Quarkonia results from PHENIX

Tony Frawley
Florida State University

On behalf of the PHENIX collaboration

Heavy Quark Workshop, LBL
Nov 1, 2007

Why are we interested in the J/ψ ?

It has long been hoped that J/ψ production in heavy ion collisions would be a **direct probe of deconfinement.** It has the following cool features as a probe of the hot dense matter produced at RHIC:

- Unlike *u,d,s* quarks, *c* quarks are too heavy to be made thermally after the collision. They are produced **only** in the initial nucleon-nucleon collisions.
- Because of the large charm mass, their formation is a point-like process, and it **scales with the number of nucleon-nucleon collisions.**
- Roughly 2% of charm-anticharm pairs produced in the initial nucleon-nucleon collisions are in a region of phase space allowing them to (**eventually**) bind into a J/ψ.
- The J/ψ is a tightly bound, and thus **small**, meson that becomes unbound due to Debye screening only at high energy density, (likely above deconfinement temperature).
- The J/ψ has a significant branch for decay into the e^+e^- and $\mu^+\mu^-$ channels.
- Because the decay electrons and muons do not interact strongly with the nuclear medium, the J/ψ can always be reconstructed experimentally, even if it decays in dense nuclear matter.

These features make the J/ψ an attractive probe of the effects of the hot dense matter created in heavy ion collisions **because the baseline production cross sections can be measured in pp collisions** and then scaled up to predict what we would see in heavy ion collisions using Glauber simulations to tell us the number of nucleon-nucleon collisions.

There are, of course, a few complications....

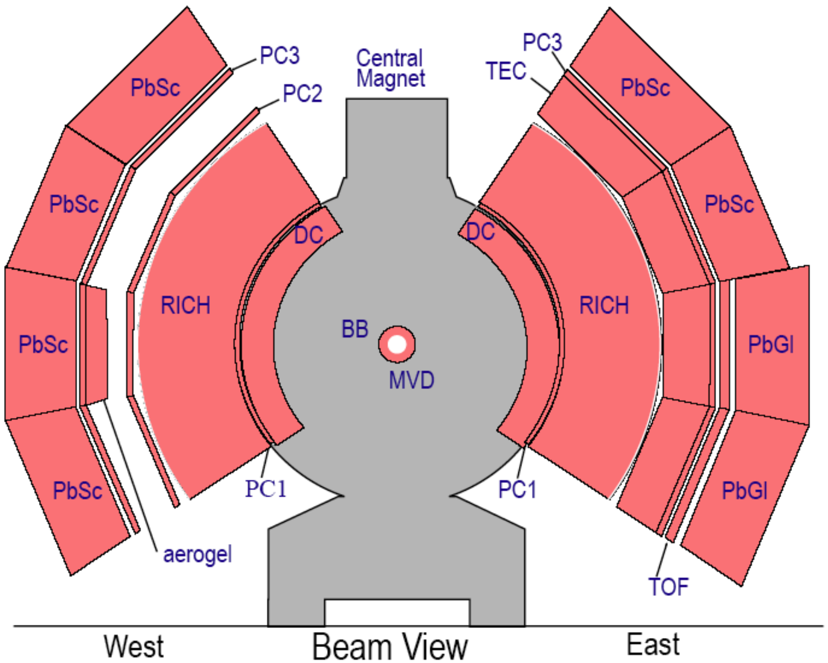
Introduction to PHENIX

PHENIX was designed to optimize **electron, muon and photon** measurements.

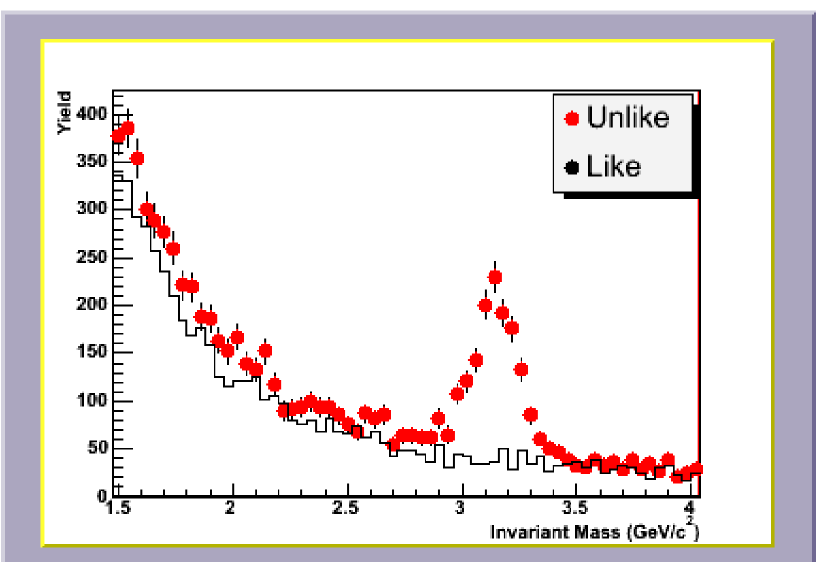
We detect electrons, photons and charged hadrons in the central arms at mid rapidity.

We detect muons in the muon arms at forward and backward rapidity.

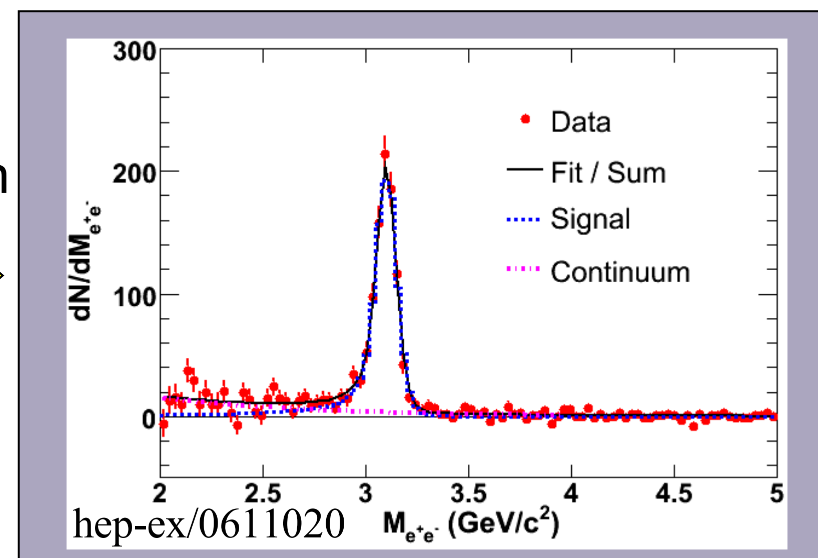
PHENIX Detector: Central Arms



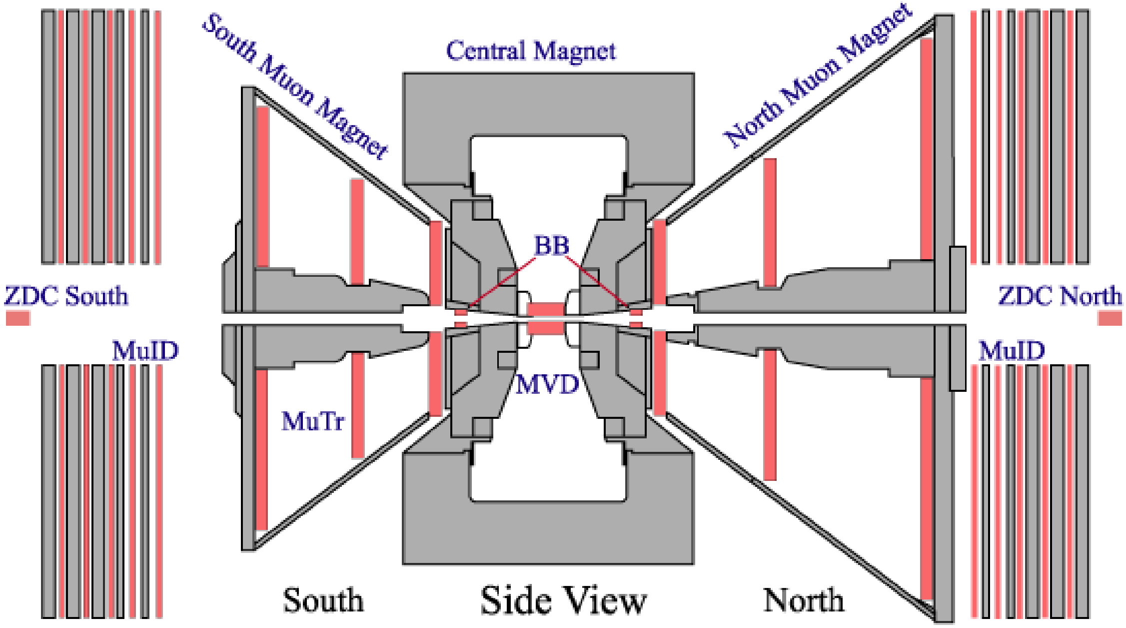
$$J/\psi \rightarrow e^{+} e^{-}$$
$p > 0.2\text{GeV}/c$
$|\eta| < 0.35$
$\Delta\phi = \pi$



Like Sign Subtraction



PHENIX Detector: Muon Arms



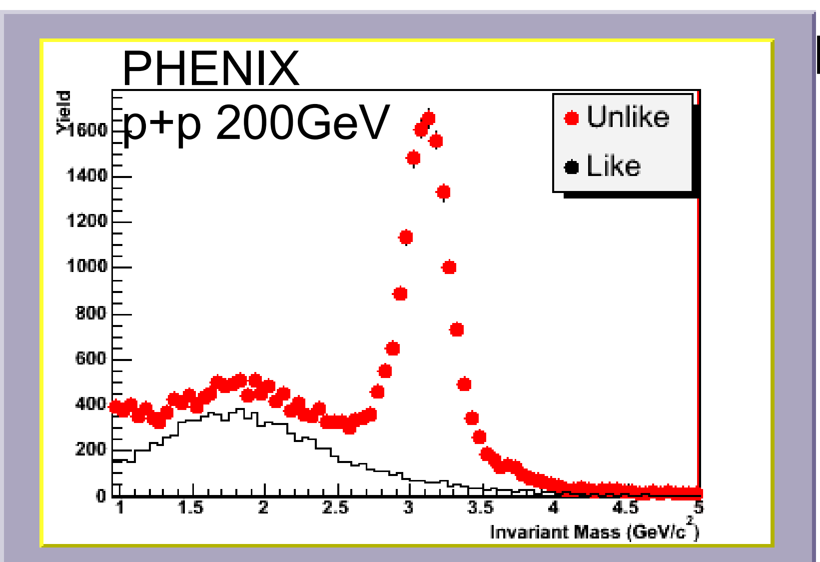
$J/\psi \rightarrow \mu^+ \mu^-$

$p > 2GeV/c$

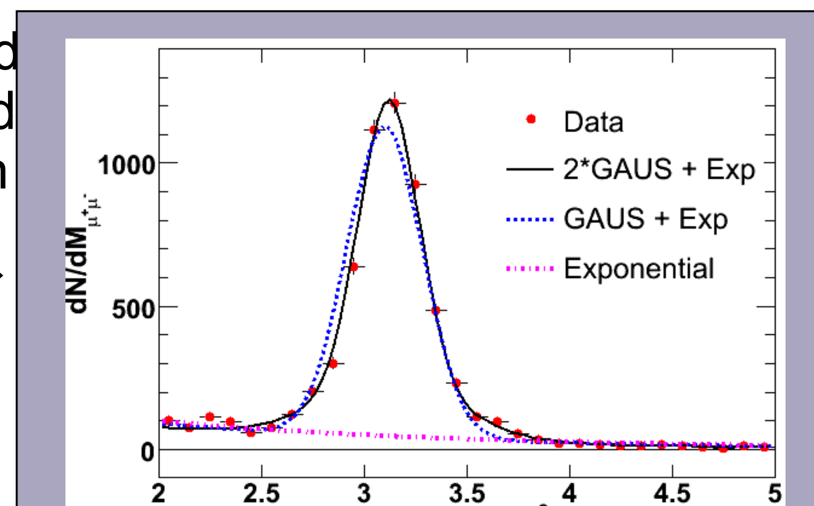
$1.2 < |y| < 2.2$

$\Delta\phi = 2\pi$

Poster #163: Silvestre



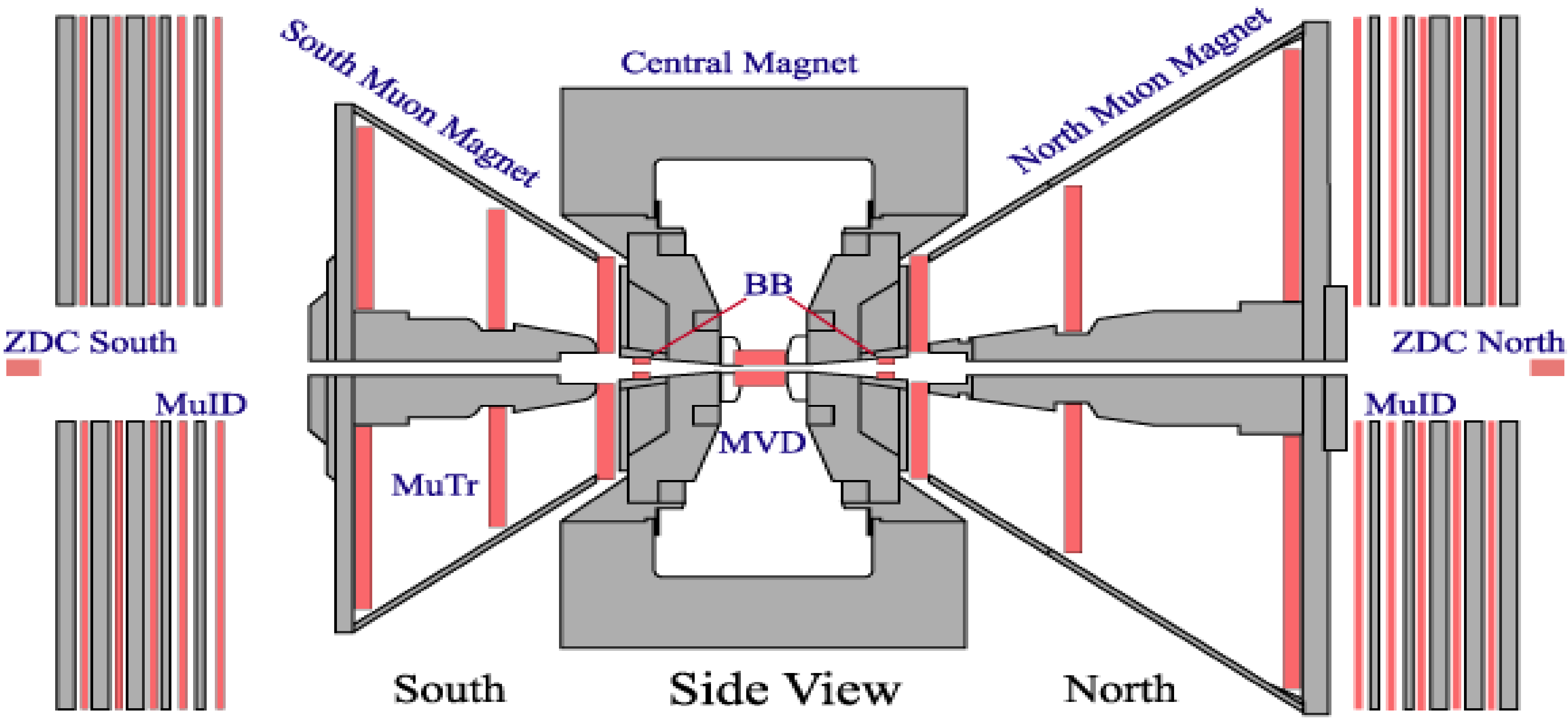
Event Mixed Background Subtraction



hep-ex/0611020

Event characterization and triggers

- **Beam-Beam: Minbias** event trigger - efficiency 52 % (pp), 88% (d+Au), 94 % (Au+Au) Covers $3.3 < |\eta| < 3.9$
- Heavy ion **centrality** estimated using GEANT simulations of the BB detector response combined with a **Glauber model** of the collision.
- BB Trigger Efficiency higher for events containing a J/ψ.
- Additional hardware triggers needed for pp, d+Au and CuCu for dielectrons and dimuons.
- J/ψ efficiency typically 70%, good efficiency down to $p_T = 0$.



The PHENIX J/ψ program

PHENIX has mounted a systematic program at **200 GeV/A** to try to characterize the effect of hot dense matter in the final state on J/ψ production. It consists of collisions of:

pp	Baseline J/ψ production cross sections
d+Au	The cold nuclear matter baseline (J/ψ breakup cross section and shadowing effects)
Au+Au	Hot + cold nuclear matter effects versus Npart
Cu+Cu	Same as Au+Au, but much better precision at low Npart

The idea is that we can make a survival probability by taking the ratio of R_{AA} from Au+Au and Cu+Cu to the R_{AA} expected from cold nuclear matter effects. This survival probability then shows us the effect of **hot dense matter in the final state**.

