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Fifth International Conference on
**PERSPECTIVES IN HADRONIC PHYSICS**
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

**22 - 26 May 2006**

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# Quarkonia Production in pp, p(d)A & AA Collisions

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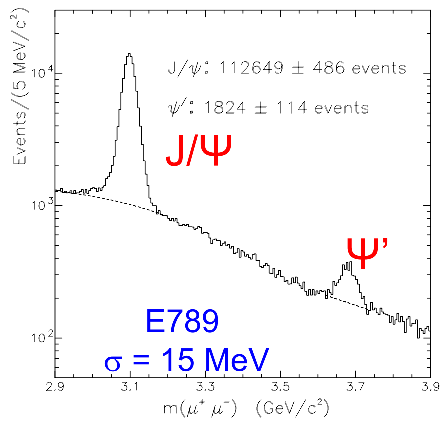
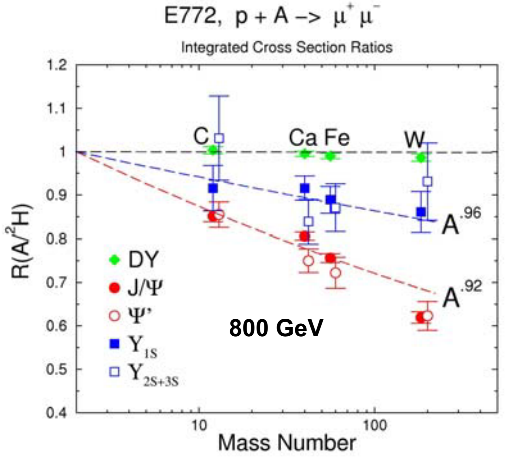
# Quarkonia Production in pp, p(d)A & AA Collisions

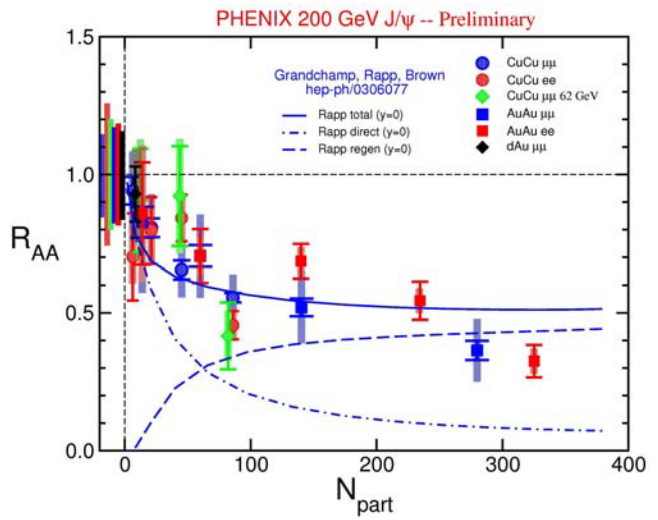
*Mike Leitch – LANL - leitch@lanl.gov*

*Perspectives in Hadronic Physics, INFN Trieste – 22-26 May 2006*

- production
  - cross section & polarization
  - feed-down
- cold nuclear matter
  - shadowing or gluon saturation
  - absorption
  - gluon energy loss
  - contrasting open & closed charm
  - initial-state $p_T$ broadening
- hot-dense matter in A-A collisions
  - PHENIX results
  - cold-nuclear matter effects in A+A
  - sequential suppression & regeneration
- future prospects
- summary

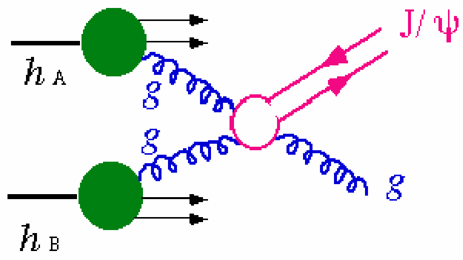


# J/ψ production, parton level structure & dynamics

Production of heavy vector mesons, J/ψ, ψ′ and ϒ




Gluon fusion dominates (NLO calculations add more complicated diagrams, but still mostly with gluons)

- color singlet or octet $c\bar{c}$: absolute cross section and polarization? Difficult to get both correct!

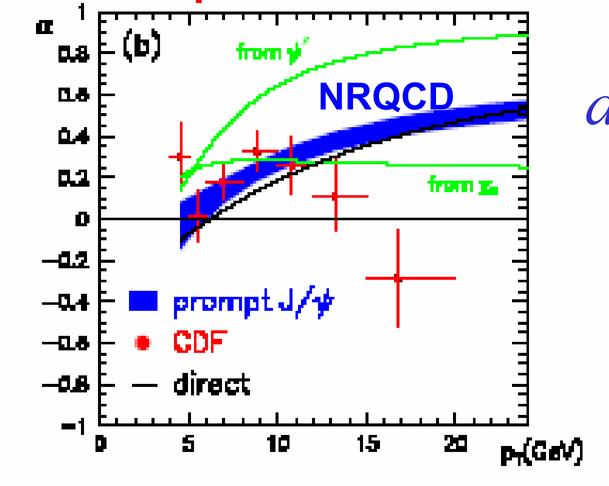
Hadronization time (important for pA nuclear effects)

Complications due to substantial feed-down from higher mass resonances, from ψ′, $\chi_c$

| | |
|---|---|
| $\chi_{,1,2} \rightarrow J/\psi$ | ~30% |
| $\psi' \rightarrow J/\psi$ | 5.5% |

# J/ψ Production - Polarization

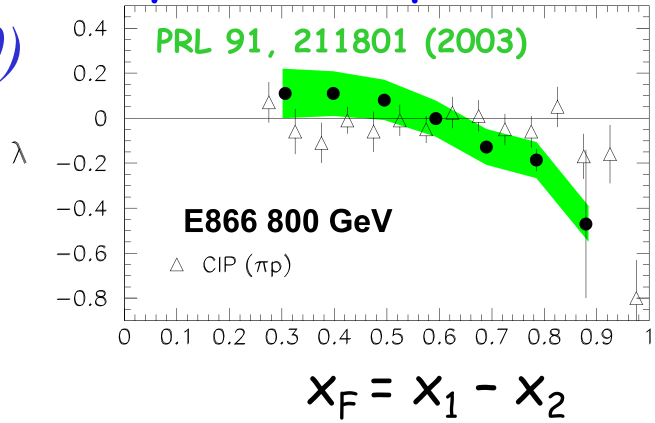
**J/ψ Polarization**



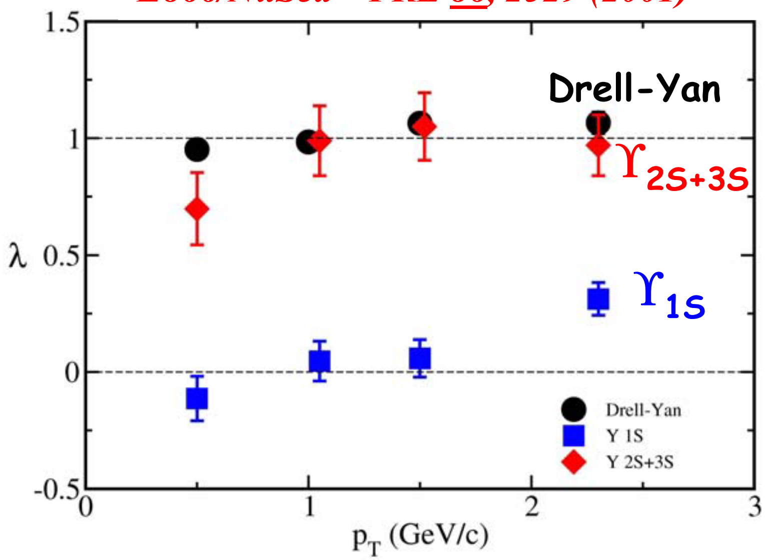

$$d\sigma/d\cos\theta = A(1+\lambda\cos^2\theta)$$

***λ = +1 (transverse)***
***= -1 (longitudinal)***

**E866/NuSea**
**very small J/ψ polarization**




*E866/NuSea – PRL 86, 2529 (2001)*

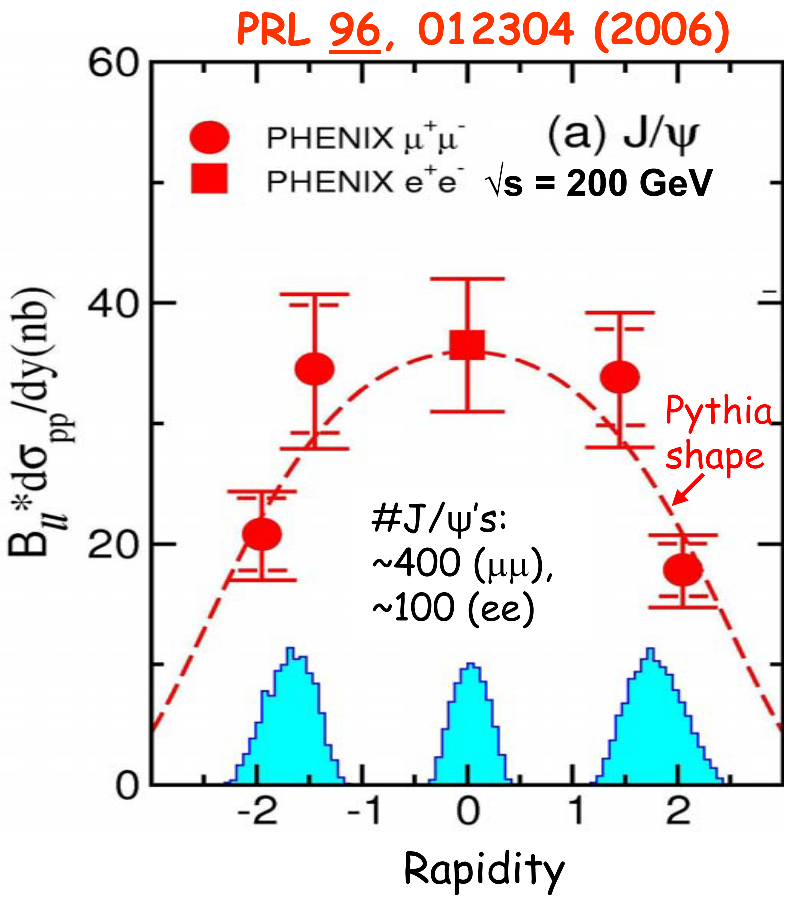


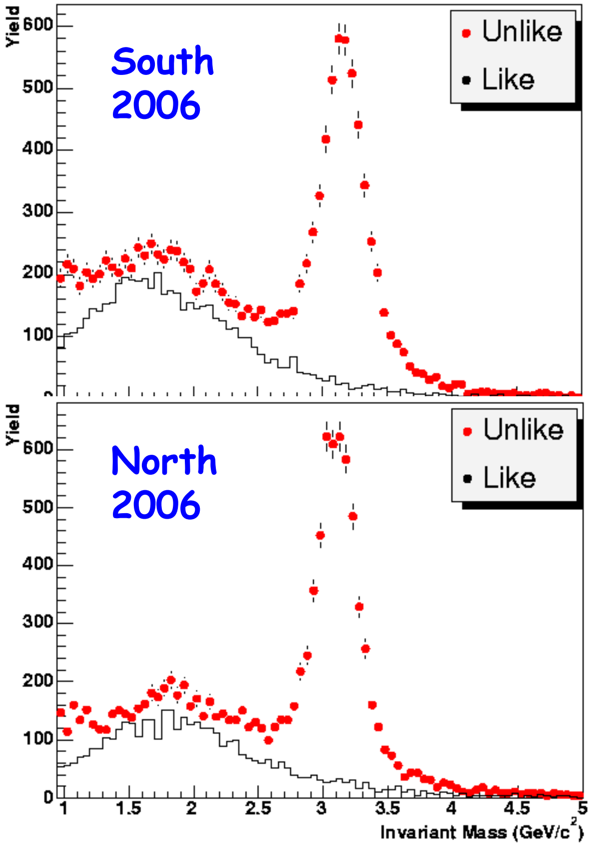

- Octet models get correct cross section size (unlike singlet), but…
- CDF and Fermilab E866 J/ψ data show little polarization & disagree with NRQCD predictions

But Υ maximally polarized for (2S+3S), but NOT (1S)
- Is feed-down washing out polarization? (~40% of 1S from feed-down)

(also need ψ′ polarization measurement)

# PHENIX - J/ψ cross section vs rapidity




More pp J/ψ's coming from PHENIX - ~5k/arm in 2005 run; 2006 online analysis above.

