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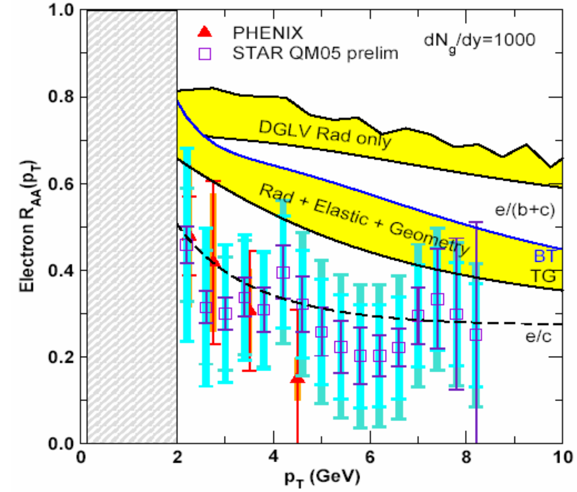
# Overview of Charm Physics at RHIC

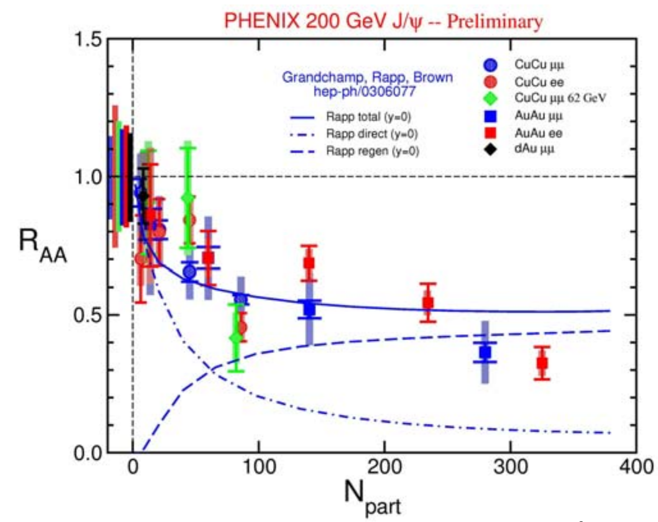
*Mike Leitch - LANL - leitch@lanl.gov*

*Quark Confinement & the Hadron Spectrum VII*

*Ponta Delgada, Azores - 2-7 Sept. 2006*

- production
  - cross sections & J/ψ polarization
- 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
  - J/ψ suppression
  - sequential suppression vs. regeneration
  - heavy-quark dE/dx & flow
- future prospects
- summary



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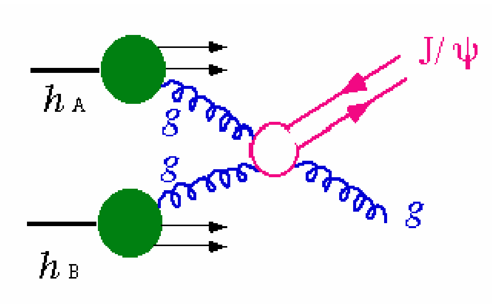
# Heavy-quark production, parton level structure & dynamics



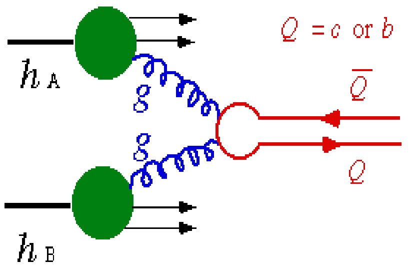

## Production of heavy vector mesons, J/ψ, ψ′ and ϒ

- 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 (ψ′, $\chi_c$)

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

## Open charm

- shares sensitivity to gluon distributions and initial-state effects such as $p_T$ broadening, initial-state energy loss
- but different final-state effects

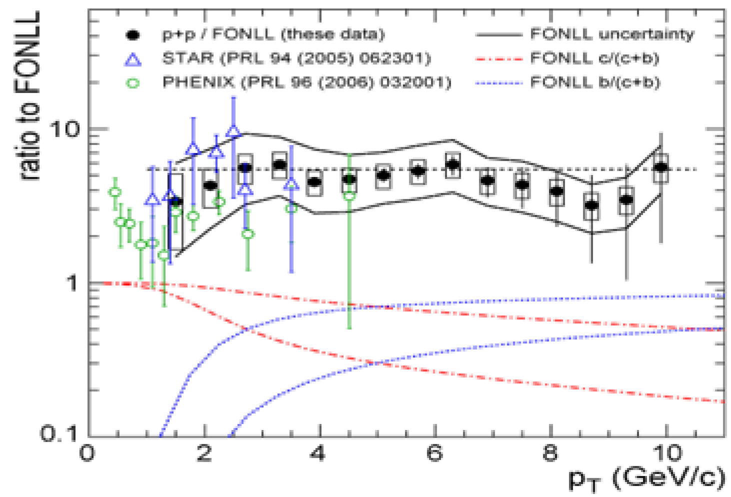


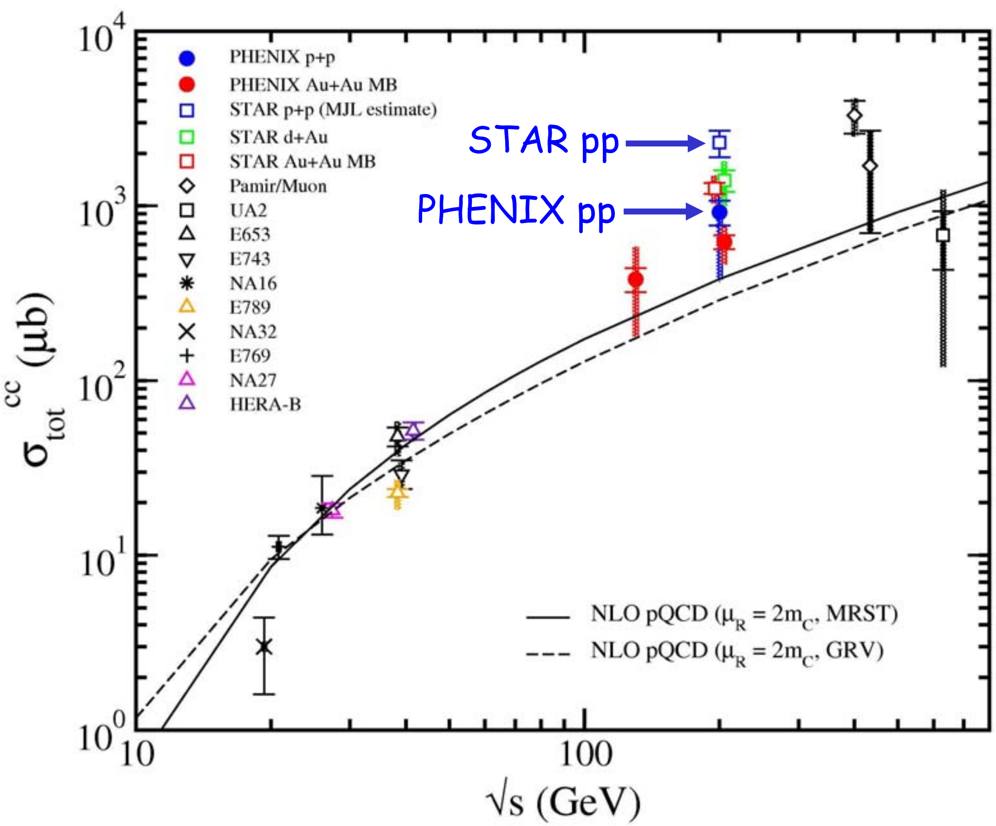
# Open charm production in p+p collisions at RHIC

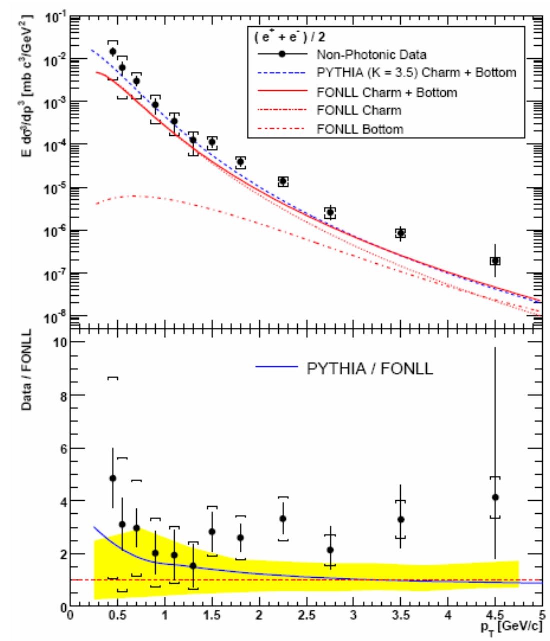
Consistency of 200 GeV measurements?

- STAR: 1.4 ± 0.2 ± 0.4 mb
  - newest STAR result: 2.2 ± 0.4 (MJL est.)
- PHENIX: 0.92 ± 0.15 ± 0.54 mb
  - newest PHENIX result: smaller than this (release next week)

All data lies above the FONLL (fixed-order next-to-leading log) calculation…

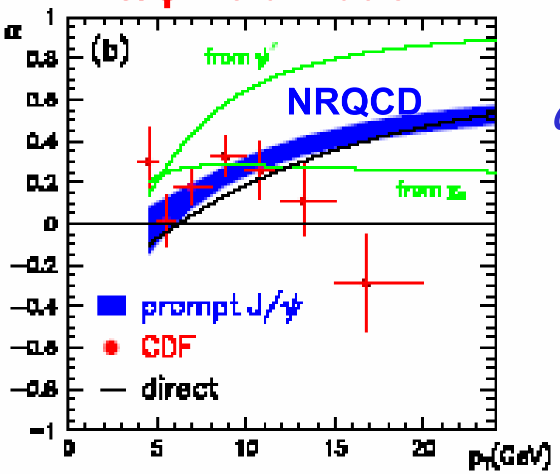


# $J/\psi$ Production - Polarization

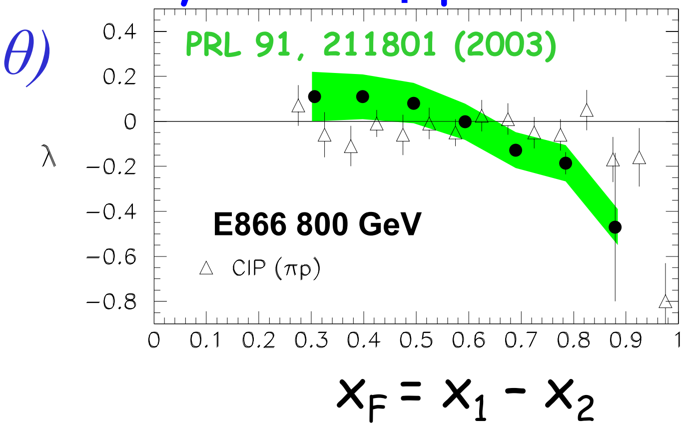
**J/ψ Polarization**



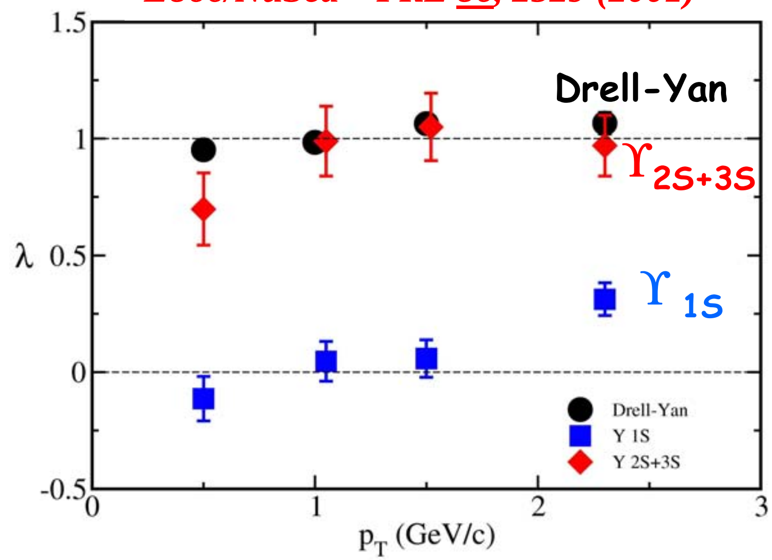

$$d\sigma/d\cos\theta = A(1+\lambda\cos^2\theta)$$

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

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



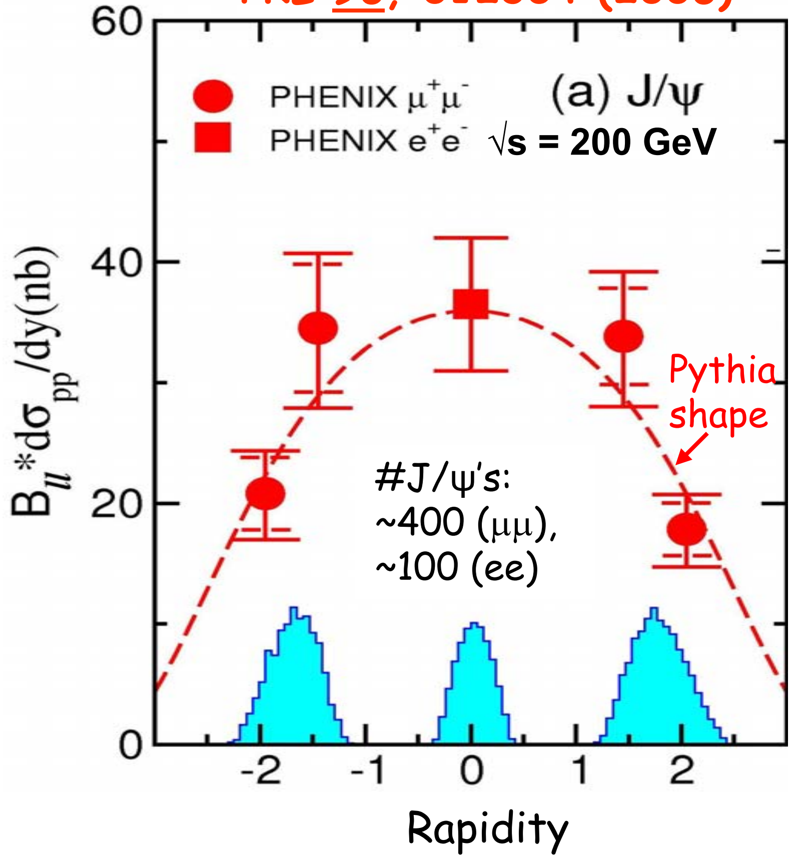

*E866/NuSea – PRL 86, 2529 (2001)*

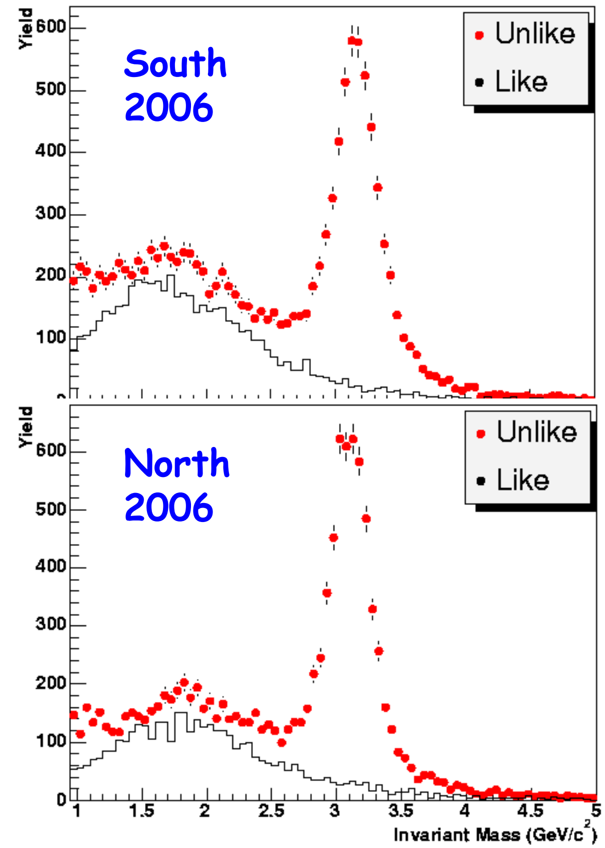



- Octet models get correct cross section size (unlike singlet), but…
- CDF and Fermilab E866 $J/\psi$ data show little polarization & disagree with NRQCD predictions