J/ψ measurements with PHENIX so far

In the **di-electron channel at mid-rapidity** $|\eta|<0.35$
In the **di-muon channel at forward/backward rapidity** $1.2<|\eta|<2.2$.

Run	Ions	Luminosity	J/ψ (ee + μμ)	Status
3	dAu @ 200 GeV	2.74 nb-1	360 + 1700	PRL 96, 012304 (2006) New Analysis almost final
4	AuAu @200 GeV	241 μb^{-1}	1000 + 4500	PRL 98, 232301 (2007)
5	CuCu @200 GeV	4.8 nb-1	2100 + 10000	Almost final
	pp @ 200 GeV	3.8 pb-1	1500 + 8000	PRL 98, 232302 (2007)
6	pp @ 200 GeV	10.7 pb-1		Analysis in progress
7	AuAu 2 200 GeV	~850 μb-1		Data reconstruction in progress

Almost all measurements done at 200 GeV, with only a small amount of 64 GeV J/ψ data.

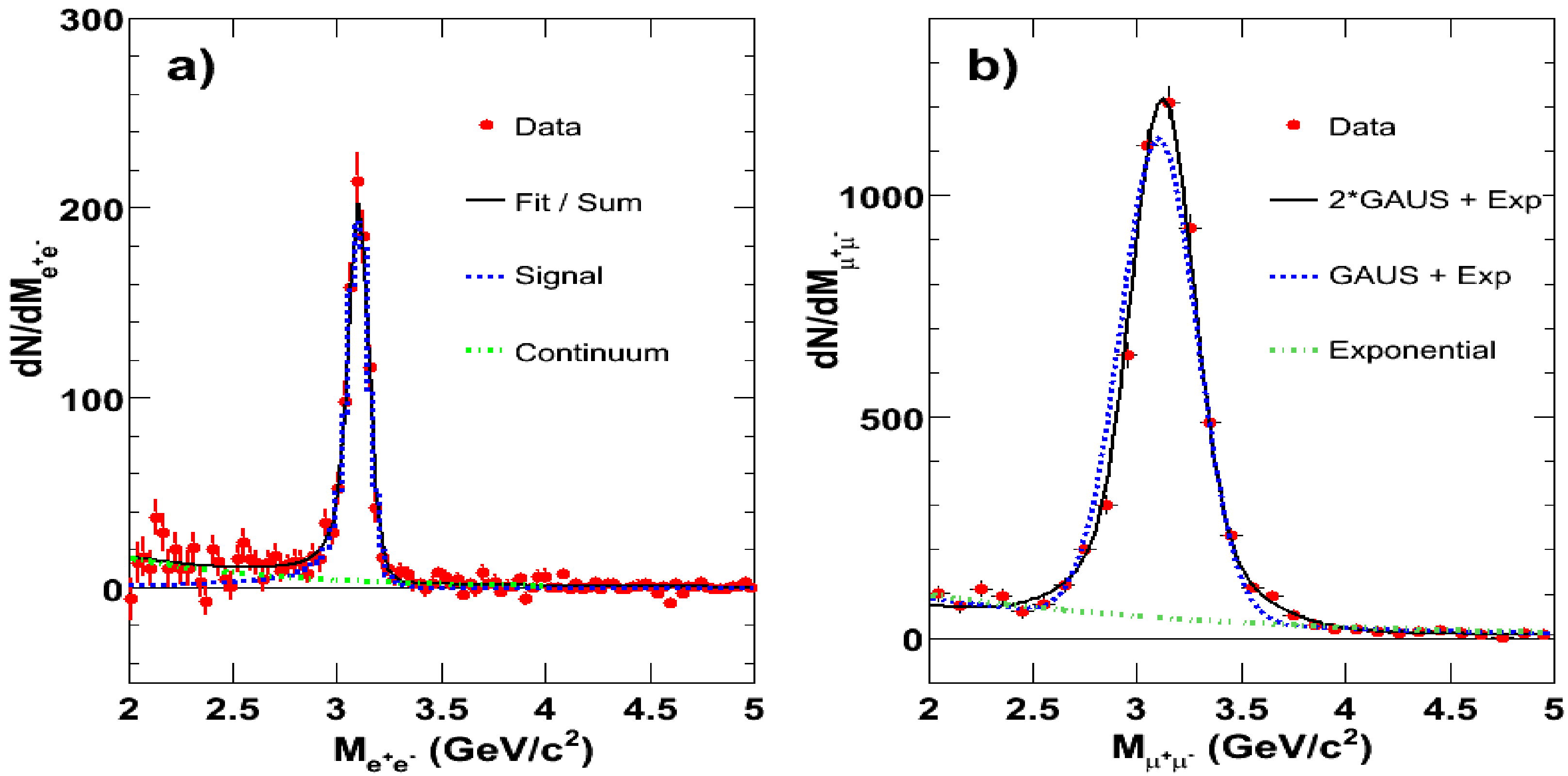
J/ψ→e^+e^- yield: Use like sign subtraction to estimate background, correct for:

- Radiative tail due to internal and external Bremstrahlung: 7.2% +/- 1%
- Continuum e^+e^- pairs due to open charm, Drell-Yan: 10% +/- 5%

J/ψ→$\mu^+\mu^-$ yield: Use event mixing to estimate background

- Exponential fit used to subtract continuum from open charm, Drell Yan
- Then direct counting or fitting with lineshapes to get net yield

Run 5 pp Mass spectra



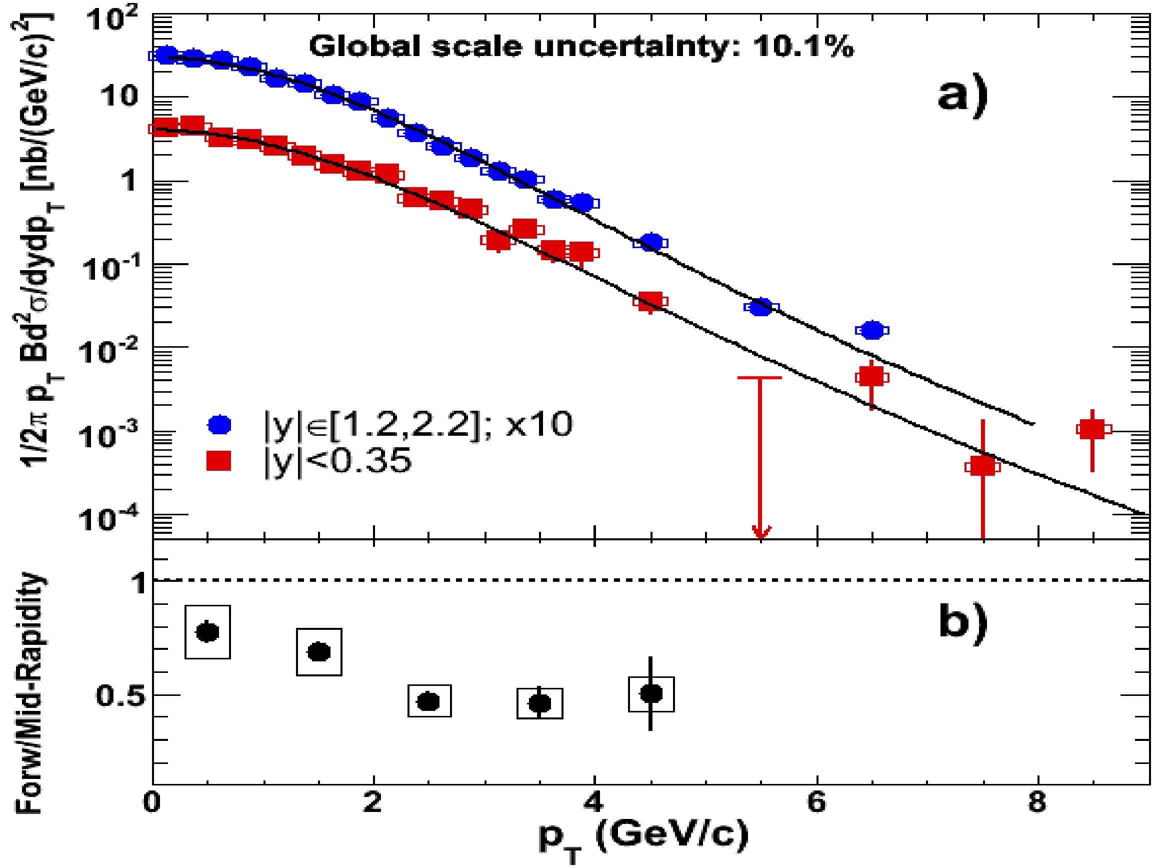
The basic cross sections – pp collisions

The pp collisions provide the **reference cross sections** against which we compare heavy ion collision results.

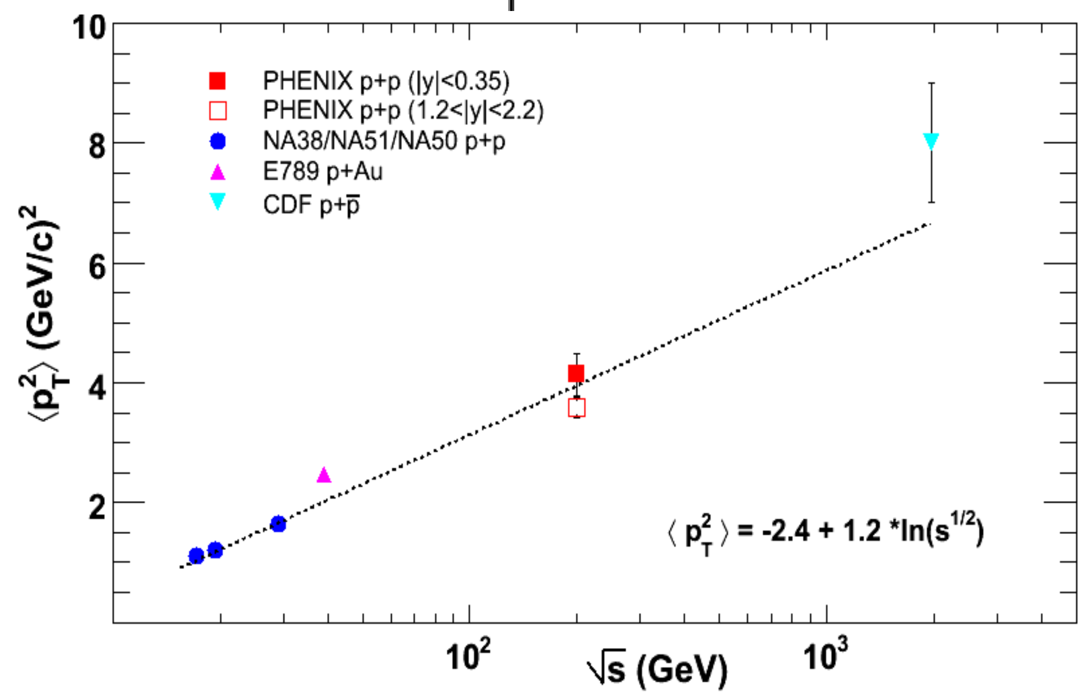
$$R_{AB}(y, p_t) = \frac{d^2 N_{AB} / dy dp_t}{< N_{coll} > \times d^2 N_{pp} / dy dp_t}$$

The number of nucleon-nucleon collisions Ncoll is estimated from the signals in the BB counters.

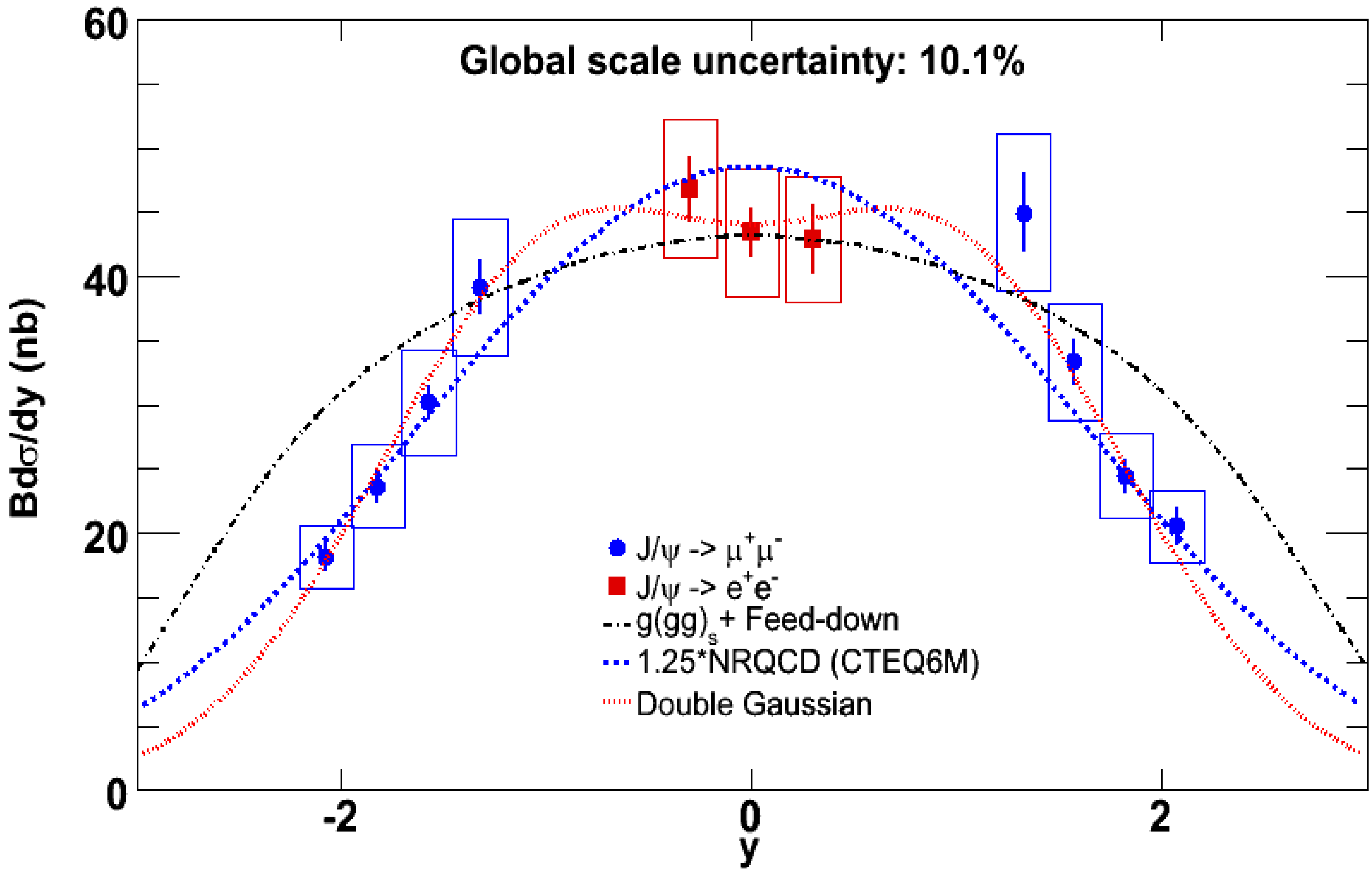
The p_T dependence of the J/ψ cross sections in pp collisions from Run 5.



Comparison of PHENIX J/ψ $\langle p_T^2 \rangle$ with measurements in pp collisions at other energies.