(ψ' may be coming soon, at least for $e^+e^-$, but higher luminosities will be needed to get significant # of counts)

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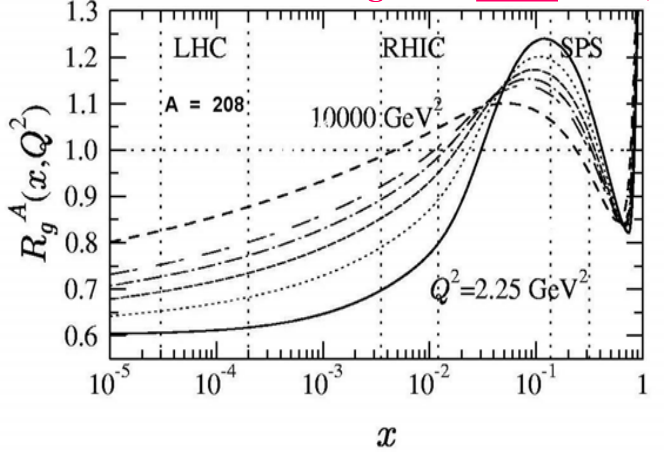
# Nuclear effects on Onia Production

Modification of parton momentum distributions of nucleons embedded in nuclei

- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation at small x – e.g. Color Glass Condensate (CGC) model

*Eskola, Kolhinen, Vogt, NP A696, 729 (2001)*

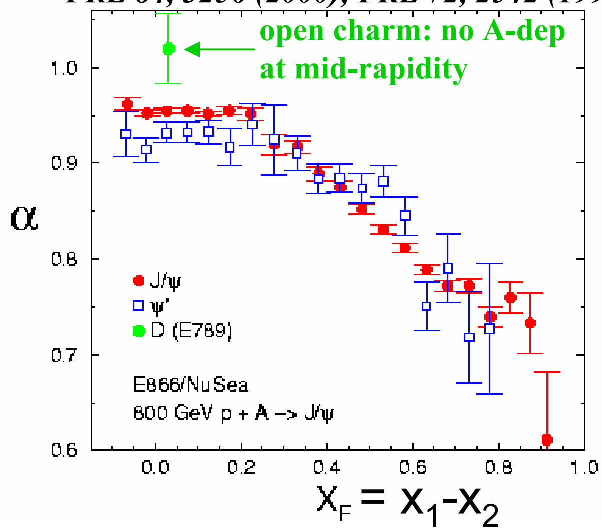



Nuclear effects on parton "dynamics"

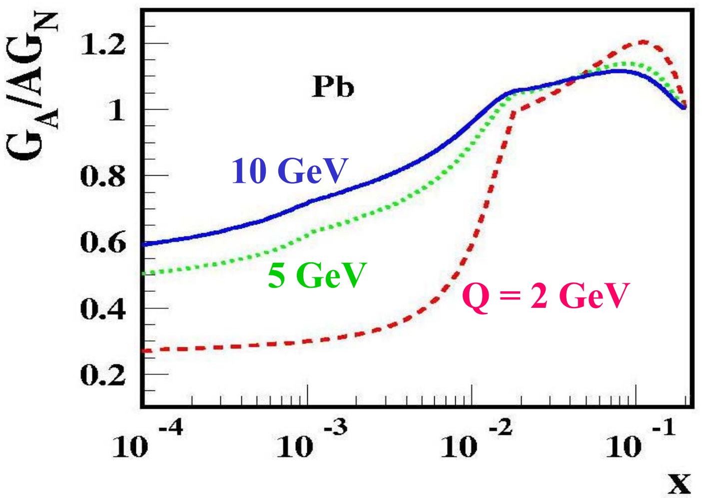
- absorption (or disassociation) of J/ψ by nucleons or co-movers
- energy loss of partons as they propagate through nuclei
- multiple scattering effects (Cronin effect) causing $p_T$ broadening

**800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$**

*PRL 84, 3256 (2000); PRL 72, 2542 (1994)*



# Gluon Shadowing and Saturation




Leading twist gluon shadowing

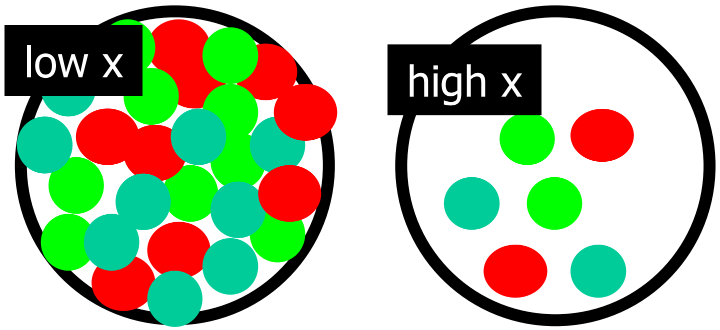
- e.g. "FGS", Eur. Phys. J A5, 293 (1999)

Phenomenological fit to DIS & Drell-Yan data

- e.g. "EKS", Nucl. Phys. A696, 729 (2001).

Coherence approach and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!



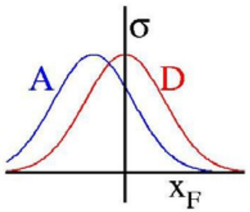

Saturation or Color Glass Condensate (CGC)

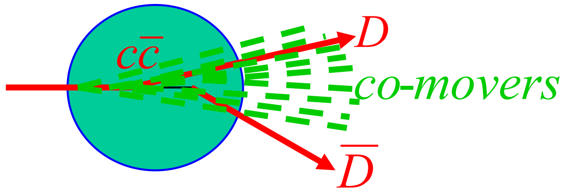
- At low-x there are so many gluons that 2→ 1 diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

# The J/ψ - a Cold Nuclear Matter (CNM) Puzzle

J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:

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

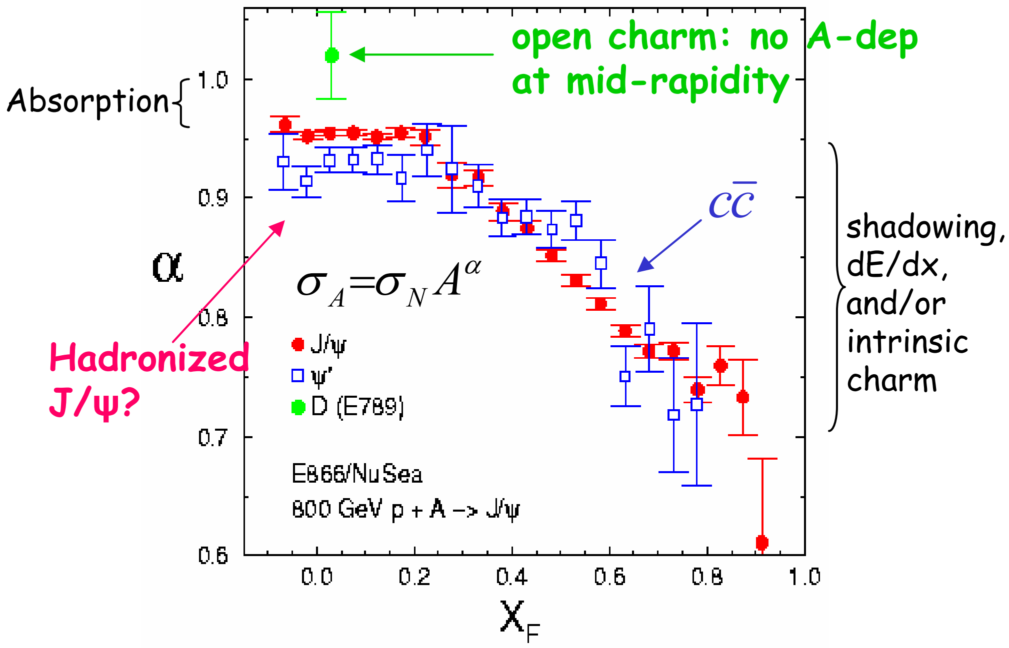


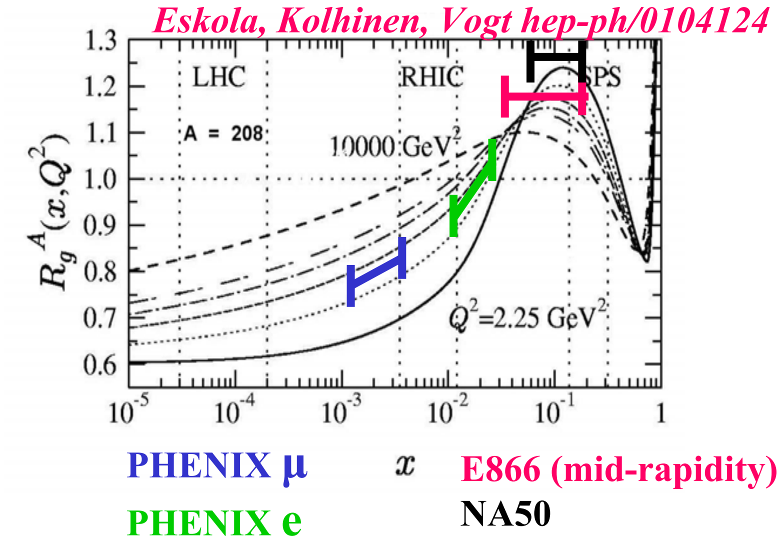

**Absorption** (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

**800 GeV p-A (FNAL)**

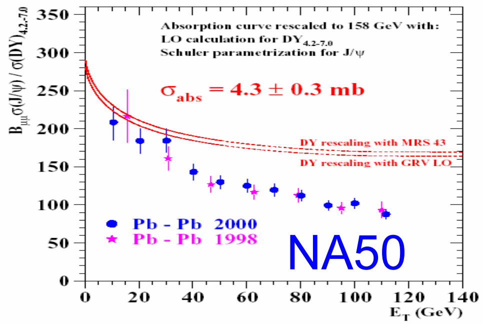
***PRL 84, 3256 (2000); PRL 72, 2542 (1994)***



# Absorption of J/ψ's not so simple?



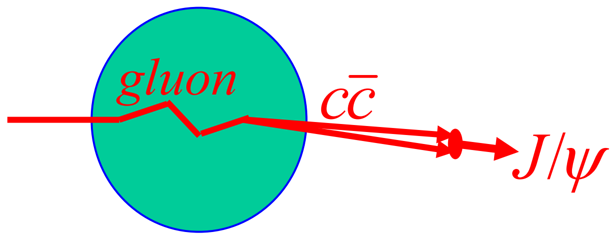

| Set | $P_{lab}$ | $N_0$ (nb) | $\sigma_{abs}$ (mb) |
|---|---|---|---|
| NA50 | 450 GeV | 5.6±0.1 | 4.1±0.4 |
| NA50 | 400 GeV | 5.1±0.1 | |
| NA38 (corrected) | 400 GeV | 5.5±0.2 | |




- What really is $\sigma_{abs}^{J/\psi}$ ?
  - An effective quantity
  - What is crossing the nucleus and how does it evolve?
    - pre-resonant $c\bar{c}$ state, fully formed resonance?
  - Are we measuring primary J/ψ?
    - feed-down from ψ' and $\chi_c$
    - will fraction of feed-down change in AA collisions?
  - Does anti-shadowing make absorption appear smaller than it is?

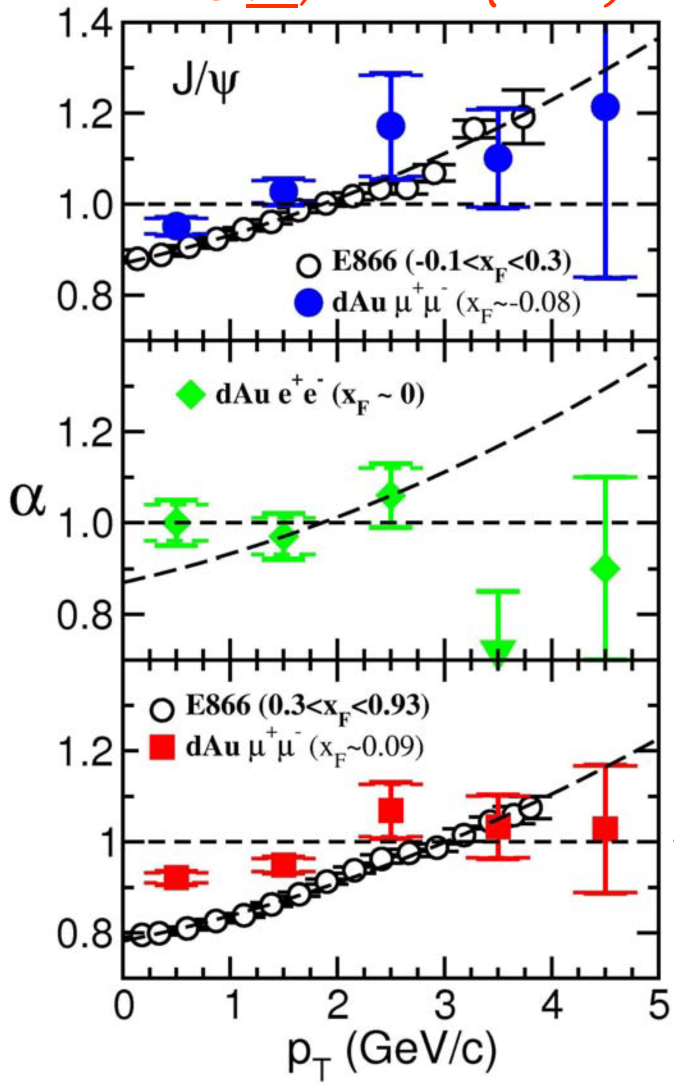
# Transverse Momentum Broadening for J/ψ's

