The PHENIX Quarkonium Program

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for the PHENIX Collaboration

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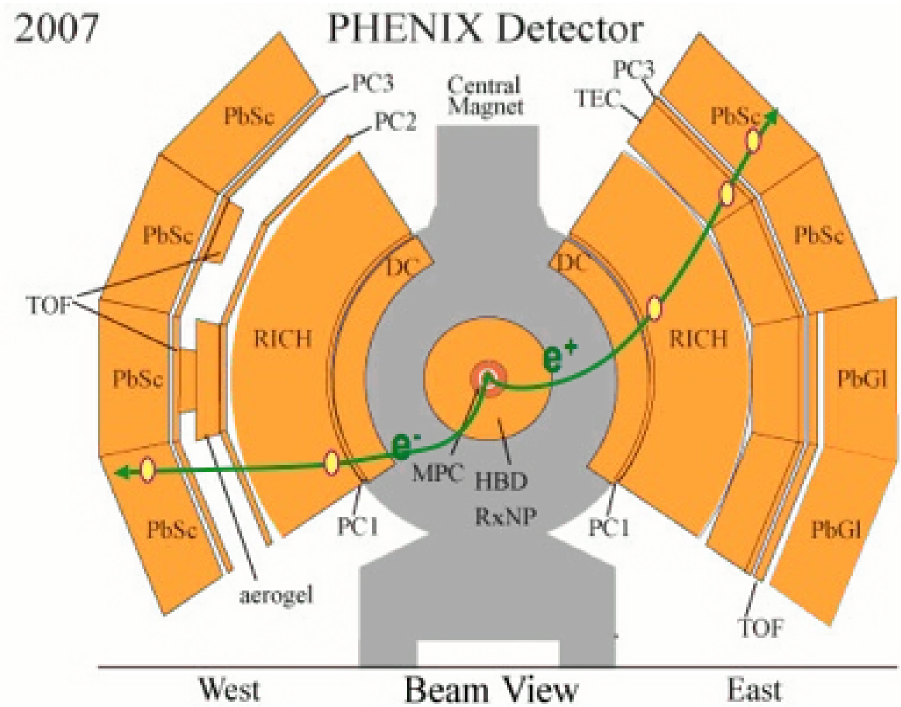
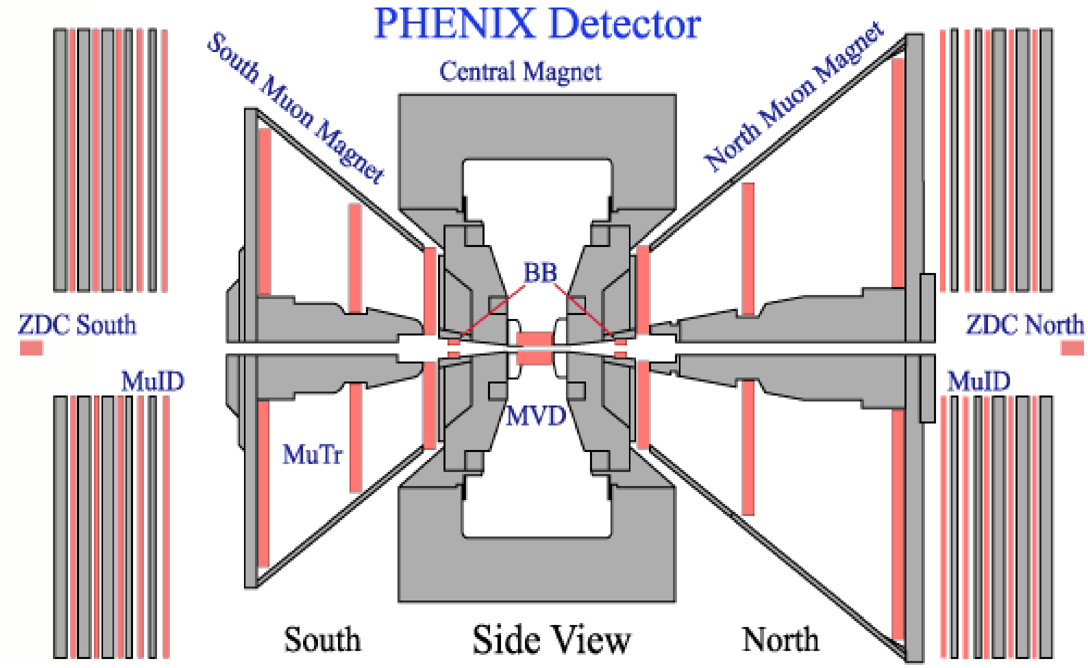
PHENIX coverage for heavy flavor measurements





$|y| < 0.35 \qquad \Delta\Phi = \pi/2 \times 2$

Electrons

$1.2 < |y| < 2.4 \qquad \Delta\Phi = 2\pi$

Muons

Open heavy flavor: B, D mesons via semileptonic decays

Heavy quarkonia: J/ψ, ψ', χ_C, Υ(1S,2S,3S) via dilepton decays

Heavy quarkonia - overview

Goal of the heavy ion program: The Debye screening length in hot matter

Requires:

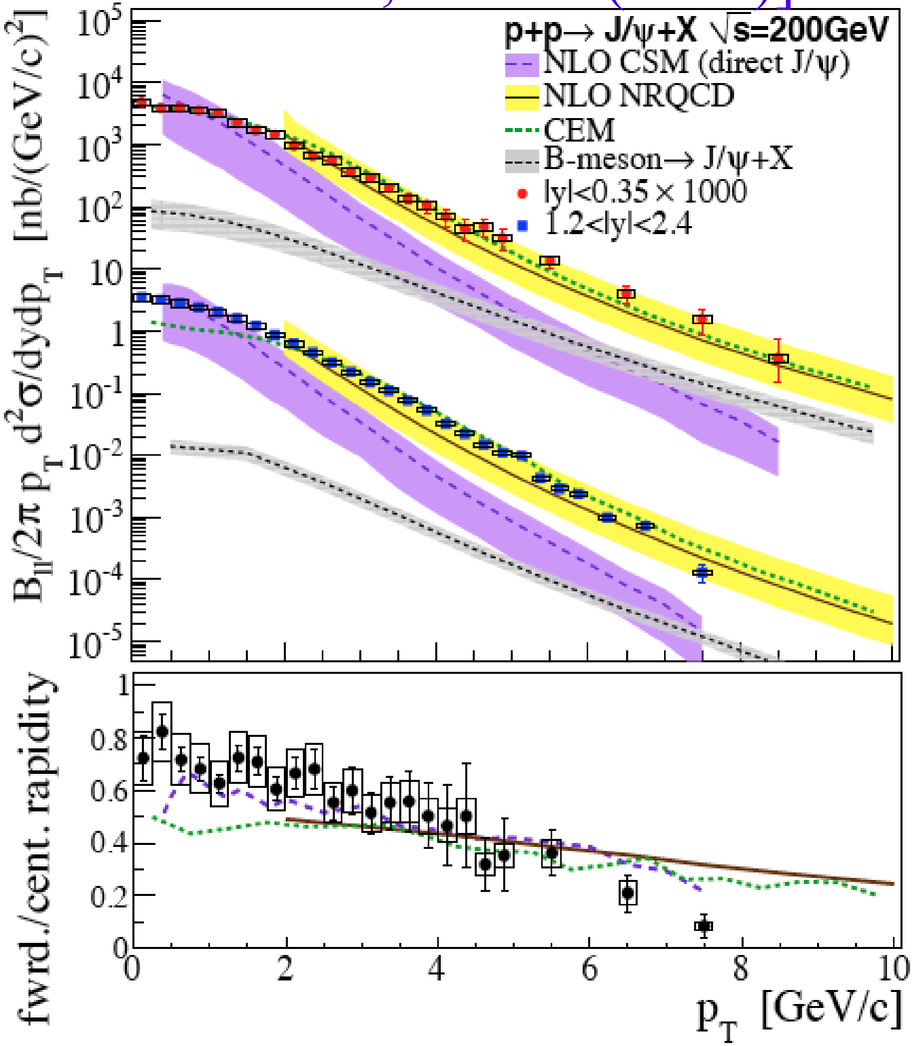
The production baseline from p+p
The cold nuclear matter baseline from d+Au
The hot matter effects from Au+Au

Data available so far:

- J/ψ measurements for p+p, d+Au, Cu+Cu, Au+Au collisions
- J/ψ polarization measurements for p+p
- ψ' and χ_C measurements for p+p (d+Au coming)
- Υ(1S+2S+3S) measurements for p+p, d+Au (Au+Au coming)