And ϒ maximally polarized for (2S+3S), but NOT (1S)
* Is feed-down washing out polarization? (~40% of 1S from feed-down)
(ψ′ polarization measurement would be helpful here)

# 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)

# Nuclear effects on Onia Production

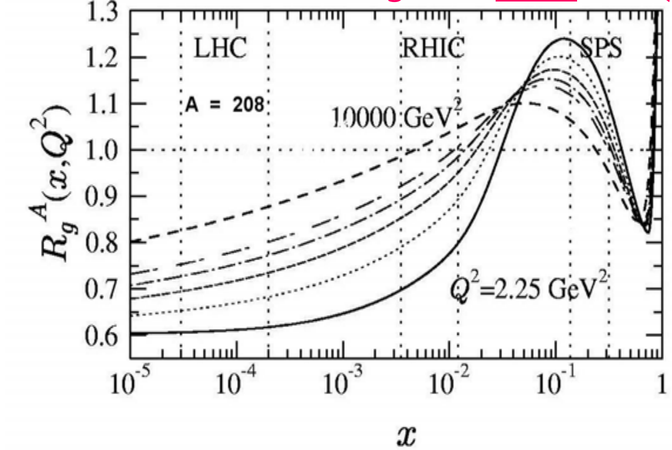
Modification of parton momentum distributions of nucleons embedded in nuclei

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

Nuclear effects on parton "dynamics"

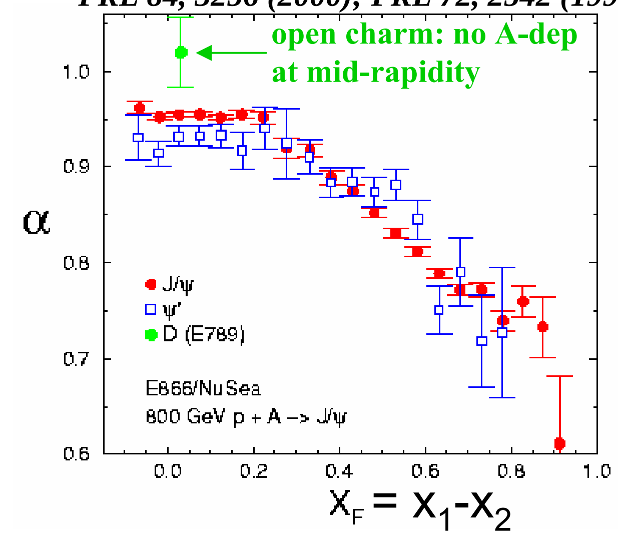
- absorption (or disassociation) of J/ψ by nucleons or co-movers
- energy loss of partons as they propagate through nuclei
- multiple scattering effects (Cronin effect) causing $p_T$ broadening

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



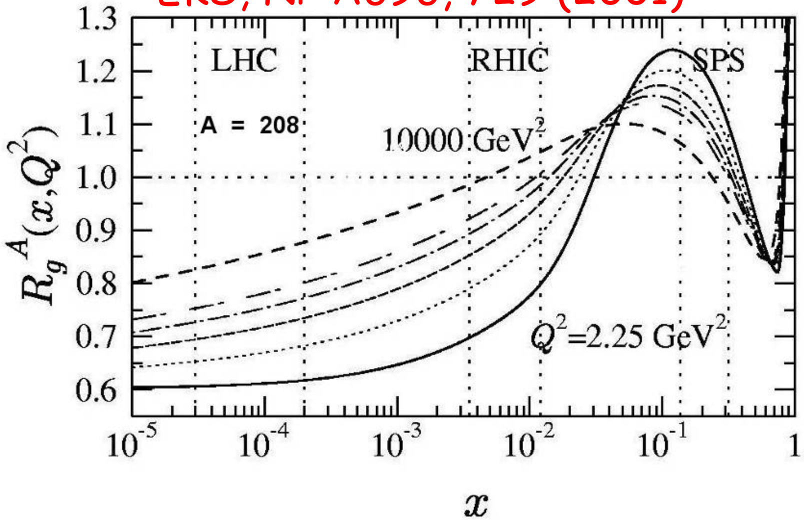

**800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$**

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



# Cold Nuclear Matter Effects
## Gluon Shadowing

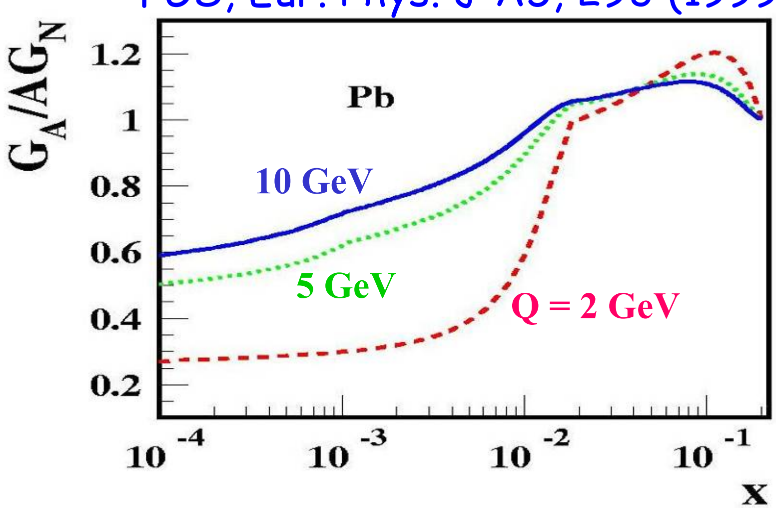
EKS, NP A696, 729 (2001)



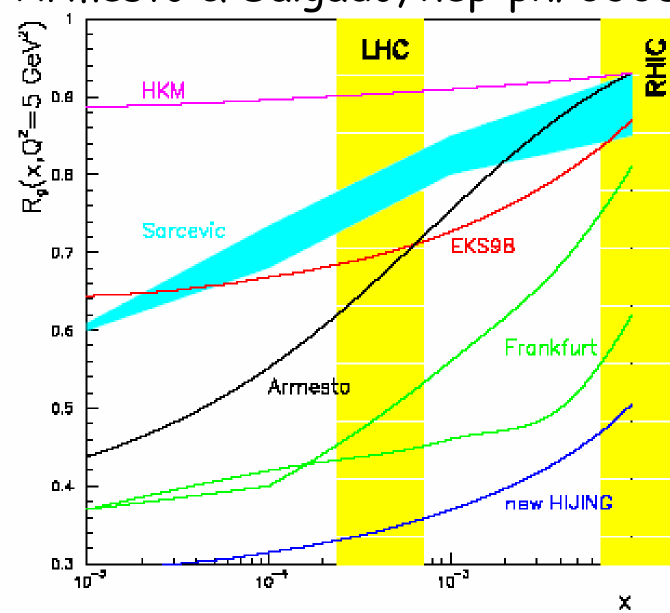

- Phenomenological fit to Deep-Inelastic Scattering & Drell-Yan data
- Leading twist gluon shadowing
- Coherence approach, and many others

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

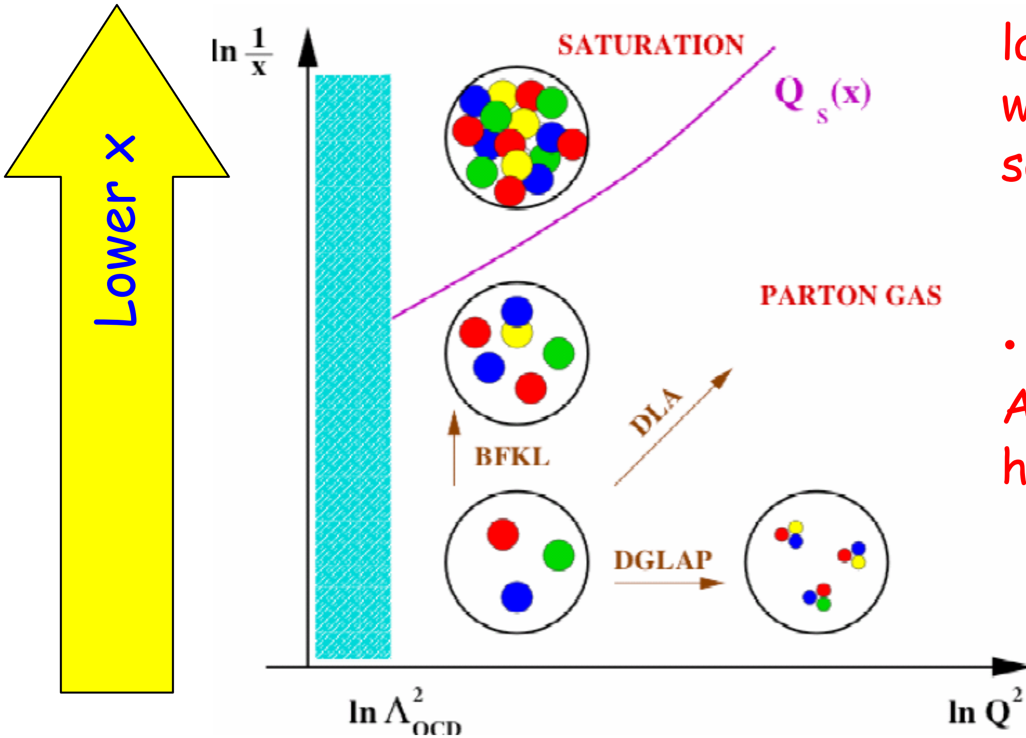
FGS, Eur. Phys. J A5, 293 (1999)




Armesto & Salgado, hep-ph/0308248



# Cold Nuclear Matter Effects
# Gluon Saturation & the Color Glass Condensate (CGC)




At low-x gluon density becomes very large & a non-linear evolution regime with 2 → 1 gluon processes sets in at saturation scale $Q_s$

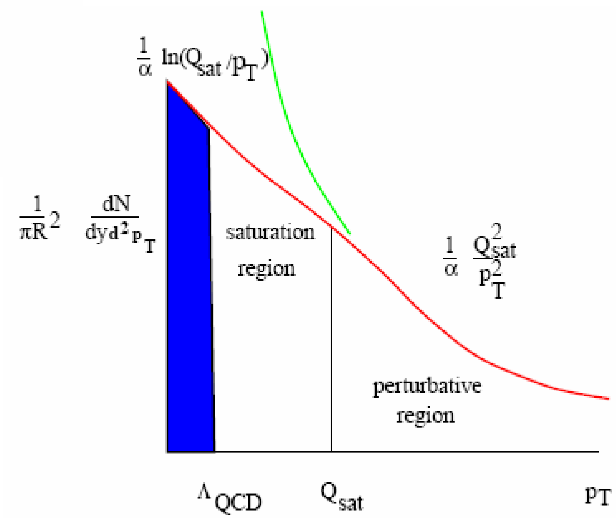
- CGC is an effective theory for that regime

- 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
  - gives "shadowing"

More saturation at Lower x

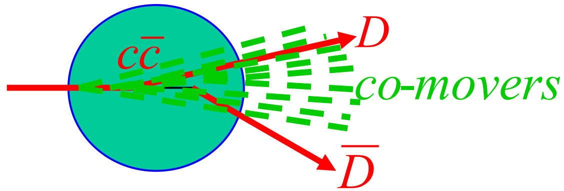
y~log(1/x)

Lower x → forward rapidity



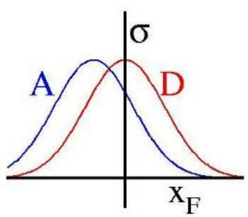
# Cold Nuclear Matter Effects
# The J/ψ - a Puzzle

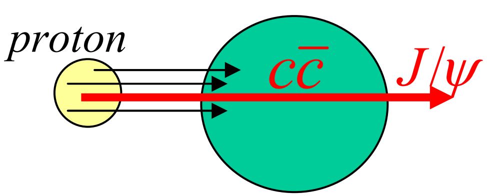
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:




**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)

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

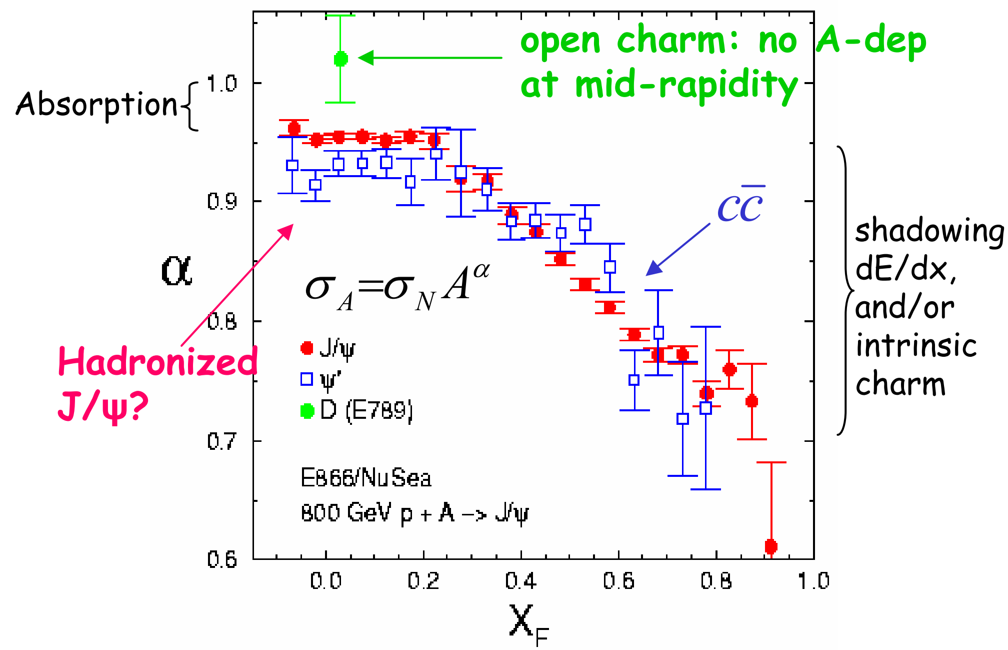



**Intrinsic charm** components of incident proton produce J/ψ at large $x_F$. $A^{2/3}$ dependence from surface stripping of proton's light quarks (Brodsky)

