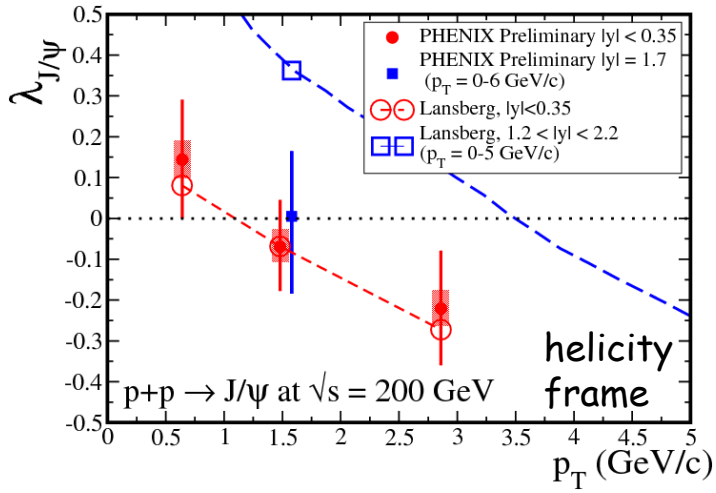
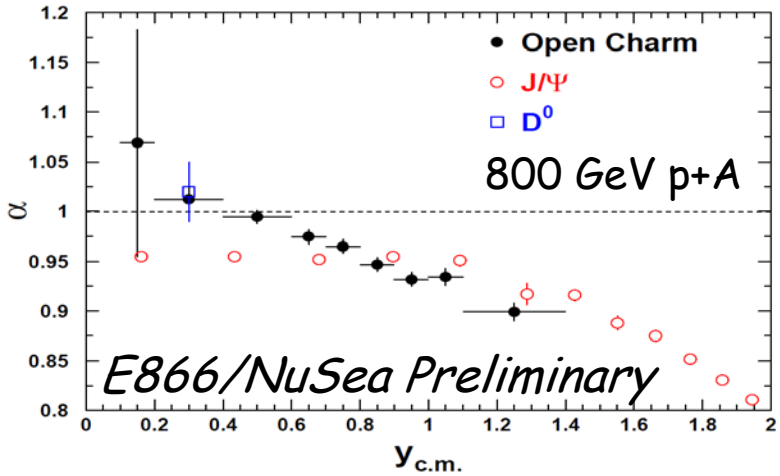
# Charmonia Production in p(d)+A and A+A Collisions

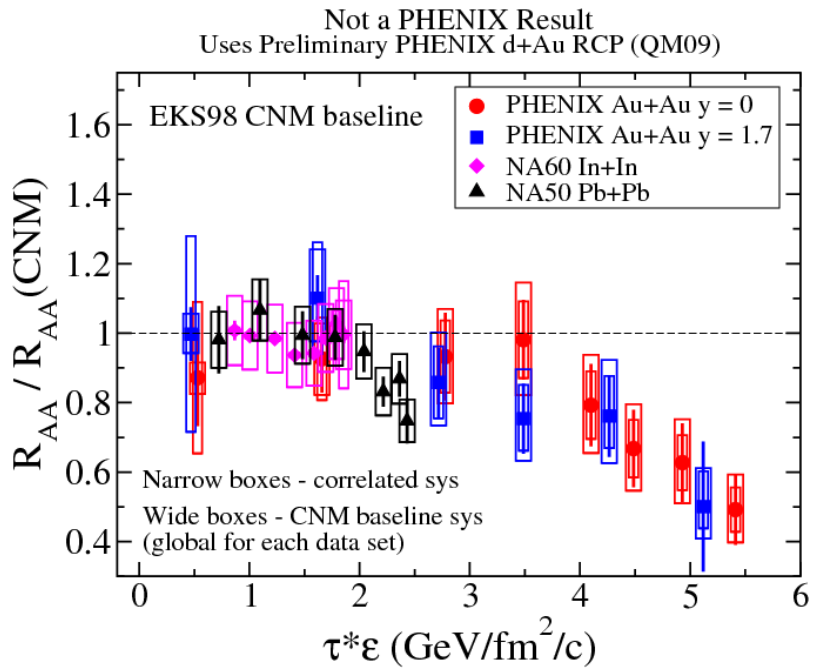
*Mike Leitch – LANL– leitch@bnl.gov*

*INT, Seattle - 16-26 June 2009*




- p+p – one comment
- p+A and d+A
- CNM in A+A & PHENIX compared to SPS

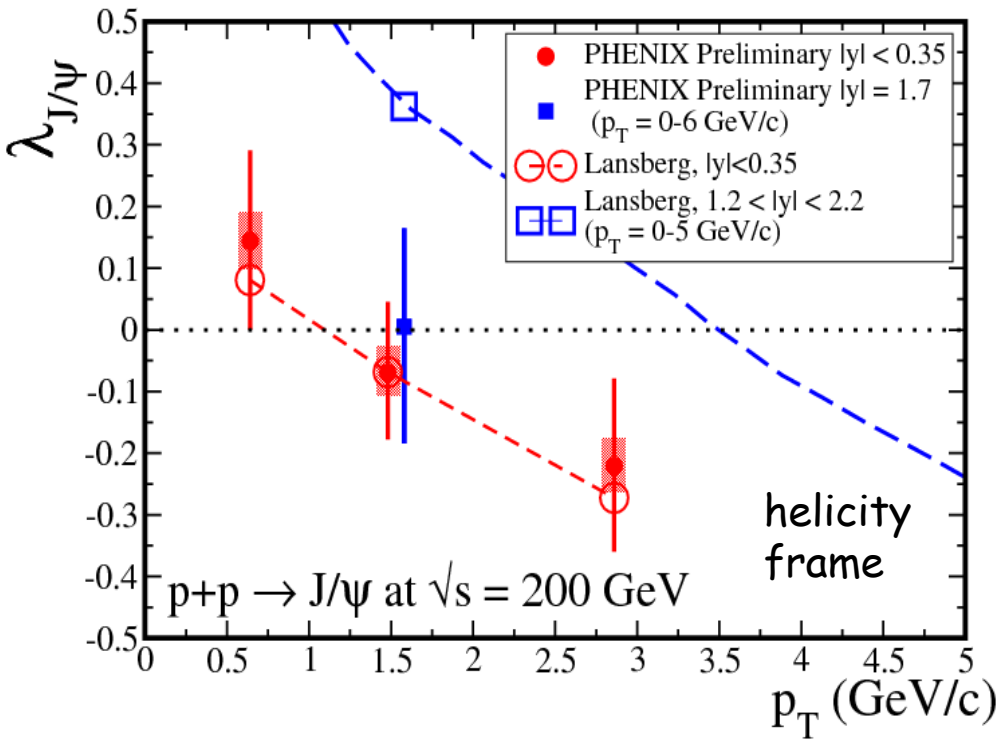


# Quarkonia Polarization
# p+p Collisions
# - One comment -

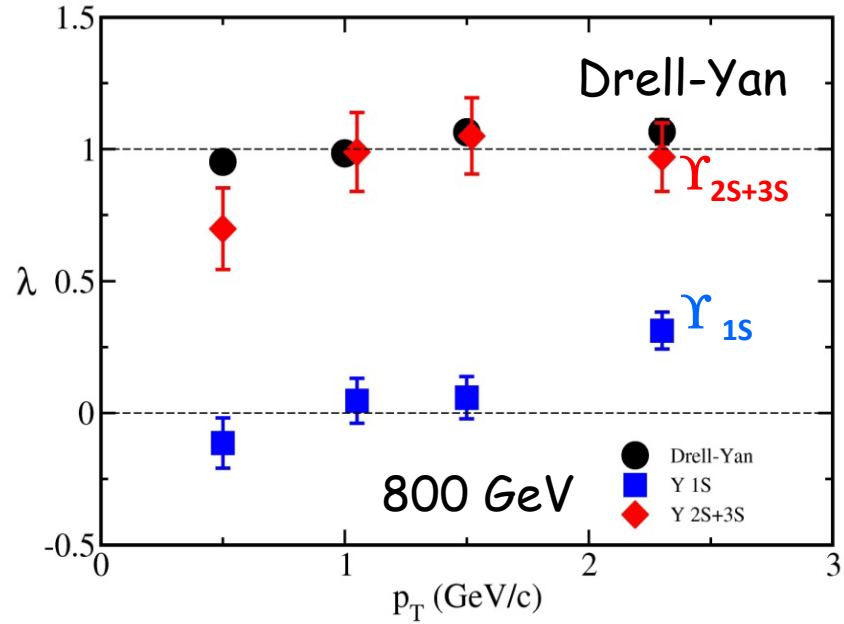
# Quarkonia Production – Polarization

*Haberzettl, Lansberg PRL 100, 032006 (2008)*




(does not include effect of feeddown from $\chi_c$ & $\psi'$)

*E866/NuSea – PRL 86, 2529 (2001)*



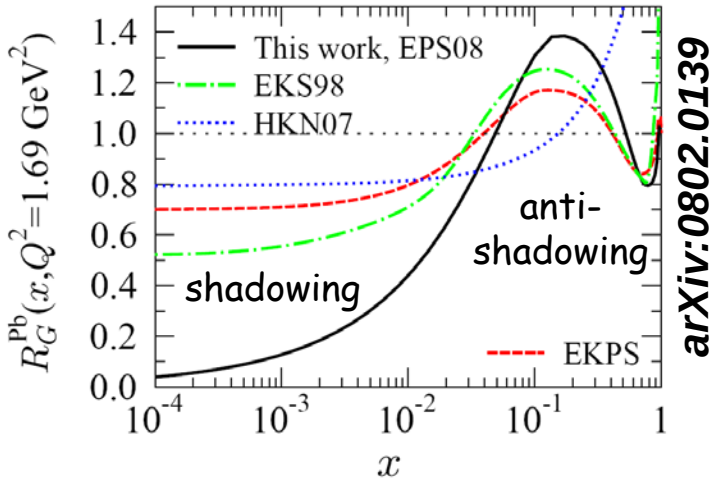

$\Upsilon$ maximally polarized for (2S+3S), but NOT for (1S)

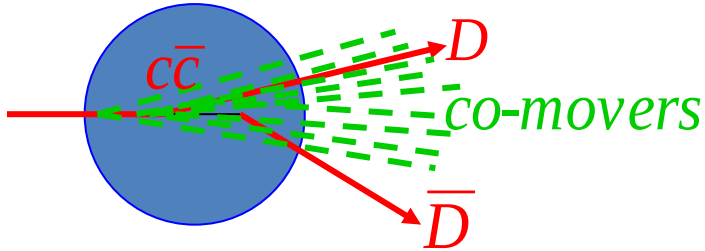
* Is feed-down washing out polarization? (~40% of 1S from feed-down)

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

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

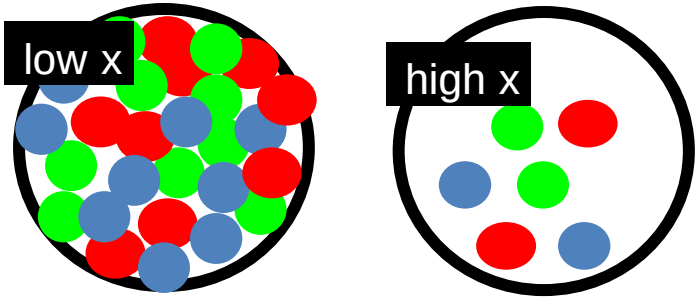
Traditional shadowing from fits to DIS or from coherence models



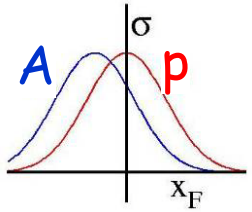



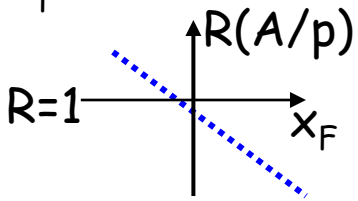

Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

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

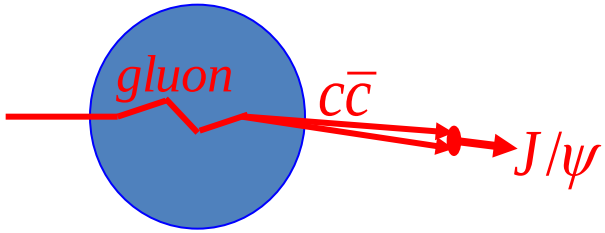



Energy loss of incident gluon shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$



# Transverse Momentum Broadening
# Another Cold Nuclear Matter Effect

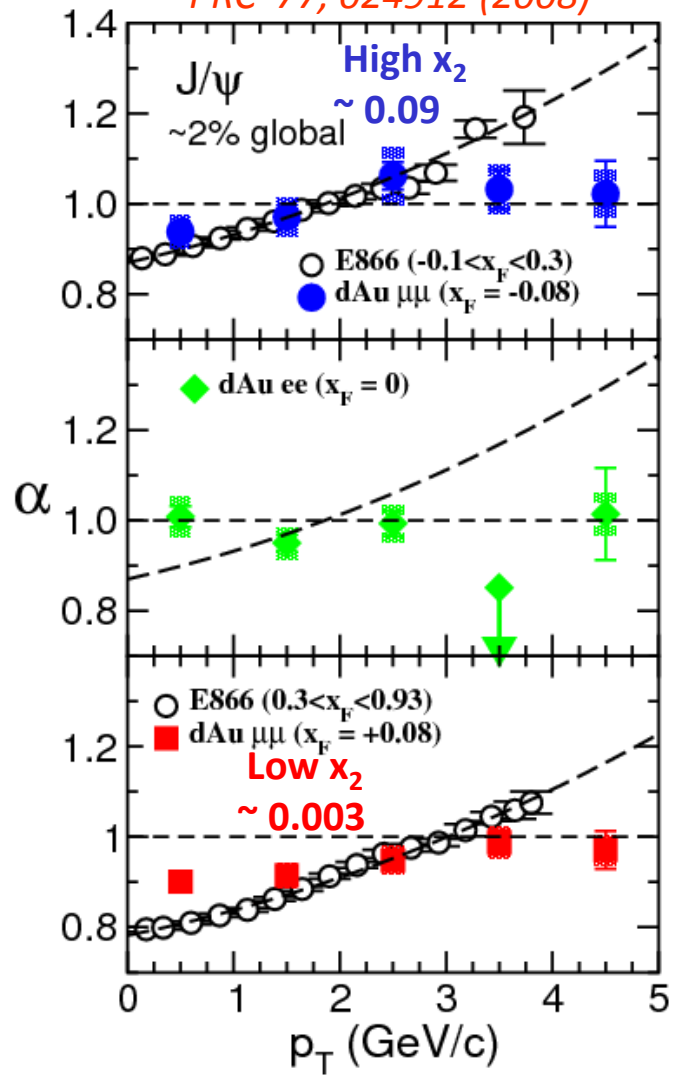



Initial-state gluon multiple scattering causes $p_T$ broadening (or Cronin effect)

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

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)*

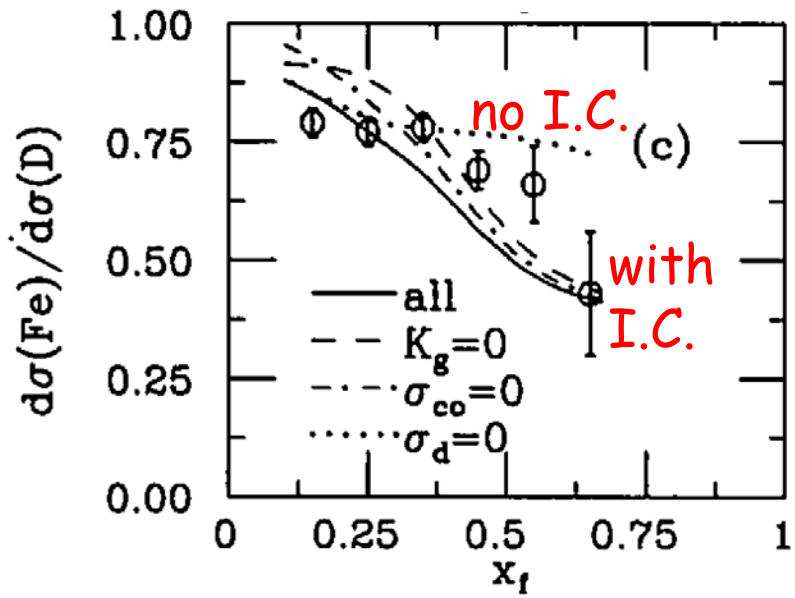


# Intrinsic charm contribution to Quarkonia

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

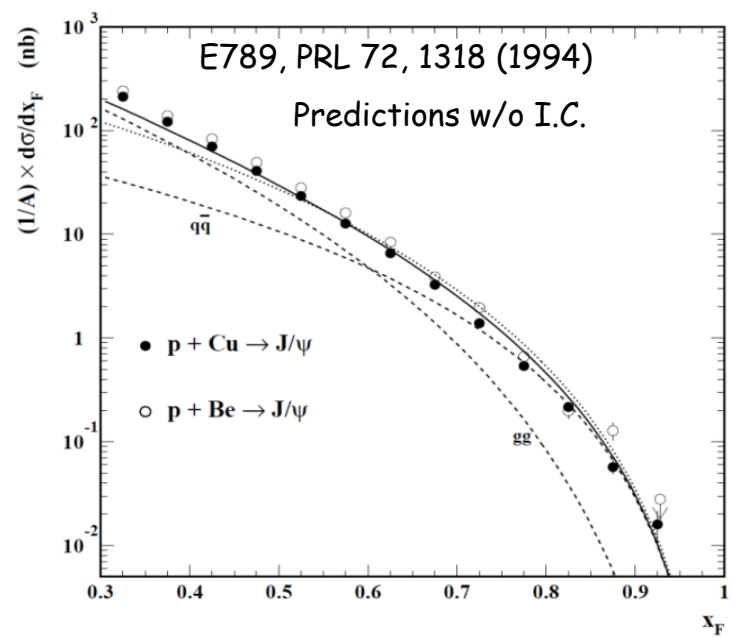
- $A^{2/3}$ dependence via surface stripping of light quarks to free charm pair component

