QUARKONIA PRODUCTION AT RHIC

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Hot and Dense Matter in RHIC LHC era
Mumbai Fev/2008

The Importance of the Quarkonia

2285 papers with J/ψ in the title according to SPIRES

	Mass	radius
π	0.14 GeV	0.06fm
p	0.94 GeV	0.87fm
ψ'	3.68 GeV	0.90fm
χ_c	3.53 GeV	0.72fm
J/ψ	3.1 GeV	0.50fm
Υ	9.5 GeV	0.28fm

$\Lambda_{QCD} \sim 200$ MeV

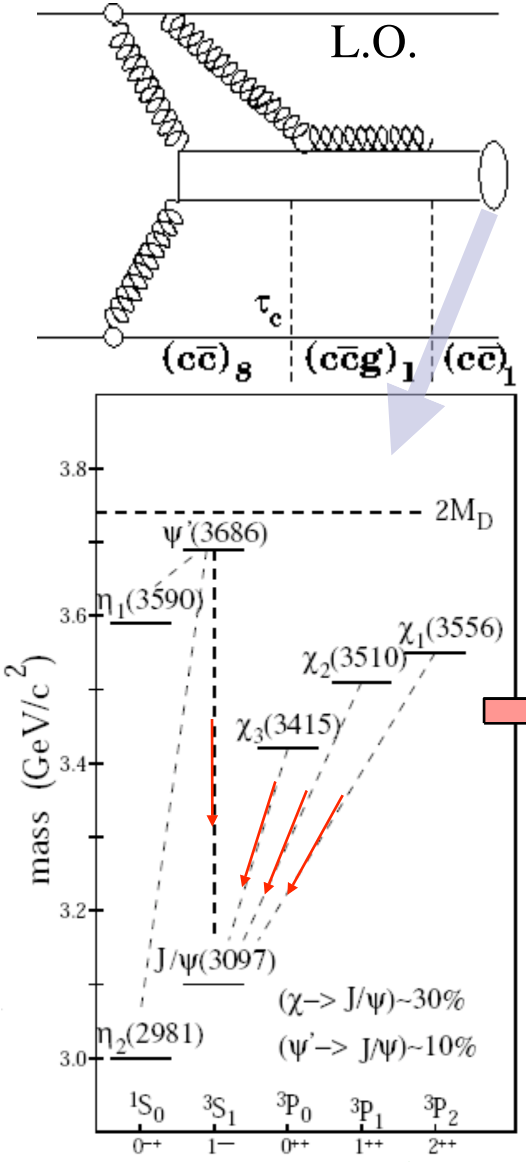
$\alpha_s(M_Q) \ll 1$

- weak coupling with light mesons
- small size
- strong biding

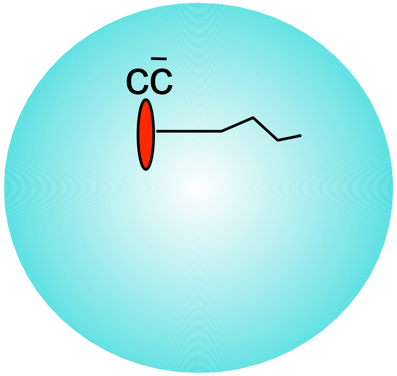
All these features make quarkonia an excellent QCD probe.

The complete quarkonia dissociation could serves as a QGP thermometer.

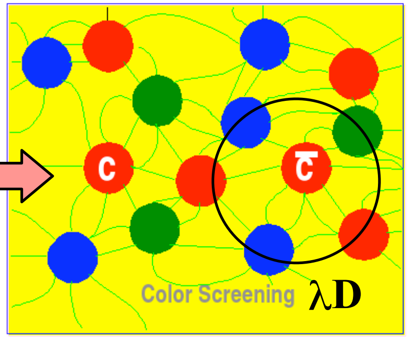
Quarkonia Production/Suppression

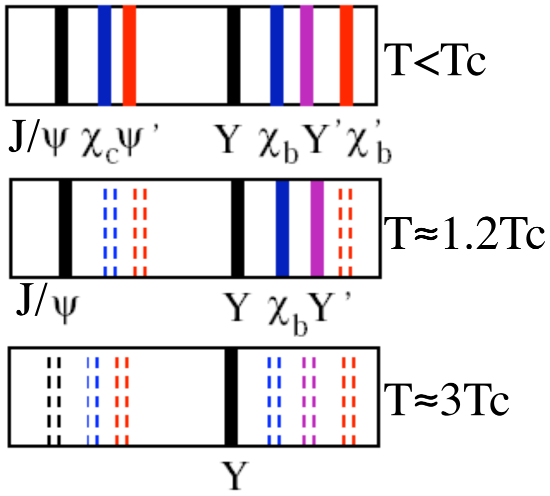


Production

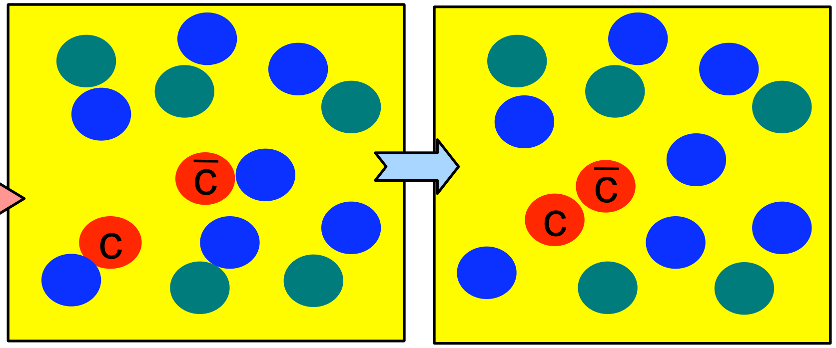


- **Nuclear Absorbtion**
- **Parton Distribution Modifications**
- **Comovers**



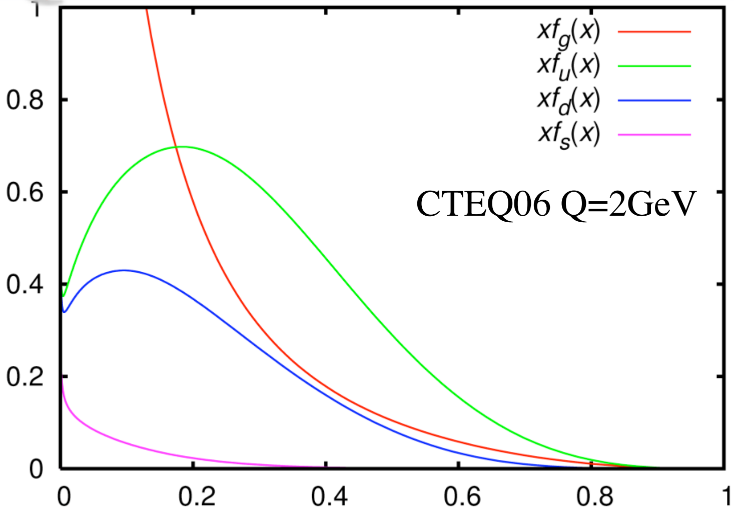


- **Dissociation in deconfined medium**

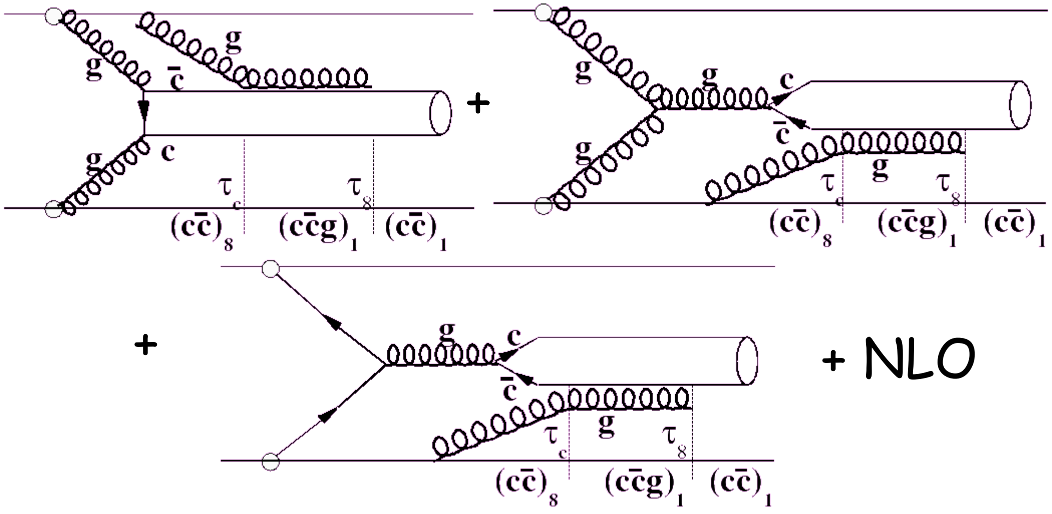


- **Recombination or Coalescence**

Quarkonia Production in p+p collisions



$\sigma_{ij}(s) =$



$$\sigma(S_{NN}\overset{x}{,}Q^2) = \sum_{i,j=\bar{q},q,g} \int_0^1 dx_1 \int_0^1 dx_2 xf_i(x_1,Q^2)xf_j(x_2,Q^2)\sigma_{ij}(\hat{s},Q^2)\delta(\hat{s}-x_1x_2S_{NN})$$

Color neutralization is a non-perturbative process. Methods to handle it :

- Non-relativistic QCD (NRQCD) : $\sigma(\hat{s},Q^2) = \sum_n \frac{C_n(\Lambda)}{m^{d_n-4}} \langle \mathcal{O}_n^H(\Lambda) \rangle$

  pQCD empirical

  PLB167 (1986) 437, PRD43 (1991) 196, PRD51 (1995) 1125.

Formation of $(ccg)_8$ agree with p+p data.

- Color Evaporation Model (CEM) : $\sigma(S_{NN},Q^2) = F_H \int_{2m_c}^{2m_D} d\hat{s} \frac{d\sigma(\hat{s},Q^2)}{d\hat{s}}$

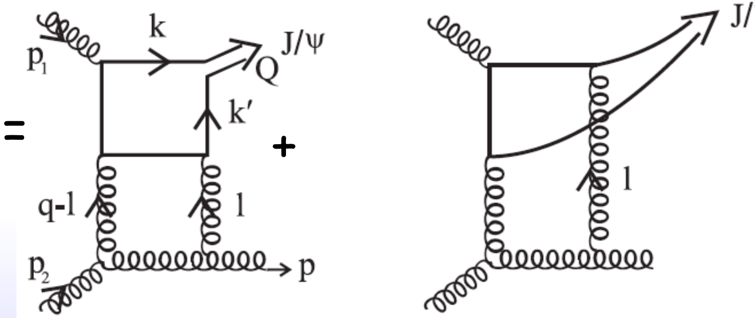
  empirical pQCD

  Int. J. Mod. Phys. A 10 (1995) 3043

- pQCD w/ 3-gluon fusion :

  Eur. Phys. J. C 39, 163–171 (2005)

$\sigma_{ij}(s) =$

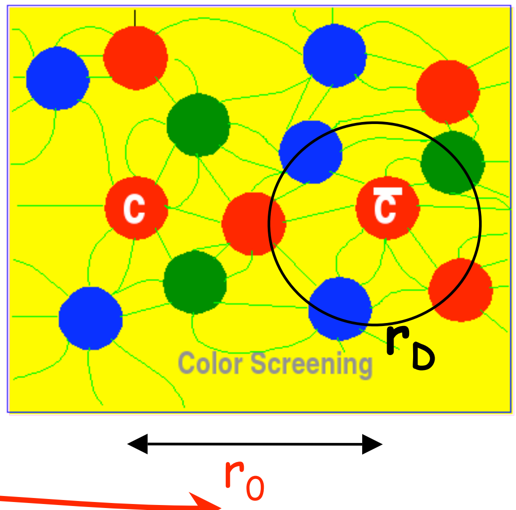


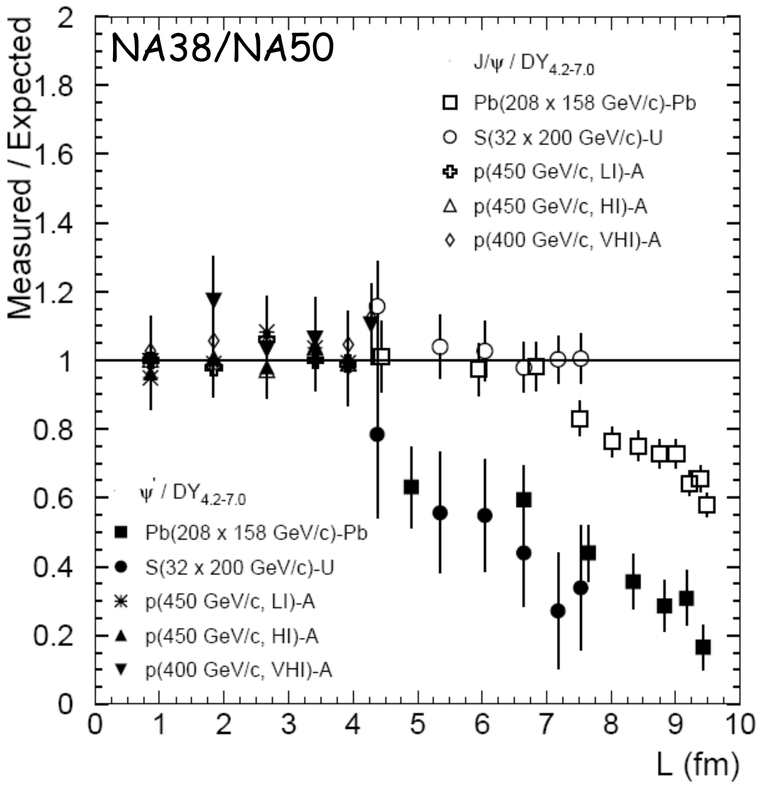
+ NLO

Screening in Colored Matter

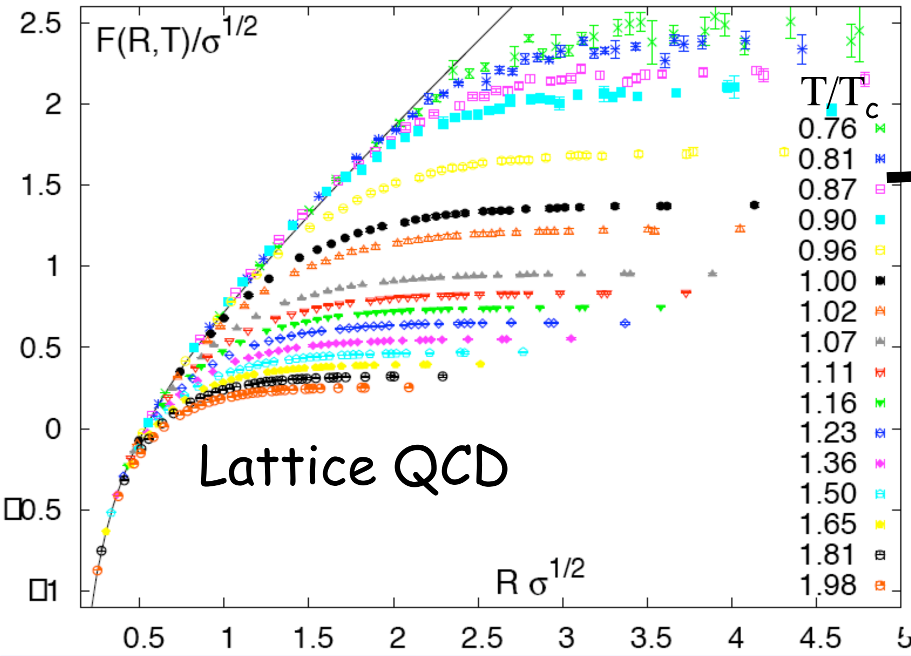
state	J/ψ	χ_c	ψ'
mass [GeV]	3.10	3.53	3.68
ΔE [GeV]	0.64	0.20	0.05
ΔM [GeV]	0.02	-0.03	0.03
r_0 [fm]	0.50	0.72	0.90

Matsui & Satz, PLB178 ('86),
Miyamura et al., PRL57 ('86)

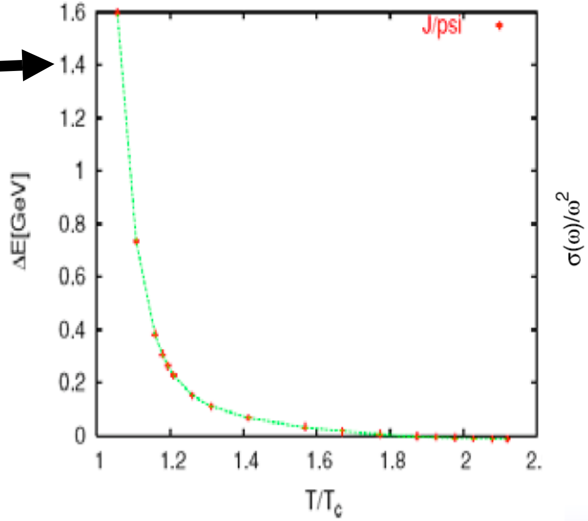




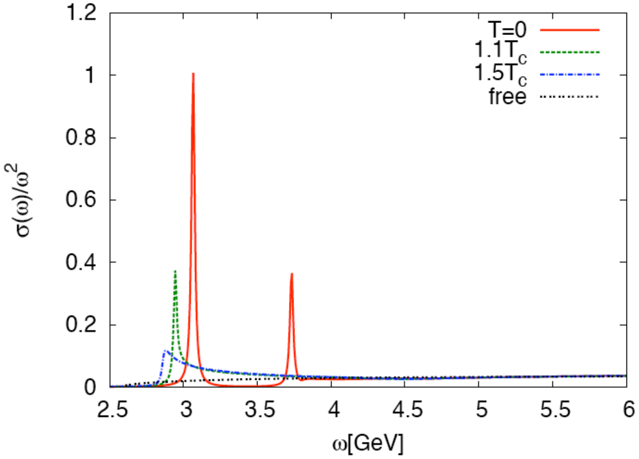
O. Kaczmarek, F. Zantow,Phys.Rev.D71 (2005)114510.



