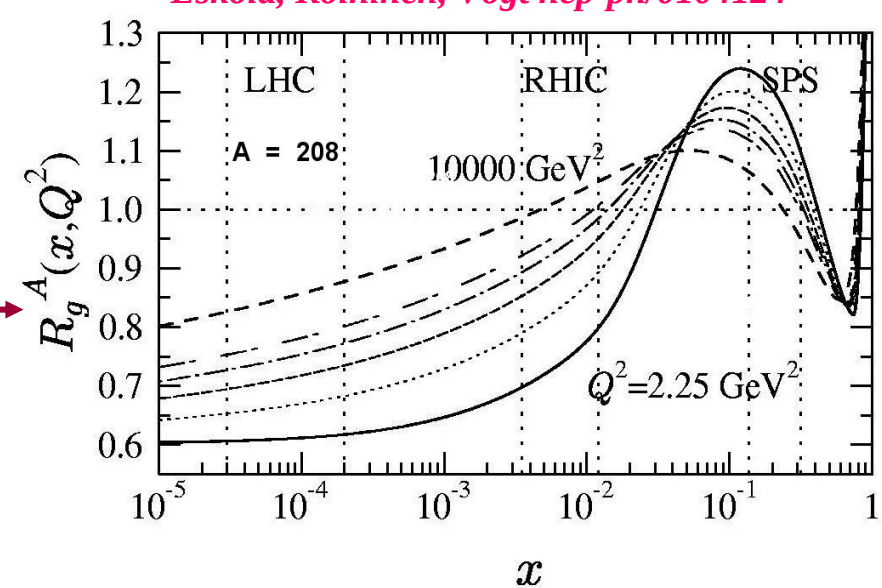
Modification of the parton distribution functions:

- Gluon shadowing would lead to reduction of production at low x. Antishadowing would give enhancement at moderate x

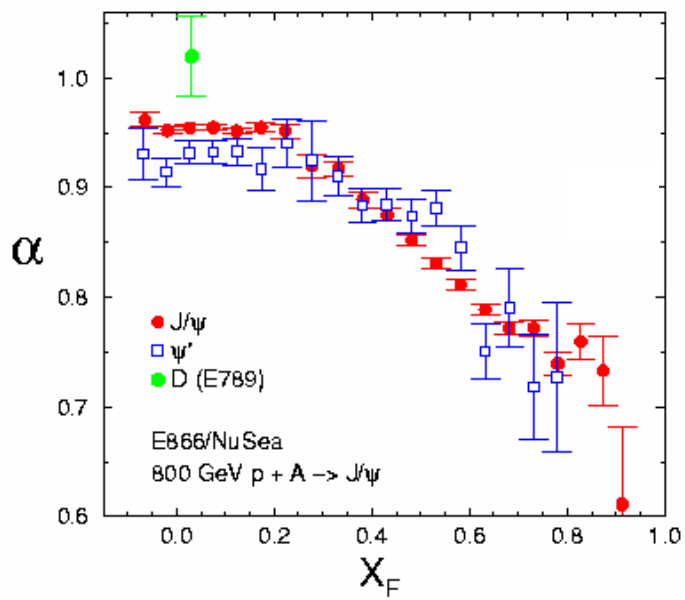
Centrality Dependence



Eskola, Kolhinen, Vogt hep-ph/0104124



J/Ψ Production From Fermilab Experiment 866 at √s=39 GeV

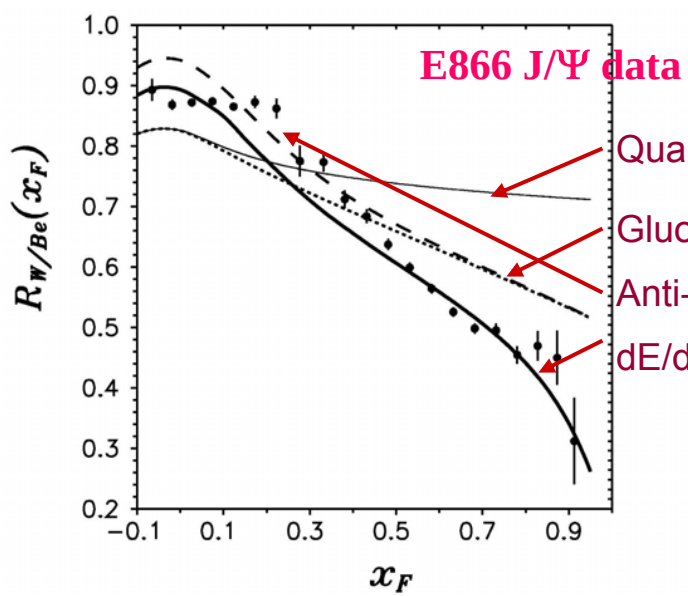


p-Be, Fe, W production of J/Ψ

$\sigma_A = \sigma_N \bullet A^{\alpha}$

A plausible production scenario to explain data:

- Production at low x_F reduced by absorption of J/Ψ and enhanced by anti-shadowing (D not affected and Ψ' absorbed more)
- Some suppression increasing with x_F due to gluon shadowing
- dE/dx shifts x_F and reduces cross section at large x_F