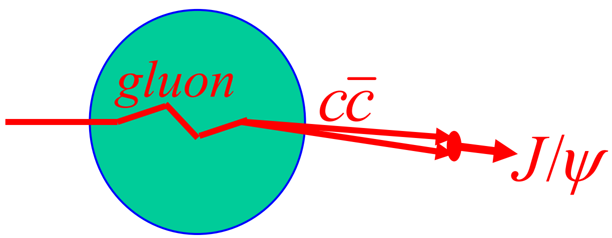
**800 GeV p-A (FNAL)**

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



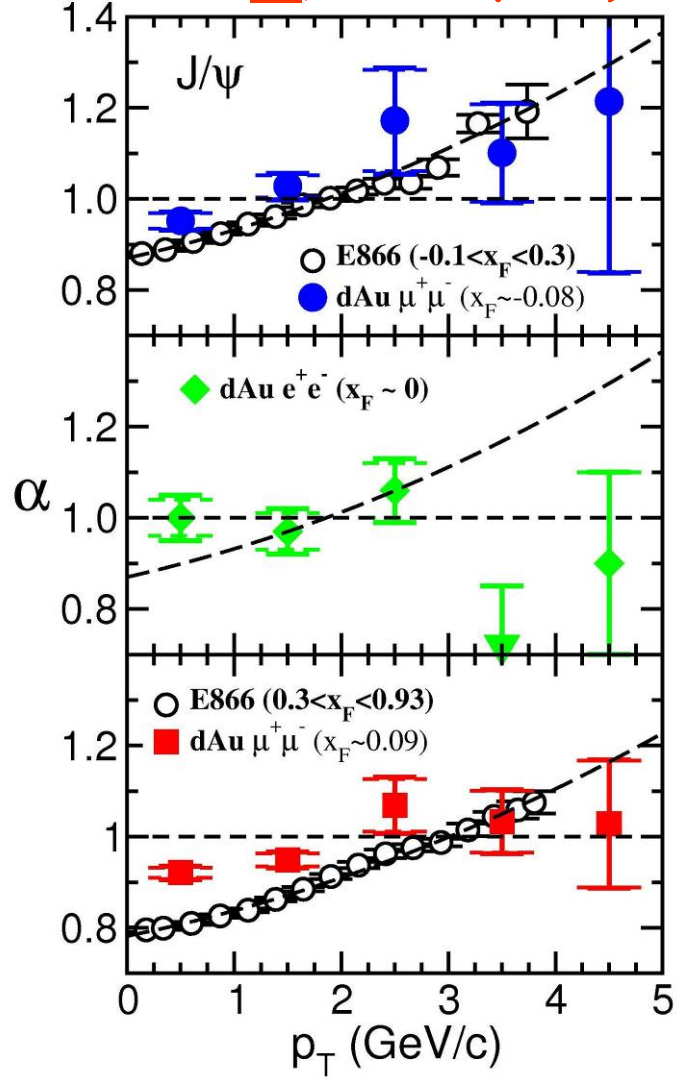
# Transverse Momentum Broadening for J/ψ's

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




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

*PRL 96, 012304 (2006)*

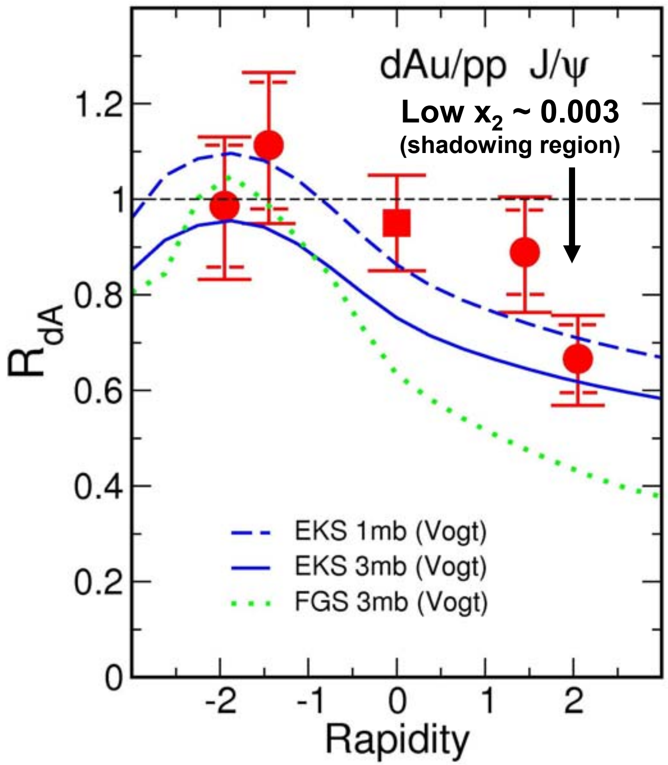



High $x_2$ ~ 0.09

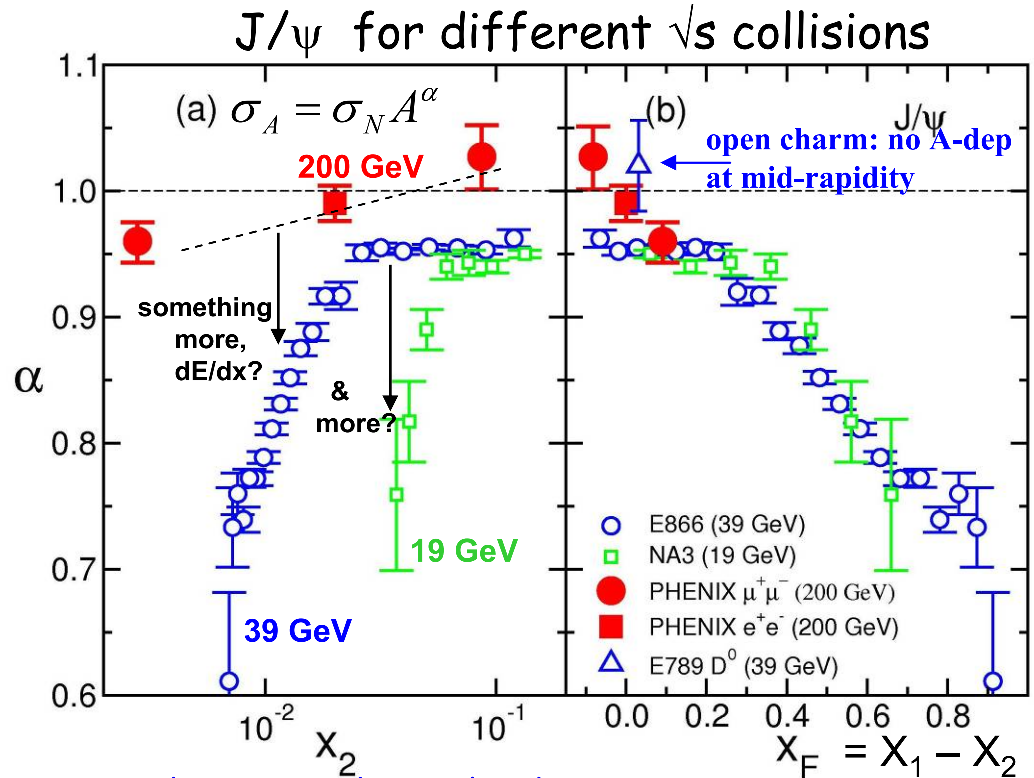
**PHENIX 200 GeV results show $p_T$ broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)**

Low $x_2$ ~ 0.003

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




Klein,Vogt, PRL 91:142301,2003




($x_2$ 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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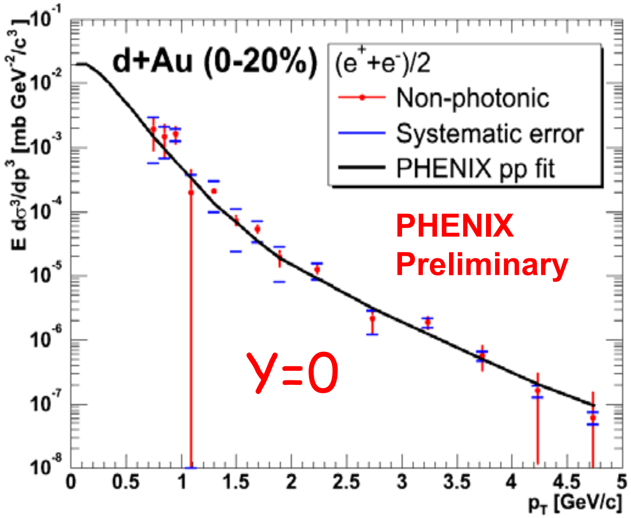
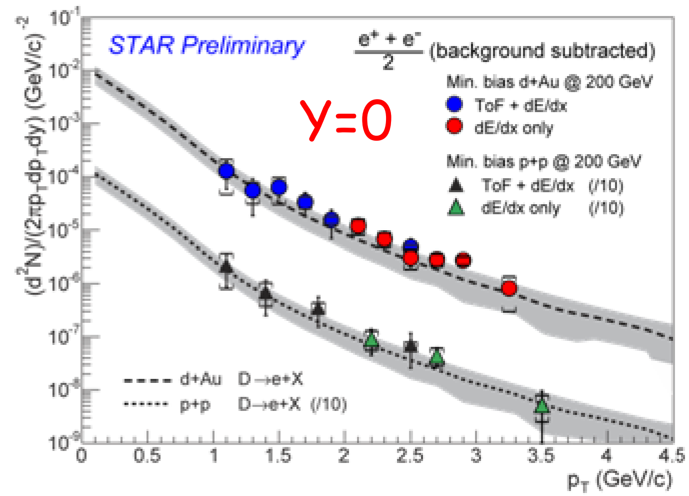
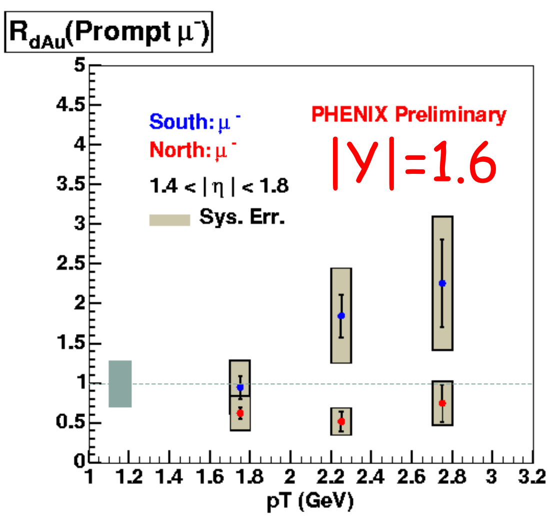
# Open charm in Cold Nuclear matter?




dAu is consistent with pp scaled by #binary collisions

RdAu consistent with no suppression for y=0 at STAR also

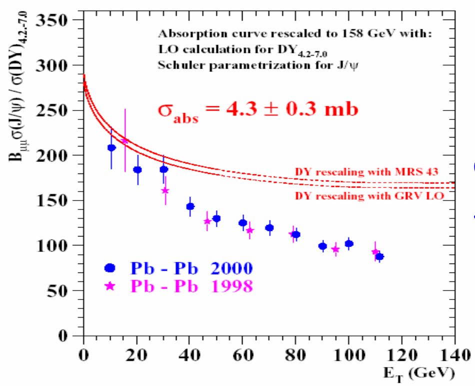


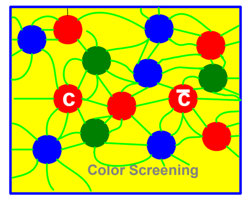

But at forward rapidity (deuteron direction) suppression is observed. And enhancement at backward rapidity

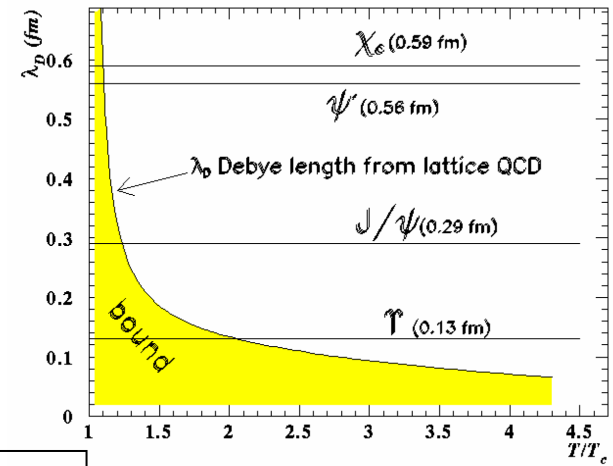
# AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

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

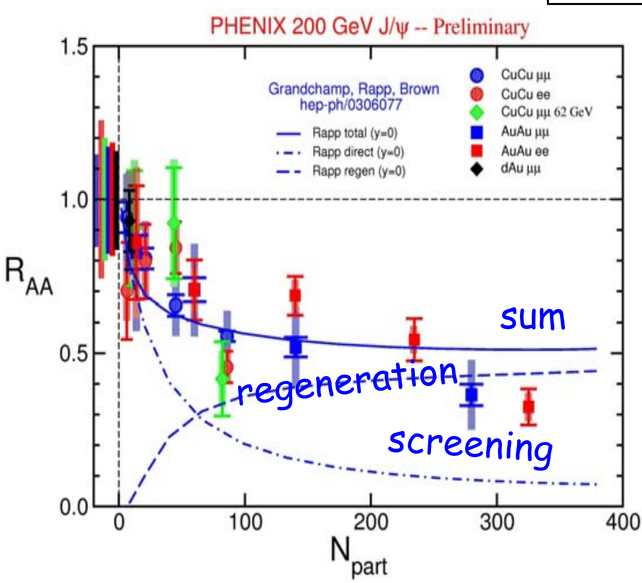



NA50 anomalous suppression

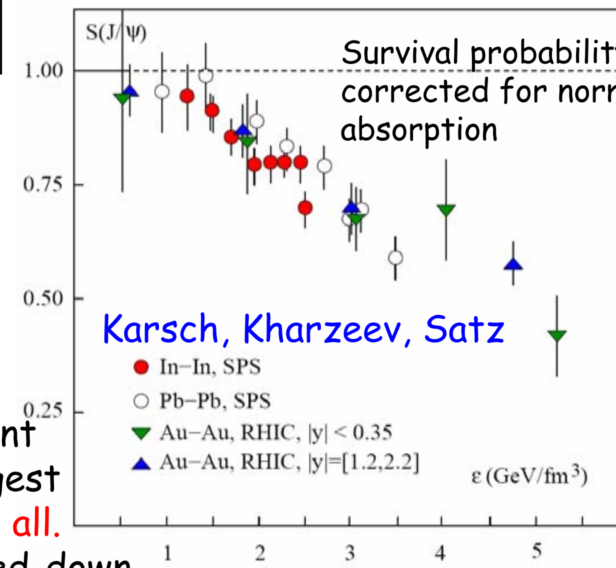



RHIC data – shows too little suppression (comp. to NA50)!