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



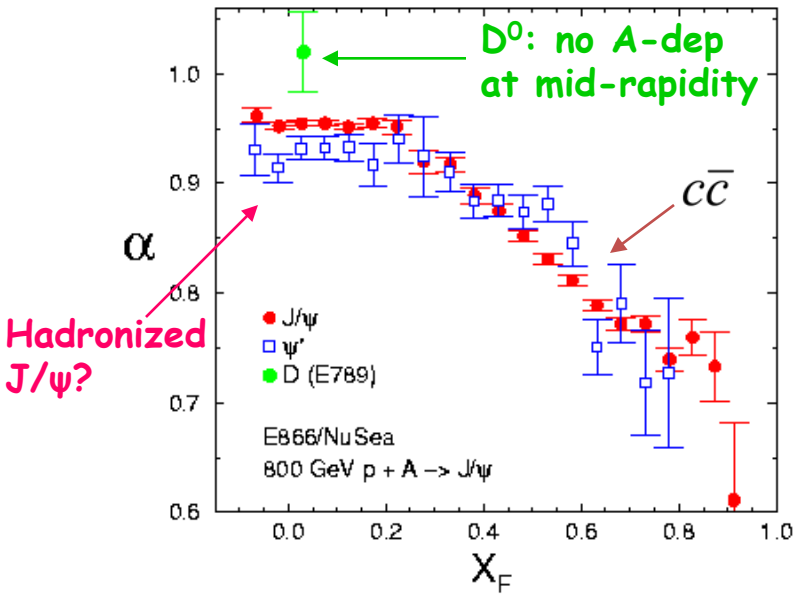

But E789 set limit on I.C. contribution via shape of cross section vs $x_F$

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

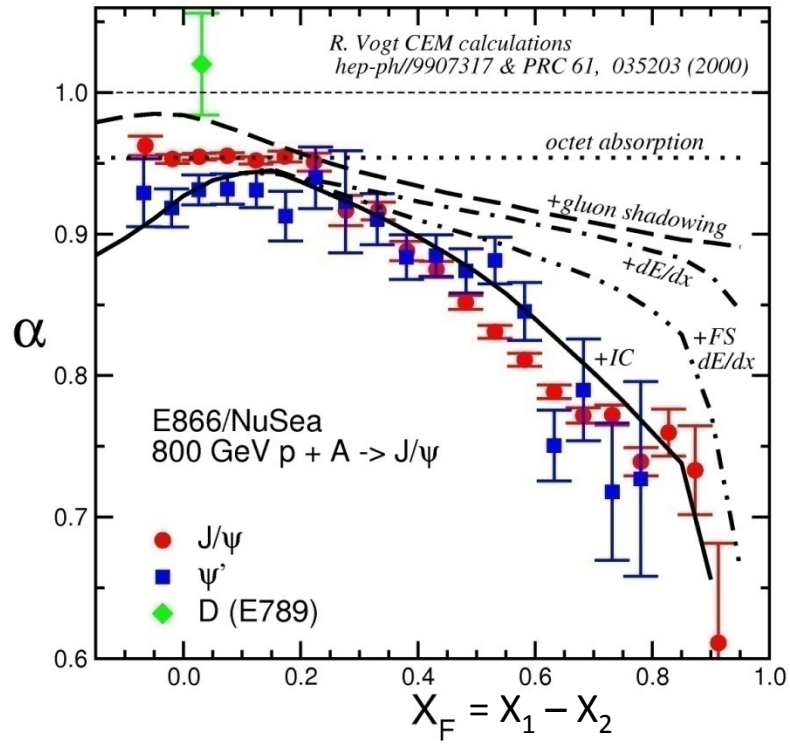


# J/ψ suppression in p+A fixed-target

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



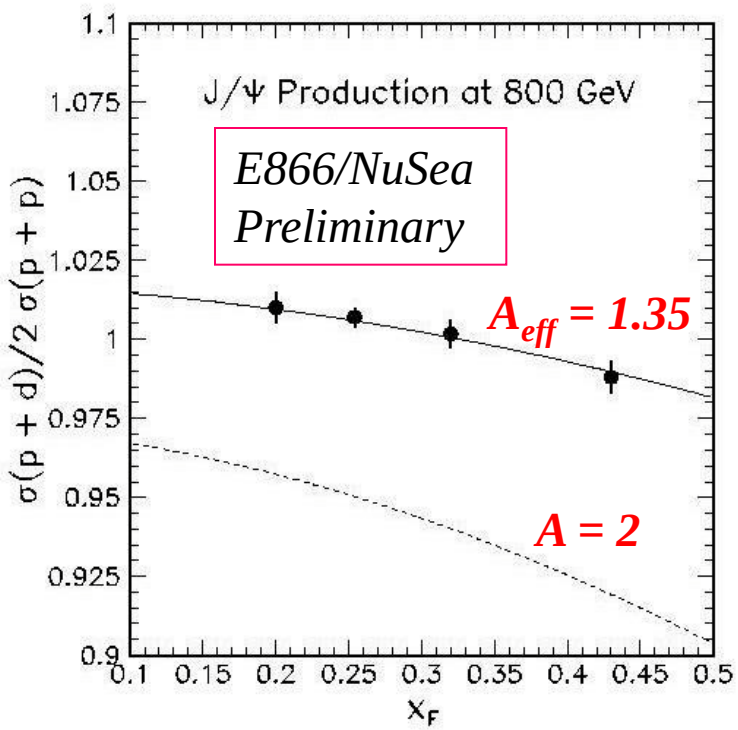

E866/NuSea, $\sigma = \sigma_N * A^{\alpha}$

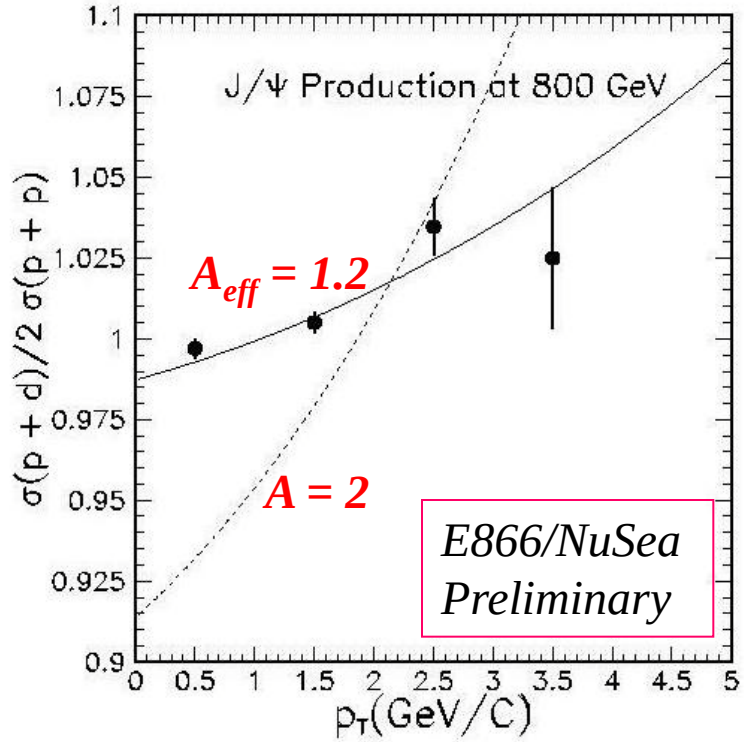



- J/Ψ and Ψ' similar at large $x_F$ where they both correspond to a $c\bar{c}$ traversing the nucleus
- Near $x_F = 0$ -- $D^0$ not suppressed, J/Ψ and Ψ' suppressed due to absorption, Ψ ' slightly stronger since both starting to become hadronized states in nucleus
- what about open charm at higher $x_F$?

Many ingredients to explain the J/ψ nuclear dependence – R. Vogt (2000)

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




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

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

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

# 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

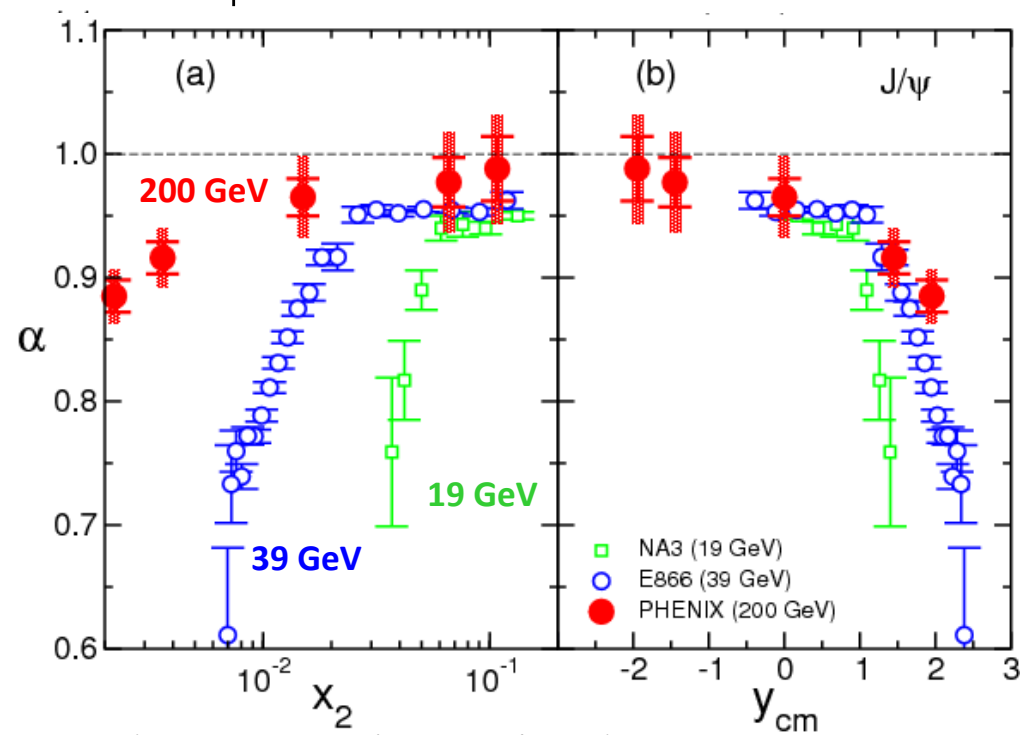
Suppression not universal vs $x_2$ as expected for shadowing, but closer to scaling with $x_F$, why?

- 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

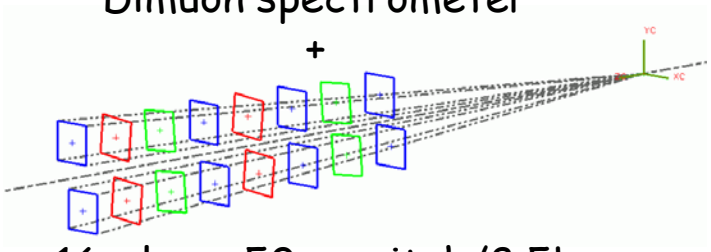



($x_2$ is x in the nucleus)

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

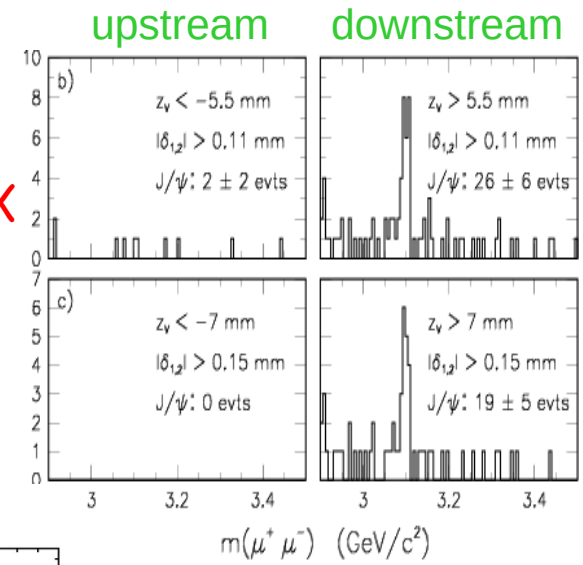
Dimuon spectrometer

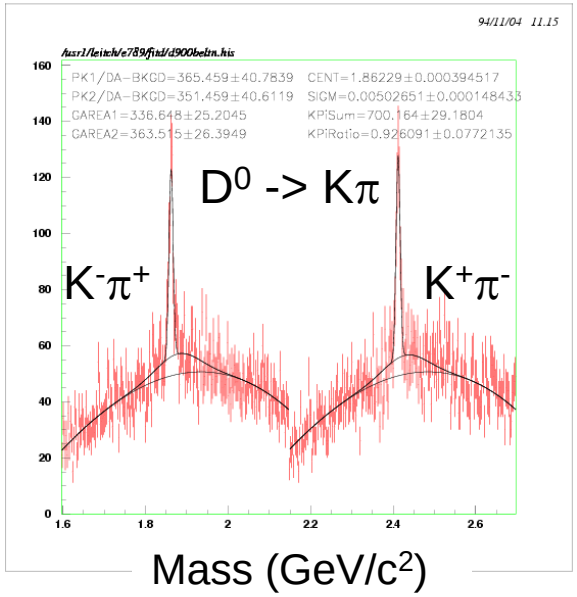
+

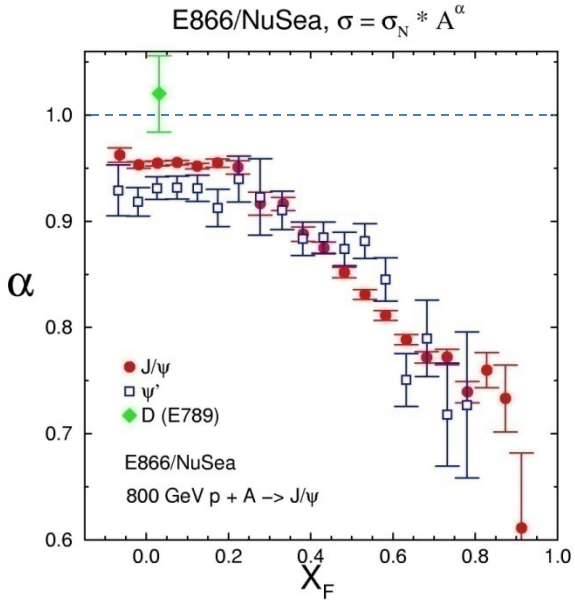


16-plane, 50μm pitch/8.5k strip silicon vertex detector

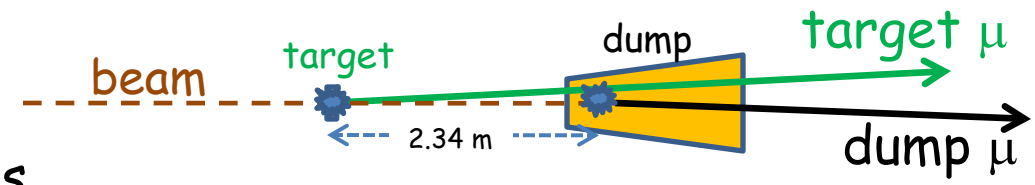
$B \rightarrow J/\psi + X$



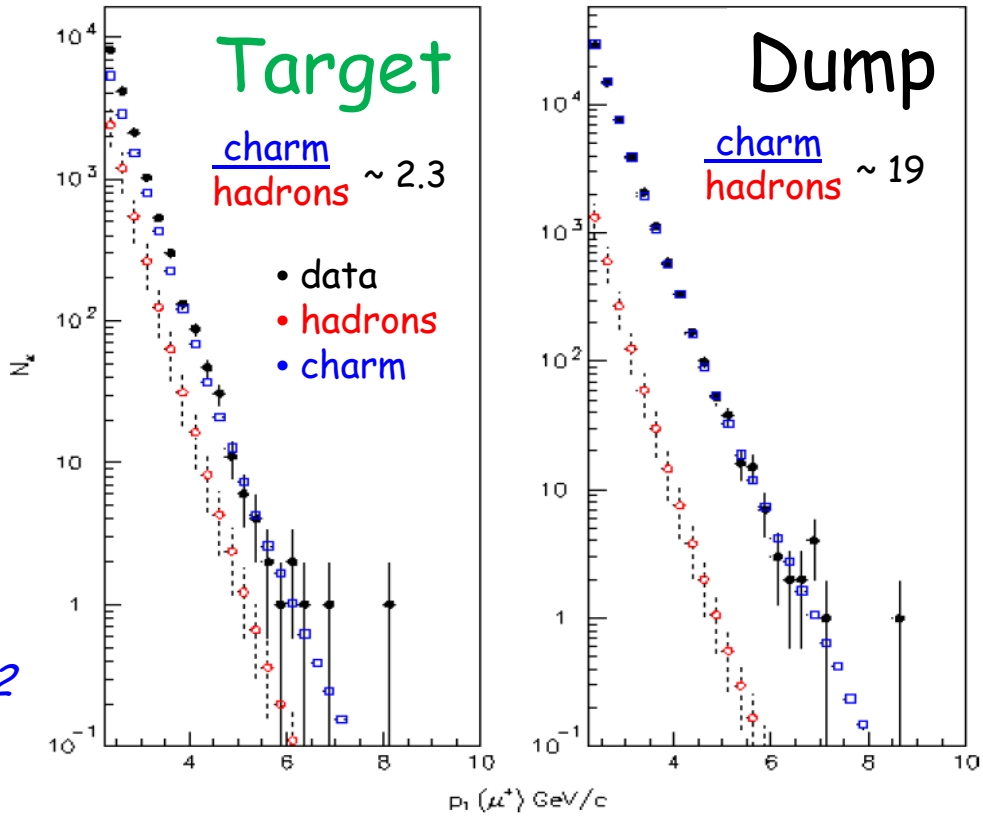



# E866/NuSea Open Charm Measurement




- 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



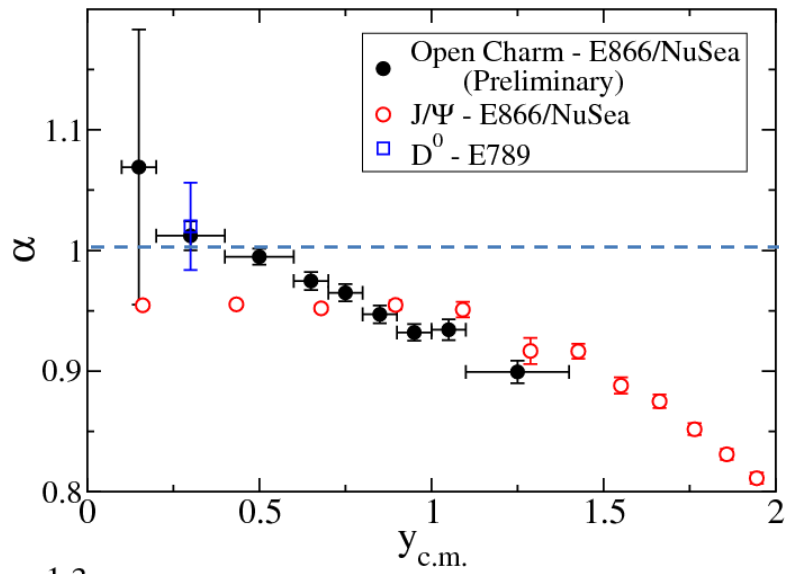

*E866/NuSea 800 GeV p+A*

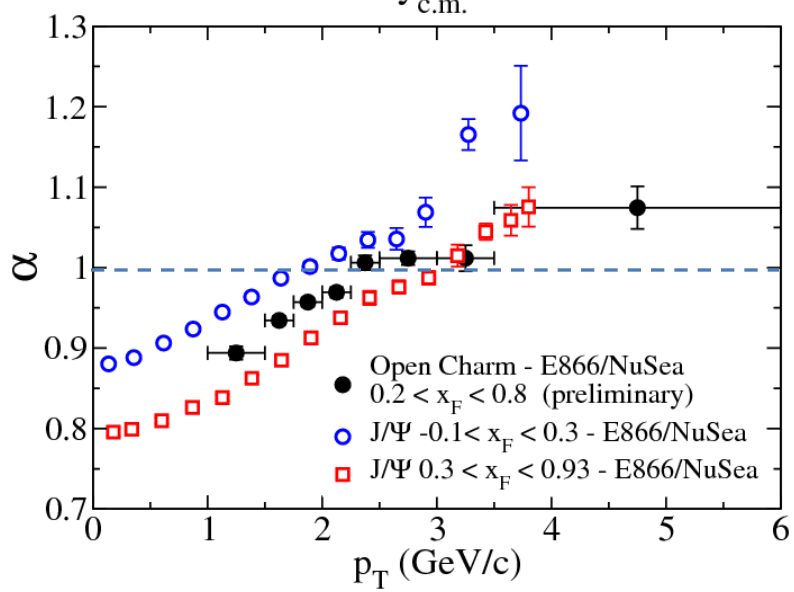
- *S. Klinksiek thesis - hep-ex_0609002*
- *paper in preparation*

# Comparing Open & Closed charm Nuclear Dependences

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

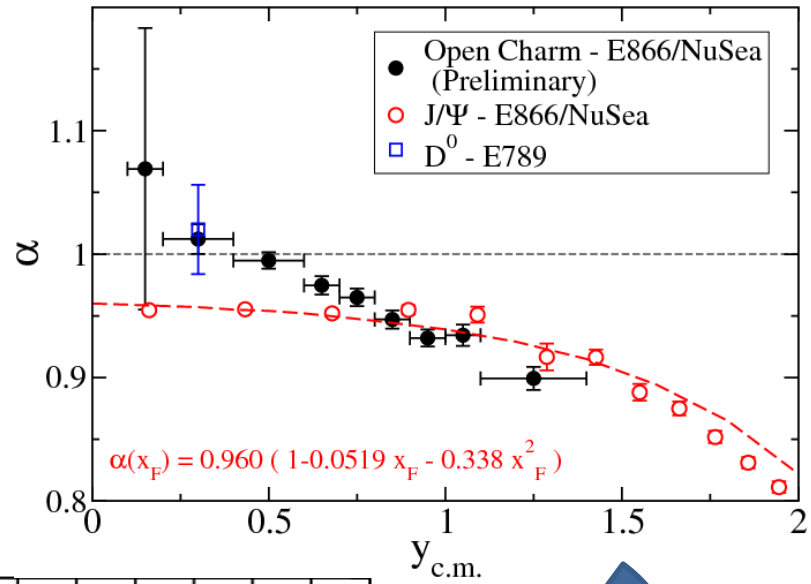
- dominant effects are in the initial state
  - e.g. shadowing, dE/dx, Cronin
- weaker open-charm suppression at y=0 attributed to lack of absorption for open charm