J/ψ in p+p - production baseline

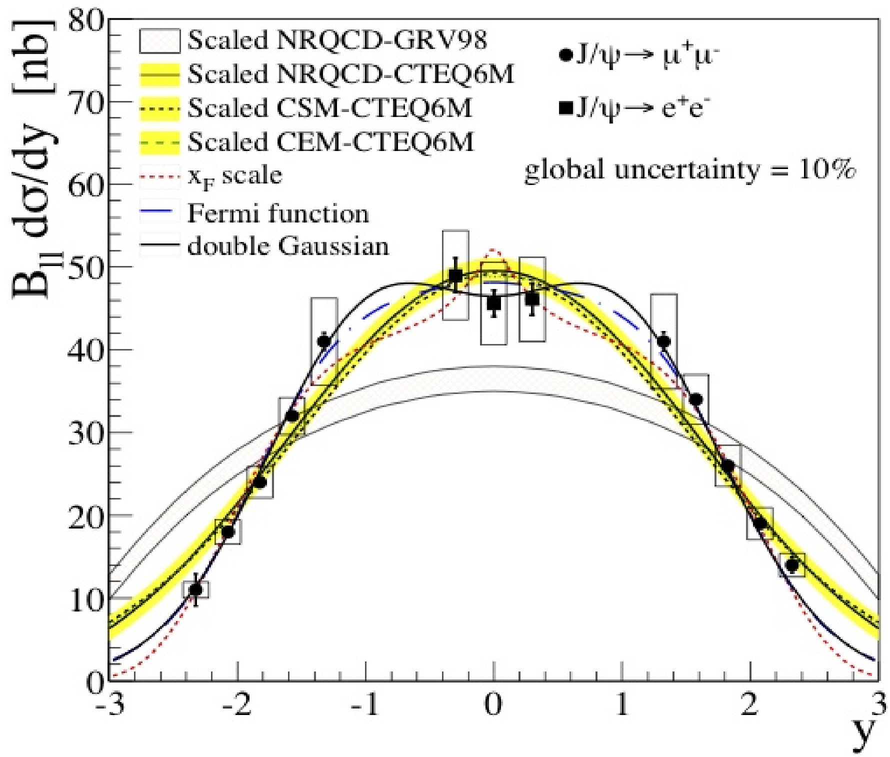
Run 6 p+p data
PRD82,012001 (2010)]



Good quality p+p reference data at:

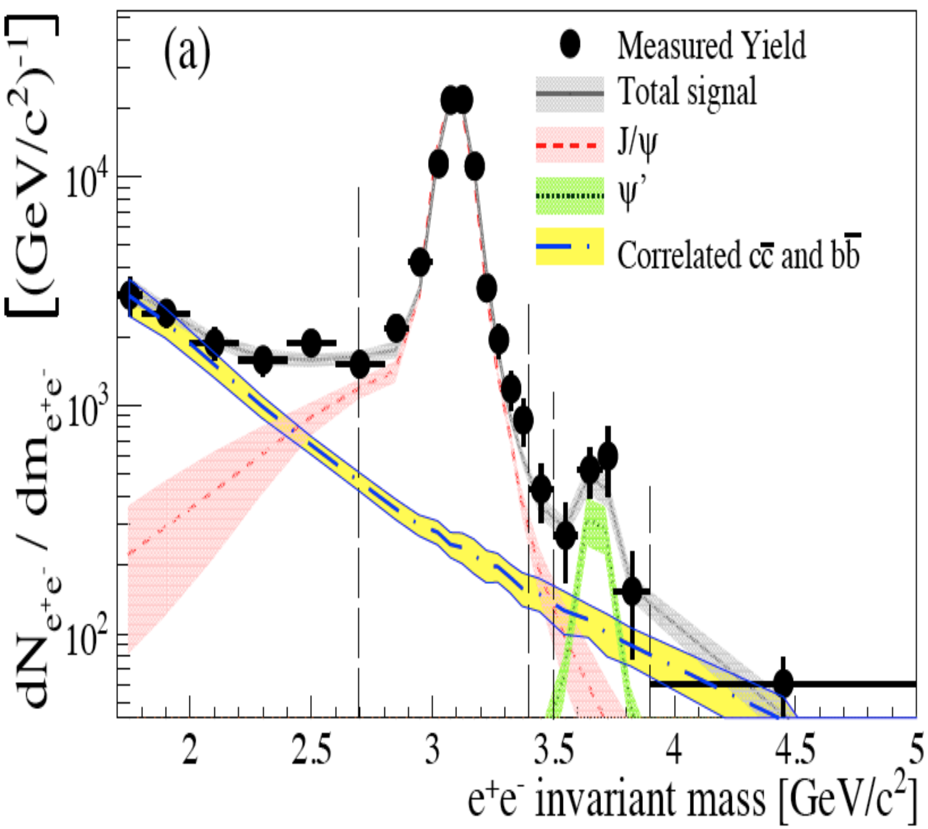
- $|y| < 0.5$
- $1.2 < |y| < 2.4$

Measured **polarization** is small
- reduces acceptance uncertainty

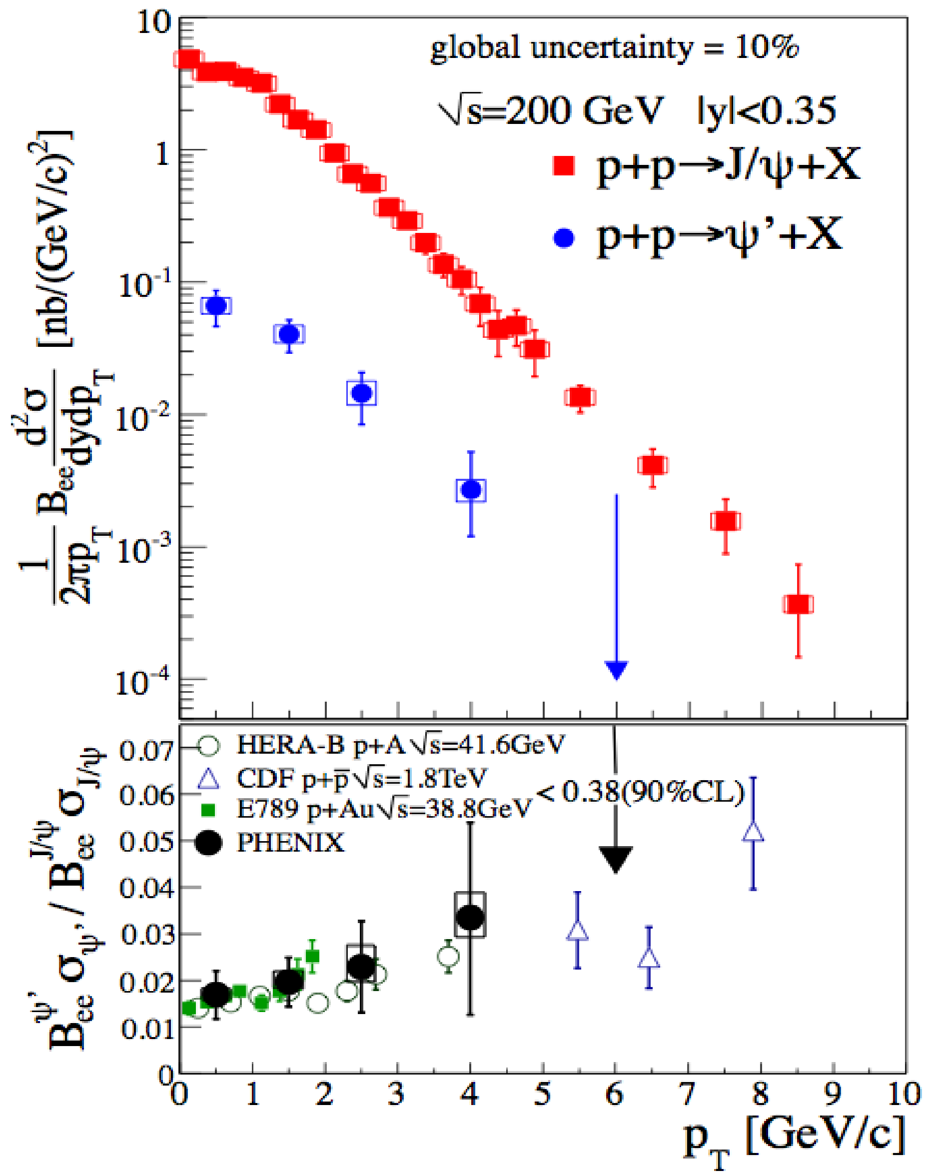


J/ψ in p+p – feed-down from ψ'

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

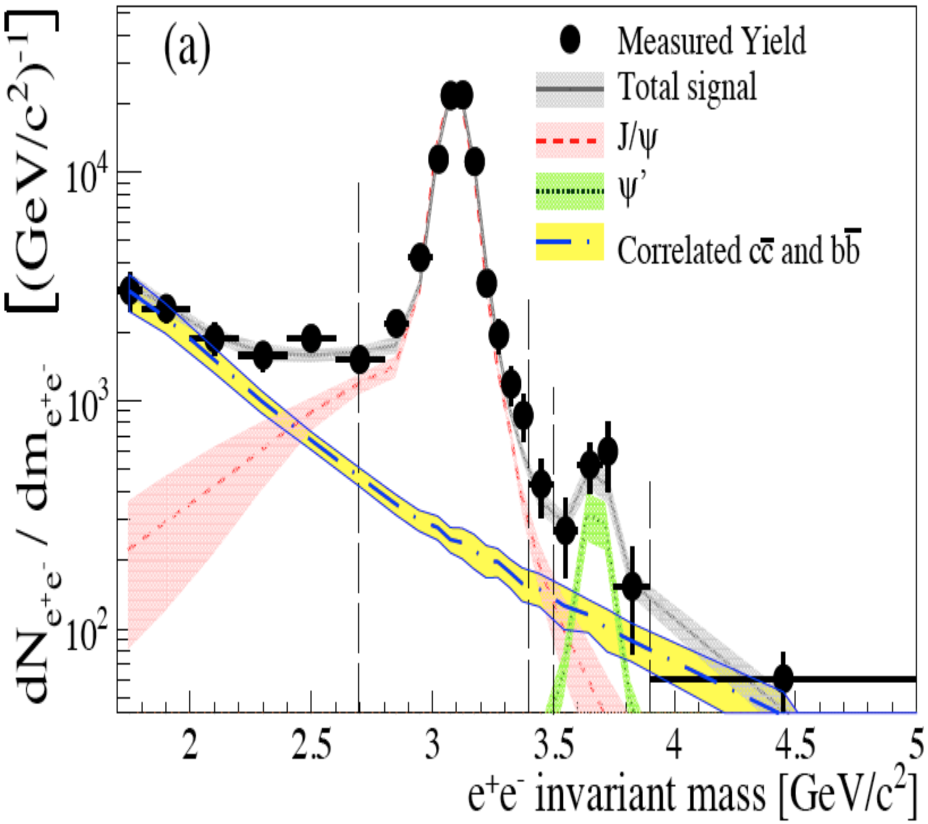


$$F_{\psi'}^{J/\psi} = \frac{B_{J/\psi}^{\psi'} \sigma_{\psi'}}{\sigma_{J/\psi}} = (9.6 \pm 2.4)$$