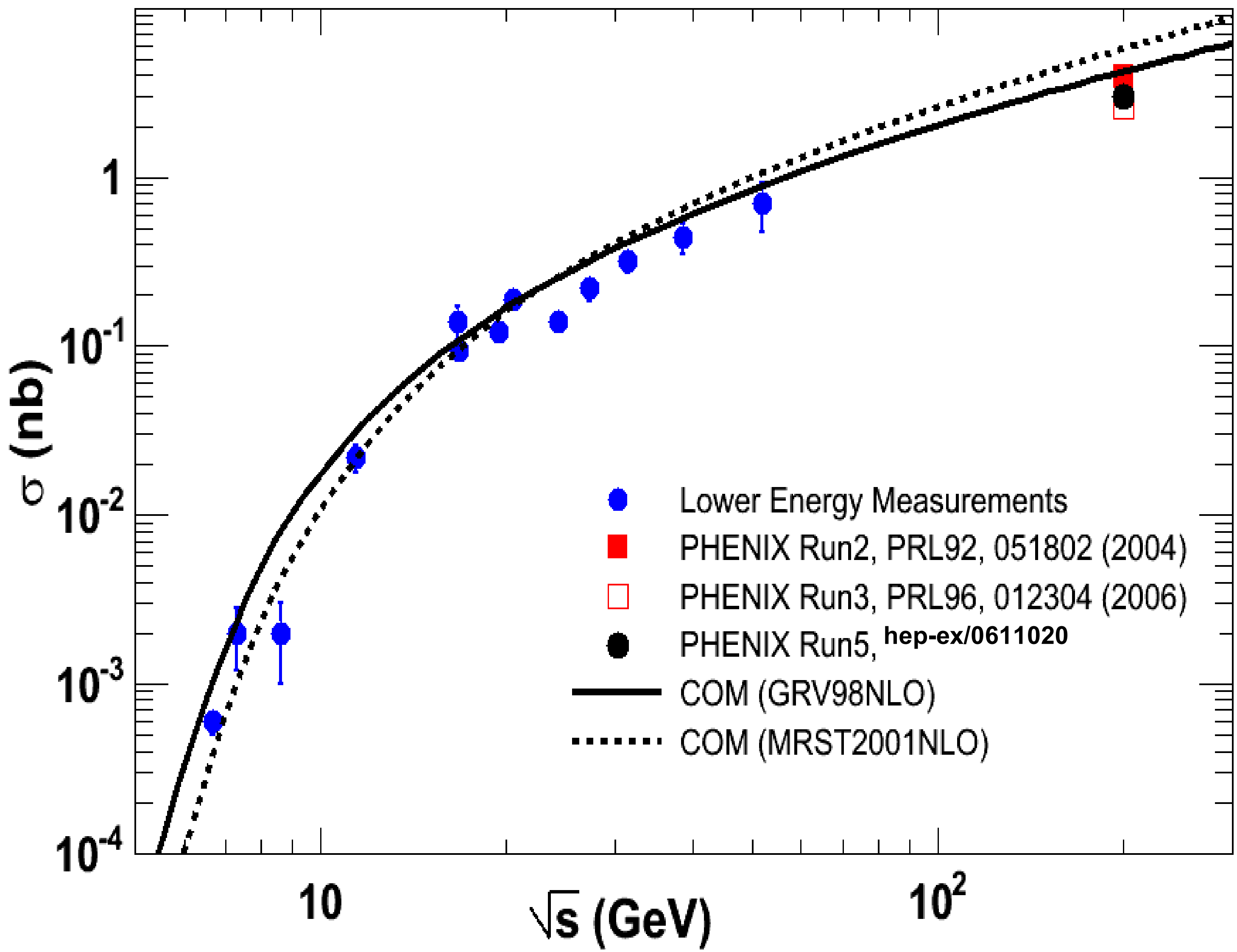


The **rapidity distribution** obtained by combining dielectron and dimuon measurements allows us to estimate the total pp J/ψ cross section from Run 5 pp data. The different curves are used to estimate systematic uncertainties

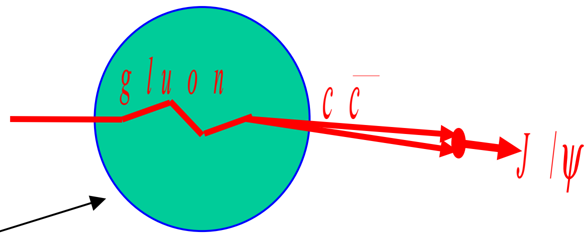


$$BR \bullet \sigma_{tot} = 178 \pm 3^{stat} \pm 53^{sys} \pm 18^{norm}\ \text{nb}$$

J/ψ cross section versus energy in p+p collisions

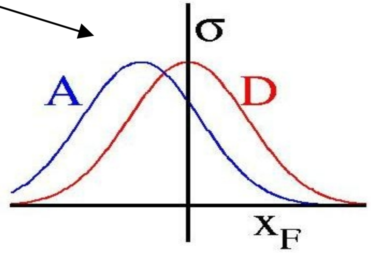


Cold nuclear matter effects



Interaction in medium
- absorption (dissociation) of J/ψ
- gluon multiple scattering in initial state (Cronin effect) resulting in P_T broadening

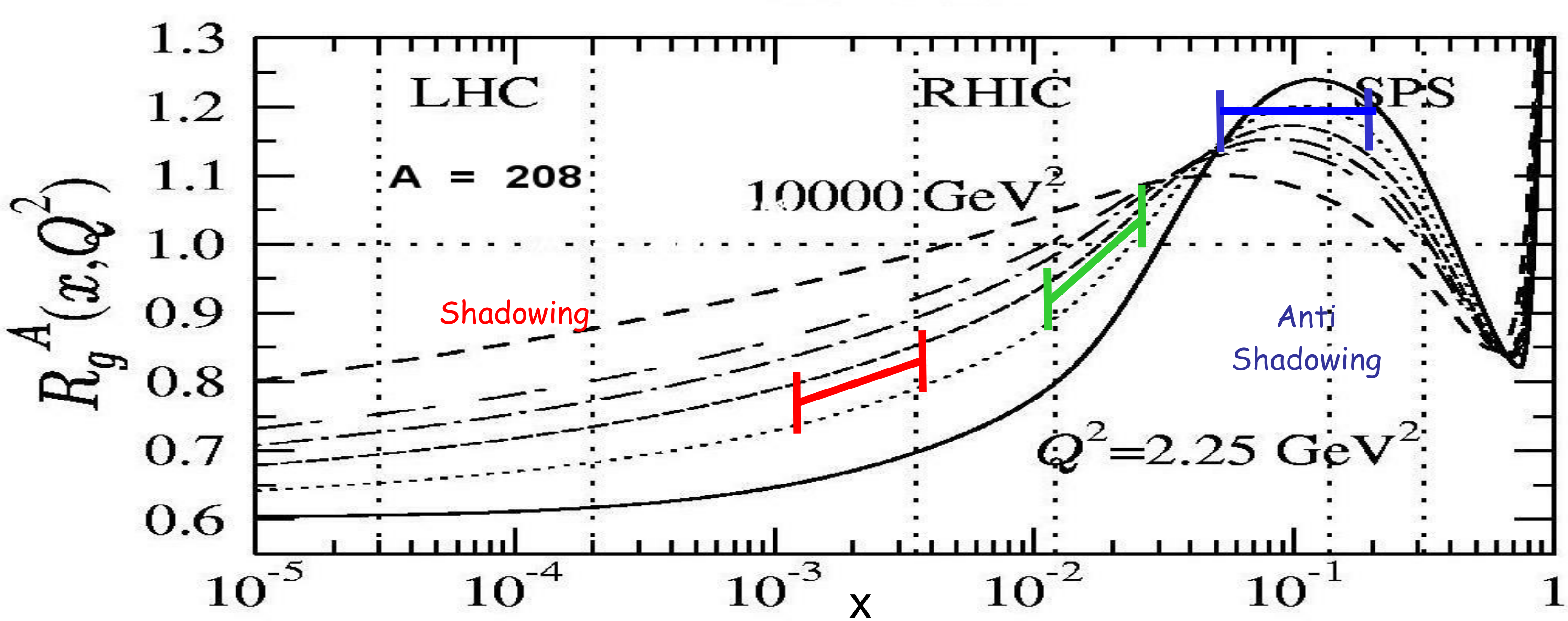
Modification of gluon parton distribution function
- shadowing: depletion of low momentum gluons (and anti-shadowing at high x)
- gluon energy loss in initial state (shift in x_F resulting in suppression)
- gluon saturation at low x: Color Glass Condensate



Cold Nuclear Matter via d+Au collisions

- Absorption of J/ψ by nuclear matter
- Modification of PDF due to gluon shadowing

Models Data



Nucl. Phys. A696 (2001) 729-746

The x ranges in Au sampled by the three rapidity intervals of PHENIX are indicated

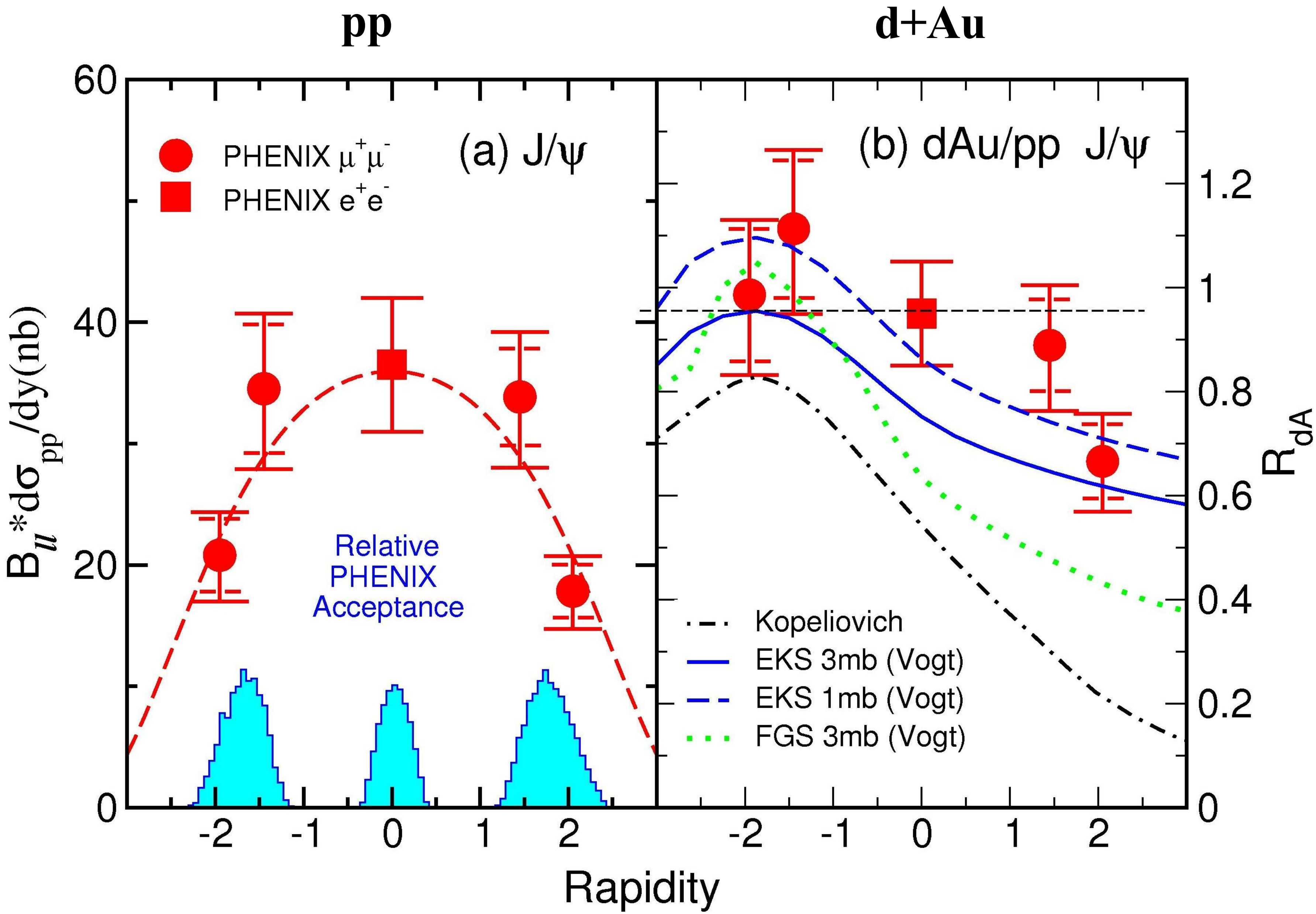
d+Au collision measurements

Here we want to measure the **collision centrality dependence** at forward, mid and backward rapidity to establish the effect of cold nuclear matter on the J/ψ production cross section in nuclear collisions.

The **centrality** for d+Au is estimated from the BB counter signal strength in the Au-going direction based on a Glauber model + Geant simulation of the detector response.

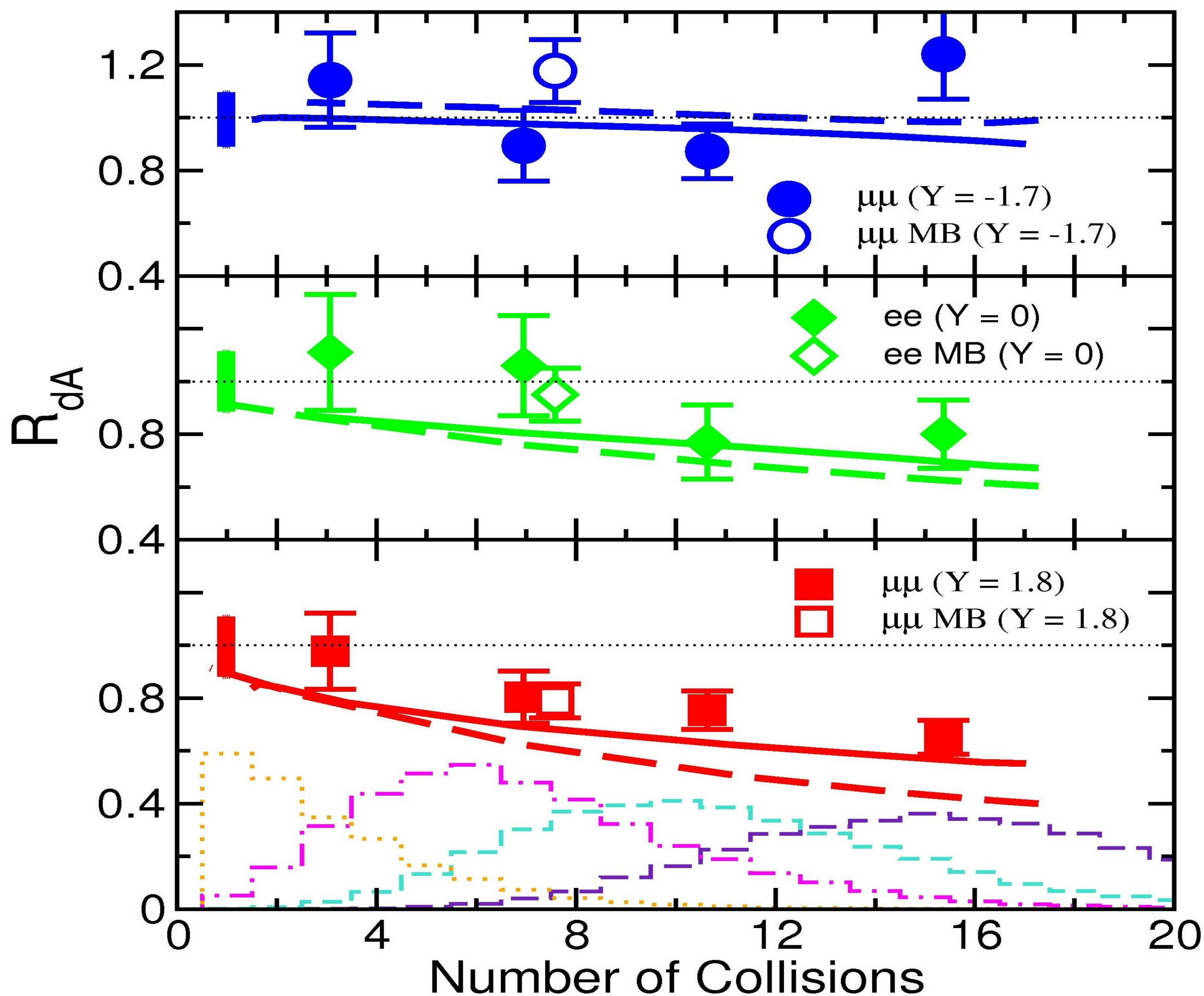
The Run 3 d+Au and reference pp data

Minbias data vs Rapidity



The Run 3 d+Au and reference pp data

Centrality dependence in three rapidity bins



What did we learn from the d+Au data?

The Run 3 d+Au data favor weak shadowing & absorption ~ 1-3 mb
But - with such limited statistics - difficult to disentangle nuclear effects
Need another d+Au run! Top priority for Run 8.

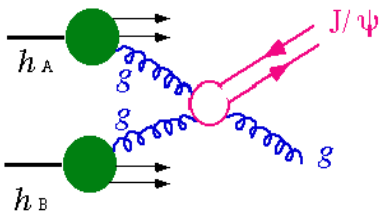
Meanwhile:

A **new analysis** of the Run 3 d+Au data is expected to be submitted for publication in the next few weeks.

This analysis uses our improved understanding of the PHENIX detector since the original Run 3 analysis **AND** Run 5 pp J/ψ reference data. It systematically quantifies the extent to which the Run 3 d+Au data constrain the cold nuclear matter baseline cross sections.