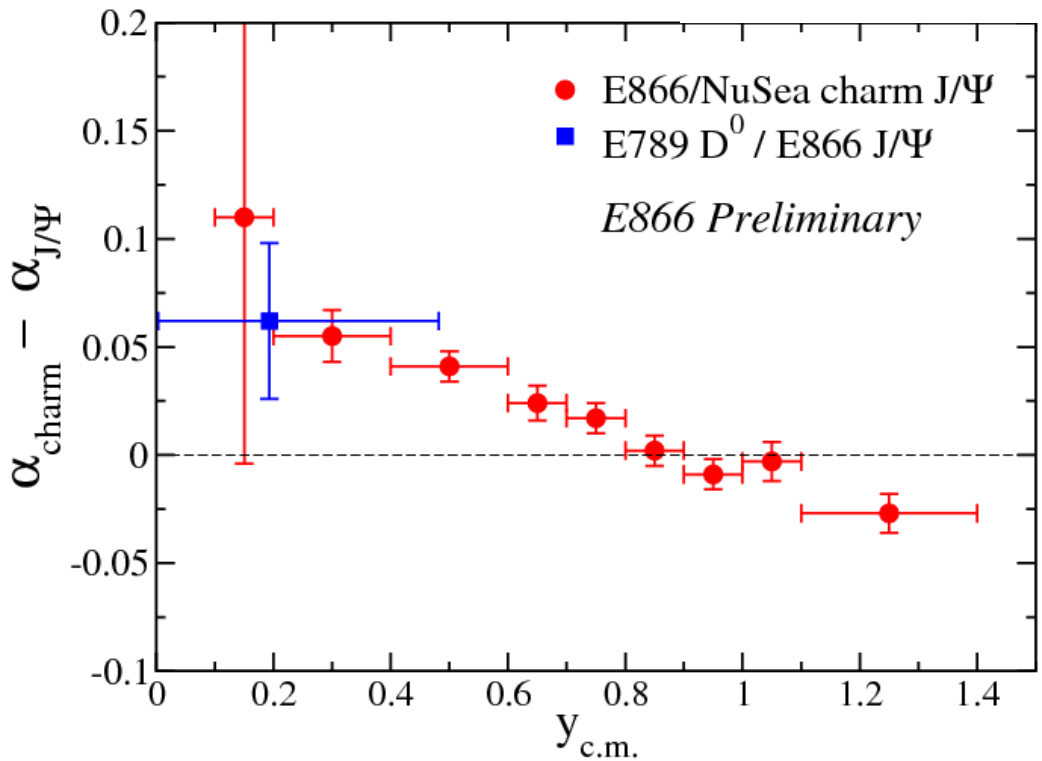



E866/NuSea 800 GeV p+A

Difference in Suppression (alpha) between Open & Closed charm



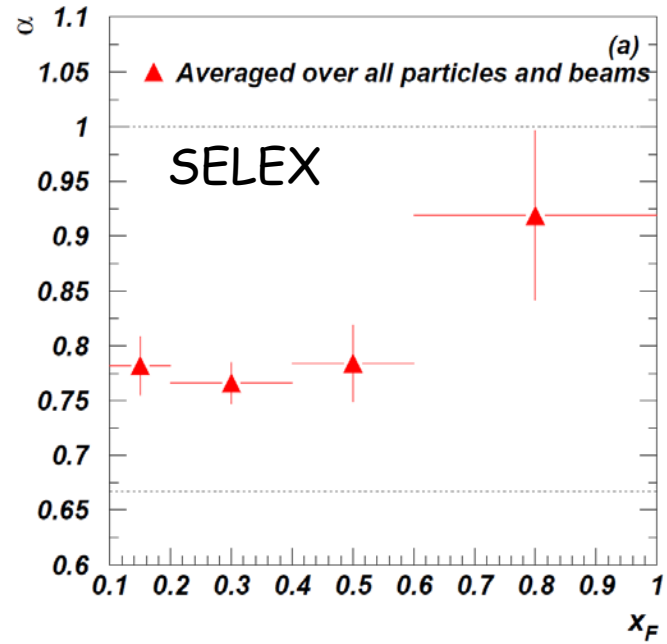



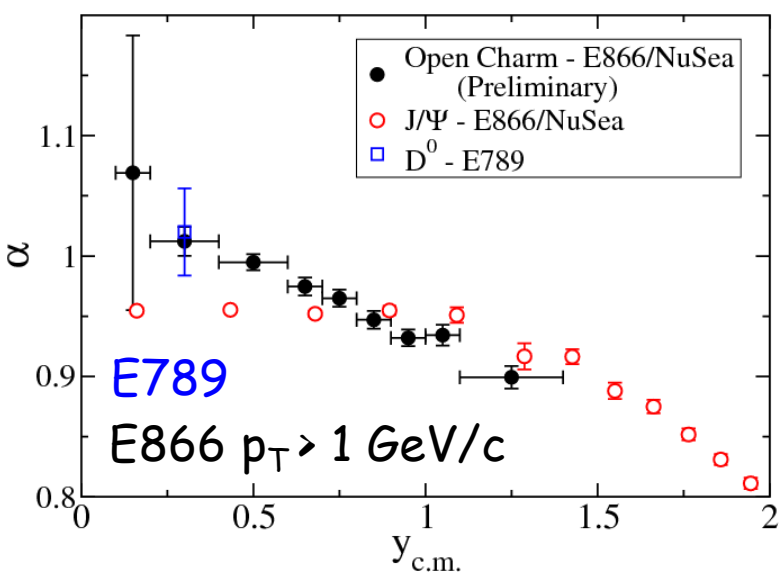
# SELEX – hep-ex_0902.0355??

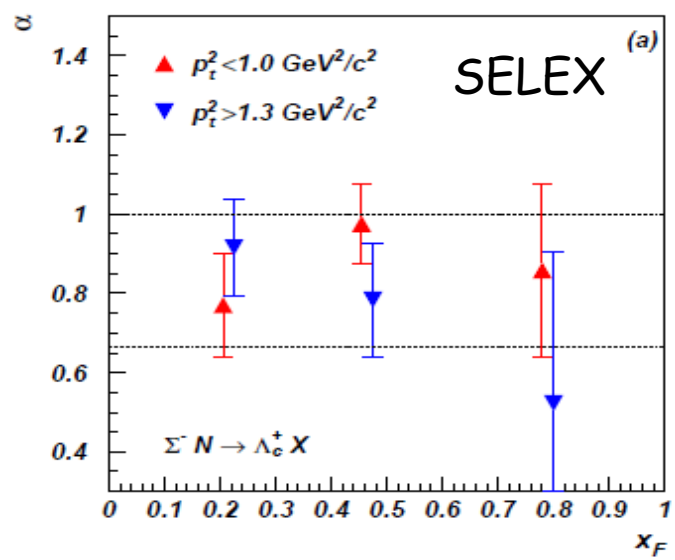
SELEX – a zoo of beams & charm particles:

- $(\pi^{\pm}, p, \Sigma^{-}) + A \rightarrow (D^0, D^*, D^{\pm}, D_s, \Lambda_c)$

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



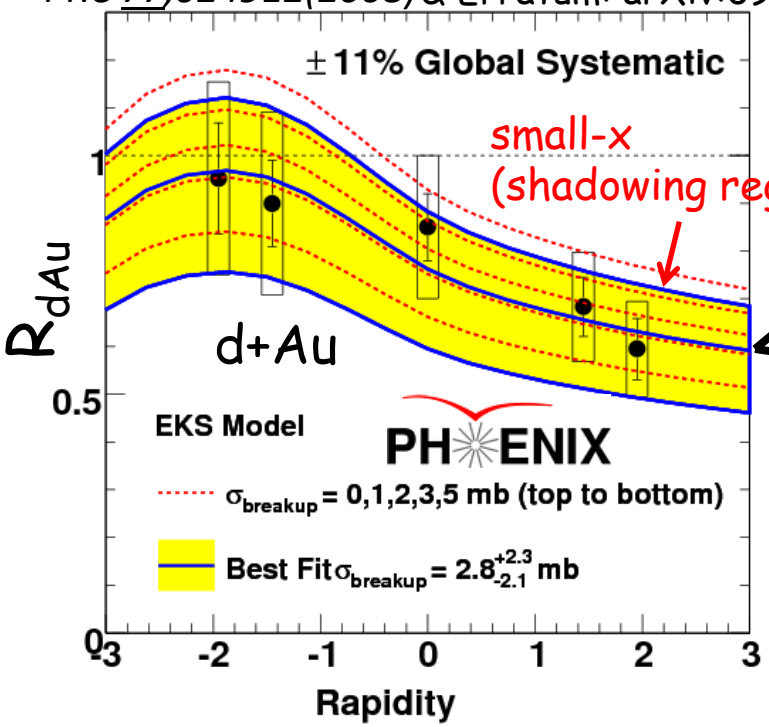




Hint of more similar result for $p_T^2$ > 1.3 GeV/c in one SELEX channel?

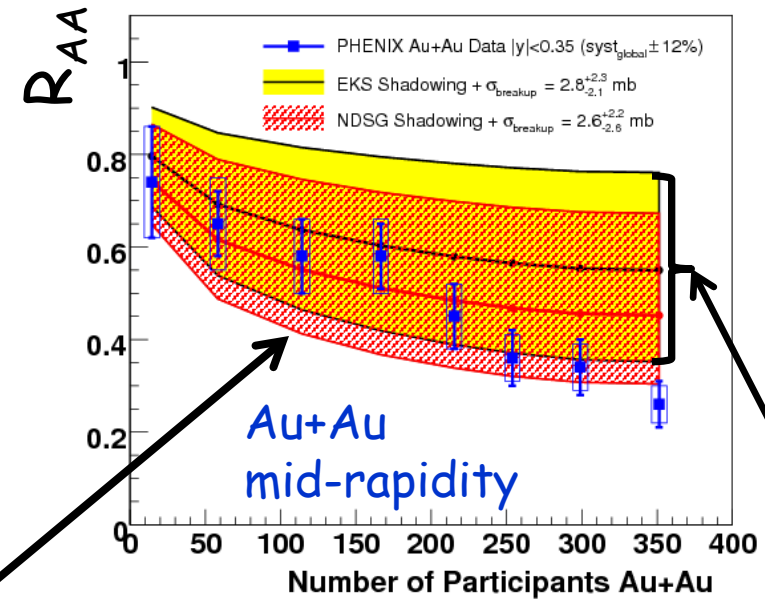
# Present CNM Constraints on A+A data

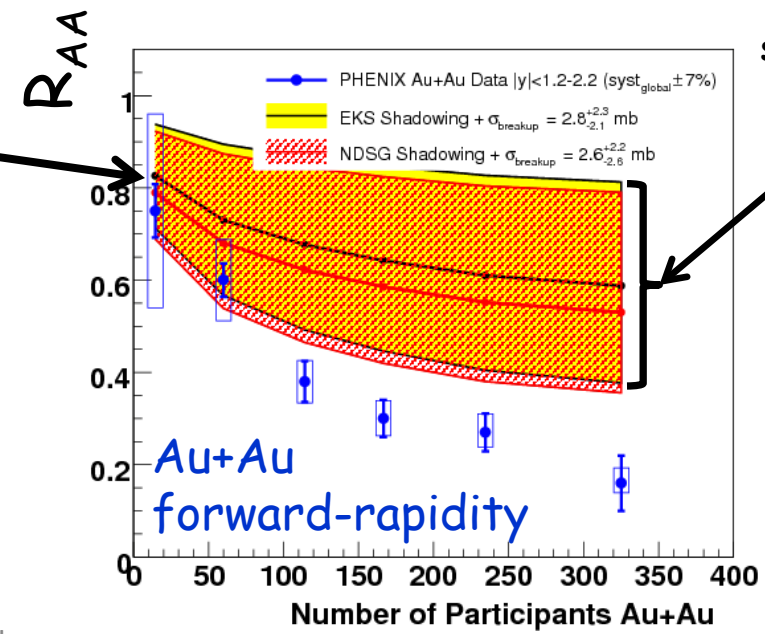
CNM effects (EKS shadowing + dissociation from fits to d+Au data, with R. Vogt calculations) give large fraction of observed Au+Au suppression, especially at mid-rapidity

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




*more accurate d+Au constraint from new 2008 data*




EKS shadowing band

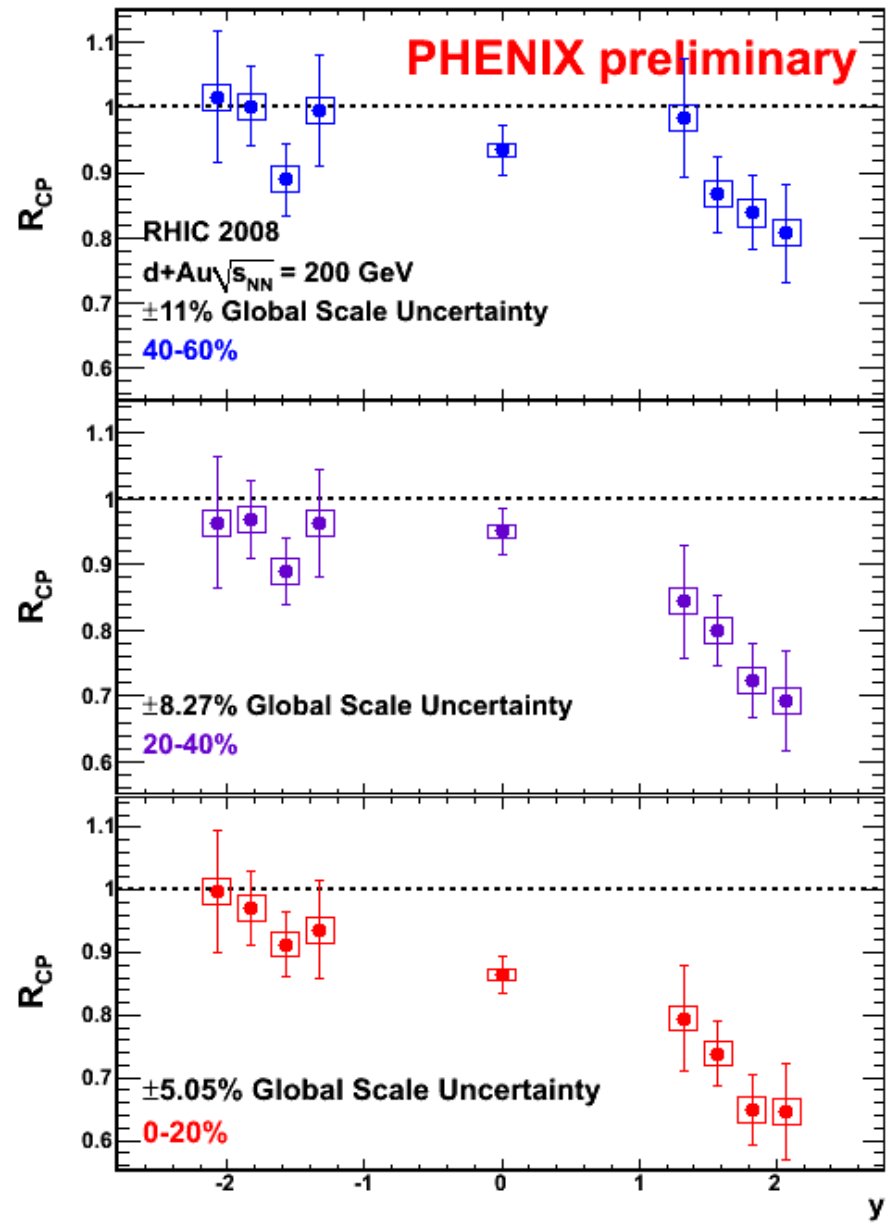
# Quarkonia Production & Suppression – J/Ψ in d+Au

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

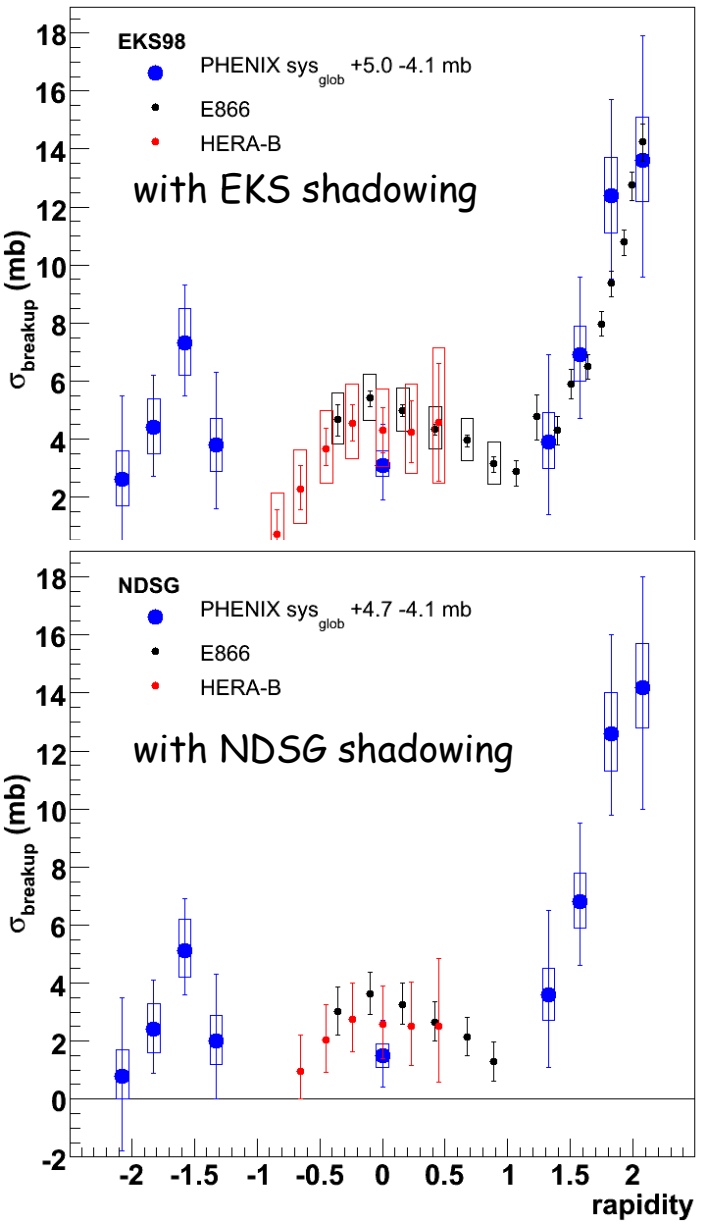


New CNM fits using 2008 PHENIX d+Au Rcp (Tony Frawley, Ramona Vogt, …)

- 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

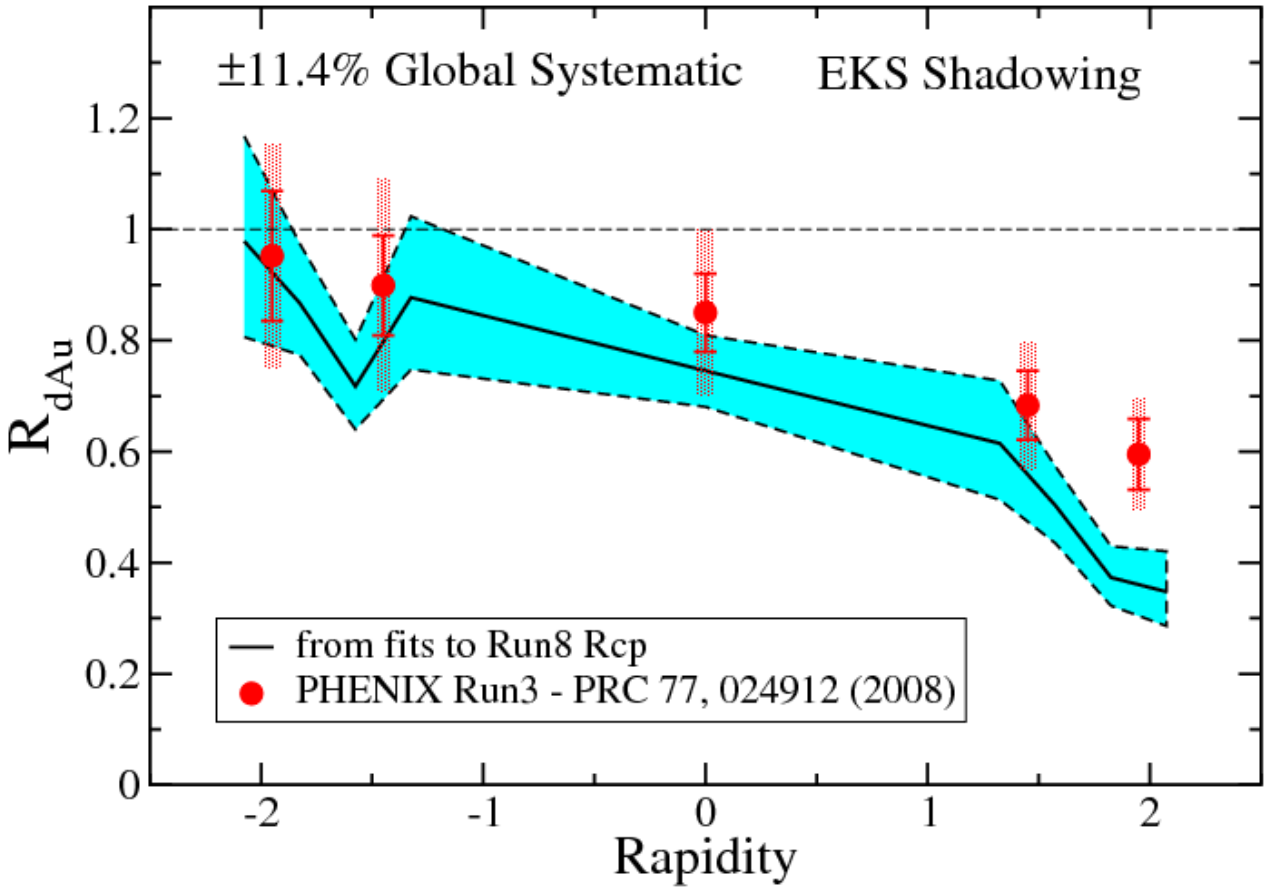
- common trend: large increasing effective breakup cross section at large positive rapidity
- need additional physics in CNM model – e.g. initial-state dE/dx