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




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

*PRL 96, 012304 (2006)*

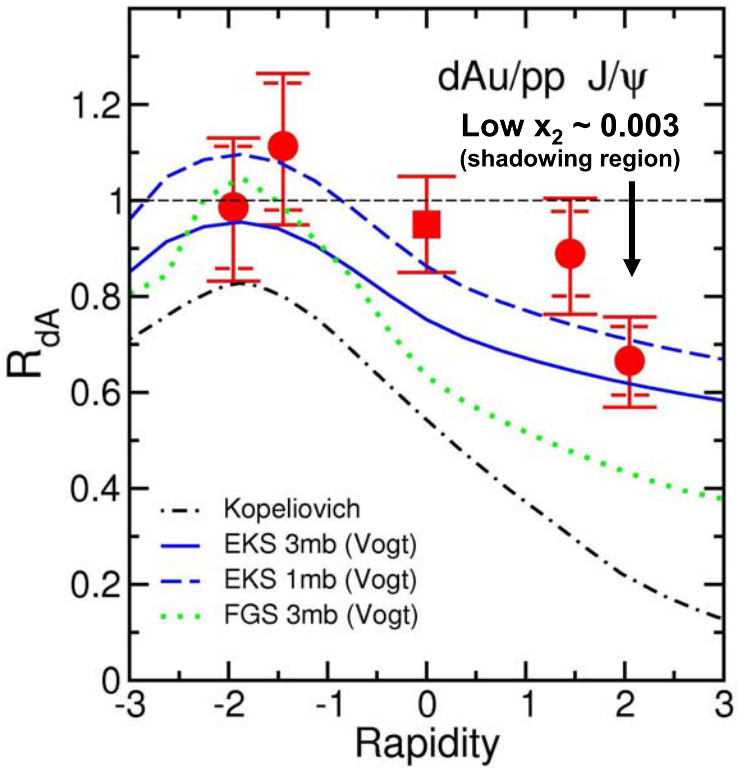



**High $x_2$ ~ 0.09**

**PHENIX 200 GeV results show $p_T$ broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)**

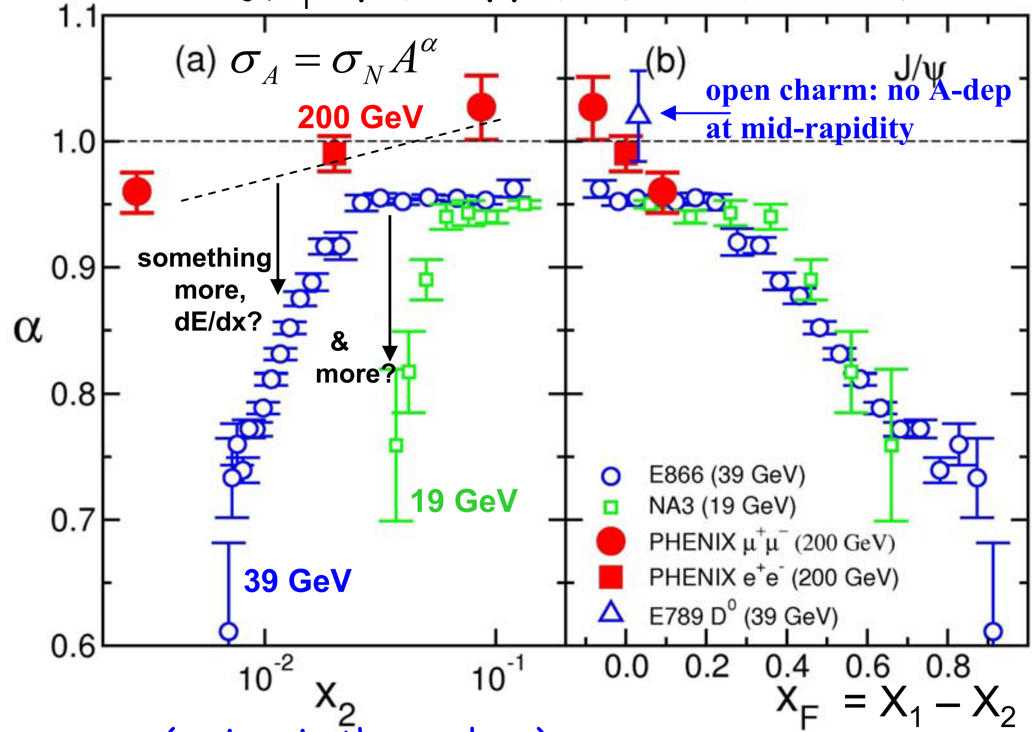
**Low $x_2$ ~ 0.003**

# PHENIX J/ψ Nuclear Dependence for 200 GeV pp and dAu collisions – PRL 96, 012304 (2006)




Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

J/ψ for different √s collisions




($x_2$ is x in the nucleus)

Data favors weak shadowing & absorption

- With limited statistics difficult to disentangle nuclear effects
- Will need another dAu run! (more pp data also)

Not universal vs $x_2$ as expected for shadowing, but does scale with $x_F$, why?

- initial-state gluon energy loss?
- Sudakov suppression (~energy conservation)?

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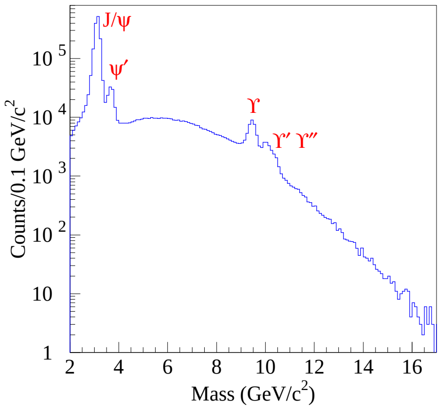
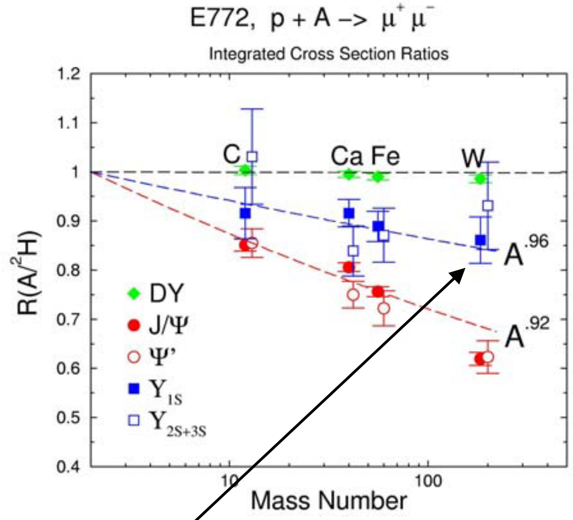
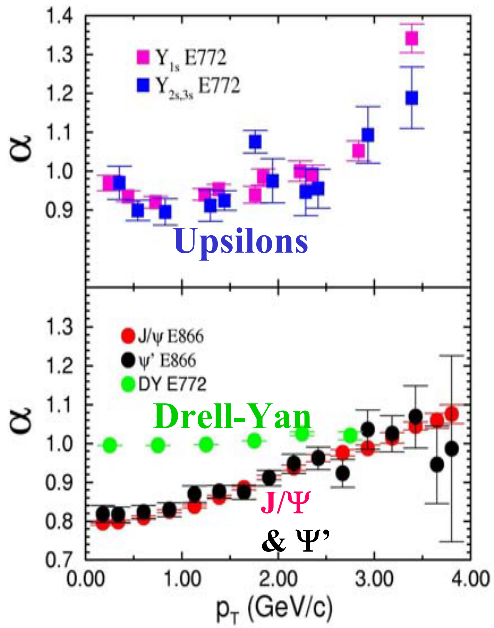
# Contrasting Υ's with J/ψ's



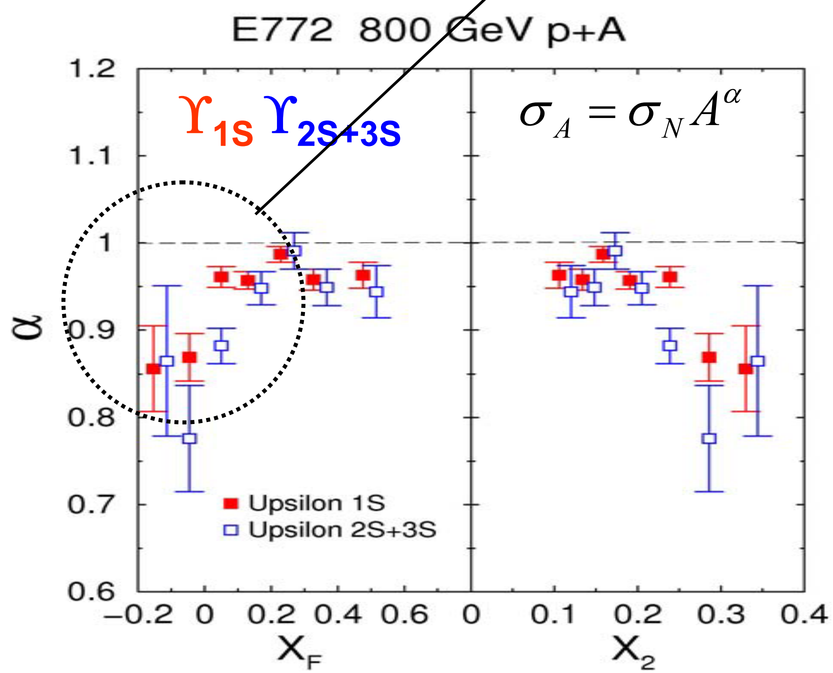

$\sqrt{S}$ =39 GeV (E772 & E866)

- 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 is from data for $x_F$ < 0 or $x_2$ > 0.2 (in the EMC region)



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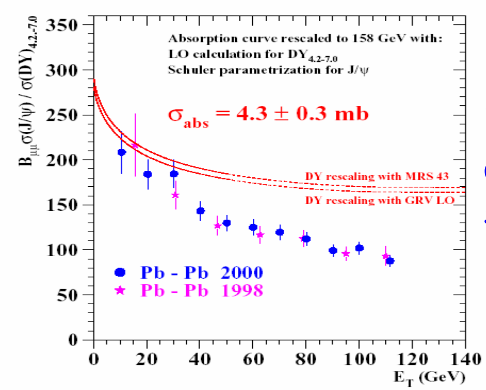
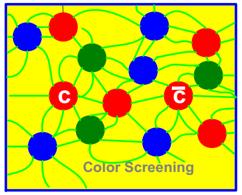
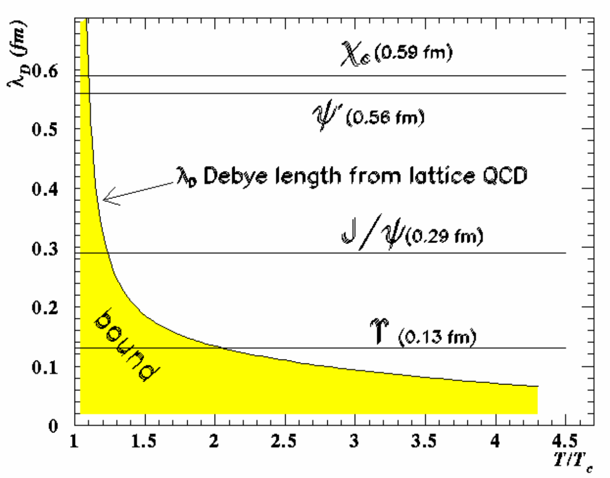
# AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

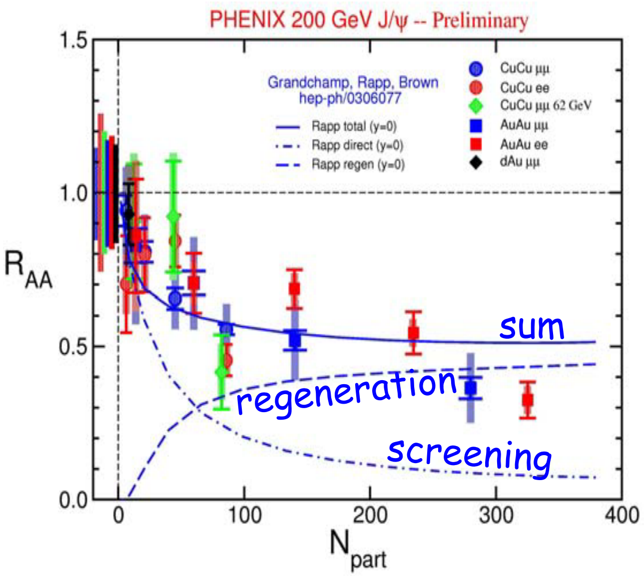
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



