Quarkonia Production in p+p, p+A and A+A Collisions

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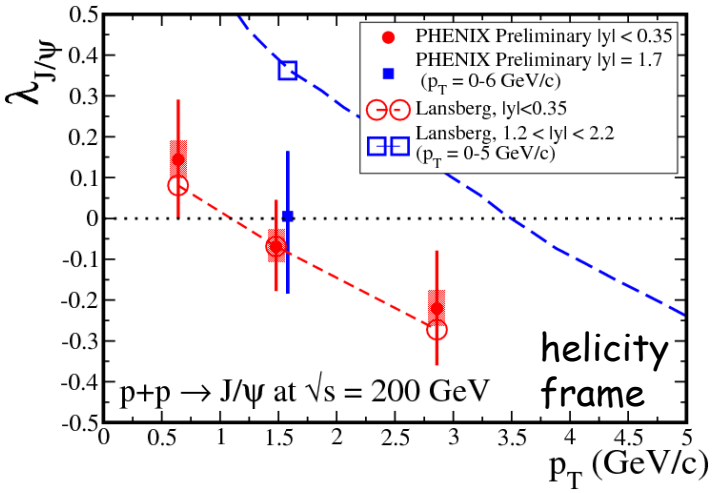
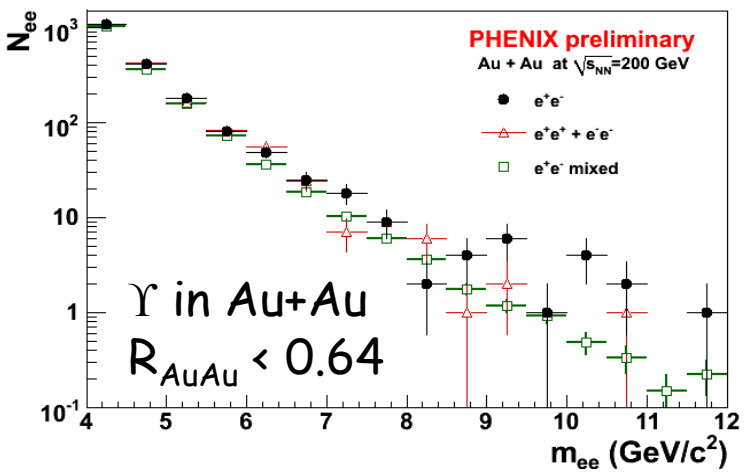
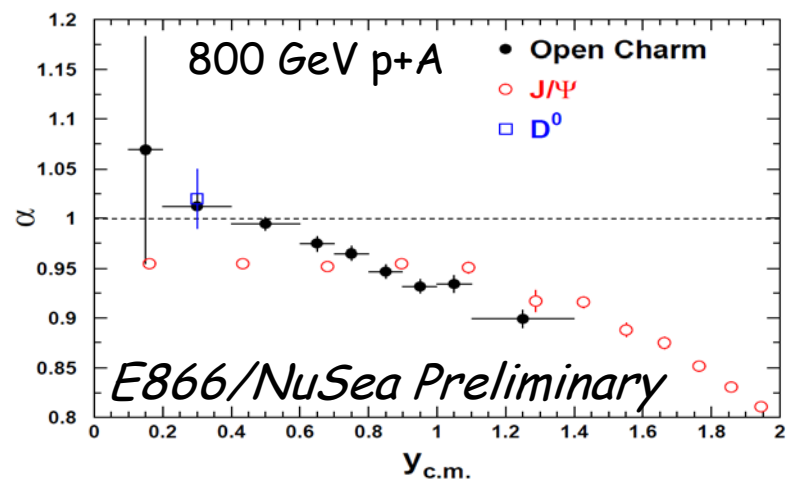
ECT, Trento, Italy - May 2009

- Latest p+p results
- p+A and d+A
- J/Ψ in A+A at RHIC
- Upsilons





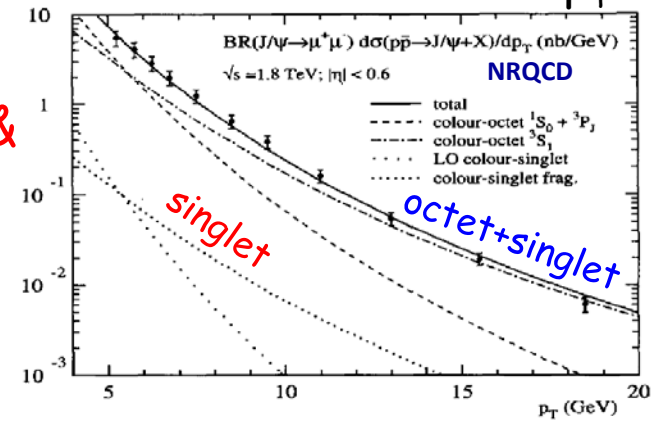


Quarkonia Production
p+p Collisions

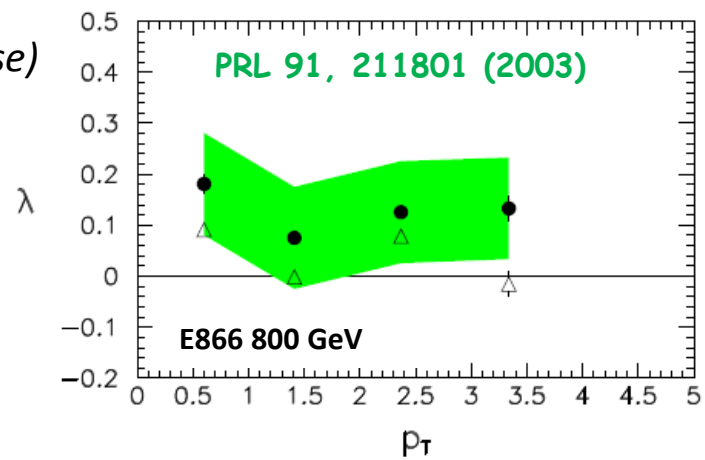
Quarkonia Production Uncertainties

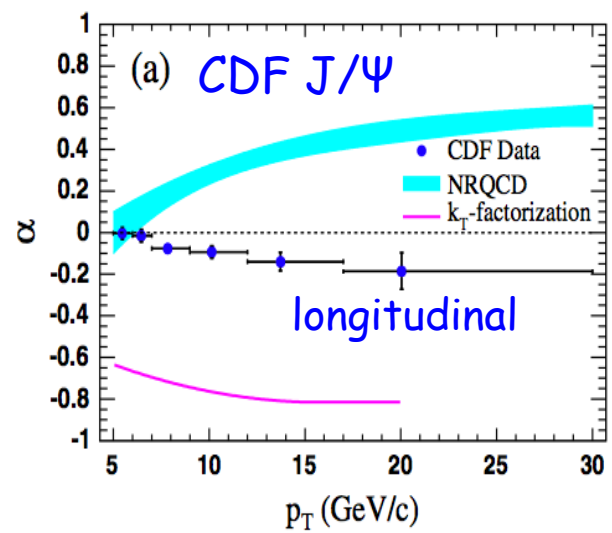
- Is $c\bar{c}$ produced in a color-singlet or –octet state?
  - important for CNM effects
- difficult to get both absolute cross section & polarization correct
  - singlet models under-predict cross sections
  - octet models get cross section but predict transverse polarization at large p_T that is not seen in data

CDF cross section vs p_T



Λ or α = +1 (transverse)
= -1 (longitudinal)





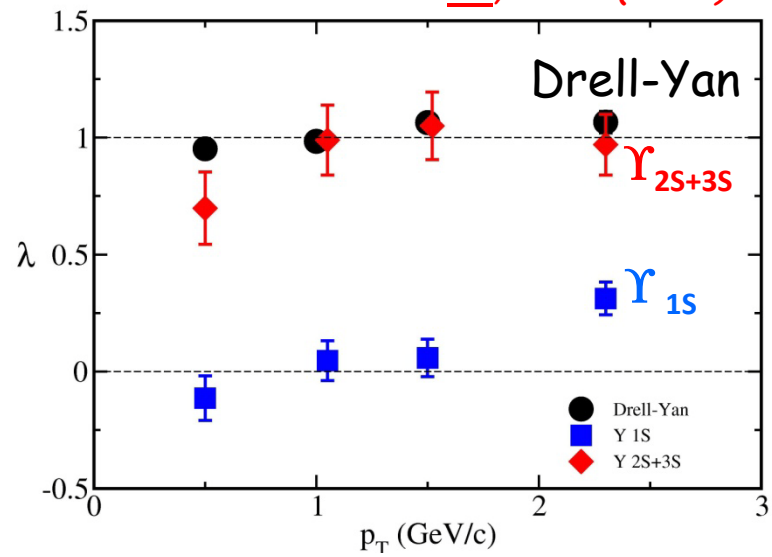
Quarkonia Production Uncertainties

Υ maximally polarized for (2S+3S), but NOT for (1S)

* Is feed-down washing out polarization? (~40% of 1S from feed-down)

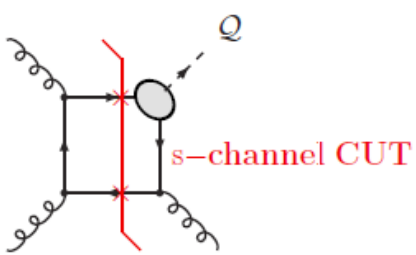
(ψ' polarization measurement would be helpful here but is experimentally challenging)

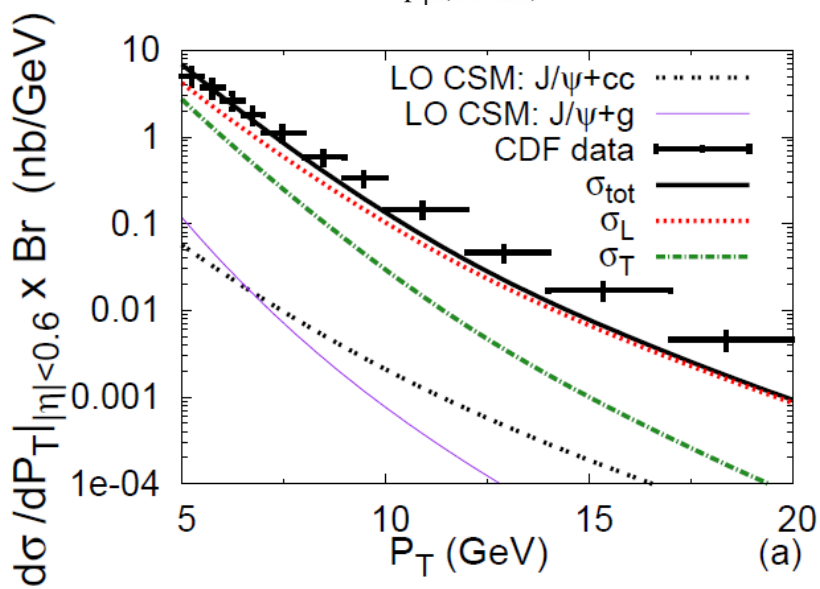
E866/NuSea – PRL 86, 2529 (2001)



Recently a new singlet model seems to get cross sections & polarization correct

Haberzettl, Lansberg, PRL 100, 032006 (2008)



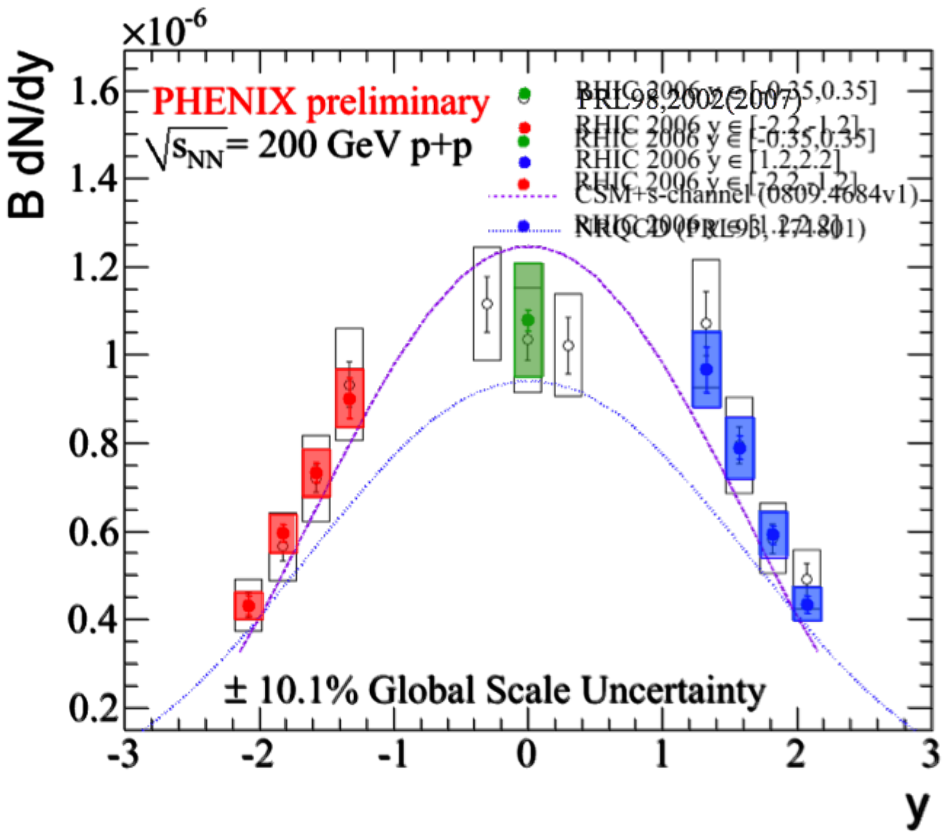


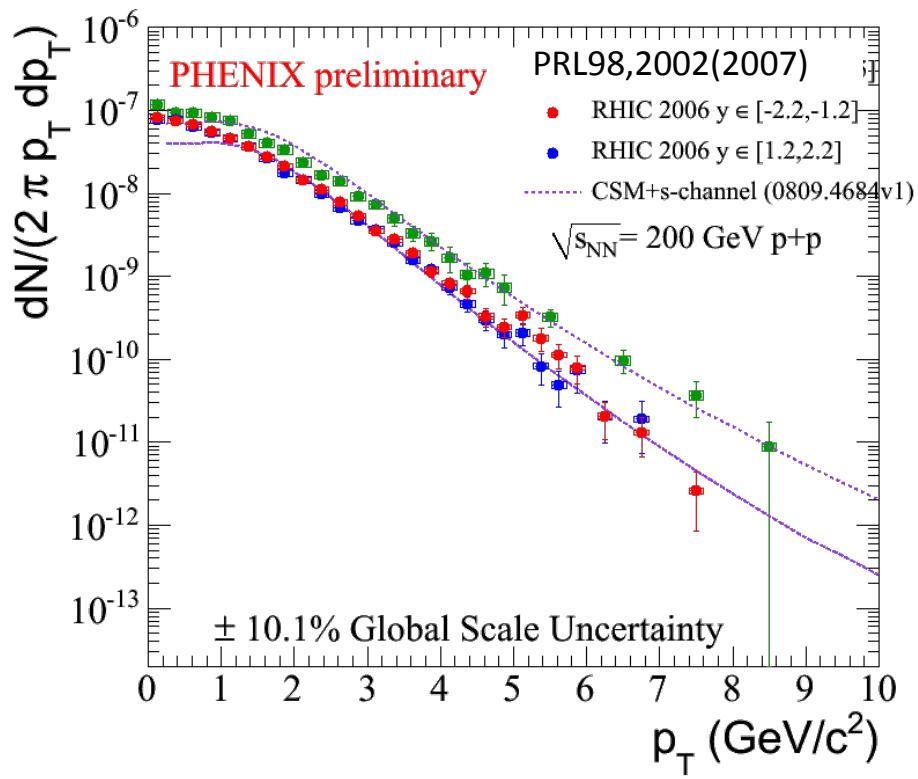
- 4-point function, c – cbar – Q – g, fit to CDF data; then predict other, e.g. RHIC data

Quarkonia Production at RHIC – p+p

One of the main deficiencies in A+A J/Ψ studies is the p+p baseline

- 2006 p+p data with ~3 times previous (2005) luminosity!
- Much improved baseline, especially for high-p_T
- Lansberg (CSM) model and NRQCD model compare well vs rapidity & p_T