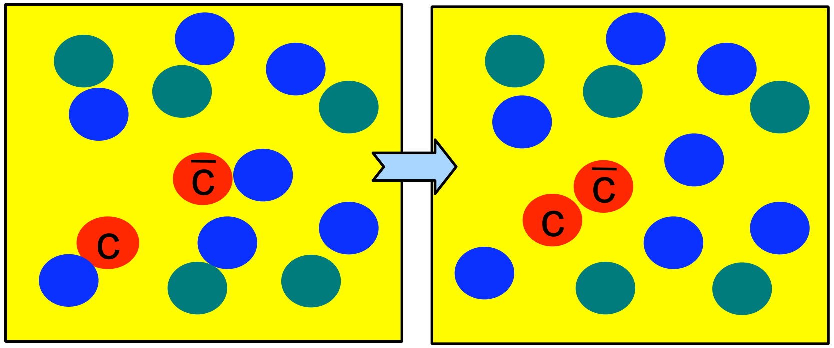
H.Satz, J. Phys. G32 (2006) R25



A.Mocsy, P.Petreczky, PRL99 (2007)211602



Recombination and Coalescence



$\sigma_{c\bar{c}}$= $\sigma(p+p \rightarrow c\bar{c}+X) = \begin{cases} 567\pm57(\text{stat}) \pm224(\text{sys})\ \mu\text{b @ PHENIX [PRL97 (2006) 252002]} \\ 256\ {+400}{-146}\ \mu\text{b by FONLL} \end{cases}$

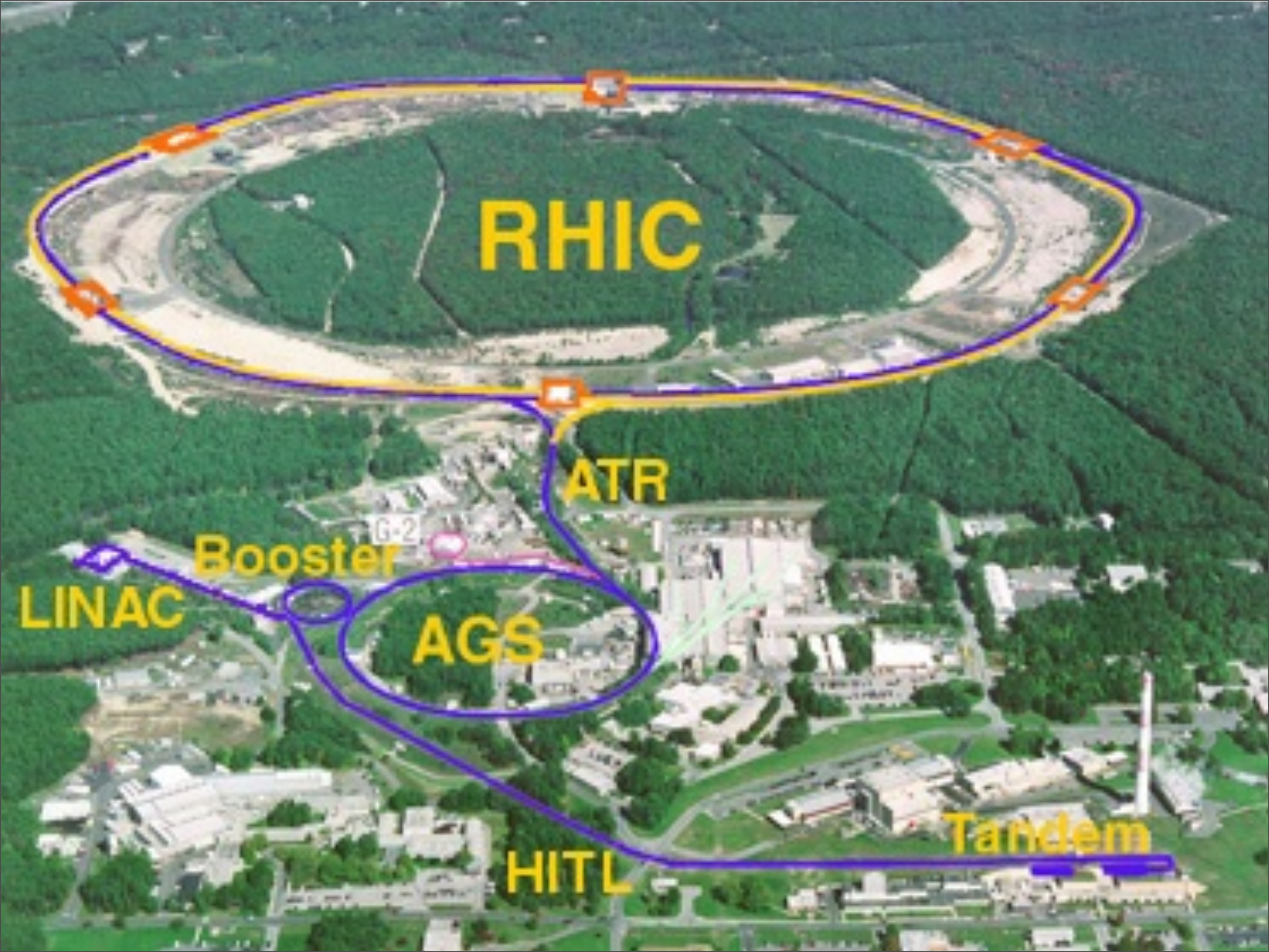
The charm cross section scales with binary scaling [PRL94 (2005) 082301]. Thus, the average number of cc̄ pairs is:

$$\langle N_{c\bar{c}} \rangle = N_{coll} \frac{\sigma_{c\bar{c}}^{p+p}}{\sigma_{inel.}^{p+p}}$$

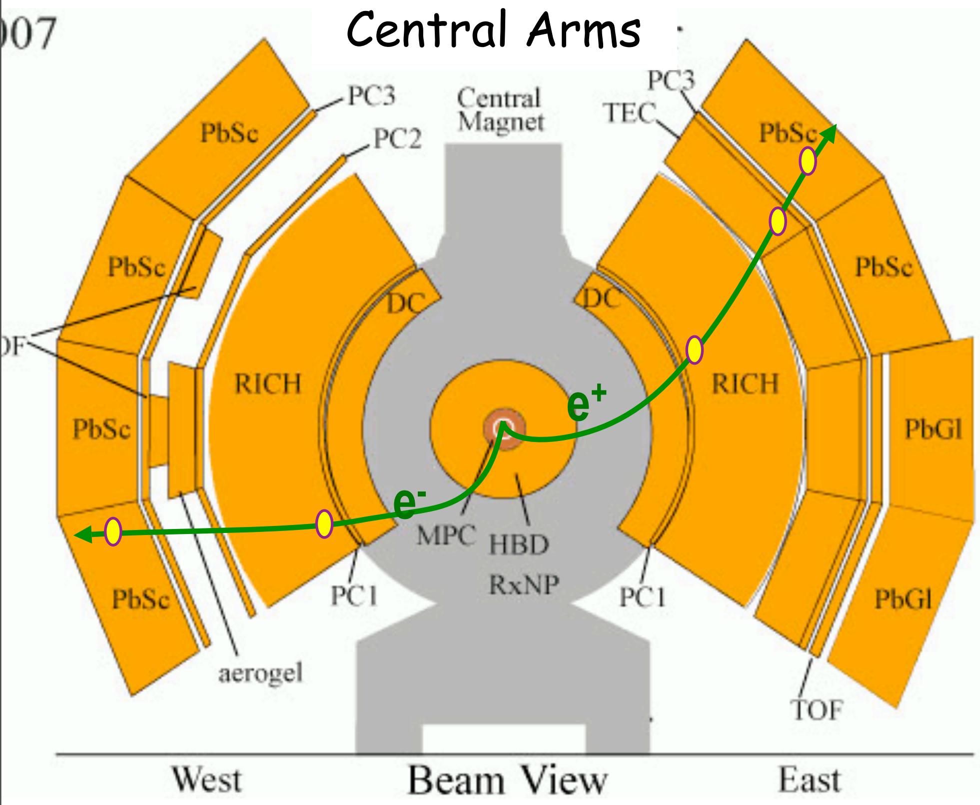
Using PHENIX $\sigma_{c\bar{c}}$, σ_{pp}=42 mb and 1000 binary collisions in very central Au+Au collisions we find **13±7 cc̄ pairs per event**.

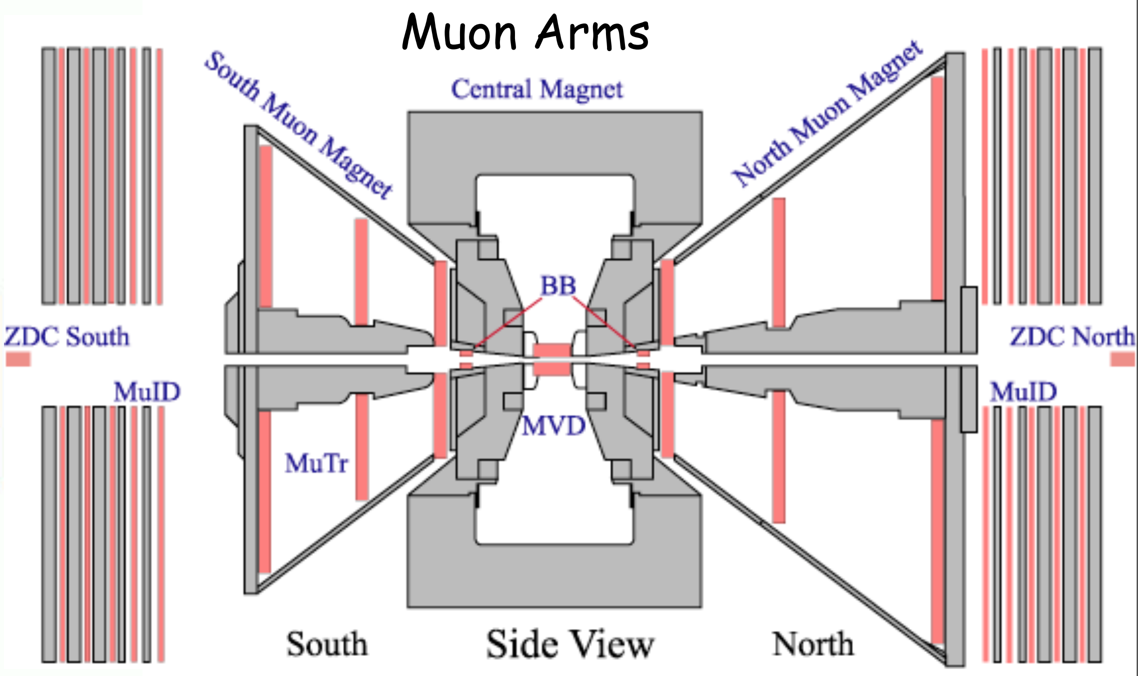
Number of J/ψs produced by recombination of charms : $N_{J/\psi} \propto \frac{N_{c\bar{c}}^2}{N_{ch}}$

The charmonium recombination may be a important source of final J/ψ yield at RHIC.


RHIC
ATR
G-2
Booster
LINAC
AGS
Tandem
HITL

PHENIX Measures Electrons and Muons

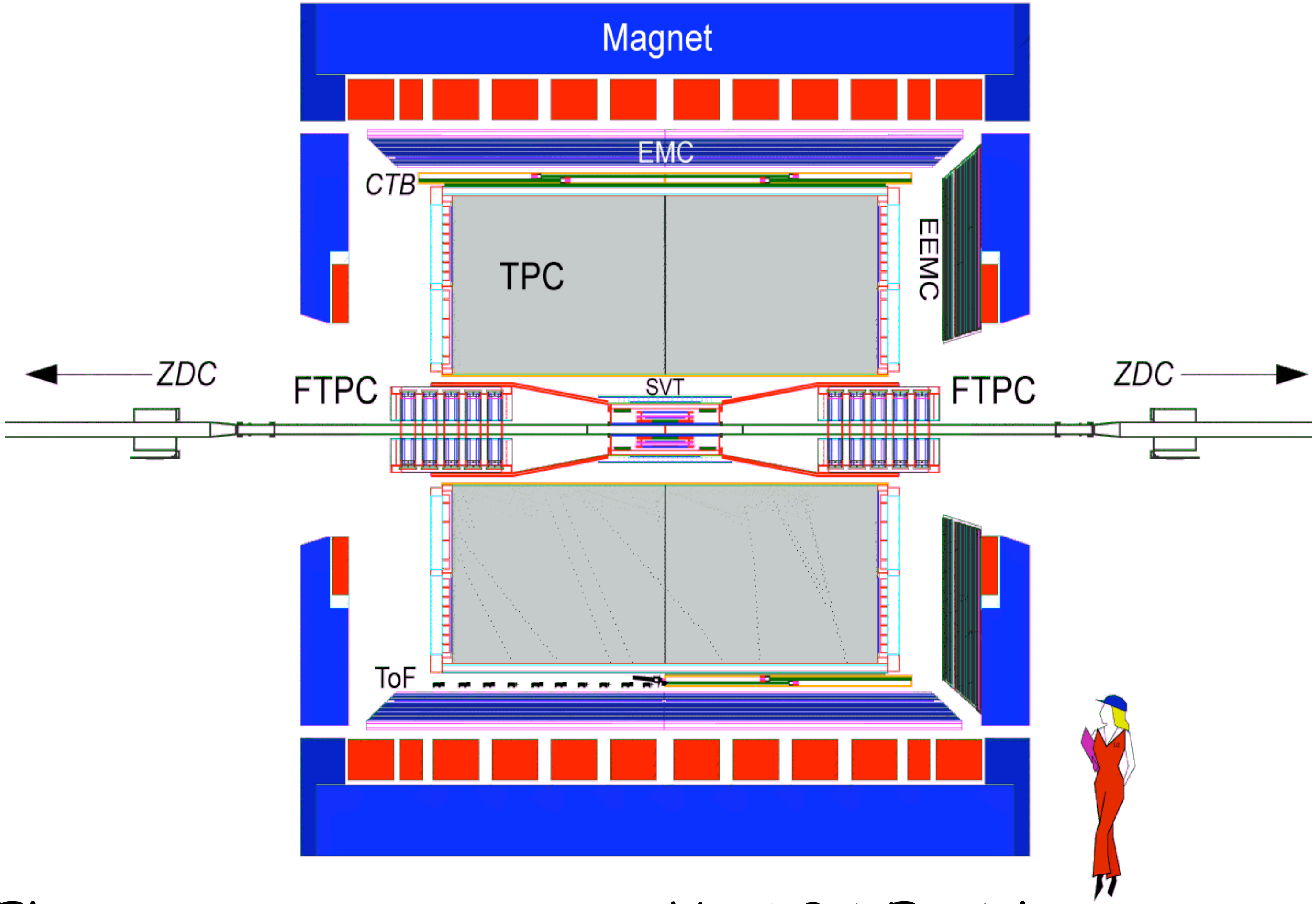




- $|\eta|<0.35$
- $\Delta\phi=2 \times \pi/2$
- eID: EmCal and RICH

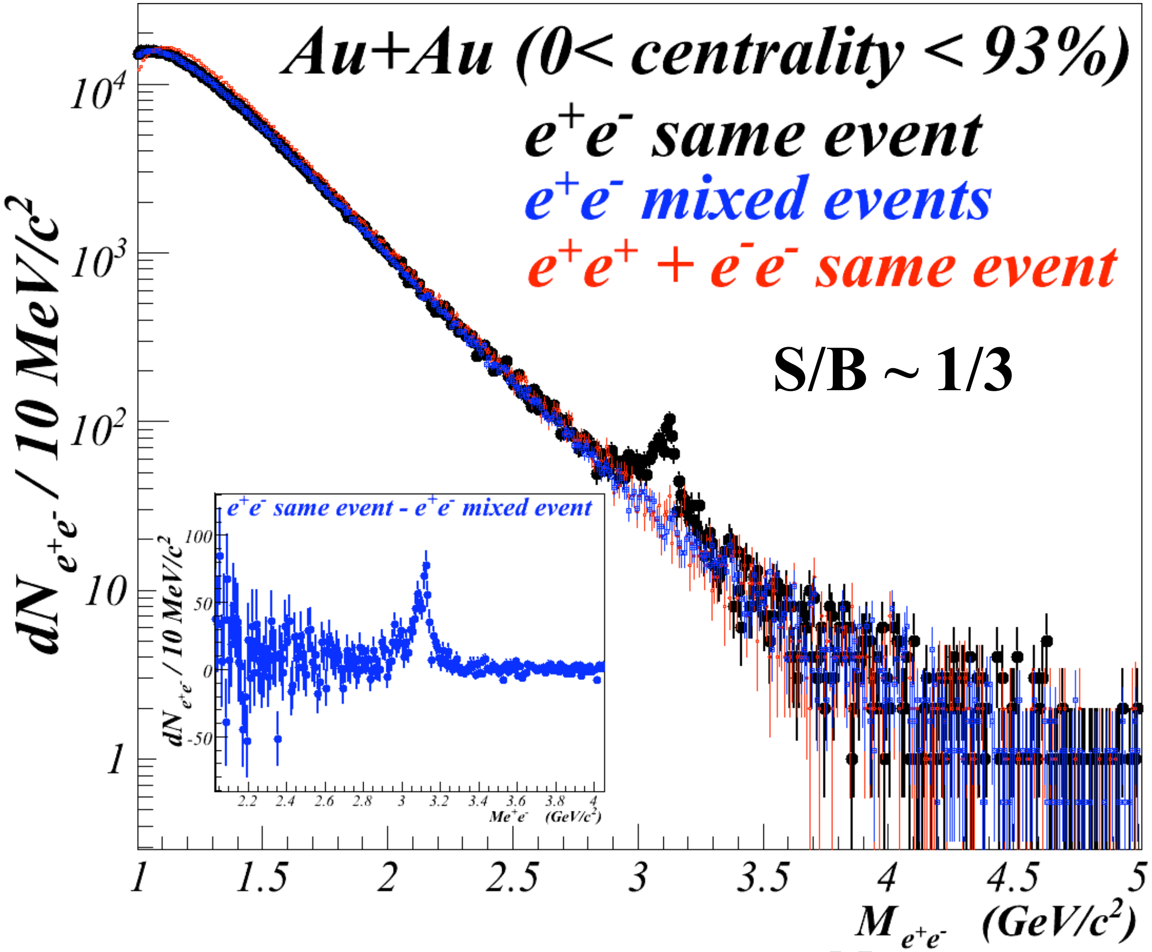
- $-1.2 > \eta > -2.2$ and $2.4 > \eta > 1.2$
- $\Delta\phi=2\pi$
- Muon $|p| > 2$ GeV/c
- muon tracking
- 4 hadron absorbers in MuID
- common accepted π/μ ~10-4