Quark shadowing and final state absorption +

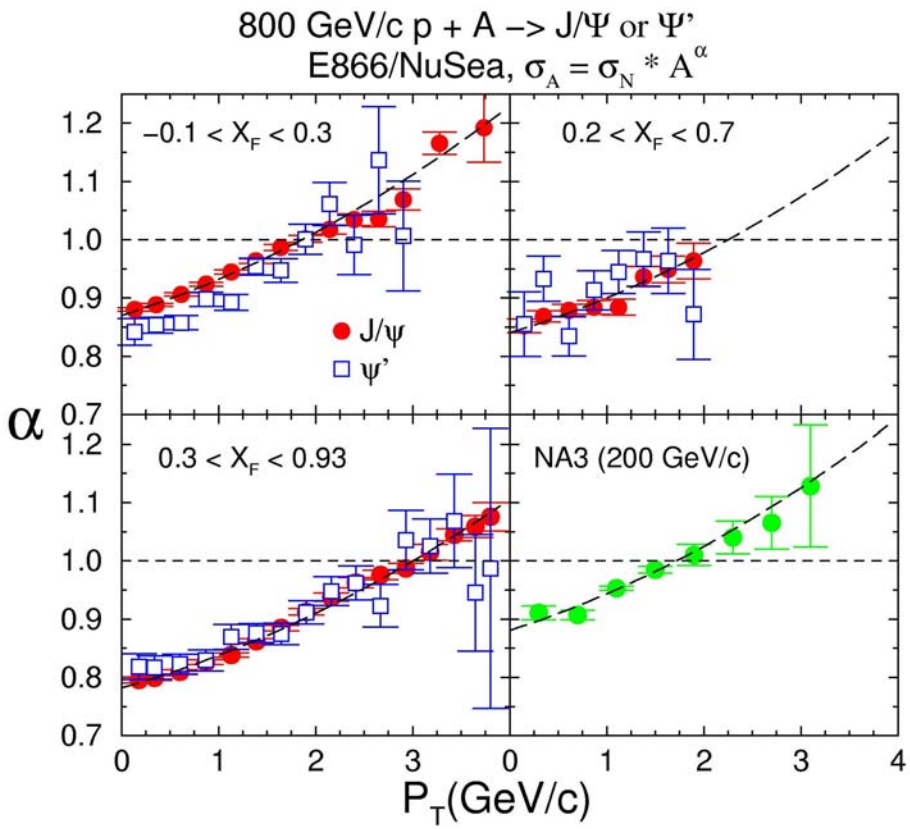
Gluon shadowing +

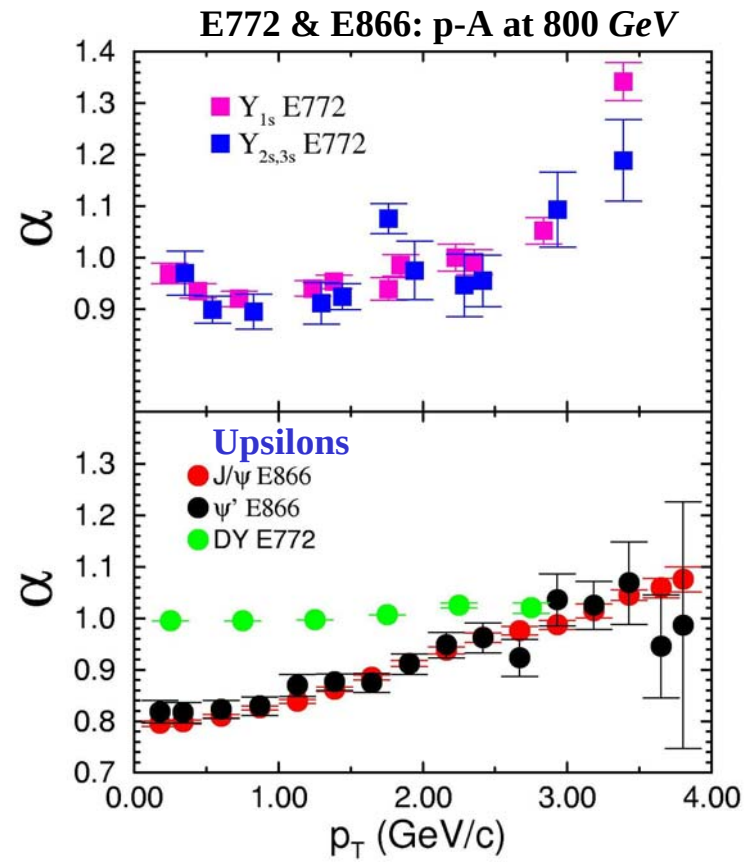
Anti-shadowing +

dE/dx

*Kopeliovich, Tarasov, Hufner Nucl Phys A696 (2001) 669-714

P_T Broadening at 800 GeV





- $\alpha(p_T)$ shape is independent of x_F and approximately the same for NA3 at a lower energy
- DY shows no broadening

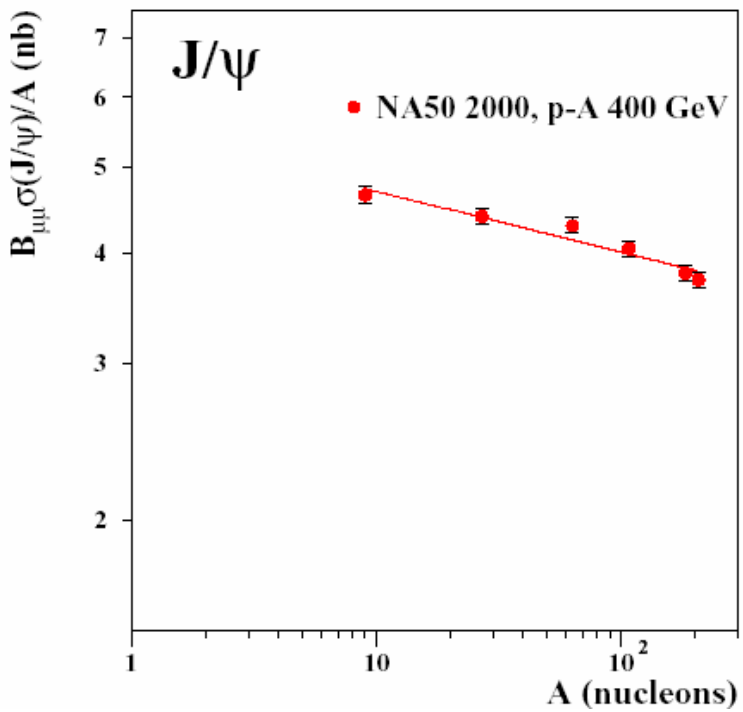
NA50: J/Ψ and Ψ' from p-Be, Al, Cu, Ag, W, Pb

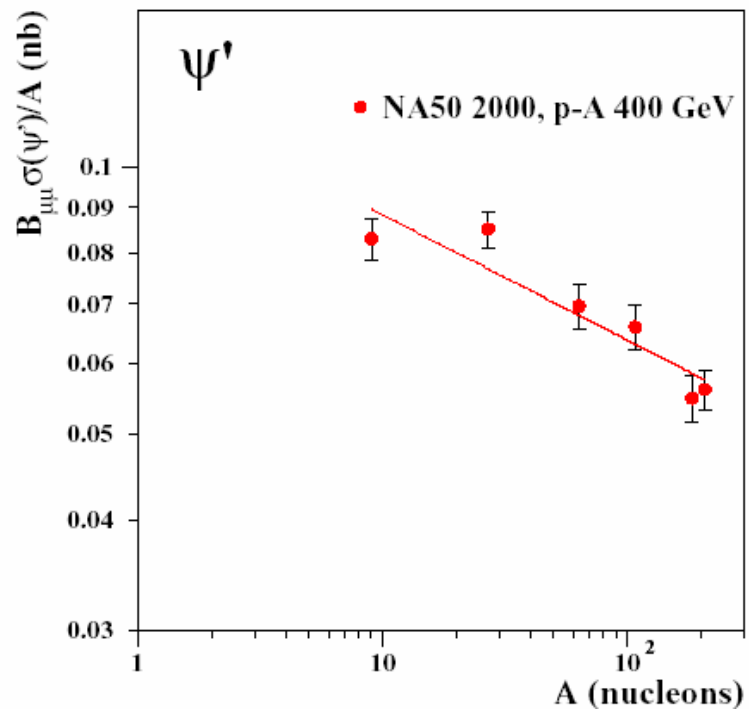
G. Borges, " New Results on J/psi and psiprime nuclear absorption in p-A and S-U collisions at the CERN/SPS "

$$\sigma^{p-A}_{J/\psi,\psi\prime} = \sigma^{0}_{J/\psi,\psi\prime} \times A^{\alpha}$$