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

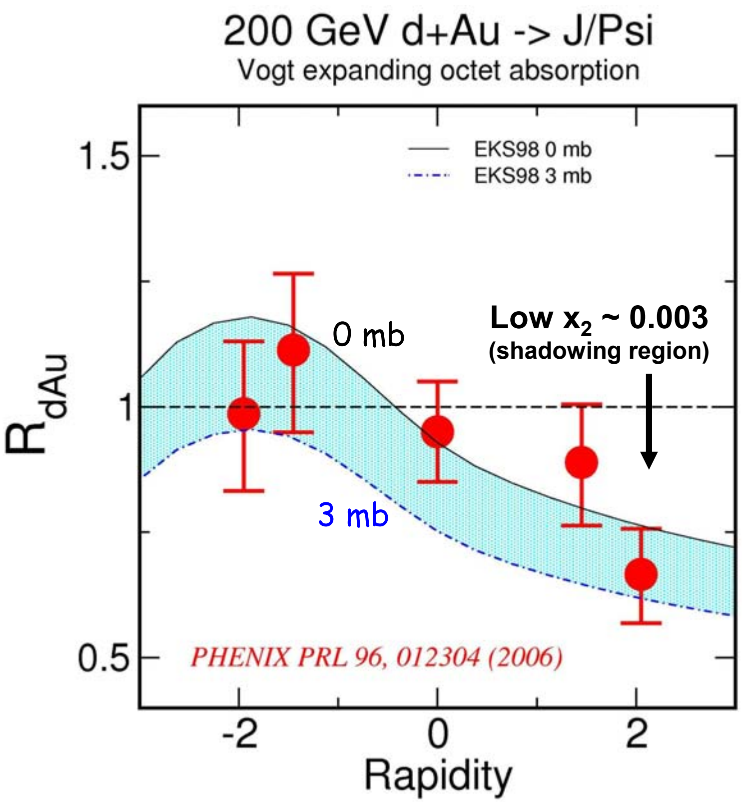


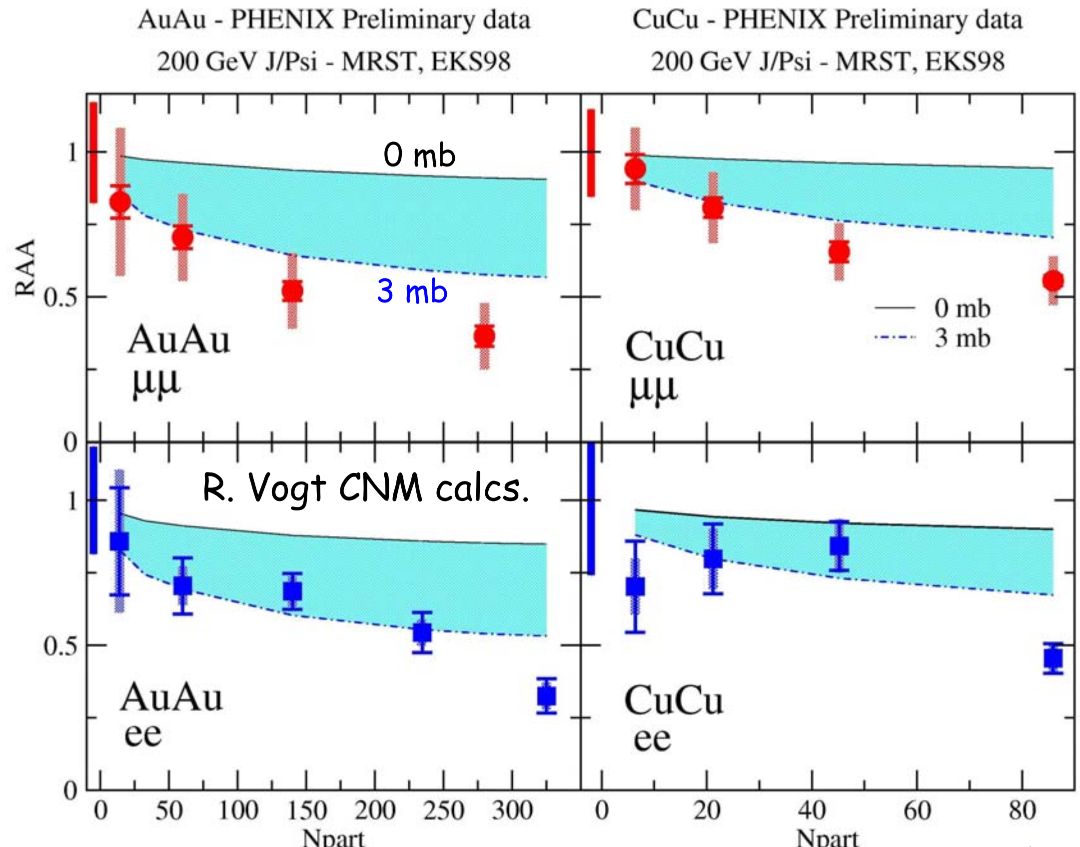

Survival probability corrected for normal absorption

energy density

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)

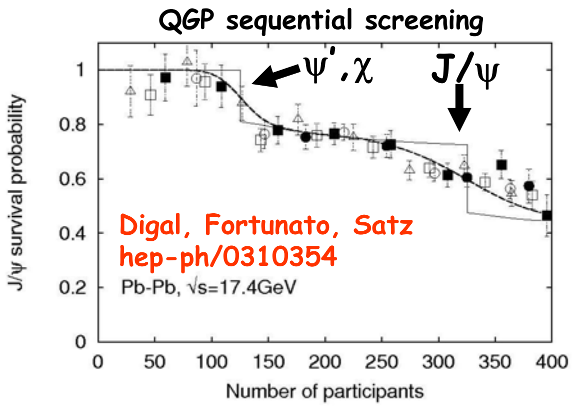


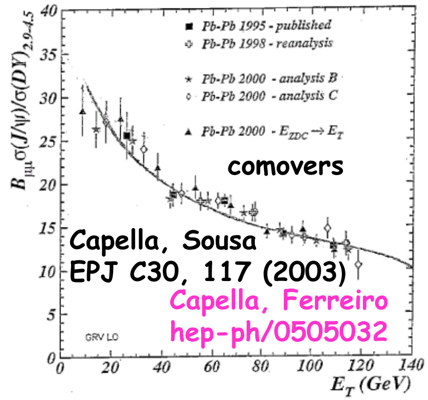



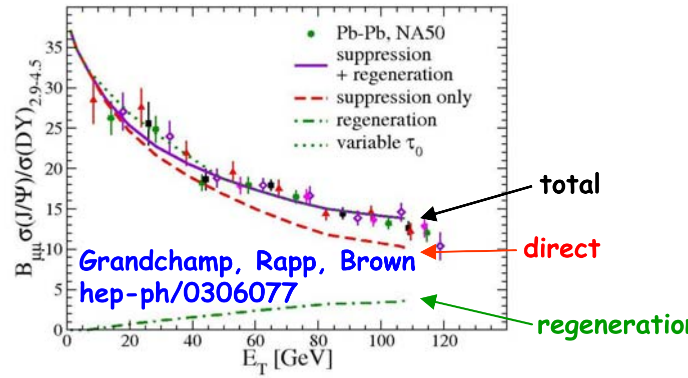

- **CNM calculations with shadowing & absorption**
- **present dAu data probably only constrains absorption to: $\sigma_{ABS}$ ~ 0-3 mb**

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

# Models without regeneration

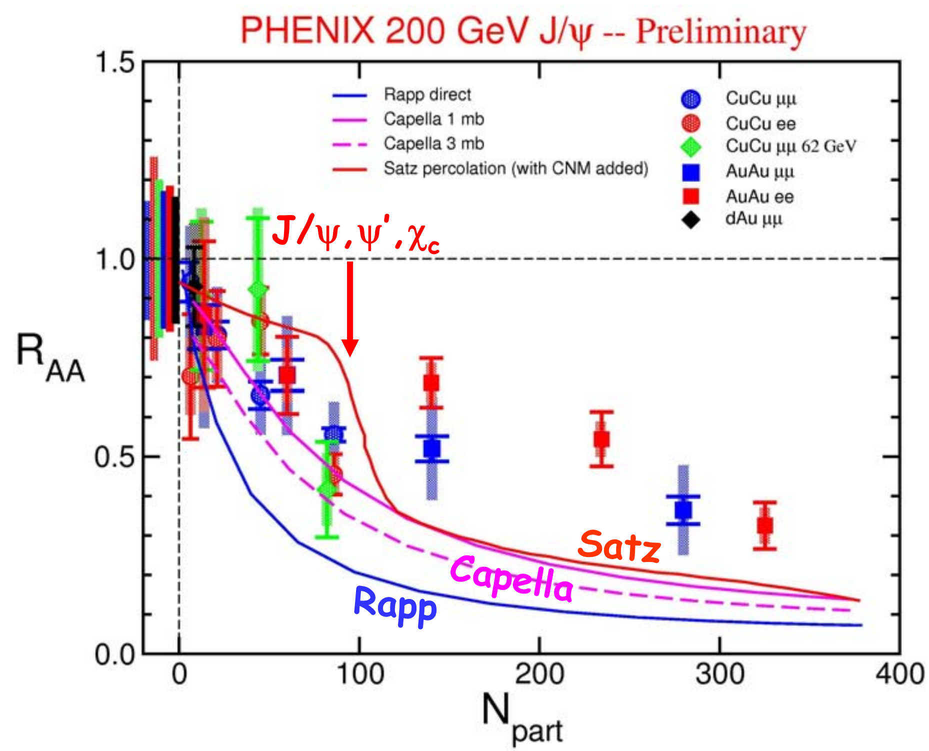



**Models that reproduce NA50 results at lower energies predict too much suppression at RHIC!**

- 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

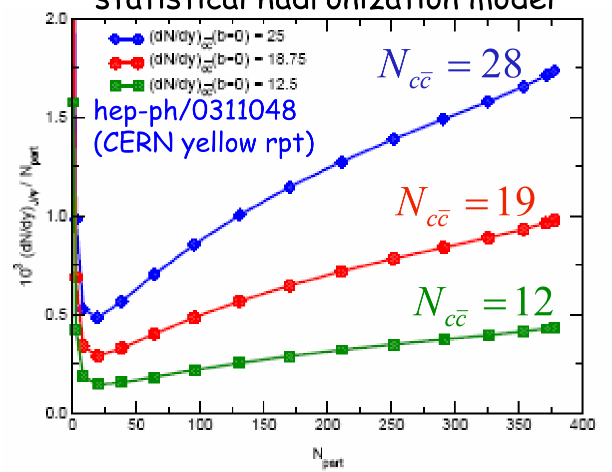


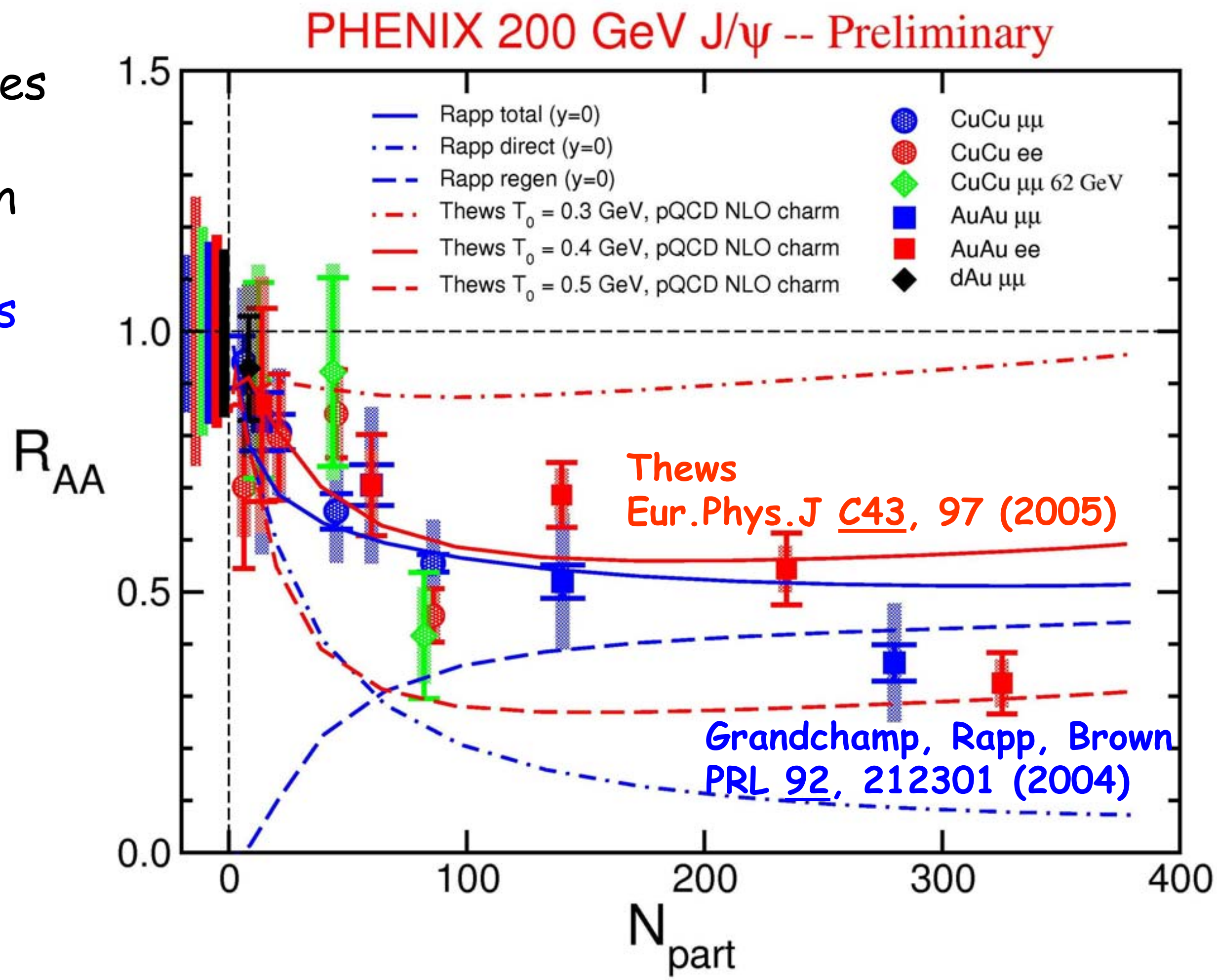
# Models with screening & regeneration

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 (see earlier discussion…)

statistical hadronization model



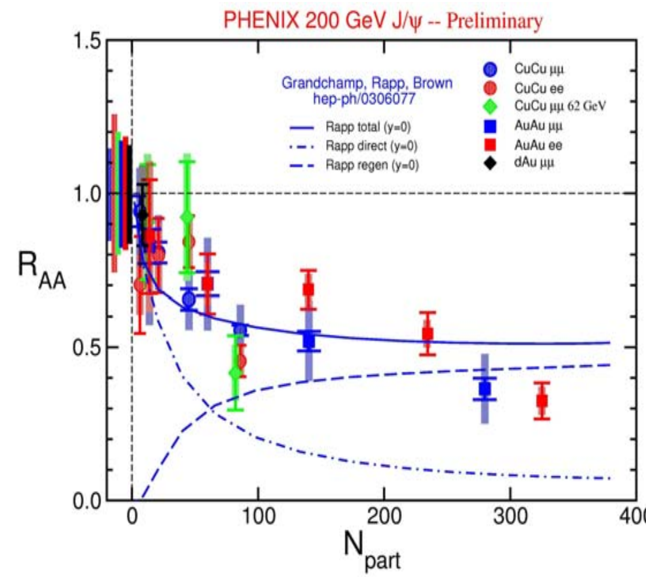
# Regeneration or Sequential Screening?

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!