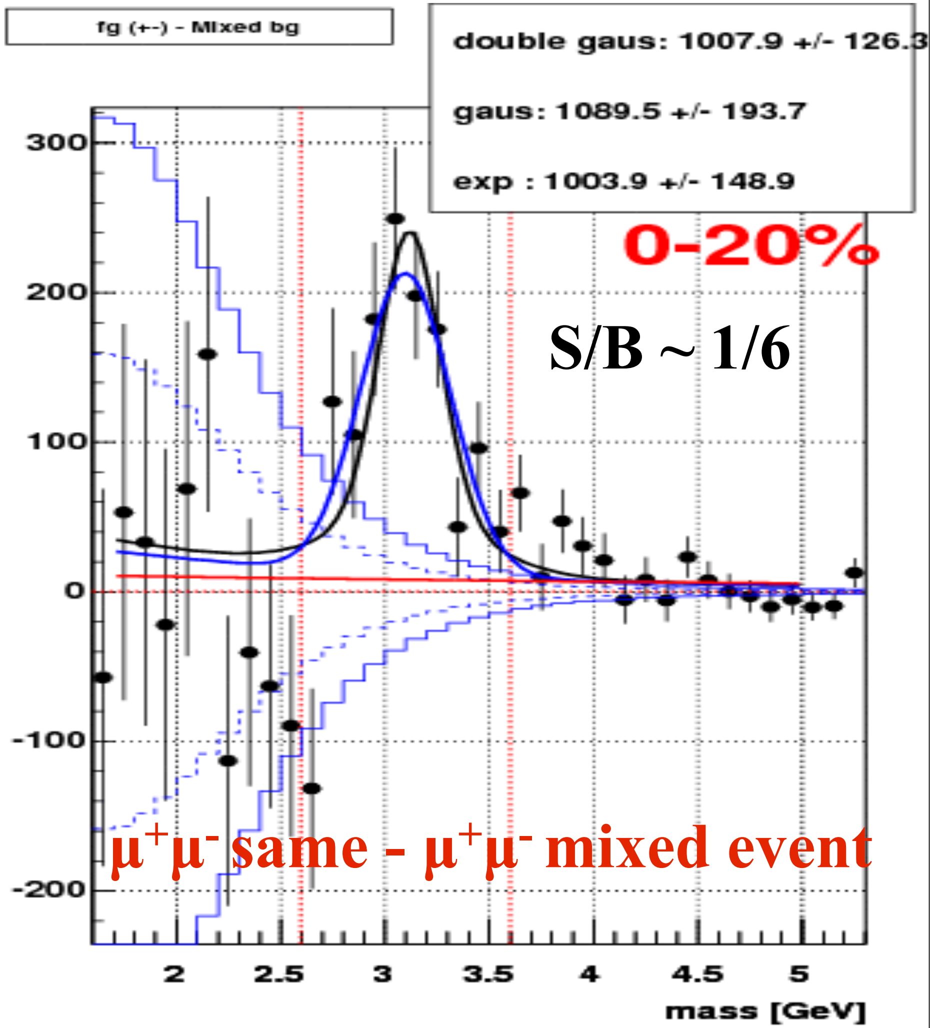
STAR Measures Electrons



- Electrons are reconstructed by TPC+EmCal
- $|\eta|<1$, $0<\phi<2\pi$
- Events are triggered by EmCal ($p_T>5$ GeV/c)

Measuring J/ψs





$$B\frac{dN}{dy} = \frac{N_{J/\psi}}{N_{ev}}\frac{1}{\Delta y \varepsilon_{acc}\varepsilon_{mult}}$$

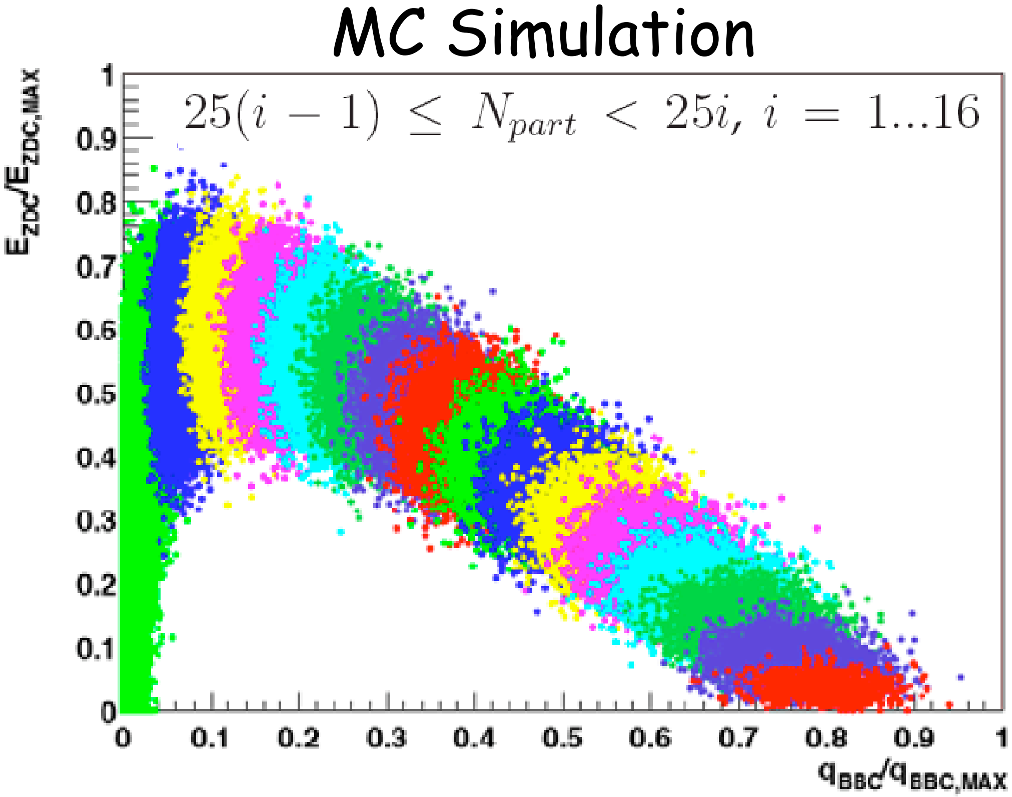
B : branching ratio for e^+e^- or $\mu^+\mu^-$ from PDG

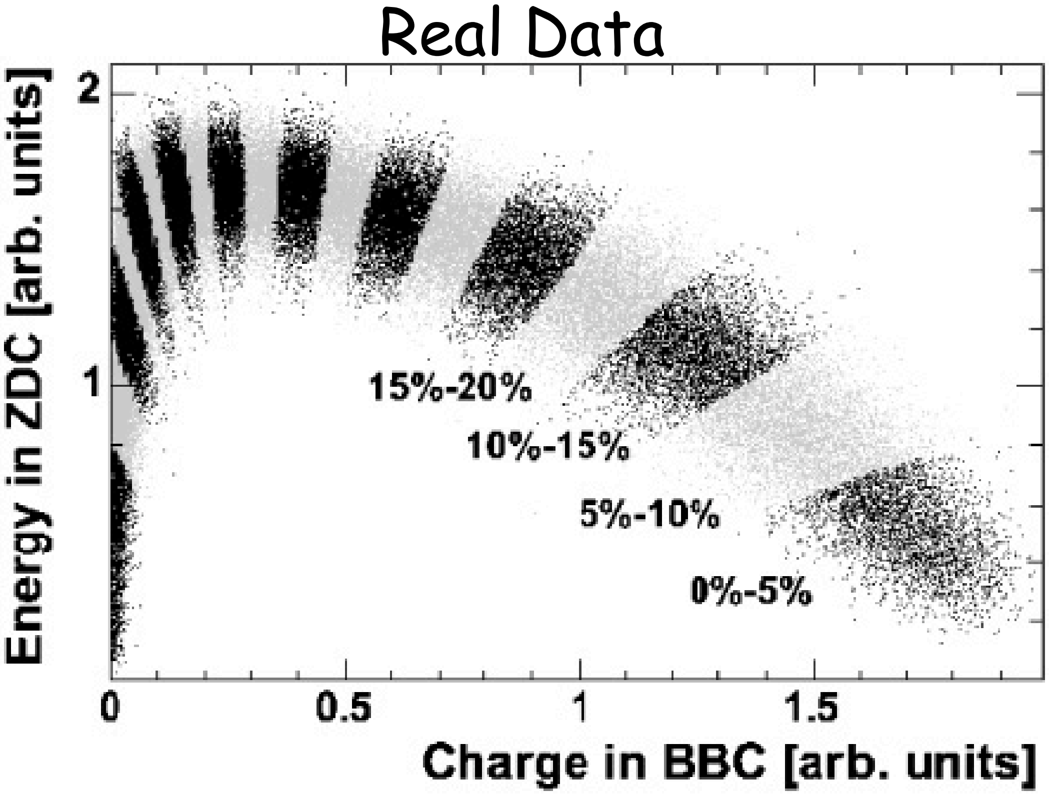
Δy : rapidity coverage

ε_{acc}:overall acceptance for J/ψ in each arm from simulation

ε_{mult} :efficiency dependence with particle multiplicity.

Determining Centrality


MC Simulation

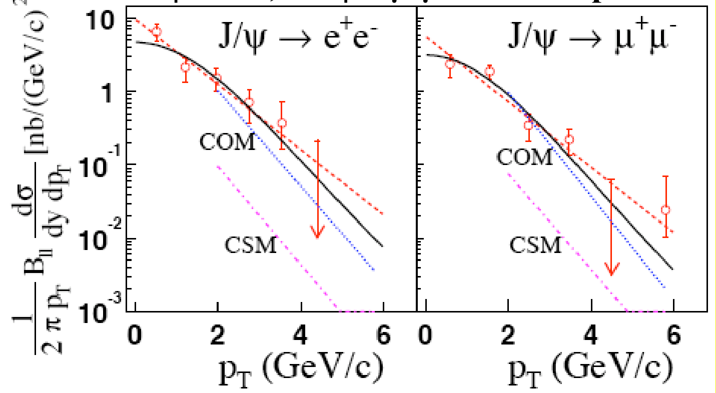

Real Data

Centrality determined by Zero Degree Calorimeter(|η|>6) and Beam Beam Counter (3.0<|η|<3.9)