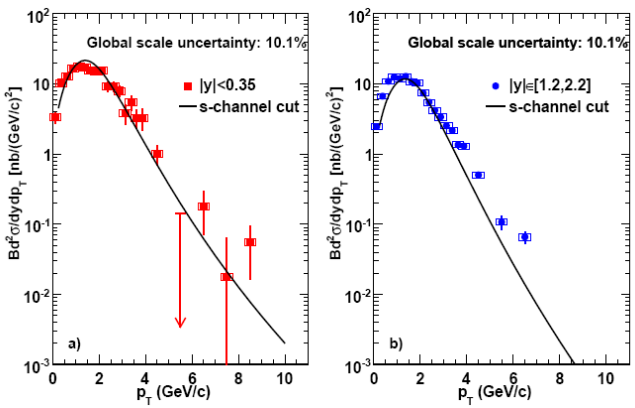




Quarkonia Production at RHIC – J/Ψ Polarization

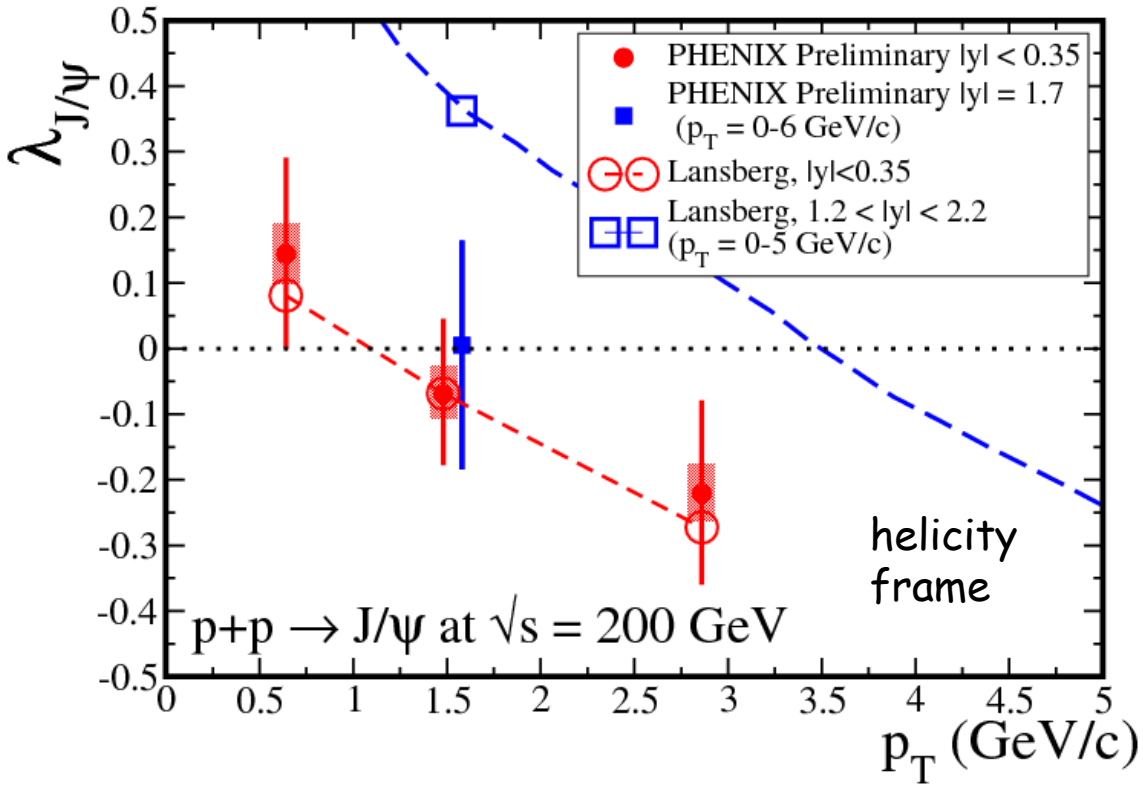
New "s-channel cut" color singlet model (CSM) - fit to CDF data:

- agrees with PHENIX cross sections



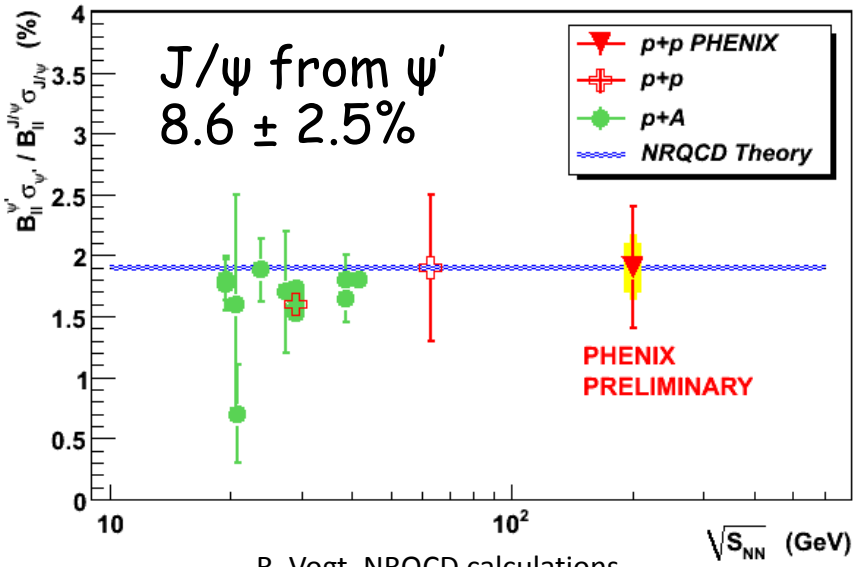
- & y=0 polarization results
- but disagrees (at 2-3 sigma level) with forward rapidity PHENIX polization result

Haberzettl, Lansberg PRL 100, 032006 (2008)



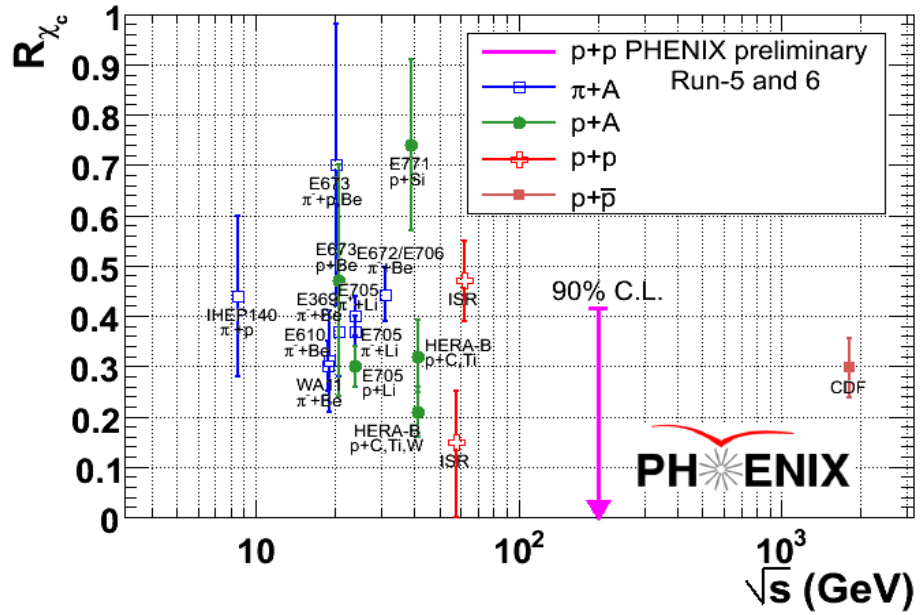
(does <u>not</u> include effect of feeddown from χ_c & ψ')

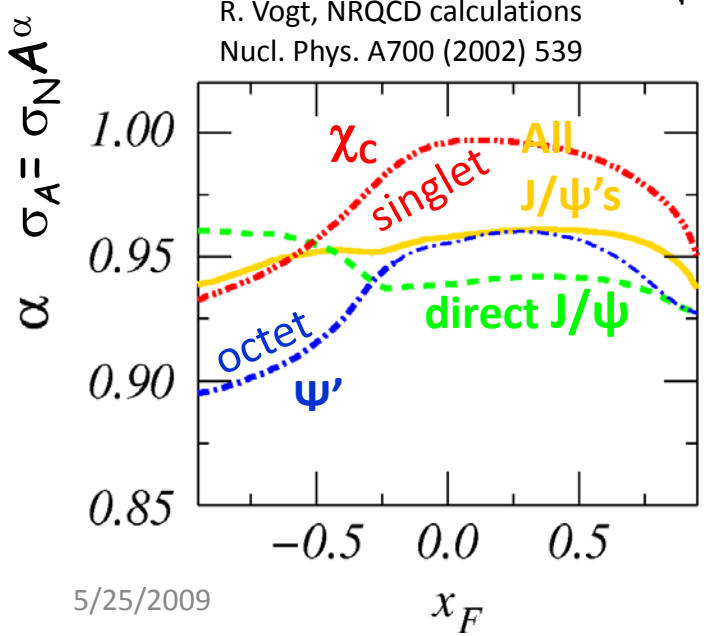
Complications due to substantial feed-down from higher mass resonances (ψ', χ_c)



R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539

J/ψ from χ_c < 42% (90% CL)





Nuclear dependence of (parent) resonance, e.g. χ_c is probably different than that of the J/ψ

Also measured

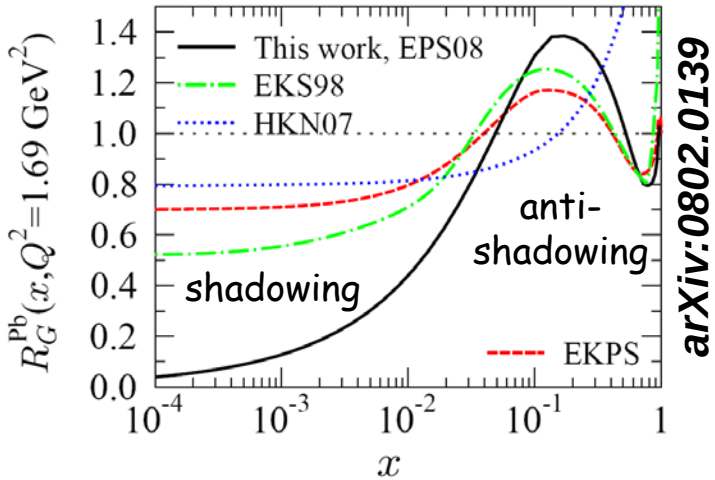
B → J/ψ - 4 $^{+3}_{-2}$ %

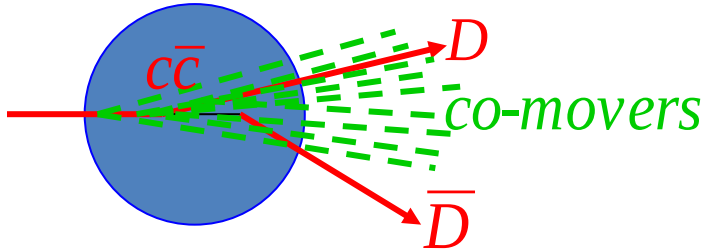
(but will be strongest at high-p_T)

CNM effects on Quarkonia p+A (FNAL) and d+A (RHIC)

What CNM effects are important? (CNM = Cold Nuclear Matter)

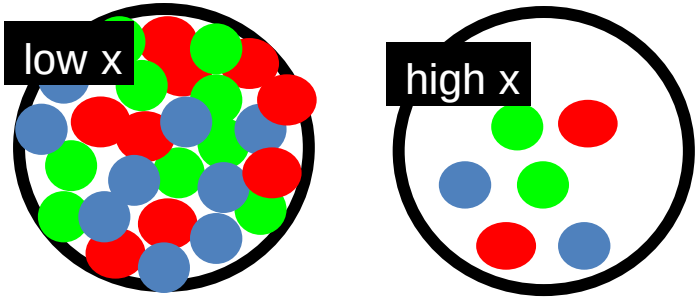
Traditional shadowing from fits to DIS or from coherence models



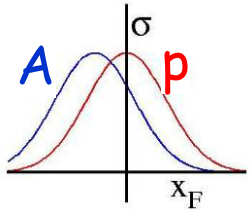


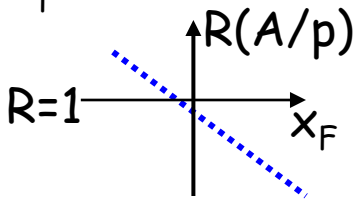
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

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

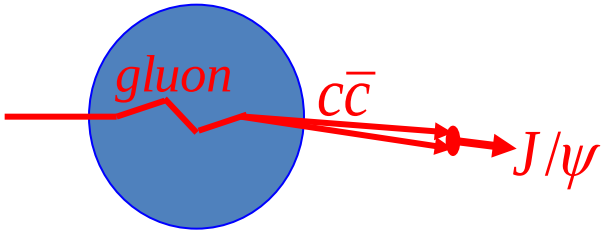


Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F





Transverse Momentum Broadening
Another Cold Nuclear Matter Effect

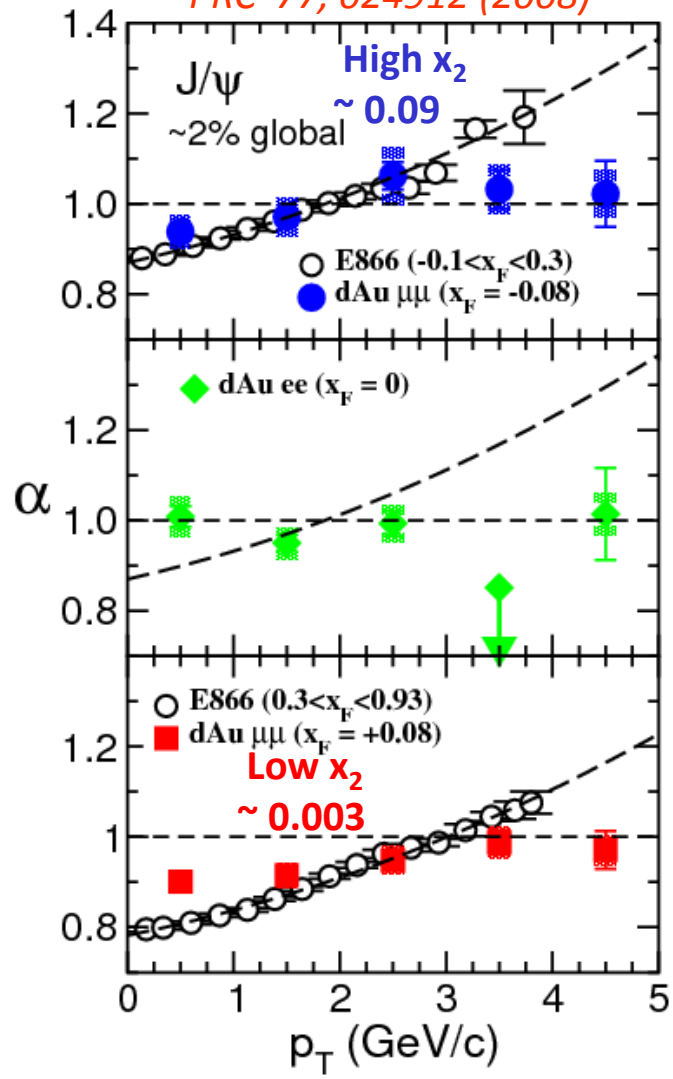


Initial-state gluon multiple scattering causes p_T broadening (or Cronin effect)

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

PHENIX 200 GeV dAu shows some p_T broadening, but may be flatter than at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

PRC 77, 024912 (2008)

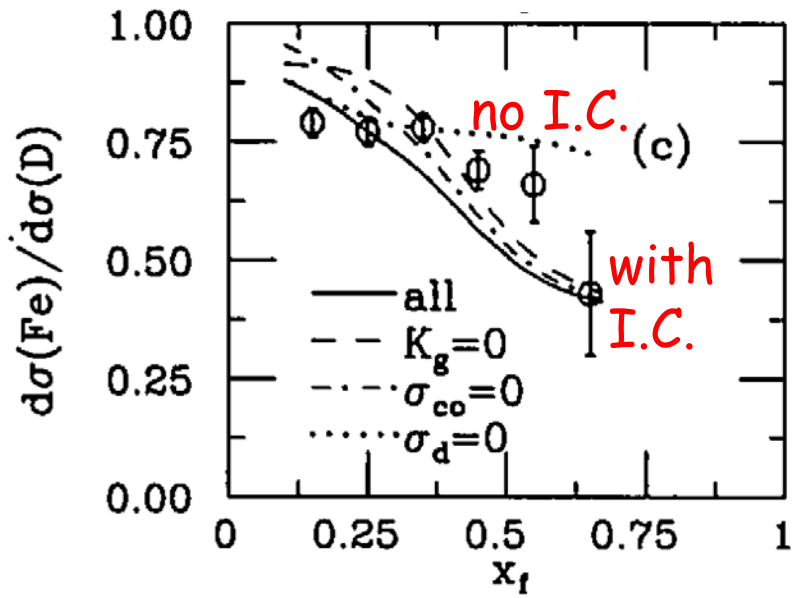


Intrinsic charm contribution to Quarkonia

At large x_F (≥ 0.5) intrinsic $c\bar{c}$ components of the projectile proton can dominate the production of charm pairs

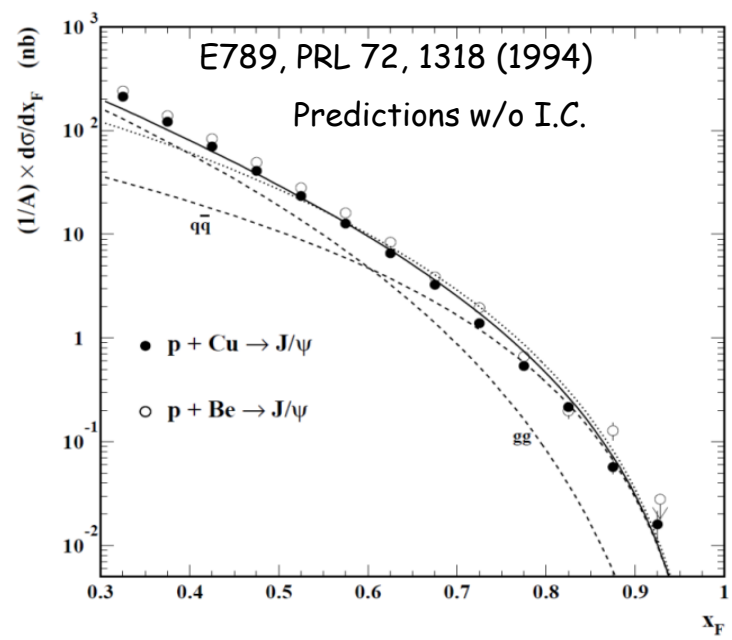
- $A^{2/3}$ dependence via surface stripping of light quarks to free charm pair component