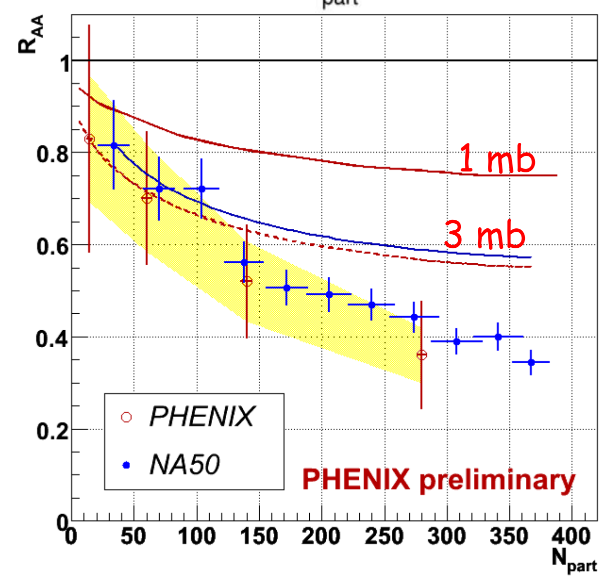



-------------- OR --------------------

(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

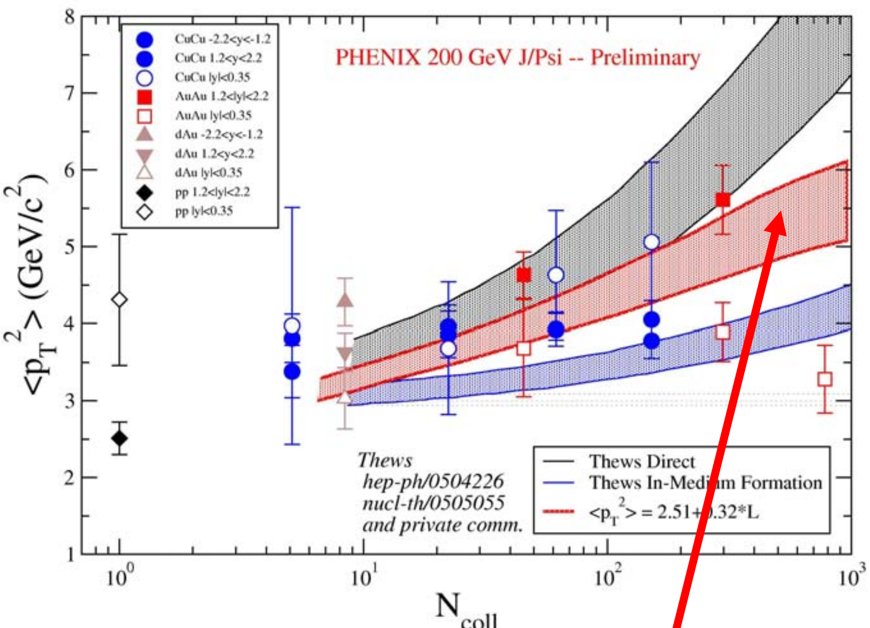
| state | $J/\psi(1S)$ | $\chi_c(1P)$ | $\psi'(2S)$ | $\Upsilon(1S)$ | $\chi_b(1P)$ | $\Upsilon(2S)$ | $\chi_b(2P)$ | $\Upsilon(3S)$ |
|---|---|---|---|---|---|---|---|---|
| $T_d/T_c$ | 2.10 | 1.16 | 1.12 | $> 4.0$ | 1.76 | 1.60 | 1.19 | 1.17 |

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

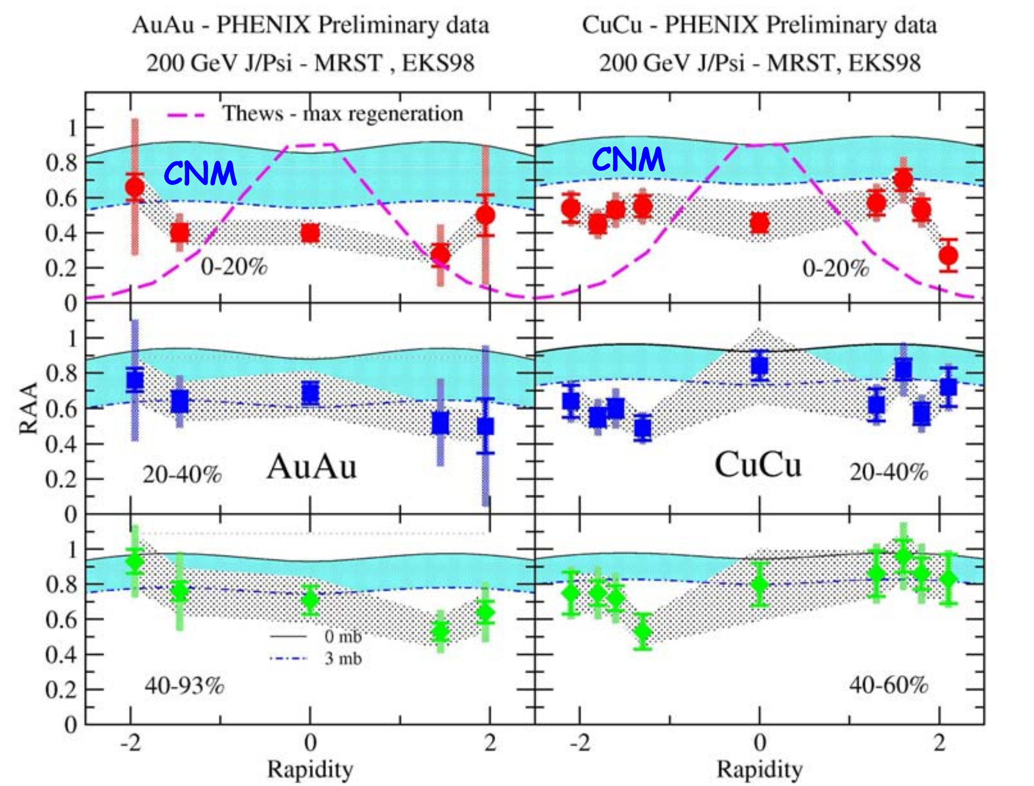
$p_T$ broadening lies in between Thews direct & in-medium formation suggesting some regeneration (but our fit to pp+dAu data vs L also reasonable)

But rapidity dependence of central AA collisions (top panels) shows no narrowing – i.e. the 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



# Open charm in AuAu collisions

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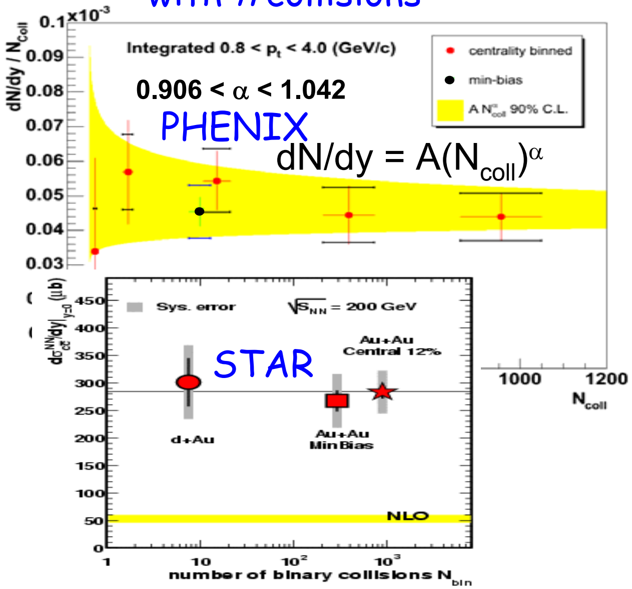
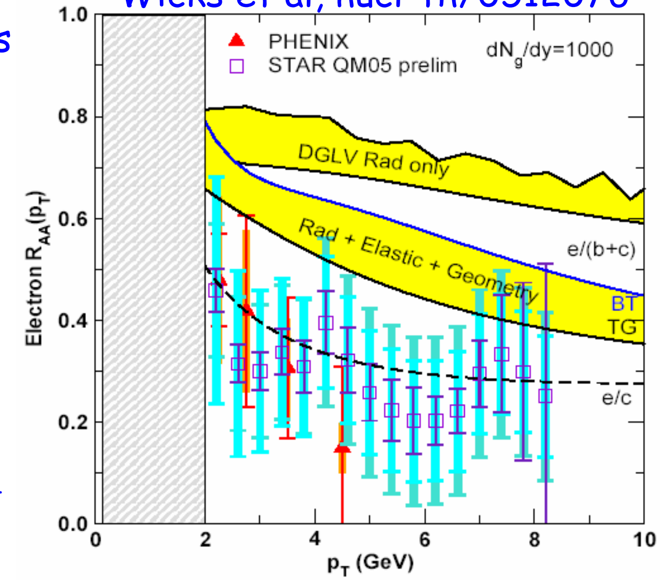
Invariant yields scale with #collisions




Charm alone gives good agreement but beauty must be there too

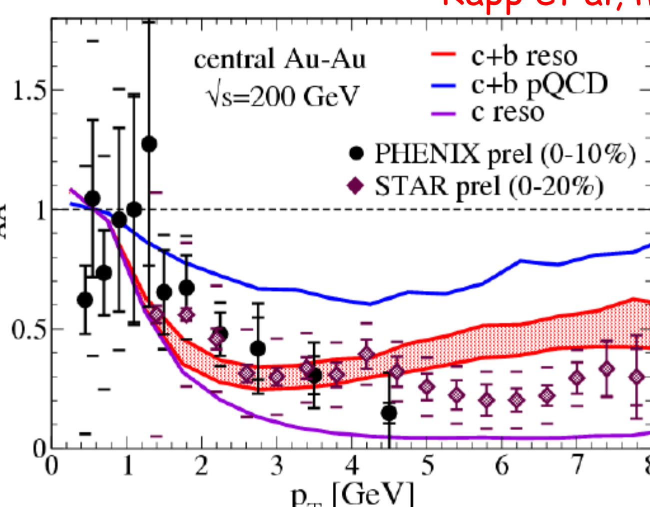
With both c & b, radiative + collisional energy loss underpredicts suppression vs $p_T$

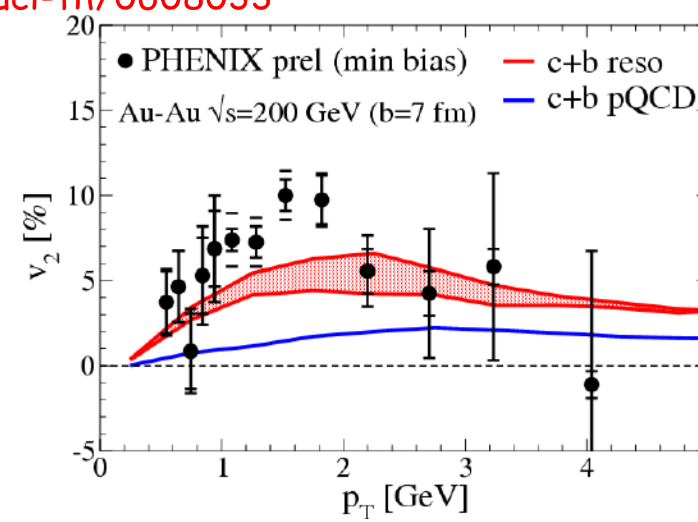
Wicks et al, nucl-th/0512076




Rapp et al, nucl-th/0608033

Rapp's predictions, which include a "non-perturbative heavy-light resonant rescattering" thermalization scheme, come closer on RAA and give flow "similar" to data (flow definition on next slide)



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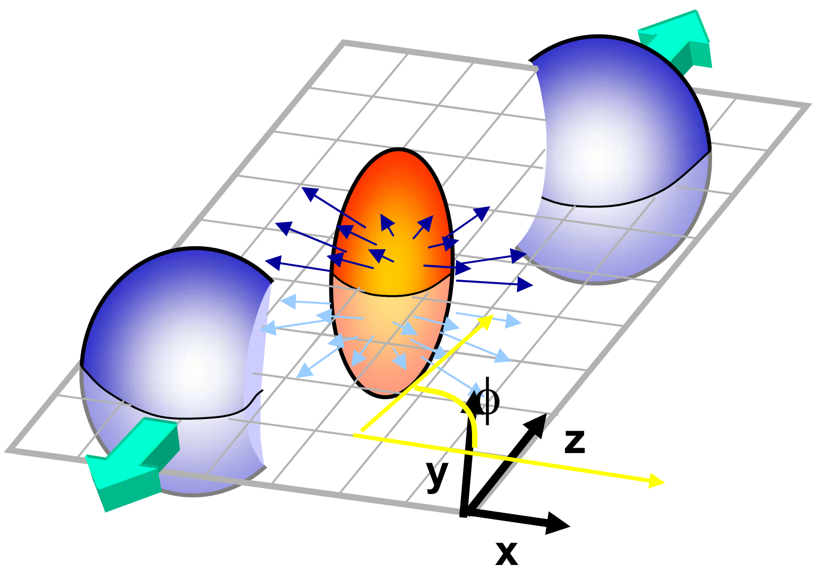
# Flow: A collective effect

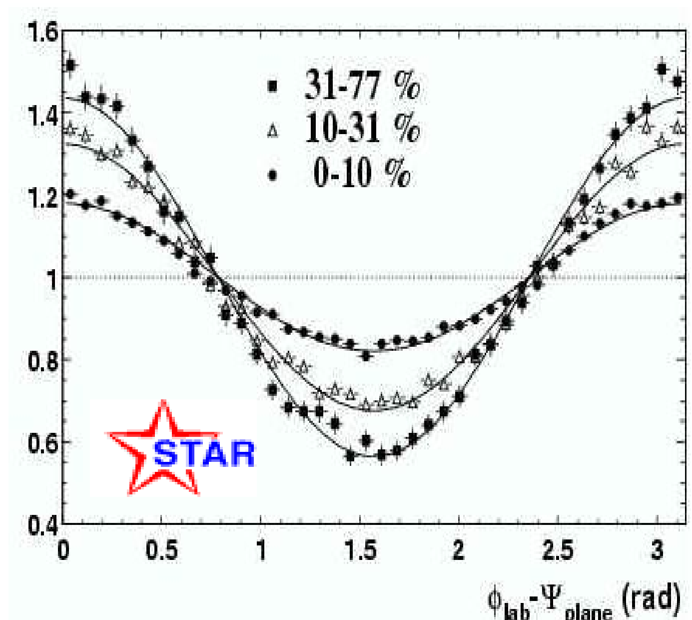
Initial spatial anisotropy converted into momentum anisotropy

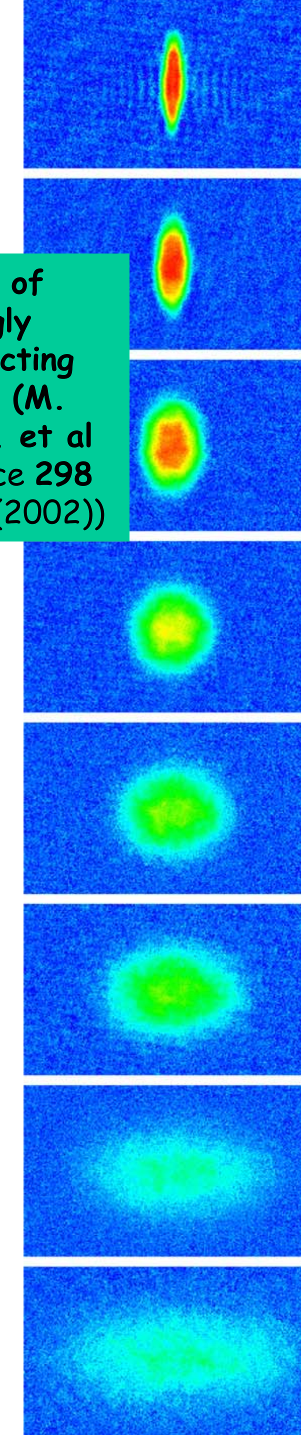
Elliptic flow = $v_2$ = 2nd fourier coefficient of momentum anisotropy

Gases of strongly interacting atoms (M. Gehm, et al Science 298 2179 (2002))

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$$



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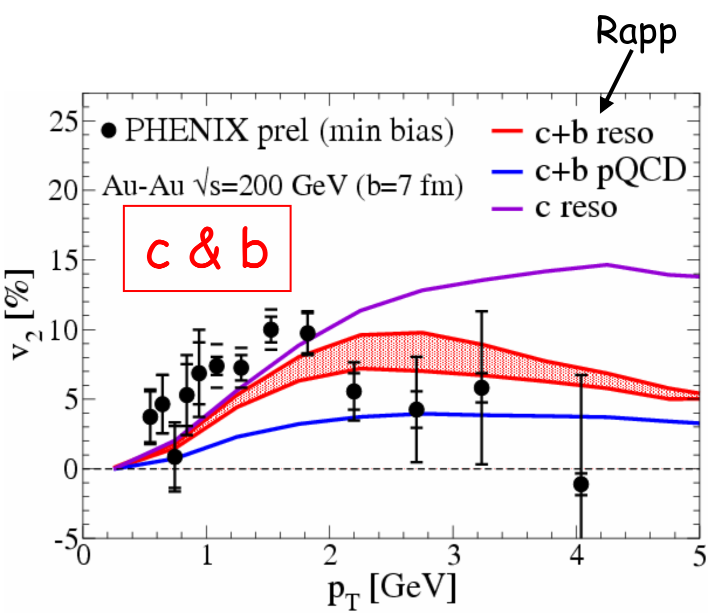
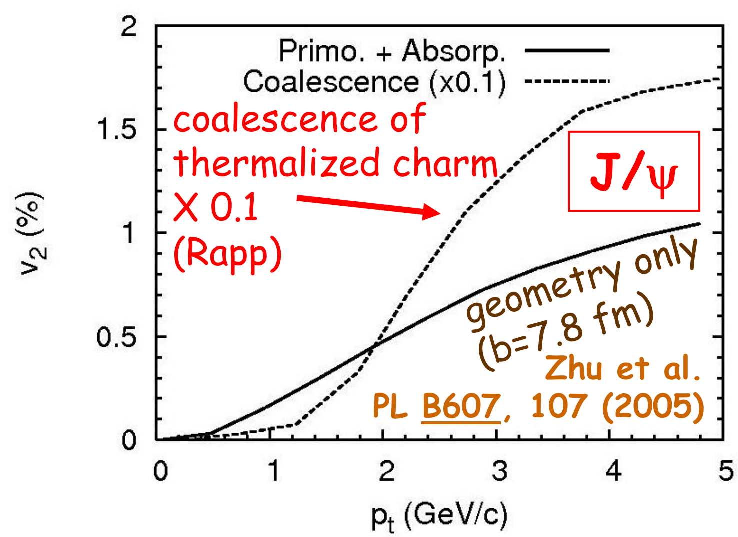
# Back to J/ψ's - Flow?