$$\alpha_{J/\psi} = 0.931 \pm 0.002 \pm 0.007 \quad (\chi^2/dof = 1.4)$$

$$\alpha_{\psi\prime} = 0.858 \pm 0.017 \pm 0.008 \quad (\chi^2/dof = 2.2)$$

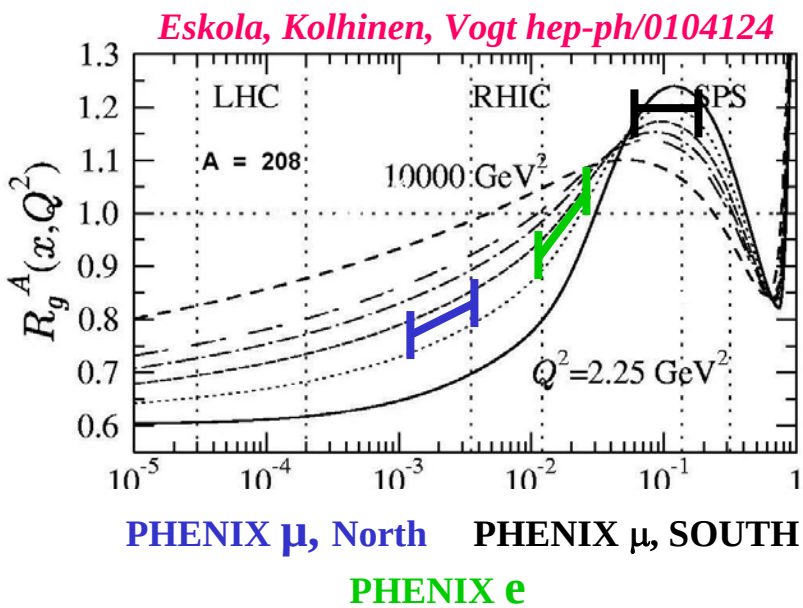


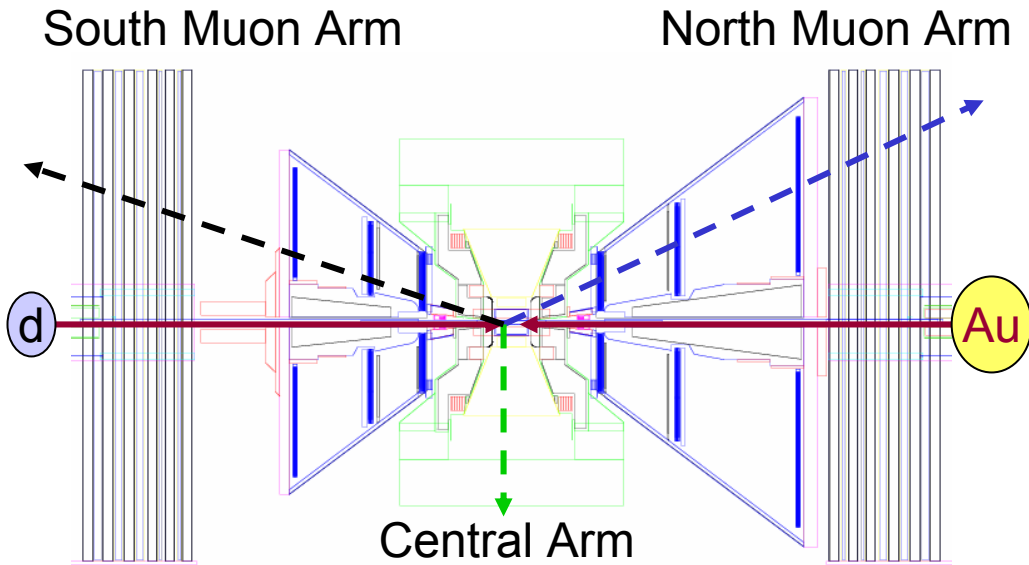


$\sigma^{\Psi}_{abs} = 4.2 \pm 0.5$ mb
(χ^2/dof = 0.9)

$\sigma^{\Psi'}_{abs} = 9.6 \pm 1.6$ mb
(χ^2/dof = 2.9)

PHENIX: J/Ψ in dA

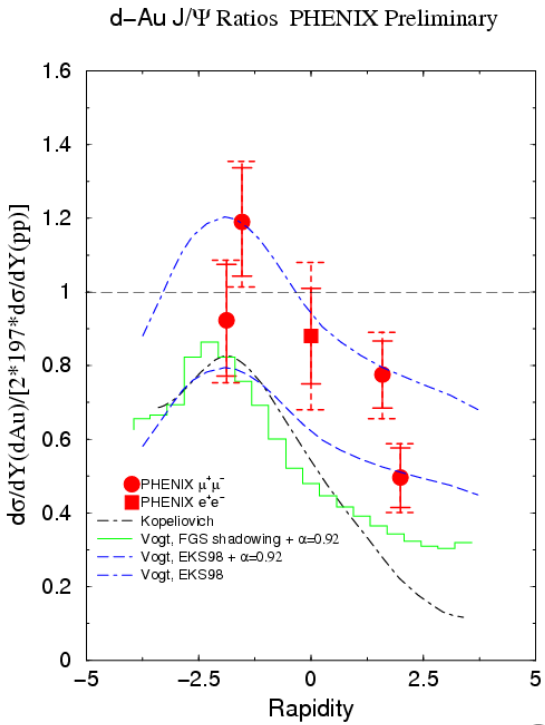


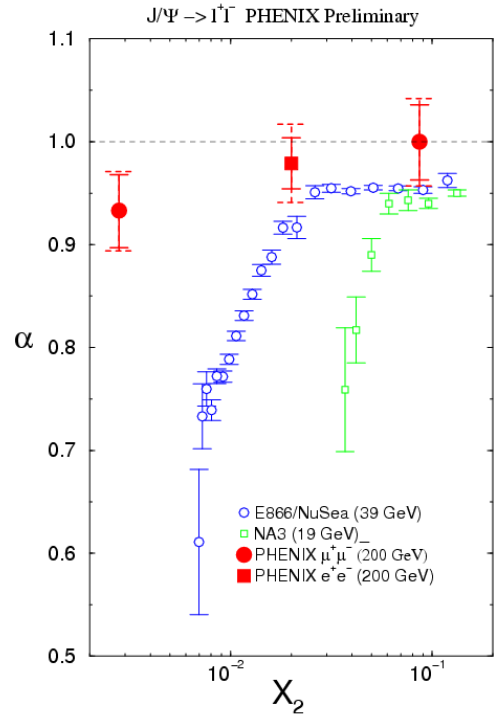


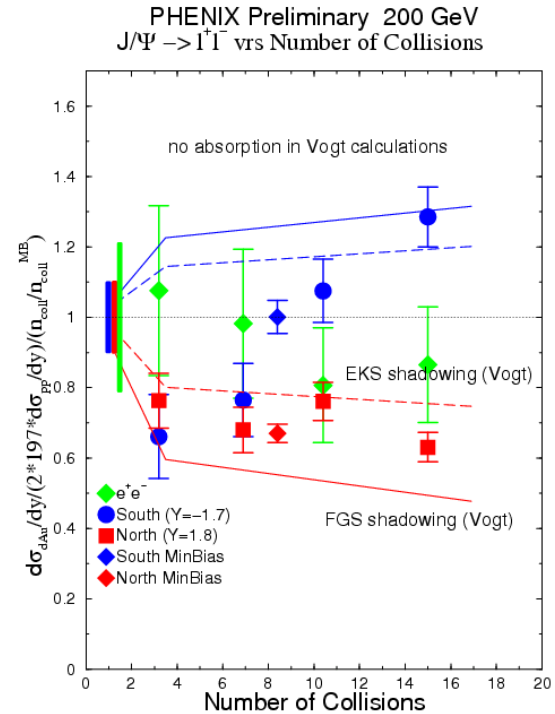
- PHENIX measurements cover expected shadowing, anti-shadowing range
- All expected to see p_T broadening
- dE/dx not expected to be significant effect at RHIC energies
- Overall absorption expected