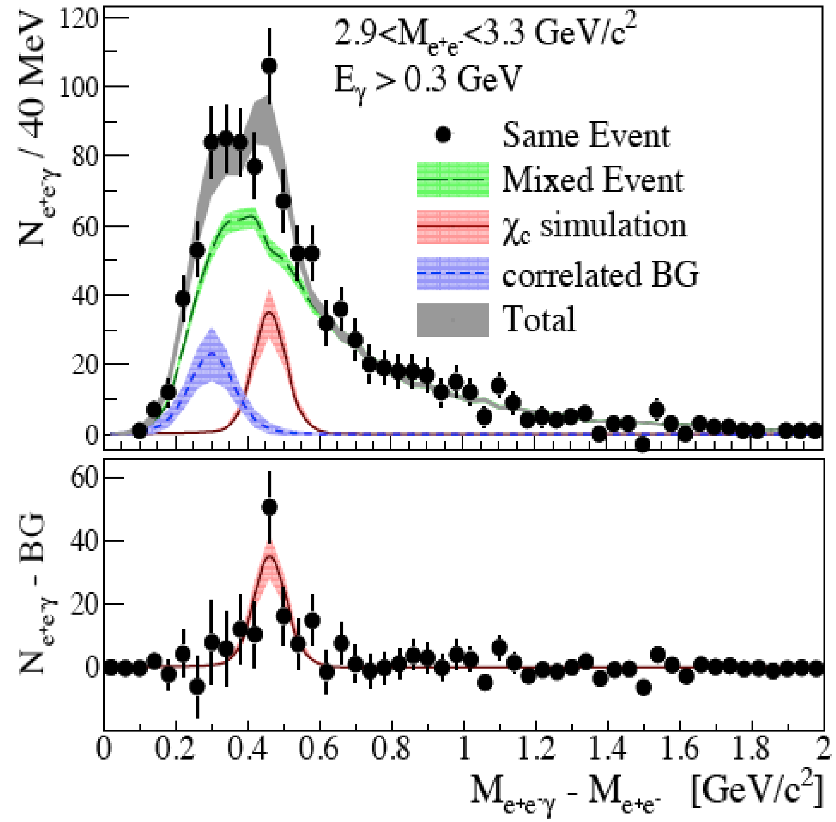
J/ψ in p+p – feed-down from ψ' and χ_C

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



$$F_{\psi'}^{J/\psi} = \frac{B_{J/\psi}^{\psi'} \sigma_{\psi'}}{\sigma_{J/\psi}} = (9.6 \pm 2.4)$$

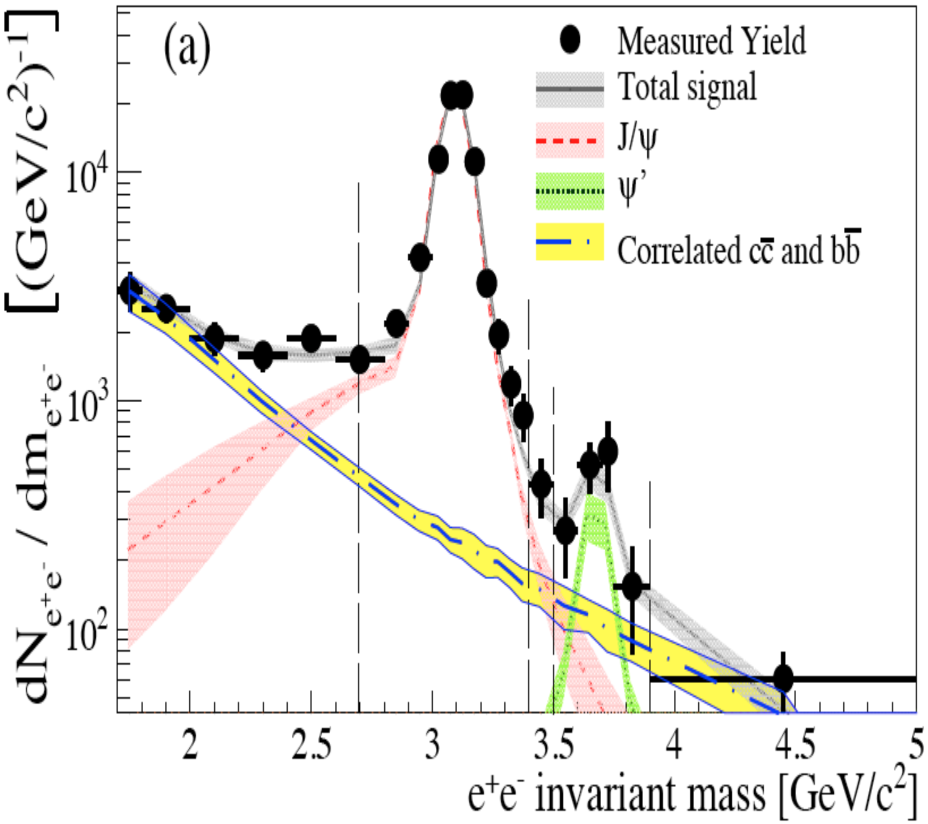
$\chi_C \rightarrow J/\psi + \gamma \rightarrow e^+e^-$



$$F_{\chi_C}^{J/\psi} = \frac{N_{\chi_C}}{N_{J/\psi}} \frac{1}{\varepsilon_{\chi_C}/\varepsilon_{J/\psi}} = (32 \pm 9)$$

J/ψ in p+p – feed-down from ψ' and χ_C

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



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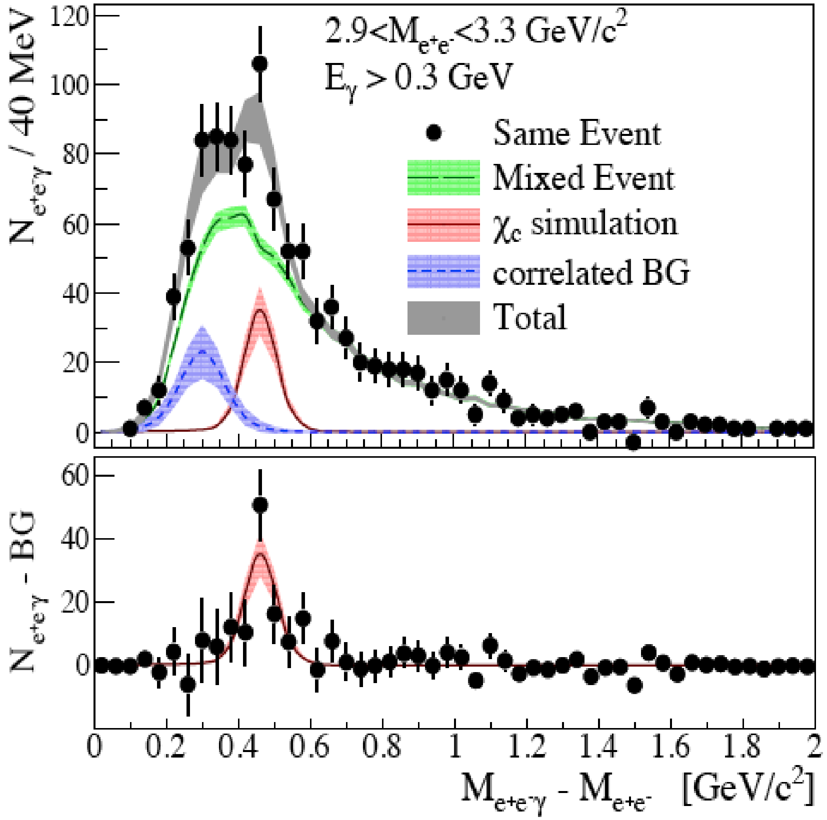


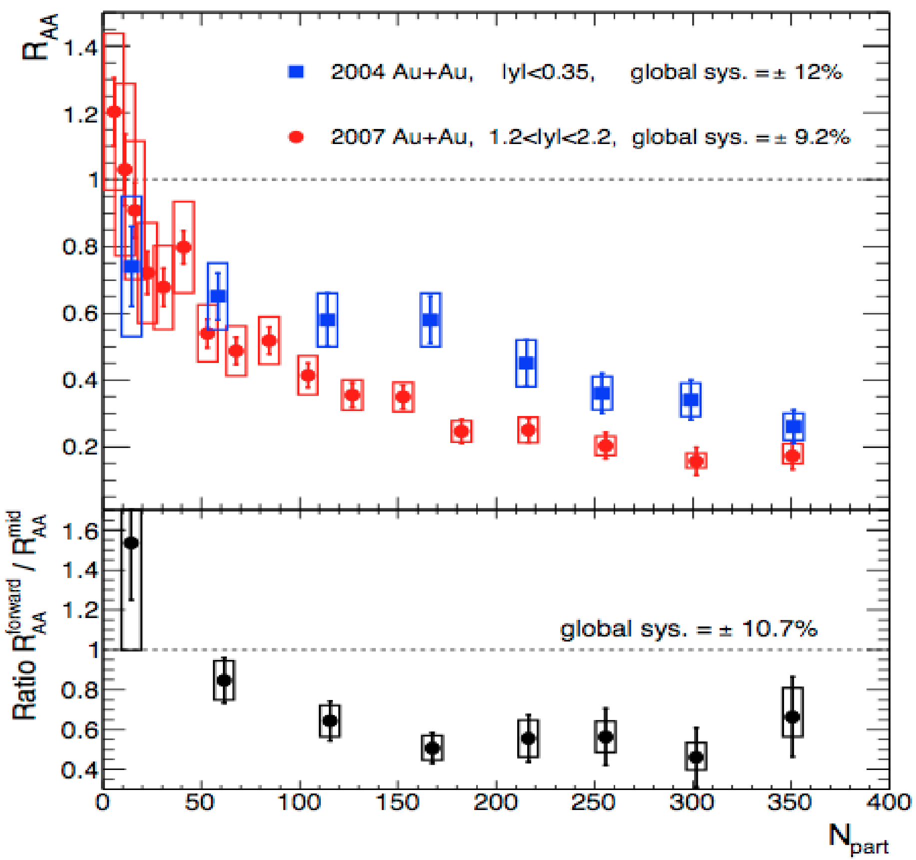
$$F_{\chi_C}^{J/\psi} = \frac{N_{\chi_C}}{N_{J/\psi}} \frac{1}{\varepsilon_{\chi_C} / \varepsilon_{J/\psi}} = (32 \pm 9)$$