Vogt, Brodsky, Hoyer, NP B360, 67 (1991)
(also includes absorption and shadowing)

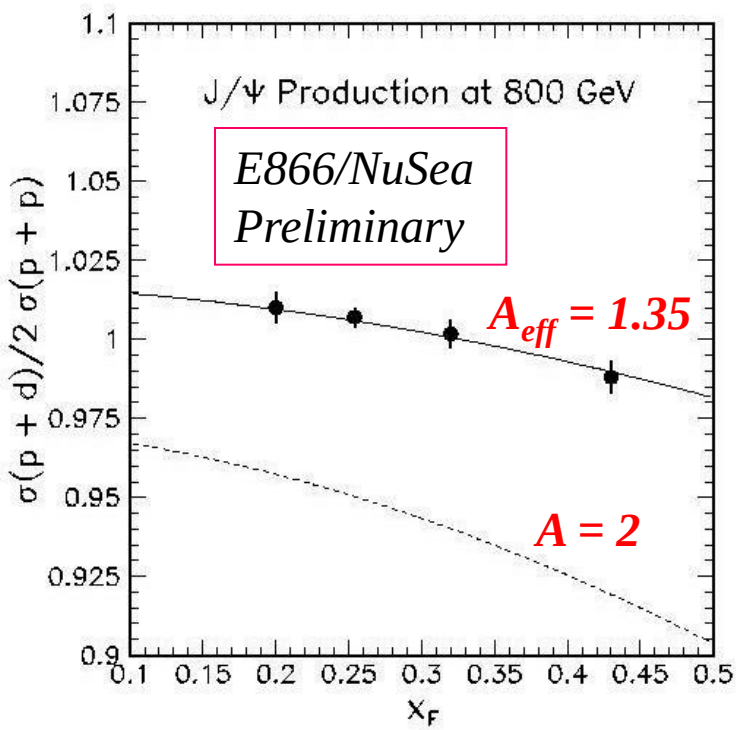


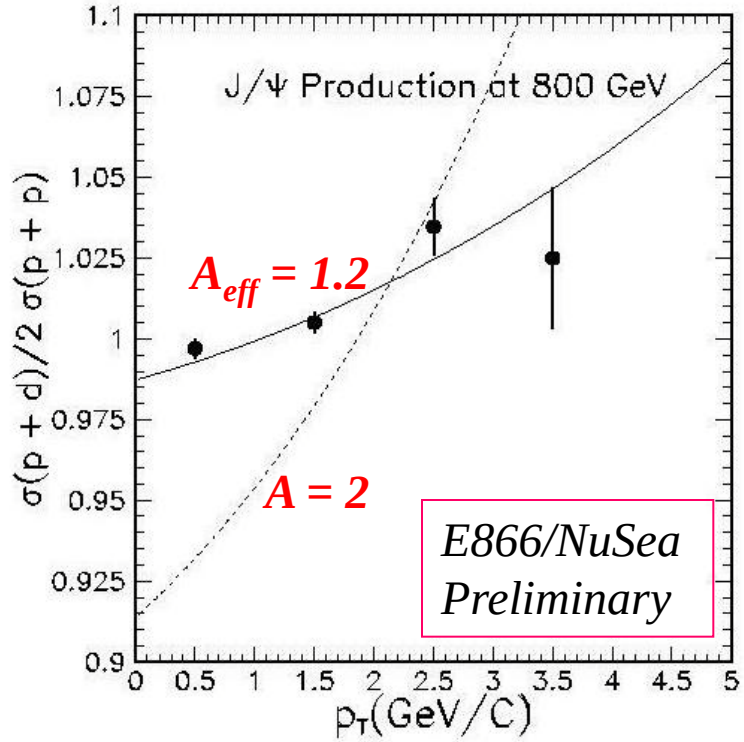
But E789 set limit on I.C. contribution via shape of cross section vs x_F

- $< 2.3 \times 10^{-3}$ nb/nucleon (1.8 nb/nucleon predicted)



(Small) J/ψ Nuclear Dependence Even for Deuterium/Hydrogen!





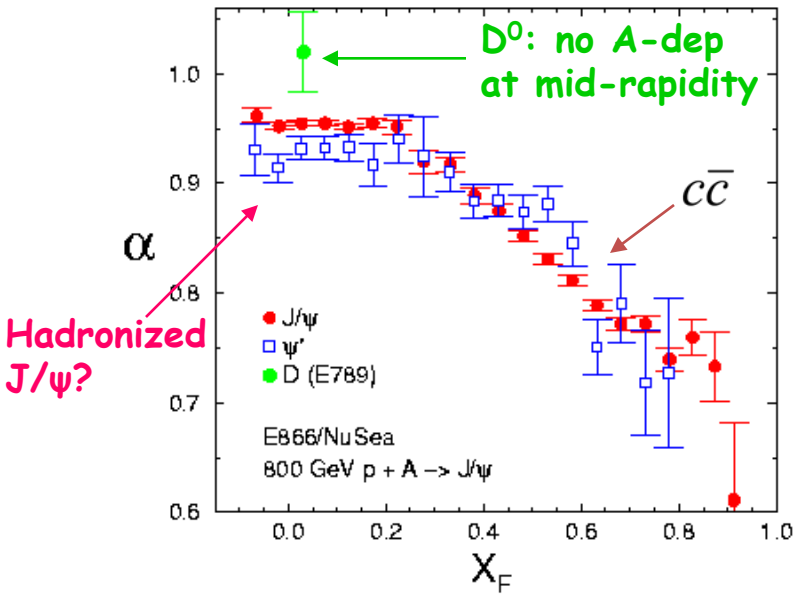
Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A, A_{eff}, smaller than two.

From fits to E866/NuSea p + Be, Fe, W data: $\sigma_{pA} \sim \sigma_{pp} A^{\alpha}$

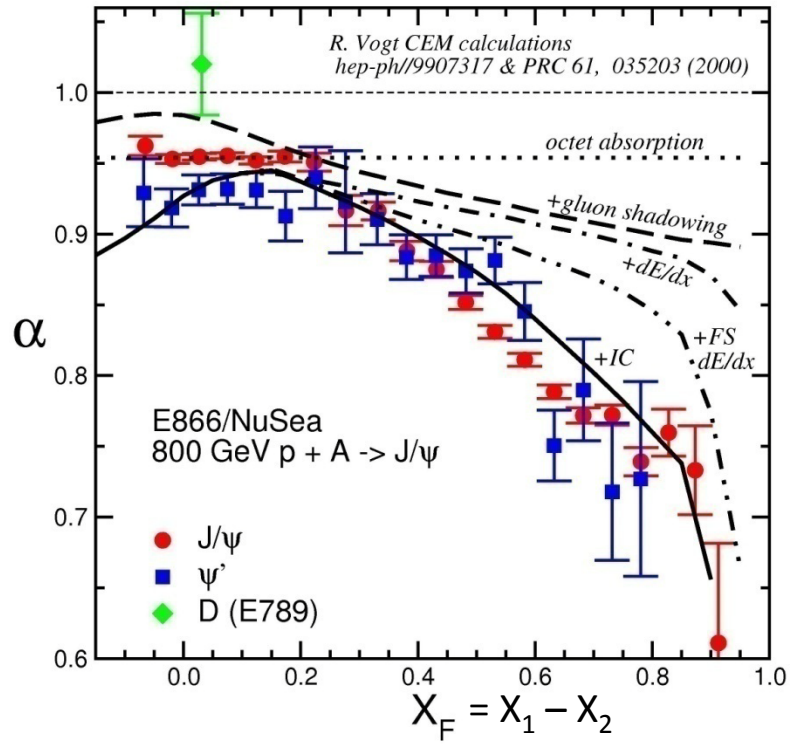
$$\alpha(x_F) \propto 1 - 0.052 x_F - 0.034 x_F^2$$
$$\alpha(p_T) \propto 0.06 p_T + 0.011 p_T^2$$

J/ψ suppression in p+A fixed-target

800 GeV p+A (FNAL)
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



E866/NuSea, $\sigma = \sigma_N * A^{\alpha}$



- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- Near x_F = 0 - D^0 not suppressed, J/Ψ and Ψ' suppressed due to absorption, Ψ ' slightly stronger since both starting to become hadronized states in nucleus
- what about open charm at higher x_F?

Many ingredients to explain the J/ψ nuclear dependence – R. Vogt

CNM Physics – PHENIX, E866, NA3 Comparison

New Analysis of Run3 d+Au with new 2005 p+p baseline

PRC 77,024912(2008)

Compared to E866/NuSea p+A results & lower-energy NA3 at CERN

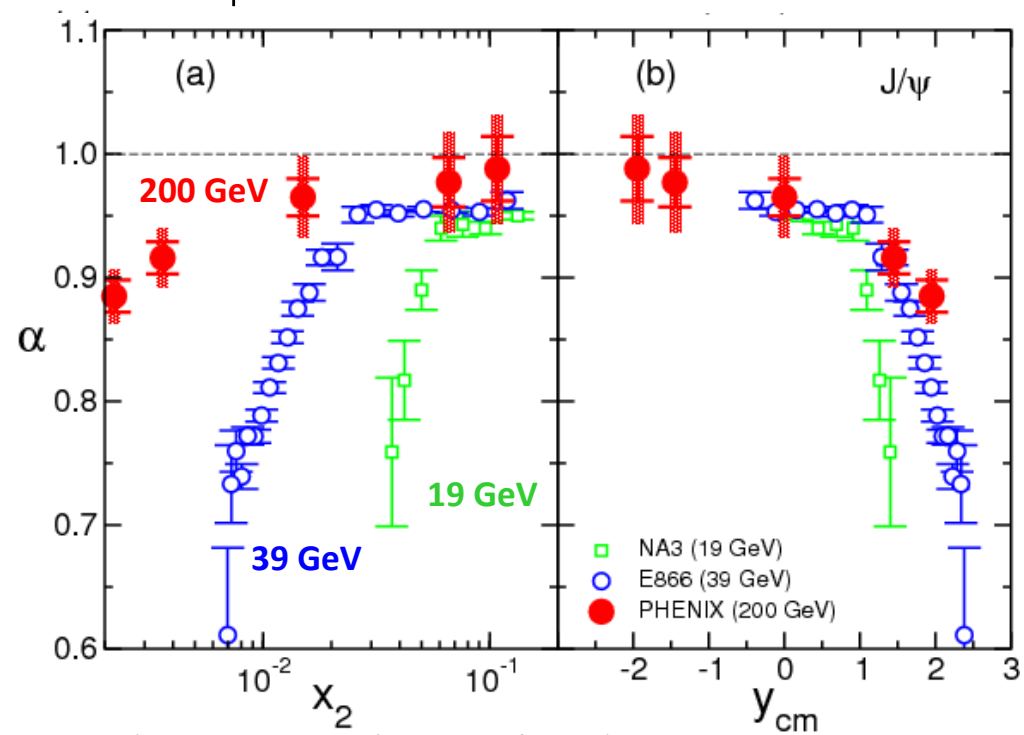
Suppression not universal vs x_2 as expected for shadowing, but closer to scaling with x_F, why?

- initial-state gluon energy loss?
- gluon saturation?

Scaling of E886 vs PHENIX better vs y_{cm}

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

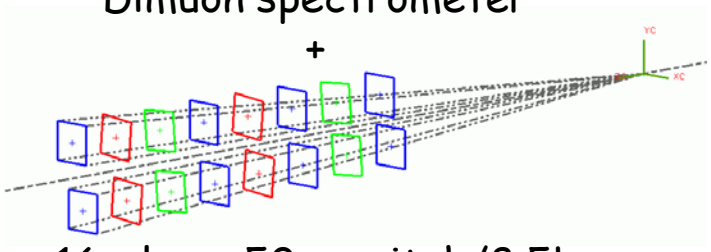
J/ψ α for different √s collisions



(x_2 is x in the nucleus)

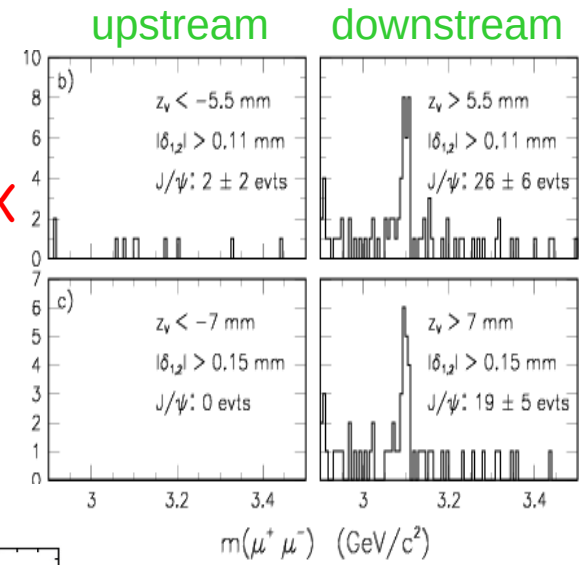
Fermilab E789: D^0 & $B \rightarrow J/\psi$ X
(charm & beauty using silicon)

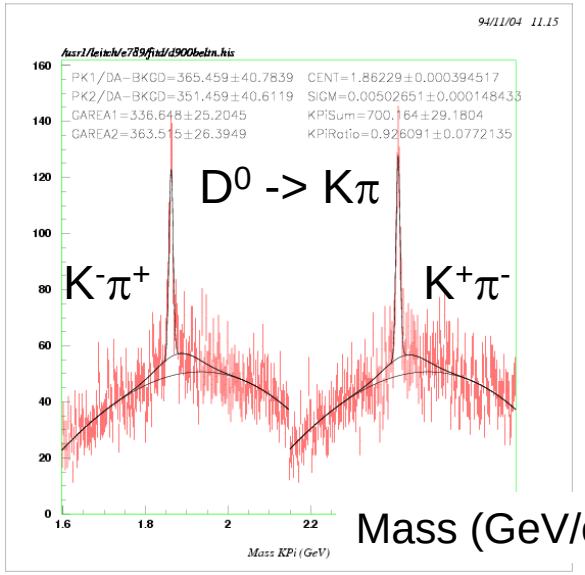
Dimuon spectrometer
+

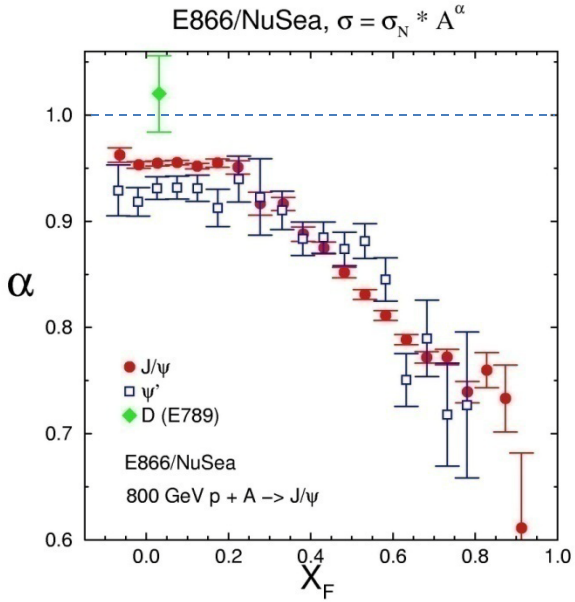


16-plane, 50μm pitch/8.5k strip silicon vertex detector

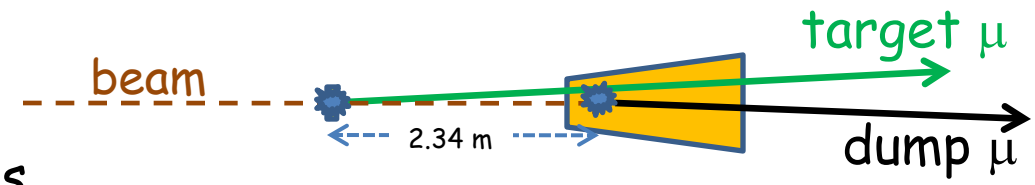
$B \rightarrow J/\psi + X$





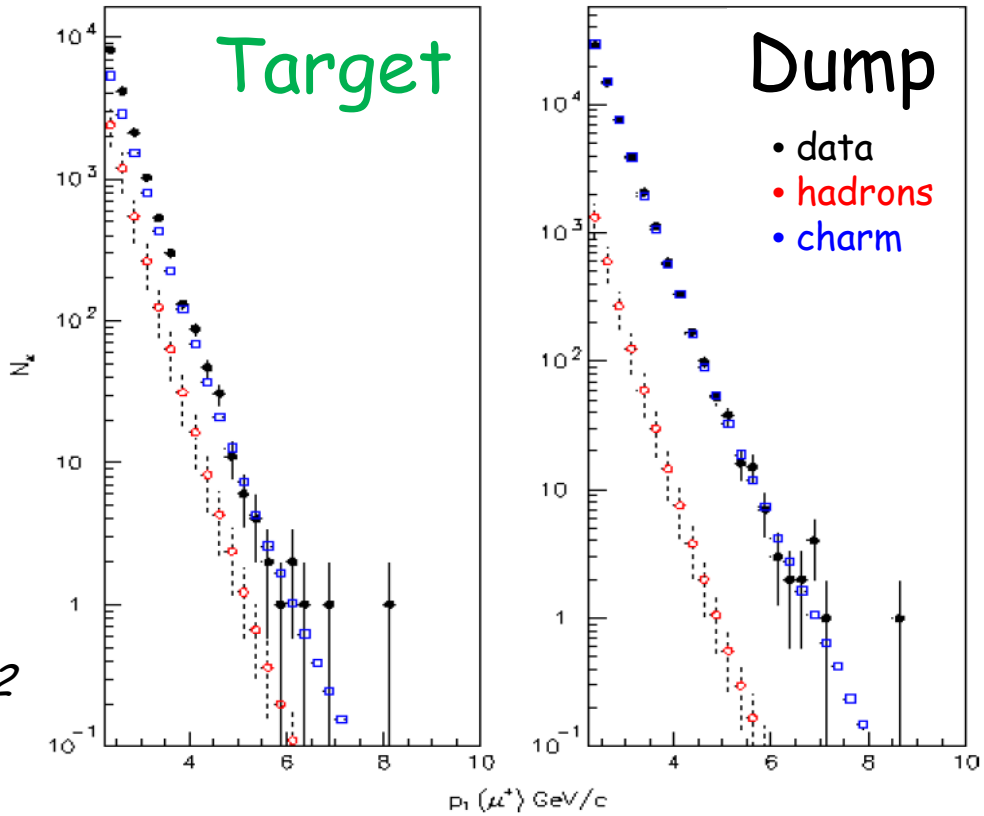


E866/NuSea Open Charm Measurement



- hadronic cocktail explains ~30% of target & ~5% of dump μ's
  - as expected since dump absorbs light hadrons before they can decay
- charm decays consistent between Cu target and Cu dump
- use same method for Be to get nuclear dependence