J/Ψ dA from PHENIX

R. Granier "J/Psi Production and Nuclear Effects for dAu and pp Collisions at RHIC"



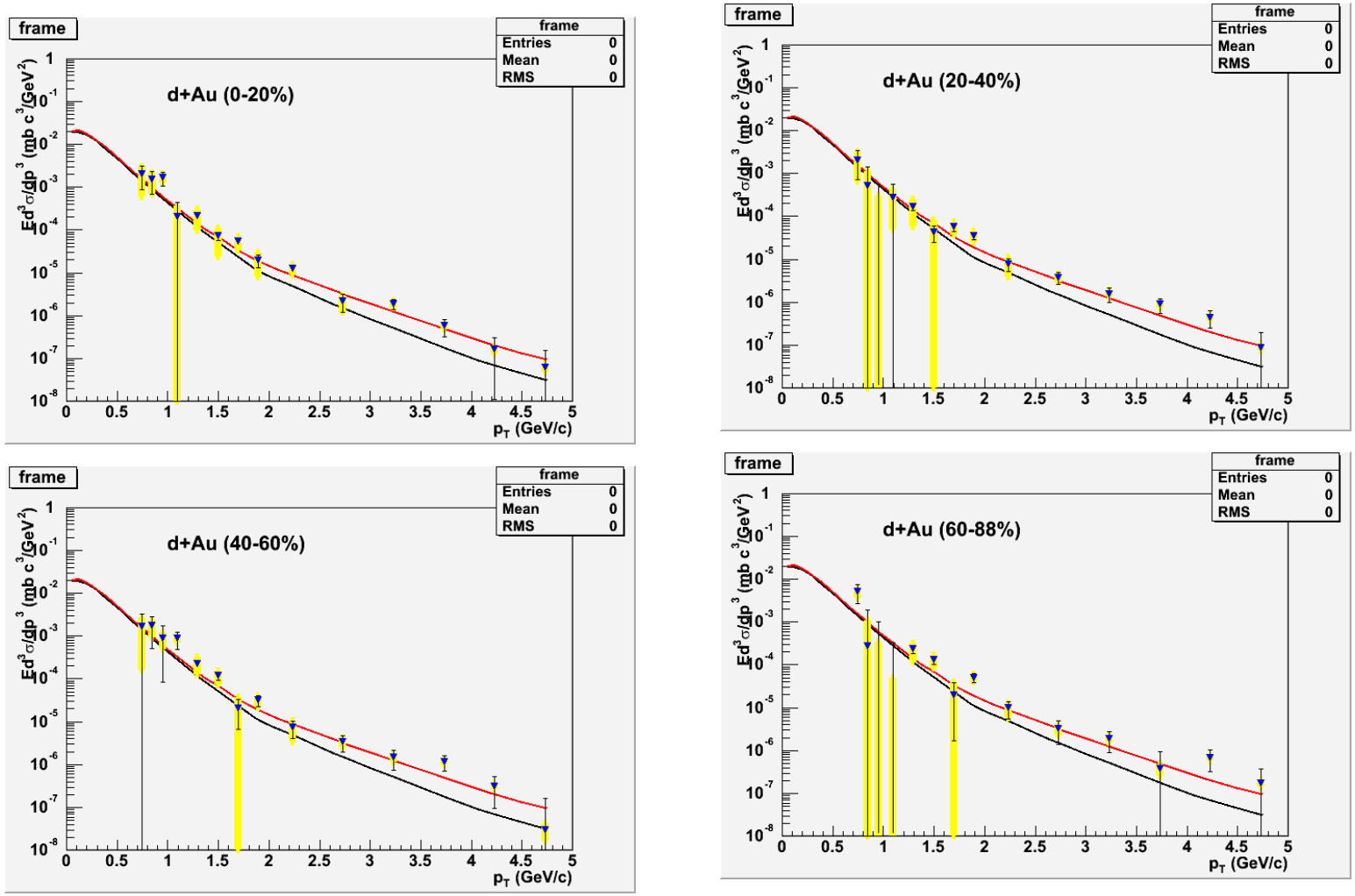




- Suppression in deuteron direction consistent with some shadowing but can't distinguish among various models
- Anti-shadowing in Au direction
- Overall absorption

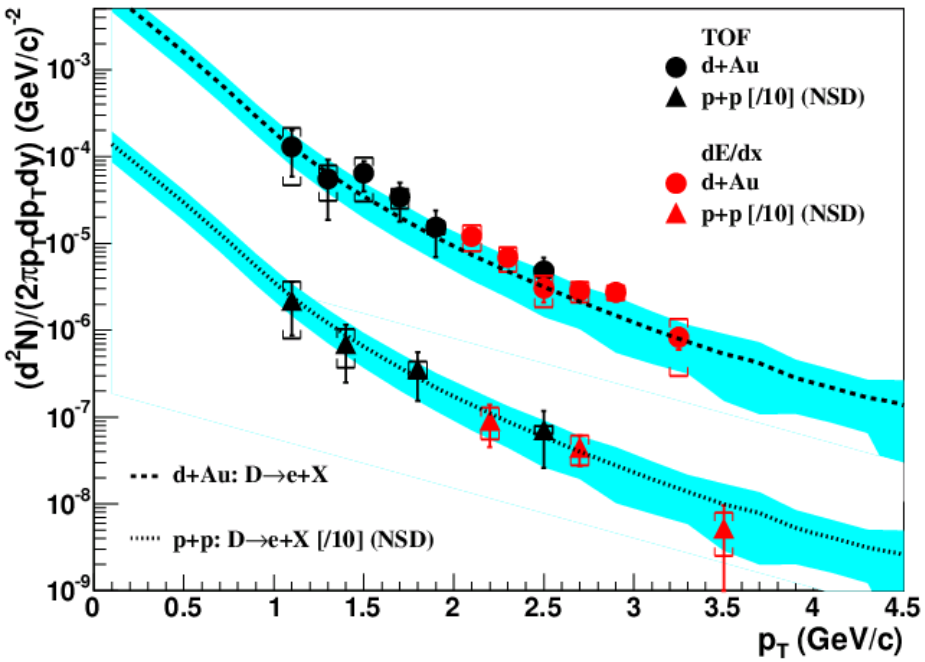
*Centrality dependence unique measurement from RHIC