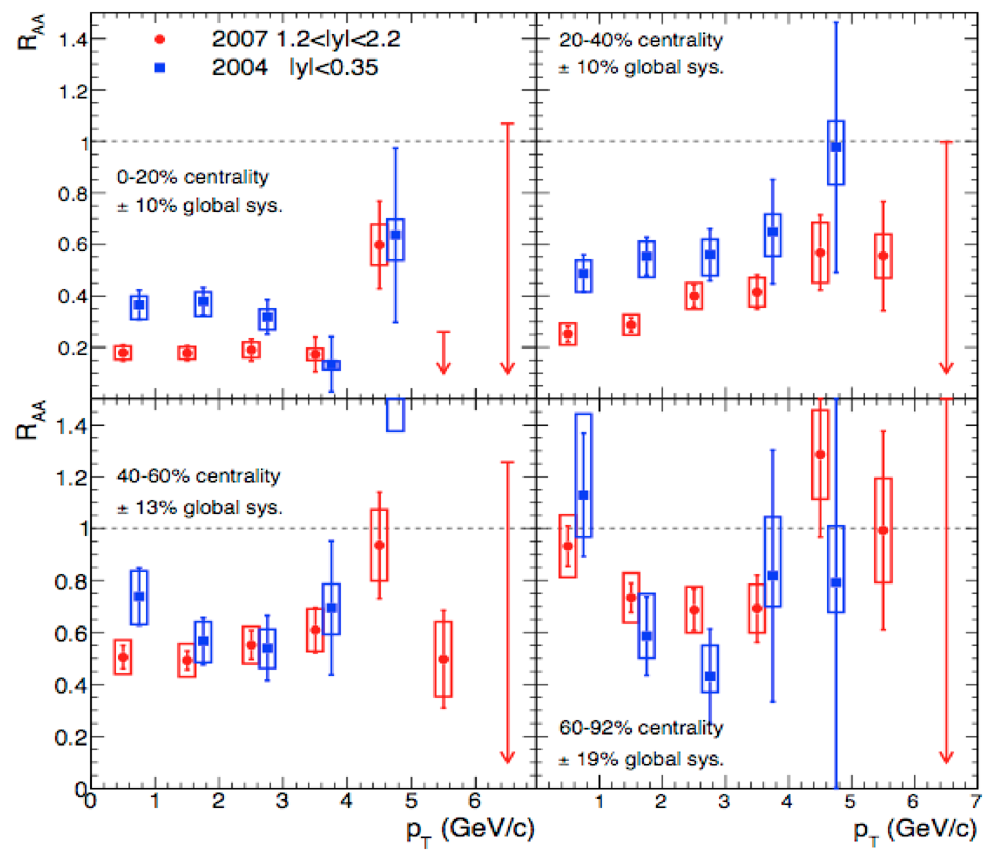
In agreement with world averages

J/ψ in heavy ions – hot matter effects + cold matter effects

Recent: improved data set from Run 7 at **1.2 < |y| < 2.2** [arXiv:1103.6269]
Still see clear increase in suppression at forward rapidity over mid rapidity

Good quality data! but how are they affected by CNM physics?





The cold nuclear matter baseline

The modification of the J/ψ yield by hot nuclear matter effects is **additional** to the modification of the initial J/ψ population due to its production in a nuclear target.

Begin by considering two CNM effects, **gluon shadowing** and **breakup** of the precursor J/ψ by collisions with nucleons during the nuclear crossing.

Note:

- Gluon shadowing affects the underlying charm yield.
- Breakup reduces the **fraction** of charm forming bound charmonium.

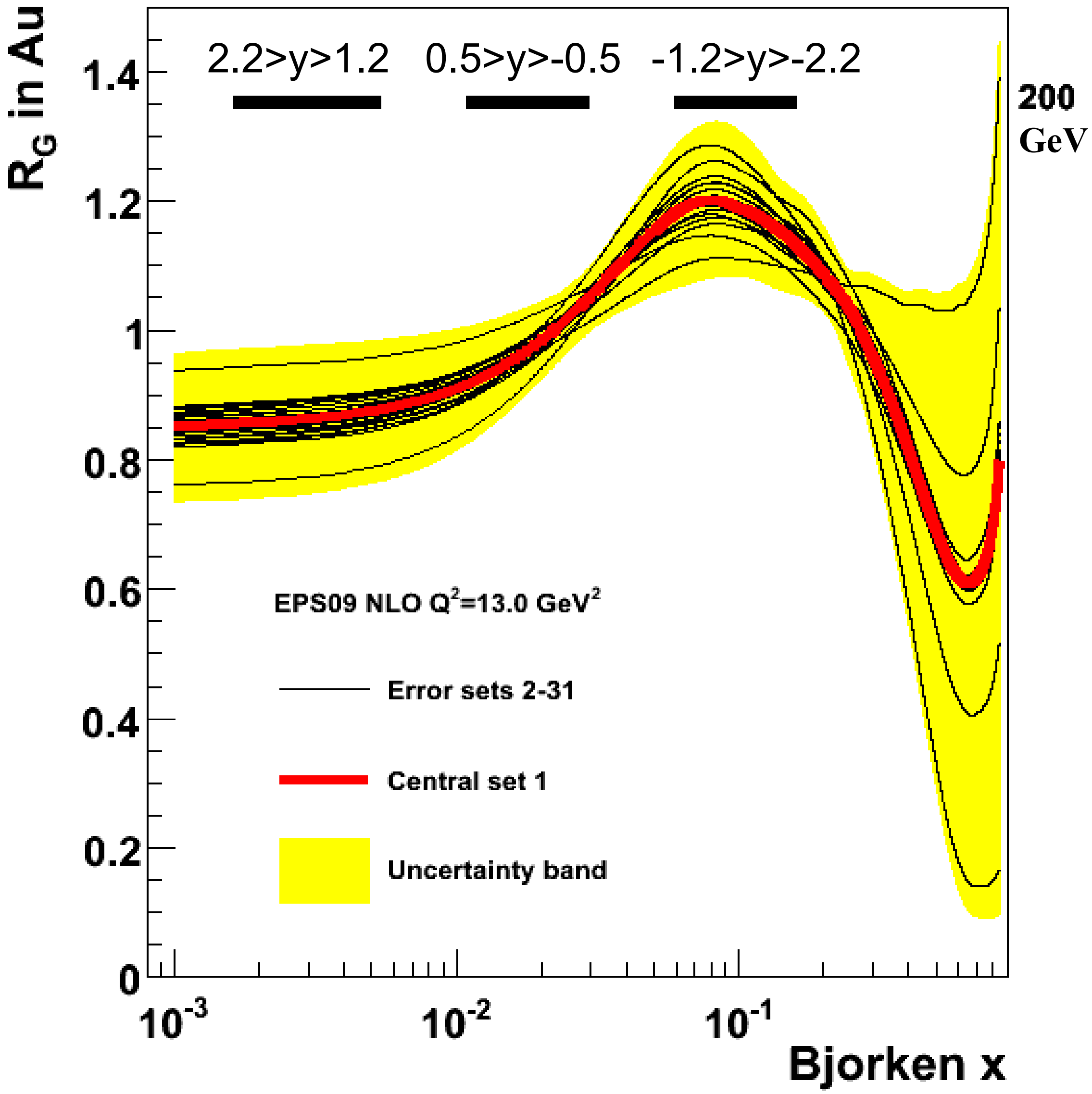
There are other possible mechanisms that modify quarkonium production. Initial state energy loss and Cronin effect are examples.

Shadowing: R_G for J/ψ production at RHIC

EPS09 **gluon** modification vs Bjorken x at ~ $(M_{J/\psi}{}^2 + \langle p_T \rangle^2)$.

It will be important later to know that the input DIS and p+A data have no **impact - parameter** information - **the modification is averaged over the nucleus**.

The approximate Bjorken **x ranges** sampled by PHENIX at 200 GeV are shown.