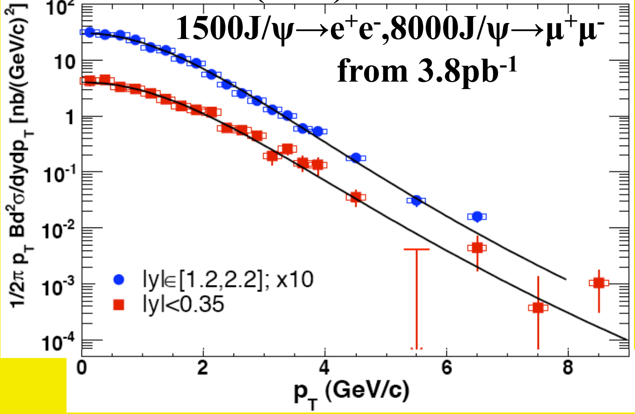
p+p

PRL92 (2004) 051802

46J/ψ→e^+e^-,66J/ψ→$\mu^+\mu^-$ from 0.15pb^{-1}



PRL98 (2007) 232002



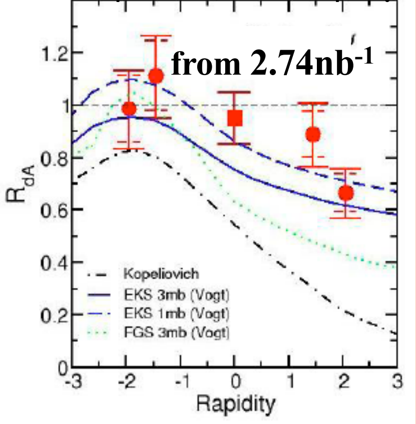
1500J/ψ→e^+e^-,8000J/ψ→$\mu^+\mu^-$

from 3.8pb^{-1}

d+Au

PRL96 (2006) 012304

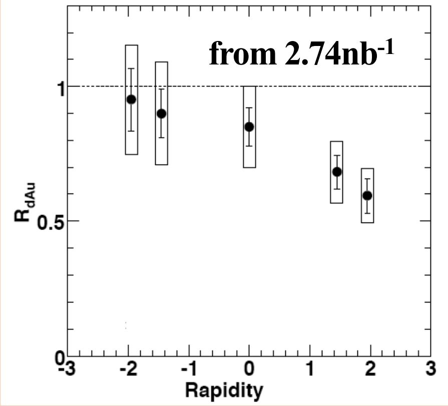
360J/ψ→e^+e^-, 1660J/ψ→$\mu^+\mu^-$



from 2.74nb^{-1}

nucl-exp/0711.3917

360J/ψ→e^+e^-,1660J/ψ→$\mu^+\mu^-$



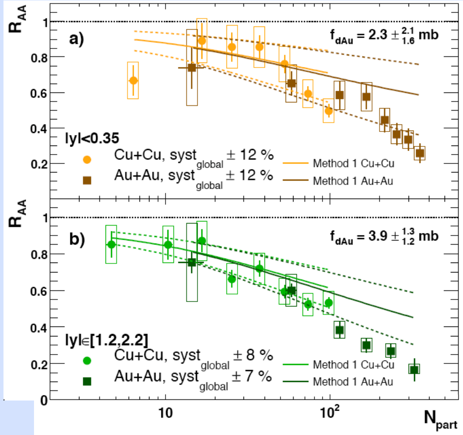
from 2.74nb^{-1}

Cu+Cu

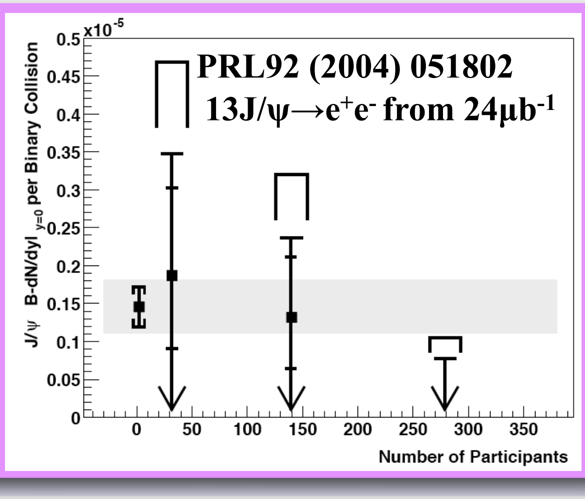
nucl-exp/0801.0220

2000J/ψ→e^+e^-,9000J/ψ→$\mu^+\mu^-$

from 2.1nb^{-1}

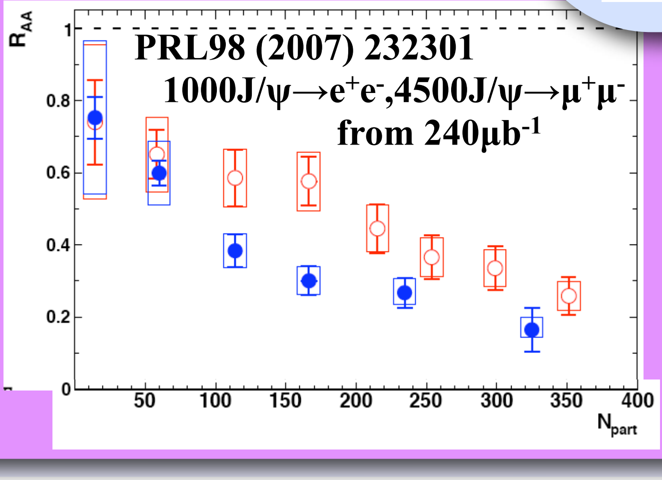


Au+Au



PRL92 (2004) 051802

13J/ψ→e^+e^- from 24μb^{-1}



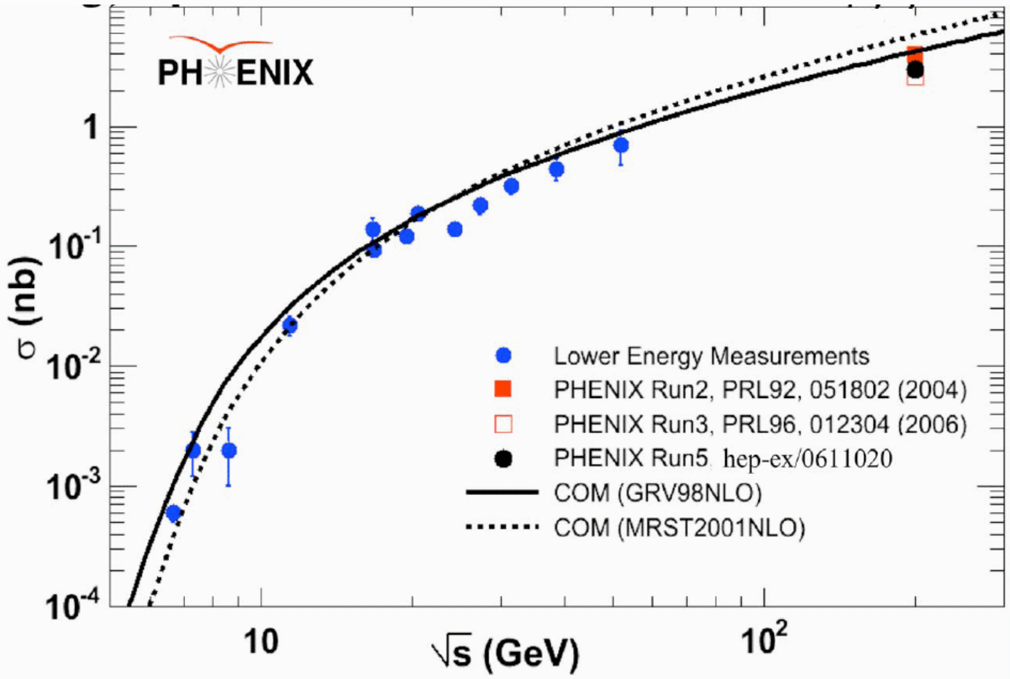
PRL98 (2007) 232301

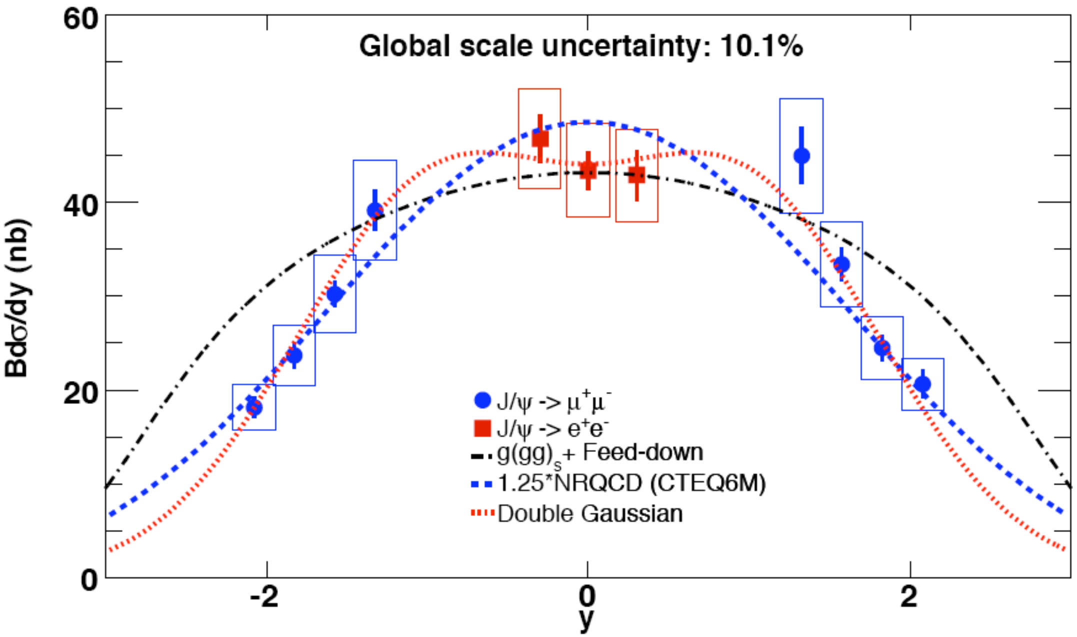
1000J/ψ→e^+e^-,4500J/ψ→$\mu^+\mu^-$

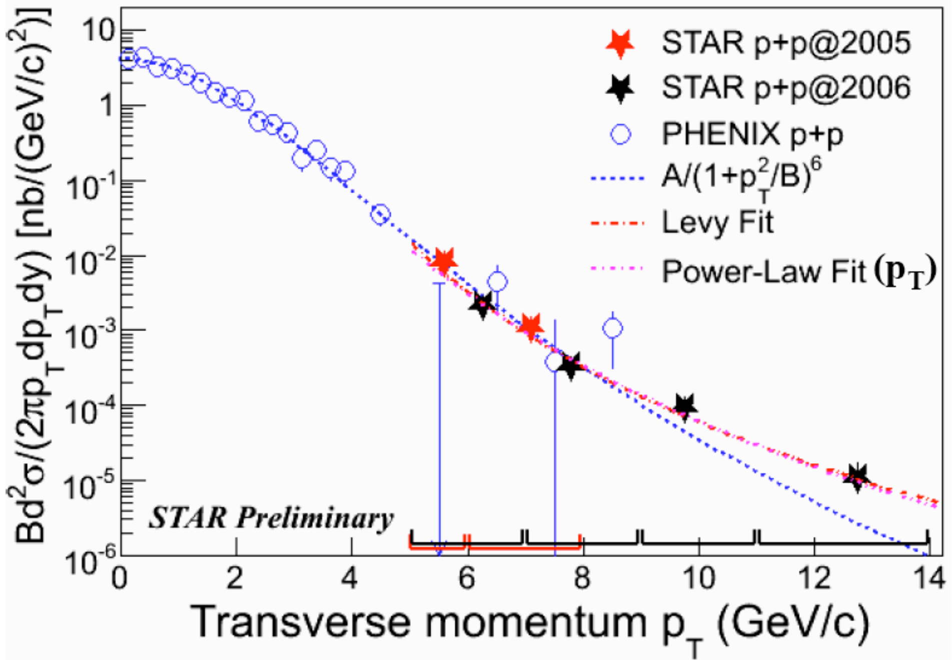
from 240μb^{-1}

p+p Data

$p+p \rightarrow J/\psi$





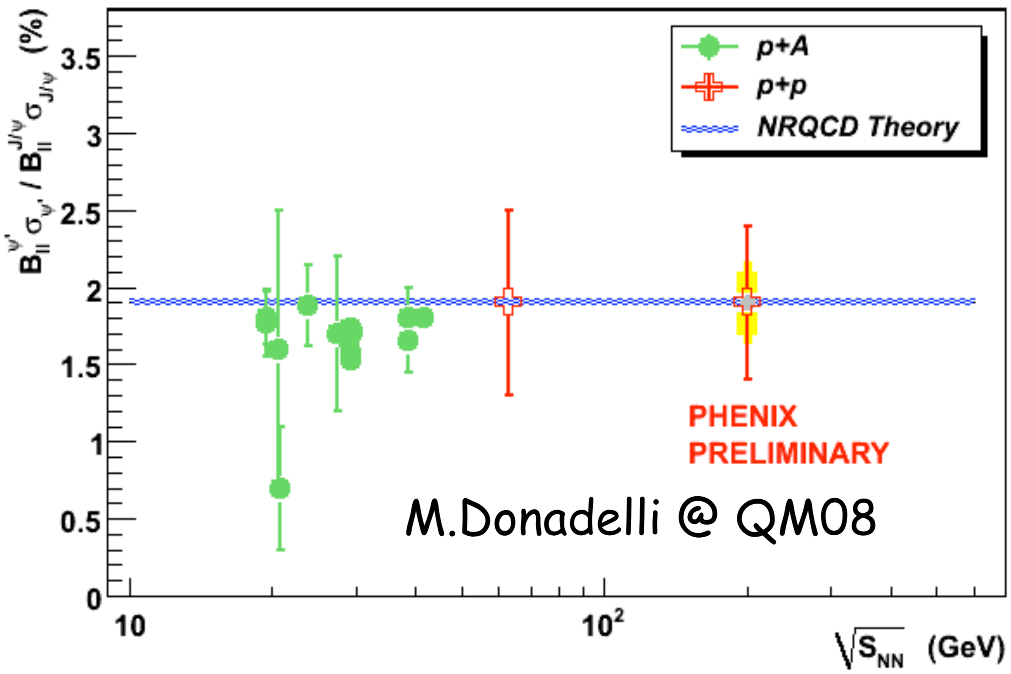


- Inclusive measurement: includes feed down
- Different models fit to the p+p data returning a total cross section

$BR_{ll}\ \sigma_{pp}(p+p \to J/\psi+X) = 178 \pm 3(stat) \pm 53\ (sys) \pm 18\ (norm)$ nb

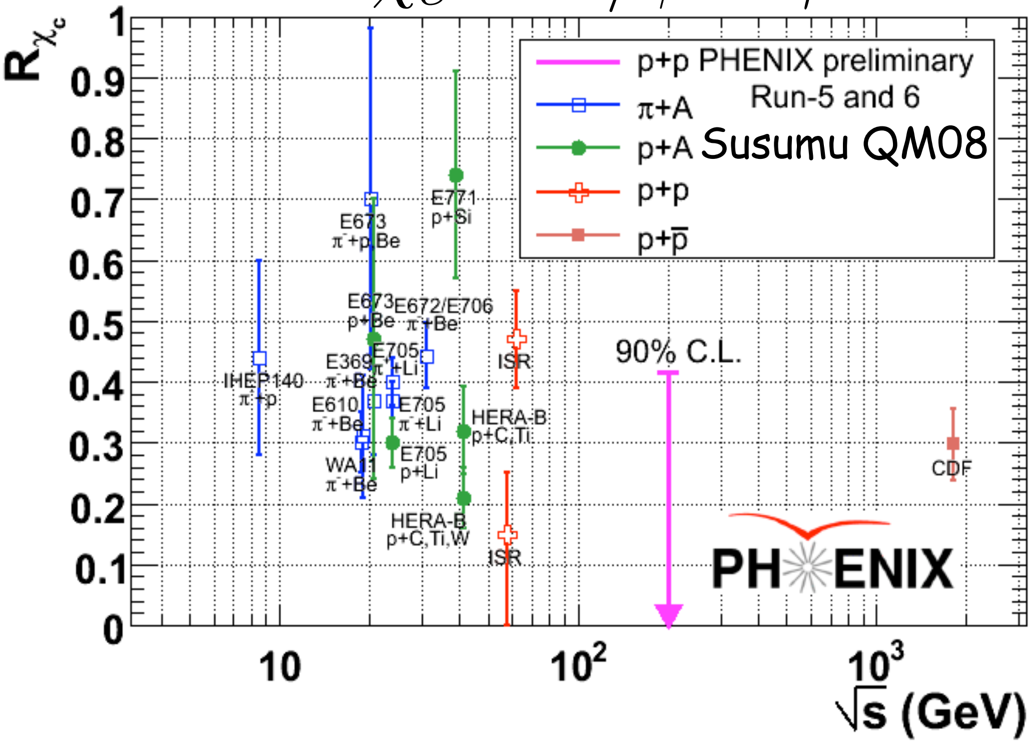
Feed Down Contributions in p+p

$\psi' \rightarrow e^+e^-$



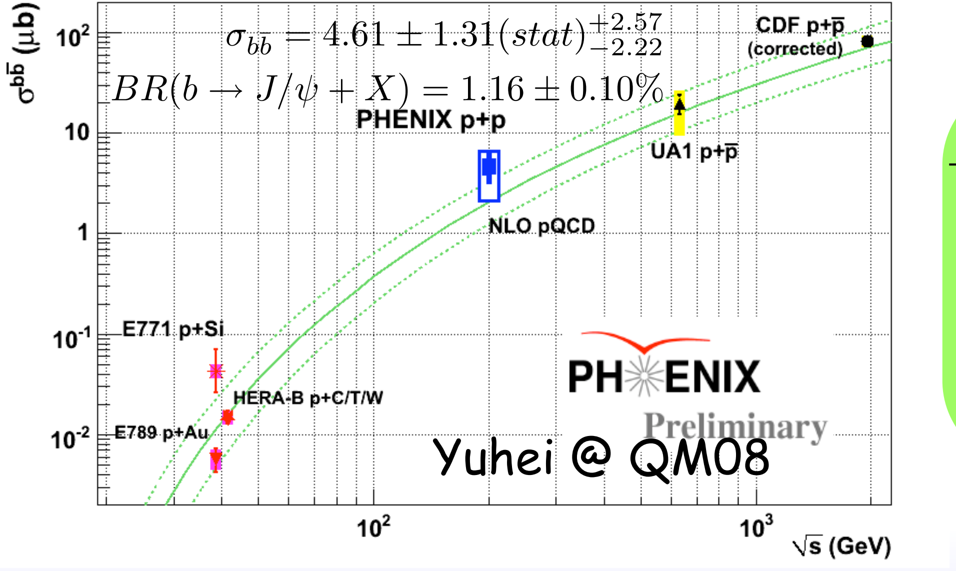
M.Donadelli @ QM08

$\chi_c \rightarrow J/\psi + \gamma$



Susumu QM08

e-h correlation → B cross section



Yuhei @ QM08

decay	PHENIX	theory
$\psi' \rightarrow J/\psi$	0.086 ± 0.025	0.08^*
$\chi_c \rightarrow J/\psi$	< 0.42 (90% CL)	0.30^*
$B \rightarrow J/\psi$	$0.036^{+0.025}_{-0.023}$	$0.02 \pm 0.01^{**}$

*Digal et al., Phys. Rev. D 64 (2001) 094015
** NLO pQCD extrapolation

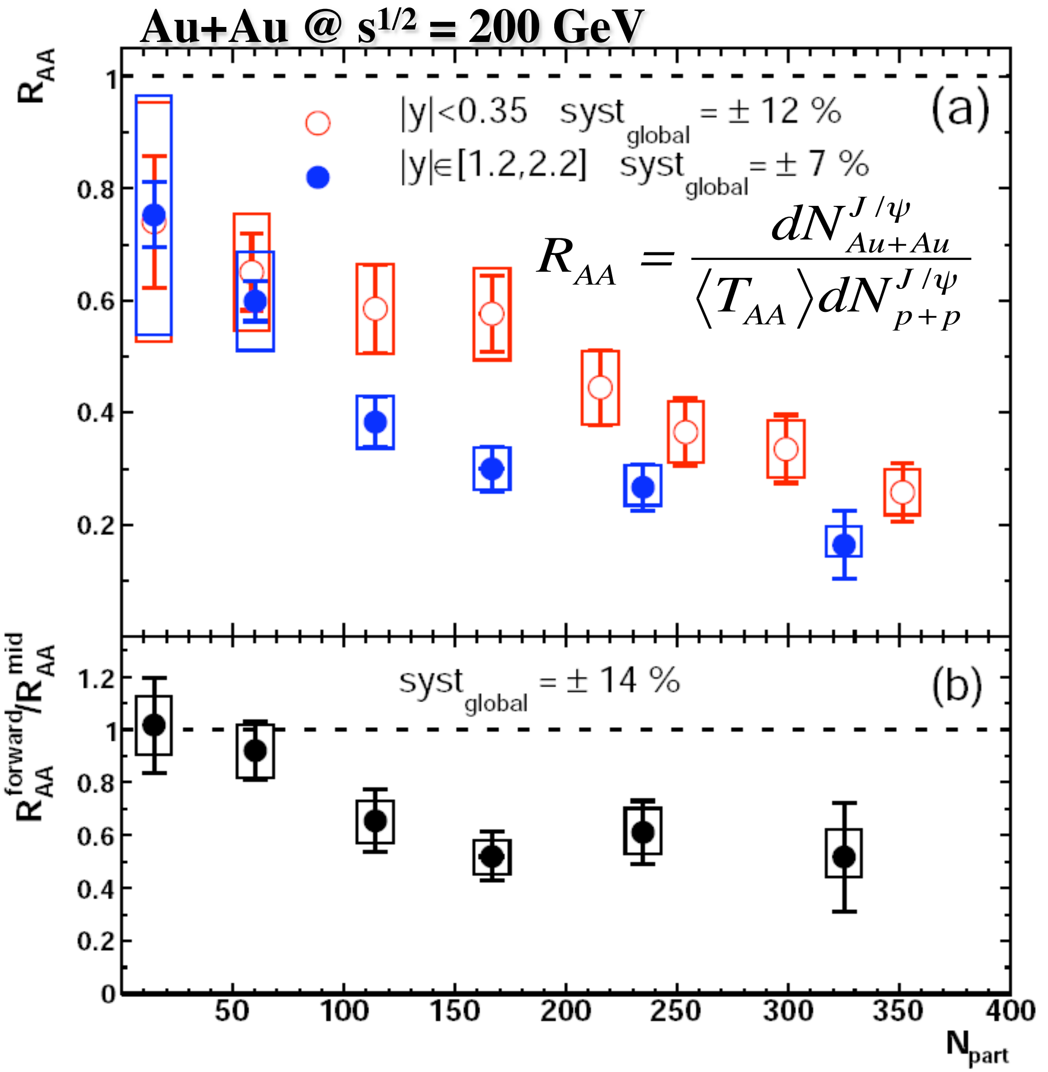
A+A Data

Au+Au → J/ψ

Stronger suppression at forward rapidities:

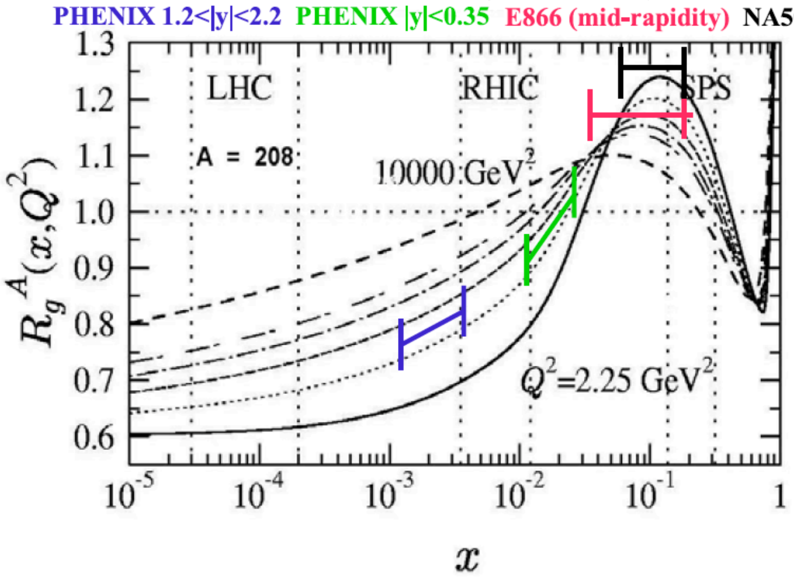
- $\sigma_{breakup}(|y|>1.2) > \sigma_{breakup}(|y|\sim0)$?
- $R_g(|y|>1.2) < R_g(|y|\sim0)$?
- regeneration at mid-rapidity ?