PHENIX: Open Charm in dA at y=0

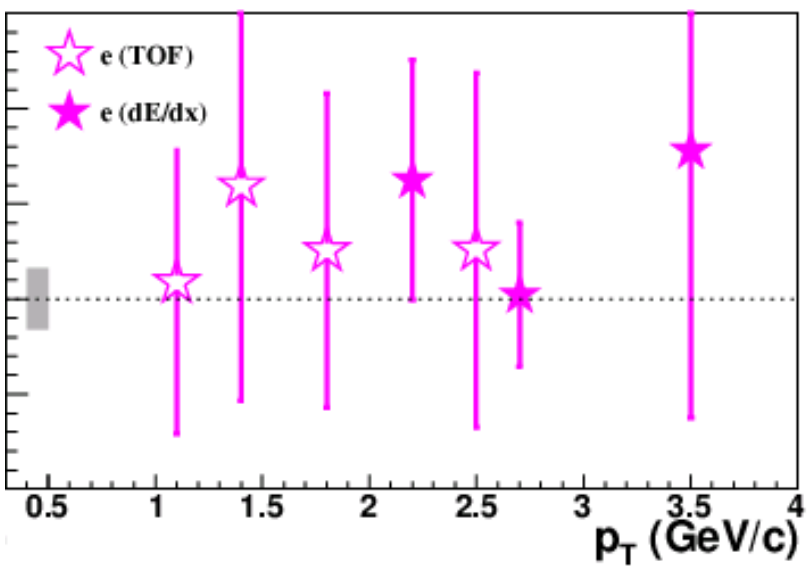


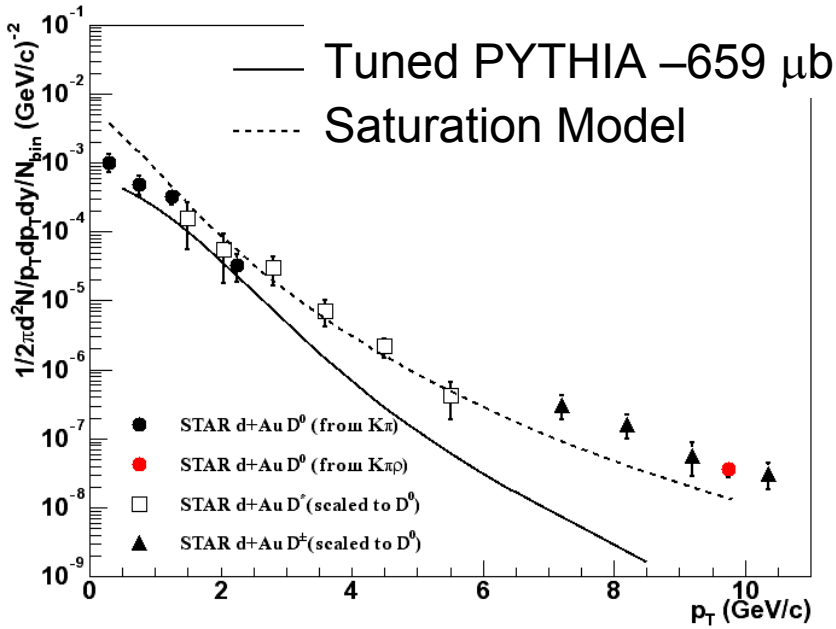
- Similar p_T shape compared to pp data
- No significant centrality dependence seen
- Seems little net nuclear effect on charm production at central rapidity

STAR: Charm at |y|<1.0 from dAu



- Single electron and D results consistent
- RdAu for charm consistent with 1 but large error bars:
- RdAu(e) = 1.23 ± 0.26 (stat)
- p_T spectrum harder than PYTHIA





Summary of pA, dA J/Ψ and Open Charm Production

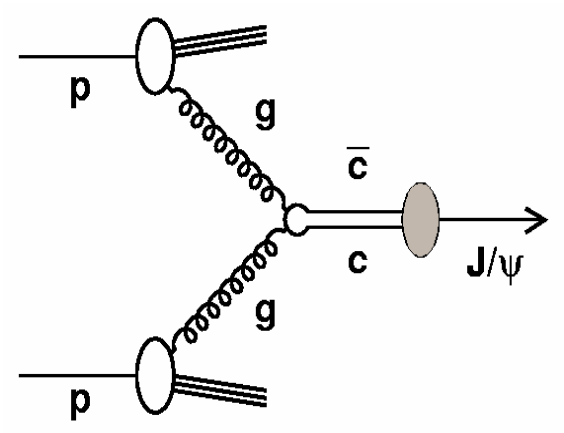
What have we learned

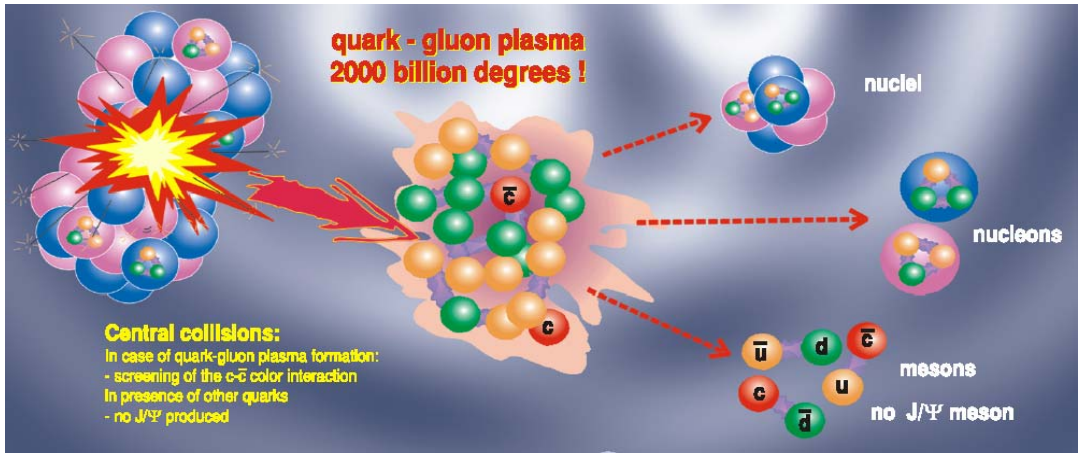
- Ψ, Ψ' nuclear dependence mapped out at CERN
- Gluon shadowing and anti-shadowing, absorption at RHIC
- New centrality dependence information from RHIC
- Open charm measurements from RHIC at central rapidity
- Very important baseline measurements to understand AA at RHIC and CERN

What would we might like:

- Forward rapidity open charm (coming)
- Higher statistics desirable to better delineate various shadowing models and other nuclear effects on J/Ψ production
- Ψ'