Factors in J/ψ production in Heavy Ion Collisions

- Creation (at RHIC energies)
  - Directly via various gluon diagrams
    - Very early in nucleon-nucleon hard scatterings



  - Feed down from excited states of charmonia, multiple measurements of branching ratio **but not at RHIC**:
    - Example HERA-B : ($\chi_c \rightarrow J/\psi X$) ~ 21±5% and ($\psi' \rightarrow J/\psi X$) ~ 7±0.4% (*)
- Gluon shadowing : modification of PDFs in nuclei
- Suppression
  - Absorption of forming J/ψ by nucleons in colliding heavy ions ($J/\psi+N\rightarrow X$)
  - **Interaction with fast moving gluons ($J/\psi+g\rightarrow X$)**
  - **Dissociation by QGP**
- Enhancement
  - **Possible coalescence of <u>uncorrelated</u> c and $\bar{c}$ quarks**

(*) Abt *et al.* Eur. Phys. J. C49 (2007) 545-558

Run 4 Au+Au data

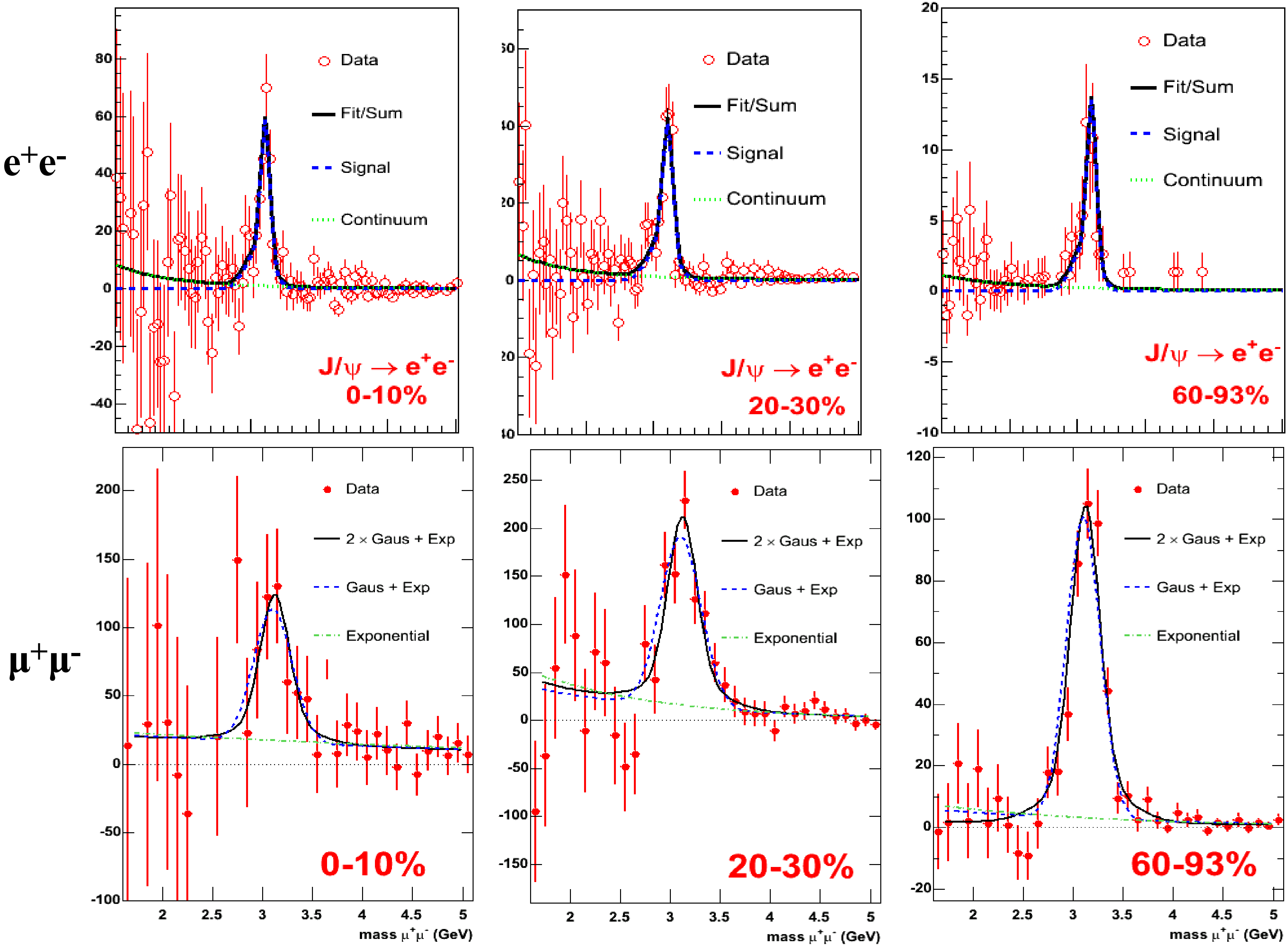
We use the **Run 5 pp data** as the cross section reference.

We have 1000 J/ψ at y = 0 and 4,500 J/ψ at y = 1.7.

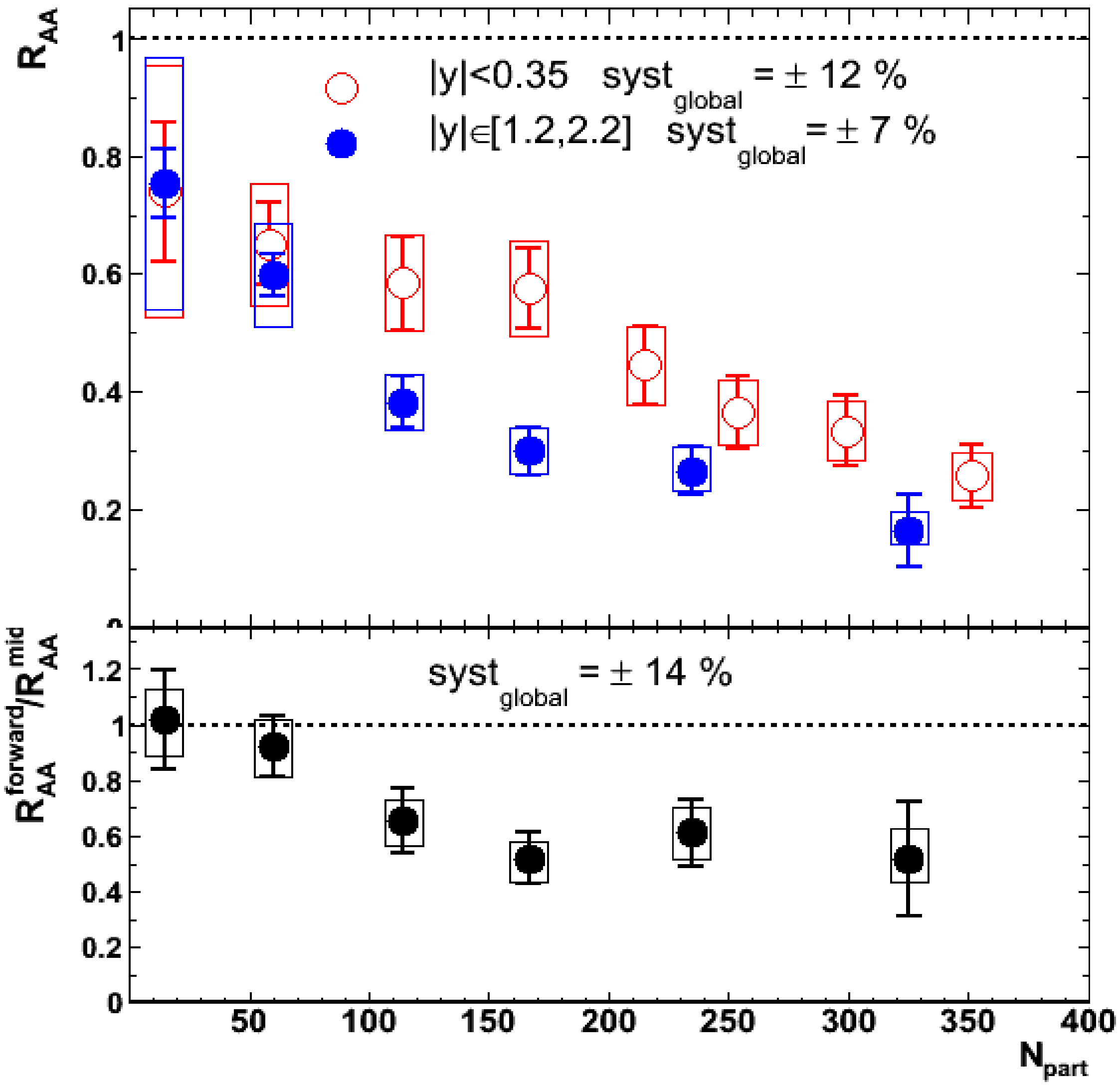
But the combinatorial backgrounds are now much larger!

We want to look at the J/ψ R_{AA} vs centrality, p_T and rapidity to look for evidence of QGP effects.

Background subtracted invariant mass spectra for Au+Au



The centrality dependence is significantly stronger at forward than at mid rapidity. This has been taken by some as evidence of stronger **coalescence** at mid rapidity, where the charm yield presumably is strongest, causing **increased**, not decreased, J/ψ cross section at the greatest local energy density.

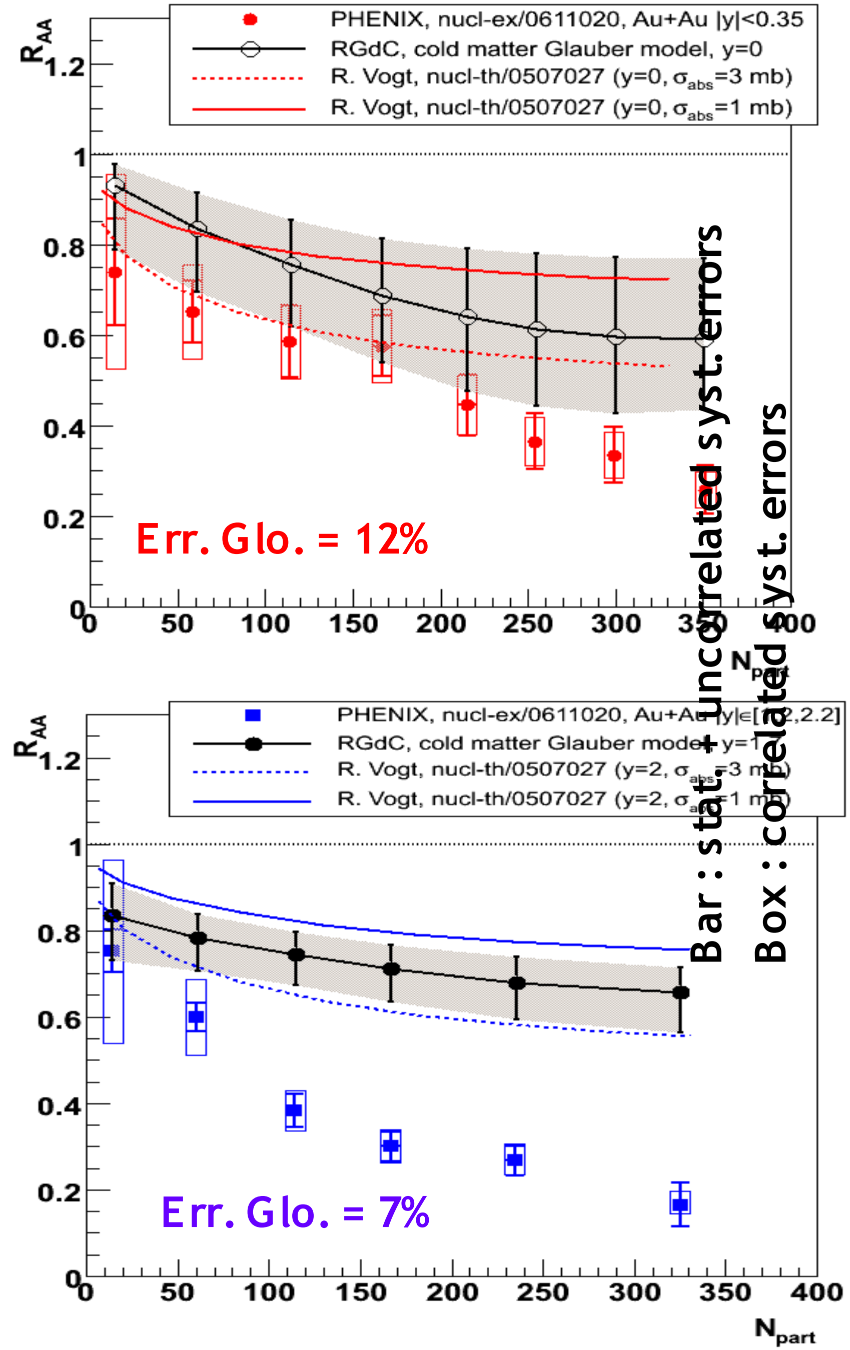


But what does the cold nuclear matter baseline look like?

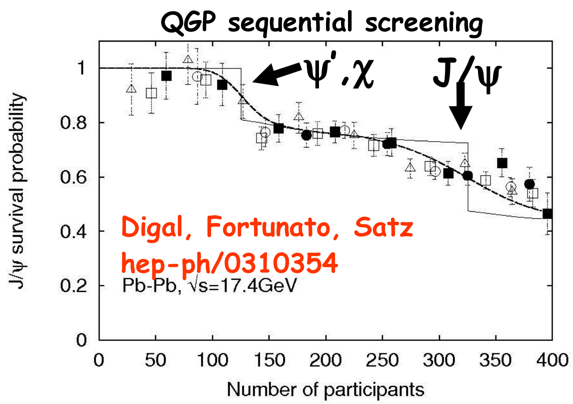
How does this compare with cold nuclear matter expectations from d+Au?

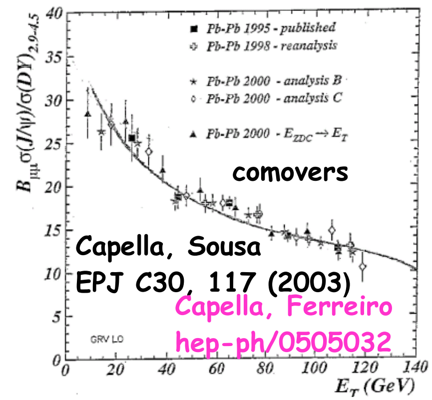
- **Two calculations shown**
  - CNM effects model based on 1-3mb absorption and shadowing. (*)
  - Glauber model + rapidity symmetrization of d+Au points (**)
    - $R_{AA}(\pm y) = R_{dA}(-y) x R_{dA}(+y)$
- Suppression higher than accountable by CNM effects
- Cold nuclear matter uncertainties are too large for any firm conclusions about the relative effects of hot nuclear matter at the two rapidities, although the impression is left that suppression is stronger at forward rapidity.