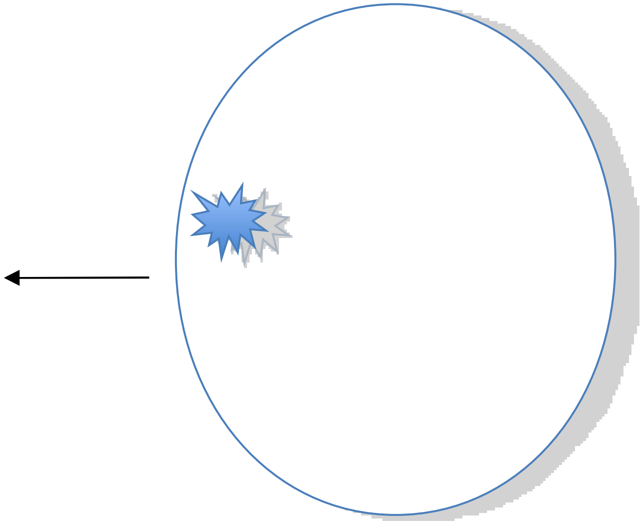


Breakup

After a bound charm pair is produced in the Au nucleus, it can be broken up by a collision with a nucleon that passes through the production point later.

Account for this loss using a cross section, σ_{br}. In general, σ_{br} depends on $\sqrt{s_{NN}}$ and rapidity – not much theoretical guidance!

It also (presumably) depends on **which state** (J/ψ, ψ', χ_c), so when we use one value of σ_{br} we are mocking up the breakup of all states that result in a J/ψ.

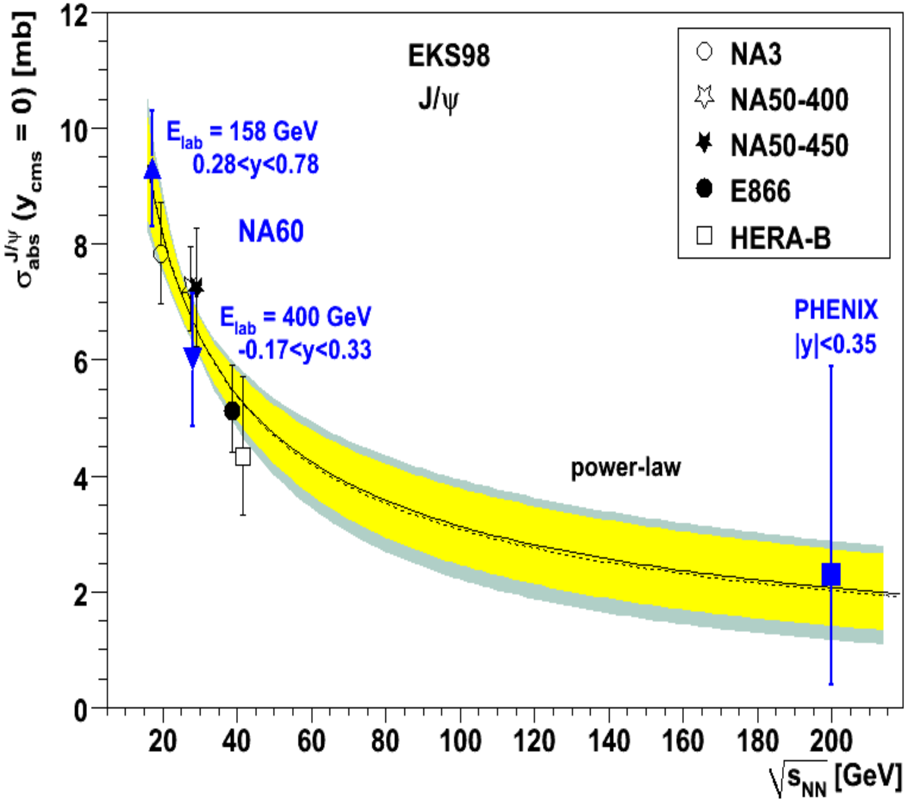


J/ψ breakup cross section

Lourenco, Woehri and Vogt made a systematic analysis at $y \sim 0$ using EKS98 + σ_{br} and saw a clear **collision energy dependence** of σ_{br}.

The PHENIX data point shown here is from the 2003 d+Au run.

JHEP 0902:014 (2009)



σ_{br} may depend on rapidity also.

J/ψ breakup cross section

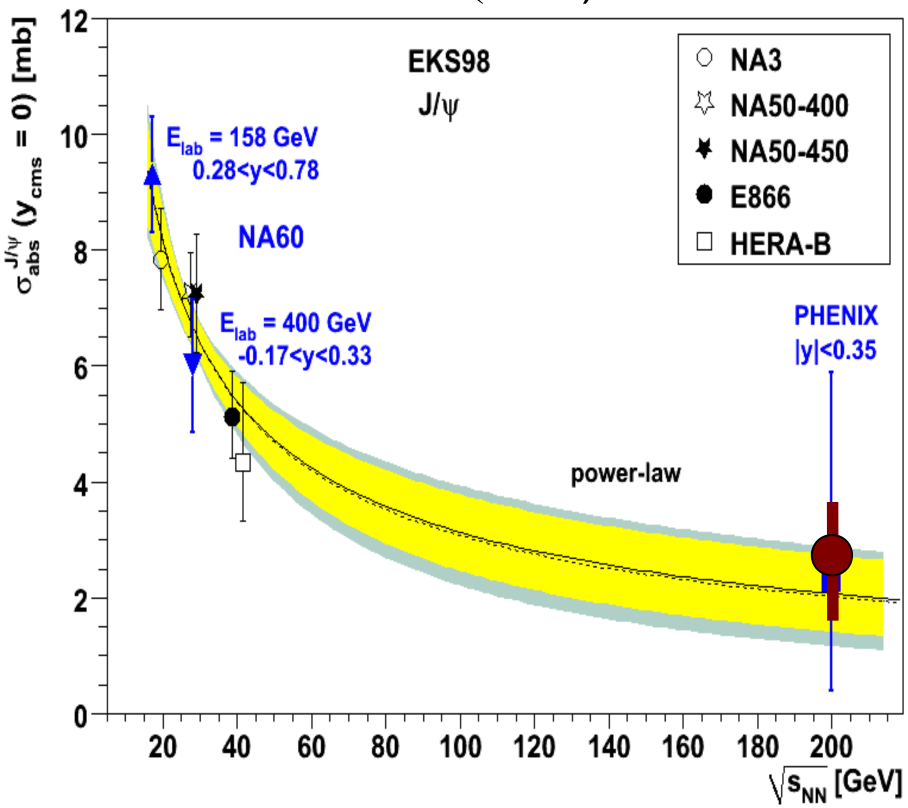
Lourenco, Woehri and Vogt made a systematic analysis at y~0 using EKS98 + σ_{br} and saw a clear **collision energy dependence** of σ_{br}.

The PHENIX data point shown here is from the 2003 d+Au run.

Add a PHENIX point from the 2008 run (2.7 +1.1 -1.2 mb) (from fit by ADF using EKS98 calculations from Ramona Vogt).

σ_{br} may depend on **rapidity** also.

JHEP 0902:014 (2009)



J/ψ in d+Au

Run 8 d+Au final data released in 2010

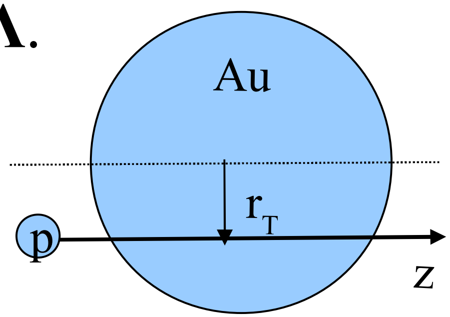
PHENIX: Phys. Rev. Lett. 107, 142301 (2011)

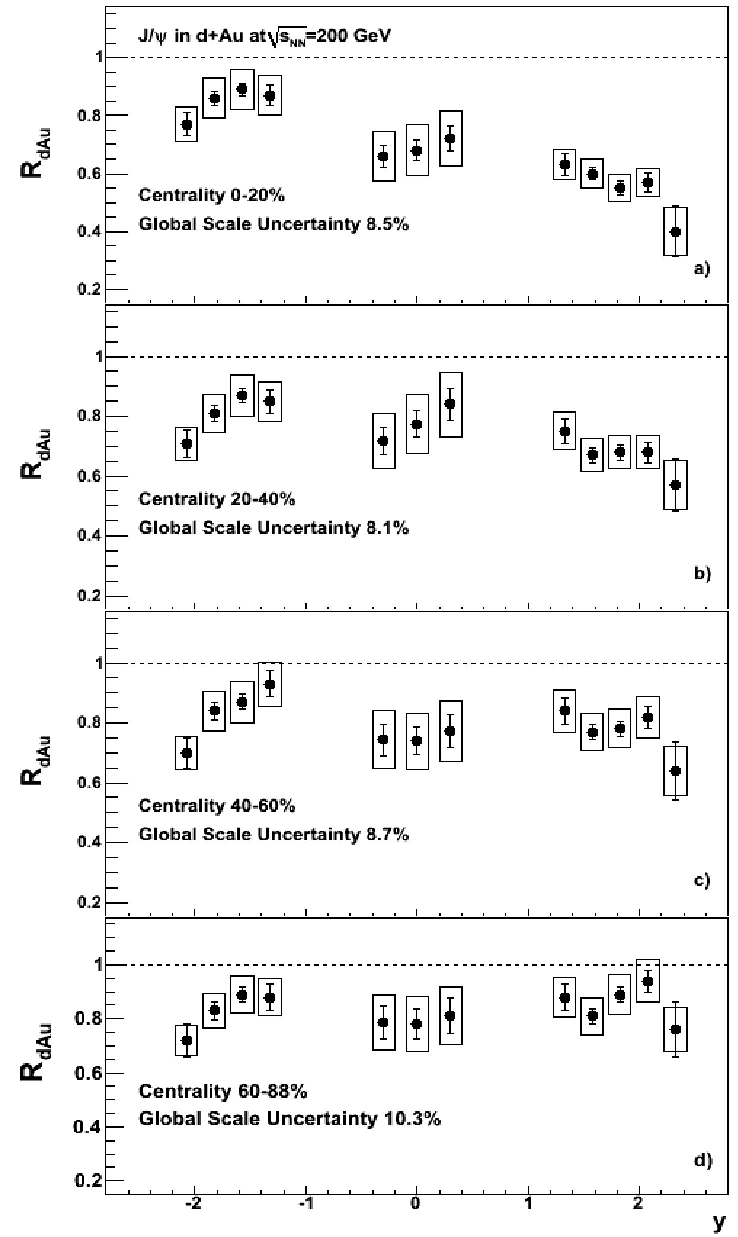
Shows strong rapidity dependence of suppression for central collisions.