Charm and J/Ψ in Heavy Ion Collisions



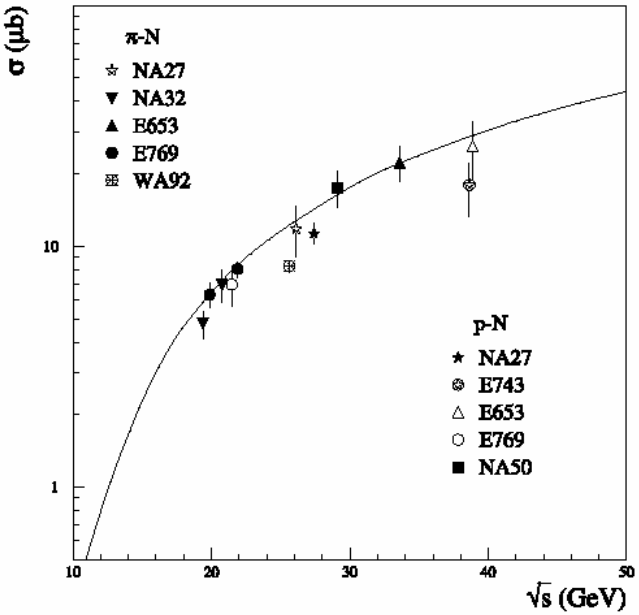


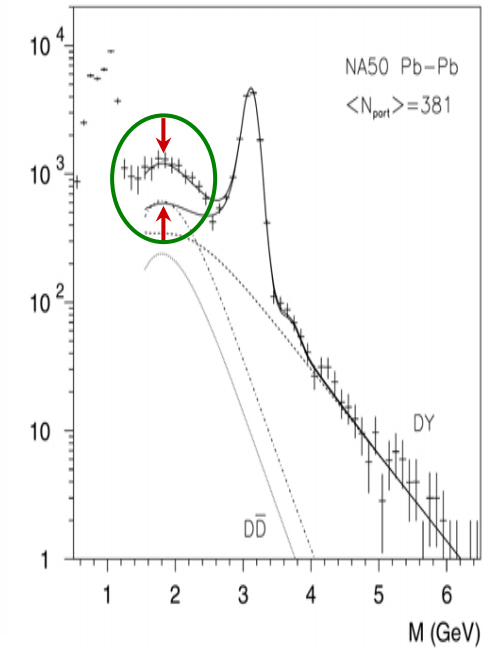
pA effects scaled up PLUS

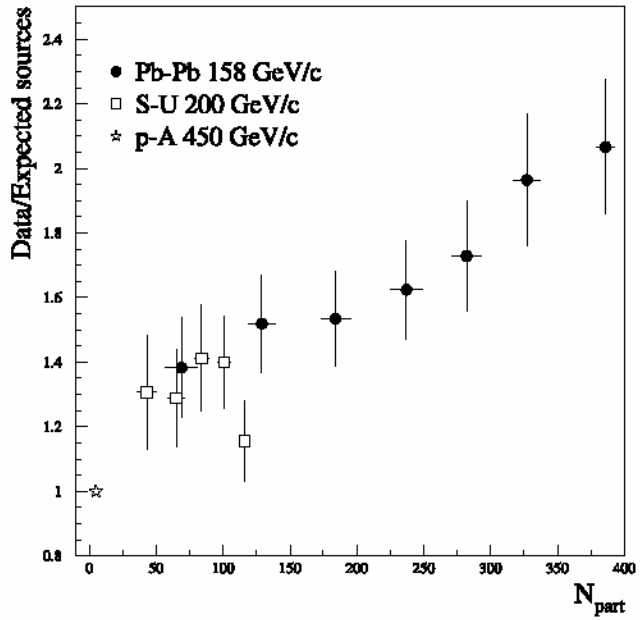
- Hot hadron gas, comovers
- QGP/dense matter modifications to production:
  - Debye screening,
  - Enhancement in coalescence models, balancing of D+D↔J/Ψ+X
  - Thermal production of charm
  - Energy loss and dead cone effect

Must fully understand pp, dAu production to see suppression/enhancement beyond "normal nuclear suppression"; measure over large kinematic regions best

Excess Open Charm in NA50, m=(1.6-2.5) GeV



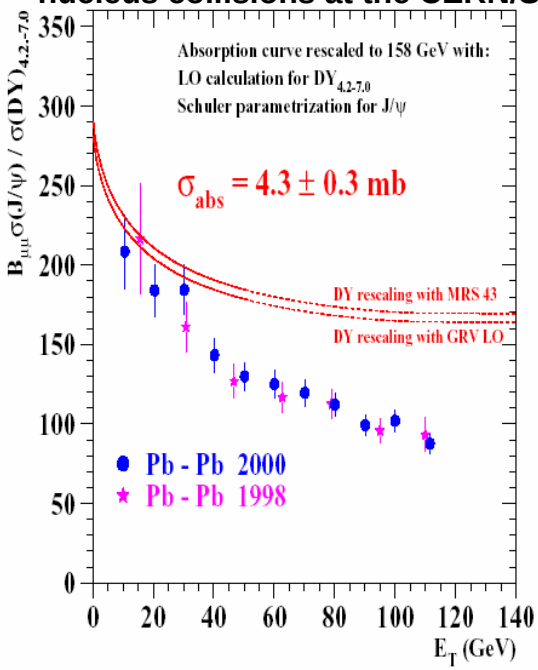


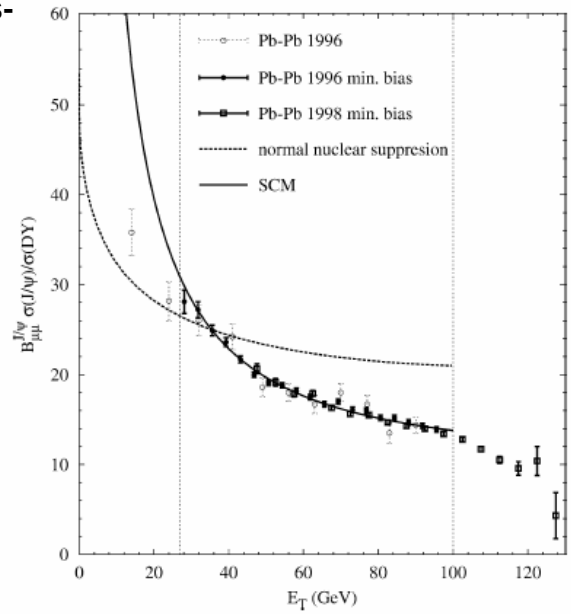


- Charm extracted by fitting dimuon spectra in range $1.6<M_{\mu\mu}<8$ GeV/c^2 and looking at m=(1.6-2.5)
- Open charm cross section from p-N, p-N data show no deviation from scaling with A
- Charm cross section from Pb-Pb shows enhancement which increases with N_{part}
- Enhanced charm or thermal production of dimuons?

J/Ψ Suppression in Pb-Pb at NA50

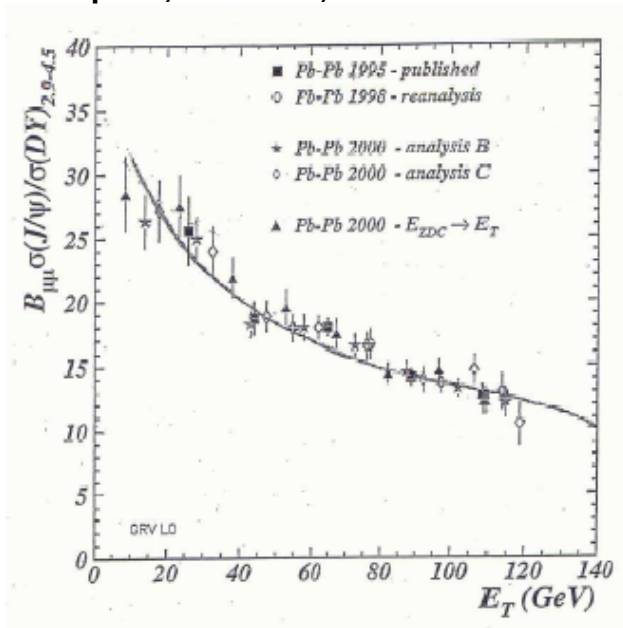
H. Santos, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".





A.P.Kostyuk, M.I. Gorenstein, H. Stocker, W. Greiner, Phys. Lett B 531, 195-202

A. Capella, D. Sousa, nucl-th/0303055



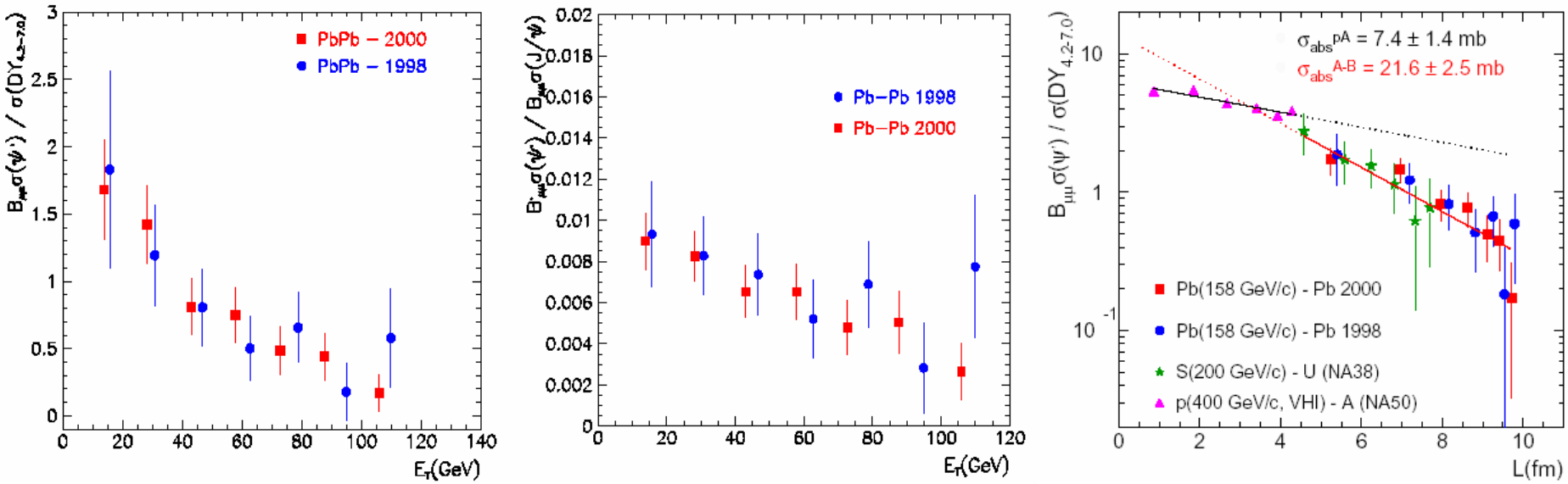
- Suppression with respect to normal nuclear suppression expectations
- Detailed data collection to measure "normal nuclear suppression"→updated results
- Theorists have produced various alternative models which also reproduce data:
  - Statistical coalescence model (also needs enhanced open charm)
  - Comovers