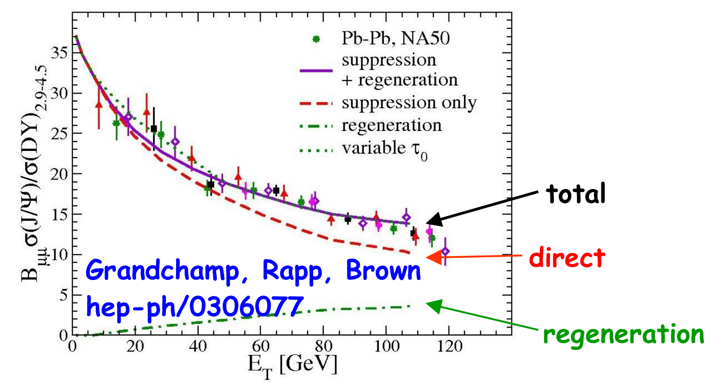
(*) R. Vogt, Acta Phys. Hung. A25 (2006) 97-103
(**) R. Granier de Cassagnac, hep-ph/0701222



Models without regeneration (Mike Leitch QM06)



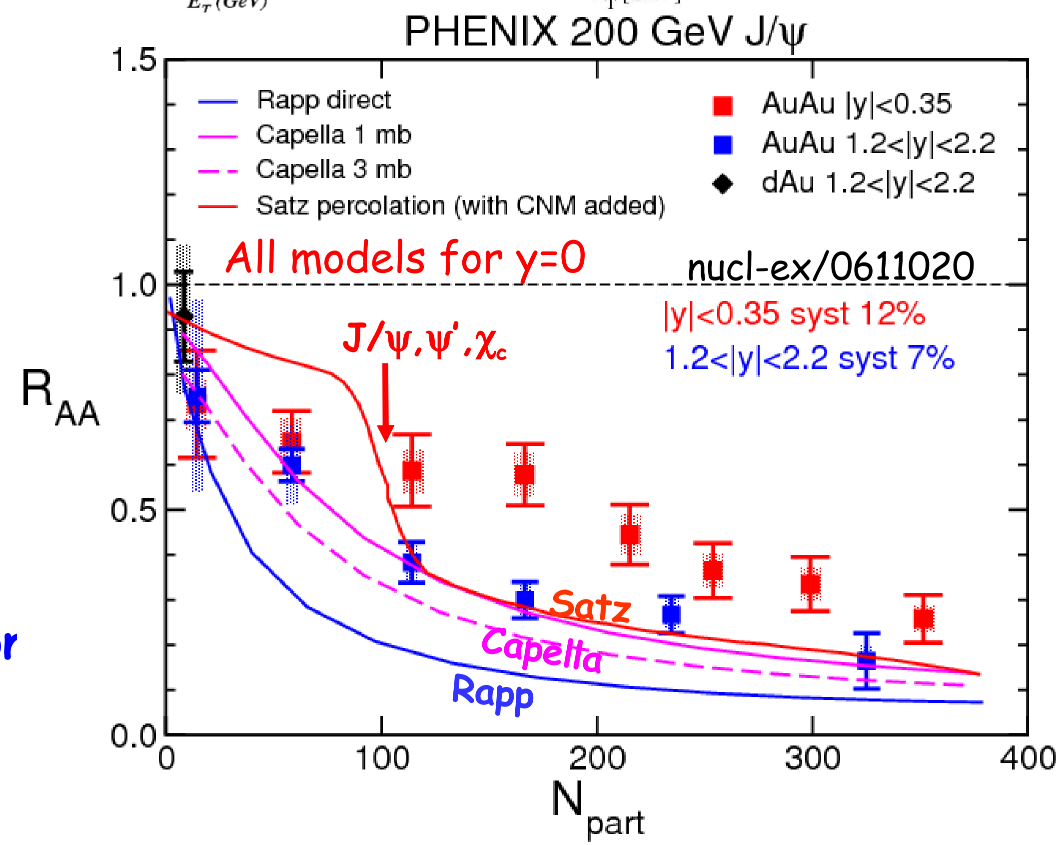




Models that reproduce NA50 results at lower energies (above):

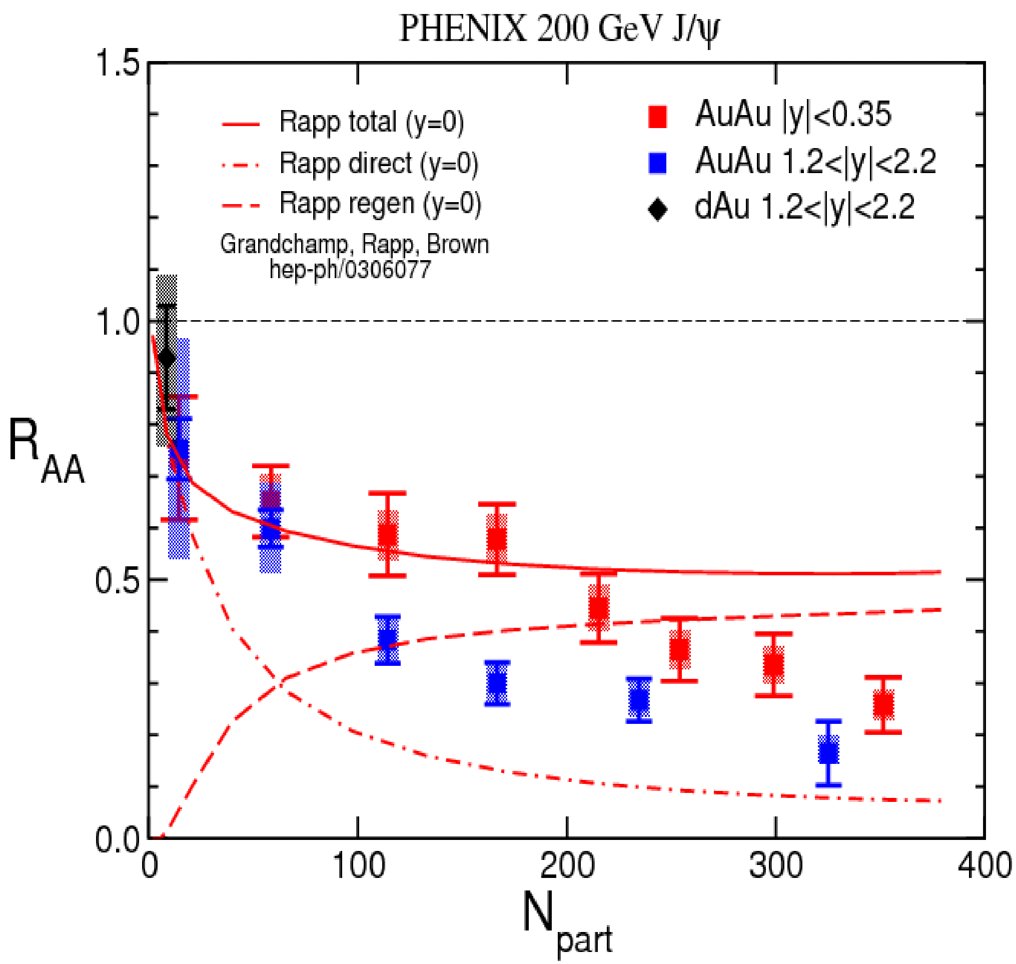
- Satz - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects (without regeneratior

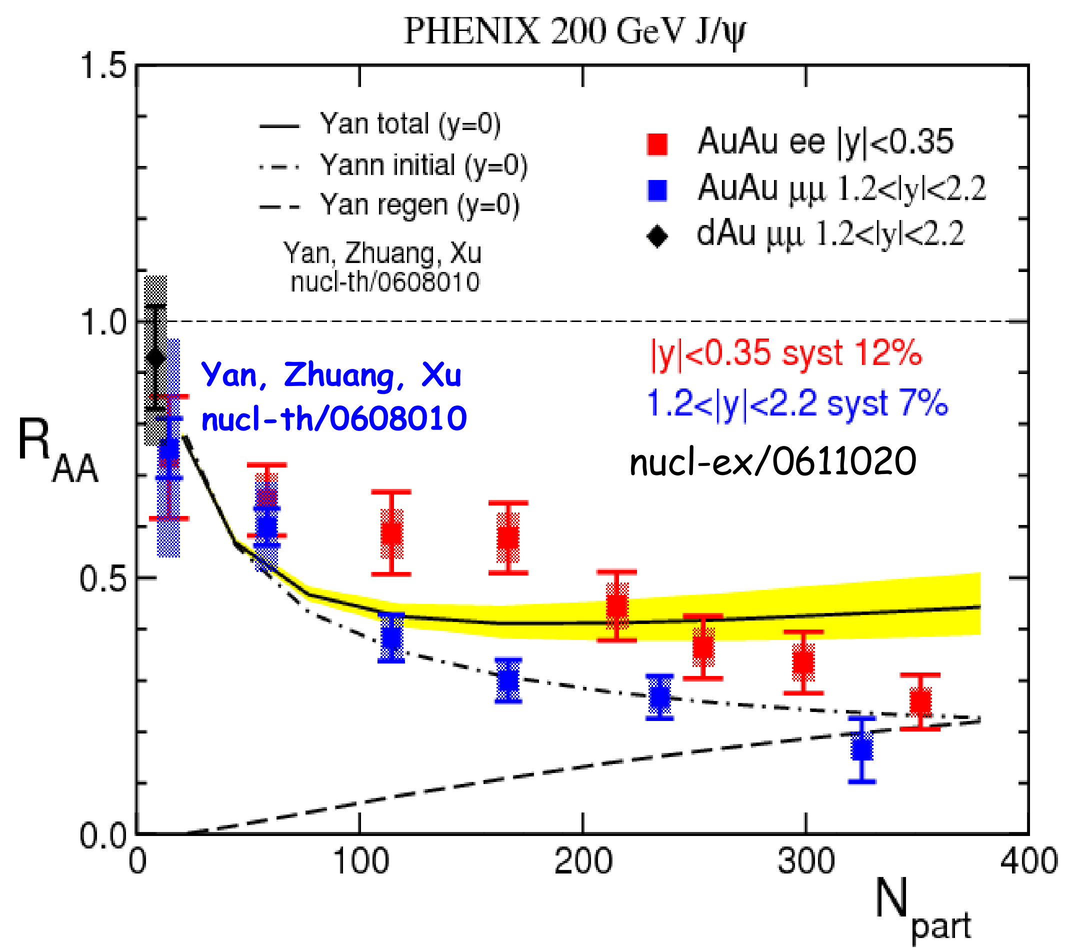
But predict too much suppression for RHIC mid-rapidity (at right)!



Models with coalescence

Two models with coalescence of J/ψ. Differing amounts of coalescence, calculations only at mid rapidity, predicted shape of mid rapidity R_{AA} is not well reproduced.

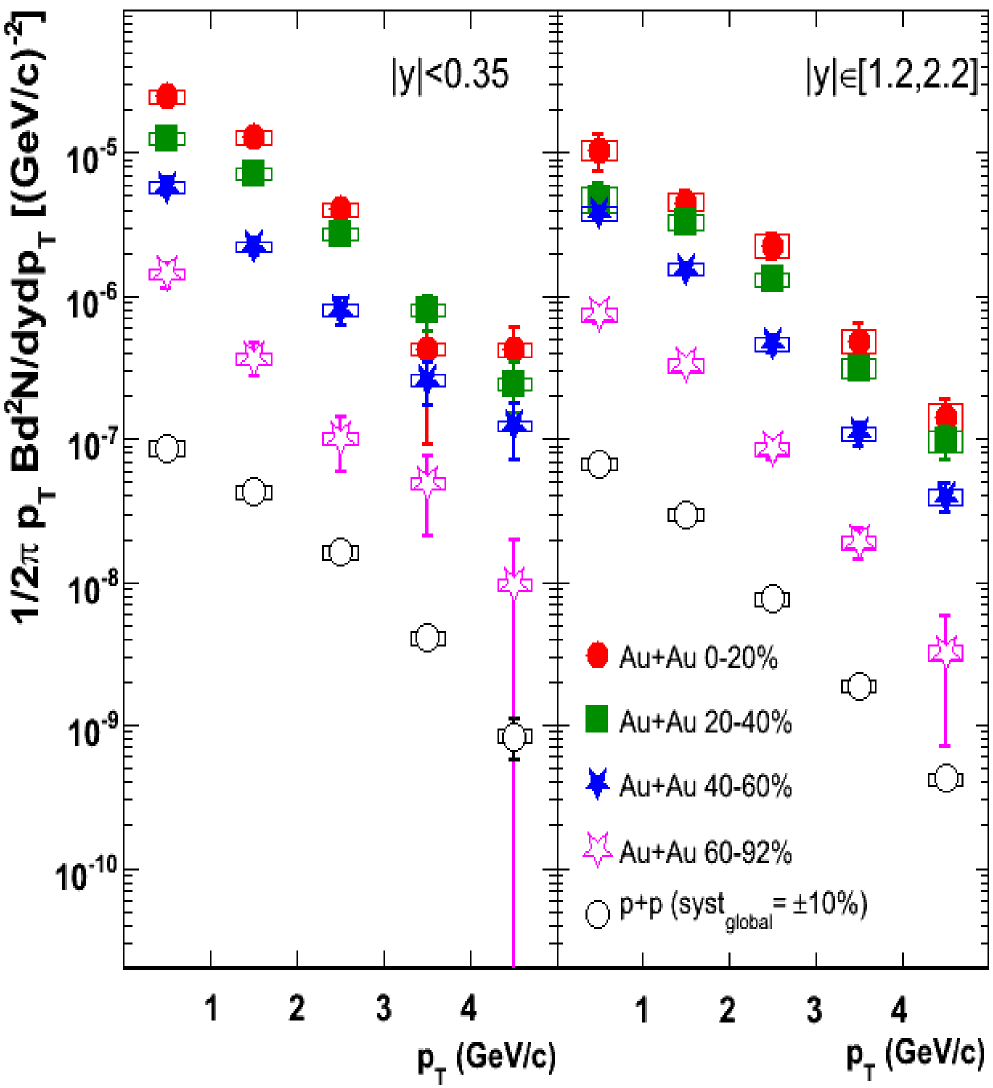


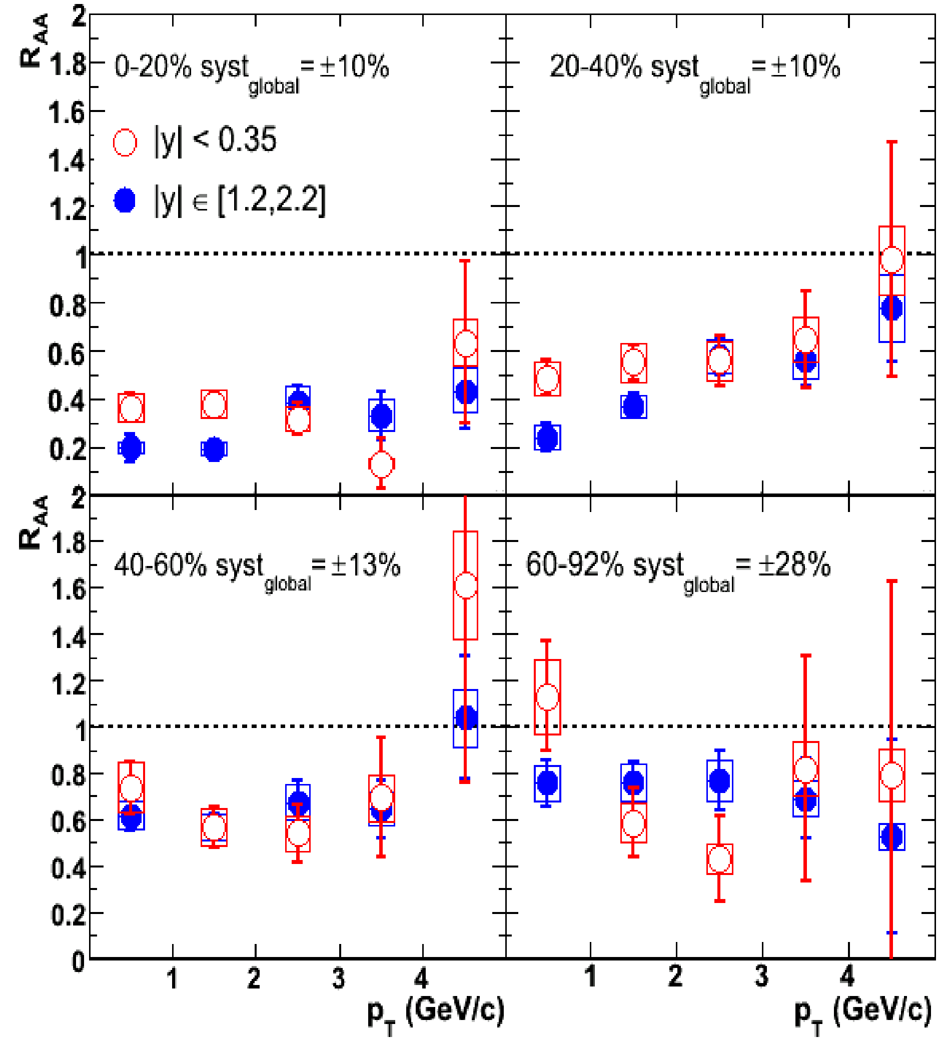


P_T distributions

Hardness of p_T spectrum may be sensitive to the formation mechanism.