# Comparision of New Effective Breakup Cross Section fits to published 2003 d+Au $R_{dAu}$ Results (cross check)

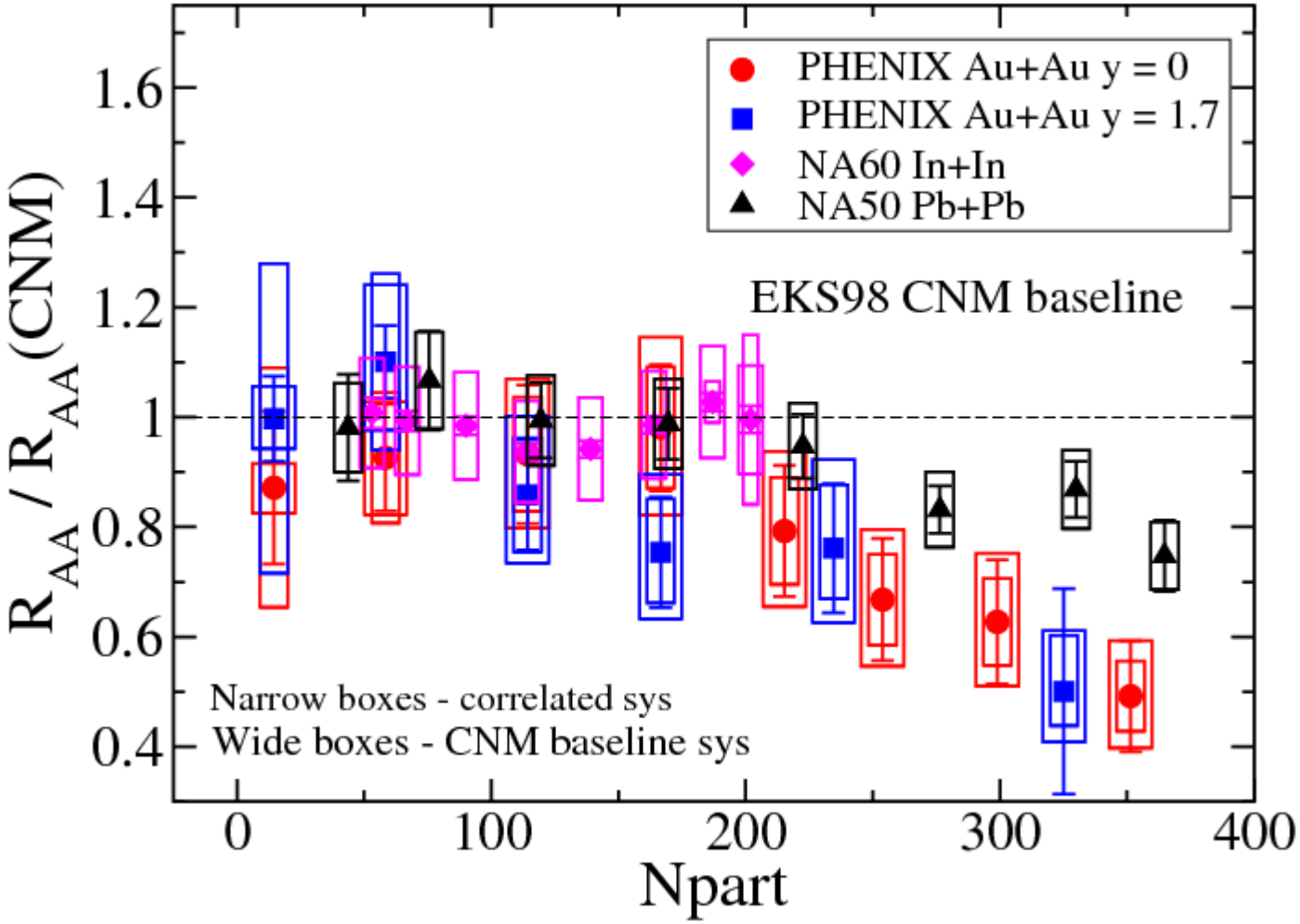
CNM derived from new Rcp is consistent with RdAu from old 2003 data

- *PRC 77,024912(2008)*

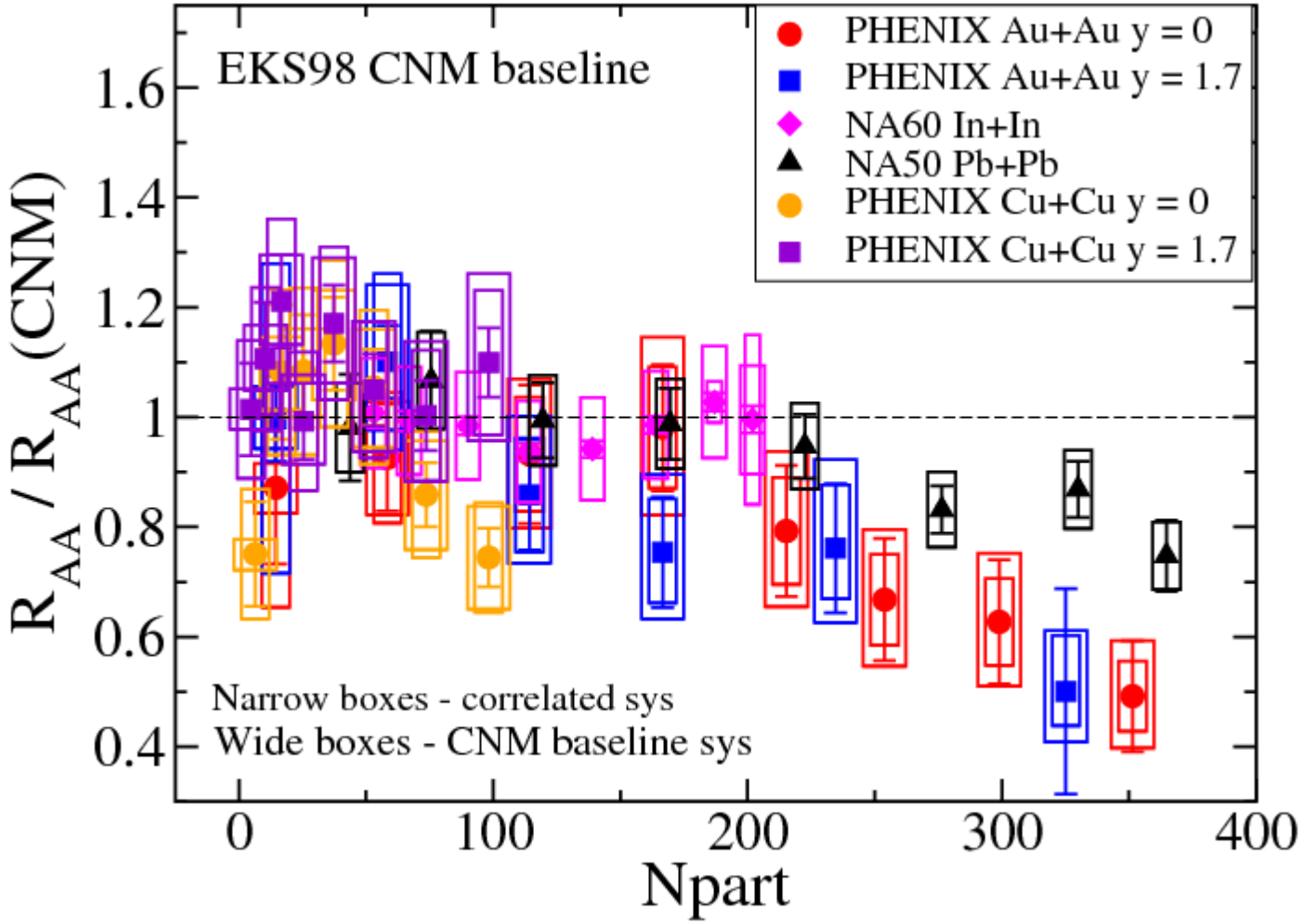


# Anomalous Suppression vs Npart

## SPS & PHENIX separate at large Npart



# Anomalous Suppression vs Npart
## With PHENIX CuCu added

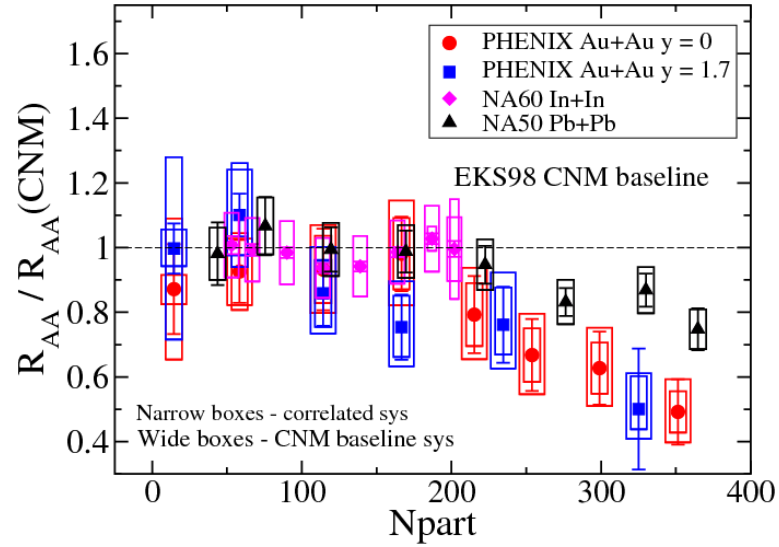


# Comparing Anomalous Suppression at RHIC & SPS vs Energy Density

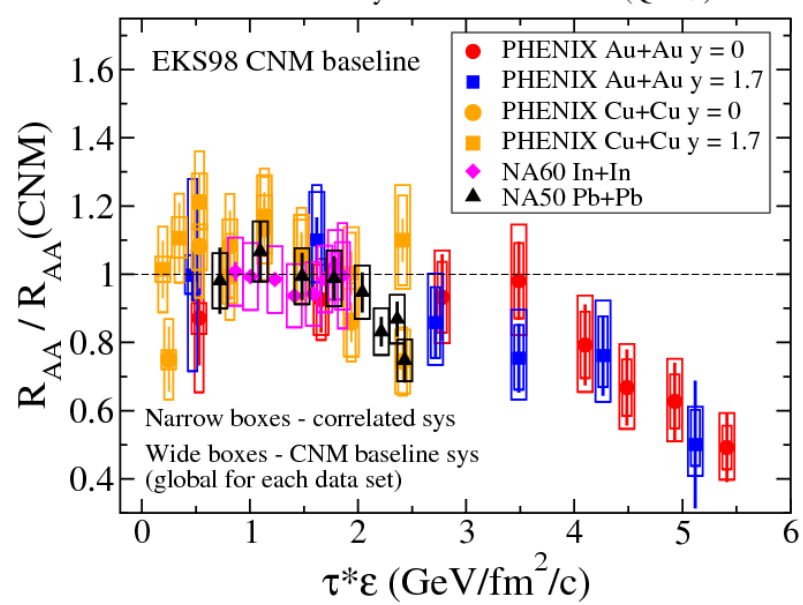
<u>Caution</u> - Many systematic uncertainties on relative (SPS vs RHIC) energy density scales:

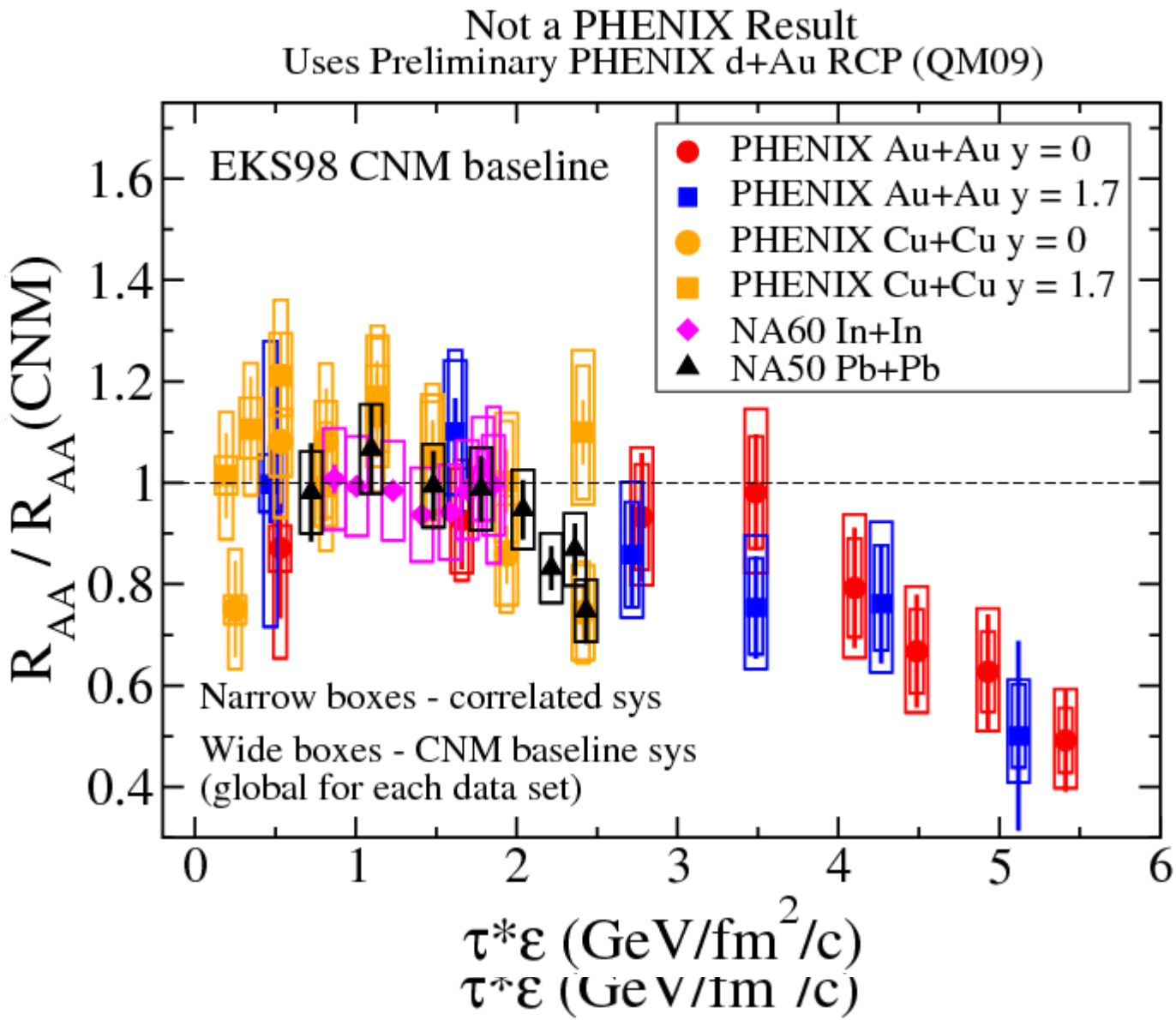
- Using WA98 for $dE_T/dy$ at NA50/60 (matches best with dN/dy from Roberta Analdi)
  - substantially different from NA49 values (~25%)?

  *see PRC 71, 034908 (2005)*
- use Glauber MC for NA50/60 areas
- Use tau*energy density scale; but is tau same or different between SPS & RHIC energy?
- No Cu+Cu dN/dy or $dE_T/dy$ at RHIC, so using Au+Au values at same $N_{part}$

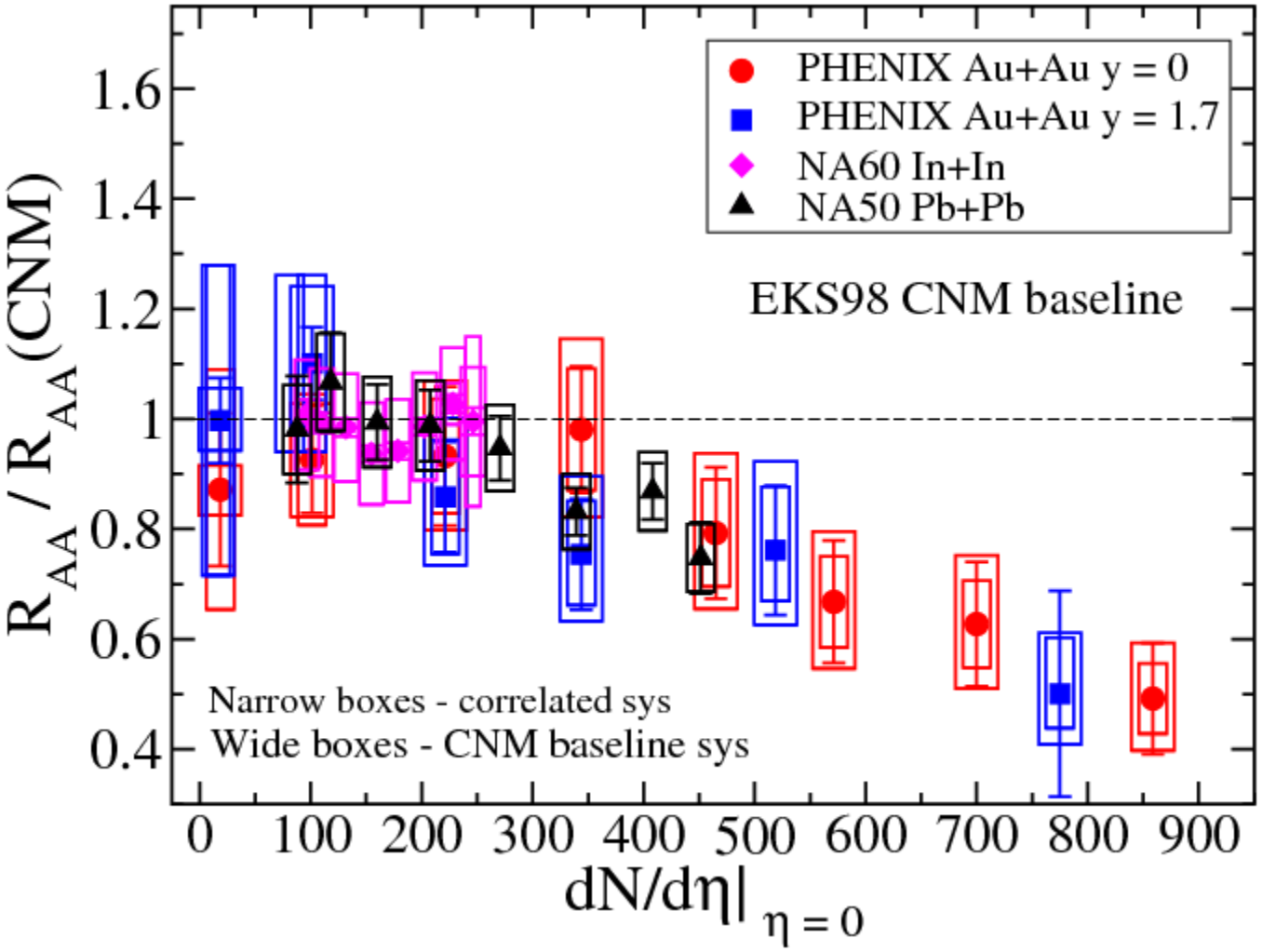



Not a PHENIX Result
Uses Preliminary PHENIX d+Au RCP (QM09)

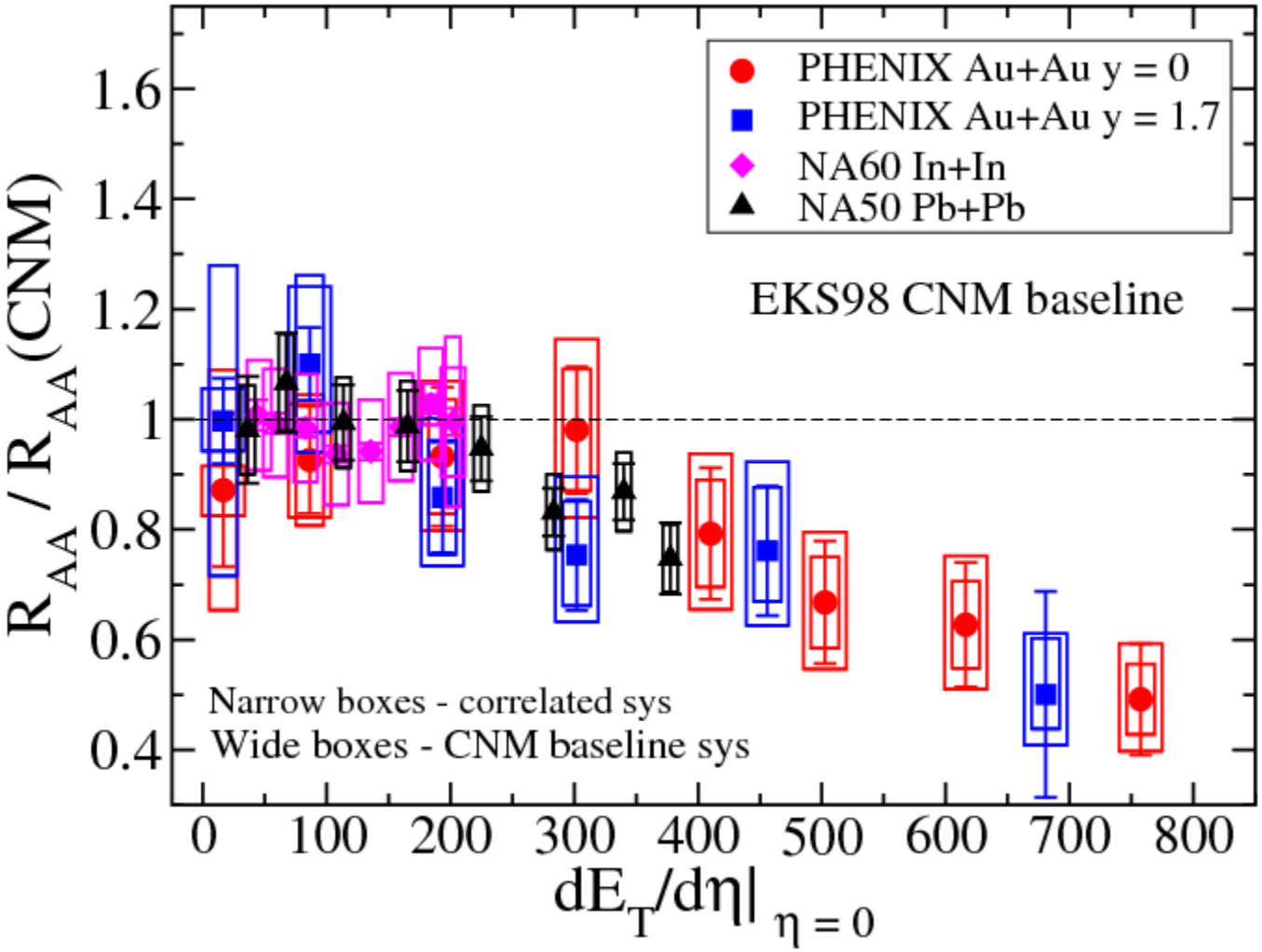



Not a PHENIX Result
Uses Preliminary PHENIX d+Au RCP (QM09)
EKS98 CNM baseline
PHENIX Au+Au y = 0
PHENIX Au+Au y = 1.7
PHENIX Cu+Cu y = 0
PHENIX Cu+Cu y = 1.7
NA60 In+In
NA50 Pb+Pb
Narrow boxes - correlated sys
Wide boxes - CNM baseline sys
(global for each data set)
$R_{AA} / R_{AA}(CNM)$
$\tau^*\varepsilon$ (GeV/fm$^2$/c)