- RHIC data on J/Ψ highly desired to give another data point(s) to compare to PbPb results and implied expectations

Ψ' Suppression in Pb-Pb at NA50

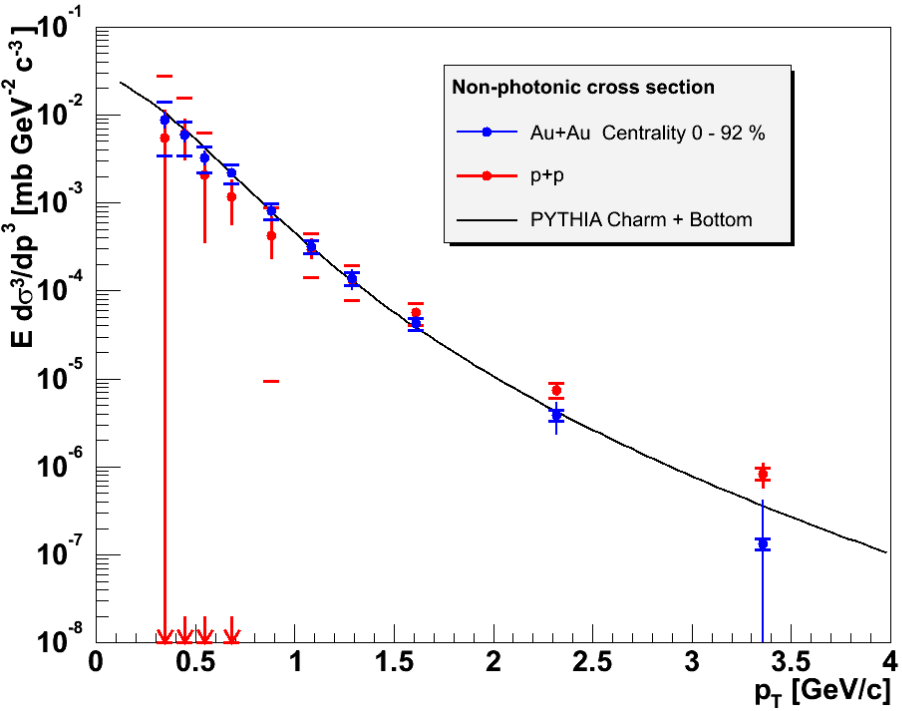
H. Santos, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".

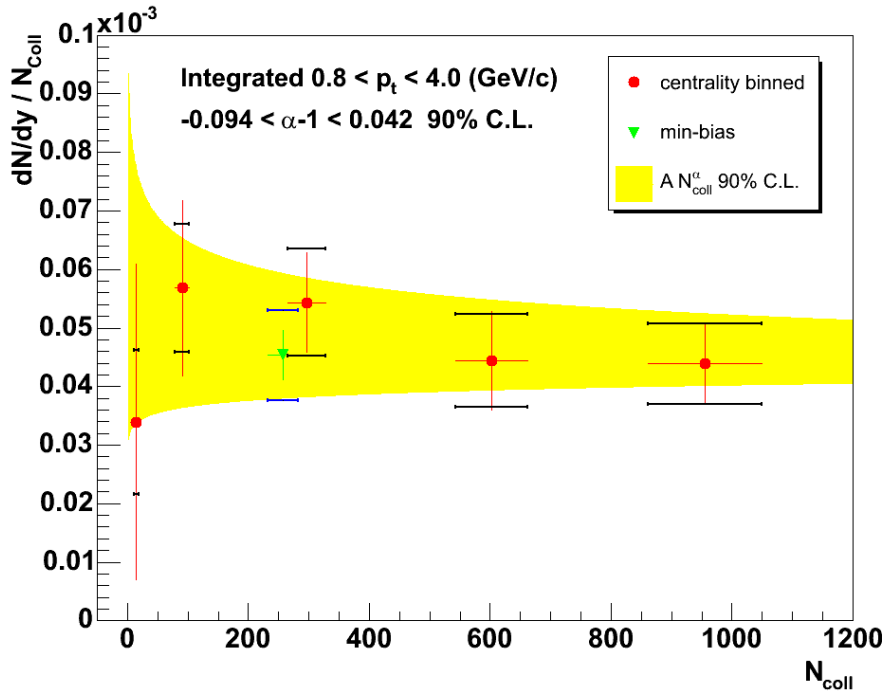
$$\sigma_0 e^{-<\rho L>\sigma_{abs}}$$



- Ψ' suppression seen with respect to DY and J/Ψ, increasing with centrality
- Different apparent behavior between pA and AA collisions
- S-U and Pb-Pb collisions behave similarly