E866/NuSea 800 GeV p+A
- *S. Klinksiek thesis - hep-ex_0609002*
- *paper in preparation*

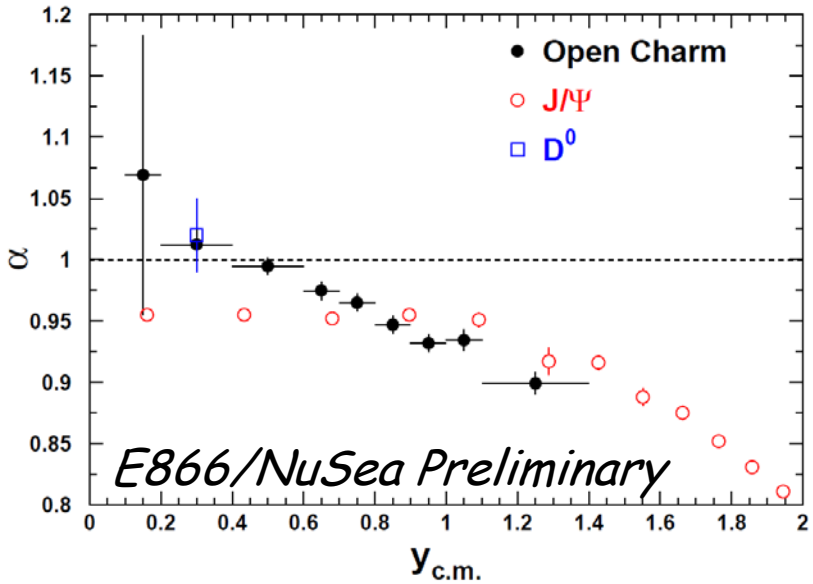


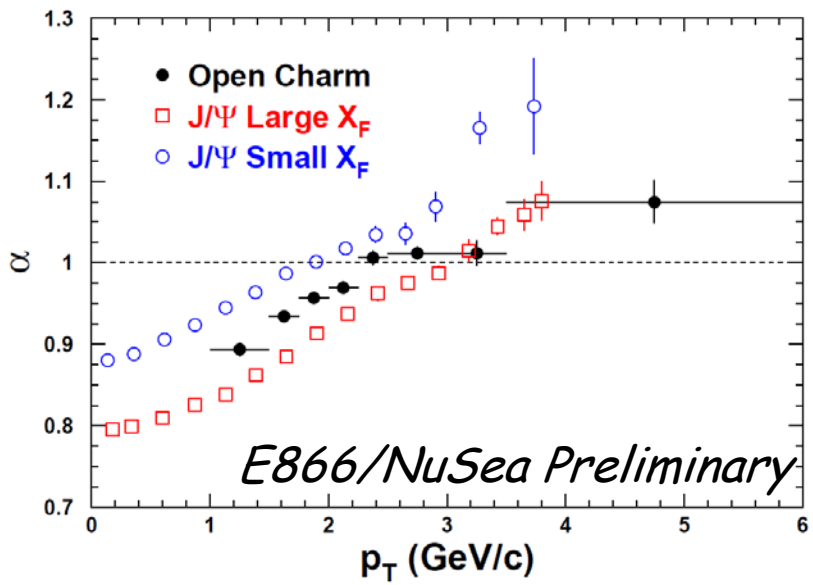
Rapidity dependence of open charm

Open-charm p+A nuclear dependence (p_T>1 GeV/c) – very similar to that of J/Ψ

- dominant effects are in the initial state
  - e.g. shadowing, dE/dx, Cronin
- weaker open-charm suppression at y=0 is lack of absorption

E866/NuSea 800 GeV p+A

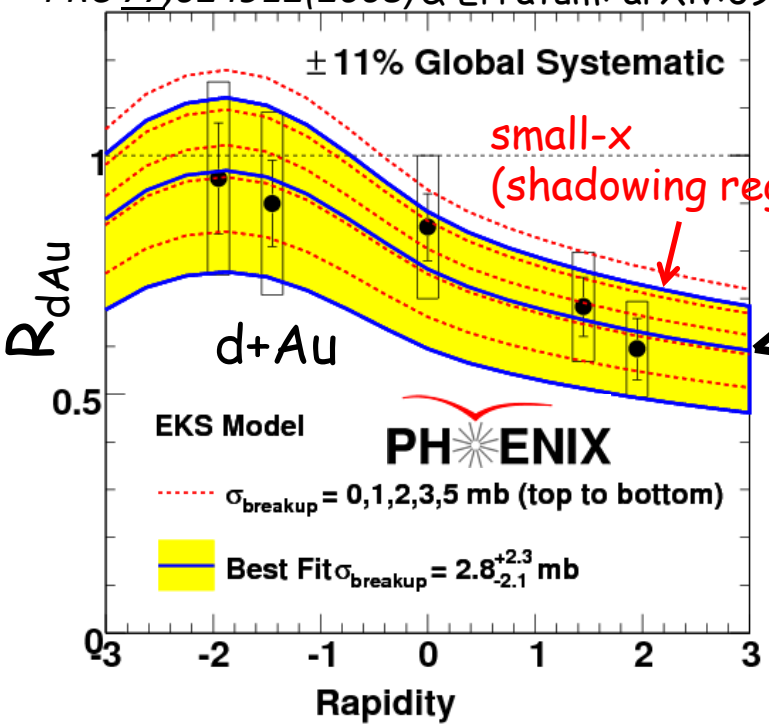


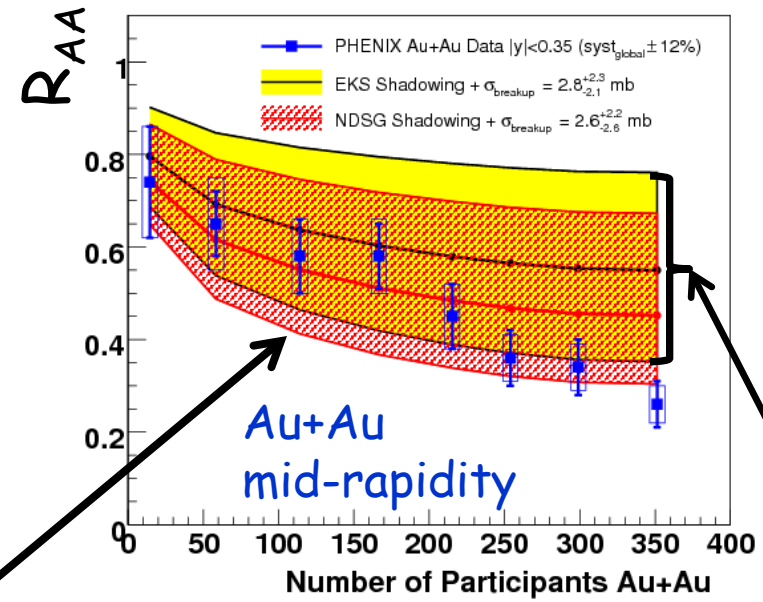


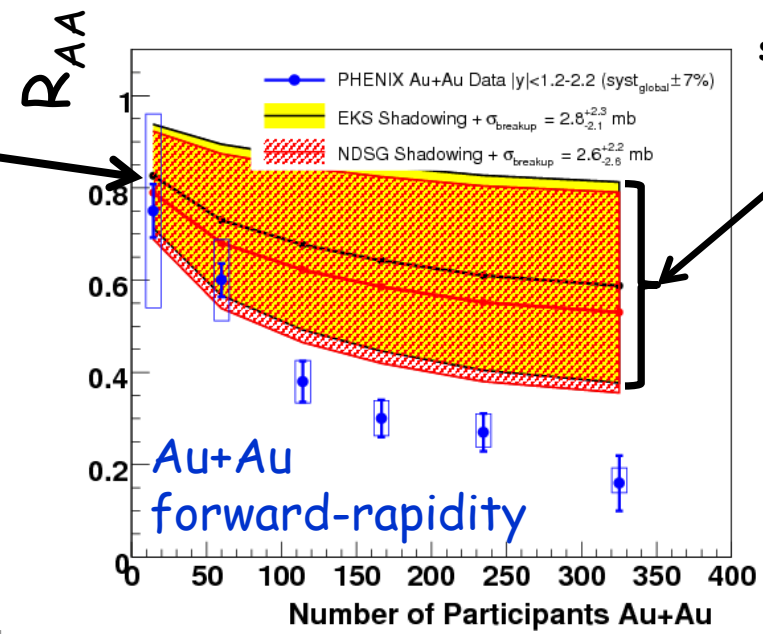
Present CNM Constraints on A+A data

CNM effects (EKS shadowing + dissociation from fits to d+Au data, with R. Vogt calculations) give large fraction of observed Au+Au suppression, especially at mid-rapidity

PRC 77,024912(2008) & Erratum: arXiv:0903.4845







EKS shadowing band

more accurate d+Au constraint soon from 2008 data

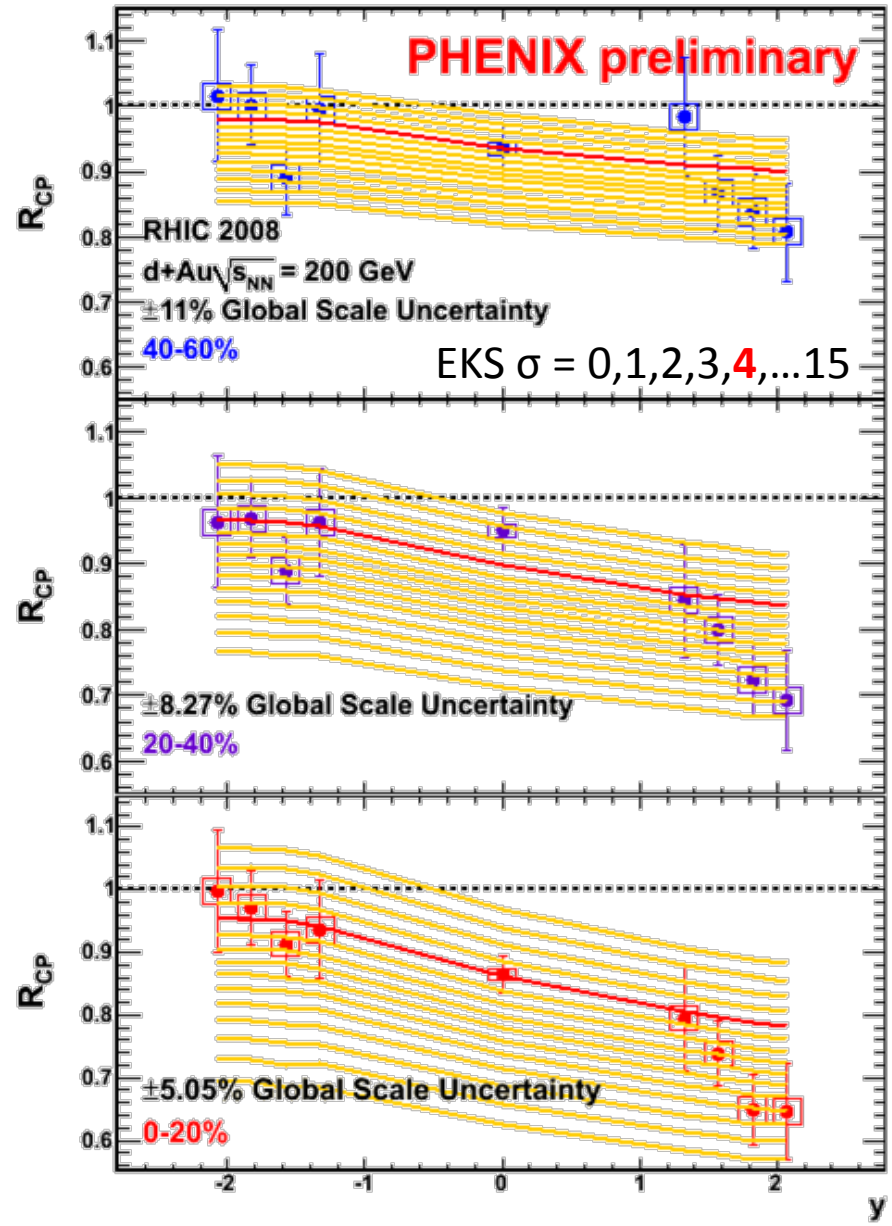
Quarkonia Production & Suppression – J/Ψ in d+Au

Initial d+Au J/Ψ update from new 2008 data (~30x 2003)

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} \Big/ \left\langle N_{coll}^{0-20\%} \right\rangle}{N_{inv}^{60-88\%} \Big/ \left\langle N_{coll}^{60-88\%} \right\rangle}$$

- R_{CP} pretty flat vs centrality at backward rapidity; but falls at forward rapidity (small-x)

- more soon – precision statistics requires precision systematics & careful analysis



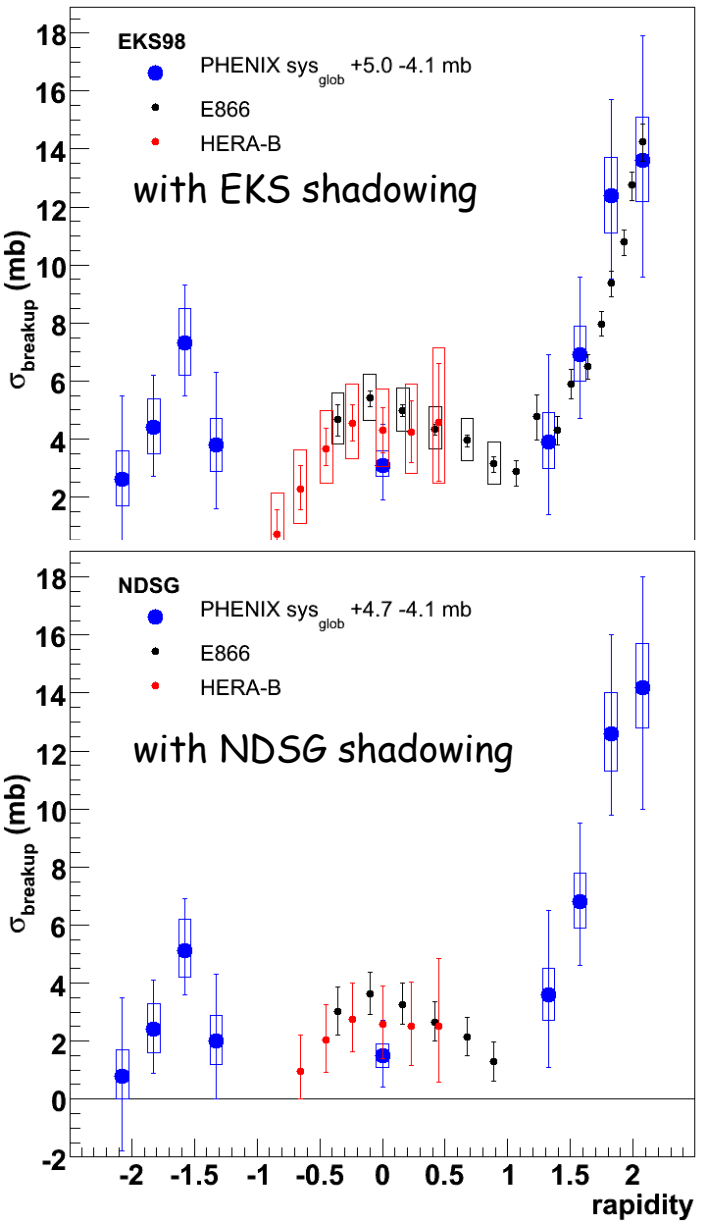
New CNM fits using 2008 PHENIX d+Au Rcp (Tony Frawley, Ramona Vogt, …)

- similar to before, use models with shadowing & absorption/breakup
- but allow effective breakup cross section to vary with rapidity
    - to obtain good description of data for projections to A+A