Good quality reference data! **How to quantify the CNM effects?** Try a shadowing + σ_{br} description.

Assume some shadowing centrality dependence. Start with **linear** dependence on **density integrated longitudinal thickness Λ.**

$$\Lambda(r_T) = \int dz\, \rho(z, r_T)$$

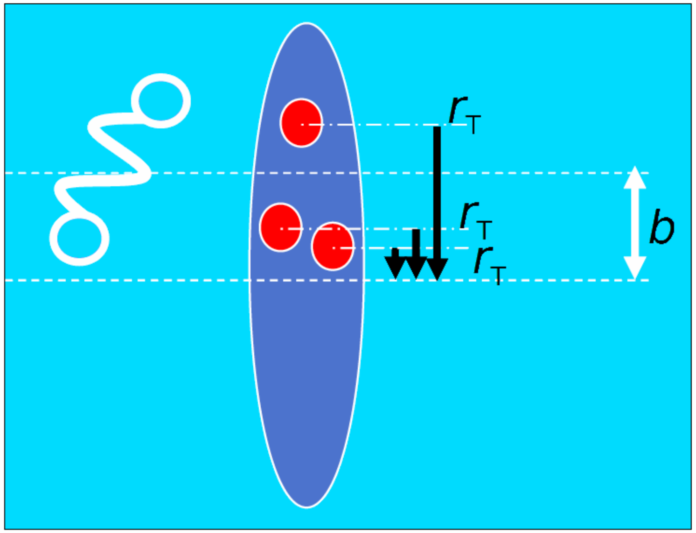


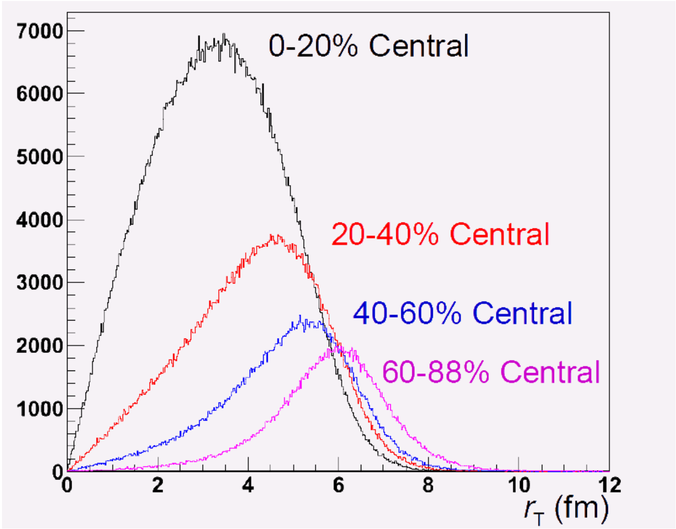


Describe the d+Au data using a Glauber model

Implement (linear for now) **shadowing** + $\boldsymbol{\sigma_{br}}$ nuclear modification in a Glauber model of the d+Au collision:

- Throw a d+Au collision
- Assign it to a **centrality** bin
- For each NN collision:
  - Use $\mathbf{r_T}$ to calculate the "thickness" Λ
  - Calculate x_2 and Q^2 for each rap. *y*
  - Use Λ to get shadowing
  - Use $\Lambda(z_1)$ to calculate breakup
- Calculate the average R_{dAu} at each y





Centrality dependence

Top: peripheral R_{dAu}.

Middle: central R_{dAu}.

Bottom: most central R_{CP}:

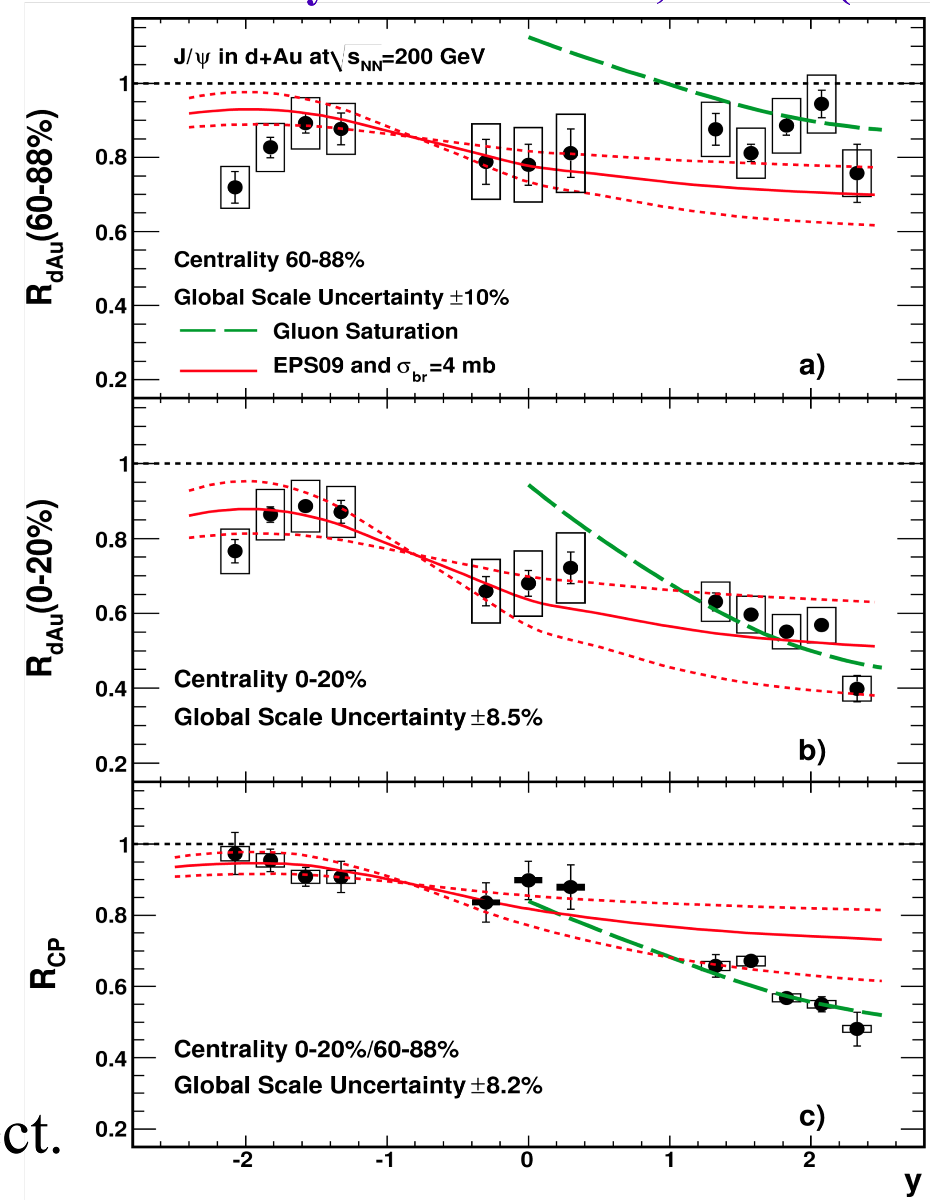
$$R_{CP}(0-20) = \frac{R_{dAu}(0-20)}{R_{dAu}(60-88)}$$

The ratio of R_{dAu} eliminates the p+p cross section, **and** some d+Au systematic uncertainties.

Suppression at forward y is **inconsistent** with **linear** EPS09 plus constant $\sigma_{breakup}$ calculation.

At very forward y, a **CGC** calculation gets the "turn-on" with centrality correct.