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

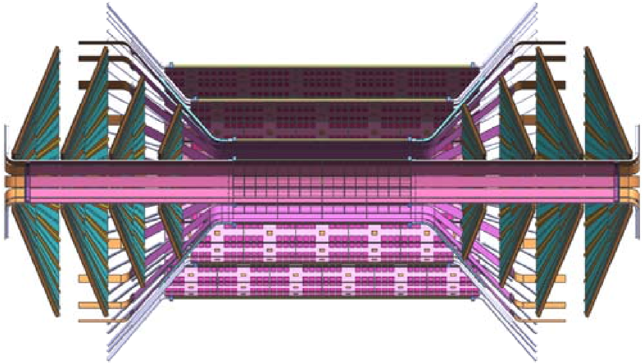
- open charm has recently been seen to flow (at least at some $p_T$ values)
- but what about geometrical-absorption effects, which could also give asymmetry wrt reaction plane?

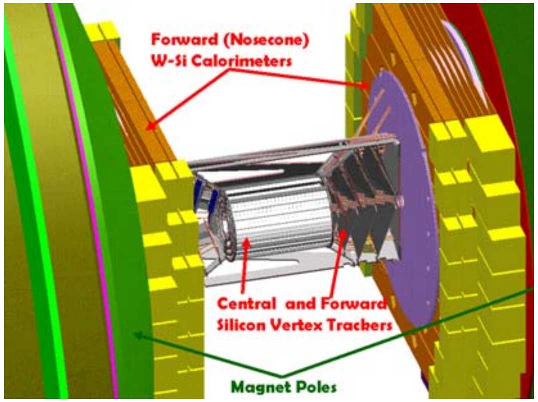


# Detector Upgrades for Heavy Quarks

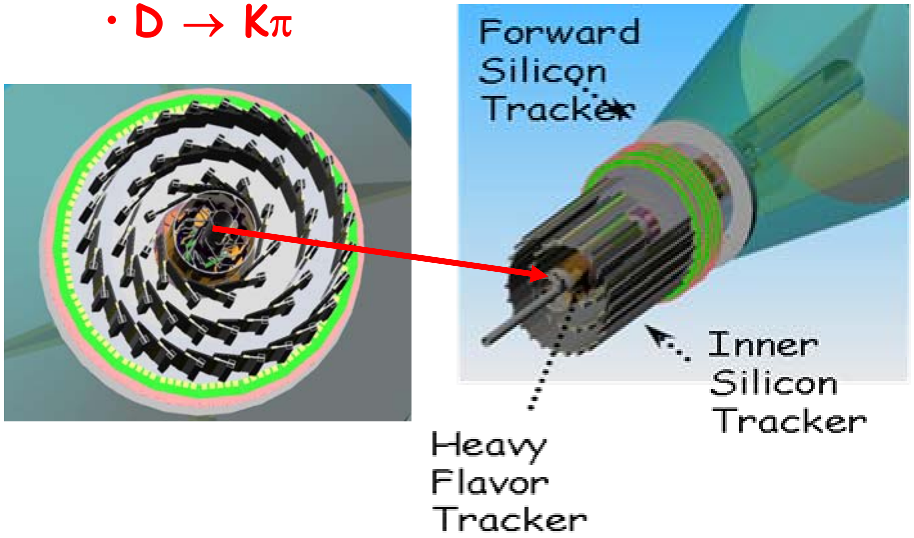
PHENIX
- Silicon vertex detector
  - mid-rapidity & forward heavy-q's, incl. $B \rightarrow J/\psi\ X$
  - improved background & mass resolution for quarkonia & dimuons
- Nose cone calorimeter $\chi_C \rightarrow J/\psi\ \gamma$






RHIC-II
- Luminosity increases via electron cooling also important:
  - x10 (AuAu); x2-3 (pp)

STAR
- Silicon vertex detectors
- Heavy Flavor Tracker & integrated central tracker
- $D \rightarrow K\pi$



# Charm Physics at RHIC - Summary

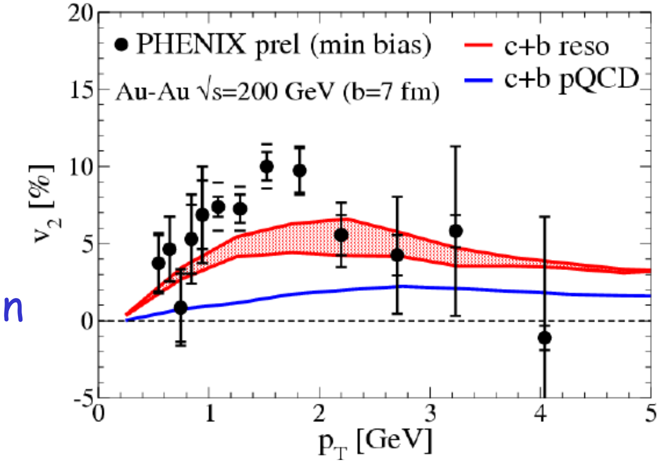
Quarkonia production cross sections and polarization still not well understood

Disagreement between PHENIX & STAR open charm cross sections and with theory (FONNL)

Weak shadowing observed at RHIC for the J/ψ in dAu collisions (need better dAu data to understand physics)

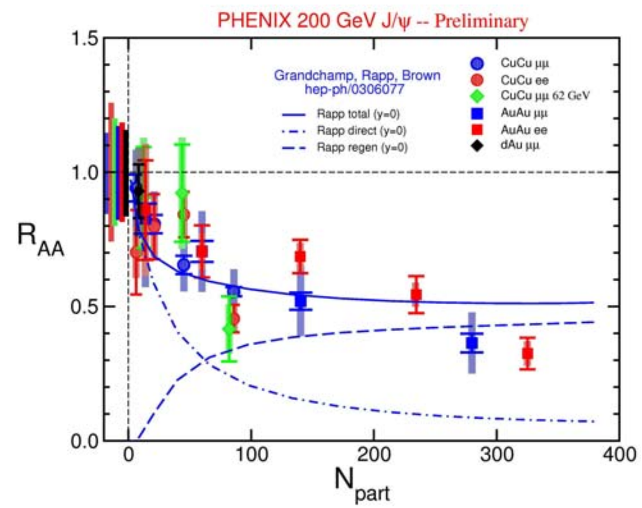
- but scaling with $x_F$ (and not with $x_2$) is still a puzzle

Open charm not modified by cold nuclear matter except in the shadowing region (forward rapidity)




*AA collisions at RHIC suggest substantial contributions from regeneration*

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



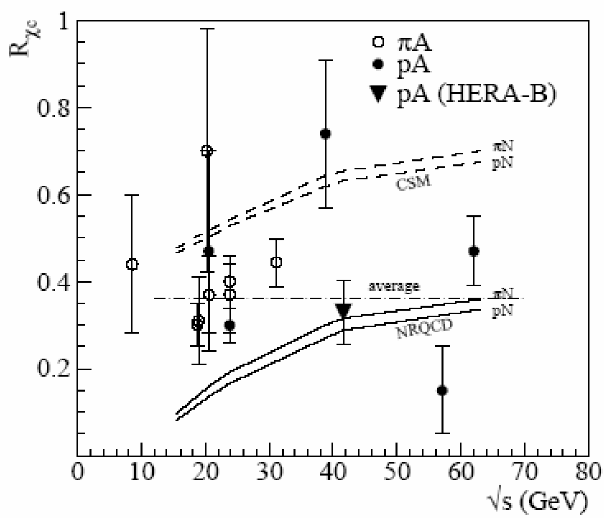

*Open charm energy loss and flow seen in AuAu, but difficult to get consistent theoretical description*

- need to look for flow from regeneration J/ψ's

Future vertex detector upgrades (& luminosity increases) will provide much higher quality data

# Backup Slides

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

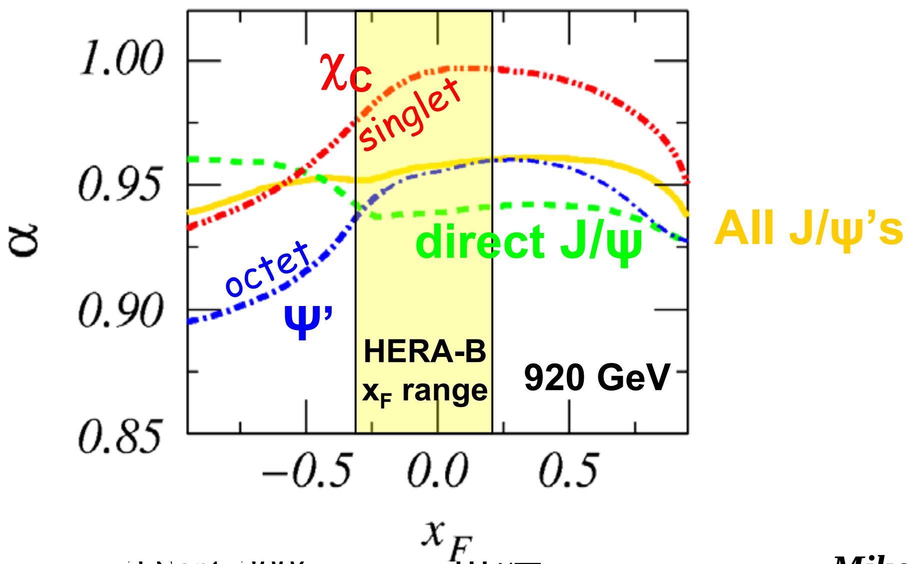



*HERA-B Phys.Lett. B561 (2003) 61-72 & E705 @ 300 GeV/c, PRL 70, 383 (1993)*

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% |

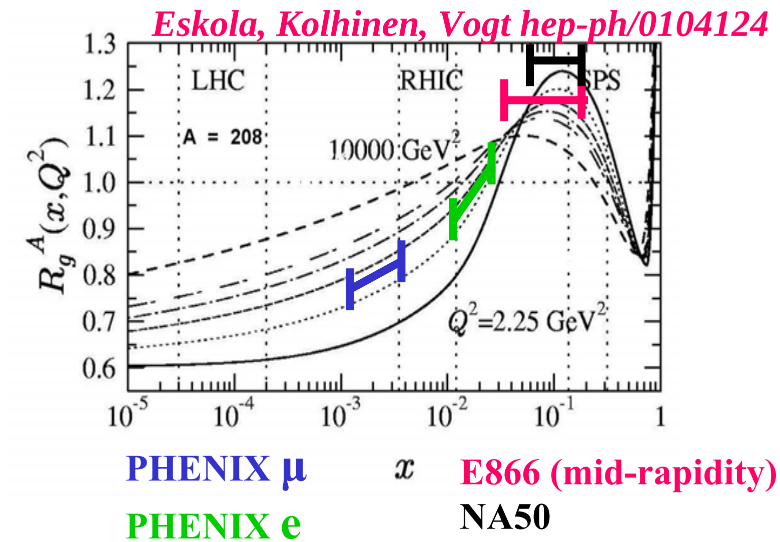
R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539



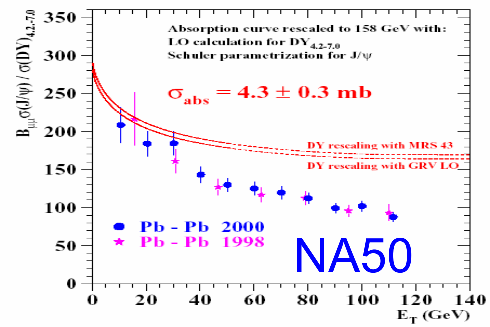

Effect on Nuclear dependence:

- 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

# Absorption of J/ψ's not so simple?

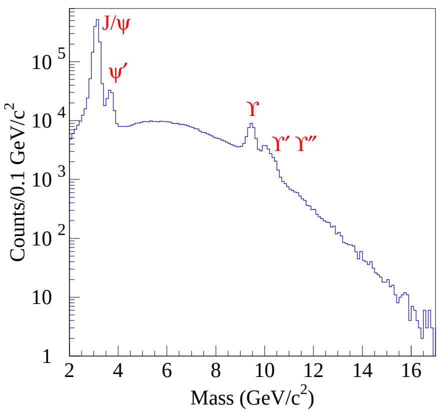



| Set | $P_{lab}$ | $N_0$ (nb) | $\sigma_{abs}$ (mb) |
|---|---|---|---|
| NA50 | 450 GeV | 5.6±0.1 | 4.1±0.4 |
| NA50 | 400 GeV | 5.1±0.1 | |
| NA38 (corrected) | 400 GeV | 5.5±0.2 | |



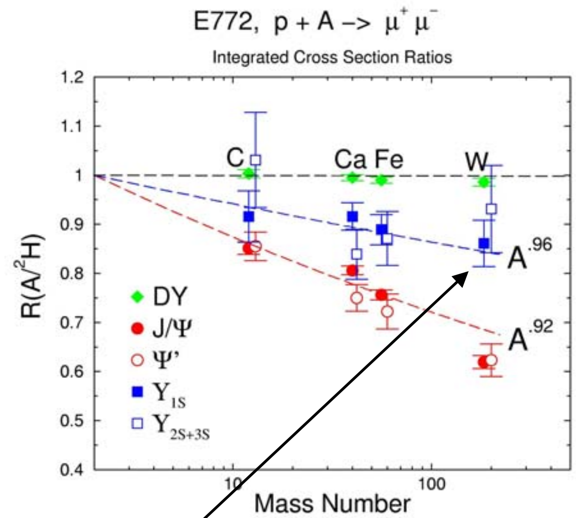

- What really is $\sigma_{abs}^{J/\psi}$ ?
  - An effective quantity
  - What is crossing the nucleus and how does it evolve?
    - pre-resonant $c\bar{c}$ state, fully formed resonance?
  - Are we measuring primary J/ψ?
    - feed-down from ψ′ and $\chi_c$
    - will fraction of feed-down change in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