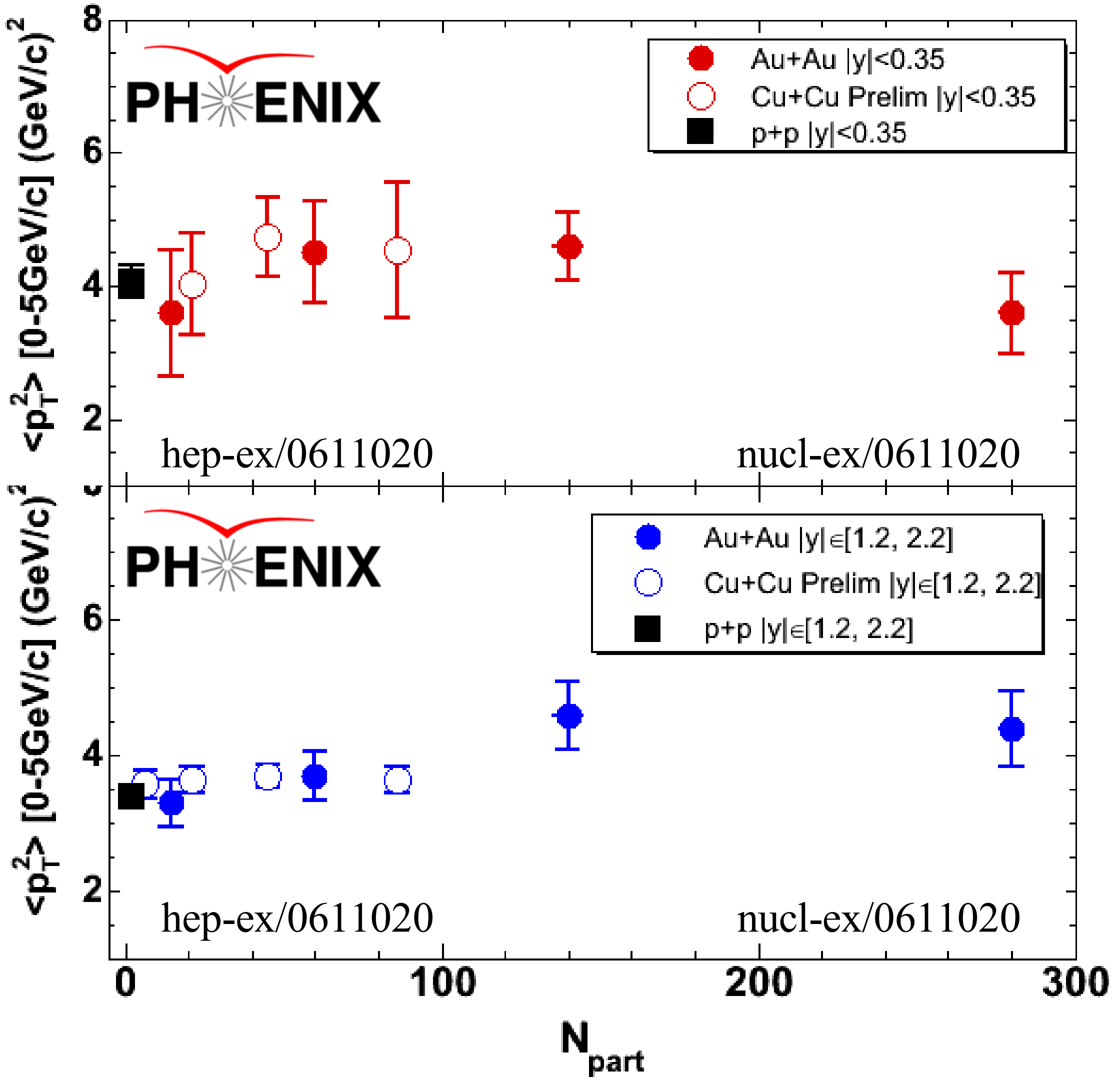
Coalescence of thermalized charm quarks would be expected to increase RAA at low p_T. But **R_{AA} vs p_T** looks fairly flat out to 5 GeV/c. Is that high enough?





The $<p_T^2>$ vs Centrality for Au+Au and Cu+Cu

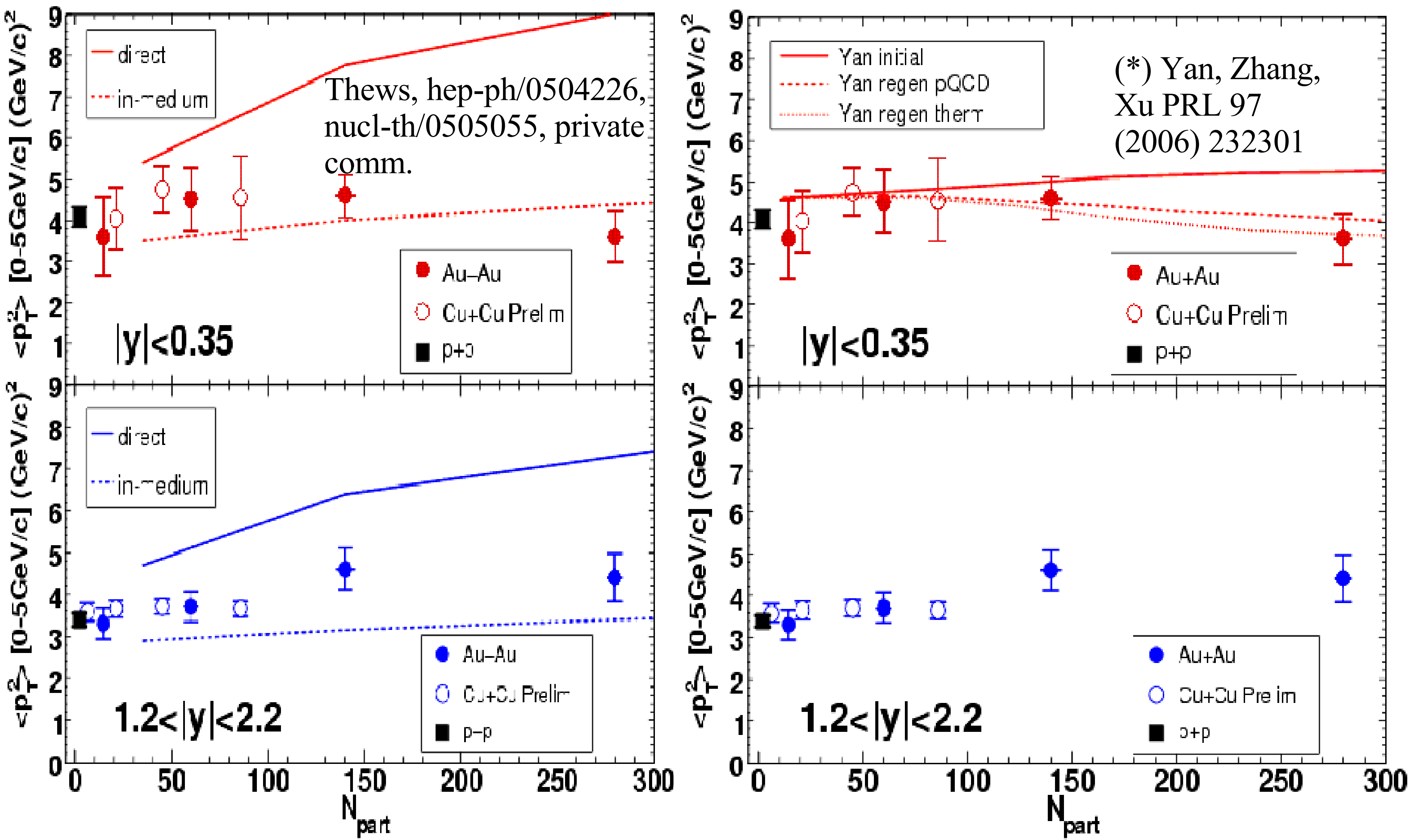
The $<p_T^2>$ is calculated directly from the measured data points (p_T<5GeV/c), no fitting or extrapolation.



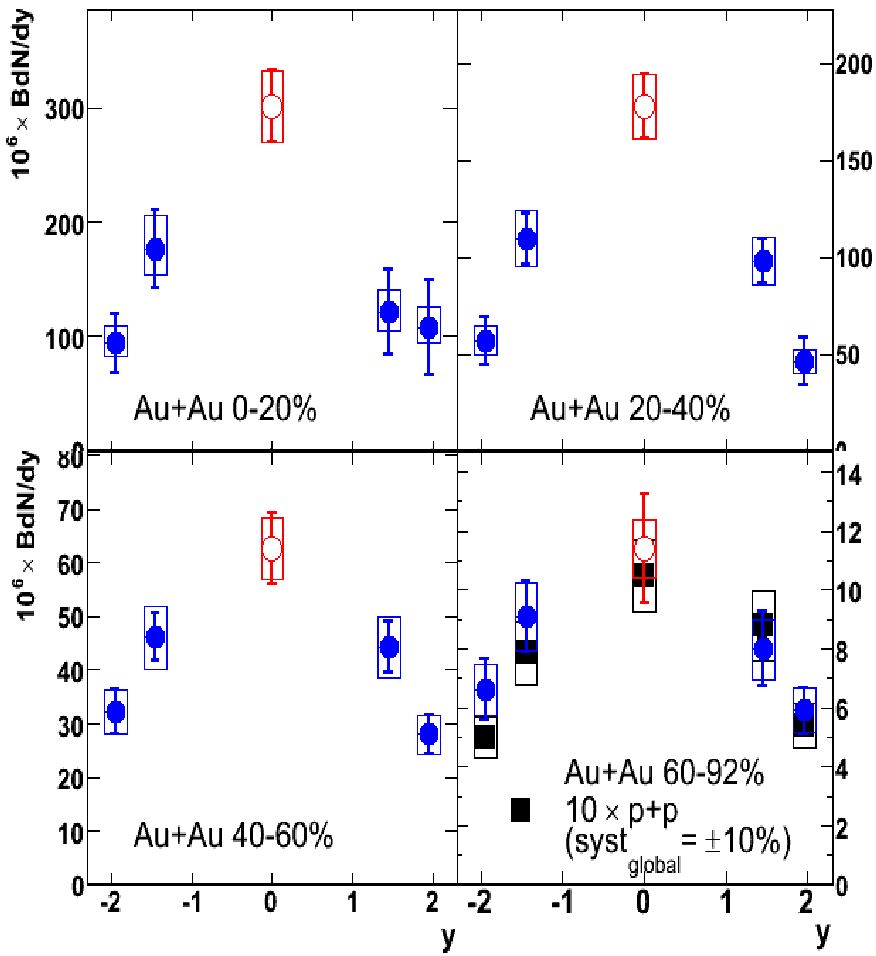
Good consistency is found between the $<p_T^2>$ in heavy ion collisions as a function of centrality and the p+p results for the $<p_T^2>$ integrated over p_T < 5GeV/c (where heavy ion data exists).

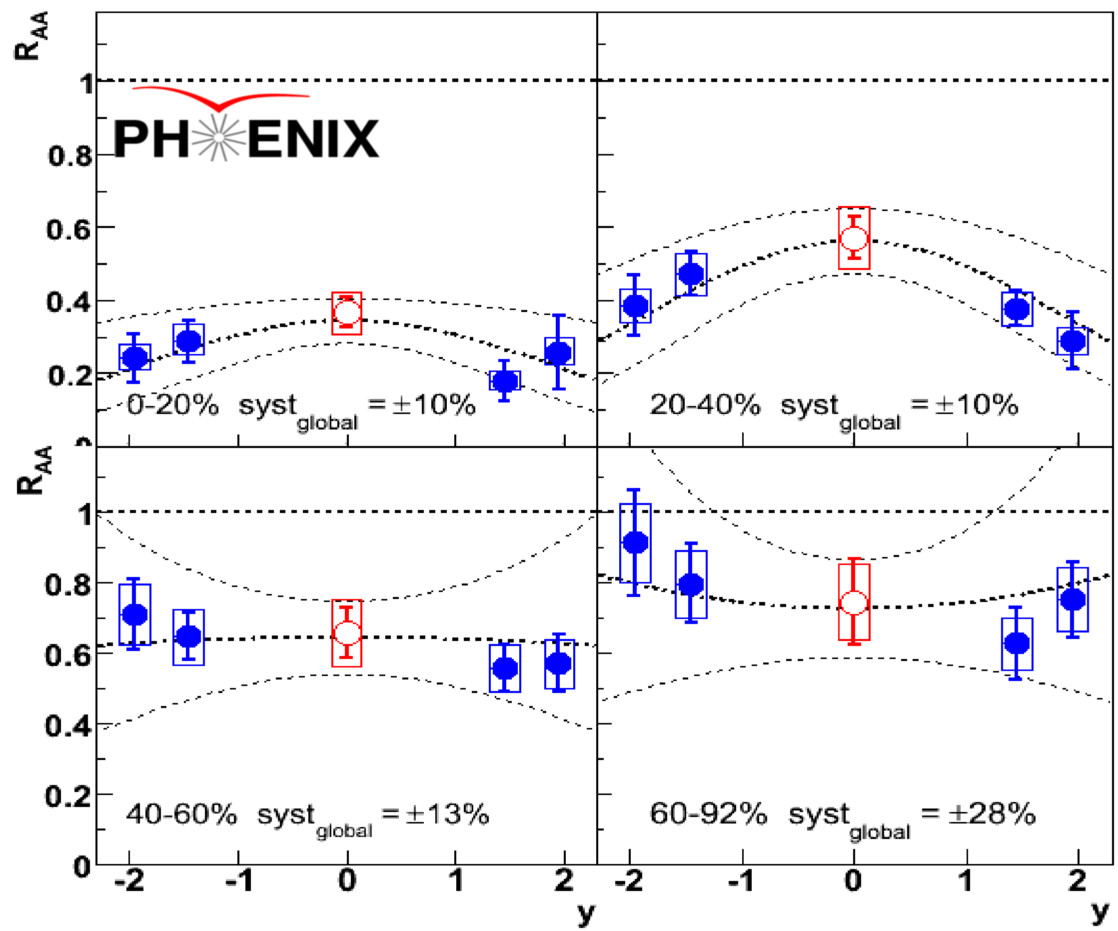
$\langle p_T^2 \rangle$ comparison with models

Tends to favor models with regeneration.



A large coalescence component is also predicted to **narrow the rapidity distribution** for central Au+Au collisions. We do observe a narrowing of the R_{AA} vs rapidity distribution for central Au+Au collisions. This is a challenge for models where suppression increases with local energy density.





Dashed lines : Gaussian fits.

Dotted lines : ± 1σ variation of fit pars.

Where do we stand?

Data:

- We have good pp reference data (and getting better every year).
- Our d+Au cold nuclear matter reference data from Run 3 are statistically inadequate to nail down the baseline cold nuclear matter R_{AA}.
- A new analysis of the Run 3 d+Au data will be published in a few weeks, but it is still statistically inadequate.
- We have decent Au+Au data in hand, more to come within a year.
- We will publish decent Cu+Cu data in a few weeks.

Physics:

- Still not clear, at least to me!
- The rapidity and $<p_T^2>$ seem to be consistent with coalescence.
- The RAA vs centrality suffers from great uncertainty about cold nuclear matter effects.
- 20 times as much baseline d+Au data from Run 8 may make things clearer.
- It would help a lot if we knew the open charm cross section precisely!
- Perhaps we need to see higher p_T reach in Au+Au, or J/ψ V_2, or ...

J/ψ projects in the pipeline now

Within weeks:

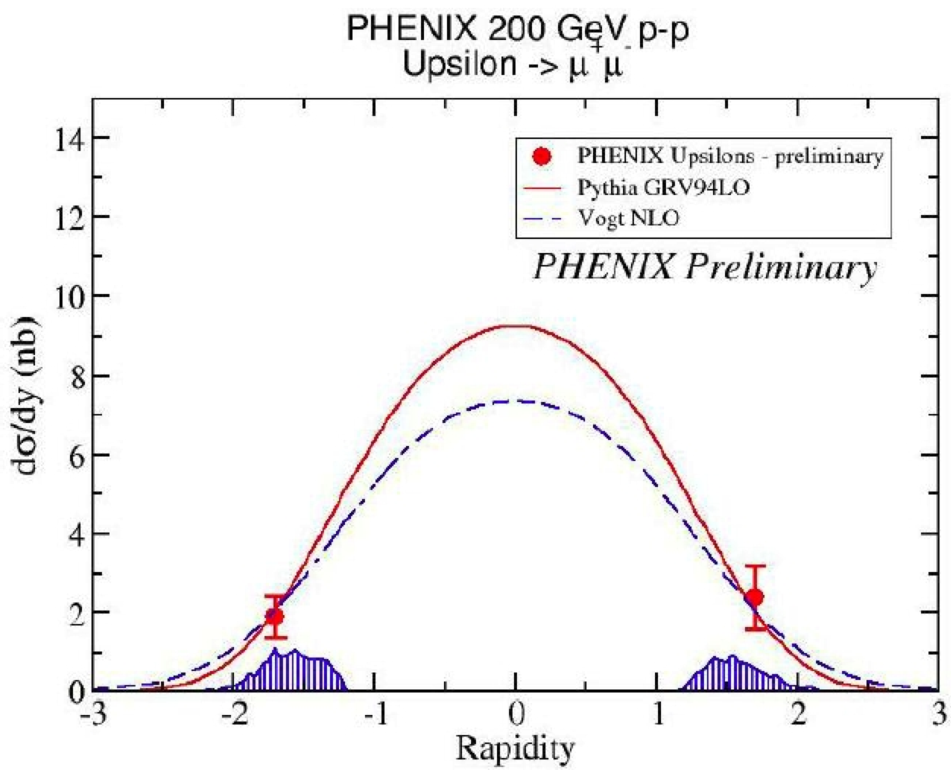
- Final Cu+Cu analysis completed – nails down **low Npart** heavy ion R_{AA} with much better precision.
- New d+Au analysis completed, quantifies the precision of the cold nuclear matter information obtained much better.