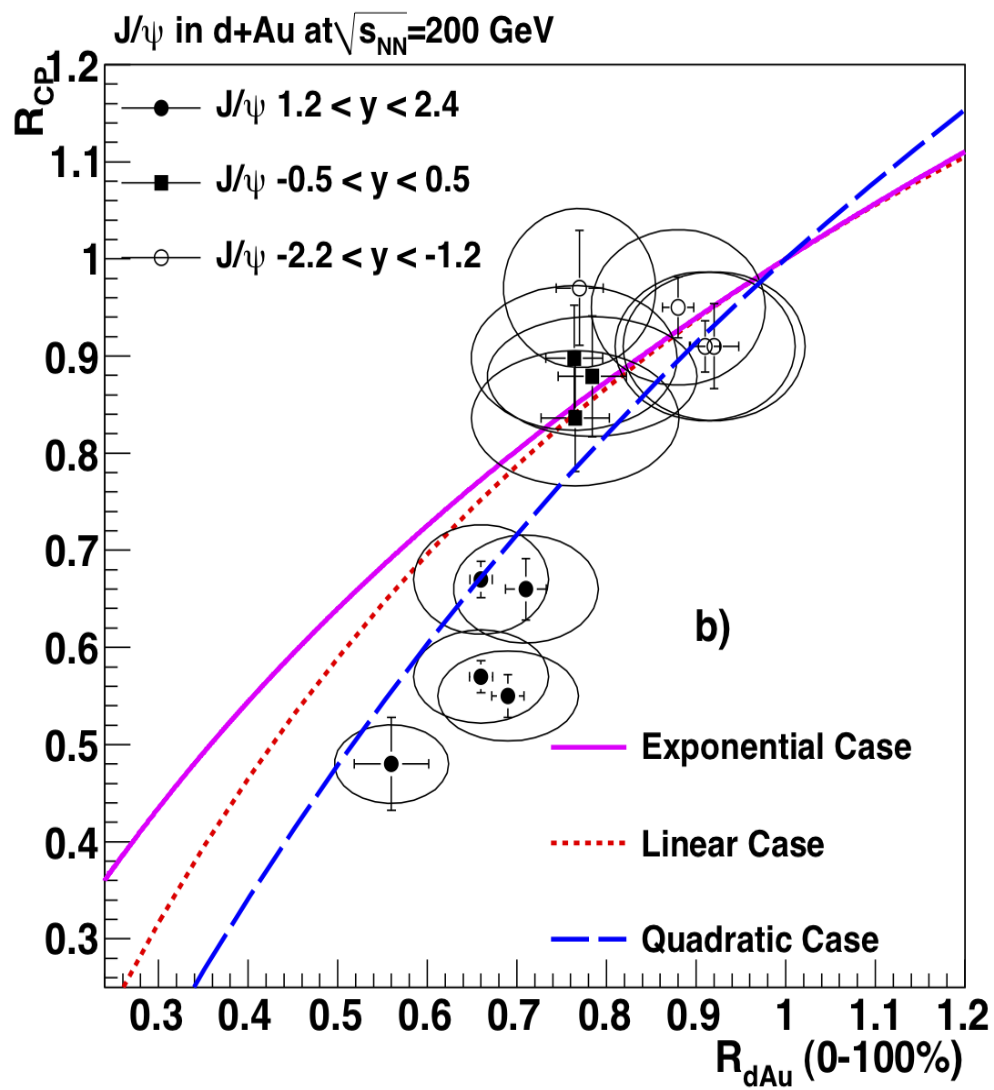
PHENIX: Phys. Rev. Lett. 107, 142301 (2011)



Explore this further

- Plot MB R_{dAu} on X axis
  - (**overall** modification)
- Plot R_{CP} on Y axis
  - (**ratio** central/peripheral)
- Add data at 12 rapidities

PHENIX: Phys. Rev. Lett. 107, 142301 (2011)



In a d+Au Glauber model, try the **purely mathematical** dependencies:

$$M(r_T) = e^{-a\Lambda(r_T)}$$

$$M(r_T) = 1 - a\Lambda(r_T)$$

$$M(r_T) = 1 - a\Lambda(r_T)^2$$

Vary the strength a, we see a **locus** for each dependence.

$y > 1.2$ data **not** consistent with linear thickness dependence

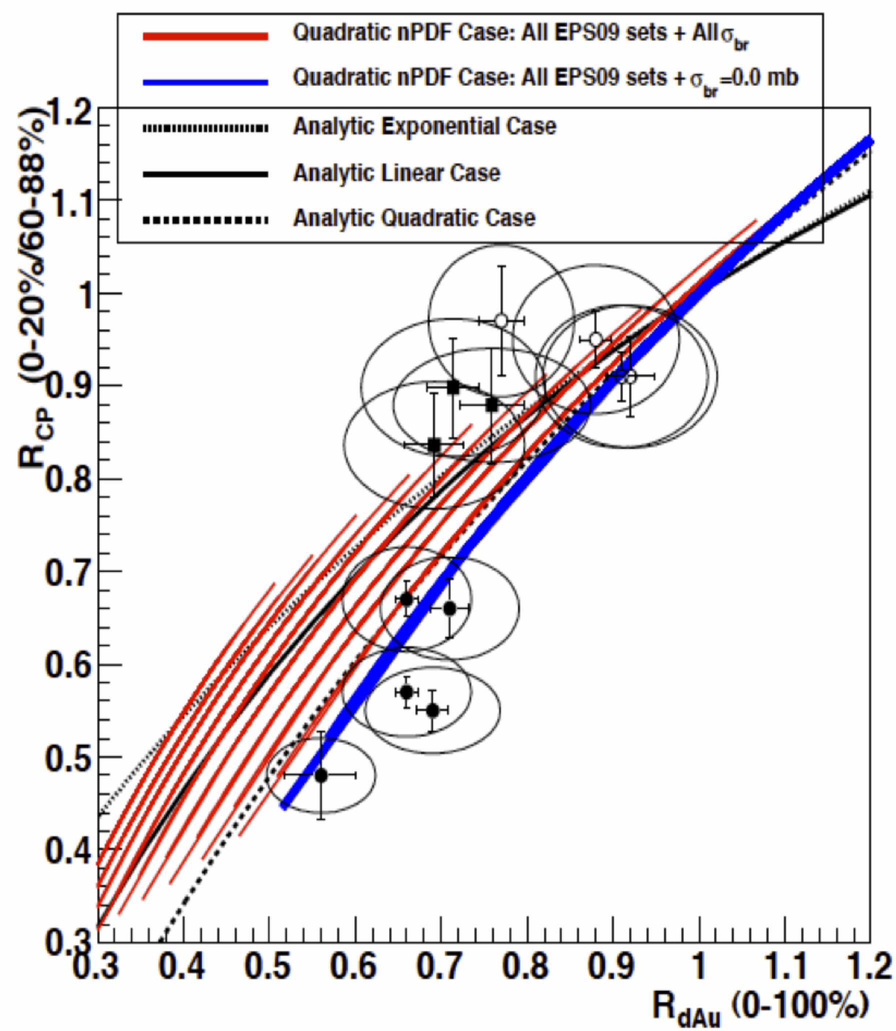
Adding more realism does not help

More realistically, the modification will combine a breakup cross section (exponential) with shadowing.

This shows a Glauber calculation using a combination of EPS09 with **quadratic** $\Lambda(r_T)$ dependence, and a range of breakup cross sections.

A significant breakup cross section worsens agreement with the data at $y > 1.2$.

Nagle et al., arXiv:1011.4534



J/ψ - cold nuclear matter effects

How can we proceed to quantify the CNM effects from the d+Au data with no definitive guidance on what centrality dependence of shadowing to use?

Arbitrarily try describing the R_{dAu} data at each rapidity with a nonlinear shadowing dependence on density integrated longitudinal thickness.

This could be expected to work if the shadowing thickness **dependence** was very different from the exponential breakup cross section thickness dependence.

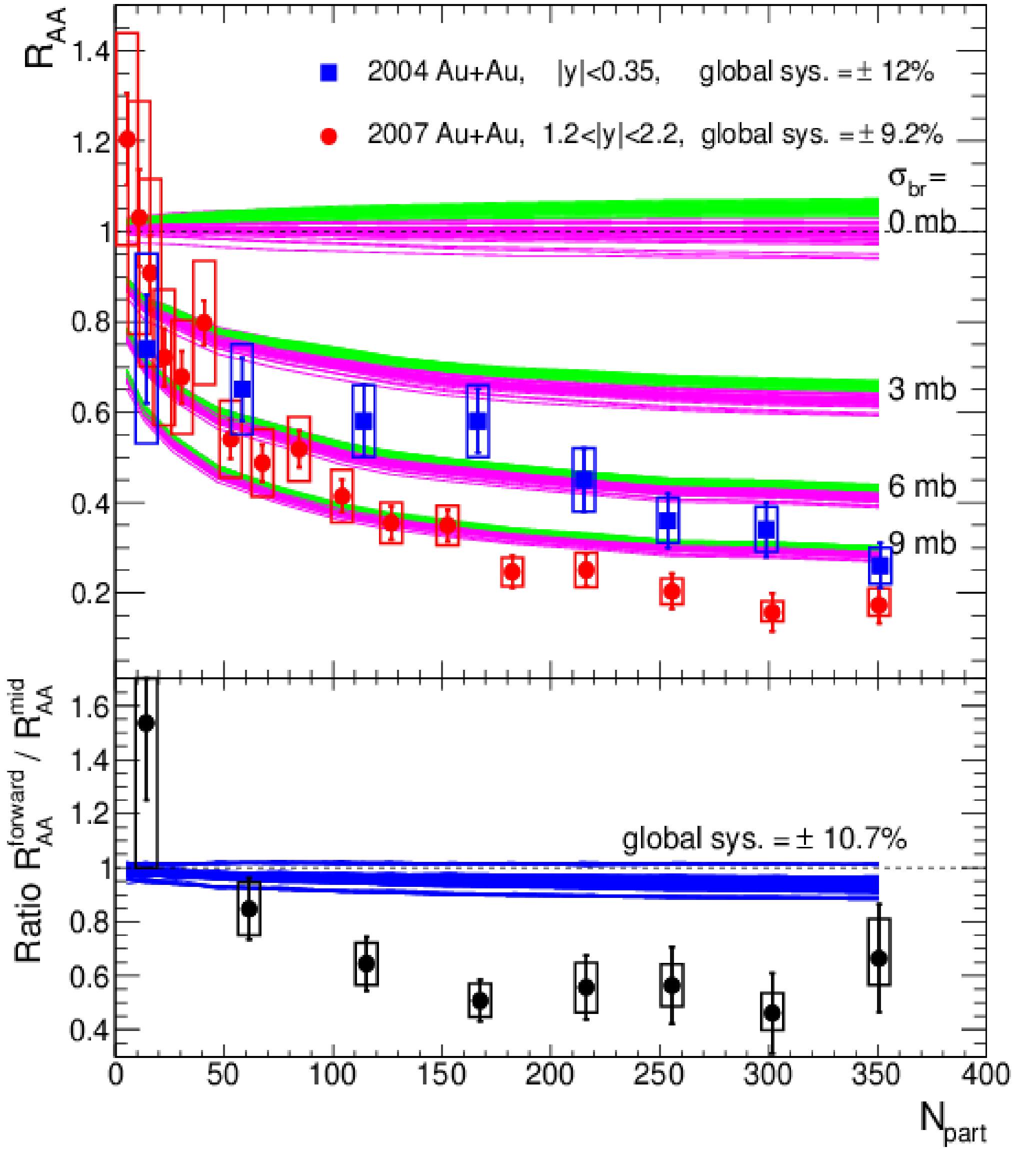
See the talk today by **D. C. McGlinchey** for the results of such an attempt to describe the d+Au data.