- get "$\sigma_{breakup}(y)$"; compare to E866/NuSea & HERA-B
- Lourenco, Vogt, Woehri - arXiv:0901.3054

- common trend, with large increasing effective breakup cross section at large positive rapidity
- need additional physics in CNM model – e.g. initial-state dE/dx

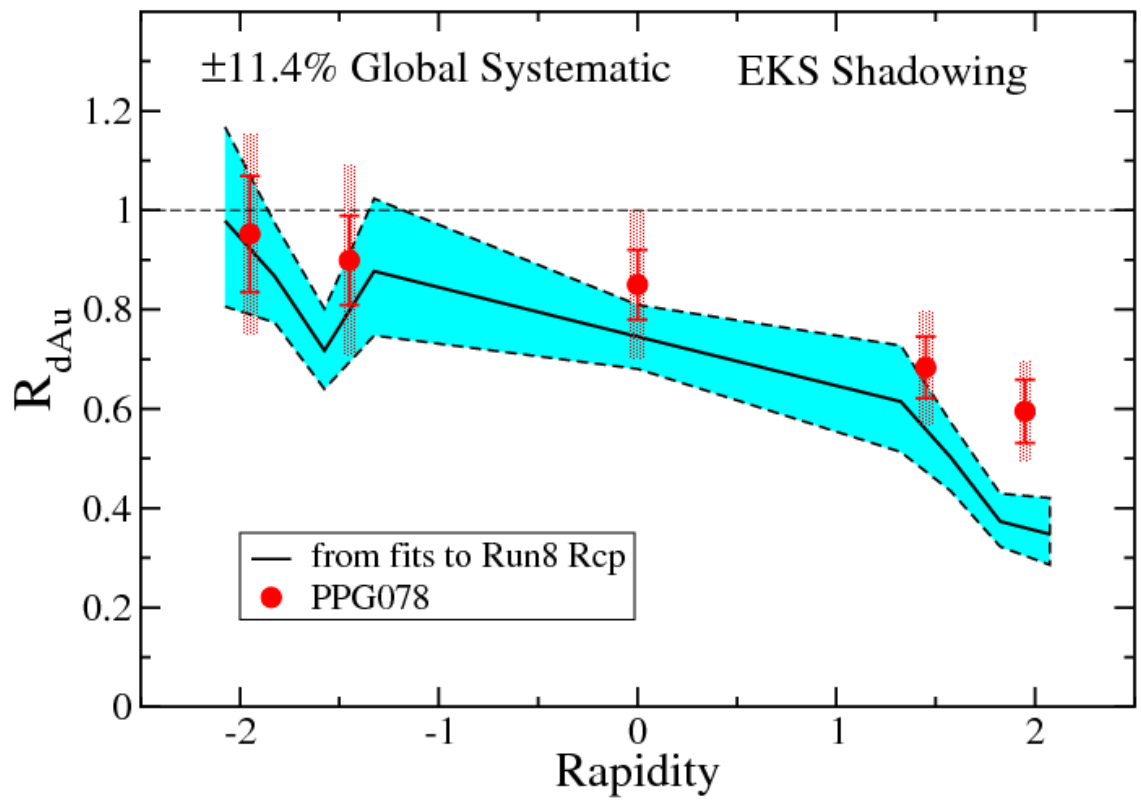
more on this in Tony' Frawley's talk



Comparision of New Effective Breakup Cross Section fits to published 2003 d+Au R_{dAu} Results

Fairly consistent with RdAu from old 2003 data

- *PRC 77,024912(2008)*

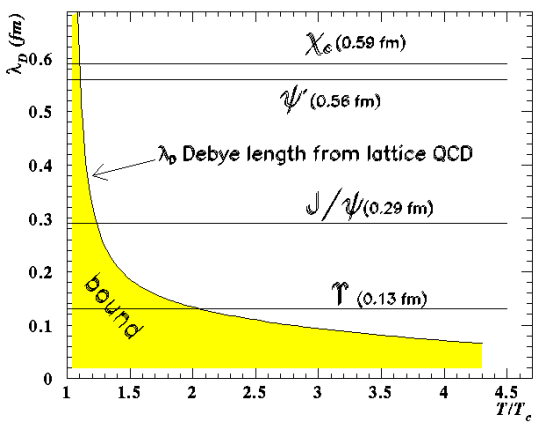


Quarkonia in the QGP
A+A Collisions at RHIC

Quarkonia & Deconfinement

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

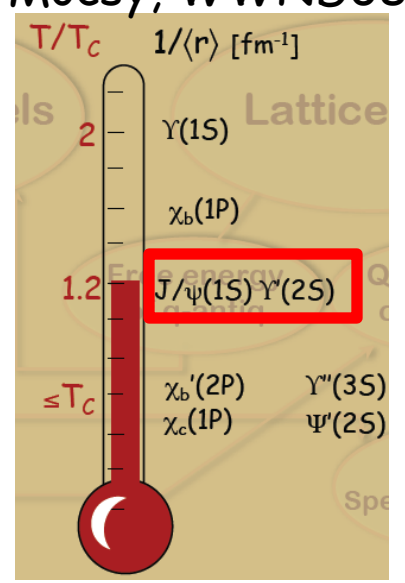
- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks
- Is there deconfinement? → look for Quarkonia screening



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

RHIC: T/T_C ~ 1.9 or higher

Mocsy, WWND08



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

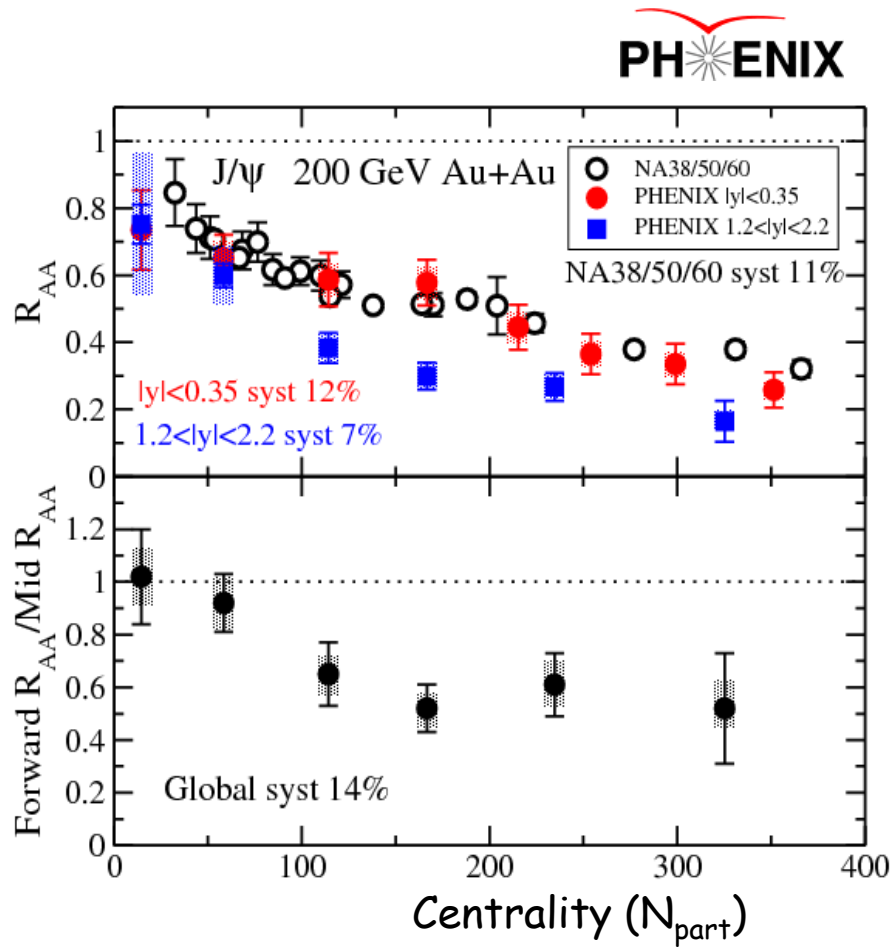
Satz, hep-ph/0512217

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

PHENIX A+A Data and Features

PHENIX Au+Au data shows suppression at mid-rapidity about the same as seen at the SPS at lower energy

- but stronger suppression at forward rapidity.
- Forward/Mid R_{AA} ratio looks flat above a centrality with N_{part} = 100



Several scenarios may contribute:

- Cold nuclear matter (CNM) effects
  - important, need better constraint
- Sequential suppression
  - QGP screening only of χ_c & ψ'- removing their feed-down contribution to J/ψ at both SPS & RHIC
- Regeneration models
  - give enhancement that compensates for screening

Reaching Higher p_T for J/ψ - probing for the "hot wind"?

New PHENIX R_{CuCu} out to p_T = 9 GeV/c !

- shows large suppression that looks roughly constant up to high p_T
- STAR points with their huge uncertainties were misleading

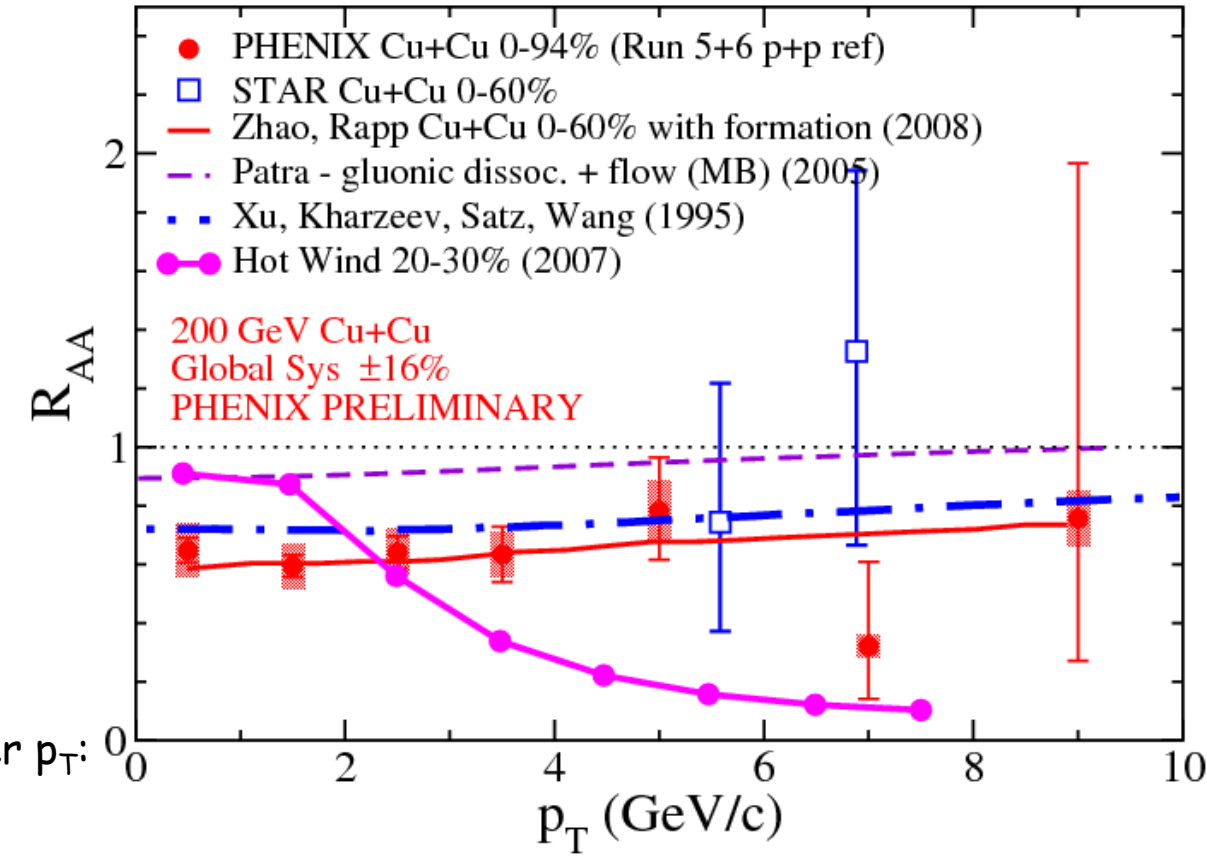
AdS/CFT ("hot wind") - more suppression at high p_T:
Liu, Rajagopal, Wiedemann
PRL 98, 182301(2007)

Regeneration (2-compenent):
Zhao, Rapp
hep-ph/07122407
& private communication

Equilibrating Parton Plasma:
Xu, Kharzeev, Satz, Wang,
hep-ph/9511331

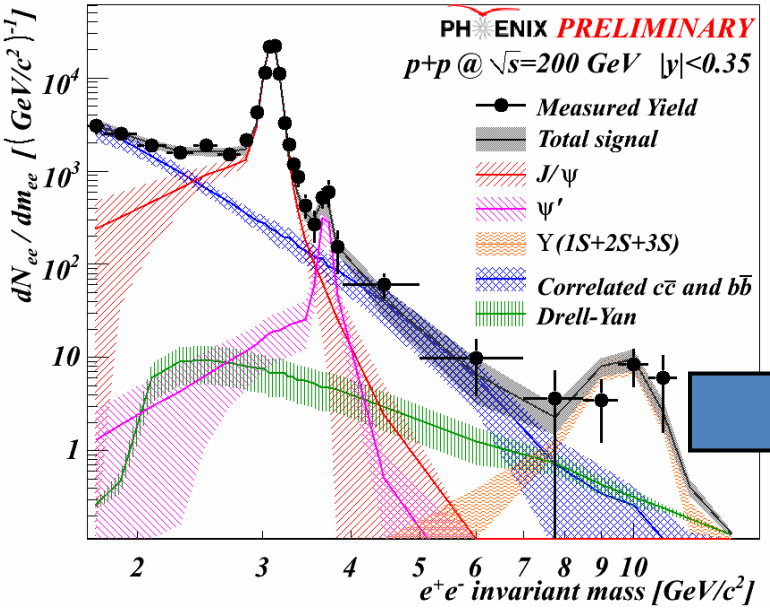
Gluonic dissoc. & flow:
Patra, Menon, *nucl-th/0503034*

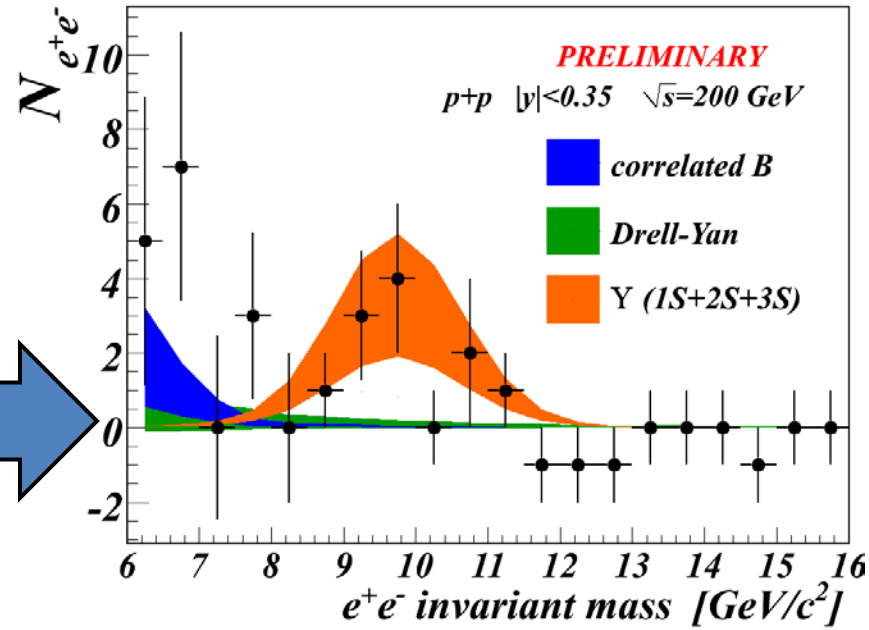
Cronin – less suppression at higher p_T:
use d+Au data as a guide



Upsilons at RHIC & Fermilab

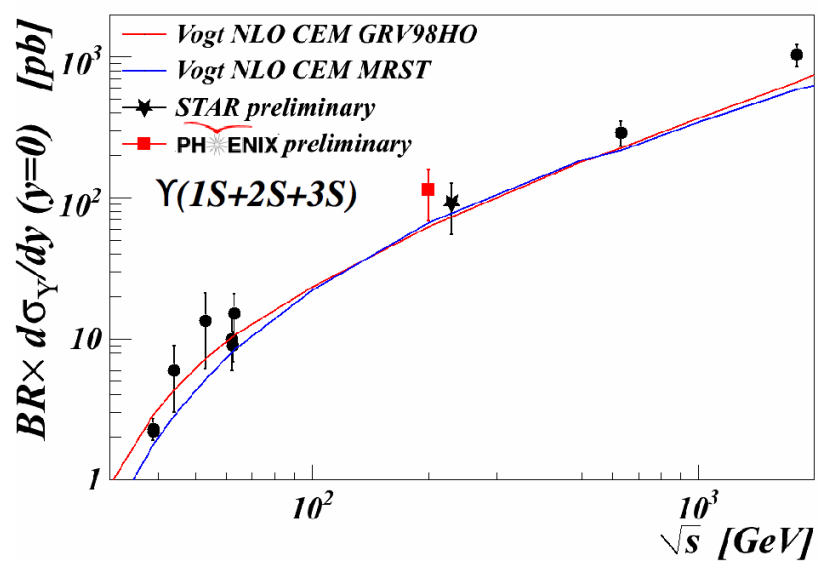
Quarkonia Production & Suppression – Upsilons in p+p