# Anomalous Suppression vs $dN_{ch}/d\eta$



# Anomalous Suppression vs $dE_T/d\eta$

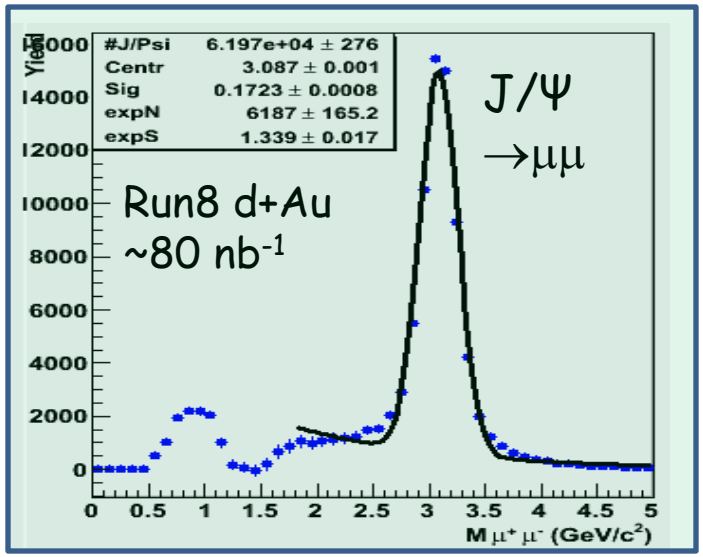


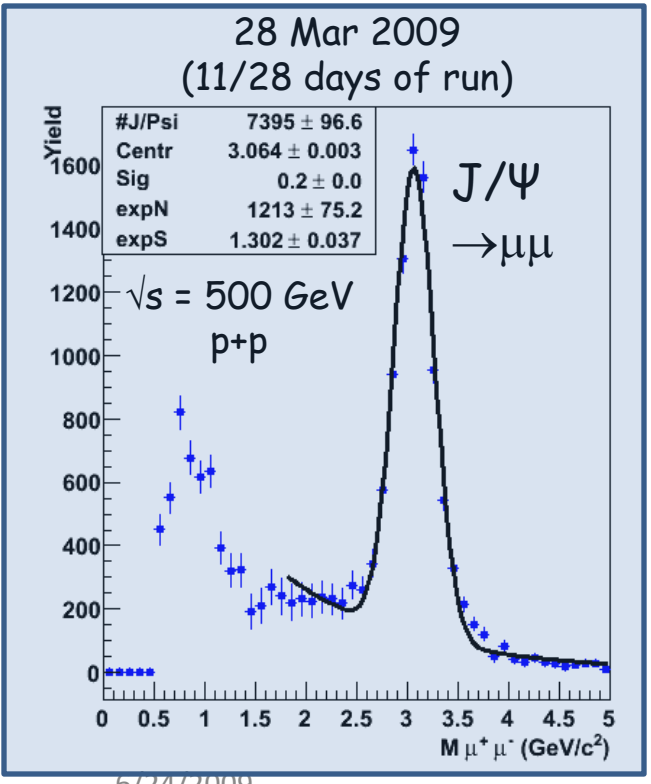
# Future

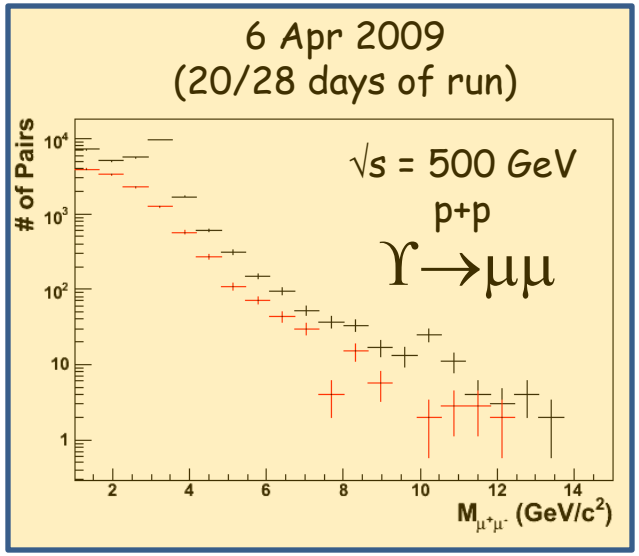
# Recent PHENIX J/Ψ→μμ data sets

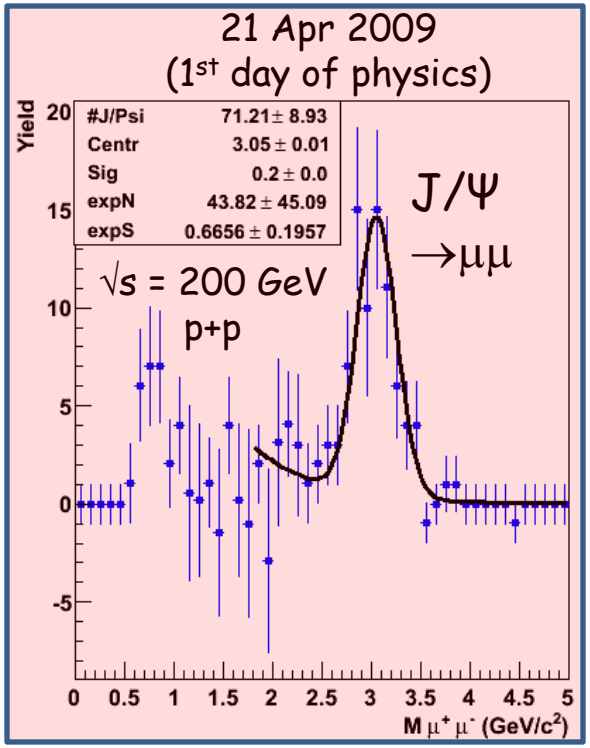
Run9 p+p now ongoing, with longitudinal polarization:

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



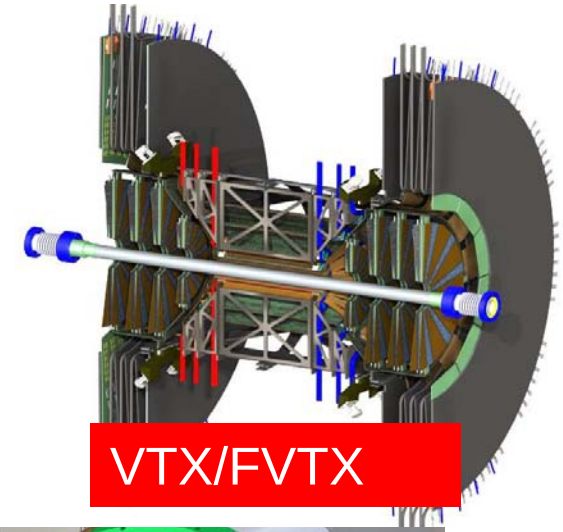
# Upgrades & Quarkonia at PHENIX

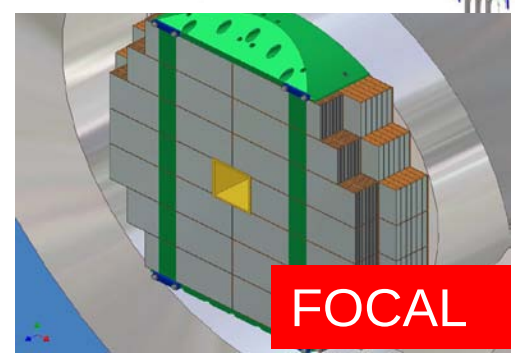
Vertex Detectors (VTX & FVTX)
- better $\Upsilon \rightarrow$ e+e- mass resolution & background at mid-rapidity
- separation of $\Psi'$ from $J/\Psi$ & reduction of backgrounds at forward-rapidity ($\mu^+\mu^-$)
- $B \rightarrow J/\Psi$ X

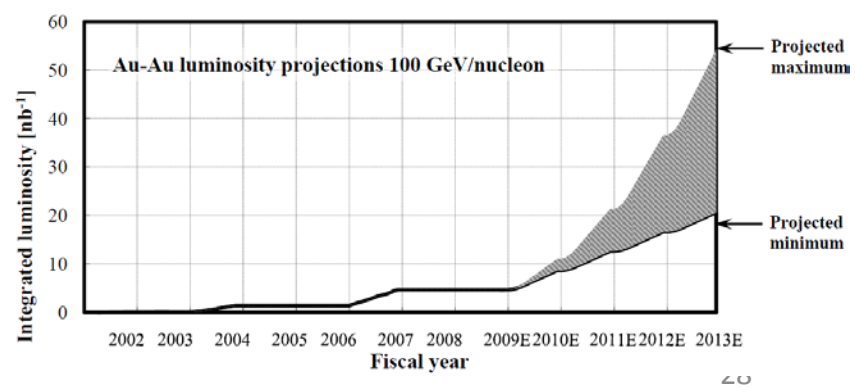
Forward Calorimetry (FOCAL)
- $\chi_C \rightarrow J/\Psi + \gamma$ in p+p & d+Au

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

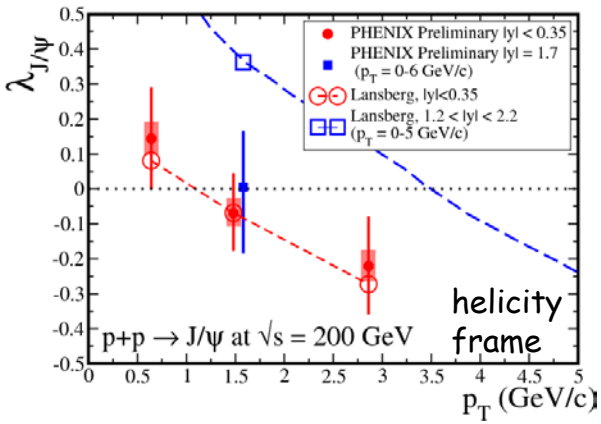
And increased machine Luminosity benefits these rare processes



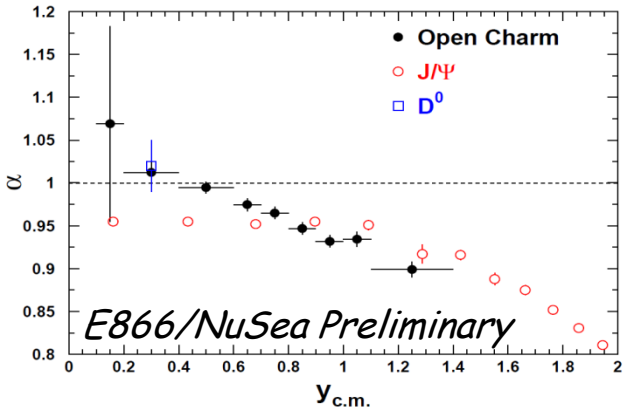



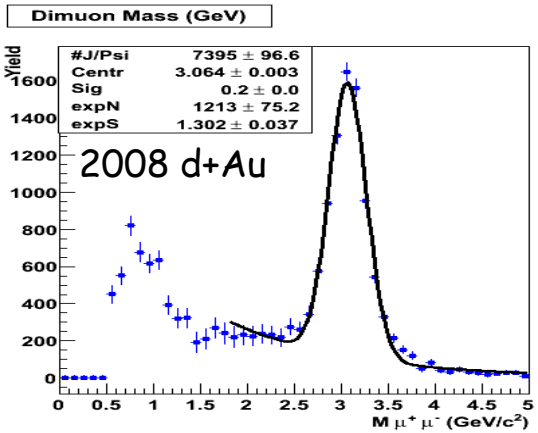
# Summary




New CSM good except for forward J/Ψ polarization

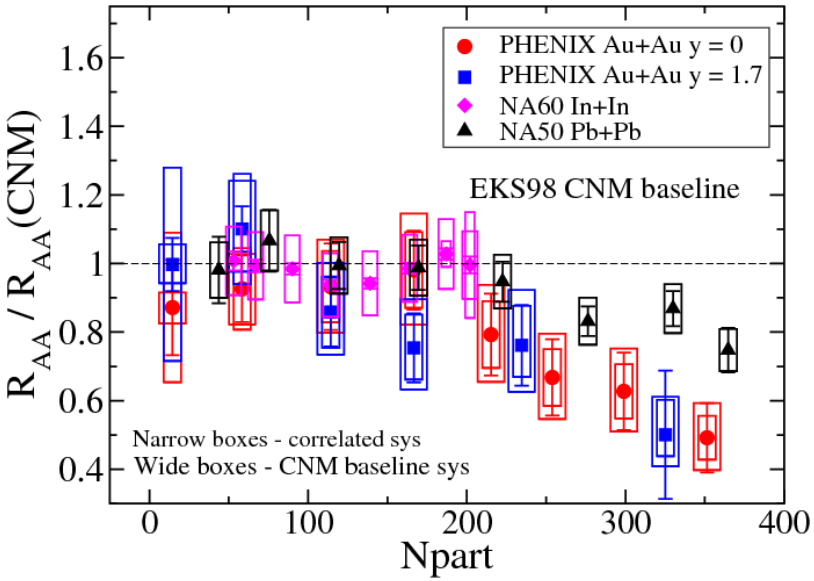



Many CNM effects possible:
- similarity of open charm → initial state
- lack of x2 scaling → not shadowing

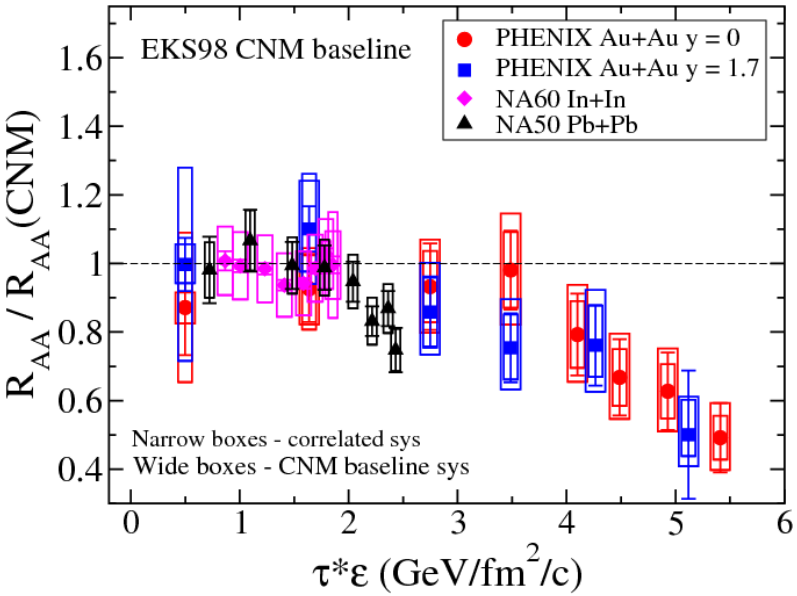



New d+Au data coming soon

Anomalous Suppression @ RHIC & SPS




Scales with Energy Density?




Mike Leitch

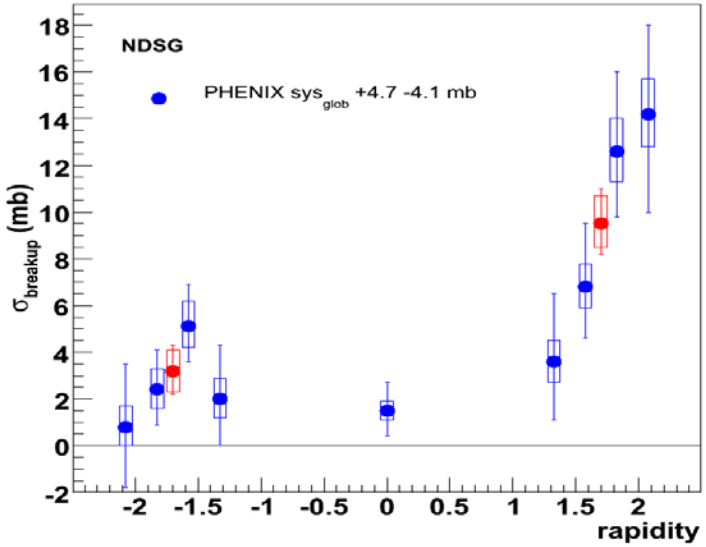
# Backup

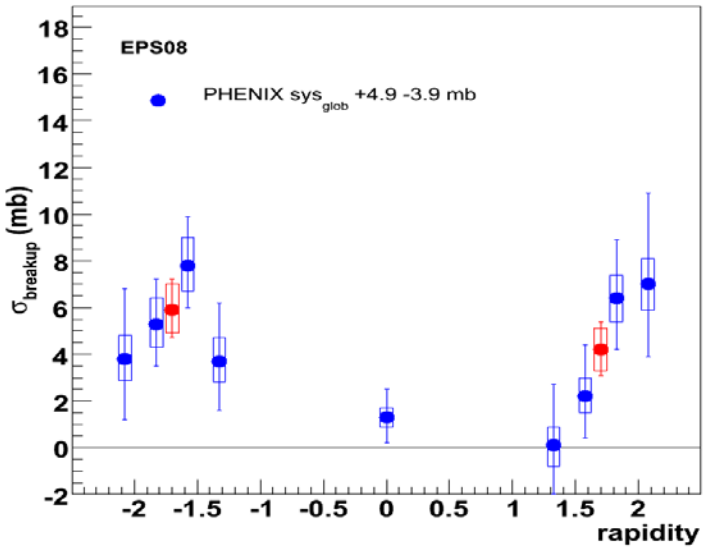
The effective absorption cross sections from fits of Ramona's calculations to PHENIX d+Au $R_{CP}$ data are shown for each shadowing model.

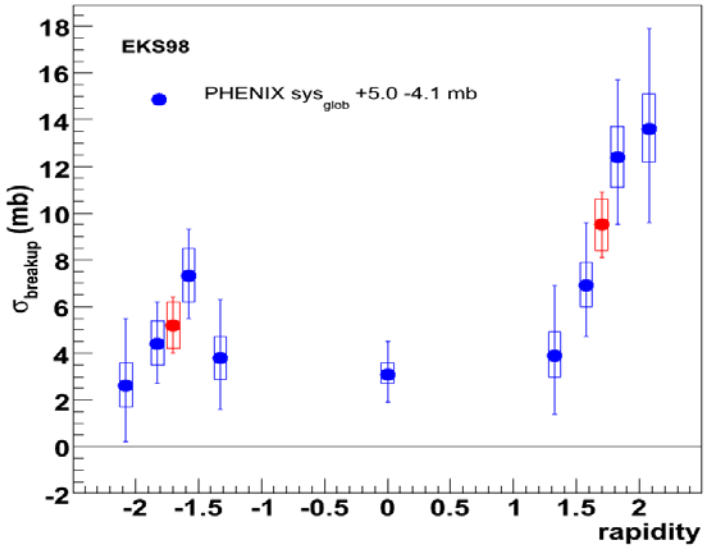
From Tony Frawley

This is **not** an attempt to extract physics from the d+Au $R_{CP}$! This is just a parameterization of the data that is independent at each rapidity.