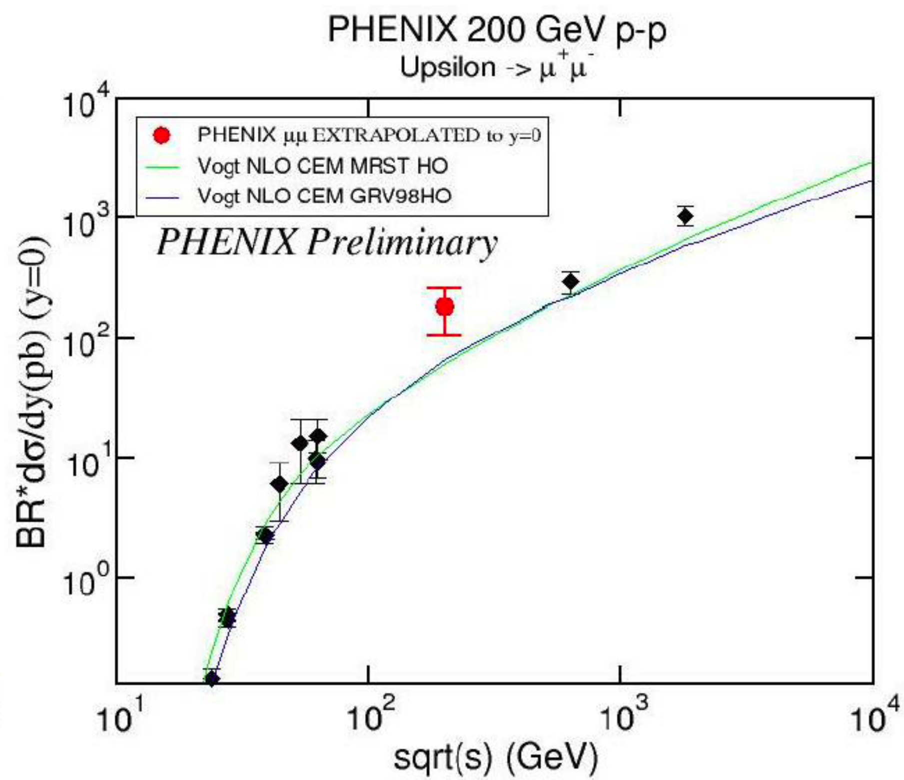
Further away:

- Run 6 pp (> 2 times Run 5 pp)
- Run 7 Au+Au (~ 4 times Run 4 Au+Au)

Other quarkonia stuff

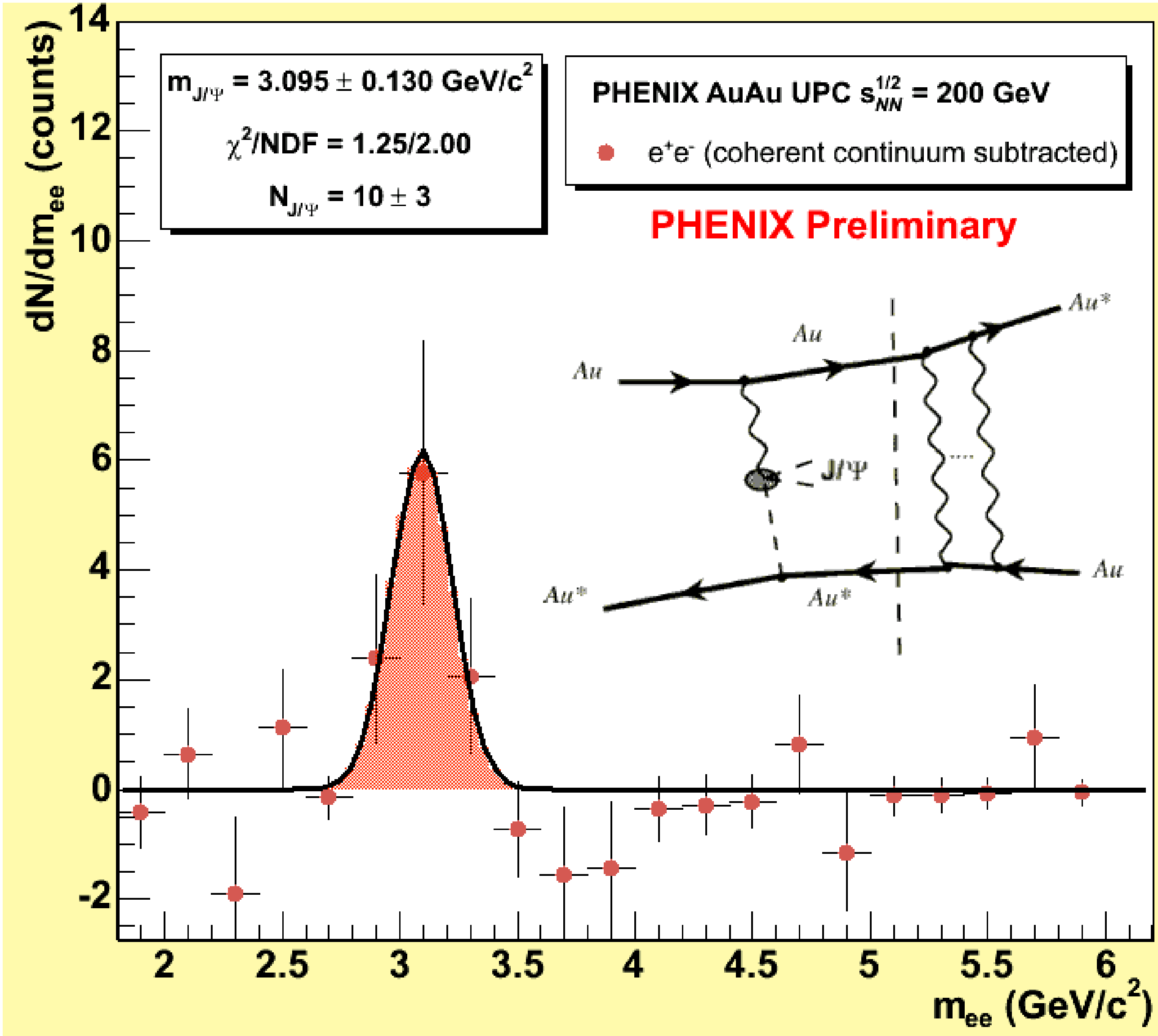
PHENIX Upsilon Measurement



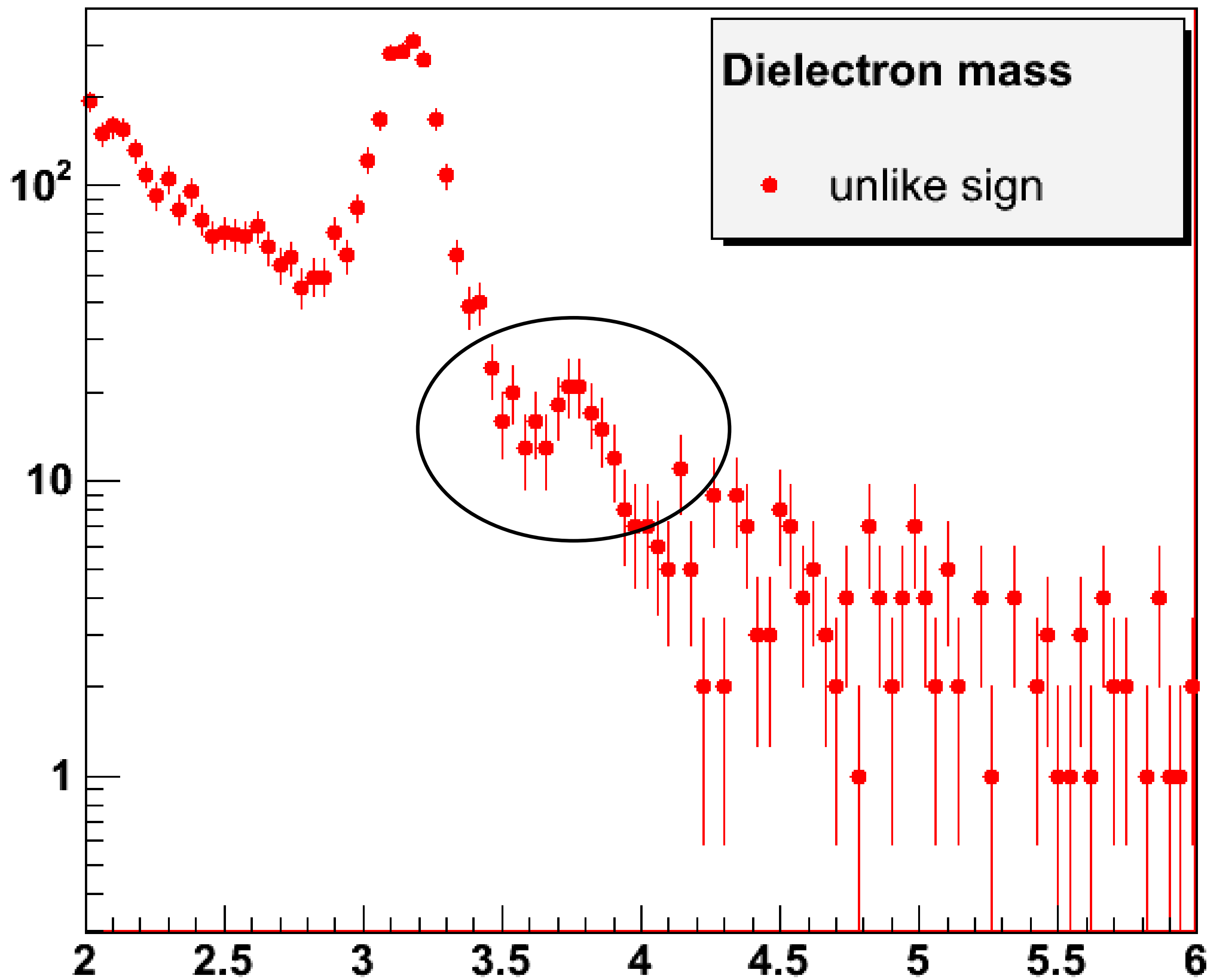


- Signal extraction assumes excess in ϒ mass region is strictly from ϒ's
- Rapidity dependence requires mid-rapidity point to constrain fit
- Preliminary cross section appears consistent with trend in world's data

Ultra-Peripheral Collisions



Future Measurements: ψ' in Run 6 pp

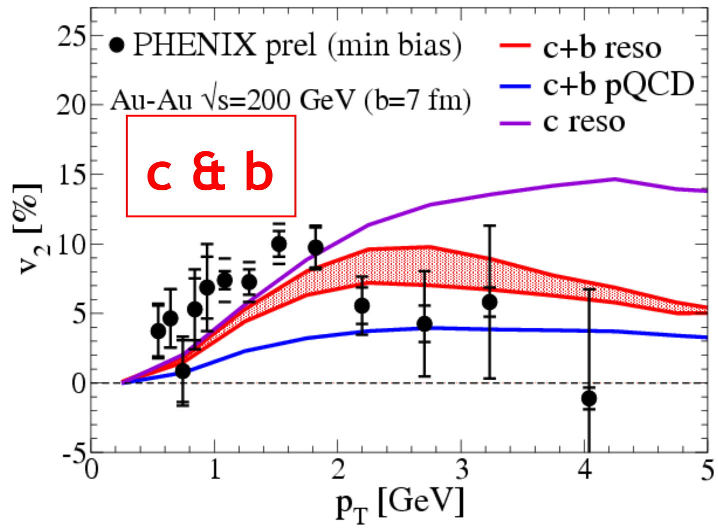


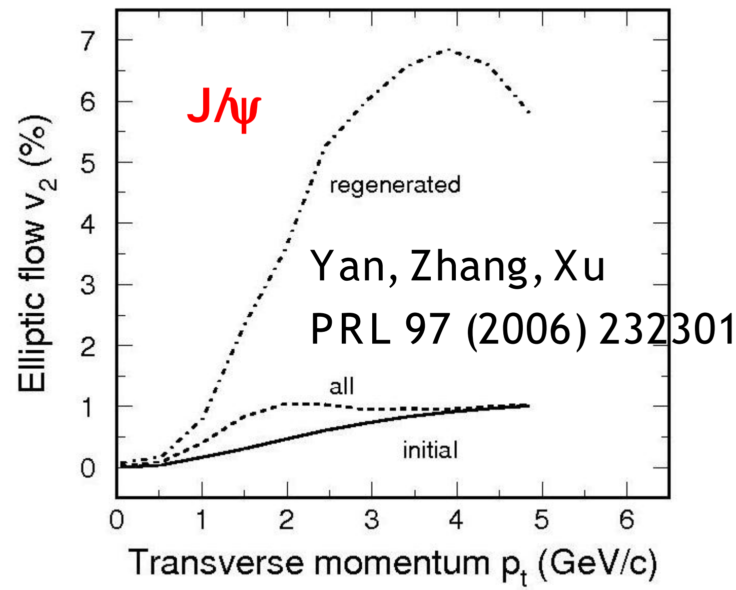
Backup

Prospects

- J/ψ flow : promising test of regeneration
  - Elliptic flow: collective phenomenon, transforms initial spatial anisotropy of collision region into momentum anisotropy
  - Electrons from c and b quark meson decays have been observed with nonzero elliptic flow

    (cf. Talk by D. Hornback)
  - If regeneration takes place, J/ψ elliptic flow should show similar trend
- New Au+Au run underway
  - ~4x higher statistics expected
  - Upgrade for better reaction plane measurement resolution



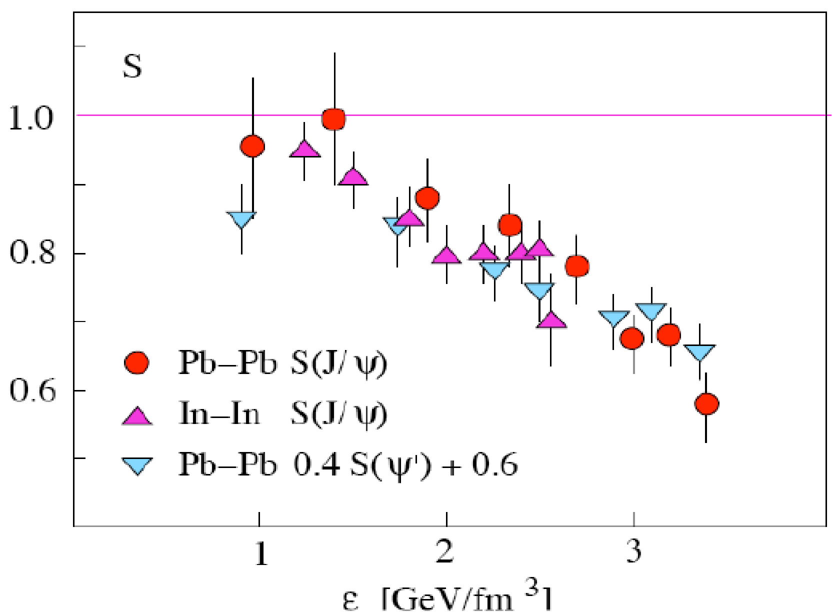


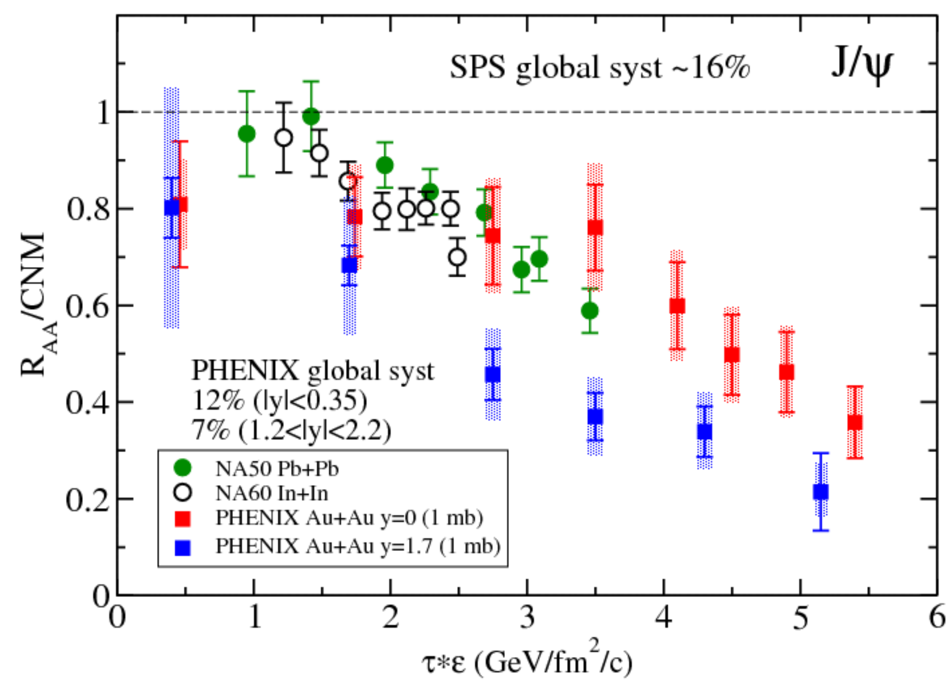
Sequential dissociation

Recent lattice QCD calculations predict high dissociation temperature for J/ψ (~$2T_C$), but rather low for ψ' and χ_C (~$1.1T_C$)