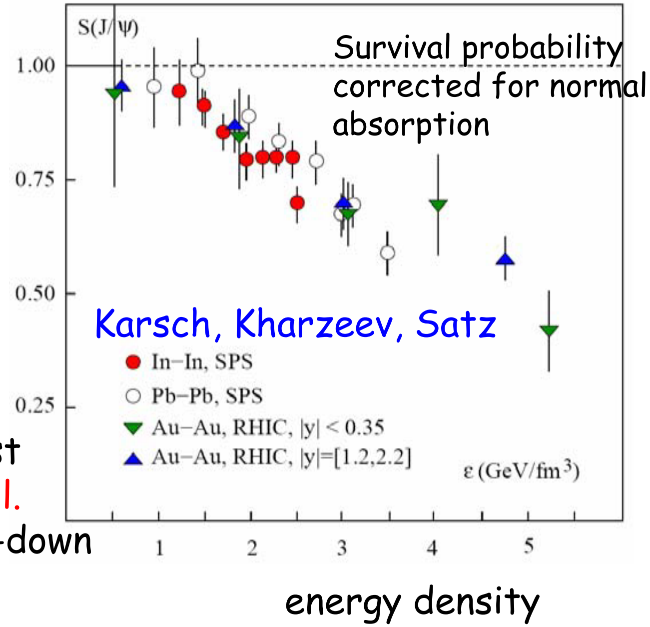

NA50 anomalous suppression



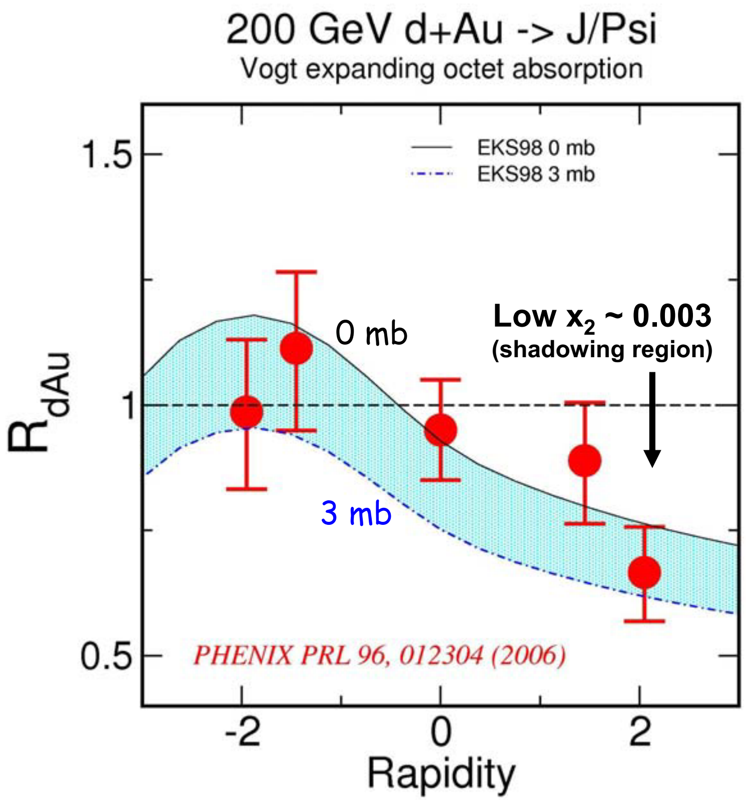

but recent regeneration models might give enhancement that compensates for screening?
Grandchamp, Rapp, Brown

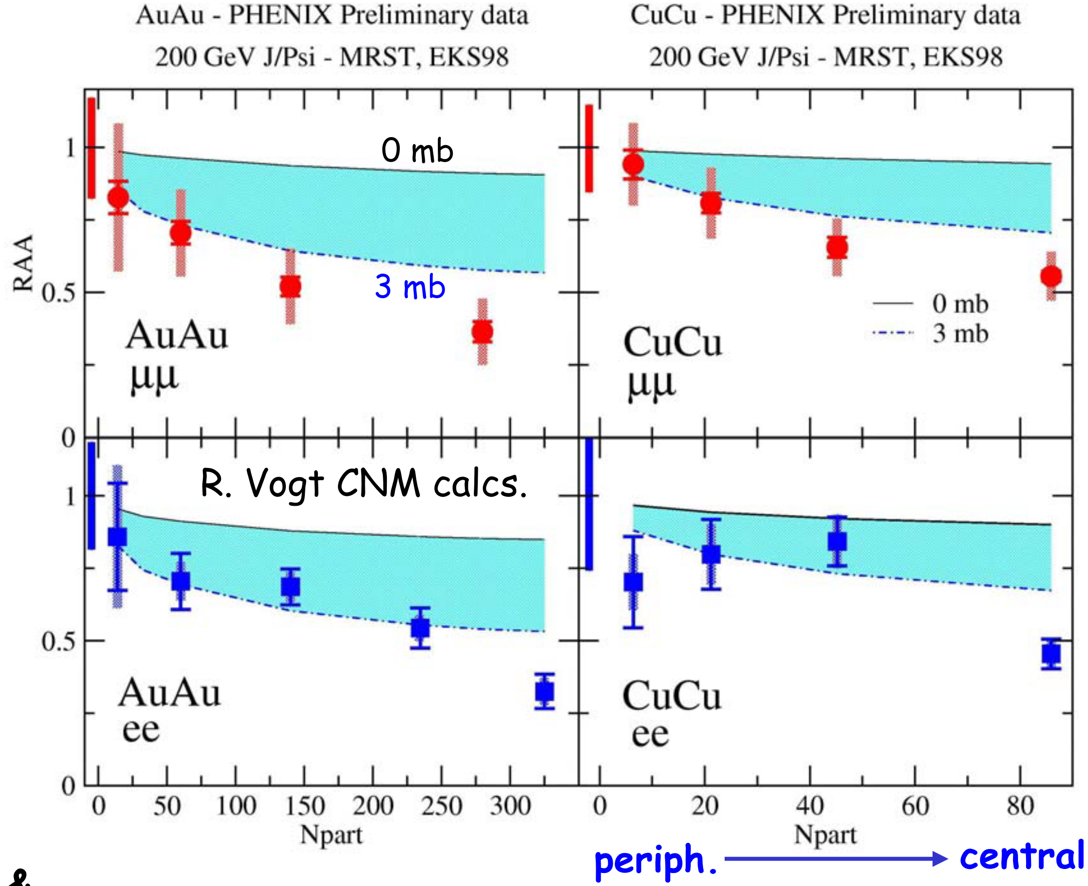



on the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened $\chi_c$ & ψ'

# J/ψ suppression in AA collisions & CNM baseline

(CNM = Cold Nuclear Matter)

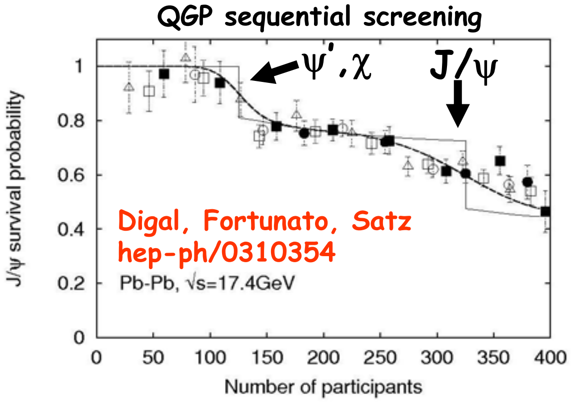


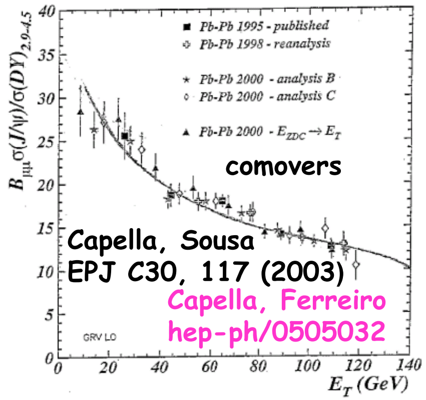



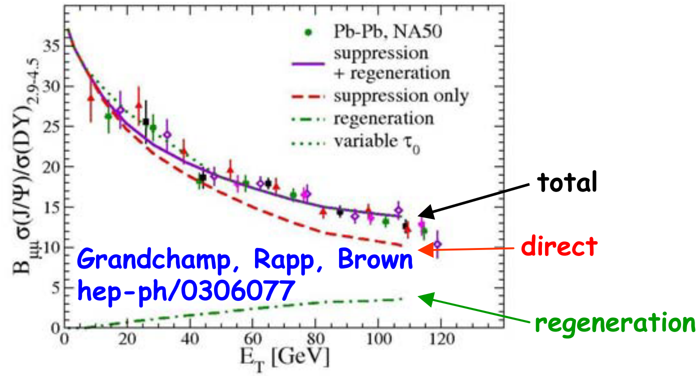

- CNM calculations with shadowing & absorption
- present dAu data probably only constrains absorption to: $\sigma_{ABS}$ ~ 0-3 mb

- AA suppression is somewhat stronger than CNM calculations predict
- but really need more precise dAu constraint!

# Models without regeneration

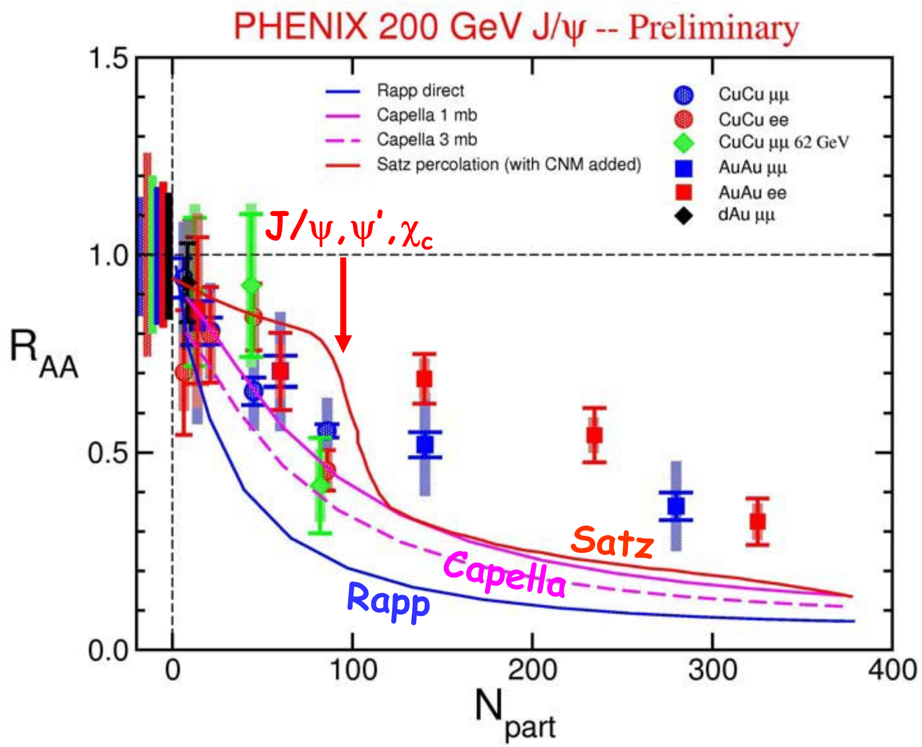



**Models that reproduce NA50 results at lower energies predict too much suppression at RHIC!**

- **Satz - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)**
- **Capella – comovers with normal absorption and shadowing**
- **Rapp – direct production with CNM effects needs very little regeneration to match NA50 data**

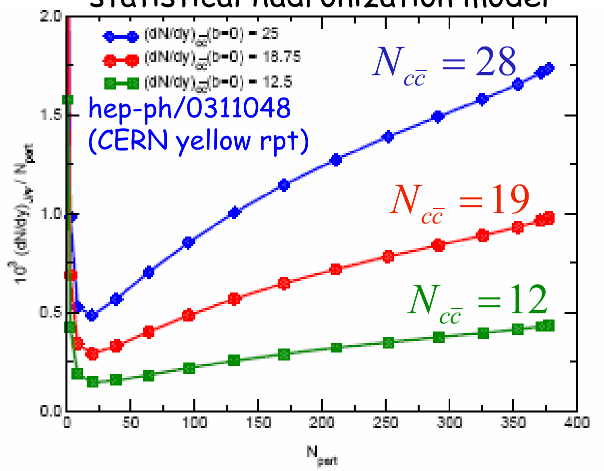


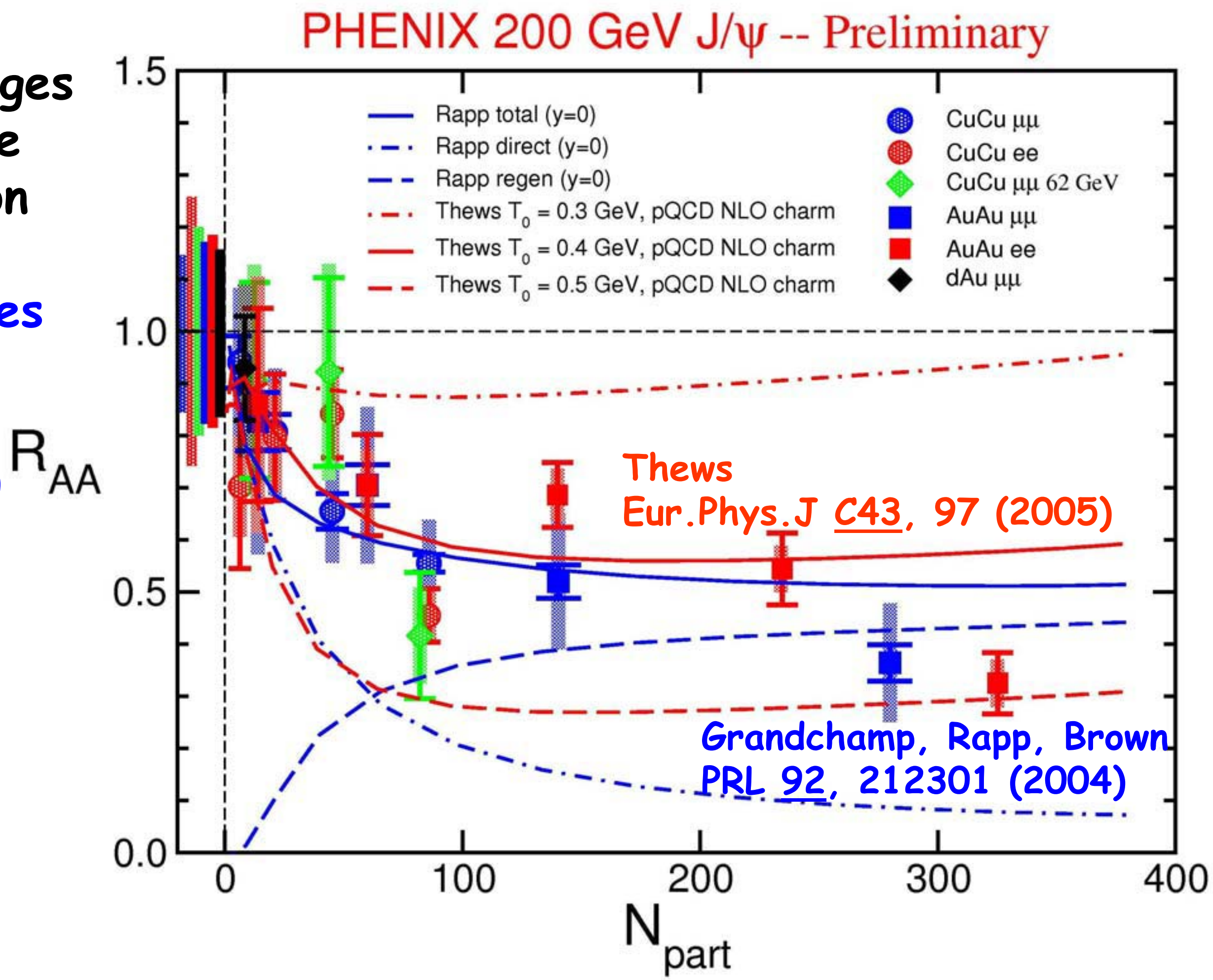
# Models with screening & regeneration

**Models with regeneration, i.e. single charm quarks combining in the later stages to form J/ψ's – match the observed RHIC suppression much better!**