$$R_g(x,Q^2) = \frac{x_g^{nucleus}(x,Q^2)}{x_g^{nucleon}(x,Q^2)}$$

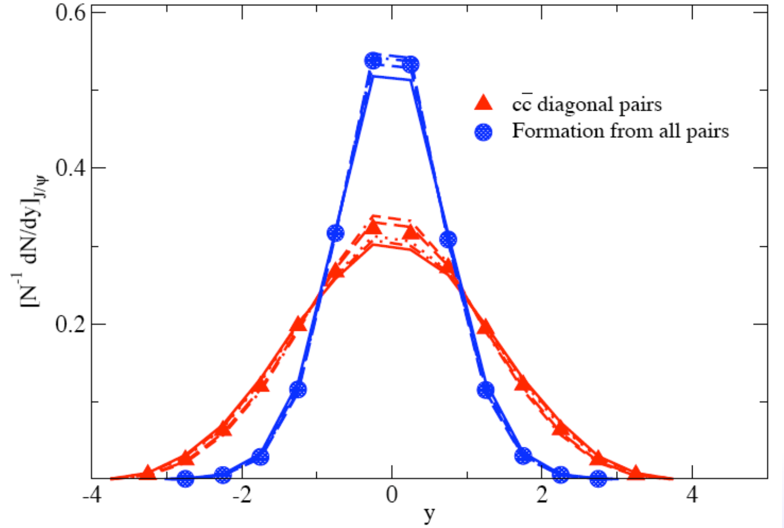


$$R_{AA} = \frac{dN^{J/\psi}_{Au+Au}}{\langle T_{AA}\rangle dN^{J/\psi}_{p+p}}$$

K.J.Eskola, V.J.Kolhinen, R. Vogt, *Nucl.Phys.* ***A696,****729*

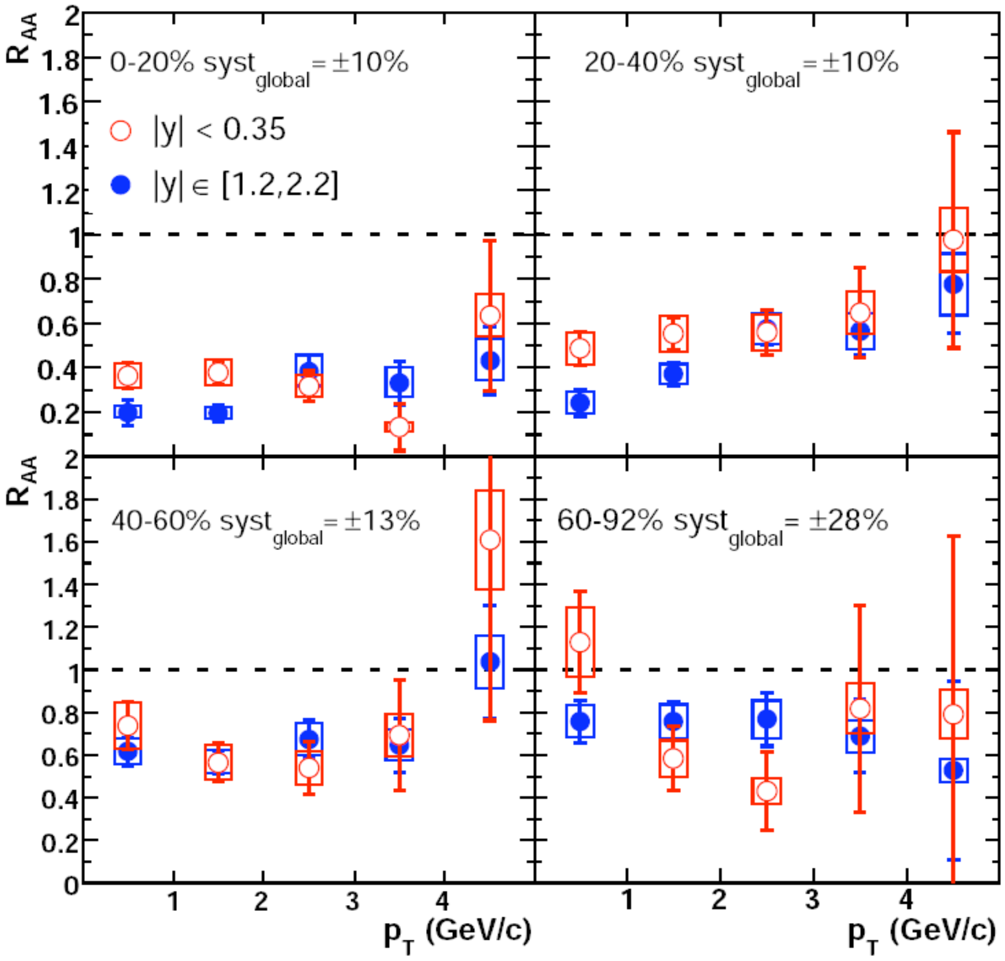


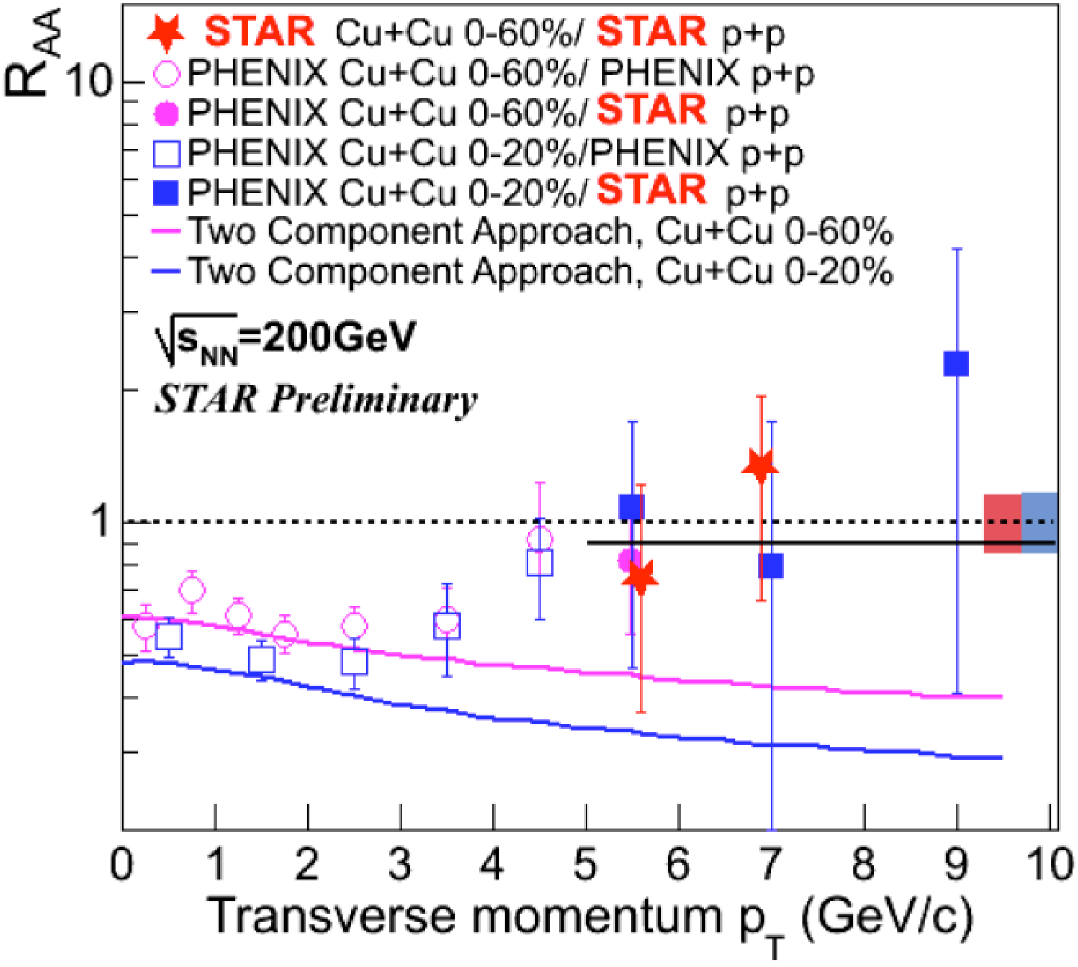
R.L.Tews, Phys.Rev.C73 (2006) 014904



R_{AA} vs p_T

Au+Au @ $s^{1/2}$ = 200 GeV

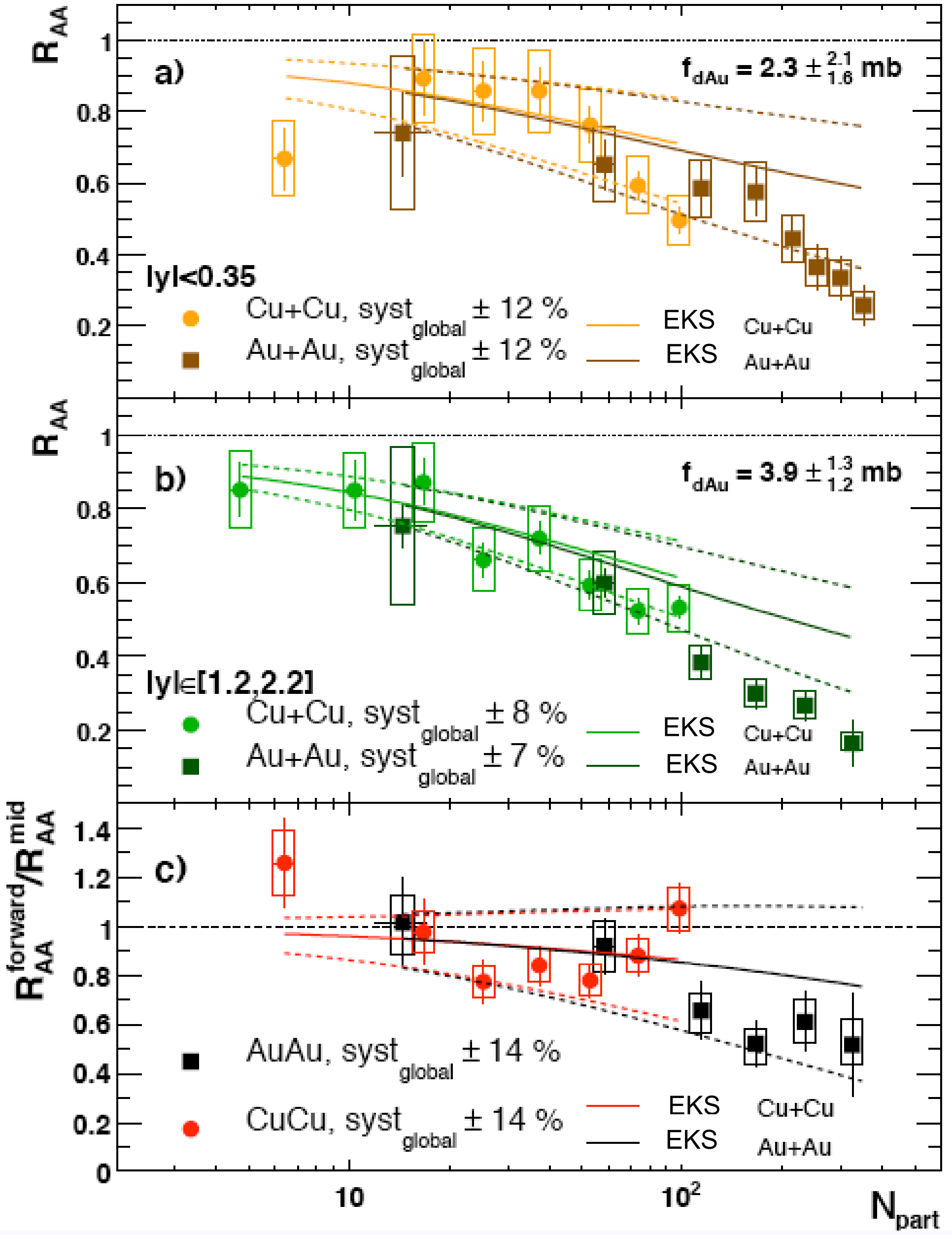




No strong messages from this side.

More data coming soon to have a complete R_{AA}×centrality×p_T picture.

Extrapolation of d+Au cold nuclear matter effects to Cu+Cu and Au+Au results



f_{dAu}= breakup cross section

arxiv:0801.0220

- there is a large room for CNM effects
- anomalous suppression is considerable at least at forward rapidity
- but the CNM is not enough constrained yet for a serious calculation of anomalous suppression R_{AA}/CNM
- see Raphael's talk

Comparison with SPS

NA50 @$\sqrt{S_{NN}} = 17GeV$

NA60 @$\sqrt{S_{NN}} = 17GeV$

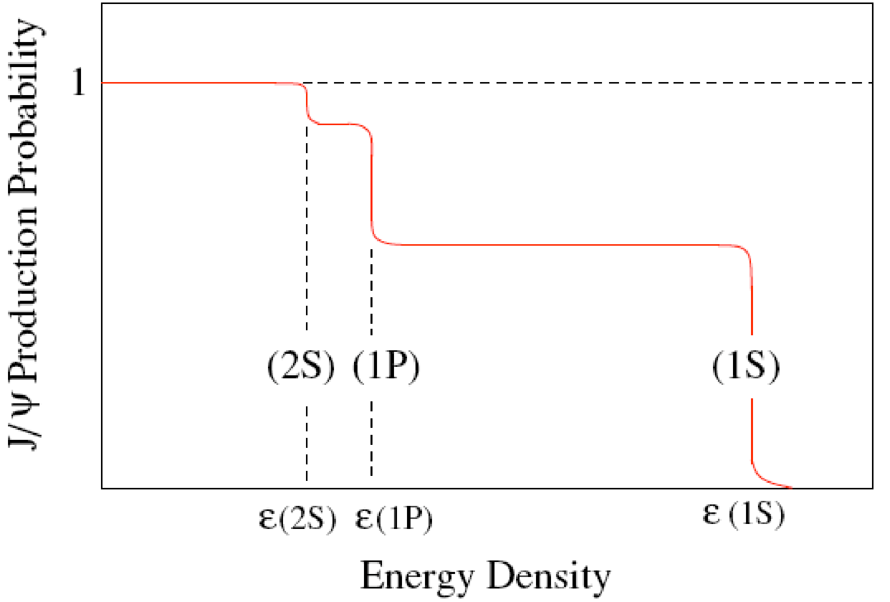
NA38 @$\sqrt{S_{NN}} = 20GeV$

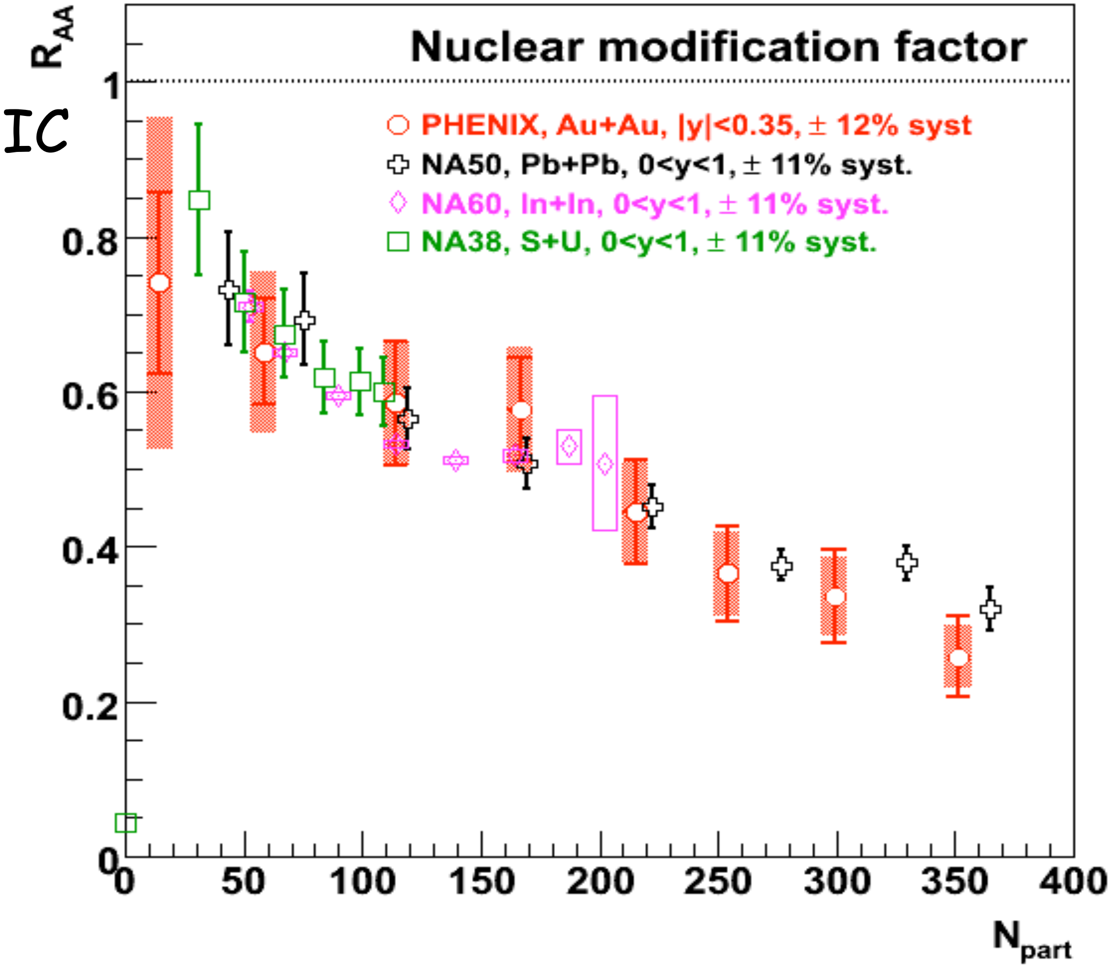
Same suppression as found in SPS

Caveat:

- different CNM
- stronger QGP suppression at RHIC
- recombination at RHIC
- melting of different feed down sources of J/ψs ?

H.Satz,J. Phys. G: Nucl. Part. Phys. **32** (2006) R25–R69



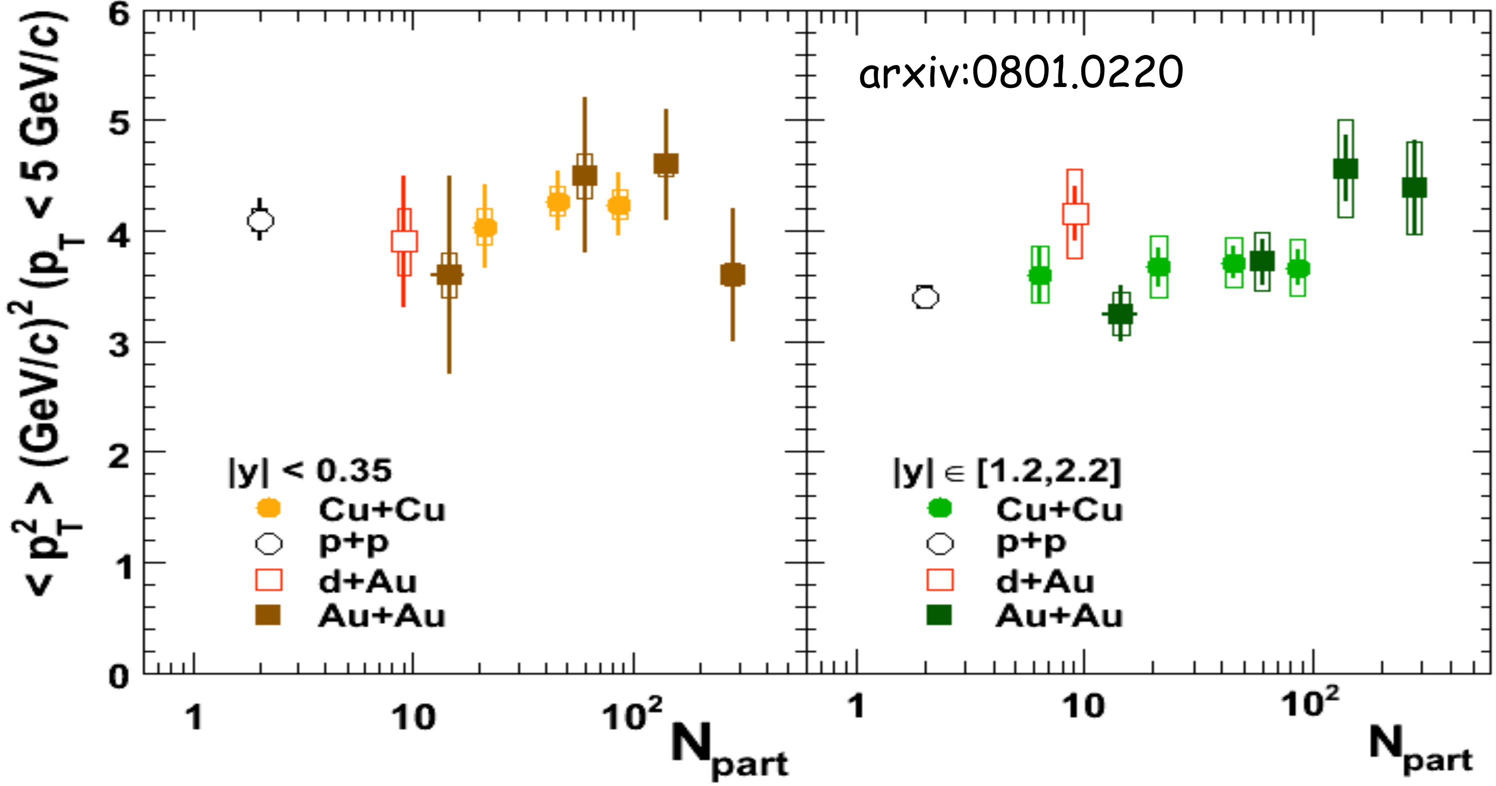


Needs $R_{AA}(\chi_c)$, $R_{AA}(\psi')$ measurements.