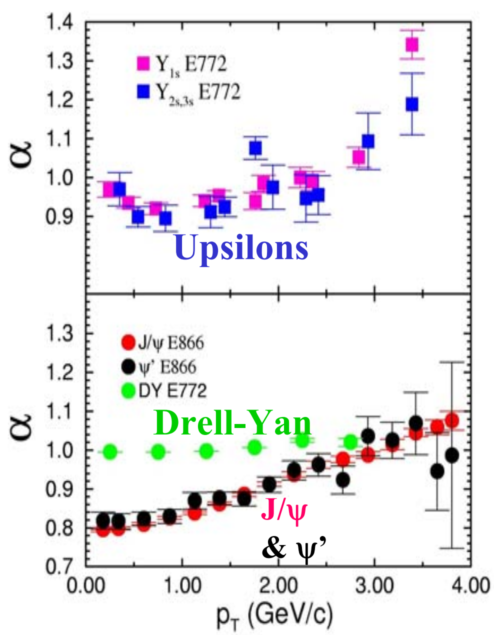
# Contrasting ϒ's with J/ψ's



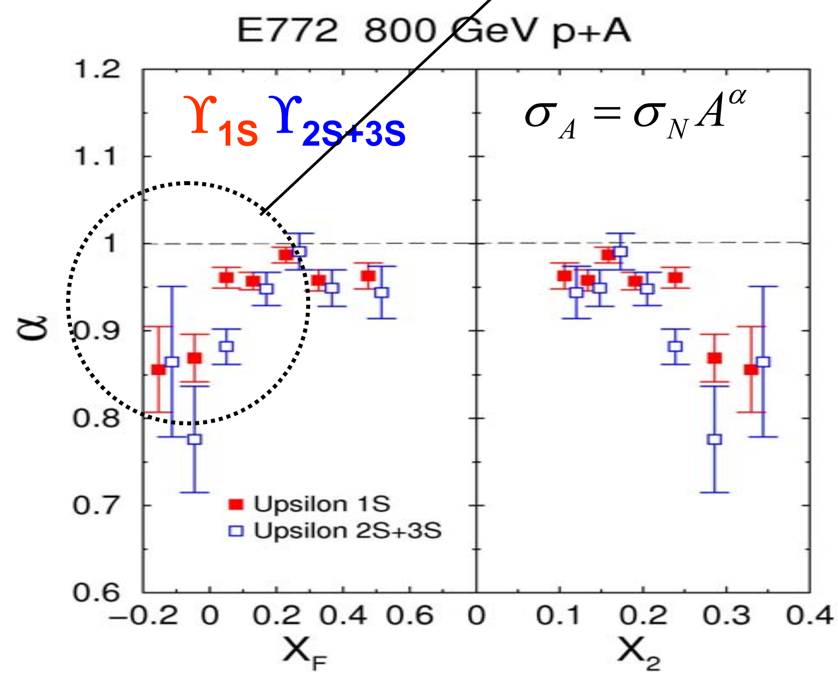

$\sqrt{S}$ =39 GeV (E772 & E866)

- 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)



# 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**

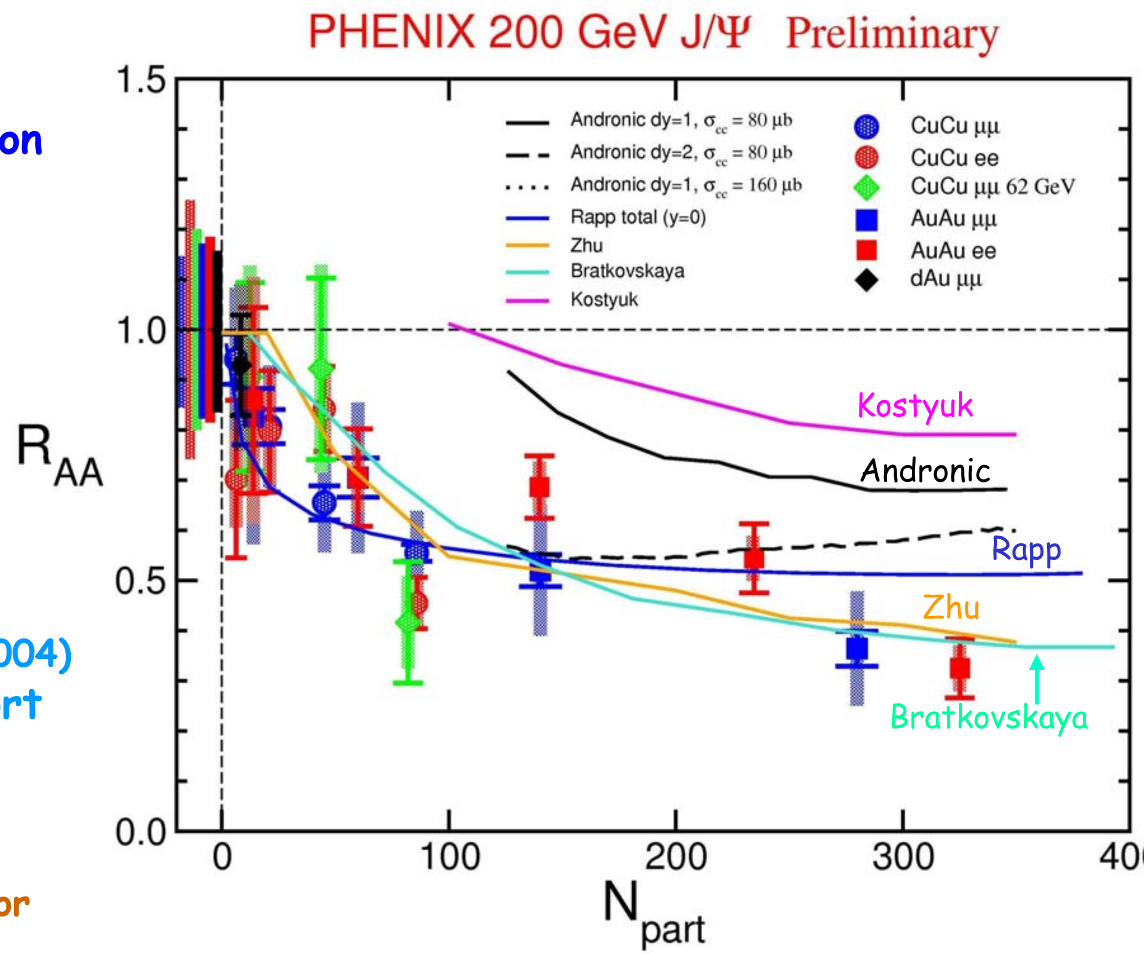
**Thews – see previous slide**

**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**



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# Sudakov suppression

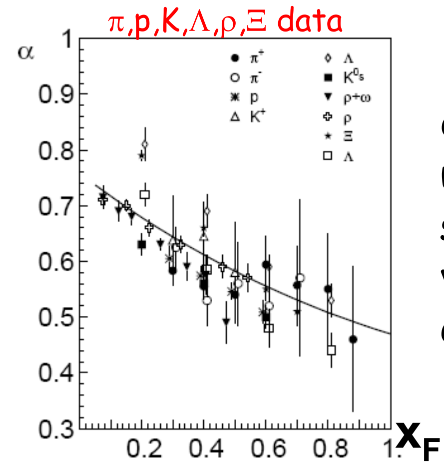
## Kopeliovich hep-ph/0501260

Universal suppression at large $x_F$ seen in data for various reactions:

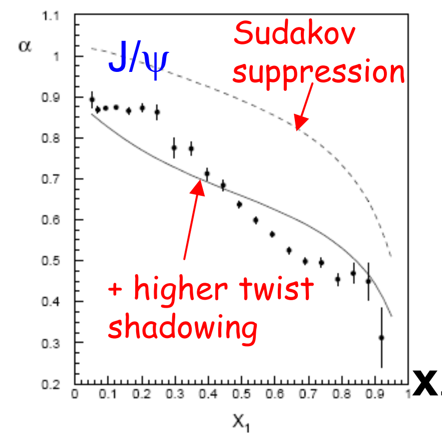
- forward light hadrons, Drell-Yan, heavy flavor
- often attributed to shadowing since $x_2$ is small

But this common suppression mechanism can also be viewed as:

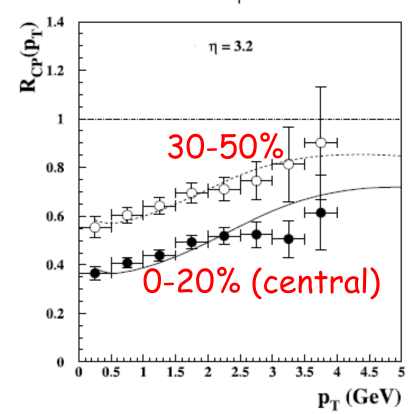
- Sudakov suppression – no particles produced as $x_F \rightarrow 1$ due to energy conservation; more multiple interactions make the effect larger in nuclei
- or Reduced survival prob. for large rapidity gap processes in nuclei as $x_F \rightarrow 1$




describes universal suppression vs $x_F$ for low energy data




Close to 800 GeV J/ψ suppression vs $x_1$ ($x_1 \approx x_F$)



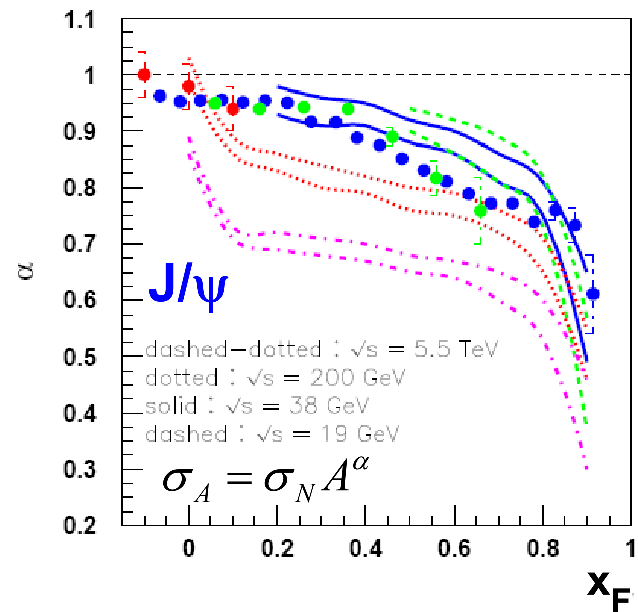

and Brahms forward rapidity (η=3.2) hadrons

# J/ψ in Color Glass Condensate (CGC) model
## Kharzeev, Tuchin, hep-ph/0510358

- Coherent production of heavy quarks at high energy, when $\tau_{Prod} > R_A$

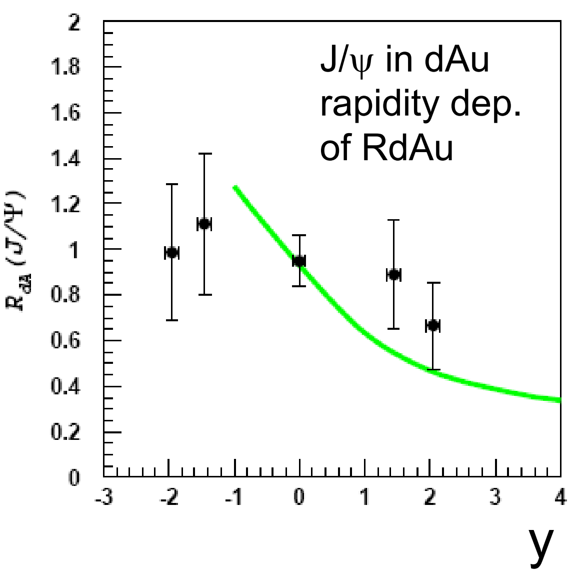
$$\tau_{Prod} \approx 15e^{y}\, fm \ \text{(at RHIC)}$$

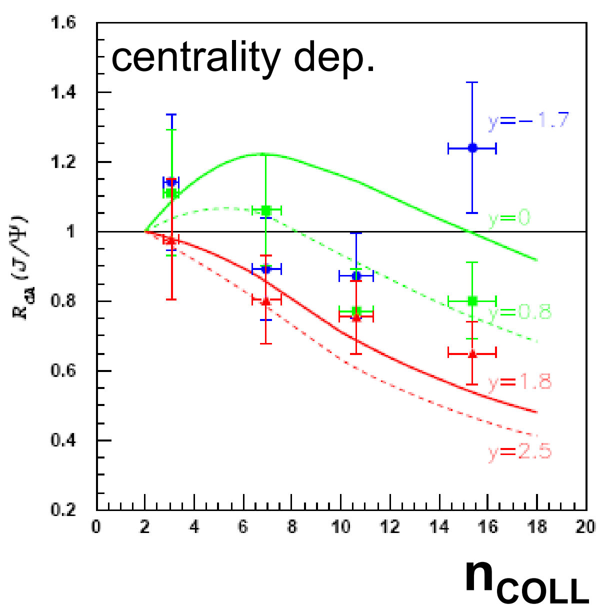
- Suppressed by saturated gluon wavefunction at forward y




$x_F$ scaling at forward rapidity

* NA3
* E866/NuSea
* PHENIX



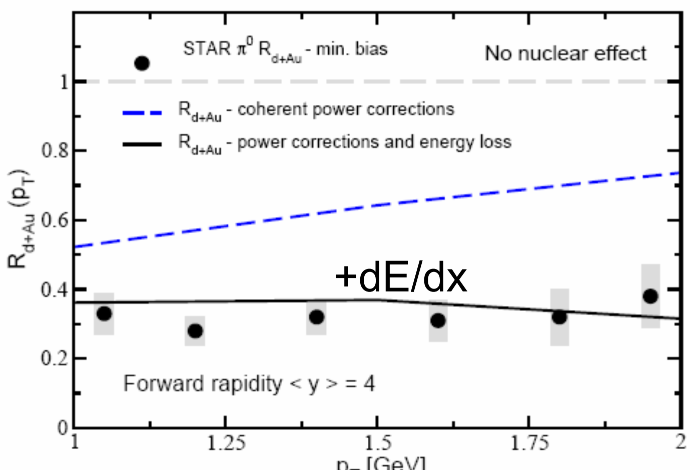

- Suppression at forward rapidity - increases with centrality;
- Enhancement for backward rapidity

# Charm production in dAu
## Vitev et al. – hep-ph/0605200

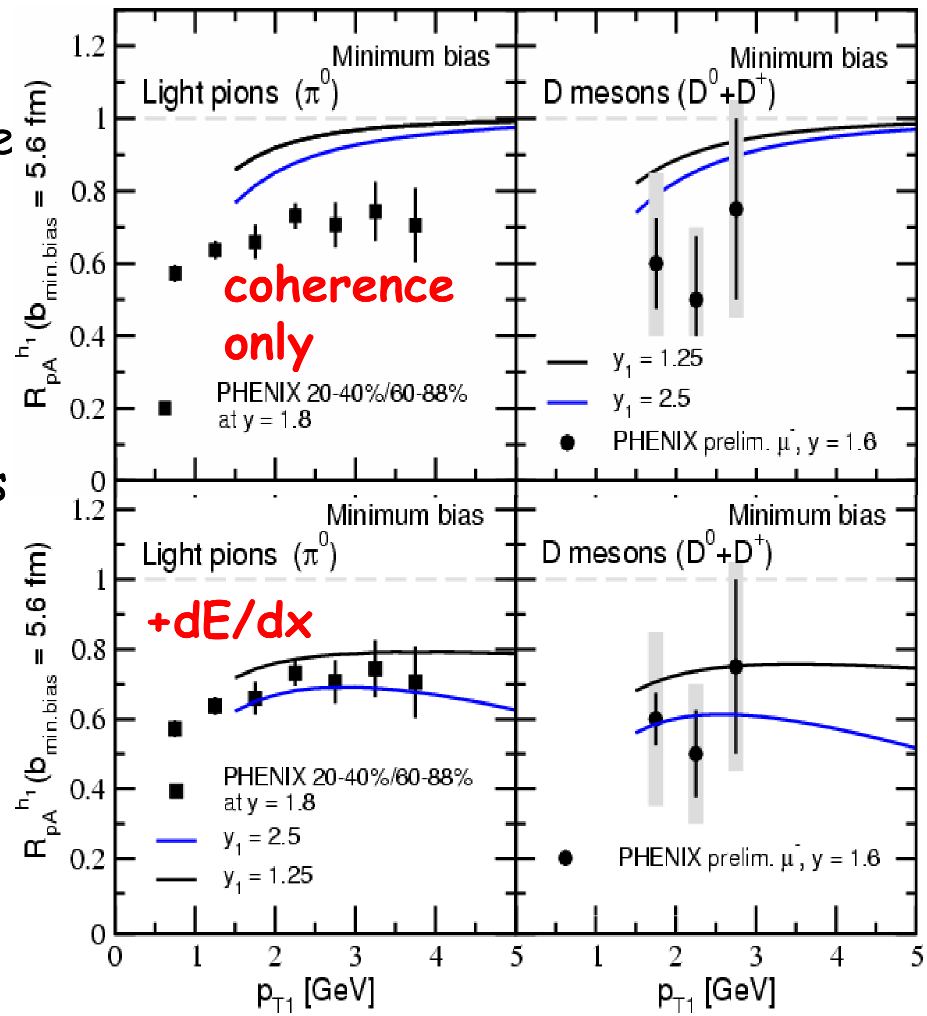
cg & cq dominate inclusive D production

final-state coherence effects
- simultaneous interaction with more than one nucleon ($x_N < 1/2r_0m_N$)
- equivalent to shift in effective x

initial-state inelastic radiative energy loss necessary to reproduce data
- large dE/dx - average parton loses 10% of its energy!