- **but the regeneration goes as $\sigma_{c\bar{c}}^2$ - which is still poorly known at RHIC (& that's another story..)**

statistical hadronization model



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# Many More Models for RHIC J/ψ suppression in CuCu & AuAu Collisions

**All have suppression + various regeneration mechanisms**

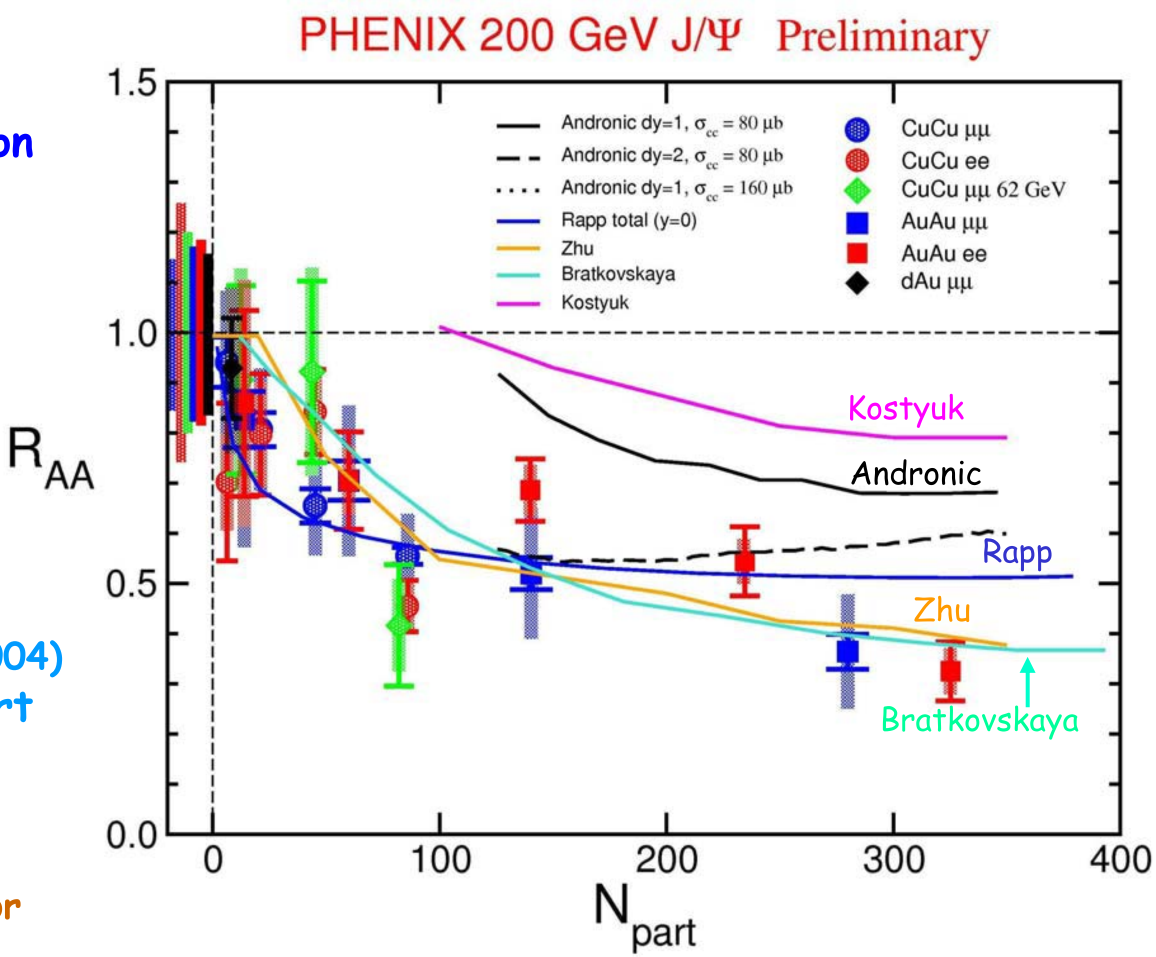
**Rapp - PRL 92, 212301 (2004)**
- **screening & in-medium production**

**Thews – see previous slide**

**Andronic - PL B57, 136 (2003)**
- **statistical hadronization model**
- **screening of primary J/ψ's**
- **+ statistical recombination of thermalized c-cbar's**

**Kostyuk – PRC 68, 041902 (2003)**
- **statistical coalescence**
- **+ comovers or QGP screening**

**Bratkovskaya – PRC 69, 054903 (2004)**
- **hadron-string dynamics transport**




**Zhu - PL B607, 107 (2005)**
- **J/ψ transport in QGP**
- **co-movers, gluon breakup, hydro for QGP evolution**
- **no cold nuclear matter, no regeneration**

# Regeneration or Sequential Screening?

RHIC suppression looks same as that at NA50

- but ~10x collision energy & ~2-3x gluon energy density at RHIC
- regeneration compensates for stronger QGP suppression?
    - if so, regeneration would be huge at the LHC!

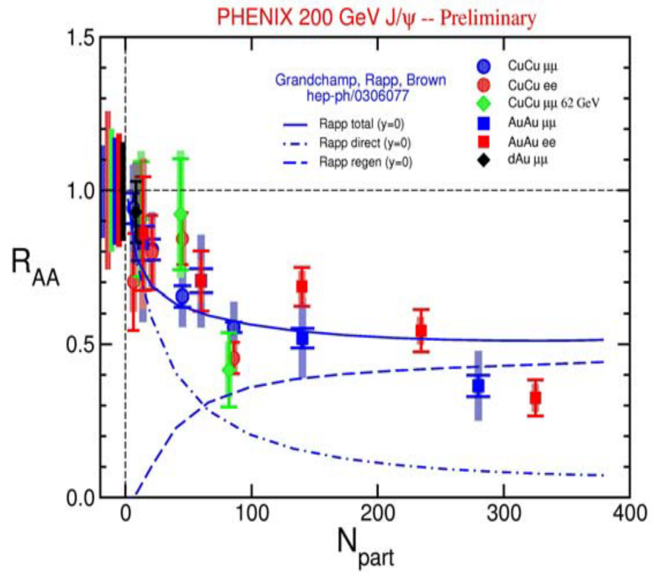
------------- OR -------------------

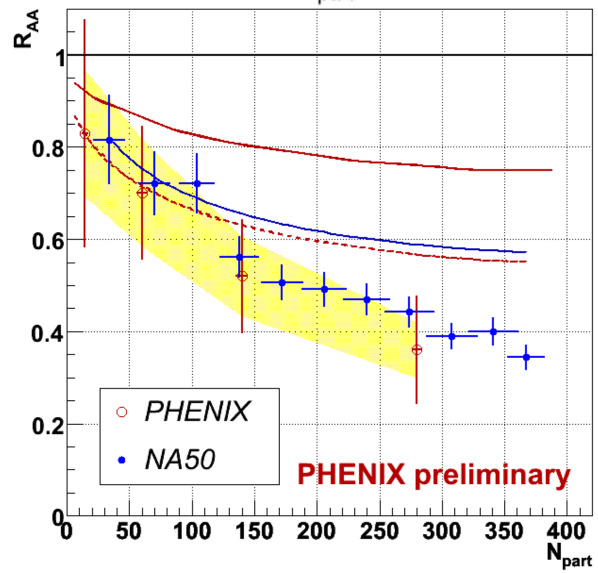
(Karsch, Kharzeev, Satz, hep-ph/0512239)

- Sequential screening of the higher-mass resonances that feed-down to the J/ψ; with the J/ψ itself still not dissolved?
- supported by recent Lattice calculations that give $T_{J/\psi} > 2\ T_C$

Quarkonium dissociation temperatures – Digal, Karsch, Satz

| 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 |



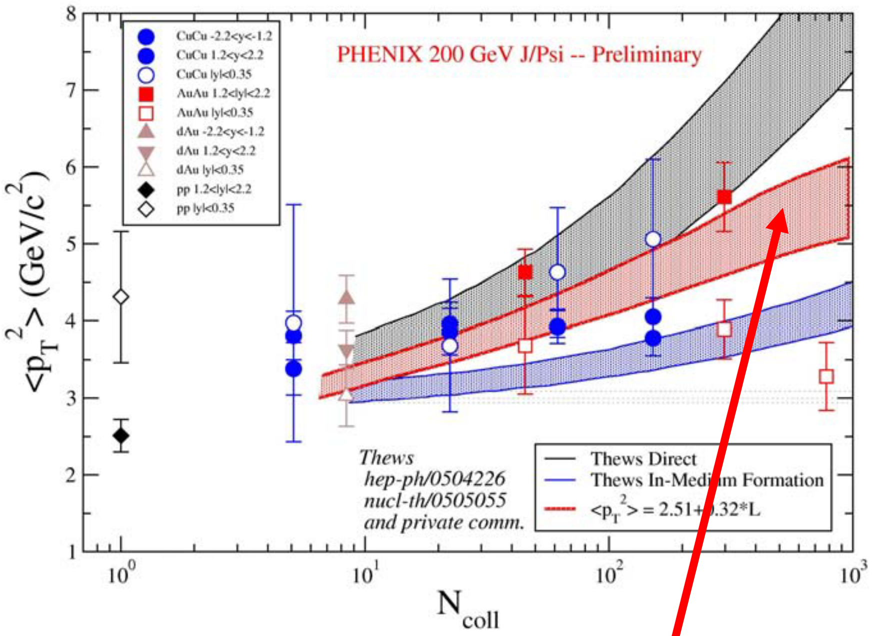



# Regeneration should cause narrowing of $p_T$ and y – does it?

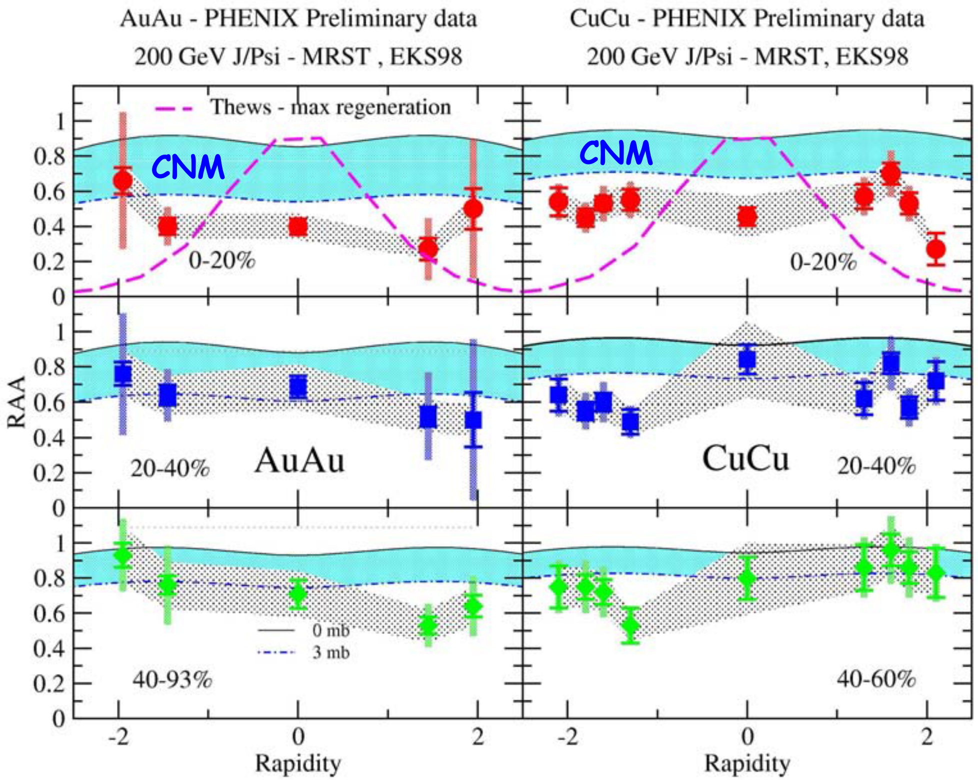
**$p_T$ broadening lies in between Thews direct & in-medium formation suggesting some regeneration (but our fit to pp+dAu data vs L also reasonable)**