Recombination/Coalescence Probe I

- Cronin effect broaden the p_T of primary J/ψs
- J/ψs from recombined charms are not affected by Cronin effect and $\langle p_T^2 \rangle$ should be flat

$\langle p_T^2 \rangle$ obtained directly from invariant p_T spectra up to 5GeV/c

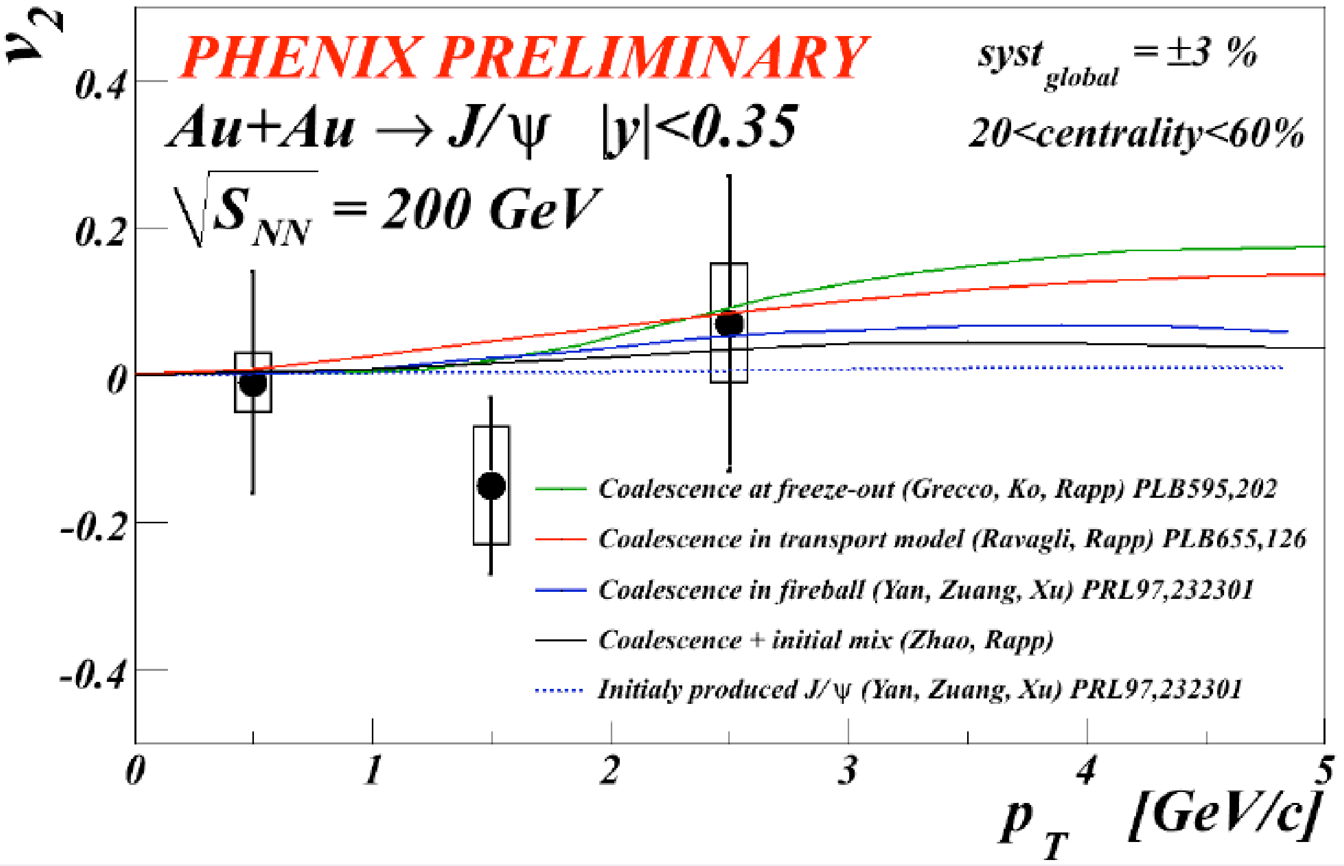


arxiv:0801.0220

- p_T broadening observed at forward rapidity but not at mid-rapidity
- but there is no broadening in d+Au data neither at mid-rapidity
- again, <u>we need more d+Au to confirm this trend</u>

Recombination/Coalescence Probe II

- primary J/ψs has isotropic behavior
- open charms flow (see A. Dion's presentation)
- J/ψs from these charms will show similar flow



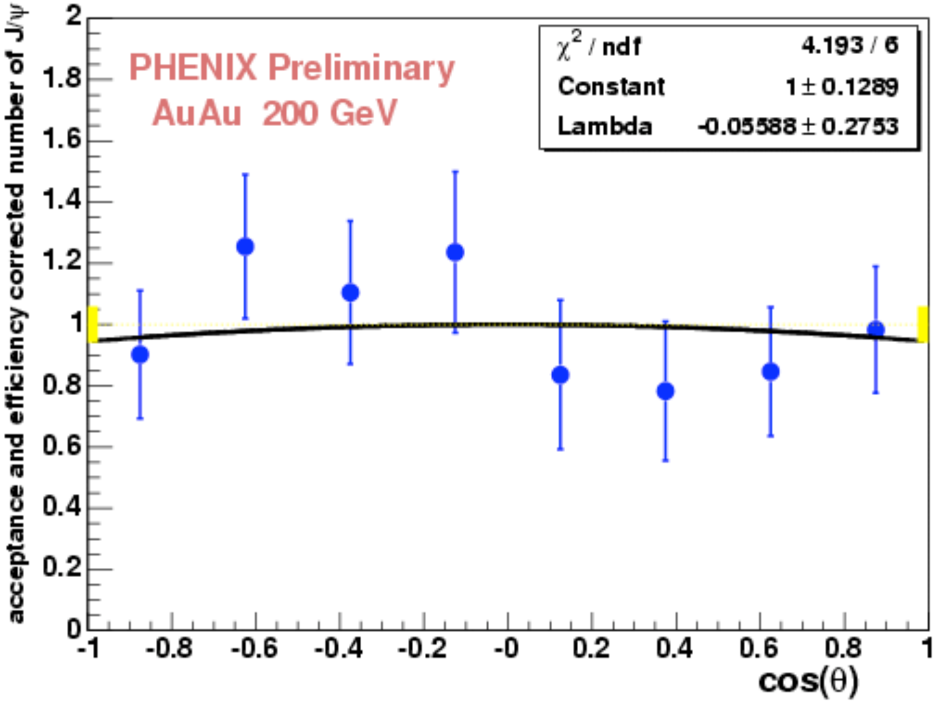
- partial data from last Au+Au run doesn't provide any hint for now
- be patient, remember the first PHENIX J/ψ R_{AA} measurement?

(Non-)Perturbative Gauge

Polarization measurement

$$N(\theta) = A[1+\lambda.\cos^2\theta\,]$$

$\theta \equiv$ angle btw. e^+ and J/ψ directions in it rest frame



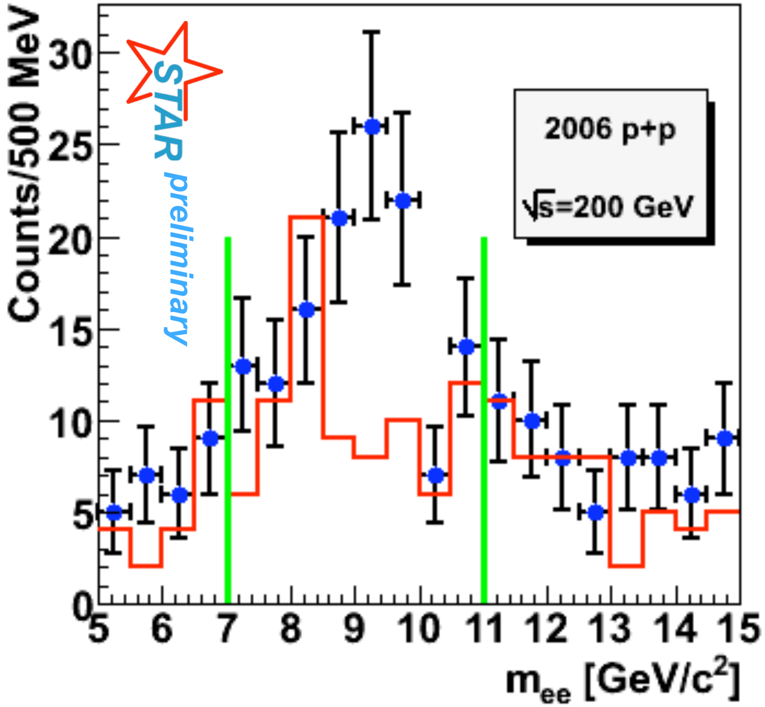
Polarization consistent with zero in the current Au+Au PHENIX preliminary result

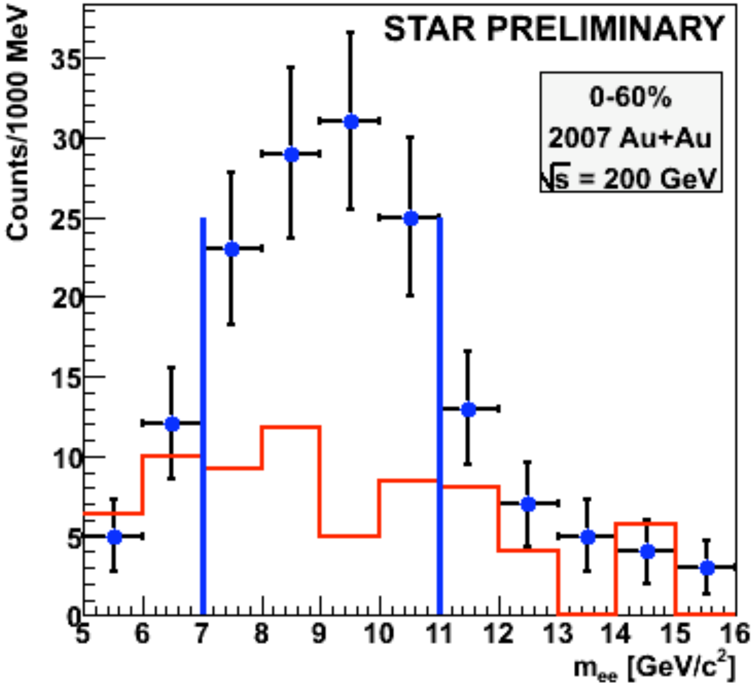
B. L. Ioffe, D. E. Kharzeev, PRC**68**, 061902 (2003)

- non-perturbative effects in J/ψ production leads to unpolarization
- perturbative behavior leads to a polarized J/ψ
- deconfined matter wash out non-perturbative effects in J/ψ and result in non zero polarization for p_T~0 in Au+Au collisions
- one needs precise measurement of polarization evolution in Au+Au, d+Au and p+p

Υ Measurement in p+p and Au+Au

$p + p \rightarrow \Upsilon \rightarrow e^+e^-$ $Au + Au \rightarrow \Upsilon \rightarrow e^+e^-$





- First measurement of Υs in A+A collision so far
- nuclear modification matter much easier to interpret
  - less shadowing (CNM)
  - negligible recombination
- nevertheless, dissociation occur only for T/Tc>3 for Υs and ~1.6 for Υ′

Detectors Upgrades

PHENIX

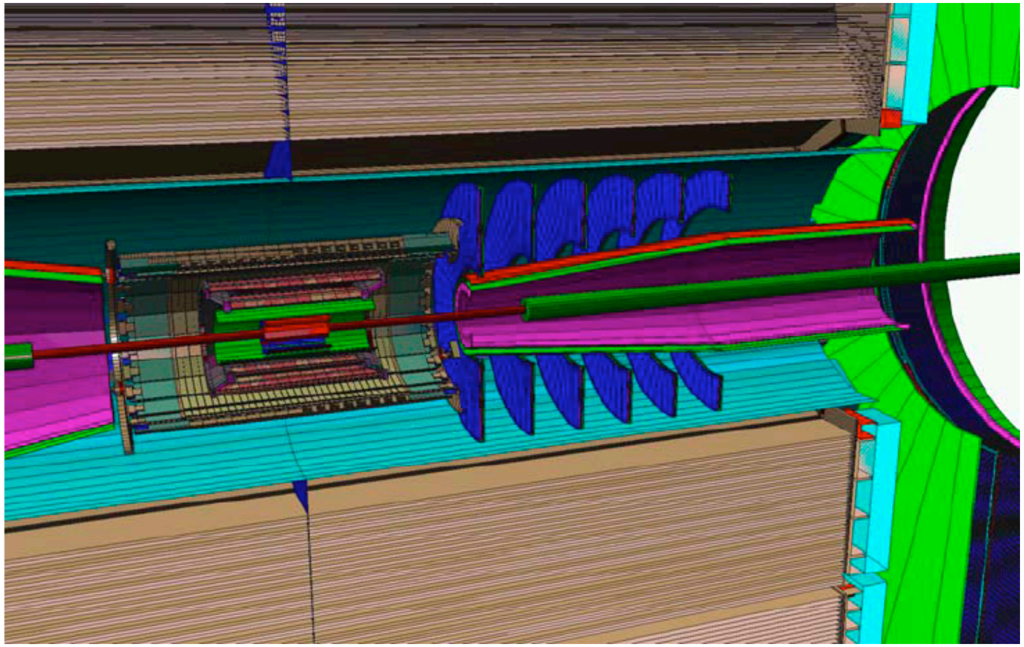
Silicon Vertex Detector

- will improve S/B
- precise measurement of B→J/ψ

Nose Cone Calorimeter

- large coverage for γ
- larger acceptance for $\chi_c \rightarrow J/\psi + \gamma$

STAR



Forward Tracker

- measures J/ψ at forward rapidity

Compact Muon Detector

- measurement of $\Upsilon \rightarrow \mu^+\mu^-$

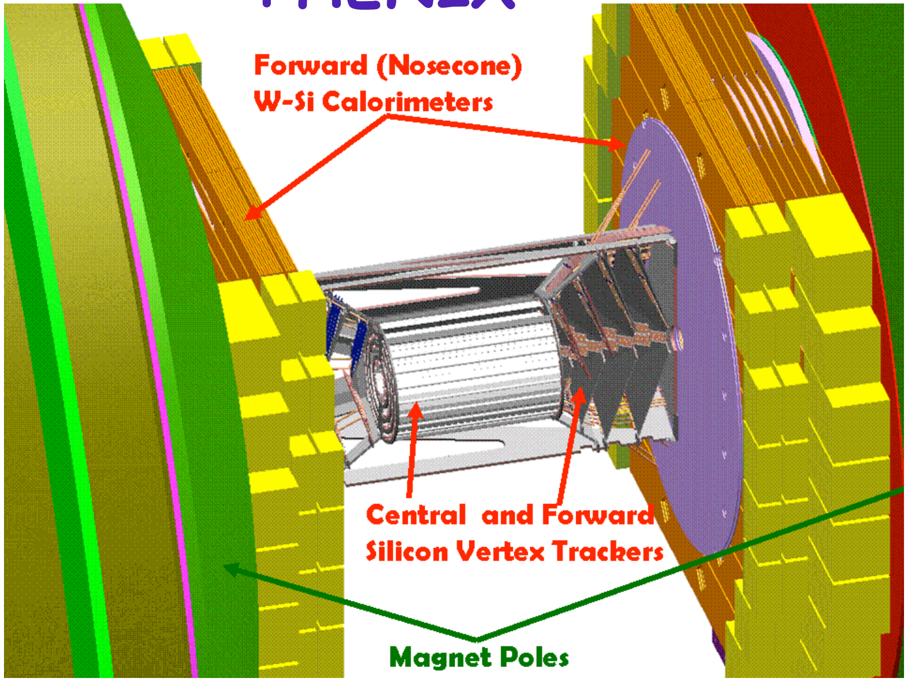
DAQ upgrate

- take advantage of higher luminosities

Stochastic cooling at RHIC will provide an order of magnitude higher luminosity in few years

Detectors Upgrades

PHENIX



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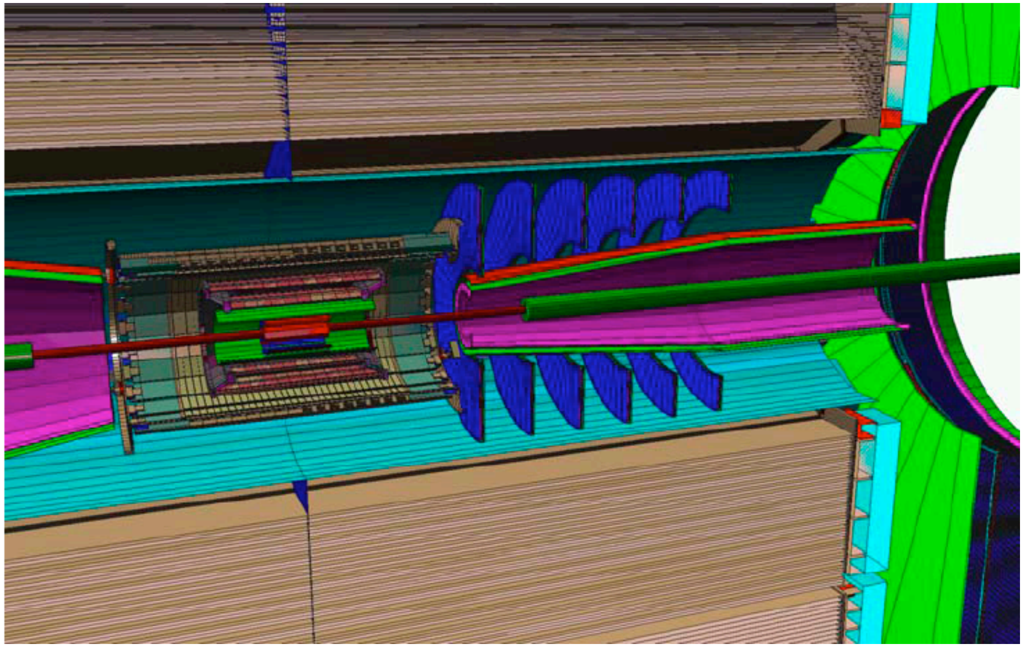

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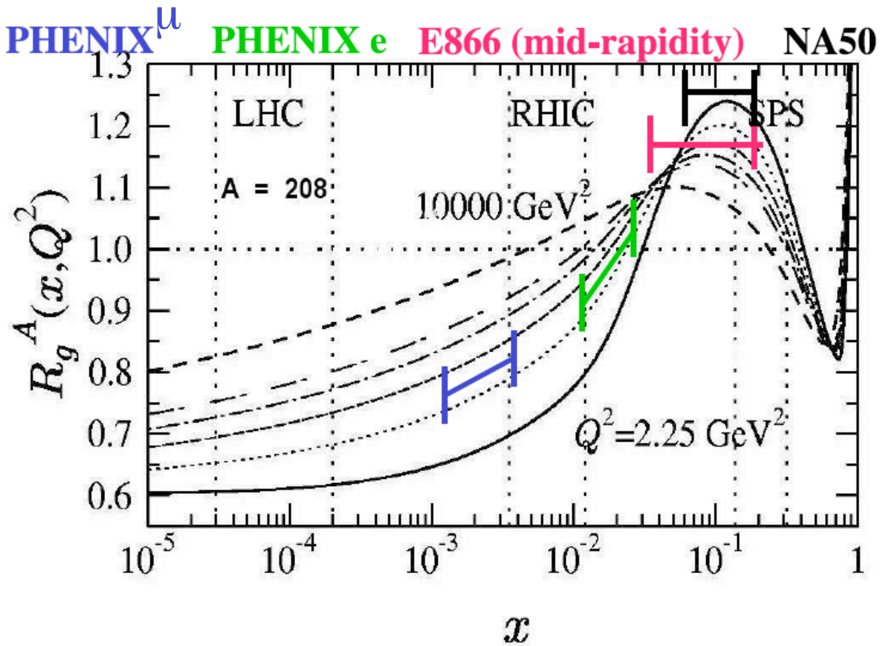
Current Status and Outlook

- a big progress in the lattice QCD was made to use quarkonia suppression as a hot and dense matter thermometer
- in the experimental side the suppression has been measured but we are still learning it components: CNM, recombination, feed down
- R_{AA} measurement is not sufficient to separate the suppression components
- other measurements which are on the way:
  - extended momentum distributions
  - elliptic flow
  - polarization
- suppression of excited states needs detector upgrades
- Υ suppression measurement seems feasible in a short term

BACKUP SLIDES

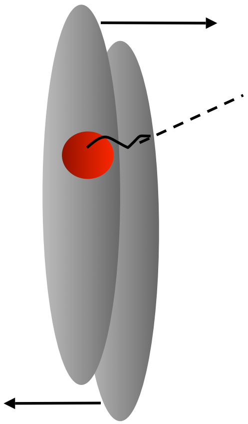
Cold Nuclear Effects

PDF modification in nucleus from DGLAP evolution equations fits to DIS and Drell-Yan data.[Nucl.Phys.B535(1998)351]



Quarkonia formation doesn't scale with number of collisions due to :

- ➡ different parton distribution
- ➡ dissociation with hadrons ($J/\psi+\pi\to D^{+}+D^{-}$)
- ➡ energy loss