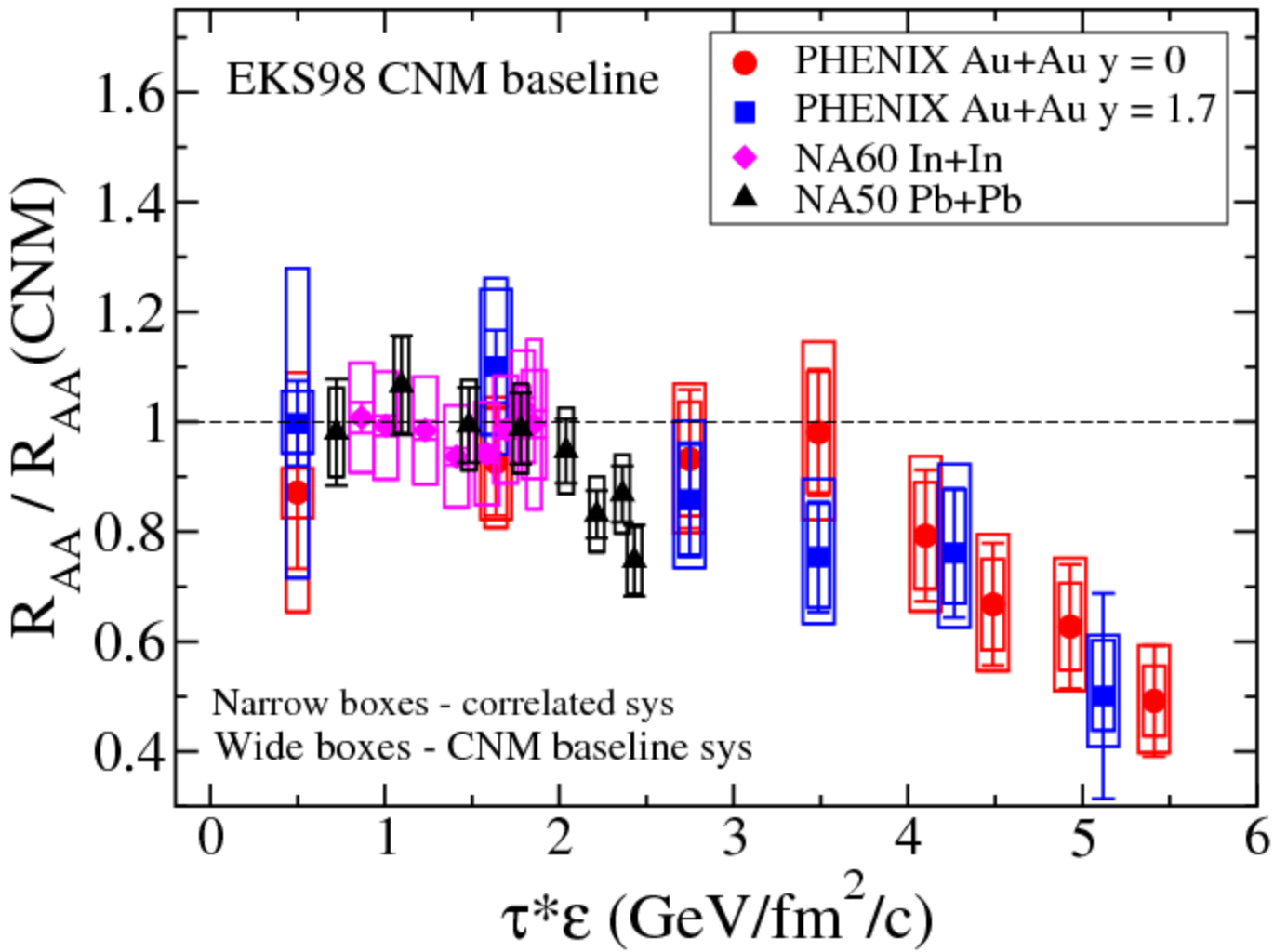
The red points are the averages at y = -1.7 and +1.7.



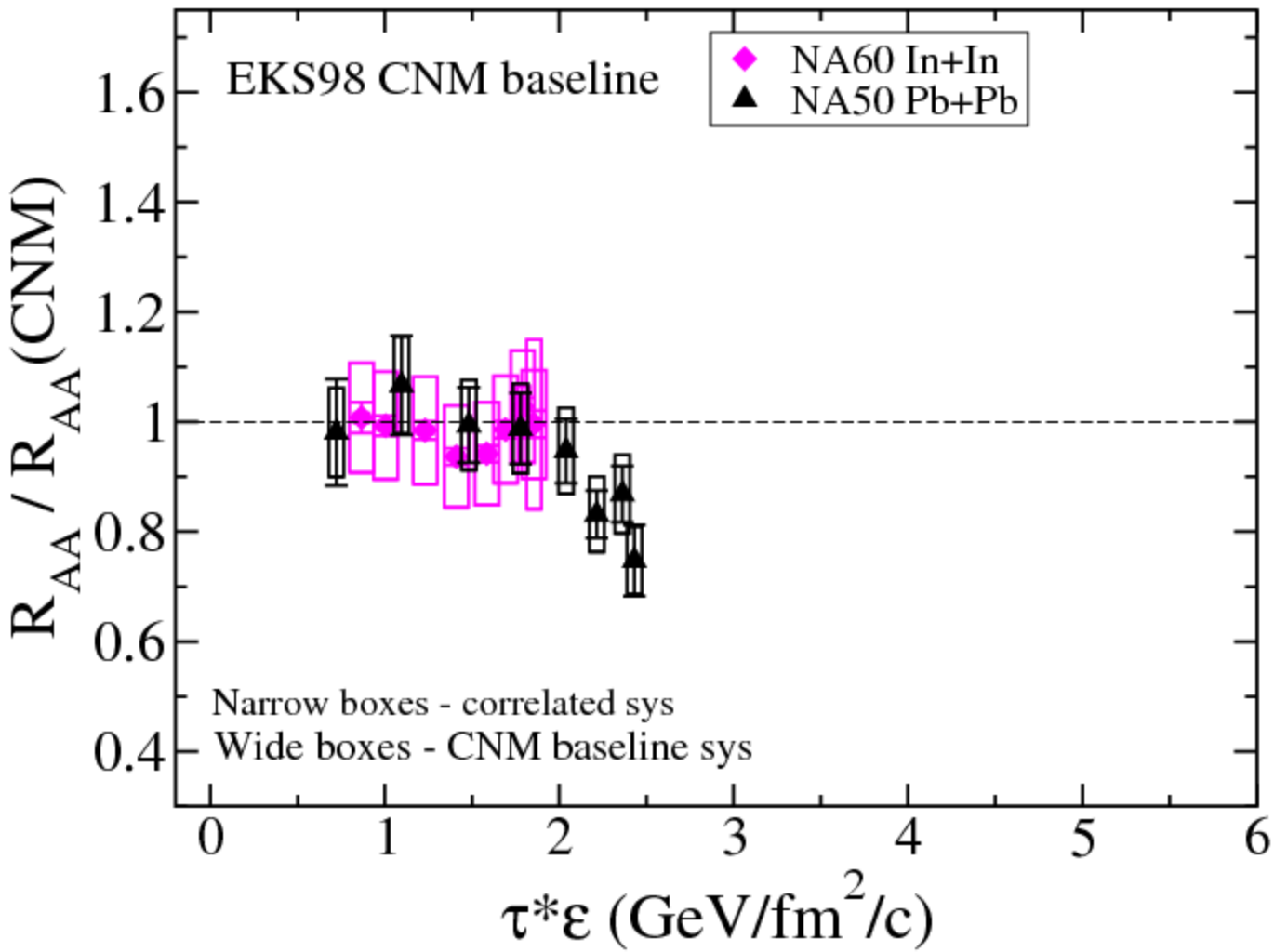



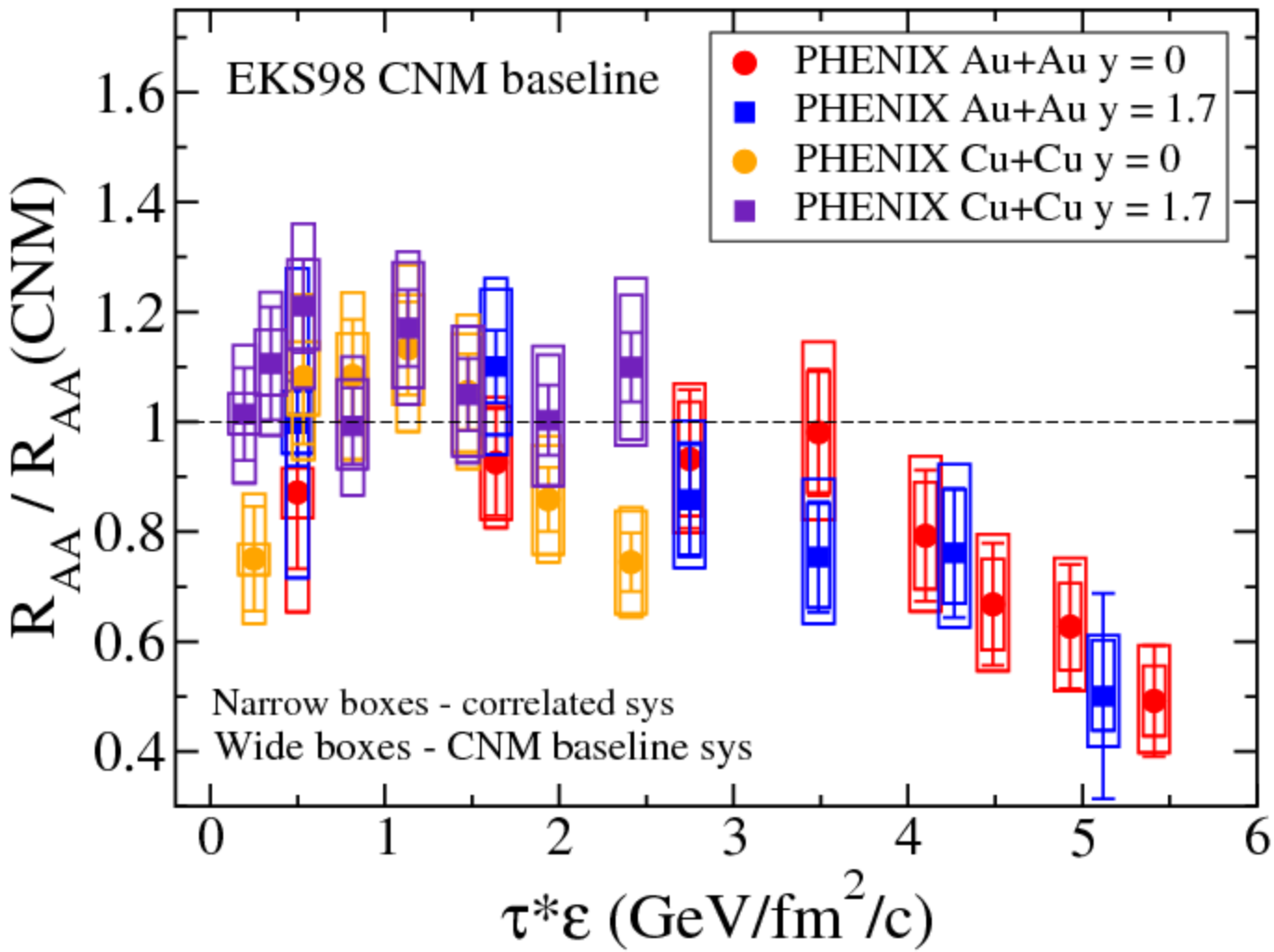
# PHENIX Au+Au & SPS



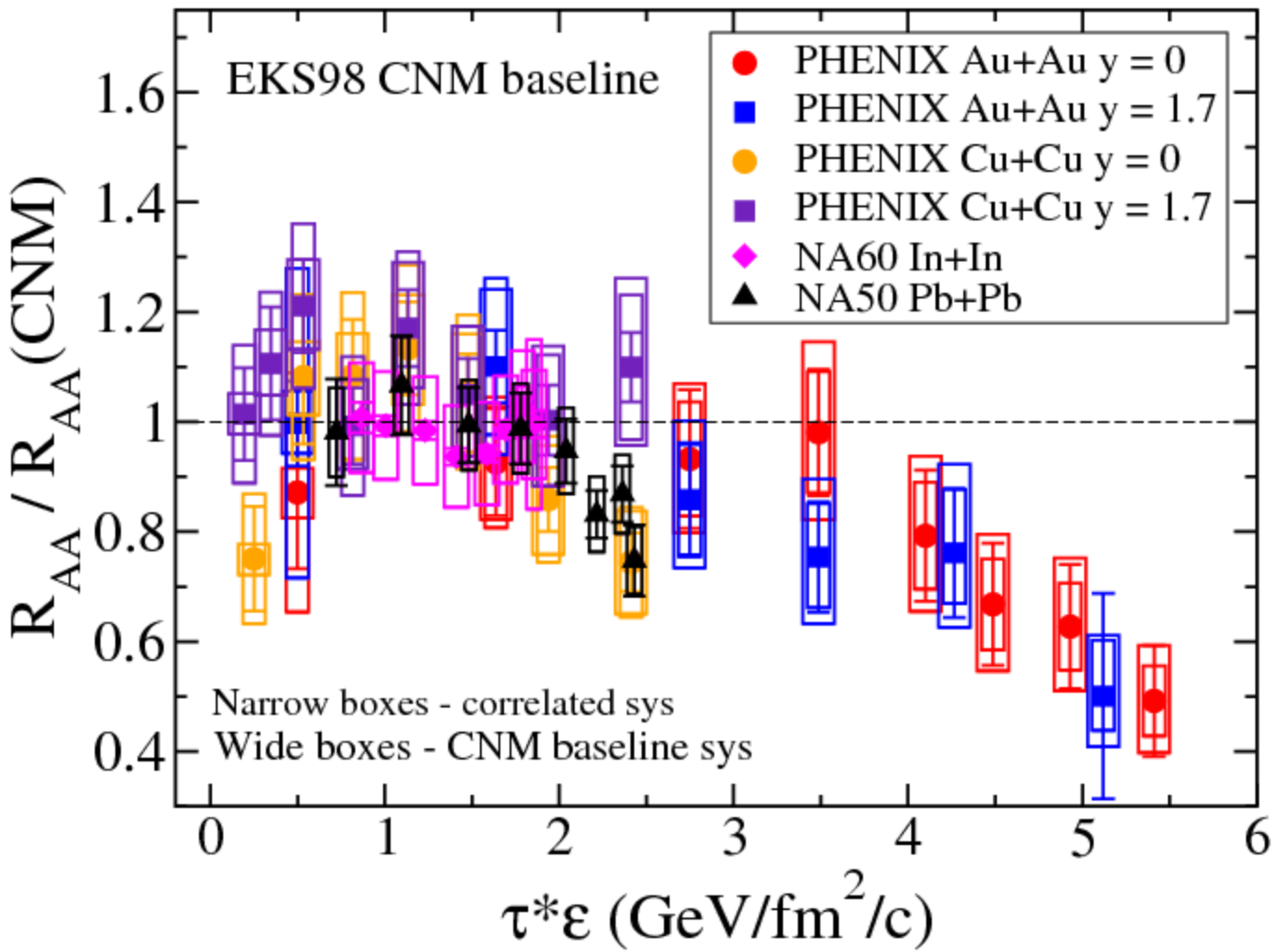
# SPS only


EKS98 CNM baseline
NA60 In+In
NA50 Pb+Pb
Narrow boxes - correlated sys
Wide boxes - CNM baseline sys
$R_{AA} / R_{AA}(CNM)$
$\tau*\varepsilon$ (GeV/fm$^2$/c)
1.6
1.4
1.2
1
0.8
0.6
0.4
0
1
2
3
4
5
6

# PHENIX only – Au+Au & Cu+Cu

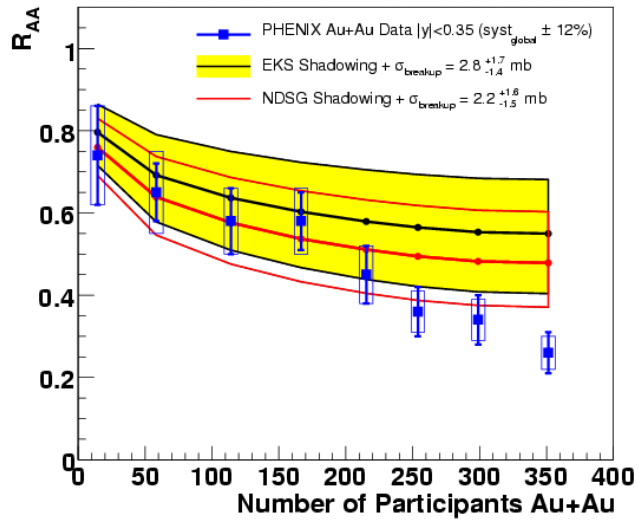


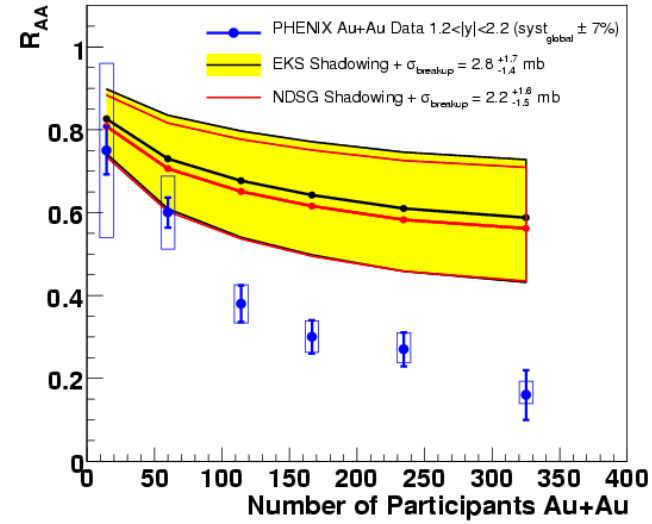
# PHENIX & SPS


EKS98 CNM baseline
PHENIX Au+Au y = 0
PHENIX Au+Au y = 1.7
PHENIX Cu+Cu y = 0
PHENIX Cu+Cu y = 1.7
NA60 In+In
NA50 Pb+Pb
Narrow boxes - correlated sys
Wide boxes - CNM baseline sys
$R_{AA} / R_{AA}(CNM)$
$\tau*\varepsilon$ (GeV/fm$^2$/c)
0.4
0.6
0.8
1
1.2
1.4
1.6
0
1
2
3
4
5
6

# How does the QGP affect Quarkonia?
# CNM Effects

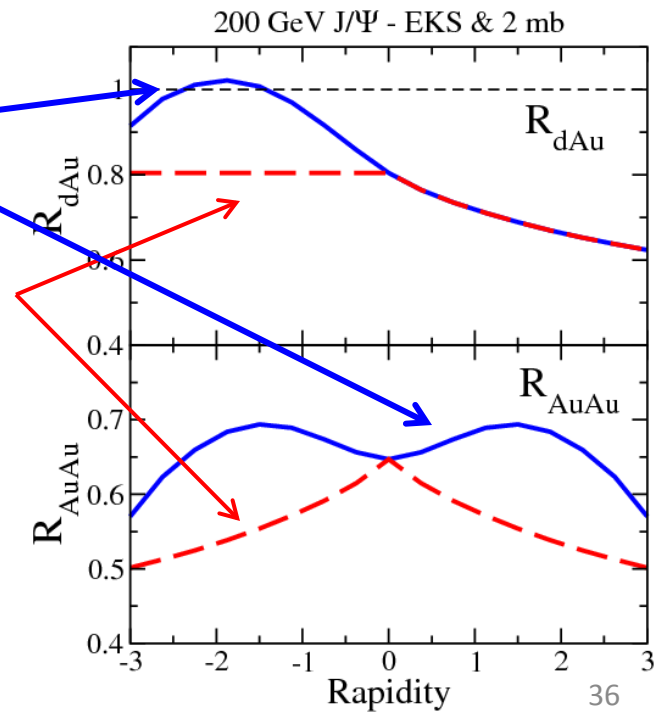
CNM effects (EKS shadowing + dissociation) give large fraction of observed AuAu suppression, especially at mid-rapidity




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

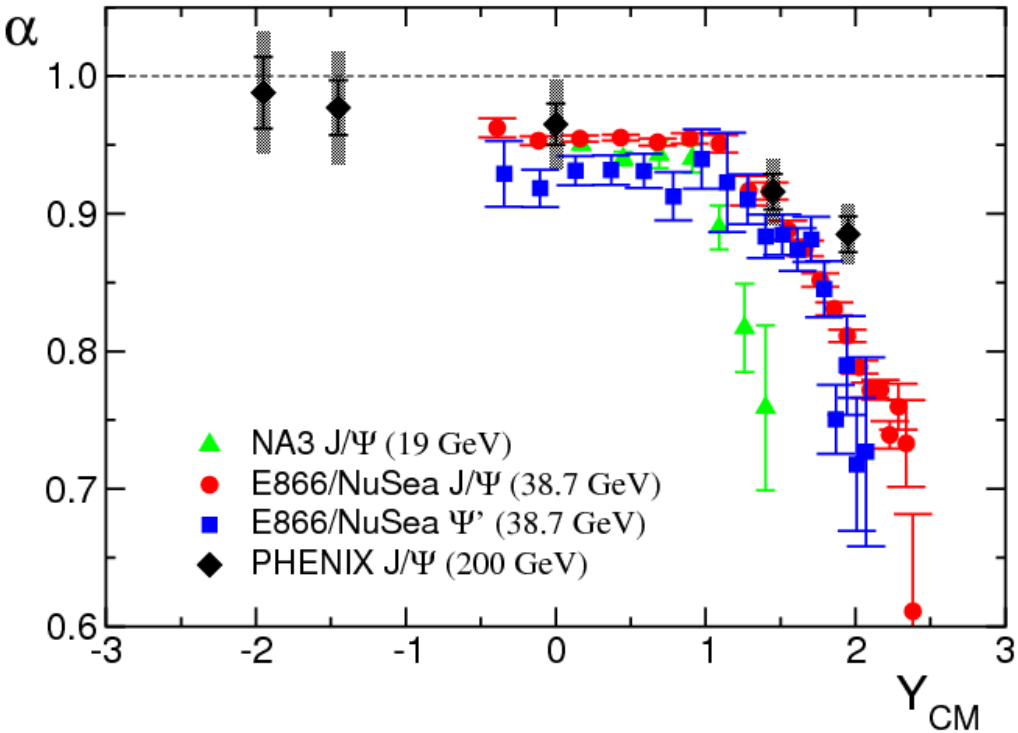
- but if peaking in "anti-shadowing" region were flat instead then one would get larger suppression for forward rapidity as has been observed in AuAu data
- could come from gluon saturation or from a shadowing prescription that has no anti-shadowing

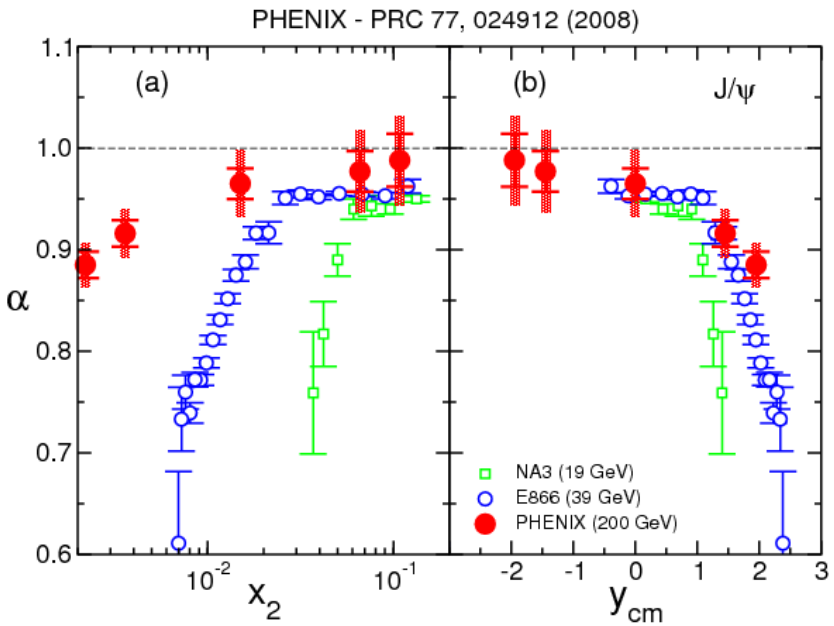



*In any case more accurate dAu data is sorely needed*

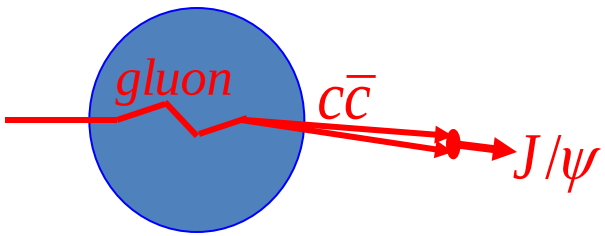
Scaling vs $Y_{cm}$?