**But rapidity dependence of central AA collisions (top panels) shows no narrowing – i.e. peaked ratios as in the Thews (maximal) regeneration, shown below**

**But careful – is $\sigma_{ccbar}$ flatter with y than we originally thought?**



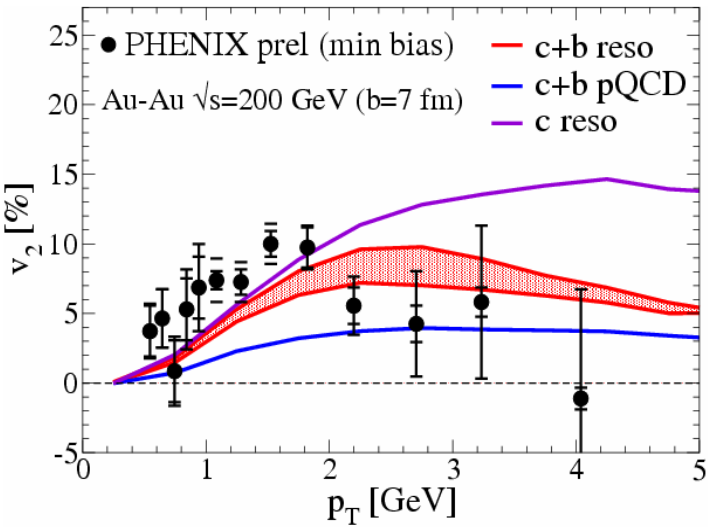

$\langle p_T^2 \rangle = 2.51+0.32*L$ from fit to dAu data vs L



# Flow of J/ψ's?

Need to look for J/ψ flow – if regeneration dominates, the J/ψ's should inherit flow from charm quarks

- open charm has recently been seen to flow (at least at some $p_T$ values)
- but what about geometrical absorption effects, which could also give asymmetry wrt reaction plane?



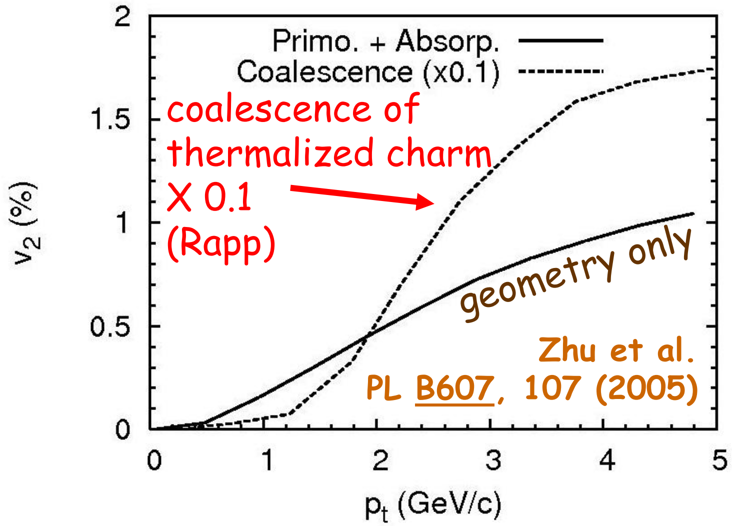
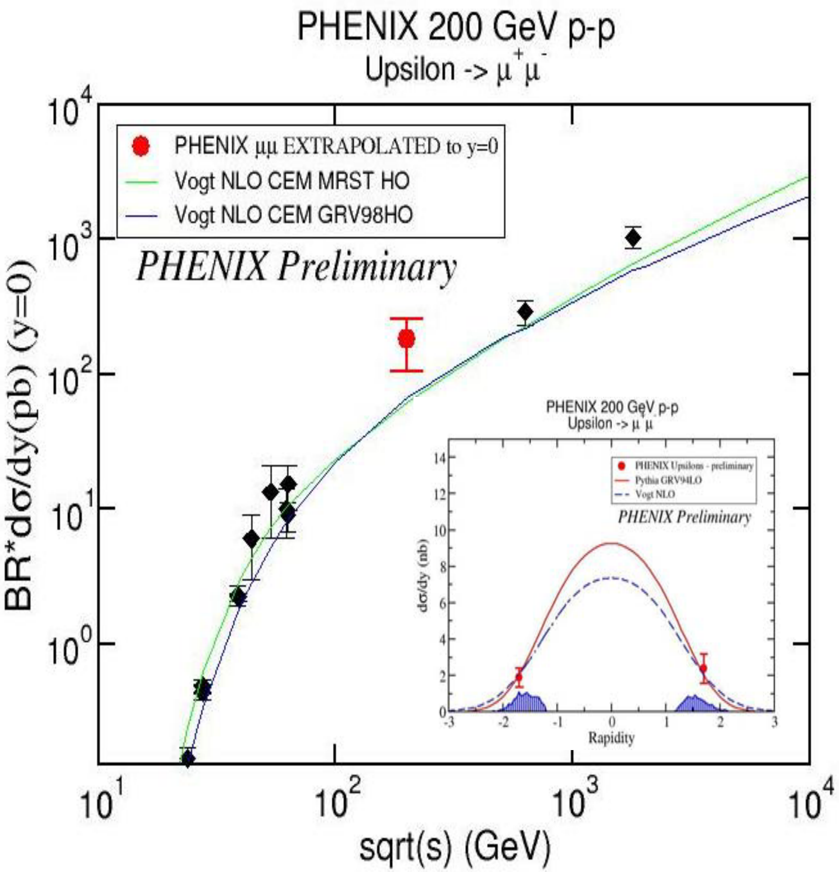



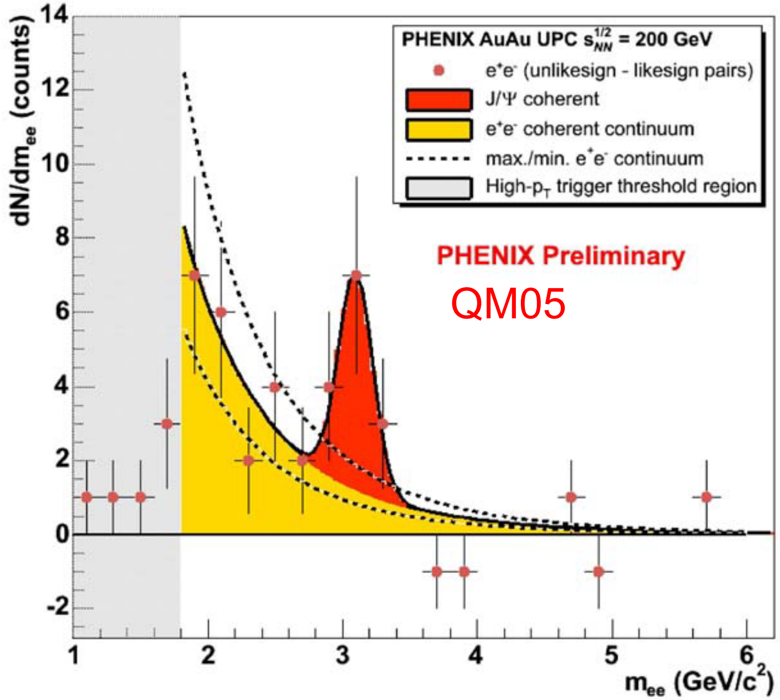

FIG. 4: The elliptical flow of $J/\psi$ as a function of $p_t$ at RHIC energy. The solid line is the maximal $v_2$ with impact parameter b=7.8 fm calculated in the frame of $J/\psi$ transport, and the dashed line is the minimum-bias $v_2$ (scaled by a factor of 0.1) of the coalescence model with the assumption of complete charm quark thermalization.

# Much More to Come!




1st Upsilons at RHIC from ~3pb$^{-1}$ collected during the 2005 run.

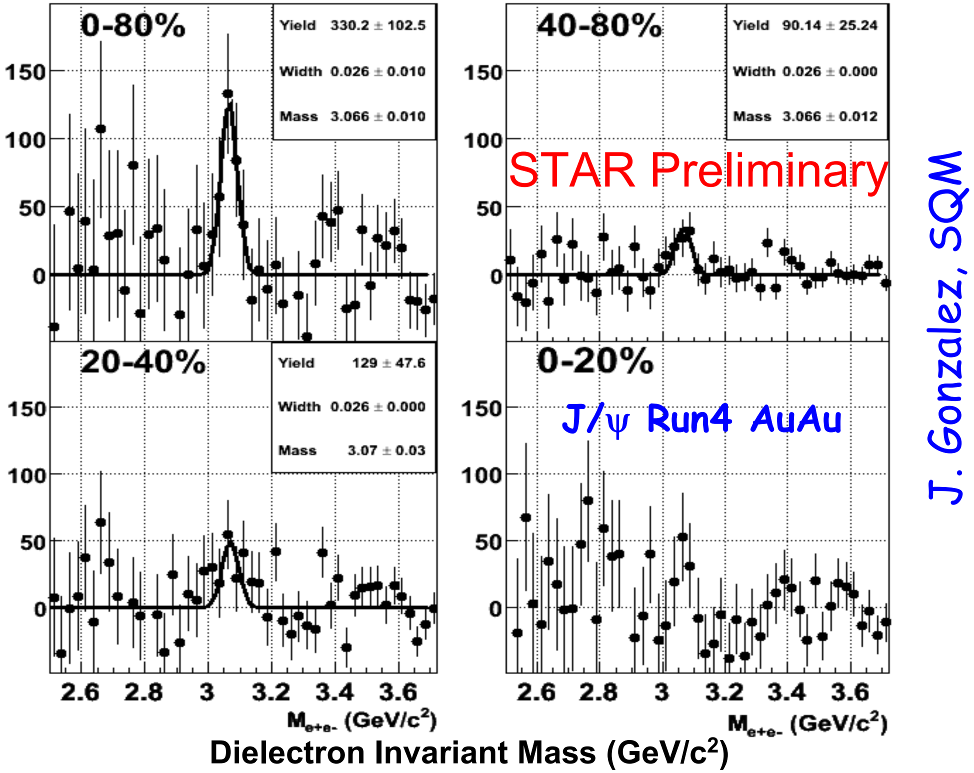
## Ultra-peripheral Collisions (UPC's)

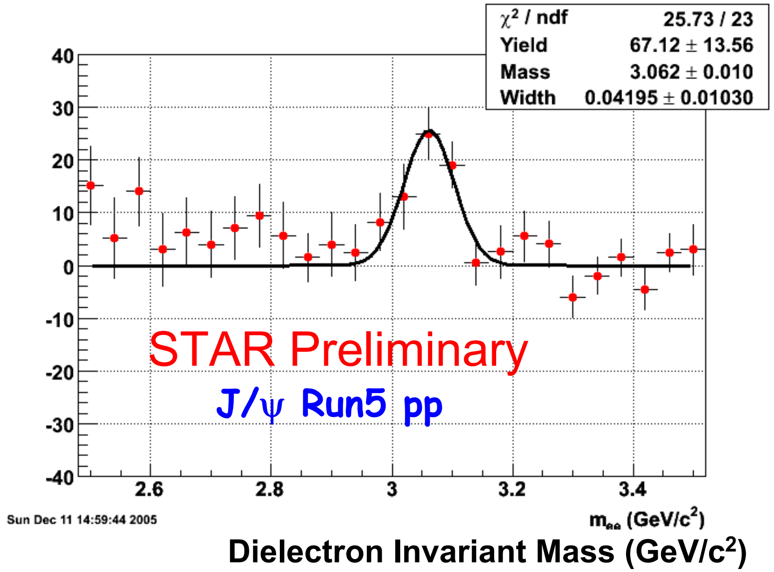



UPC's : well calibrated EM probe of small-x gluon saturation

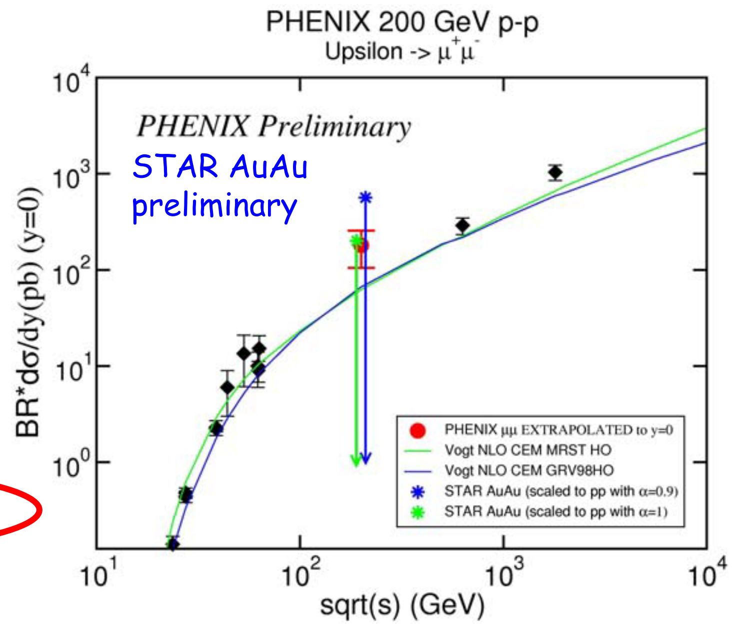
Los Alamos

# Onia in STAR




| Signal | RHIC Exp. (Au+Au) | RHIC I (>2008) | RHIC II | LHC ALICE+ |
|---|---|---|---|---|
| $J/\psi \to e^+e^-$ | PHENIX | 3,300 | 45,000 | 9,500 |
| $J/\psi \to \mu^+\mu^-$ | | 29,000 | 395,000 | 740,000 |
| $\Upsilon \to e^+e^-$ | STAR | 830 | 11,200 | 2,600 |
| $\Upsilon \to \mu^+\mu^-$ | PHENIX | 80 | 1,040 | 8,400 |