Survival probability $S_{J/\psi} = 0.6\, S_{DIRECT} + 0.3\, S\chi_C + 0.1\, S\psi'$

Karsch, Kharzeev and Satz, hep-ph/0512239





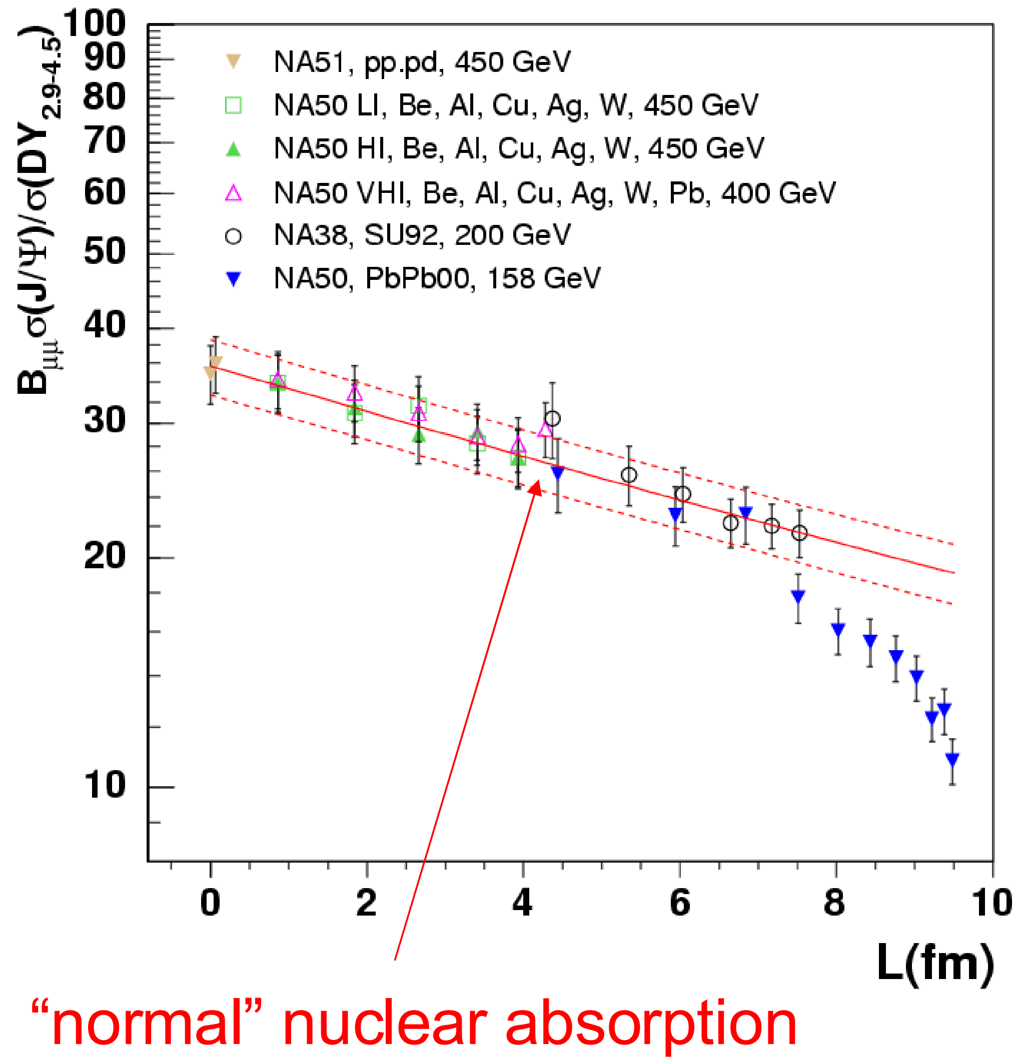
To understand J/ψ suppression at RHIC we need more charmonium measurements: ψ', χ_C, ...

J/y in dAu collisions

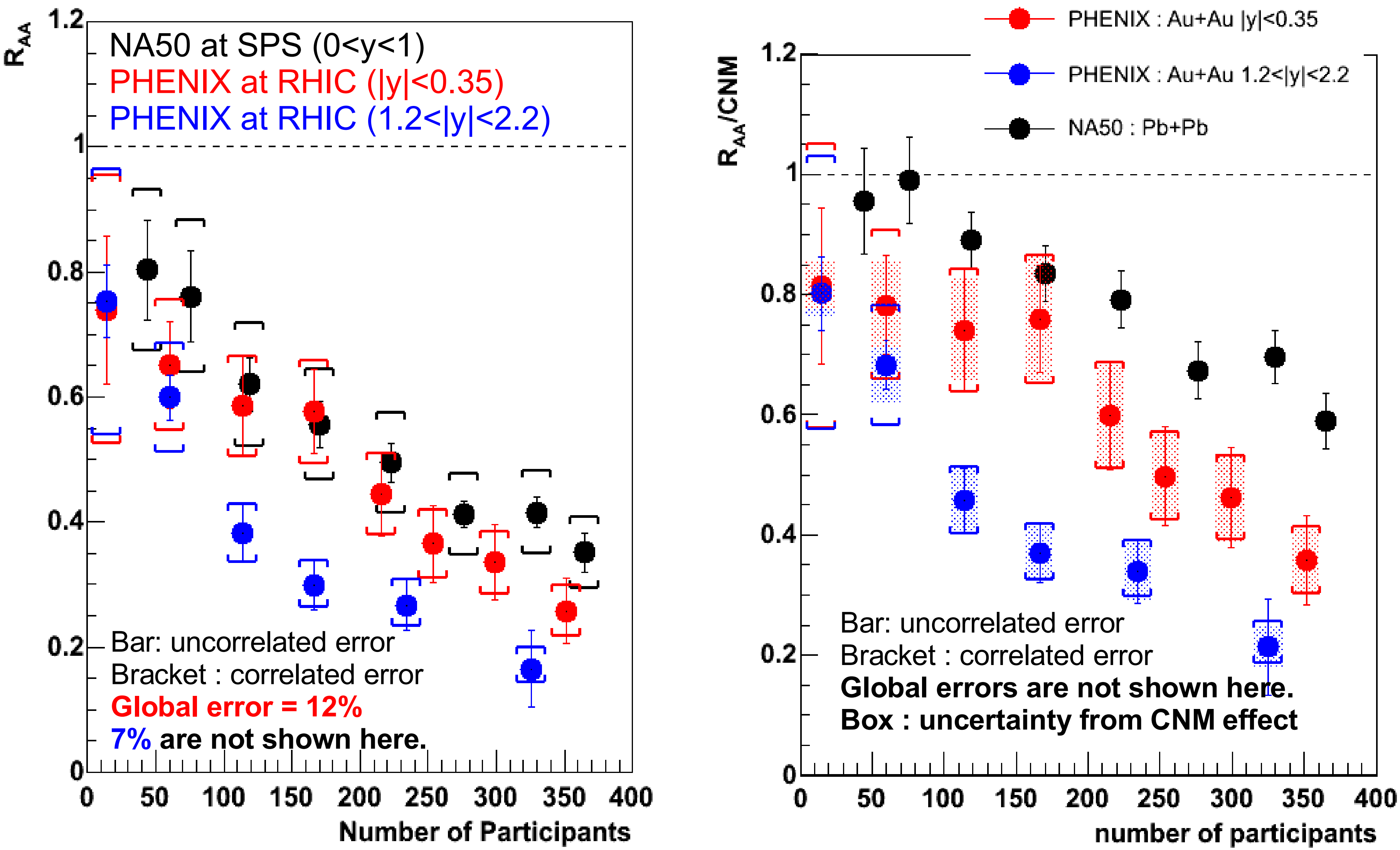
nuclear absorption

At SPS: σ = 4.18 +- 0.35 mb

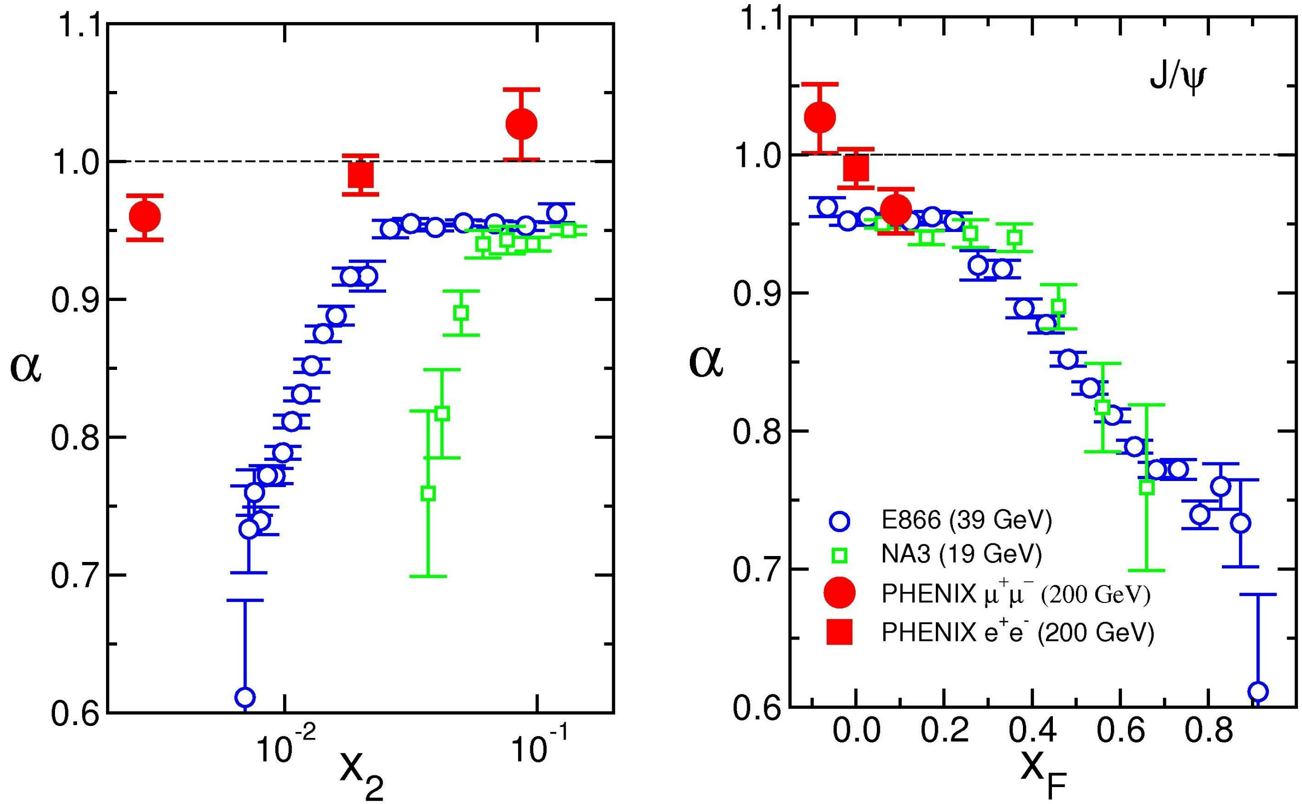
Naively one would expect larger absorption at RHIC, since energy density is higher.



R_{AA} or R_{AA}/CNM vs Number of Participants



Nuclear dependence scaling



$$\sigma_{dA} = \sigma_{pp}(2\text{x}197)^{\alpha}$$

$x_F = 2p_z/\text{sqrt}(s)$

$x_1 = 0.5(x_F+\text{sqrt}(x_F{}^2+4\tau))$

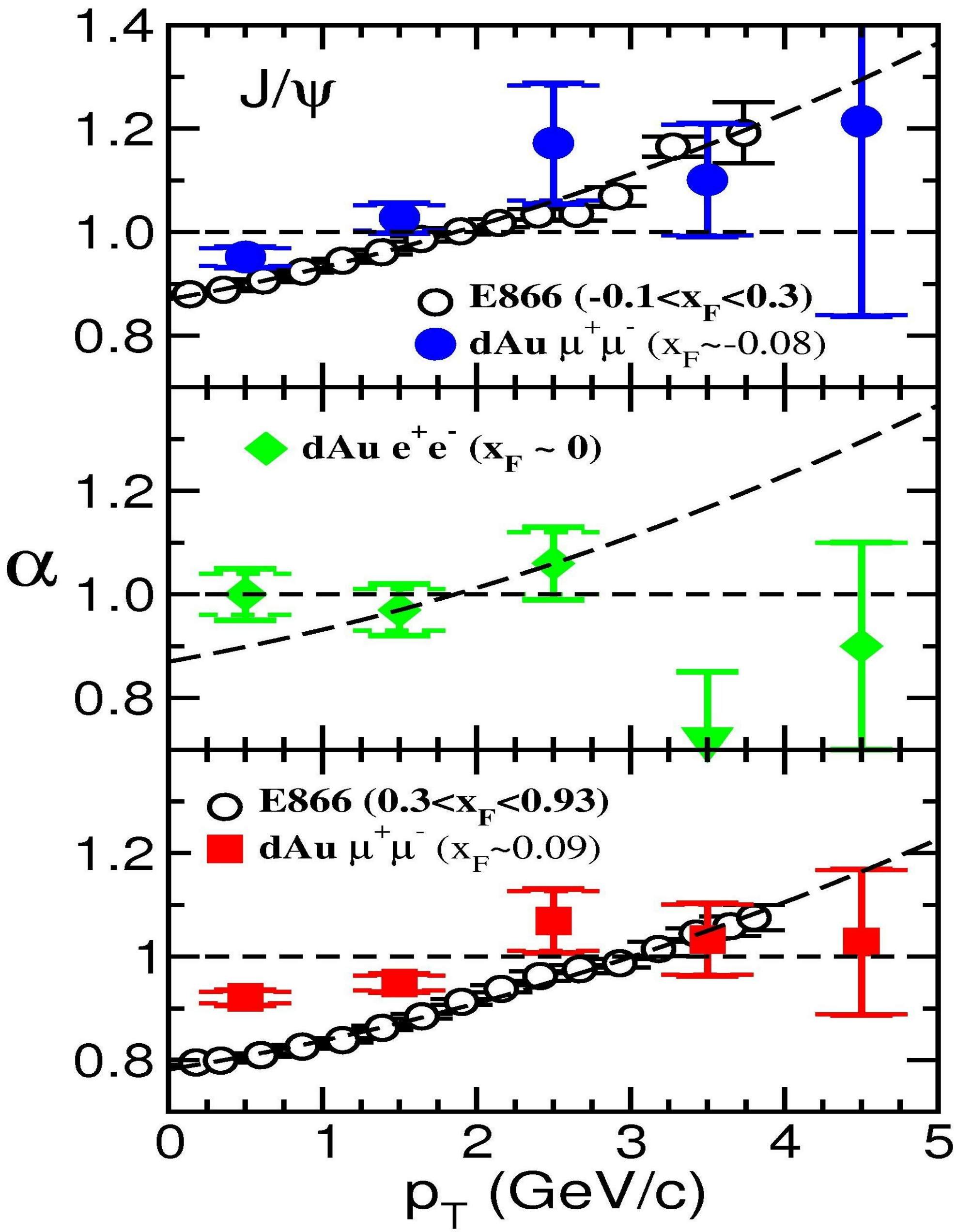
$x_2 = x_{Au} = x_1 - x_F$

Shadowing predicts scaling with x_2

Scaling with x_F instead.

- Initial state gluon energy loss?
- Sudakov form factor? ~$(1-x_F)$

P_T broadening



x ~0.1

x ~0.003

P_T broadening at RHIC comparable to that at lower $\sqrt{s}$ = 39 GeV

Brazil University of São Paulo, São Paulo

China Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecòle des Mines at Nantes, Nantes

Germany University of Münster, Münster

Hungary Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

Israel Weizmann Institute, Rehovot

Japan Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
Rikkyo University, Tokyo, Japan
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo

S. Korea Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

Russia Institute of High Energy Physics, Protovino
Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

Sweden Lund University, Lund

*12 Countries; 58 Institutions; 480 Participants**

USA Abilene Christian University, Abilene, TX
Brookhaven National Laboratory, Upton, NY
University of California - Riverside, Riverside, CA
University of Colorado, Boulder, CO
Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Florida Technical University, Melbourne, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, Urbana-Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
Los Alamos National Laboratory, Los Alamos, NM
Lawrence Livermore National Laboratory, Livermore, CA
University of New Mexico, Albuquerque, NM
New Mexico State University, Las Cruces, NM
Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
Oak Ridge National Laboratory, Oak Ridge, TN
University of Tennessee, Knoxville, TN
Vanderbilt University, Nashville, TN

*as of January 2004