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

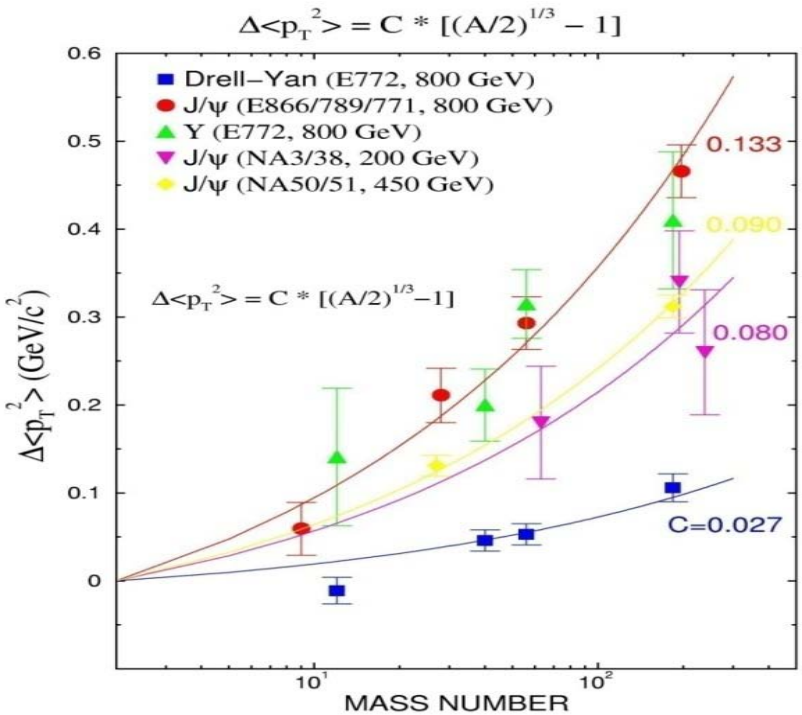


# Transverse Momentum Broadening
# Another Cold Nuclear Matter Effect



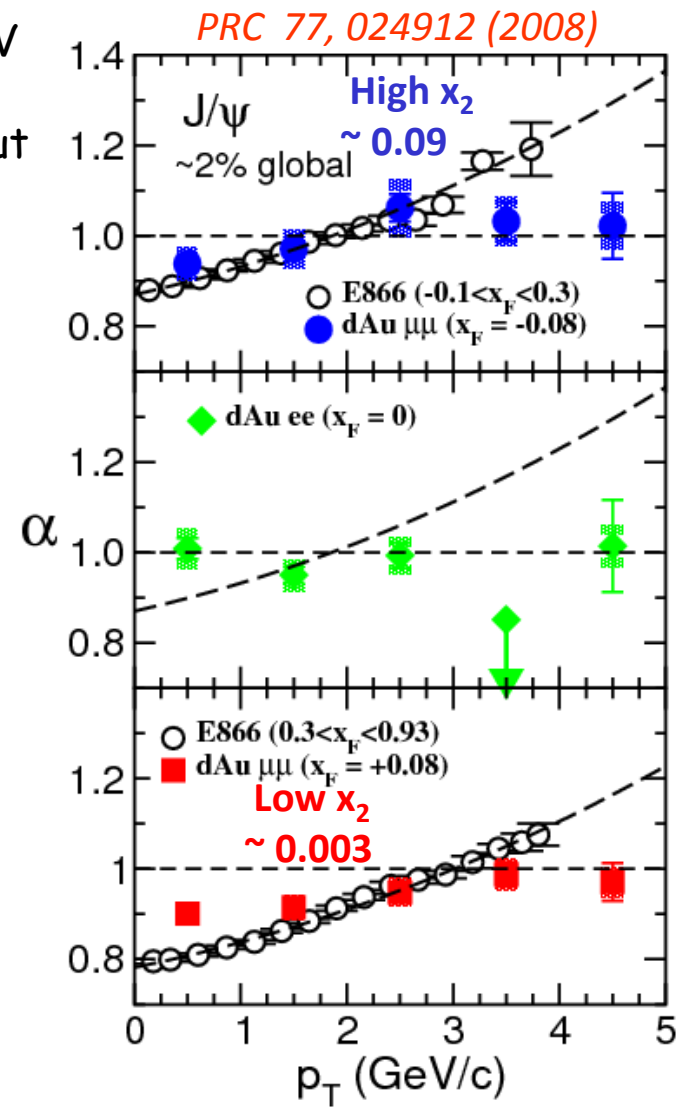

Initial-state gluon multiple scattering causes $p_T$ broadening (or Cronin effect)




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 $\pi$ PRL 70,722 (1993)*

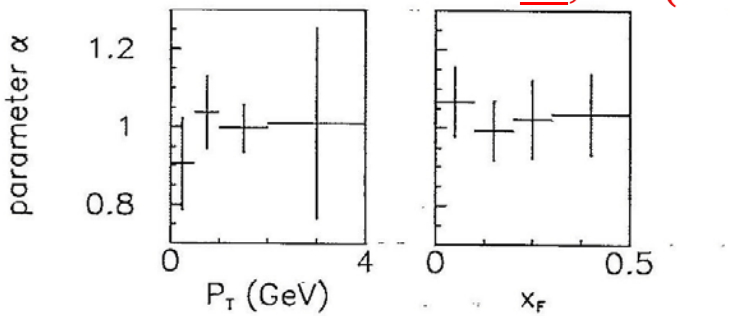



FIG. 4. Dependence of the parameter $\alpha$ on $P_T$ and $x_F$ for $D^+$ and $D^0$.

*WA82 340 GeV $\pi$ PRB 284,453 (1992)*

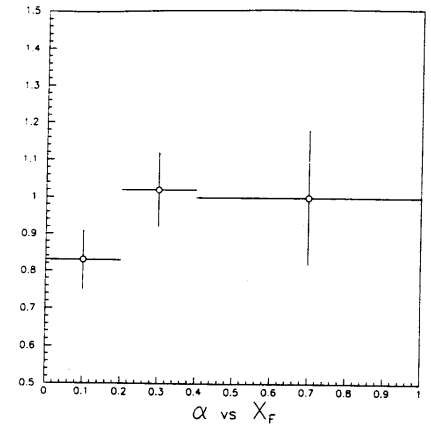
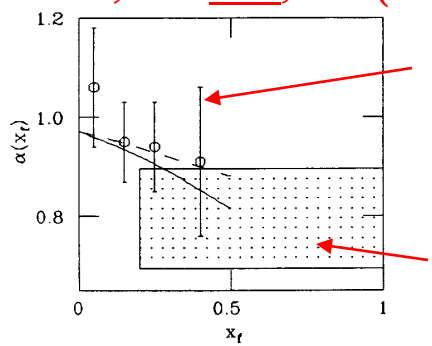



Fig. 4. The parameter $\alpha$ for charm production as measured in three $x_F$ intervals.

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

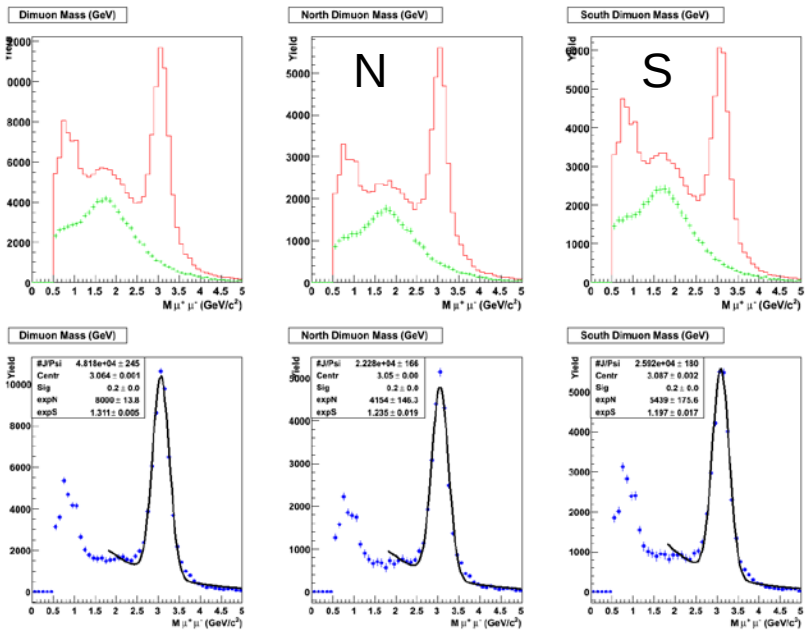



E769 250 GeV $\pi$

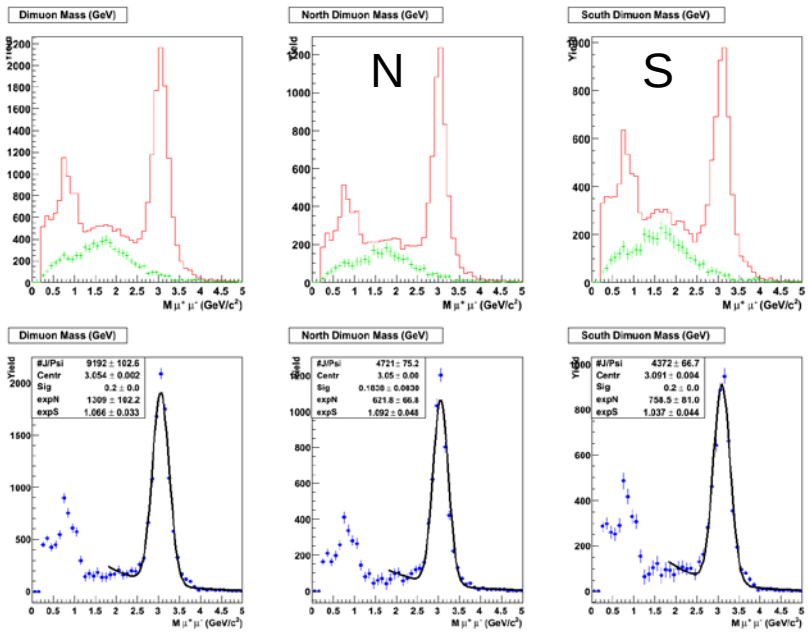
WA78 320 GeV $\pi$ *(Beam dump)*

Fig. 14. We show $\alpha(x_f)$ for $\pi^-$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 $\pi^-$A interactions [3] and the effective $\alpha$ found by the WA78 beam dump experiment [23], indicated by the band with $\langle x_f \rangle = 0.31$.

# 2009 PHENIX Run - Muon arm J/ψ's



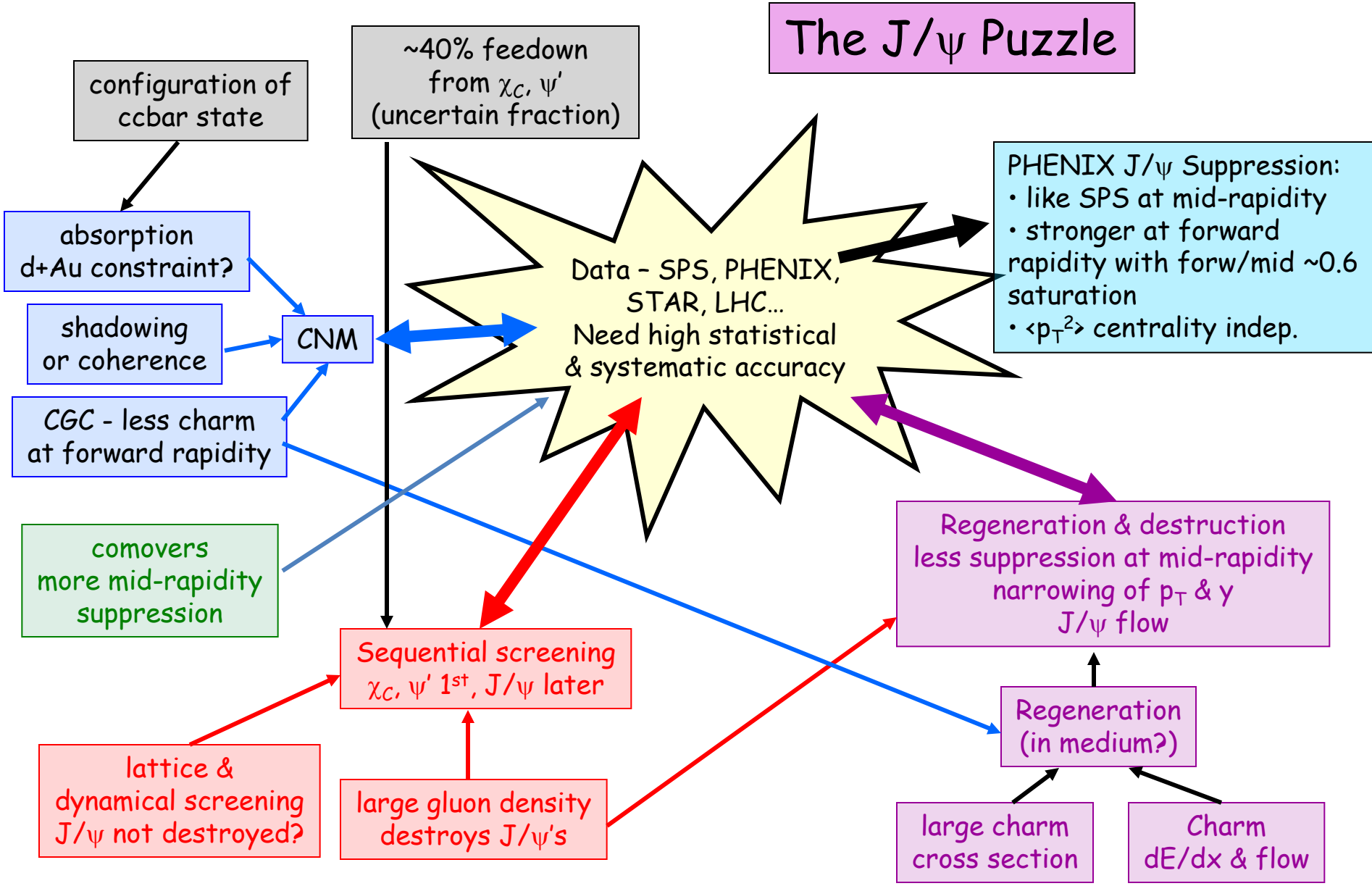

500 GeV




200 GeV

Production of muon stream allowed us to see J/ψ during the run

# The J/ψ Puzzle

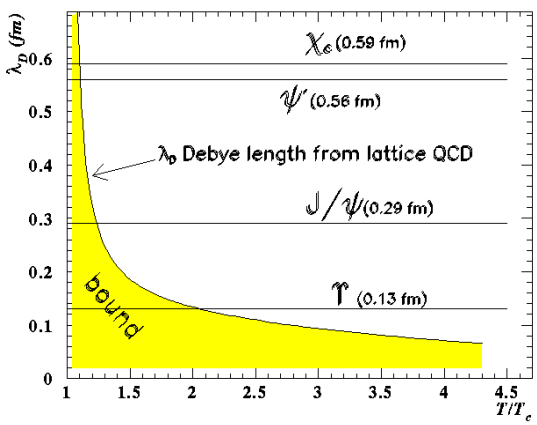


# Quarkonia in the QGP
# A+A Collisions at RHIC

# Quarkonia & Deconfinement

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

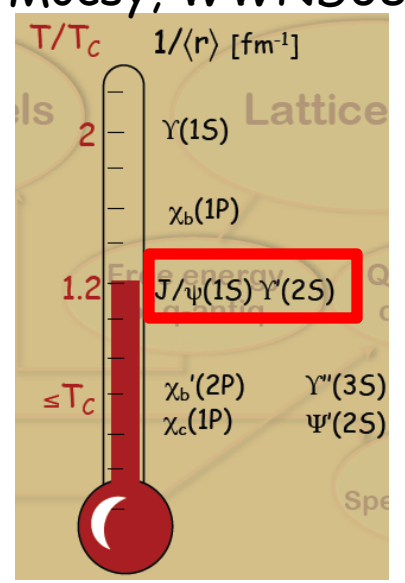
- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks
- Is there deconfinement? → look for Quarkonia screening




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!