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# RHIC-II - Quarkonia

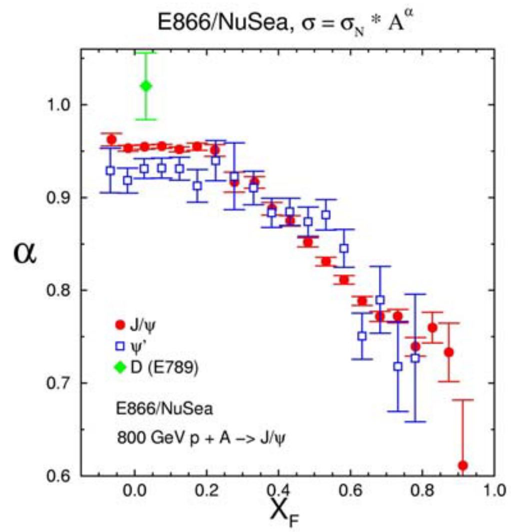
- With detector upgrades (PHENIX and STAR):
  - $J/\psi$ from B decays with displaced vertex measurement (both).
  - Reduce $J/\psi \rightarrow \mu\mu$ background with forward vertex detector in PHENIX.
  - Improve mass resolution for charmonium and resolve $\Upsilon$ family.
  - See $\chi_c$ by measuring $\gamma$ in forward calorimeter in front of muon arms (PHENIX)

- And with the luminosity upgrade:
  - Measure $B \rightarrow J/\psi$ using displaced vertex - independent B yield measurement, also get background to prompt $J/\psi$ measurement.
  - $J/\psi$ $R_{AA}$ to high $p_T$. Does $J/\psi$ suppression go away at high $p_T$?
  - $J/\psi$ $v_2$ measurements versus $p_T$. See evidence of charm recombination?
  - $\Upsilon$ $R_{AA}$. Which Upsilons are suppressed at RHIC?
  - Measure $\psi'$ $R_{AA}$. Ratio to $J/\psi$?
  - Measure $\chi_c \rightarrow J/\psi + \gamma$ $R_{AA}$. Ratio to $J/\psi$?

# Quarkonia Production in pp, p(d)A & AA Collisions
## --------------- Summary ---------------

Quarkonia production cross sections and polarization still not well understood

- causes uncertainties in the understanding of nuclear effects (e.g. J/ψ absorption)

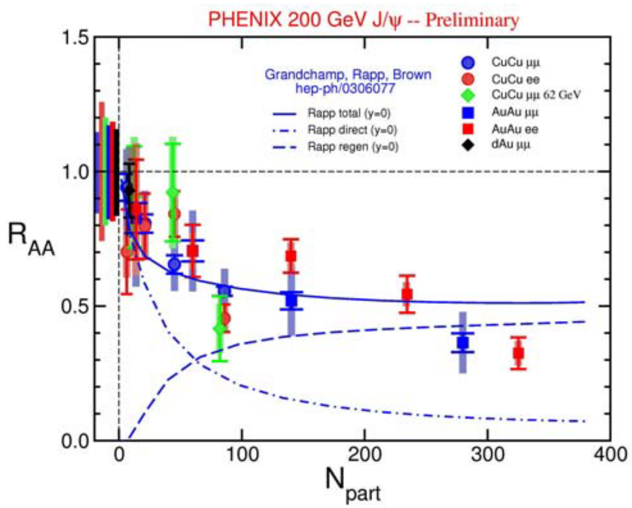



Weak shadowing has been observed at RHIC for the J/ψ in dAu collisions

- but scaling with $x_F$ (and not with $x_2$) is still a puzzle

AA collisions at RHIC suggest substantial contributions from regeneration

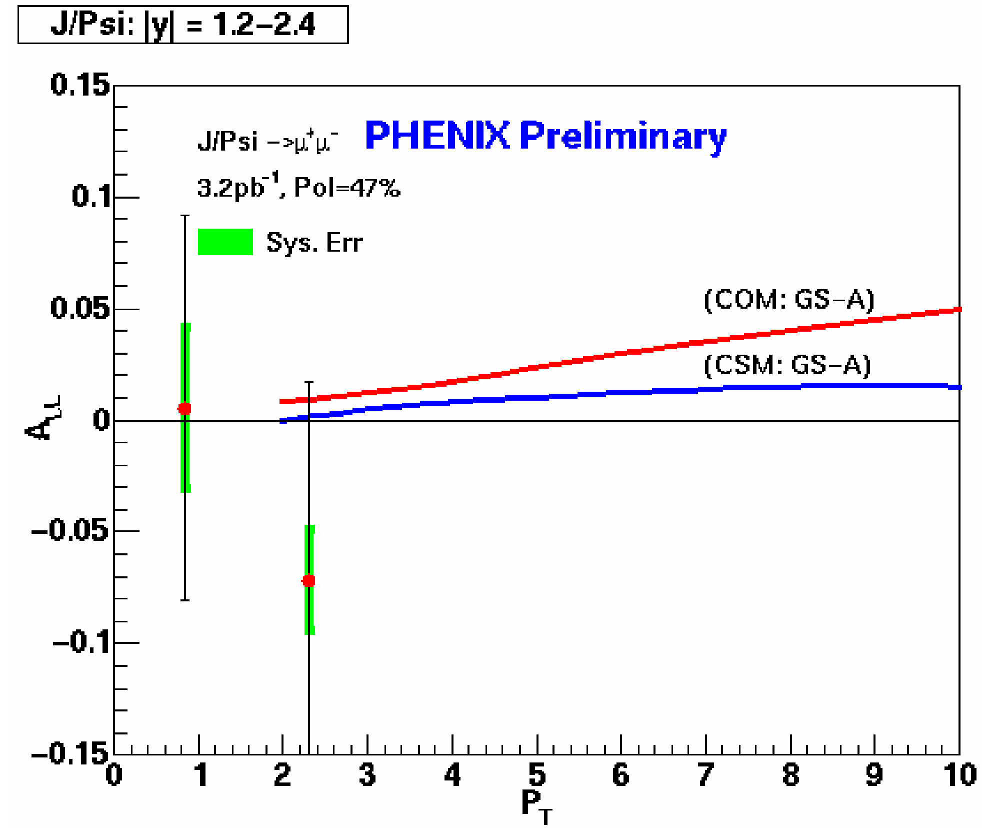
- suppression observed is very similar to NA50 at lower energies but more suppression would be expected from QGP since gluon densities are 2-3x larger at RHIC

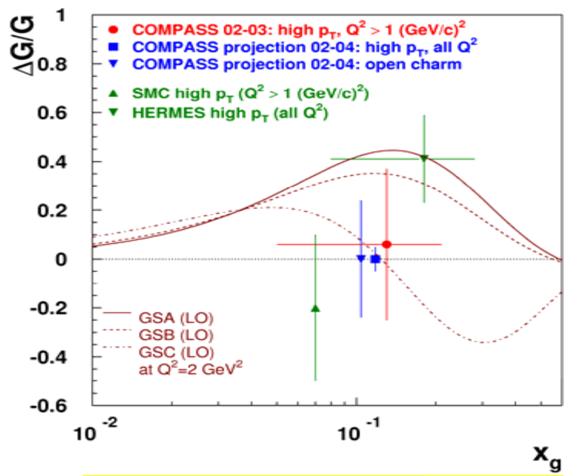


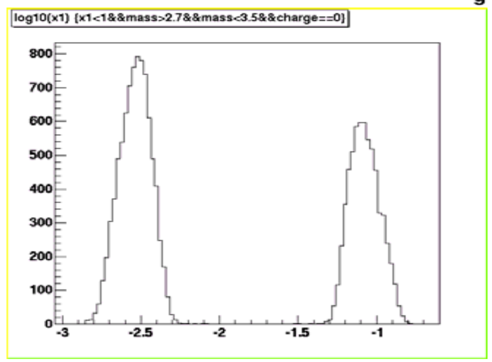

Sequential screening, where $\chi_c$ & ψ′ are screened but not J/ψ (consistent with Lattice calculations), provides a simpler picture

- need more accurate dAu data to establish level of CNM effects in AA
- need accurate open charm cross section & J/ψ flow measurement to constrain regeneration models

# $A_{LL}$ vs $p_T$




Log(x)

## First spin physics result from J/Ψ

- J/ψ: produced via almost pure gluon fusion
- sensitive to gluon polarization

$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)} a_{LL}^{gg \to J/\Psi + X}$$

# RHIC-II - Heavy Flavor Yields

All numbers are first rough estimates (including trigger and reconstruction efficiencies) for 12 weeks Au+Au run ($\int L_{eff}\, dt \sim 18\ nb^{-1}$)

| Signal | RHIC Exp. | Obtained | RHIC I (>2008) | RHIC II | LHC/ALICE+ |
|---|---|---|---|---|---|
| $J/\psi \rightarrow e^+e^-$<br>$J/\psi \rightarrow \mu^+\mu^-$ | PHENIX | ~800<br>~7000 | 3,300<br>29,000 | 45,000<br>395,000 | 9,500<br>740,000 |
| $\Upsilon \rightarrow e^+e^-$<br>$\Upsilon \rightarrow \mu^+\mu^-$ | STAR<br>PHENIX | -<br>- | 830<br>80 | 11,200<br>1,040 | 2,600<br>8,400 |
| $B \rightarrow J/\psi \rightarrow e^+e^-$<br>$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ | PHENIX | -<br>- | 40<br>420 | 570<br>5,700 | N/A<br>N/A |
| $\chi_c \rightarrow e^+e^- \gamma$<br>$\chi_c \rightarrow \mu^+\mu^- \gamma$ | PHENIX | -<br>- | 220<br>8,600 | 2,900*<br>117,000* | N/A<br>N/A |
| $D \rightarrow K\pi$ | STAR | $\sim 0.4 \times 10^6$<br>(S/B~1/600) | 30,000** | 30,000** | 8000 |

* Large backgrounds, quality uncertain as yet
** Running at 100 Hz min bias
+ 1 month (= year), P. Crochet, EPJdirect A1, a (2005) and private comm.

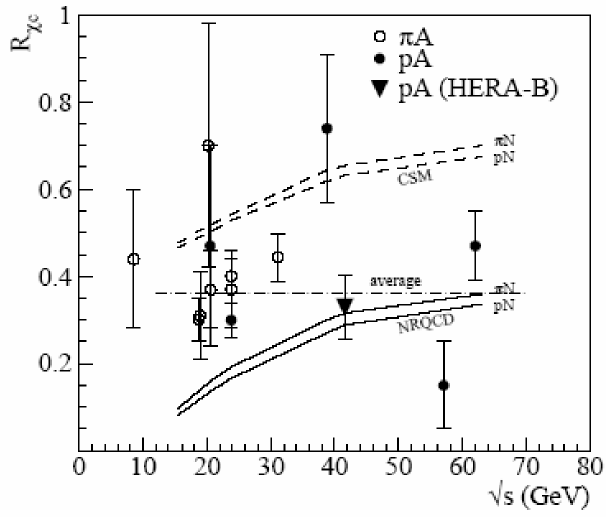
T. Frawley, PANIC'05, RHIC-II Satellite Meeting

# Onia Yields at RHIC II

| Signal/System | pp (200 GeV) | pp (500 GeV) | CuCu (200 GeV) | AuAu (200 GeV) | dAu (200 GeV) |
|---|---|---|---|---|---|
| J/Ψ→ee | 55,054 | 609,128 | 73,921 | 44,614 | 29,919 |
| Ψ′(2S)→ee | 993 | 10,985 | 1,333 | 805 | 540 |
| χ_c0→γ+J/Ψ→ee | 100 | 2,578 | 134 | 81 | 54 |
| χ_c1→γ+J/Ψ→ee | 1,340 | 40,870 | 1,800 | 1,086 | 728 |
| χ_c2→γ+J/Ψ→ee | 2,190 | 59,296 | 2,941 | 1,775 | 1,190 |
| ϒ(0,1,2)→ee | 210 | 3,032 | 547 | 397 | 184 |
| B→J/Ψ→ee | 1,237 | 41,480 | 4,567 | 3,572 | 1,085 |
| | | | | | |
| J/Ψ→μμ | 468,741 | 5,483,006 | 653,715 | 394,535 | 258,136 |
| Ψ′(2S)→μμ | 8,453 | 98,880 | 11,789 | 7,115 | 4,655 |
| χ_c0→γ+J/Ψ→μμ | 3,822 | 99,824 | 5,330 | 3,217 | 2,105 |
| χ_c1→γ+J/Ψ→μμ | 51,215 | 1,582,561 | 71,425 | 43,107 | 28,204 |
| χ_c2→γ+J/Ψ→μμ | 83,702 | 2,296,069 | 116,732 | 70,451 | 46,095 |
| ϒ(0,1,2)→μμ | 528 | 7,723 | 1,429 | 1,035 | 469 |
| B→J/Ψ→μμ | 2079 | 76466 | 5756 | 3752 | 1824 |

- Precision measurements of the J/Ψ
- Exploratory measurements of the other onium states.
- Steep increase at $\sqrt{s}$ = 500 GeV illustrates the significant difficulties for measurements at lower energies.