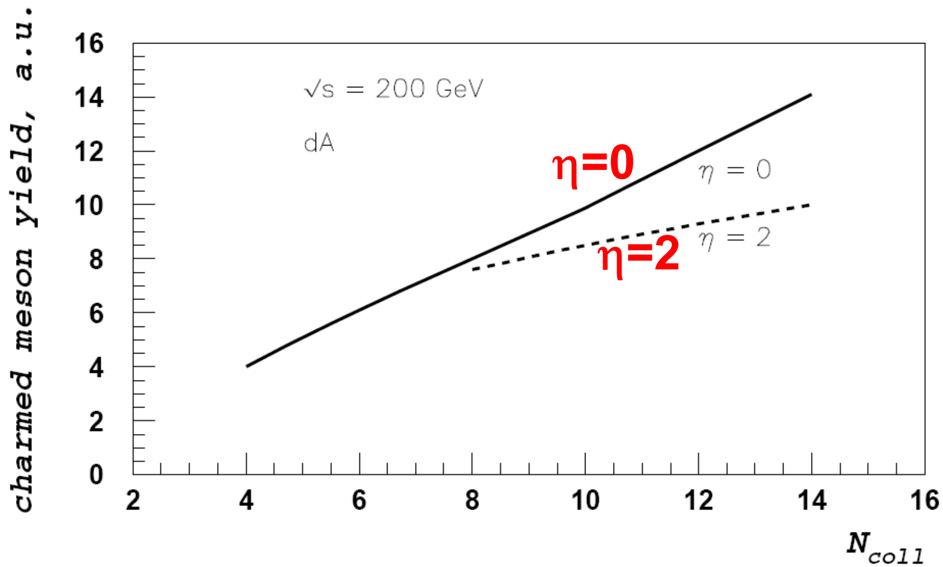

STAR $\pi^0$ at y=4



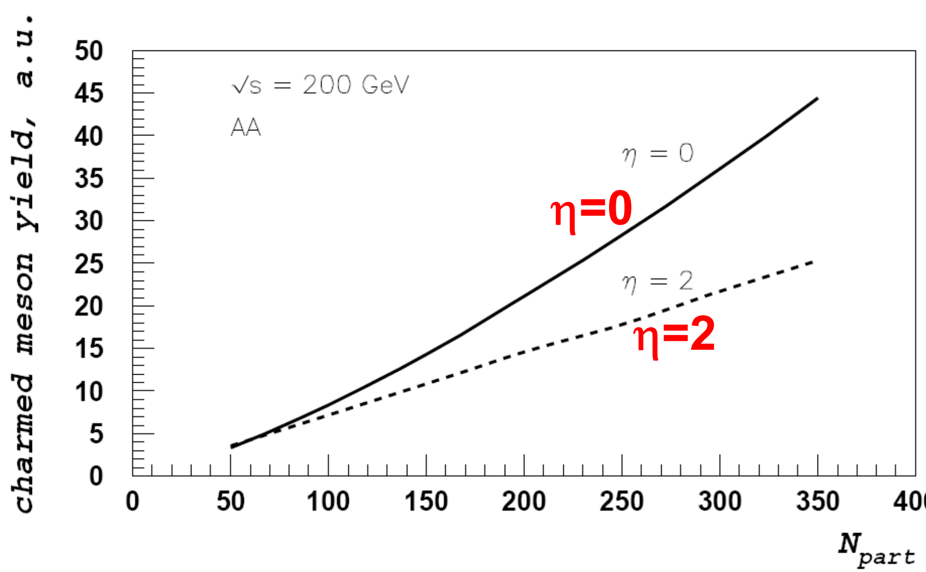
# Open charm production in the CGC model

hep-ph/0402298

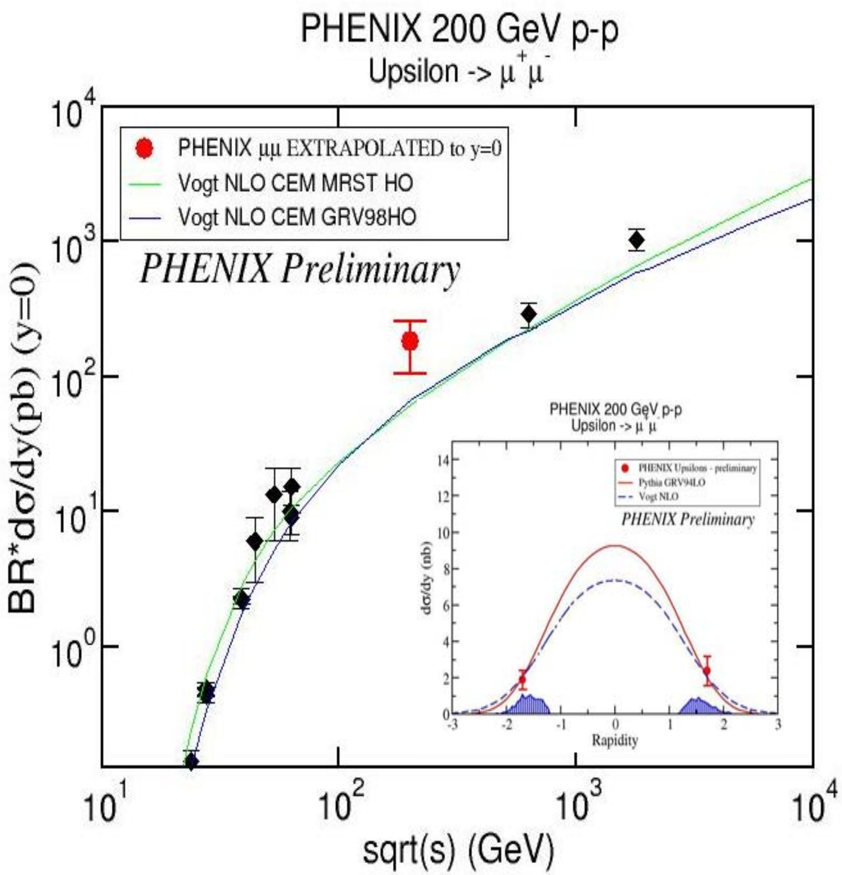
Suppression below binary scaling at forward rapidity (small-x) in dAu




Further suppression at forward rapidity in AuAu

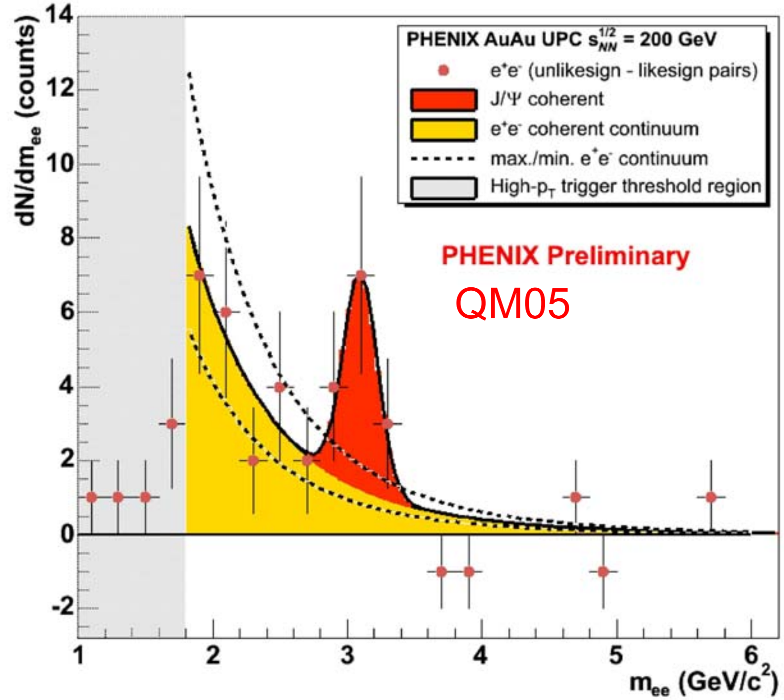


# Much More to Come!



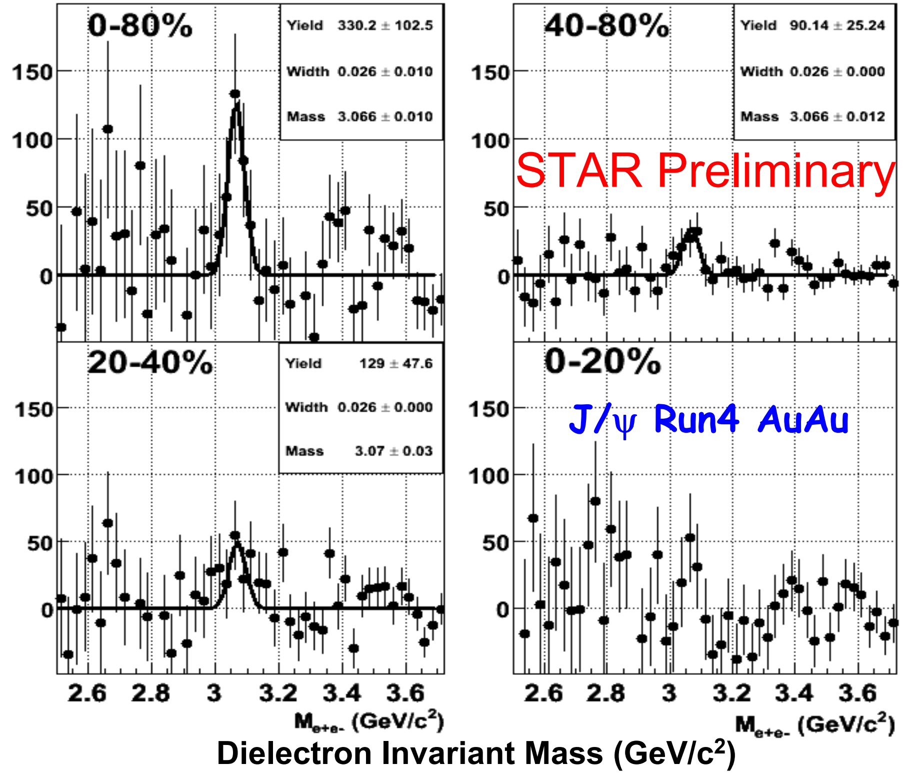

1st Upsilons at RHIC from ~3pb$^{-1}$ collected during the 2005 run.

## Ultra-peripheral Collisions (UPC's)

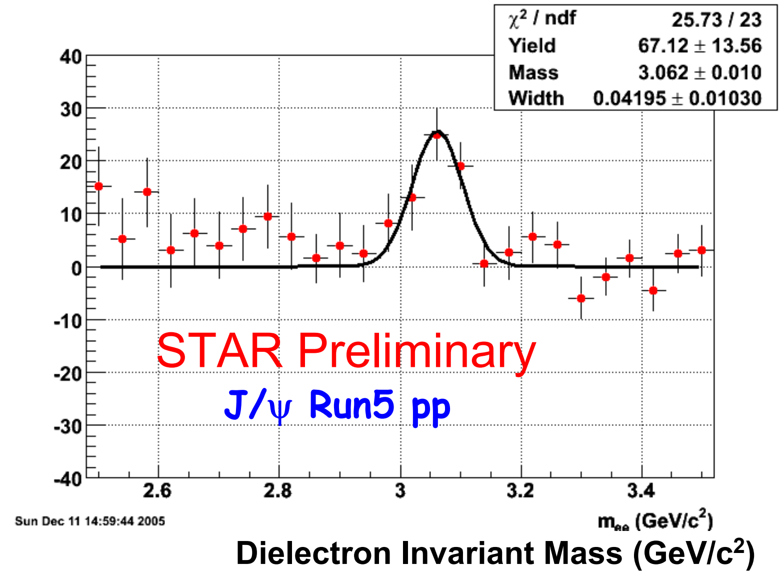


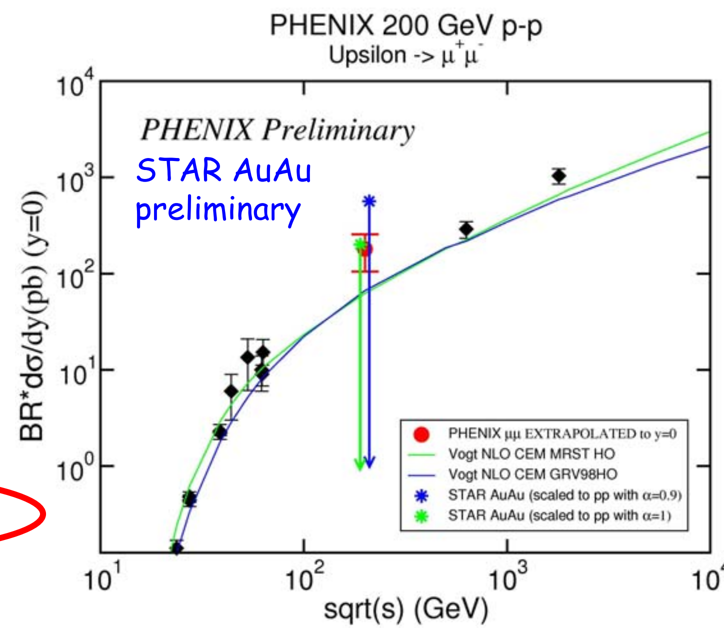

UPC's : well calibrated EM probe of small-x gluon saturation

# Onia in STAR




J. Gonzalez, SQM




| 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 |