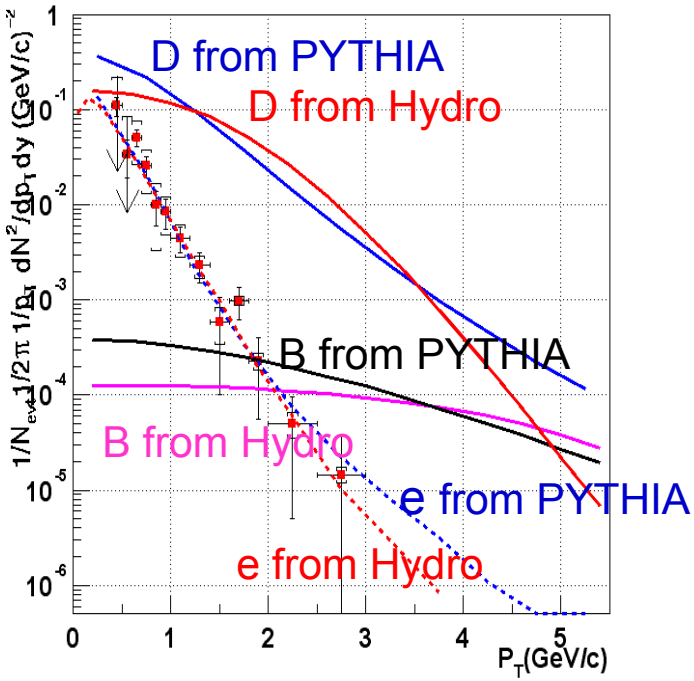
PHENIX Open Charm in AuAu at y=0

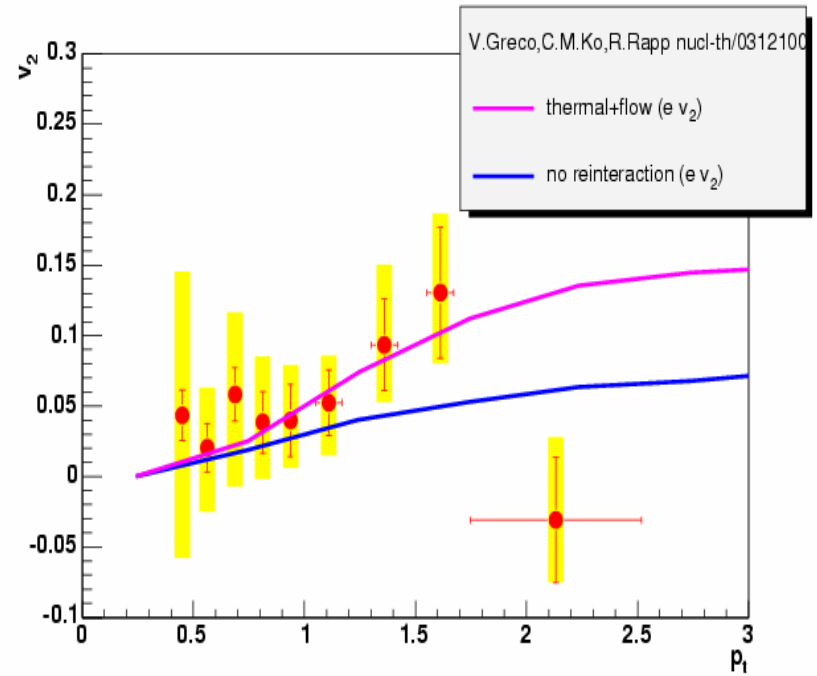




- AuAu data compared to pp data at 200 GeV
- Spectral shapes the same? Can't say definitively with these error bars.
- No significant dependence with N_{Coll}, within error bars

PHENIX: Charm Flow in AuAu?





***Batsouli, Kelly, Gyulassy, Nagle, Phys. Lett B 557, 26-32**

Why might we care?

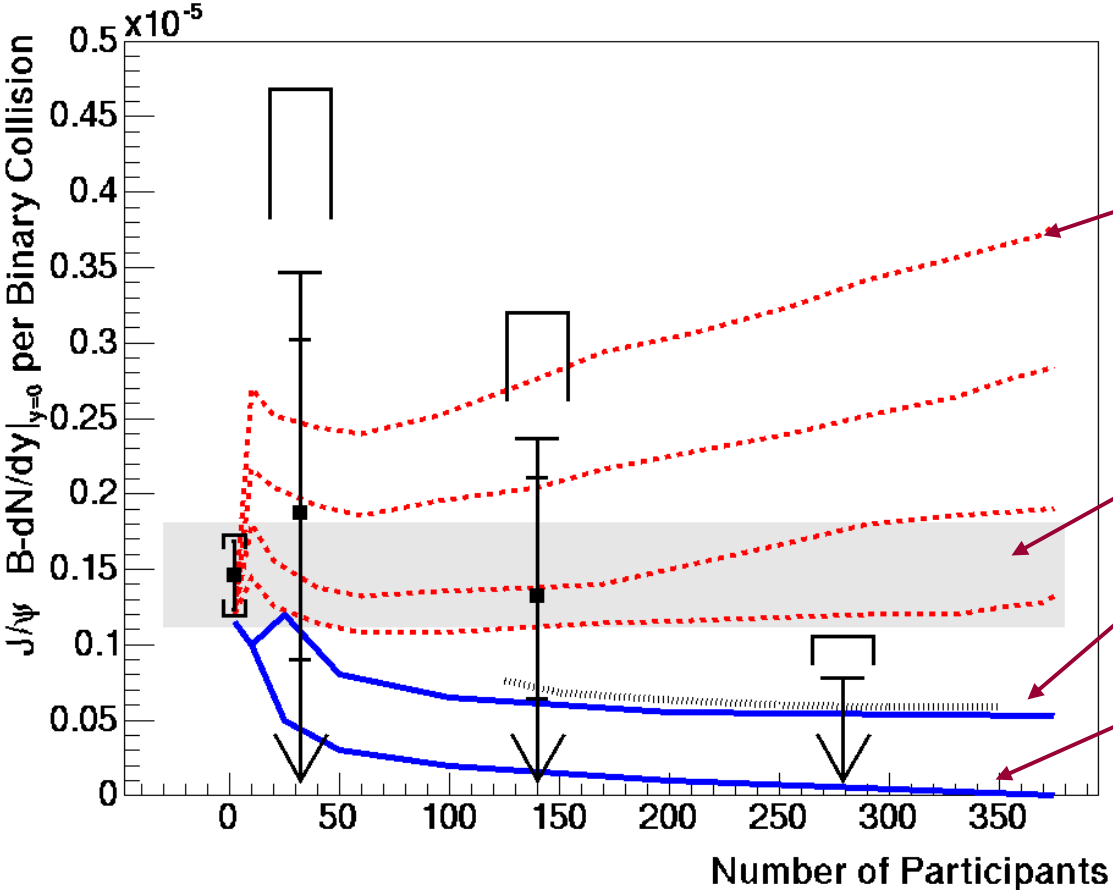
•Does charm agree with binary scaling because little interaction with the medium or does charm flow result in no net change in p_T spectrum (within our measurement)?

How do we attempt to measure it?

•Calculate flow of single electrons (remember cocktail: photon conversion, … and charm)

•Calculate flow of photonic sources and compare to model with and without charm flow

PHENIX: J/Ψ in AuAu from Run 2



R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 054905
Plasma Coalescence Model

Binary Scaling

Absorption (Nuclear + QGP) + final-state coalescence

Absorption (Nuclear + QGP)
L. Grandchamp, R. Rapp, Nucl Phys A709, 415; Phys Lett B 523, 60

- 49.3 million minimum bias events analyzed in Central Arm, Run 2
- 8, 5, 0 "most likely signal" for 3 centrality bins
- Not enough statistical significance to distinguish various models but strong enhancement seems to be disfavored.

Near Future Measurements

RHIC – 200 GeV AuAu running in Run 4, CERN Runs

- PHENIX AuAu at 200 GeV: (assume 123 μb^{-1} and $A^{2\alpha}$)
  - ~1600 J/Ψ into each muon arm
  - ~400 J/Ψ into central arm
  - Open charm at central and forward rapidities via single leptons
  - Higher statistics highly desireable to allow kinematic binning, possible large suppression, etc.

- STAR AuAu at 200 GeV:
  - Open charm via single electrons and reconstructed D mesons

- NA60 at CERN
  - χ_c from pA (Important to understand feed-down contribution to J/Ψ)
  - Tagged charm production with vertex detector (is enhancement in dimuons charm or something else?) Indium-Indium data being analyzed

- more

Summary

•Many data sets now available on open charm and J/Ψ production over large kinematic ranges to constrain pp production models

•Important pA, dA data from CERN and RHIC taken to establish suppression/enhancement in cold nuclear environment

•First data versus centrality in dA collisions available

•Production in heavy ion collisions not clear: enhancement of charm or not? abnormal suppression of J/Ψ? Difference between CERN and RHIC energies…?

•AuAu data should provide critical insights. The more statistics the better.