# Feeding of J/ψ's from Decay of Higher Mass Resonances

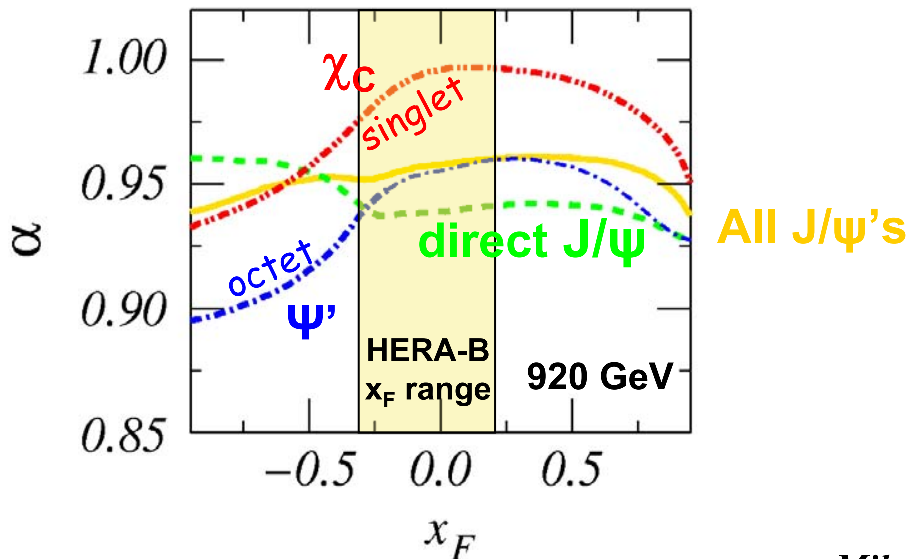



*HERA-B Phys.Lett. B561 (2003) 61-72 & E705 @ 300 GeV/c, PRL 70, 383 (1993)*

Large fraction of J/ψ's are not produced directly

| | Proton | Pion |
|---|---|---|
| $\chi_{,1,2} \rightarrow J/\Psi$ | ~30% | 37% |
| $\Psi' \rightarrow J/\Psi$ | 5.5% | 7.6% |

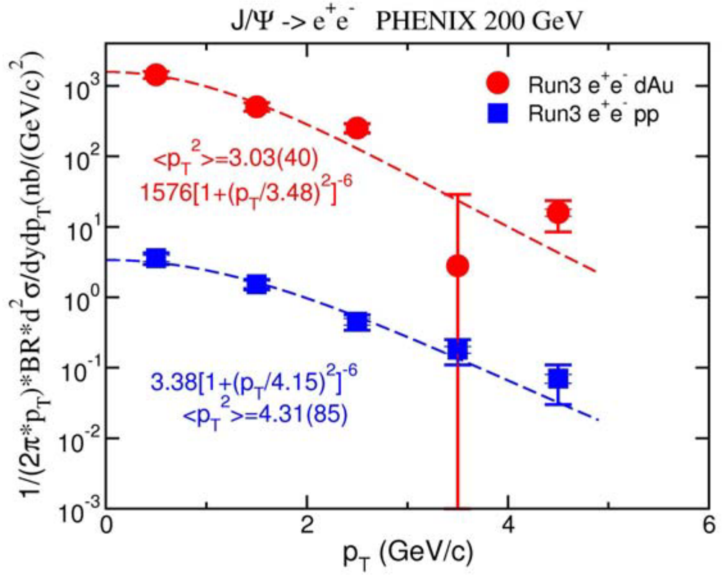
R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539

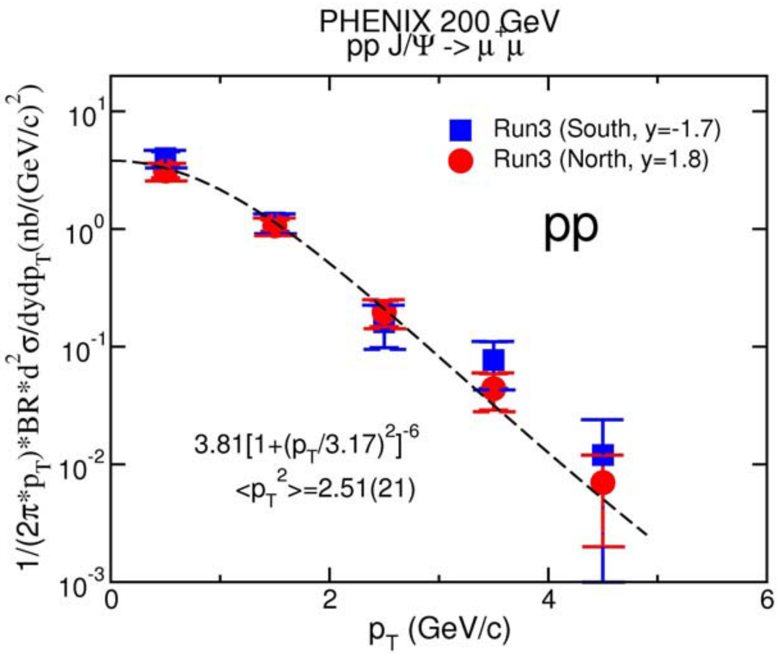


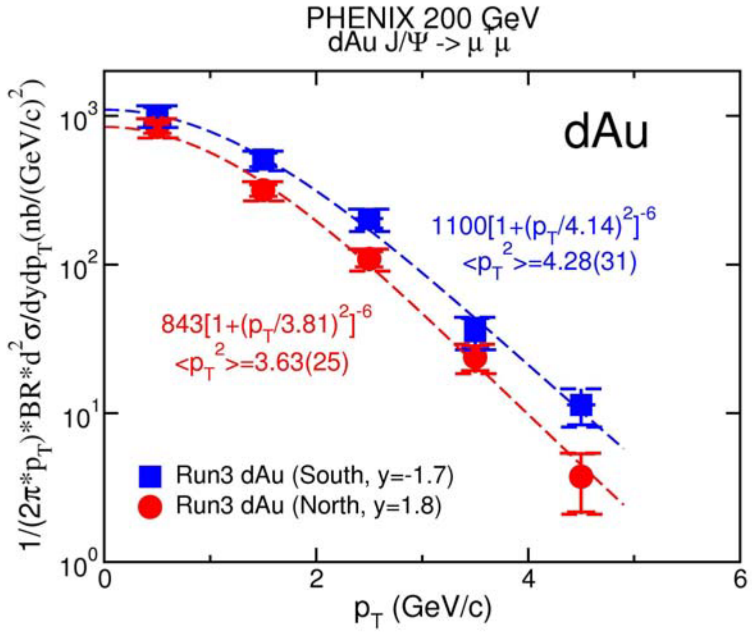

Effect on Nuclear dependence:

- Nuclear dependence of parent resonance, e.g. $\chi_C$ is probably different than that of the J/ψ
- e.g. in proton production ~21-30% of J/ψ's will have different effective absorption because they were actually $\chi_C$'s while in the nucleus

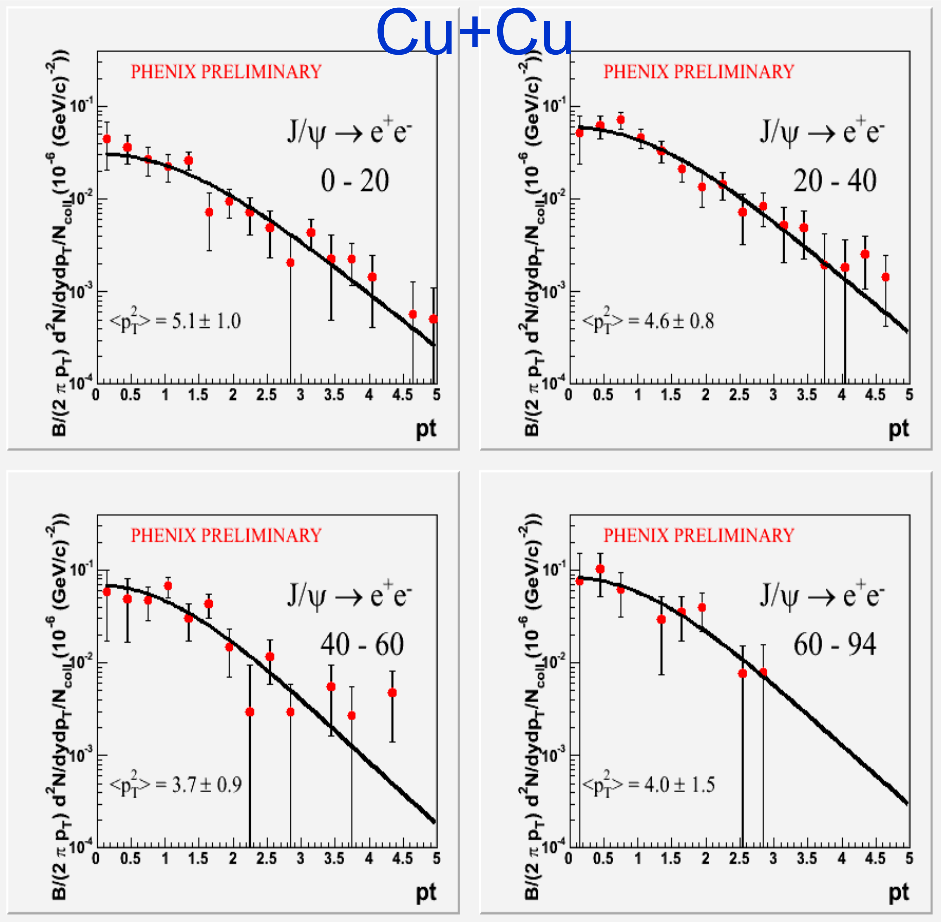
dAu $p_T$ J/$\psi$ distributions
PHENIX - 200 GeV

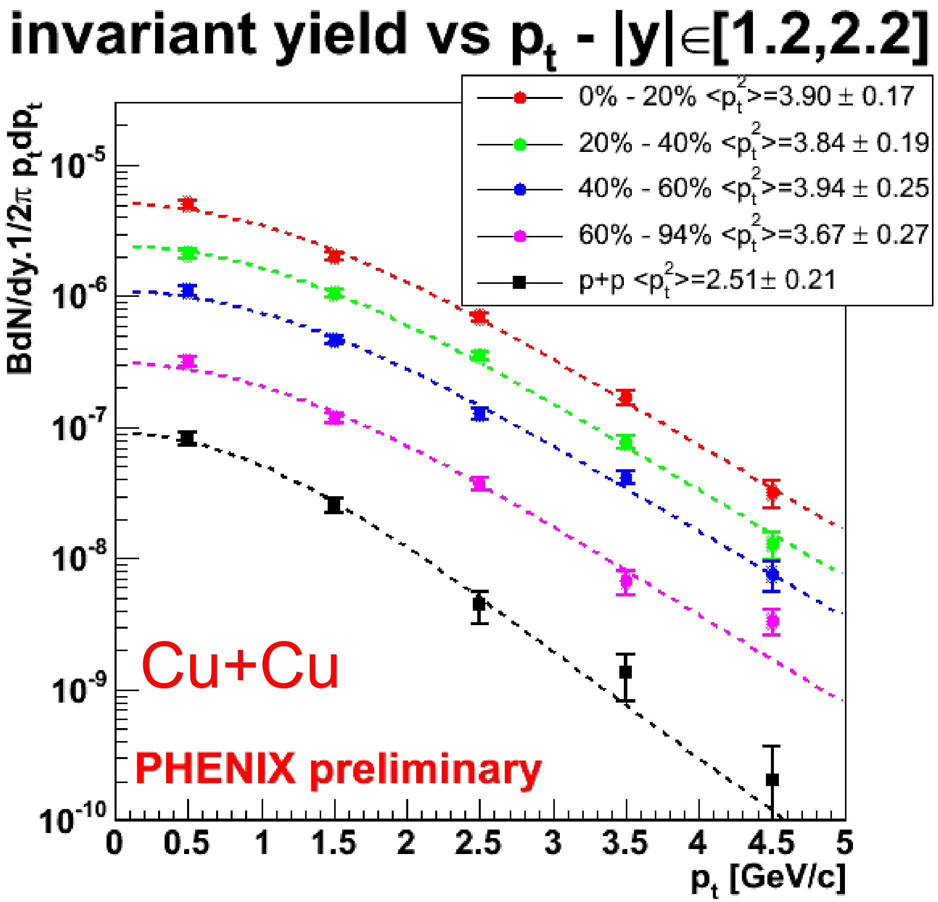


# Invariant $p_T$ distributions - CuCu




Extraction of $\langle p_T^2 \rangle$ by fitting with $A(1+(p_T/B)^2)^{-6}$

# Invariant $p_T$ distribution - AuAu

- Extraction of $\langle p_T^2 \rangle$ by fitting with $A(1+(p_T/B)^2)^{-6}$