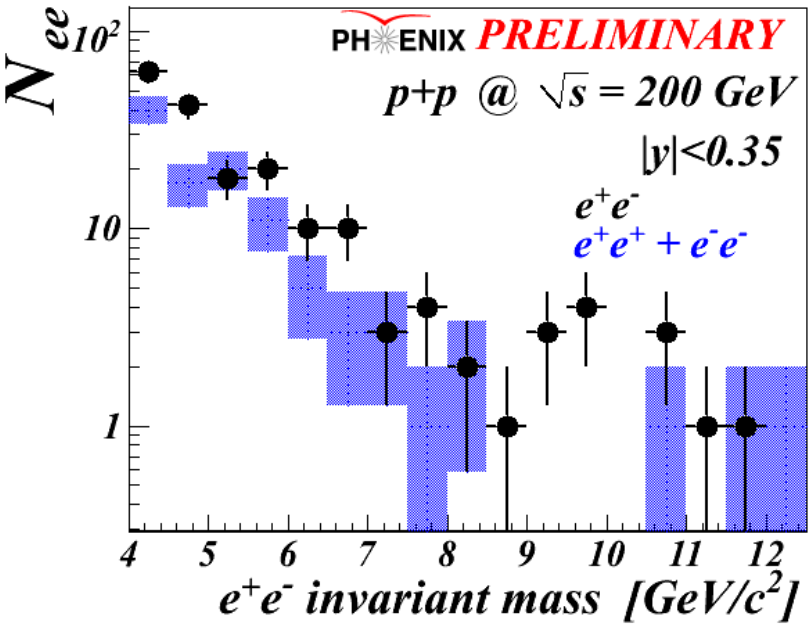


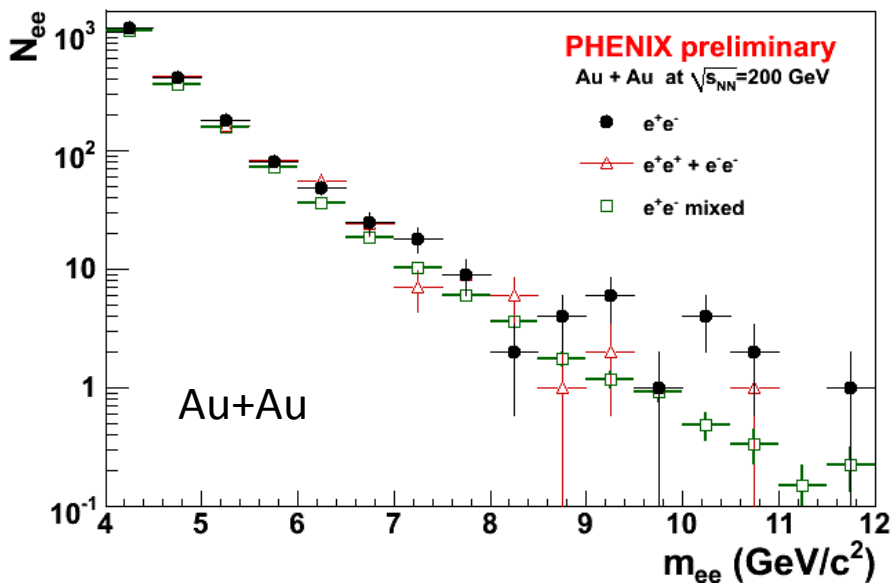
- Cross section follows world trend
- Baseline for Au+Au

$$BR * \frac{d\sigma}{dy}\Big|_{|y|<0.35} = 114^{+46}_{-45}\ pb$$

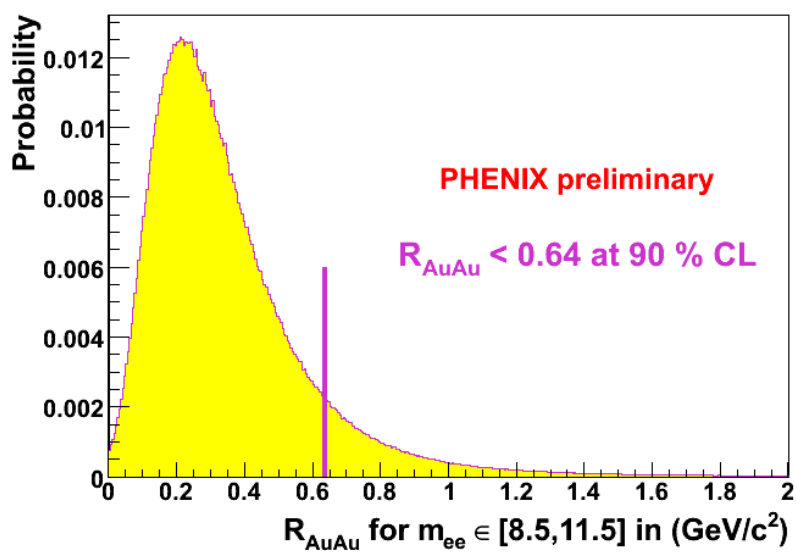


Quarkonia – Upsilons Suppressed in Au+Au





	p+p	Au+Au
N[8.5,11.5]	10.5(+3.7/-3.6)	11.7(+4.7/-4.6)
$N_{J/\psi}$	2653 ±70±345	4166 ±442(+187/-304)
$R_{AA}(J/\Psi)$	---	0.425 ±0.025±0.072



R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.

--- Includes $\Upsilon_{1S+2S+3S}$ ---

Should Υ's be Suppressed?

Υ's long touted as a standard candle for quarkonia melting - *but what should we really expect?*

	$R_{AuAu}(y=0)$
J/Ψ	0.425 ± 0.025 ± 0.072
M_{e+e-}= [8.5,11.5 GeV]	< 0.64 at 90% C.L.

- σ_{abs} of Υ ~1/2 of that for J/Ψ – E772 (*PRL 64, 2479 (1990)*)
  - E772 Υ nuclear dependence corresponds to $R_{AuAu} = 0.81^2$
- Lattice expectations in Au+Au - Υ_{2S+3S} destroyed: $R_{AuAu} = 0.73$
- so absorption x lattice ~ $0.73 \times 0.81^2 \sim 0.48$??? – but need serious theory estimate instead of this naïve speculation!
  - e.g. Grandchamp et al. hep-ph/0507314

Other considerations:

- Υ in anti-shadowing region (for mid-rapidity)
- CDF: 50% of Υ from χ_b for p_T>8 GeV/c - but less (25%?) at our p_T
  - *CDF, PRL84 (2000) 2094, hep-ex/9910025*

Grandchamp et al., hep-ph/0507314
Phys.Rev.C73:064906,2006

prompt $\Upsilon(1s)$	$\sim 51\%$,
$\Upsilon(1s)$ from $\chi_b(1P)$ decays	$\sim 27\%$,
$\Upsilon(1s)$ from $\chi_b(2P)$ decays	$\sim 10\%$,
$\Upsilon(1s)$ from $\Upsilon(2s)$ decays	$\sim 11\%$,
$\Upsilon(1s)$ from $\Upsilon(3s)$ decays	$\sim 1\%$.

TABLE I: Decomposition of the inclusive Υ yield into prompt and feeddown contributions from excited bottomonia in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 39$ GeV [43].

- Suppression of direct Υ's due to color screening
- Loss of feeddown contributions from more easily destroyed excited bottomonia
- but negligible regeneration (at RHIC)

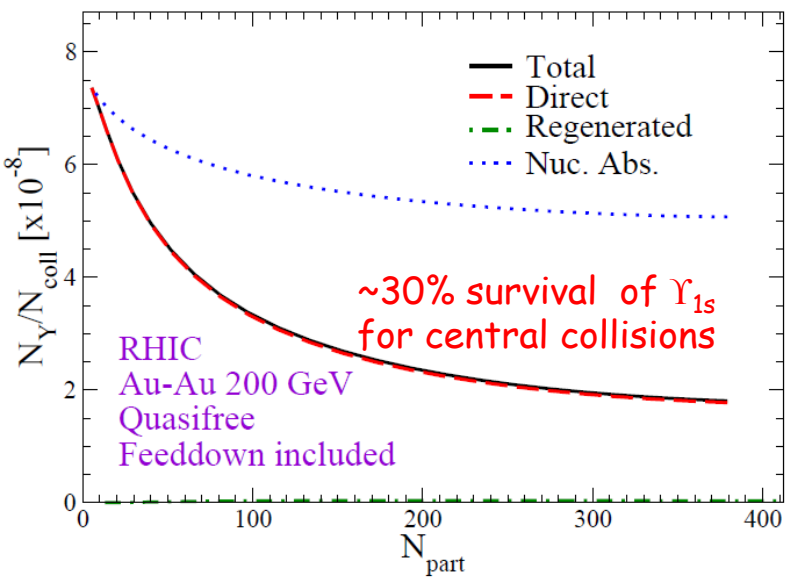
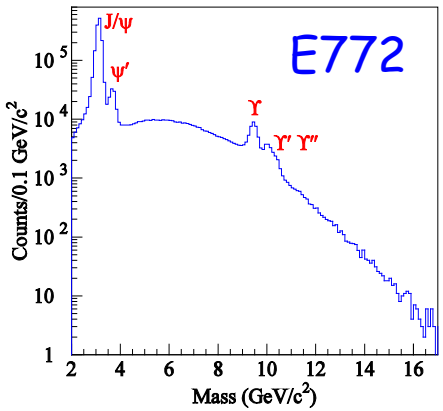


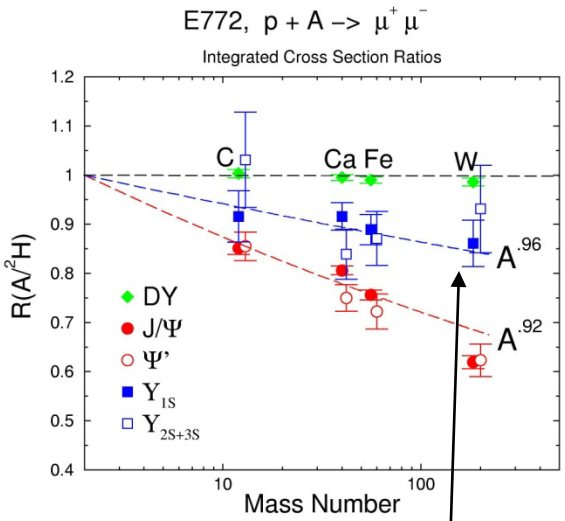
FIG. 14: (Color online) Centrality dependence of $N_\Upsilon/N_{\rm coll}$ at RHIC (Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV) using the quasifree suppression mechanism including color-screening. Dashed line: suppressed primordial Υ. Dash-dotted line: regenerated Υ. Solid line: total Υ.

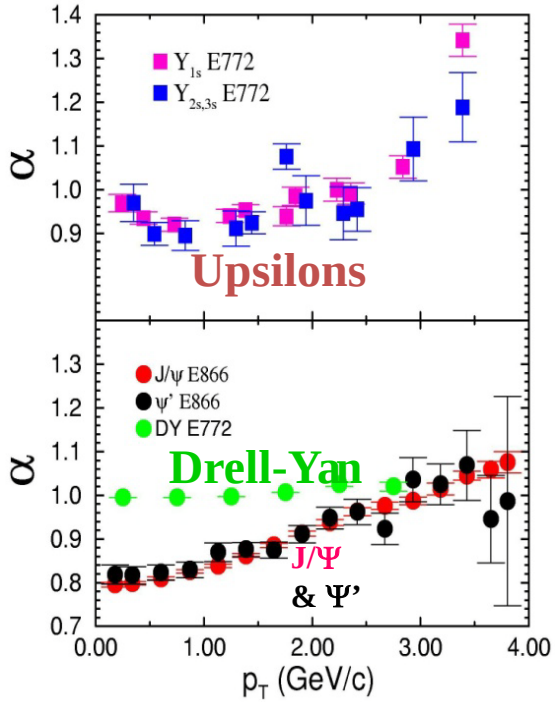
Contrasting ϒ's with J/Ψ's



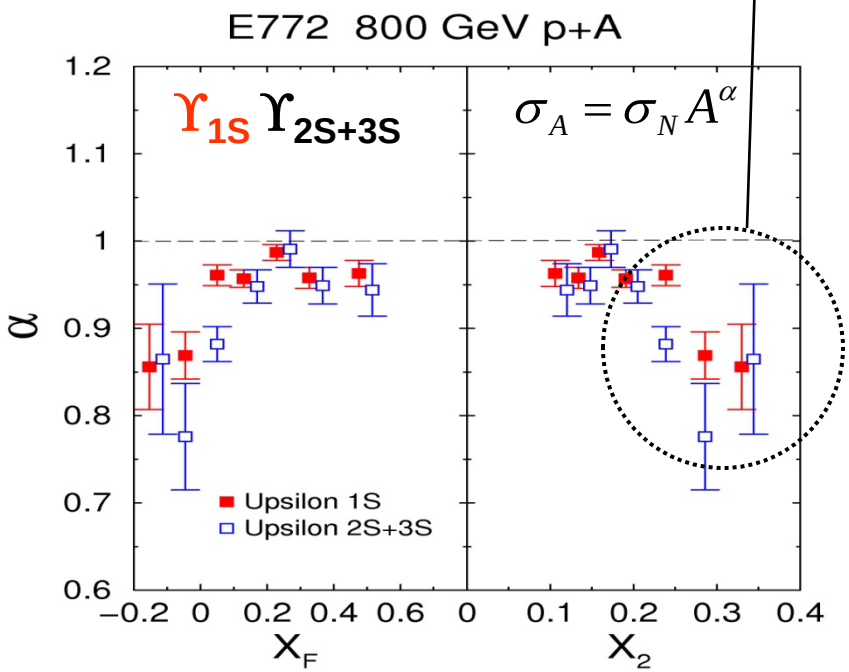
$\sqrt{s}$ =39 GeV (E772 & E866)

- less absorption
- not in shadowing region (large x_2)
- similar p_T broadening
- Υ_{2S+3S} have large transverse polarization - unlike Υ_{1S} or J/ψ (as was shown earlier)





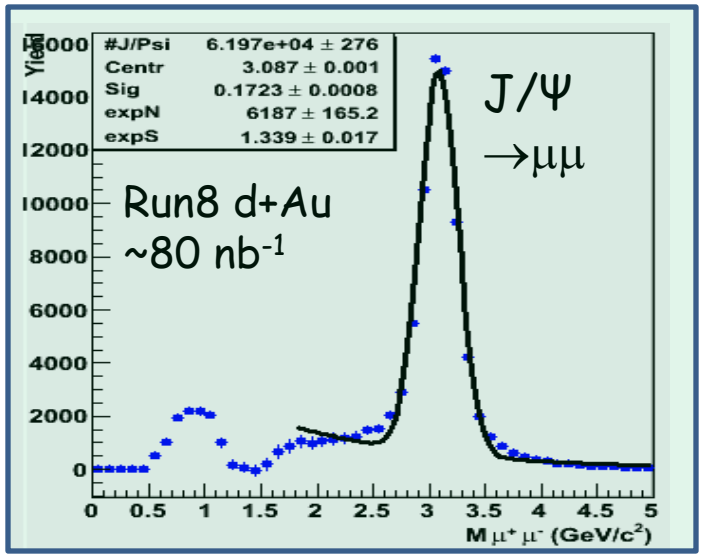
But careful: ϒ suppression includes data for $x_2 > 0.1$