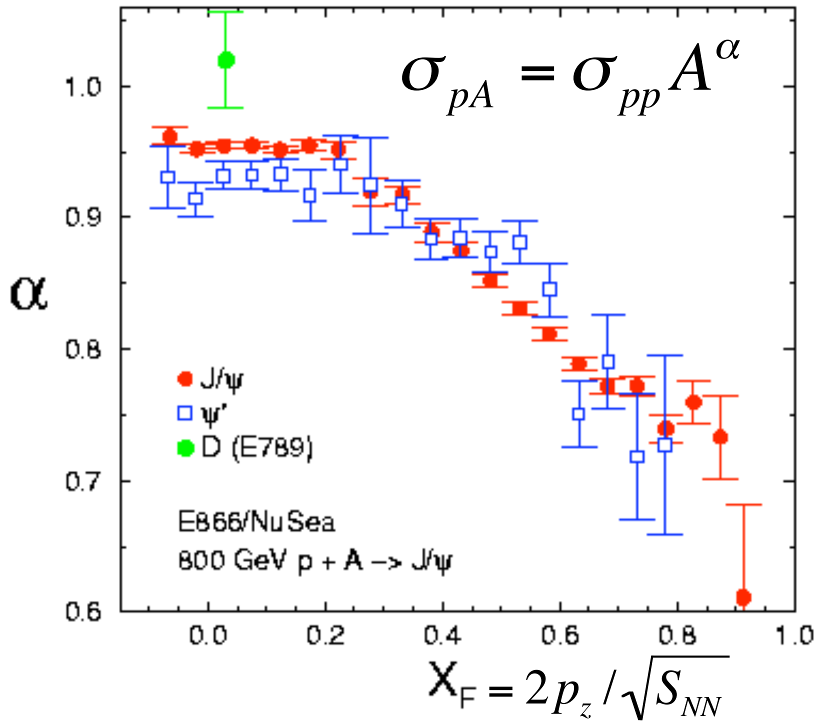


(ccg)$_8$ formation : $\tau_c \approx \hbar/2m_c \approx 0.07\,fm/c$

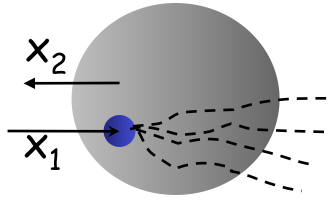
Color neutralization : $\tau_8 \approx \hbar/\sqrt{2m_c\Lambda_{QCD}} \approx 0.25\,fm/c$

Path @ RHIC : $d_8(x_F \sim 0) \approx 26\,fm \quad R_{Au}=6.38fm$

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

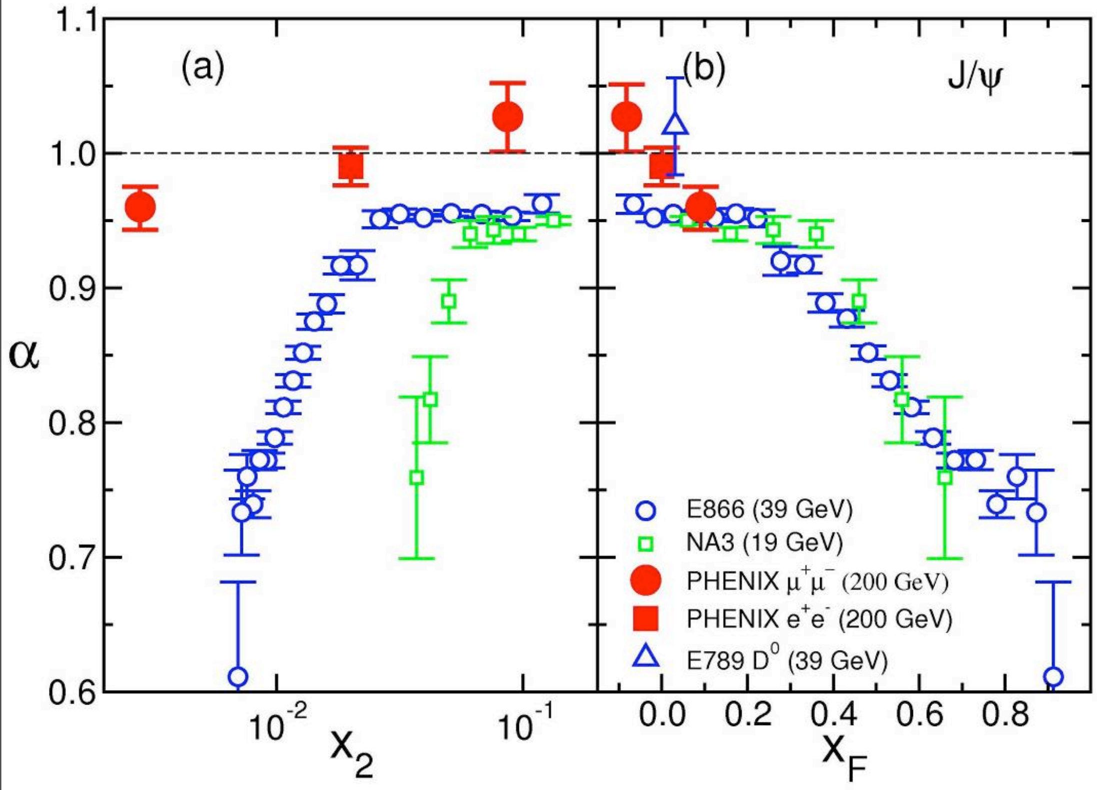


$x_F=x_1-x_2$



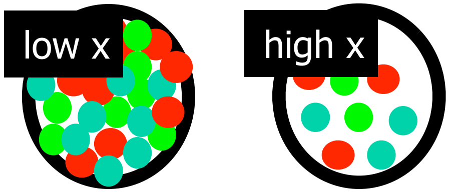
Most of Cold Nuclear Effects probed with p+Au or d+Au

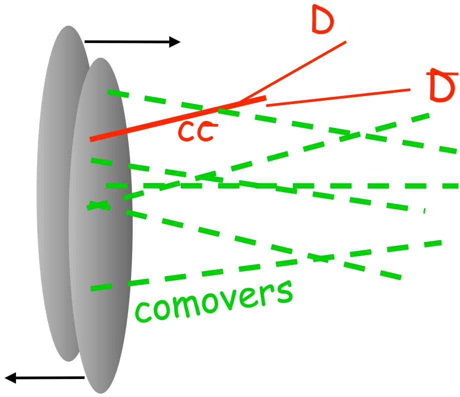
Cold Nuclear Effects II



Absorption scales with $x_{F,}$ but not in x_2 (nucleus frame). Possible explanation :

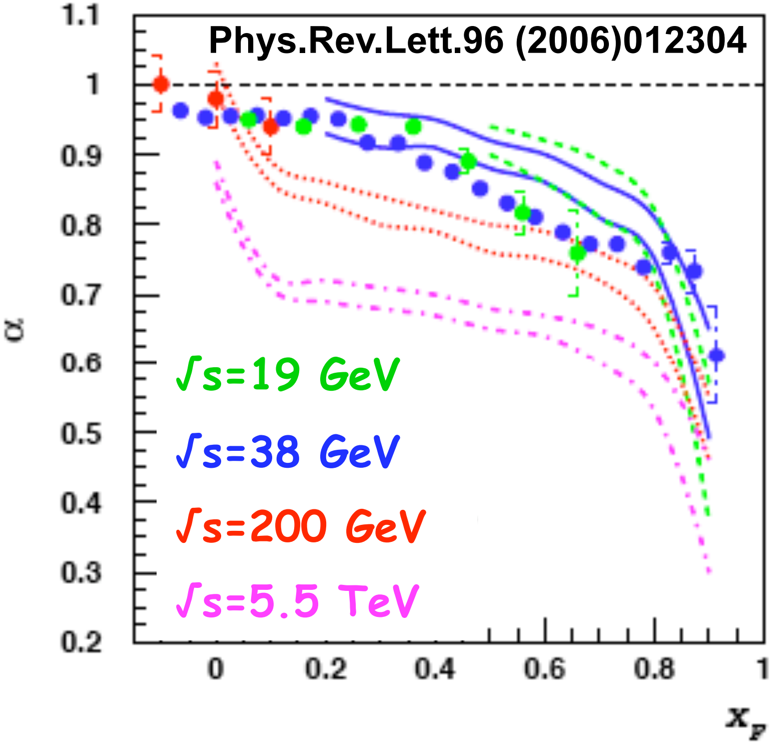
- ➡ limiting fragmentation caused by saturation of gluons (color glass condensate)





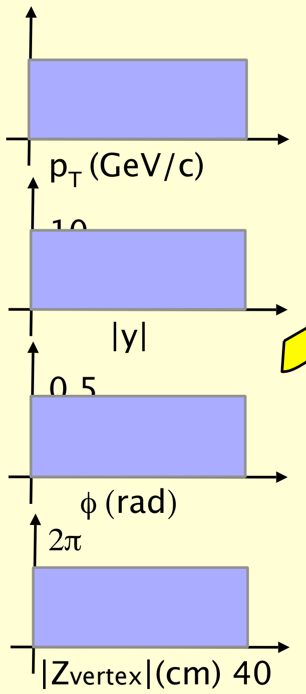
Charmonium can also be dissociated with hadronized particles after collision (comovers).

$\sigma(J/\psi+\pi \to D^+ + D^-)$ ~0.5-10mb

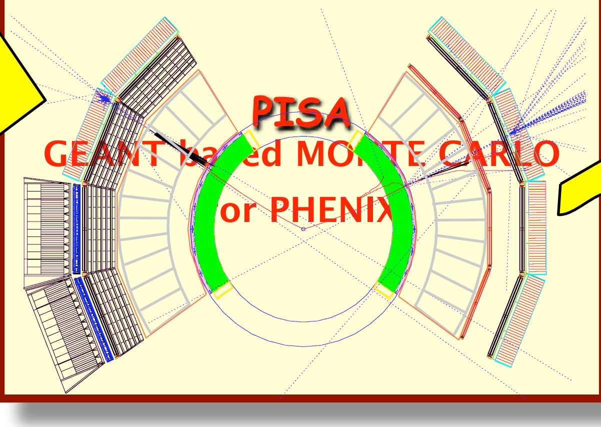


Detector Efficiency Estimation

Simulated J/ψ



- Geometry
- Material composition



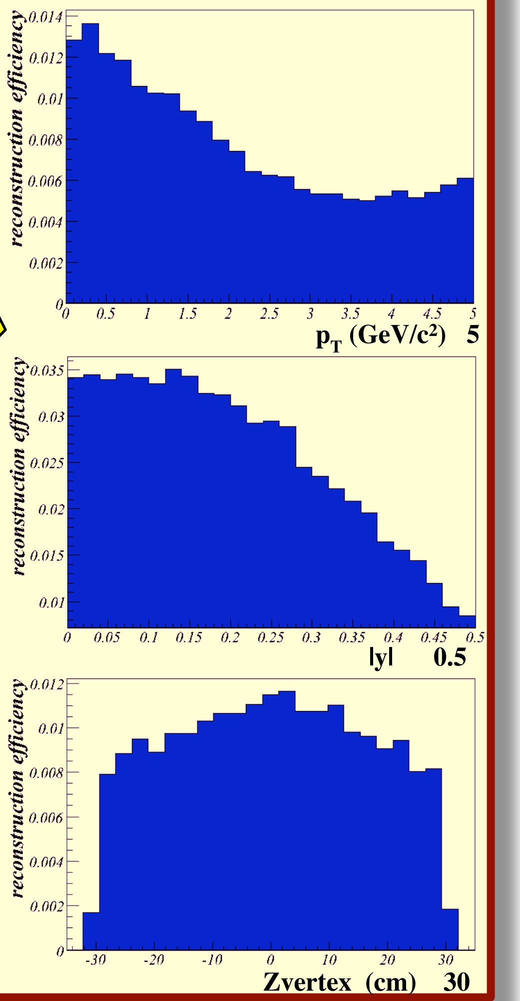
- Tuning calibration to match $\gamma \to e^+e^-$ response