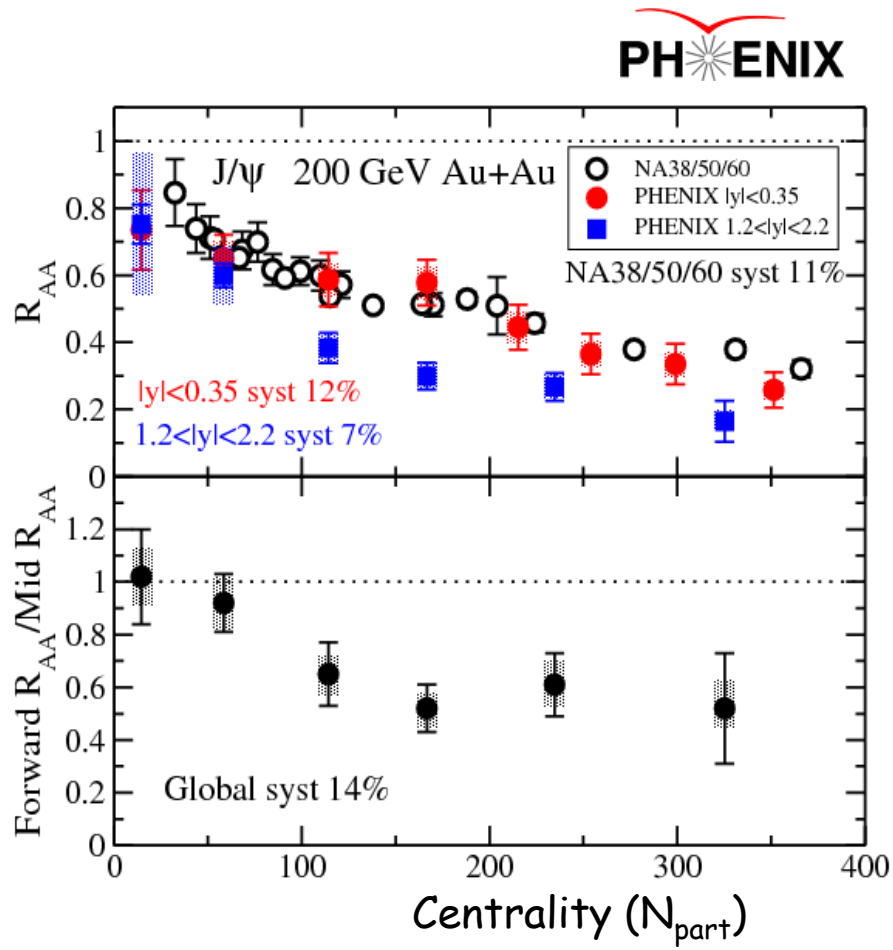
Satz, hep-ph/0512217

| 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 $\chi_c$ & $\psi'$- removing their feed-down contribution to $J/\psi$ at both SPS & RHIC
- Regeneration models
  - give enhancement that compensates for screening

# Reaching Higher $p_T$ for $J/\psi$ - 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

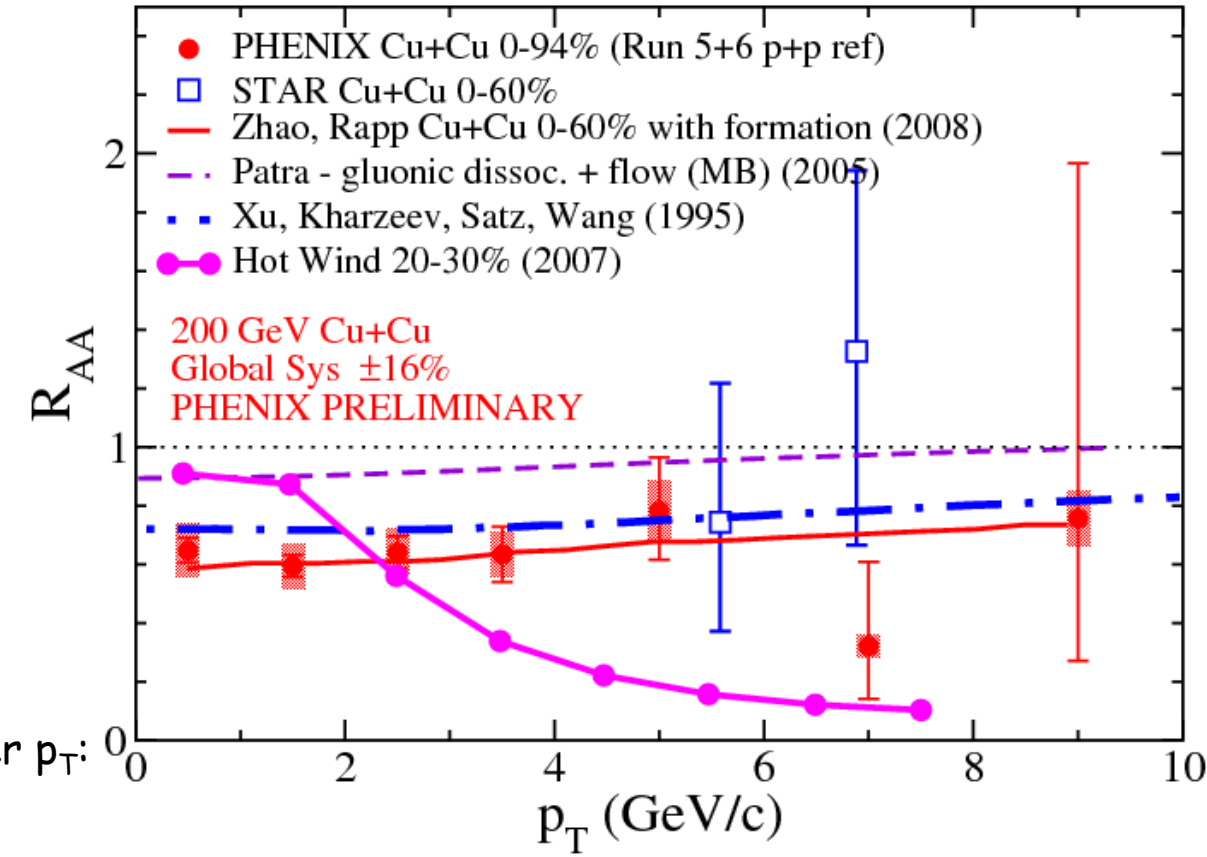
AdS/CFT ("hot wind") - more suppression at high $p_T$:
*Liu, Rajagopal, Wiedemann*
*PRL 98, 182301(2007)*

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

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

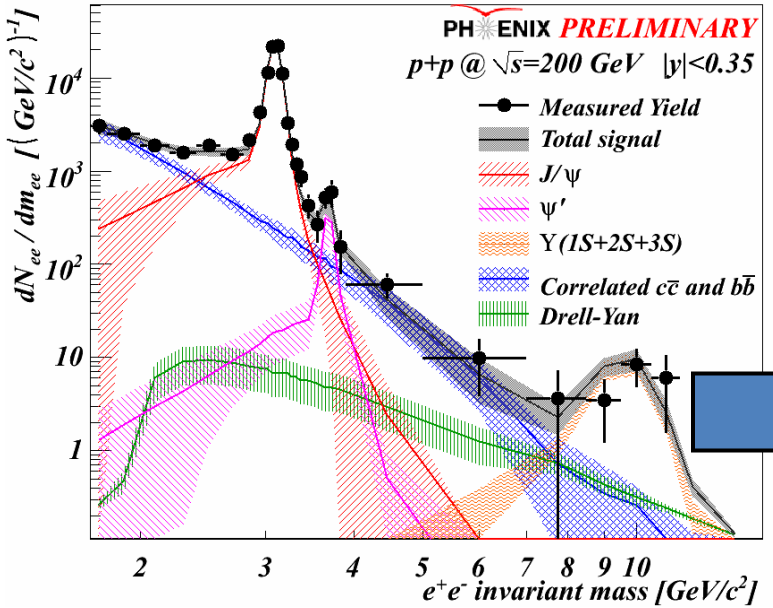
Gluonic dissoc. & flow:
Patra, Menon, *nucl-th/0503034*

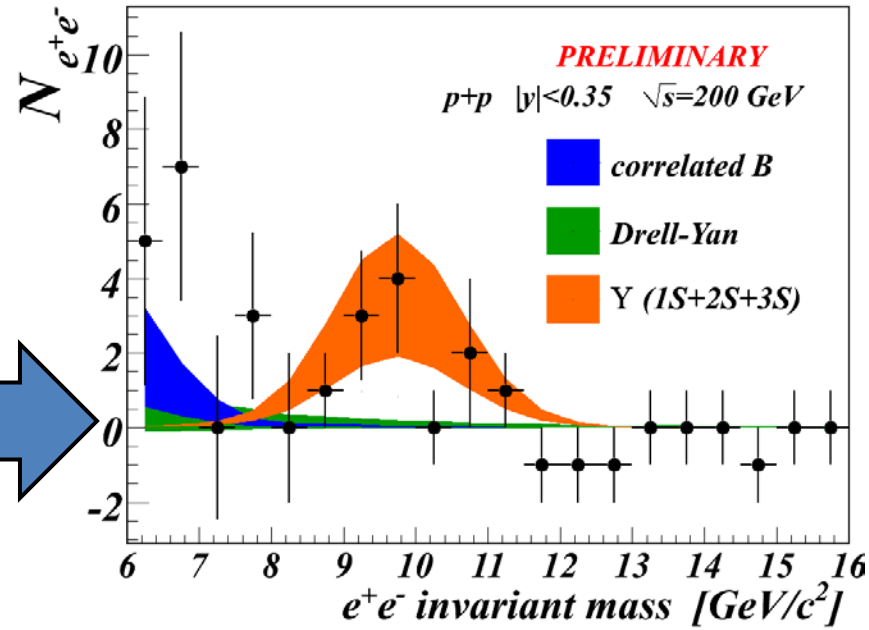
Cronin – less suppression at higher $p_T$:
use d+Au data as a guide



# Upsilons at RHIC & Fermilab

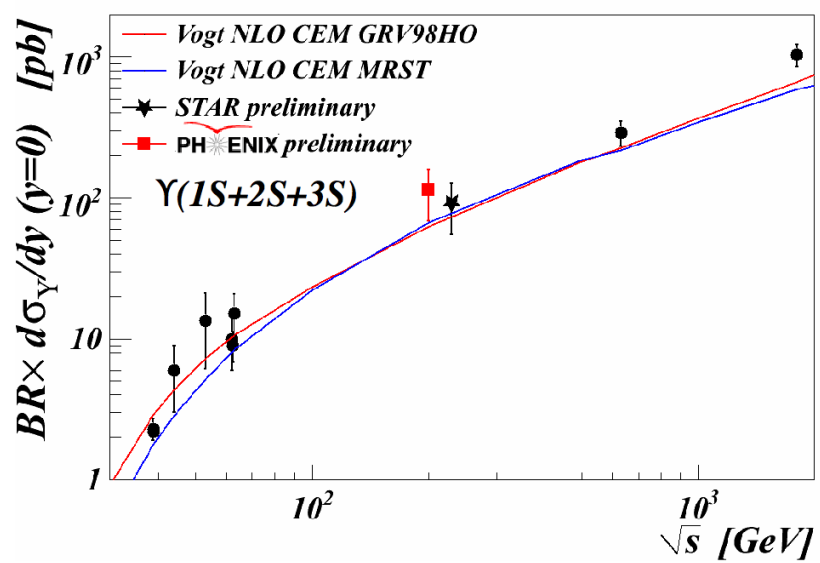
# Quarkonia Production & Suppression – Upsilons in p+p



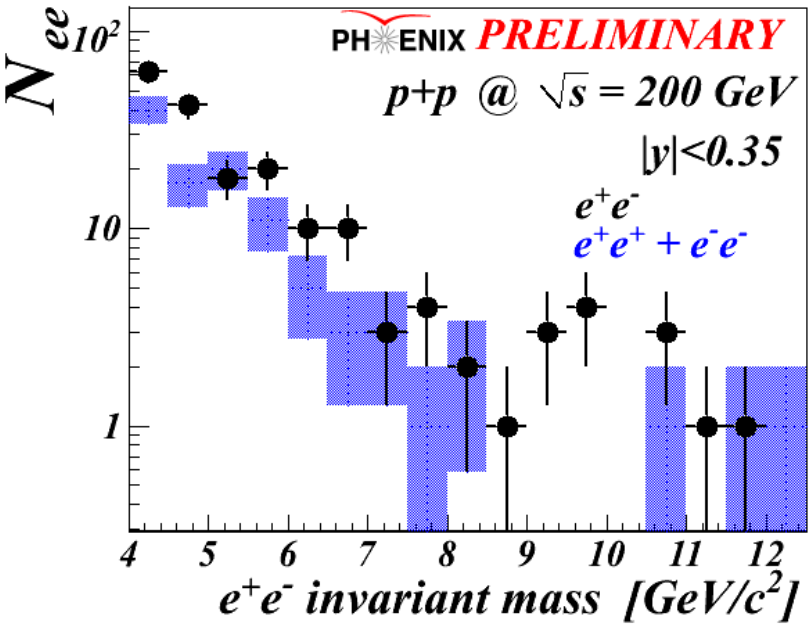



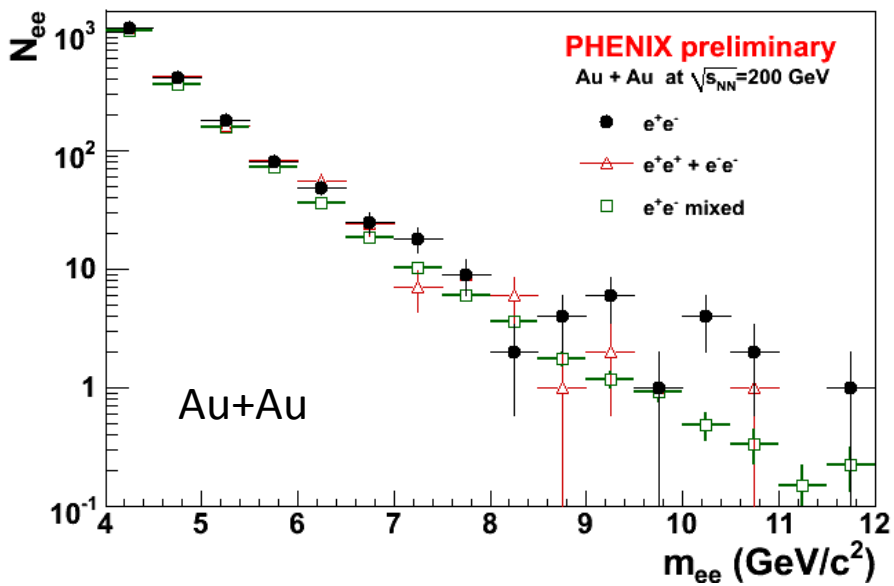

- Cross section follows world trend
- Baseline for Au+Au

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

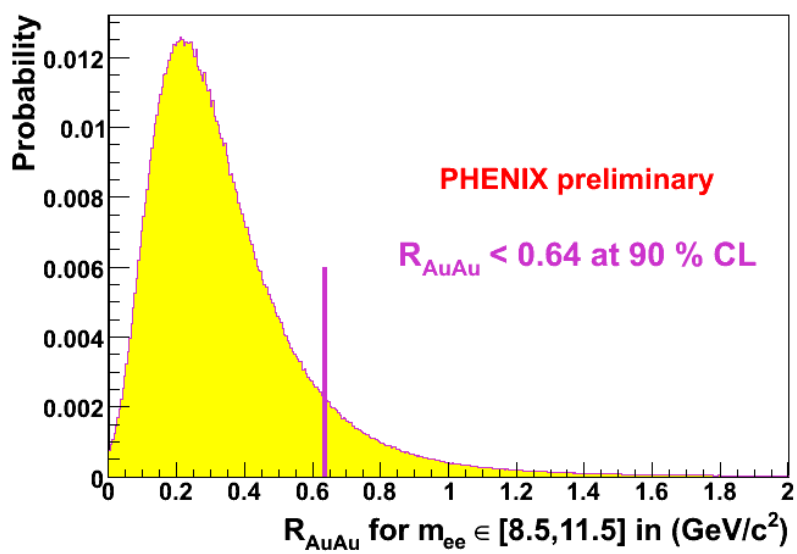


# Quarkonia – Upsilons Suppressed in Au+Au




| | 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 $\Upsilon$'s be Suppressed?

$\Upsilon$'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. |

- $\sigma_{abs}$ of $\Upsilon$ ~1/2 of that for J/Ψ – E772 (*PRL 64, 2479 (1990)*)
  - E772 $\Upsilon$ nuclear dependence corresponds to $R_{AuAu} = 0.81^2$
- Lattice expectations in Au+Au - $\Upsilon_{2S+3S}$ 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:

- $\Upsilon$ in anti-shadowing region (for mid-rapidity)
- CDF: 50% of $\Upsilon$ from $\chi_b$ 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 $\Upsilon$ yield into prompt and feeddown contributions from excited bottomonia in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 39$ GeV [43].

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

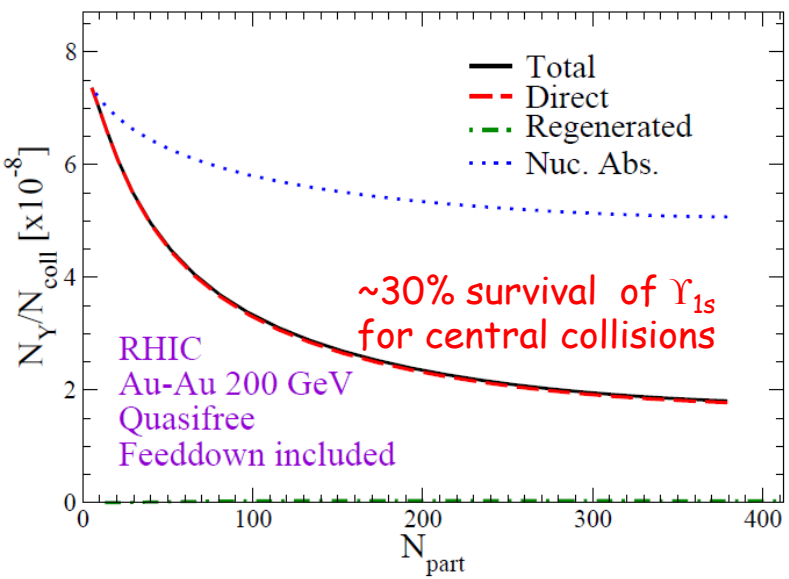
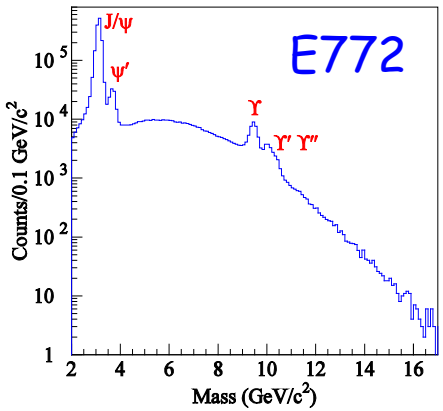


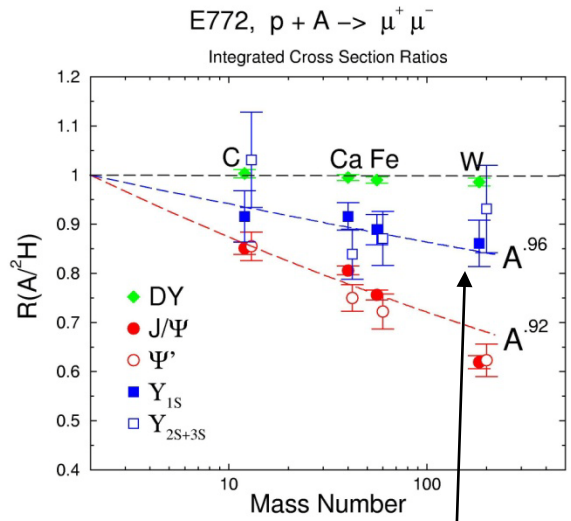

FIG. 14: (Color online) Centrality dependence of $N_\Upsilon/N_{\rm coll}$ at RHIC (Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV) using the quasifree suppression mechanism including color-screening. Dashed line: suppressed primordial $\Upsilon$. Dash-dotted line: regenerated $\Upsilon$. Solid line: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

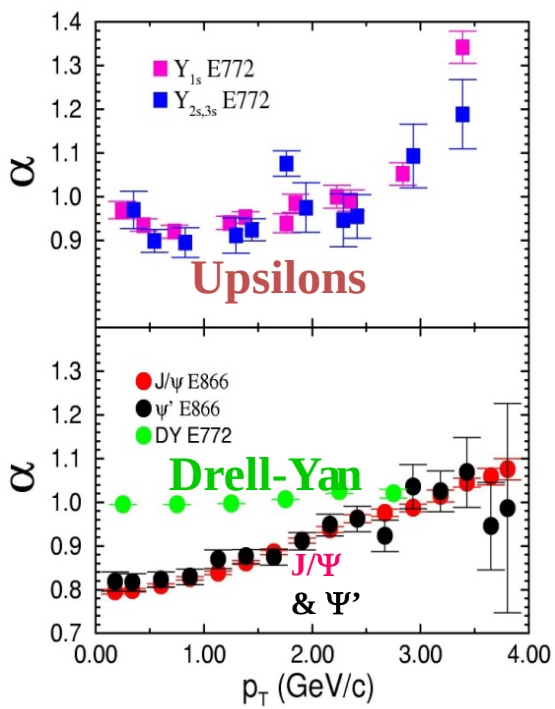
# Contrasting ϒ's with J/Ψ's

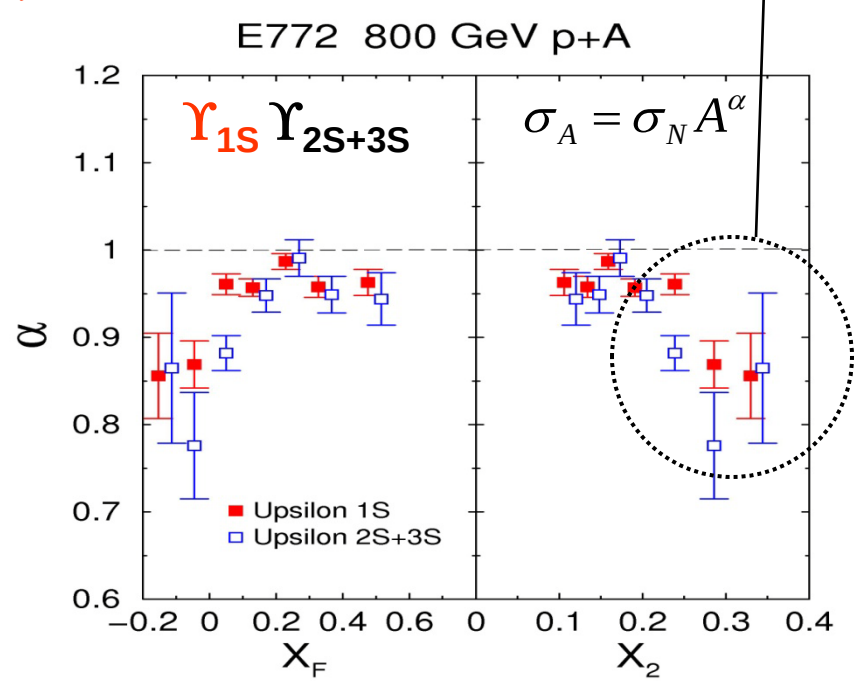



$\sqrt{s}$ =39 GeV (E772 & E866)

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




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