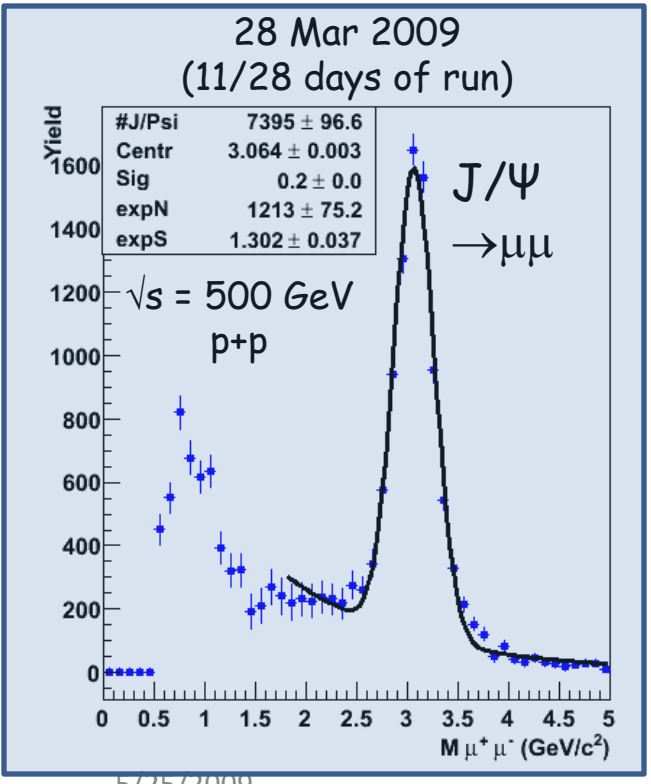


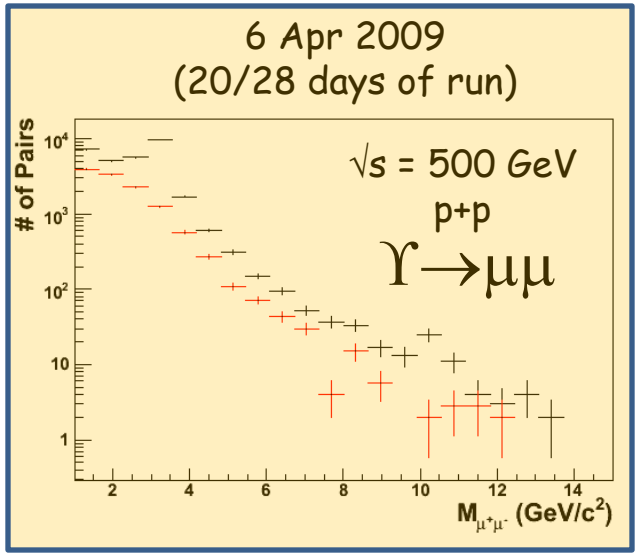
Recent PHENIX J/Ψ→μμ data sets

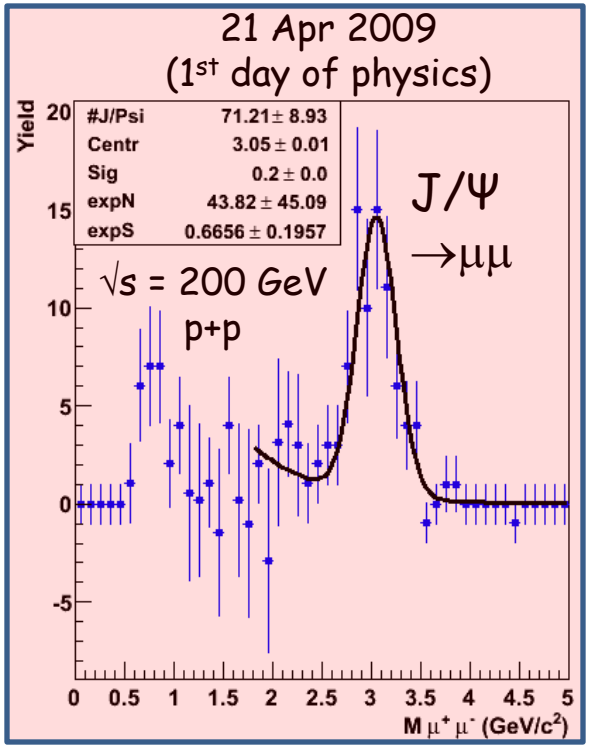
Run9 p+p now ongoing, with longitudinal polarization:

- 28 days of 500 GeV
- ~64 days of 200 GeV









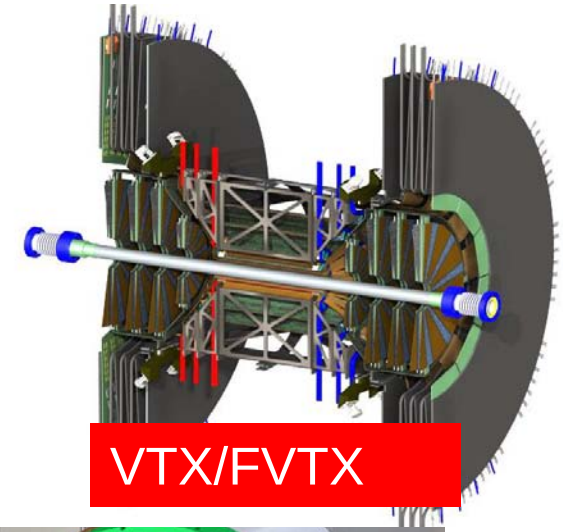
Upgrades & Quarkonia at PHENIX

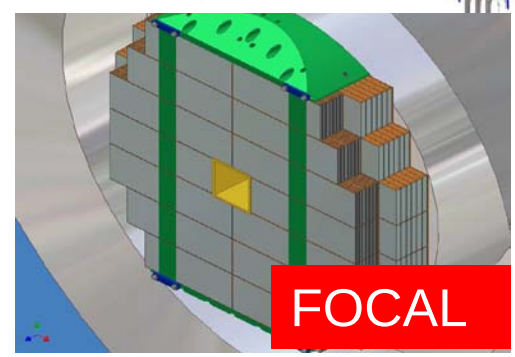
Vertex Detectors (VTX & FVTX)
- better $\Upsilon \rightarrow$ e+e- mass resolution & background at mid-rapidity
- separation of Ψ' from J/Ψ & reduction of backgrounds at forward-rapidity ($\mu^+\mu^-$)
- $B \rightarrow J/\Psi$ X

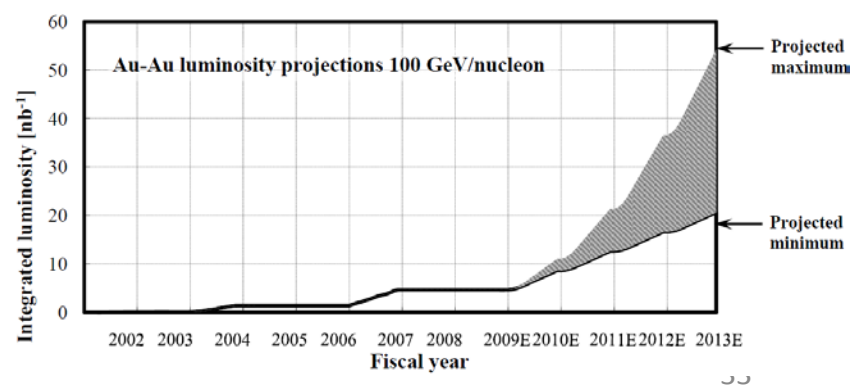
Forward Calorimetry (FOCAL)
- $\chi_c \rightarrow J/\Psi + \gamma$ in p+p & d+Au

Removing Hadron Blind Det. (HBD)
- when vertex detectors go in, HBD comes out

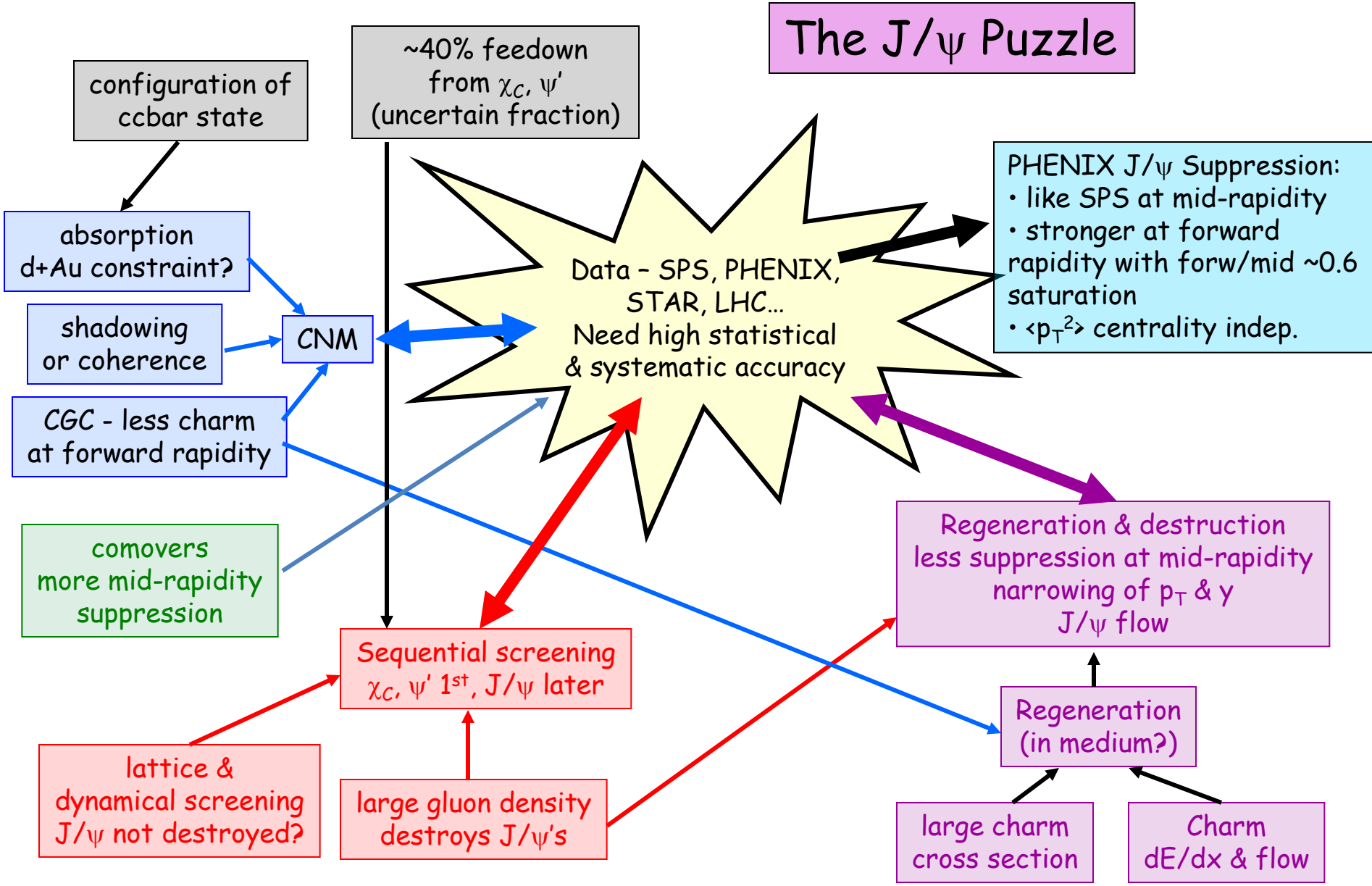
Increased machine Luminosity benefits these rare processes



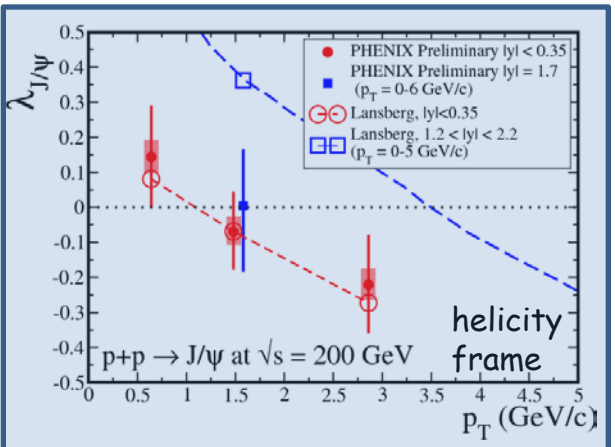




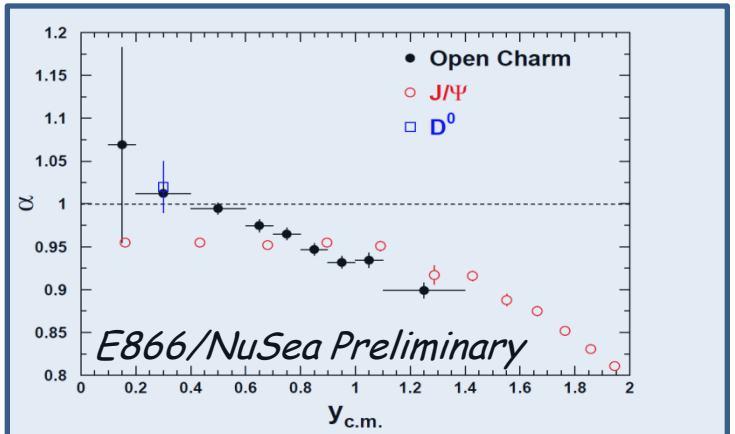
The J/ψ Puzzle



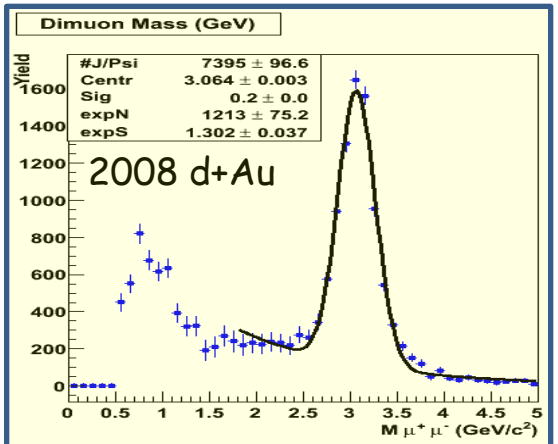
Summary



New CSM good except for forward J/Ψ polarization

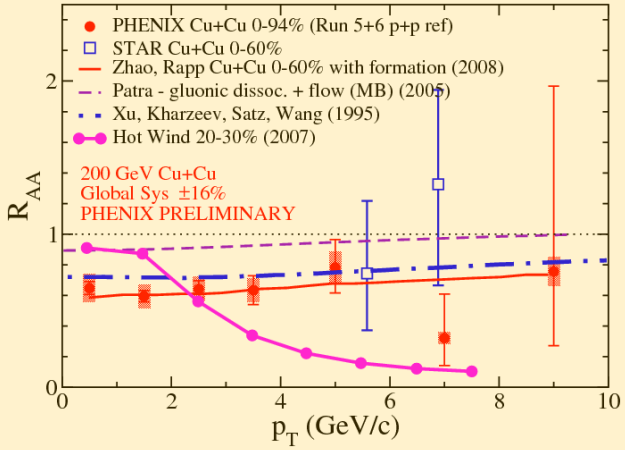


Many CNM effects possible:
- similarity of open charm → initial state
- lack of x2 scaling → not shadowing

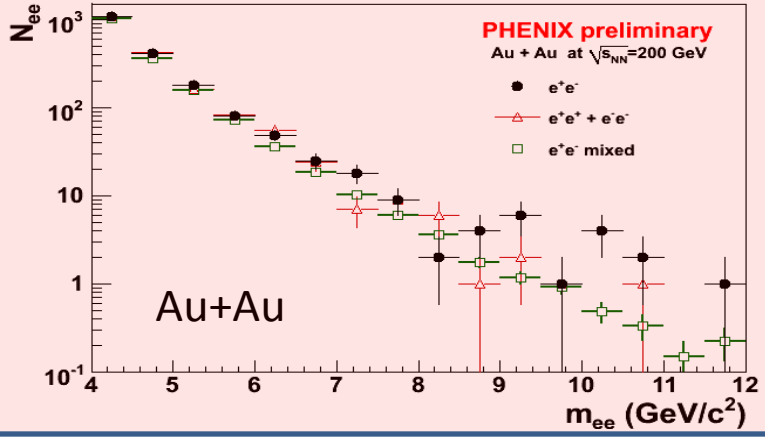


New d+Au data coming soon

High-p_T J/Ψ still Suppressed in Cu+Cu



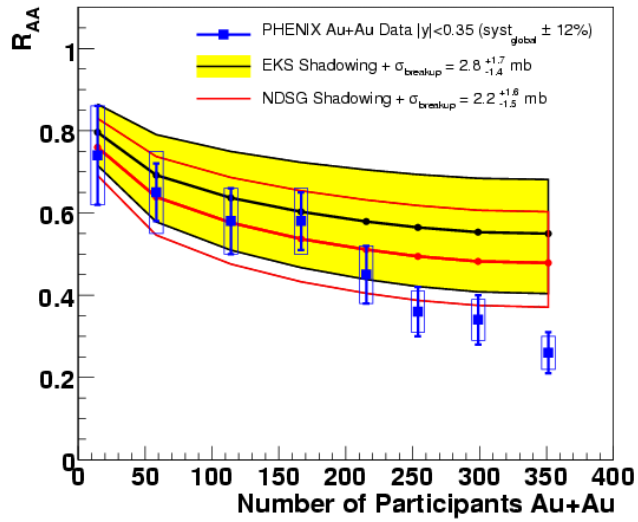
R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.
ϒ 's suppressed in Au+Au
48% expected from CNM & Υ_{2S+3S}

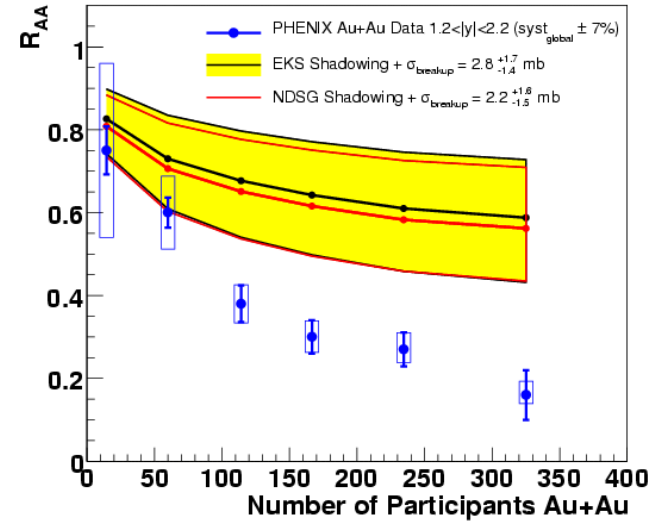


Backup

How does the QGP affect Quarkonia?
CNM Effects

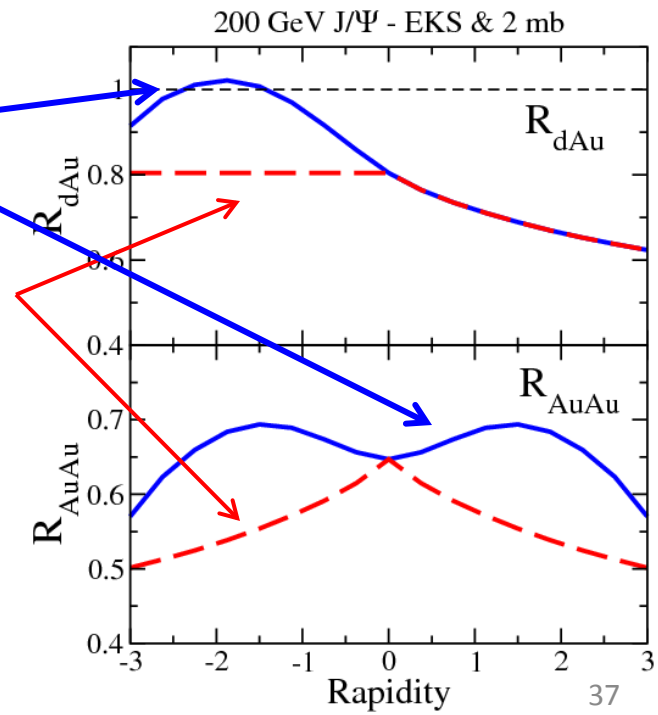
CNM effects (EKS shadowing + dissociation) give large fraction of observed AuAu suppression, especially at mid-rapidity