Event reconstruction

Simulation of Electronic Signal from the activated areas

- Dead areas
- Gains

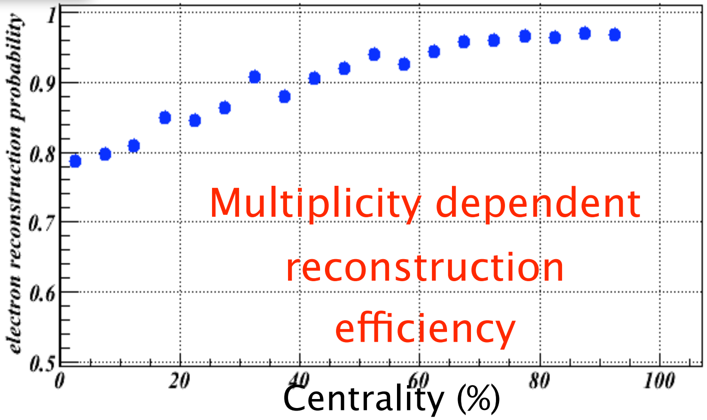
Single J/ψ efficiency



Minimum Bias Real Data

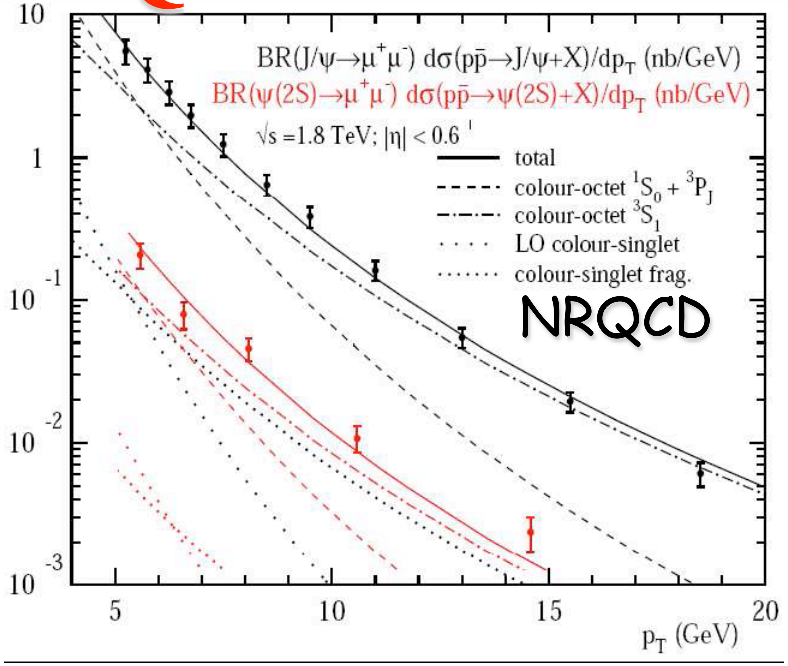
Raw data embedding

Event reconstruction

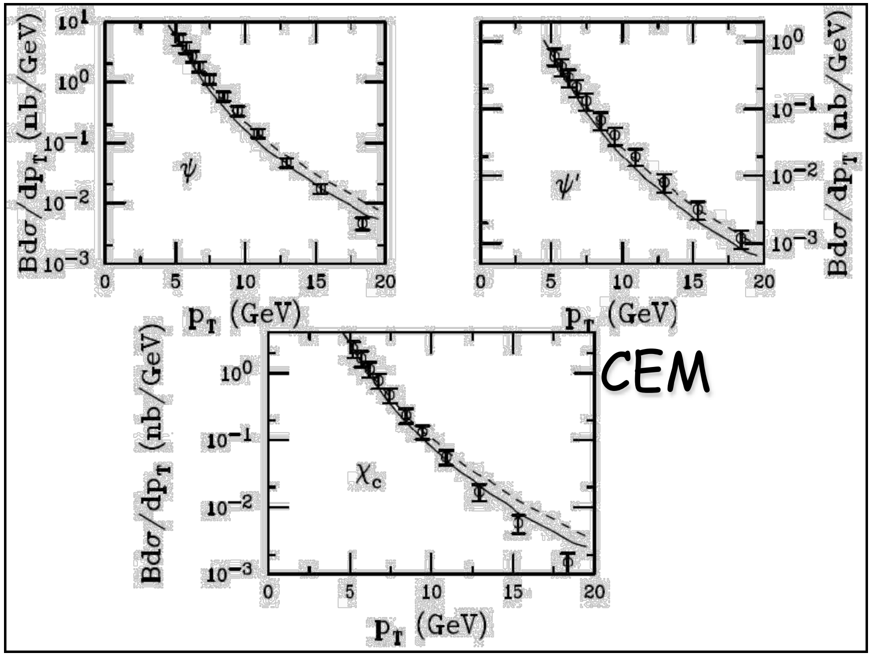


Multiplicity dependent reconstruction efficiency

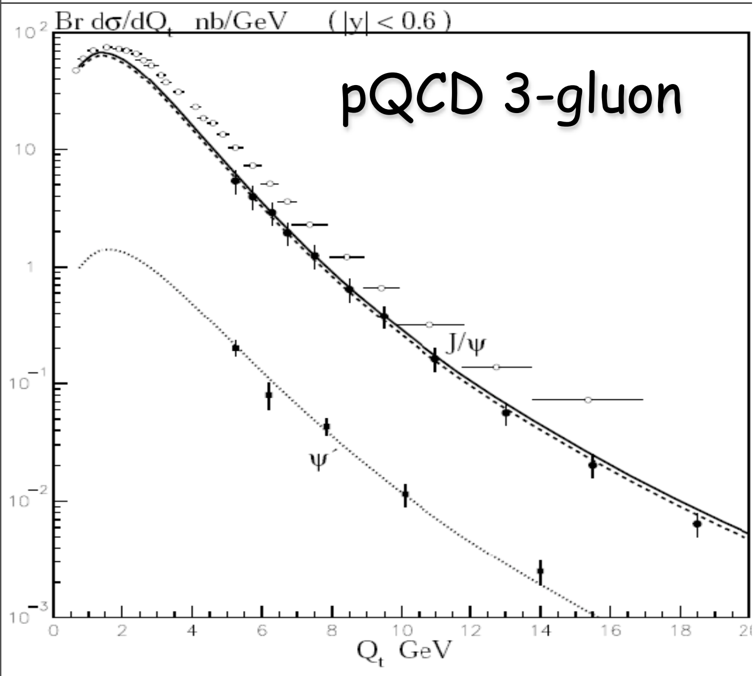
Quarkonia Production in Tevatron



NRQCD

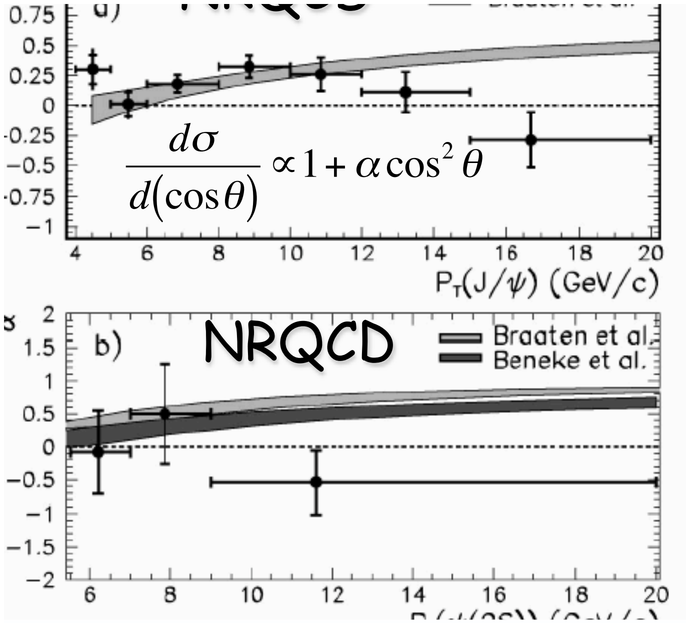


CEM



pQCD 3-gluon

polarization



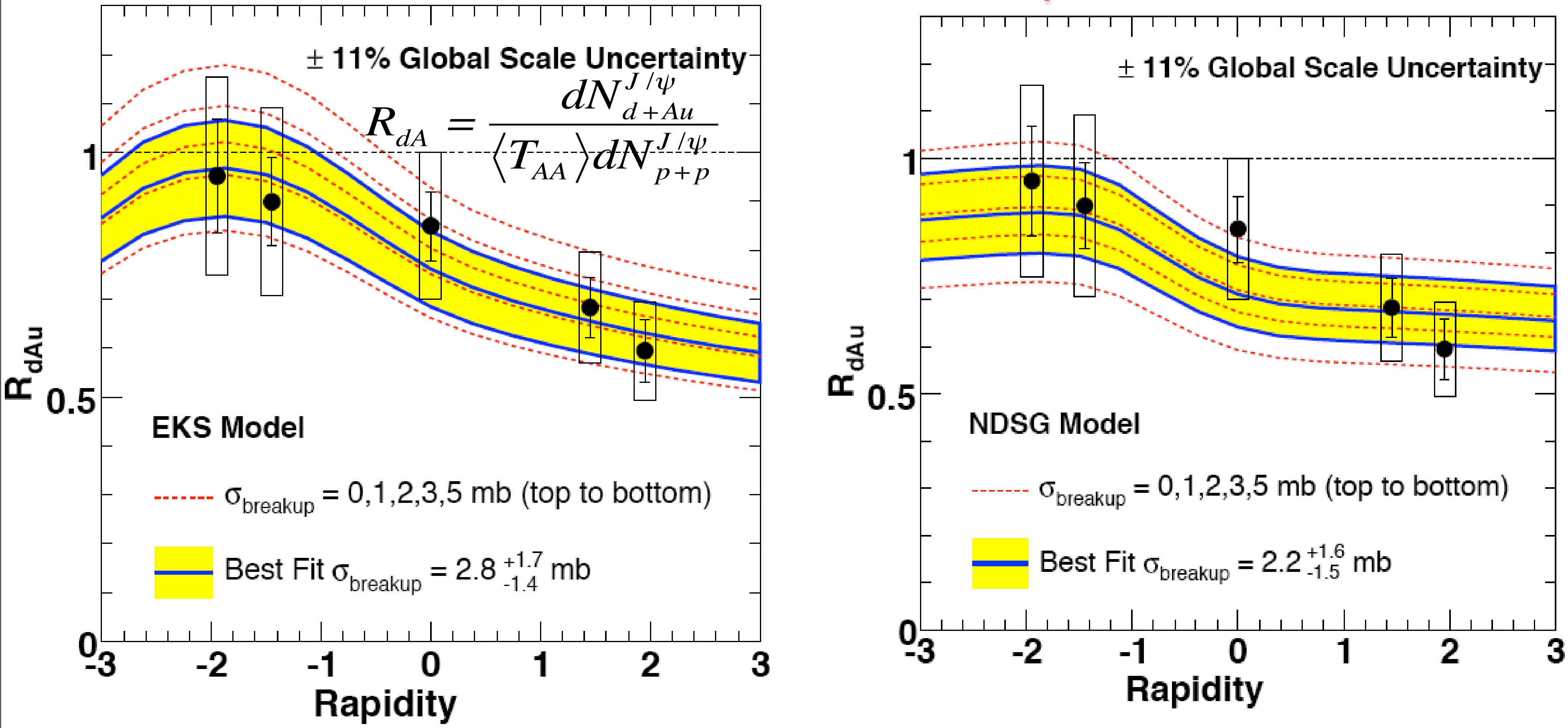
$$\frac{d\sigma}{d(\cos\theta)} \propto 1+\alpha\cos^2\theta$$

NRQCD

All models can describe Tevatron p+p->J/ψ+X cross section @$s^{1/2}$=1.8TeV

Only pQCD predict longitudinal polarization for high p_T

$d+Au \rightarrow J/\psi$

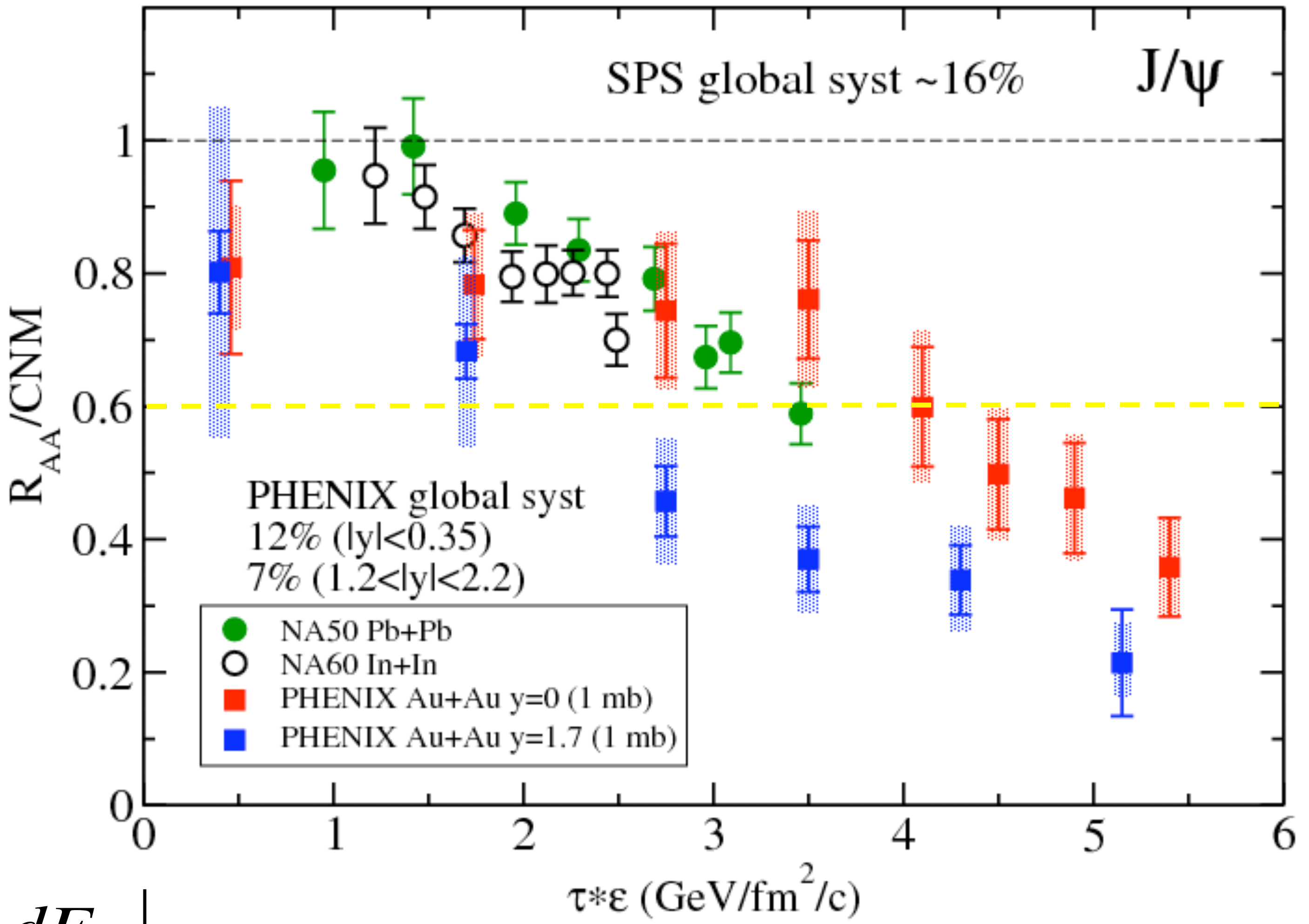


EKS: K. J. Eskola et al., Nucl. Phys. A696, 729 (2001)

NDSG: D. deFlorian and R. Sassot, Phys. Rev. D 69, 074028(2004).

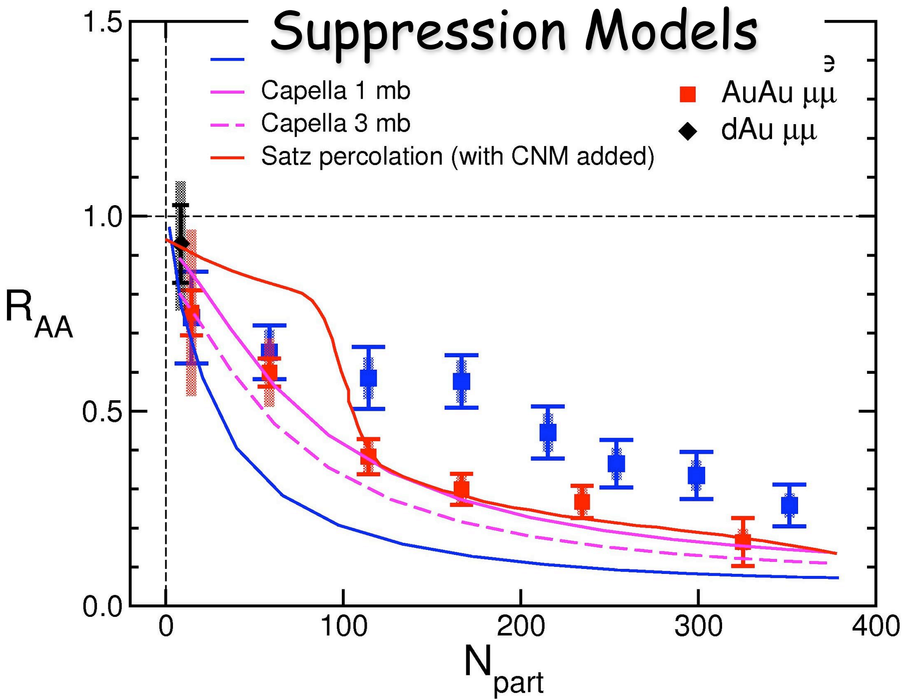
Modest absorption at RHIC energies.
Brand new d+Au data with 30x more statistics will constrain CNM models.

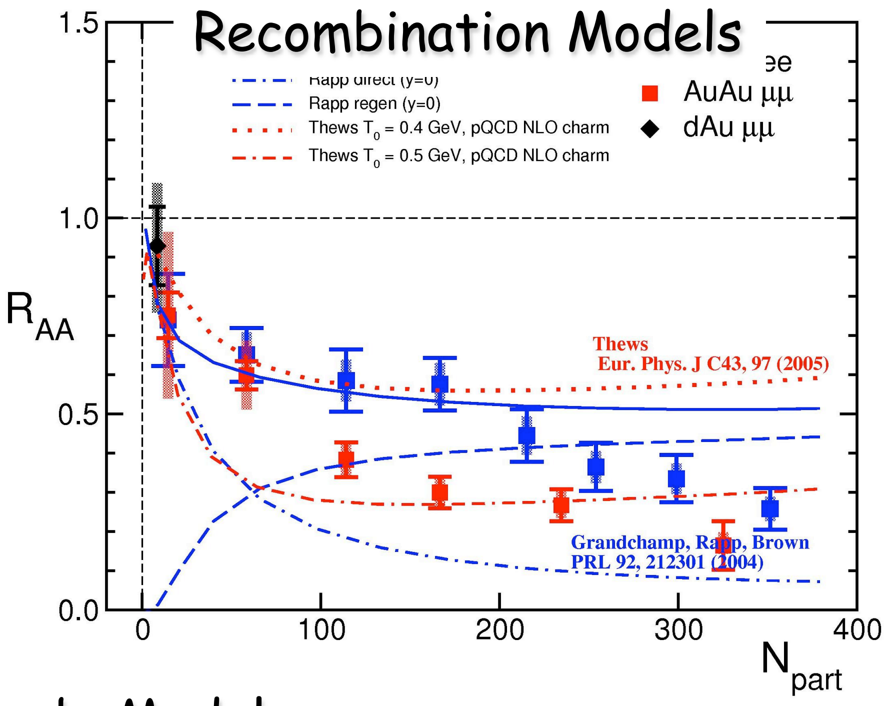
Sequential Screening

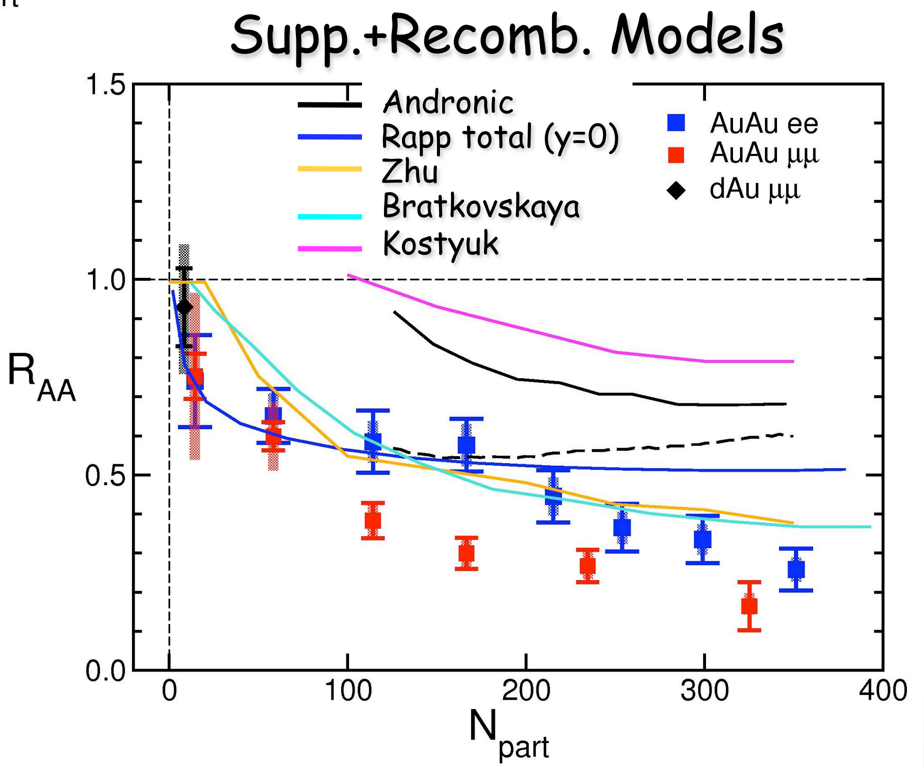


$$\varepsilon = \frac{1}{\tau_0 \pi R^2} \frac{dE_T}{dy}\bigg|_{y=0}$$

Models to Au+Au collisions

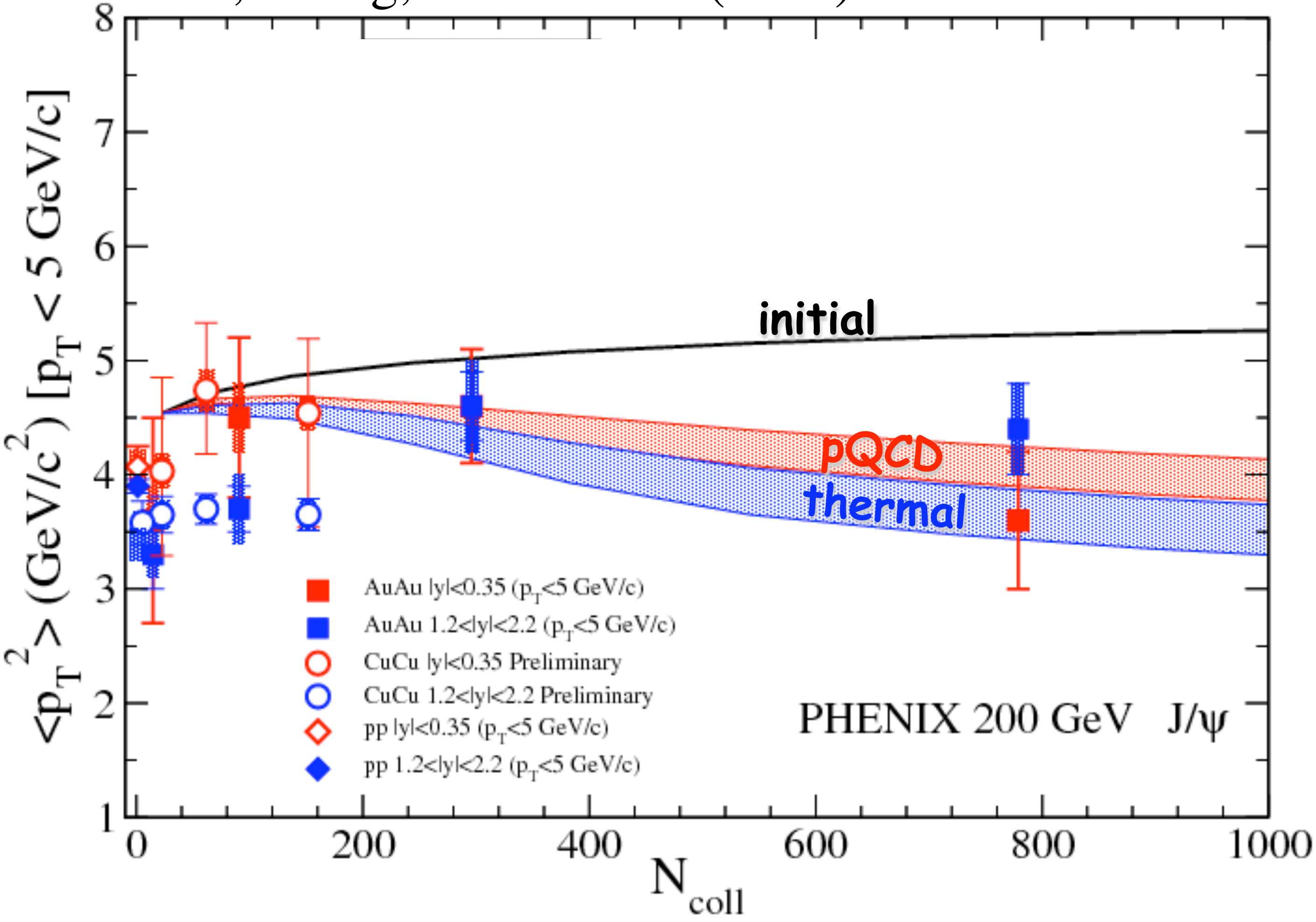

Suppression Models


Recombination Models


Supp.+Recomb. Models

$\langle p_T^2 \rangle$

Yan, Zhang, Xu - PRL97 (2006) 232301.



$\langle p_T^2 \rangle$ is obtained directly to invariant p_T spectra for different centralities. Only $p_T < 5$ GeV/c was accounted for in this calculation.