Normal CNM descriptions give similar AuAu suppression at mid vs forward rapidity

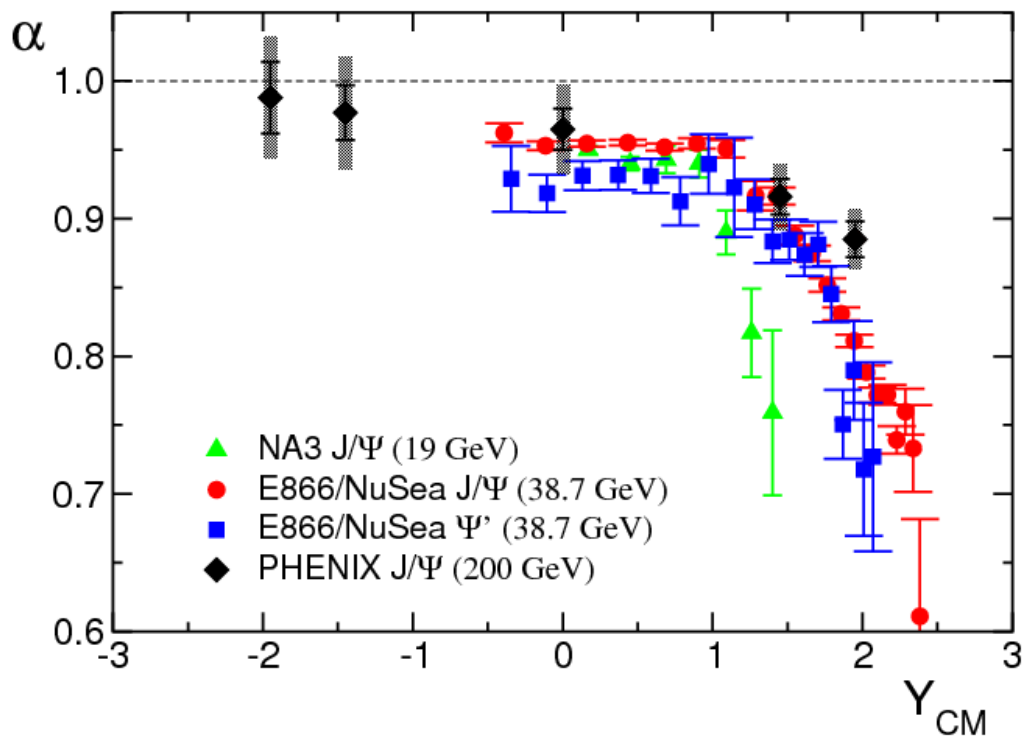
- but if peaking in "anti-shadowing" region were flat instead then one would get larger suppression for forward rapidity as has been observed in AuAu data
- could come from gluon saturation or from a shadowing prescription that has no anti-shadowing

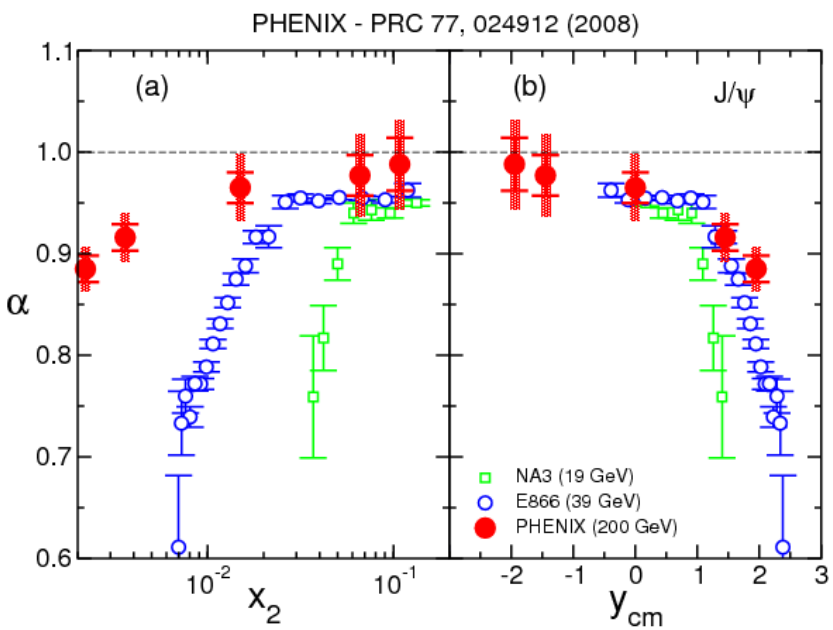


In any case more accurate dAu data is sorely needed

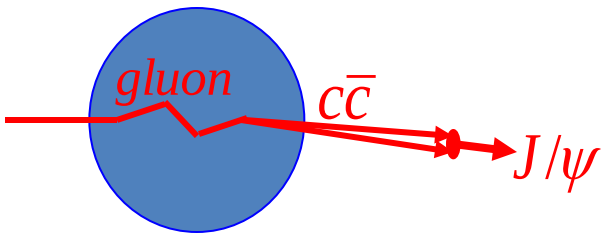
Scaling vs Y_{cm}?

- E866 & PHENIX appear to match vs y_{cm}
- but NA3 does not

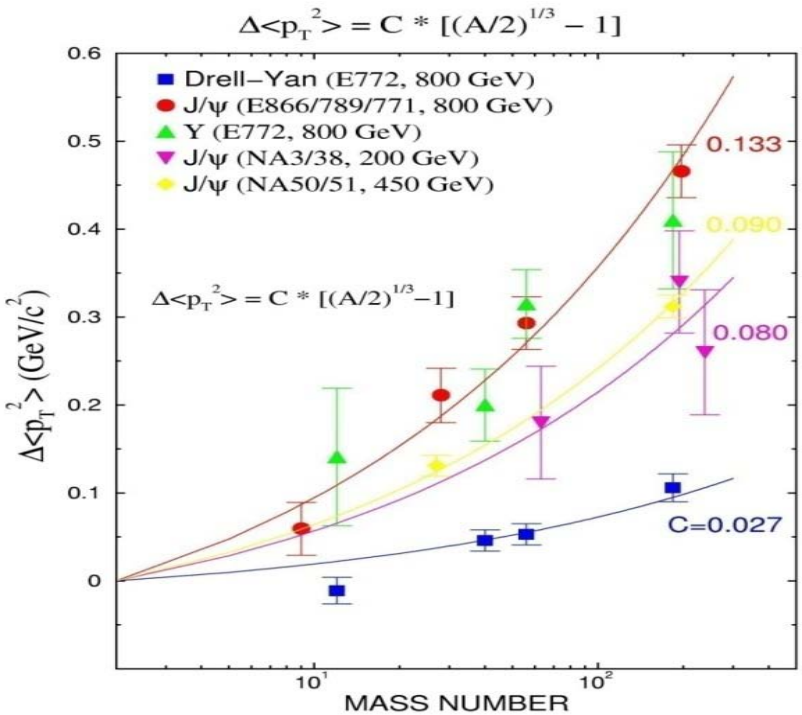




Transverse Momentum Broadening
Another Cold Nuclear Matter Effect



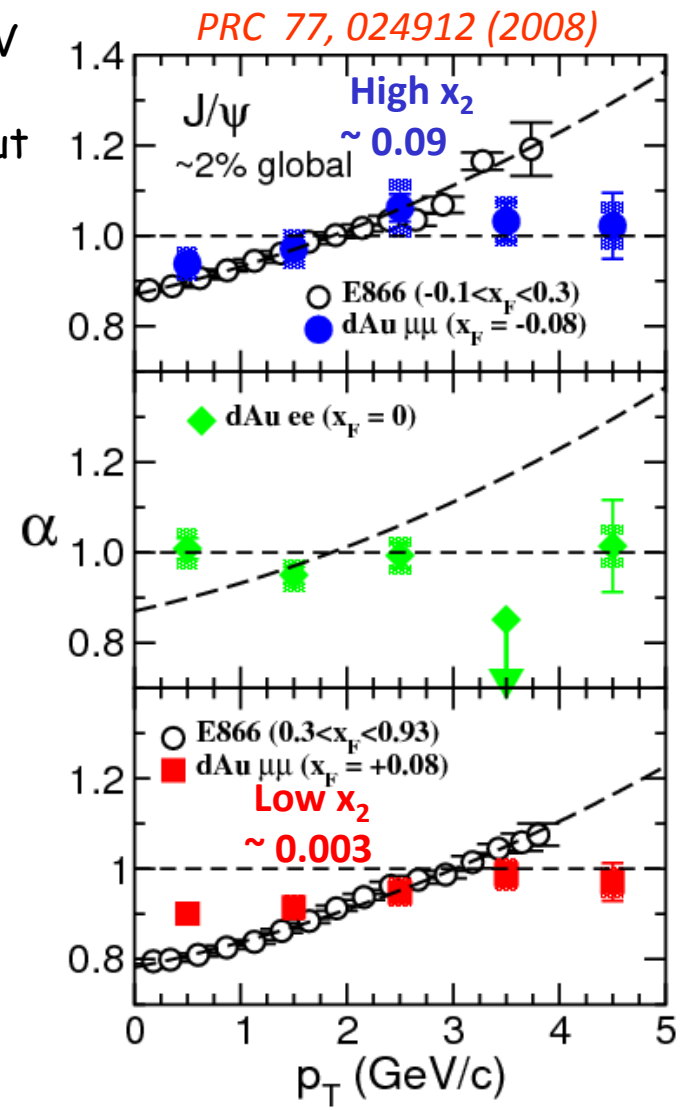
Initial-state gluon multiple scattering causes p_T broadening (or Cronin effect)



PHENIX 200 GeV dAu shows some p_T broadening, but may be flatter than at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

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

Also can be looked at in terms of $\Delta\langle p_T^2\rangle$



Open Charm Nuclear Dependence : x_F Dependence?

E769 250 GeV π PRL 70,722 (1993)

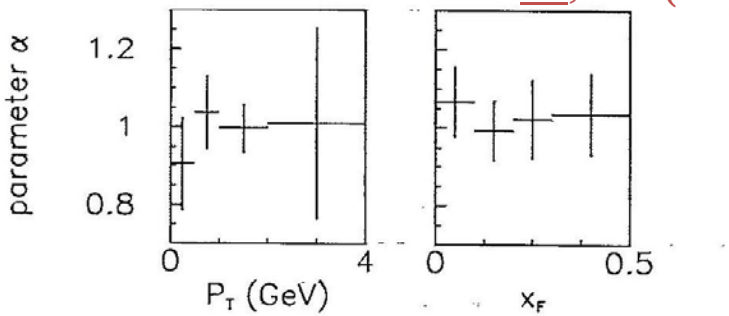


FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

WA82 340 GeV π PRB 284,453 (1992)

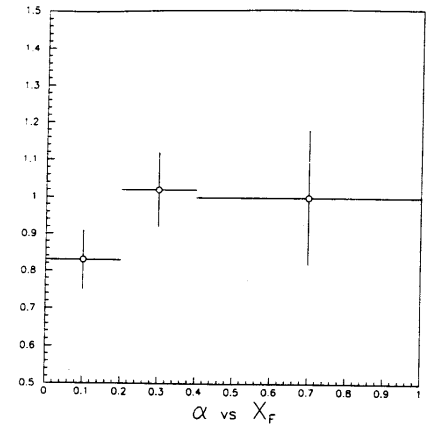
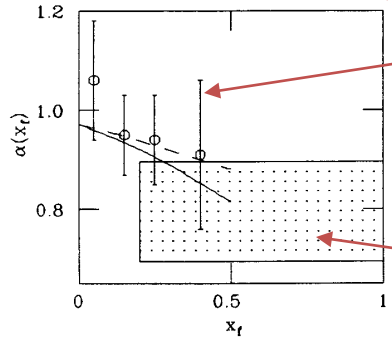


Fig. 4. The parameter α for charm production as measured in three x_F intervals.

Vogt et al., NP 383,643 (1992)



E769 250 GeV π

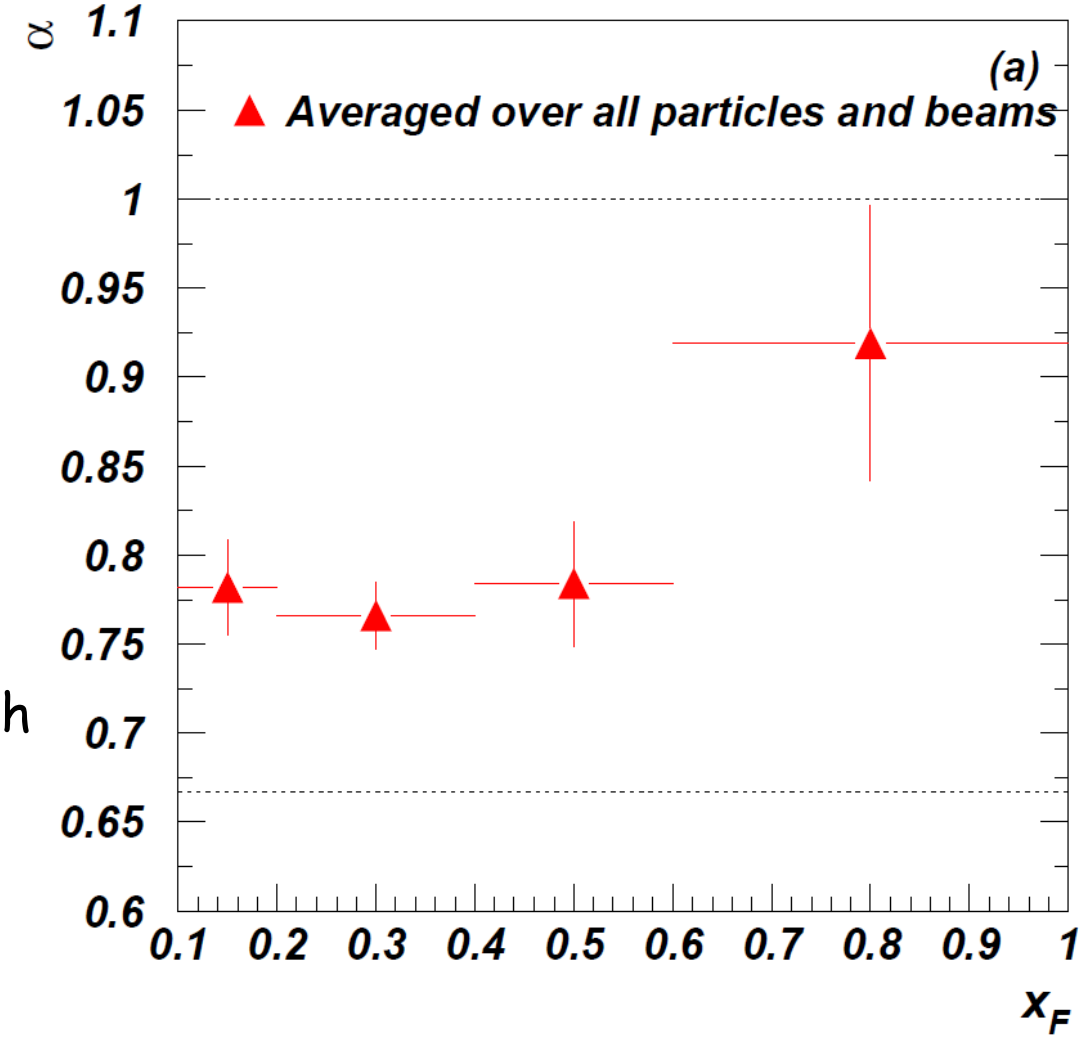
WA78 320 GeV π *(Beam dump)*

Fig. 14. We show $\alpha(x_f)$ for π^-A interactions at 300 GeV as calculated in our model. The dashed curve shows delta function fragmentation, the solid curve, the Peterson function. These results are compared to those for $D^\pm$ mesons produced by 250 GeV π^-A interactions [3] and the effective α found by the WA78 beam dump experiment [23], indicated by the band with $\langle x_f \rangle = 0.31$.

SELEX – hep-ex_0902.0355

Averaged Over:

Incident beams:
- $\pi^{\pm}$, p, Σ^{-}

Produced charmed particles:
- D^0, D^*, $D^{\pm}$, D_s
- Λ_c

Appears to be inconsistent with both E789 D^0 & E866/NuSea open charm single muon msmts