Can CNM effects describe the Au+Au modification?

The effects of shadowing, breakup and initial state energy loss have been explored in detail in a recent PHENIX paper [**arXiv:1103.6269**].

Concludes that the Au+Au suppression can not plausibly be attributed to CNM effects. It is larger than predicted by any CNM model that is consistent with **midrapidity d+Au data**.

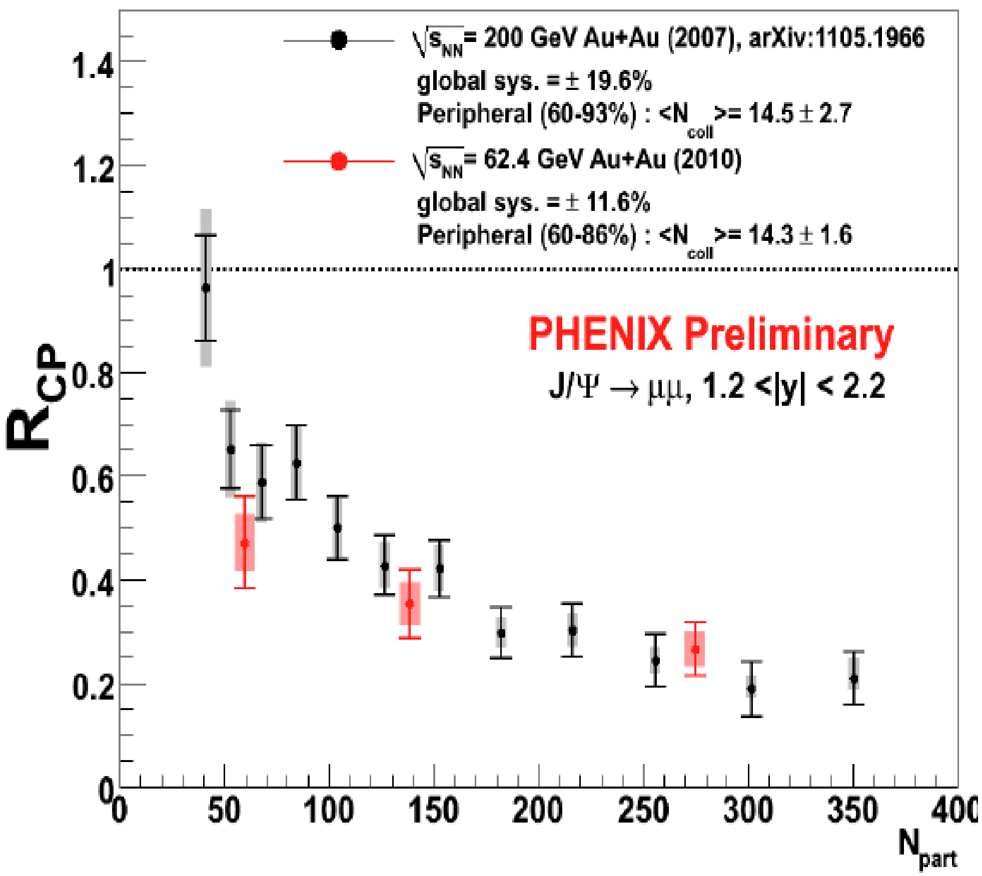
But CNM effects are necessarily **very** important in Au+Au because they are important in d+Au (see Darren's talk).

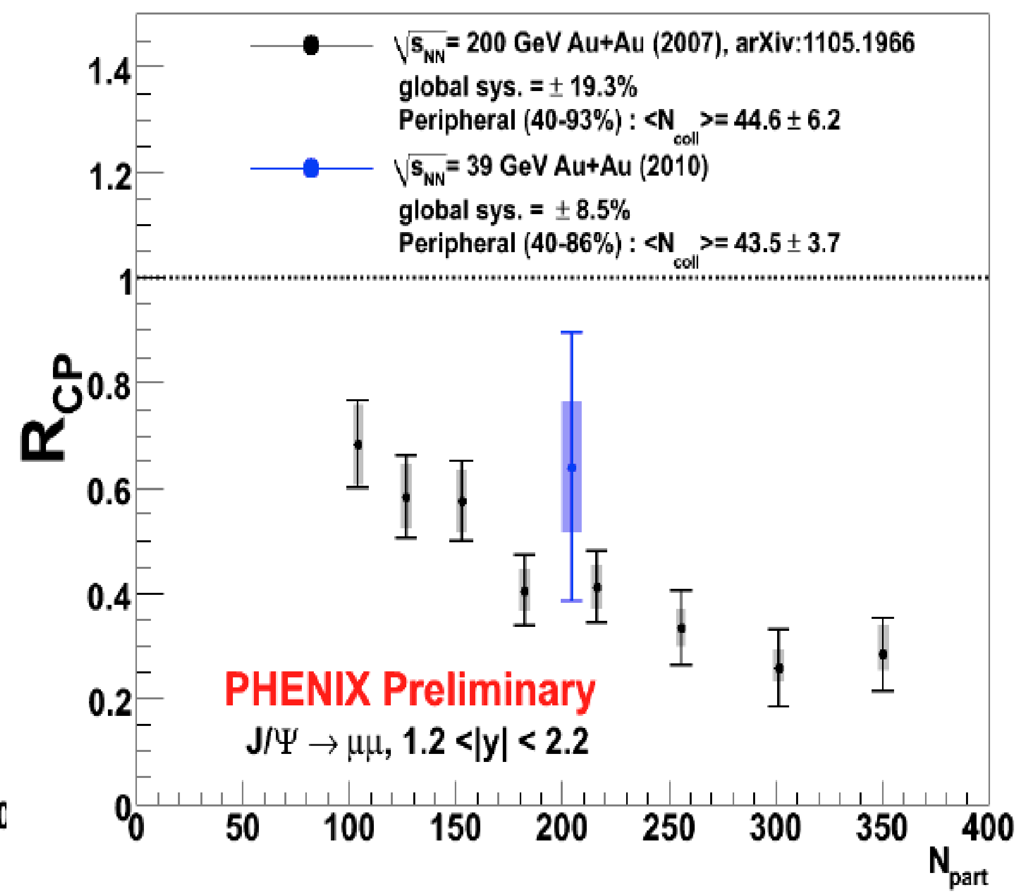


Lower energy J/ψ measurements

We show R_{CP} for now, since we don't have p+p reference data yet.

Suppression at 62 GeV is very similar to 200 GeV.





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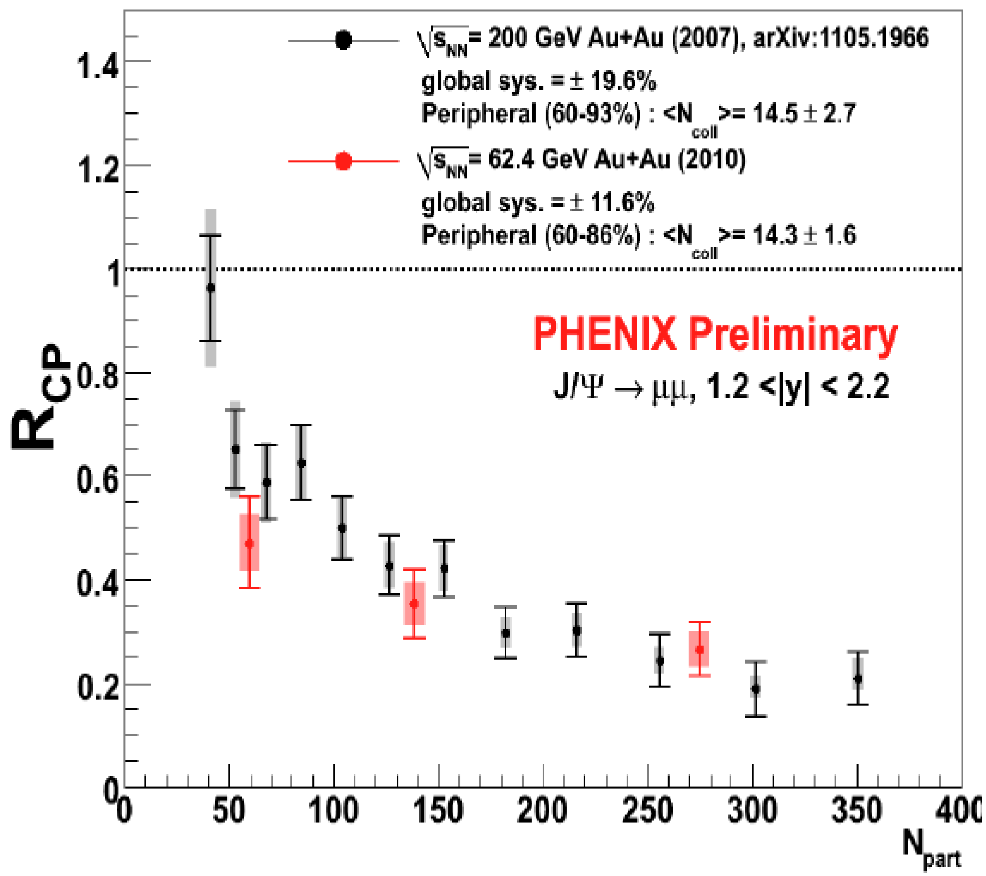
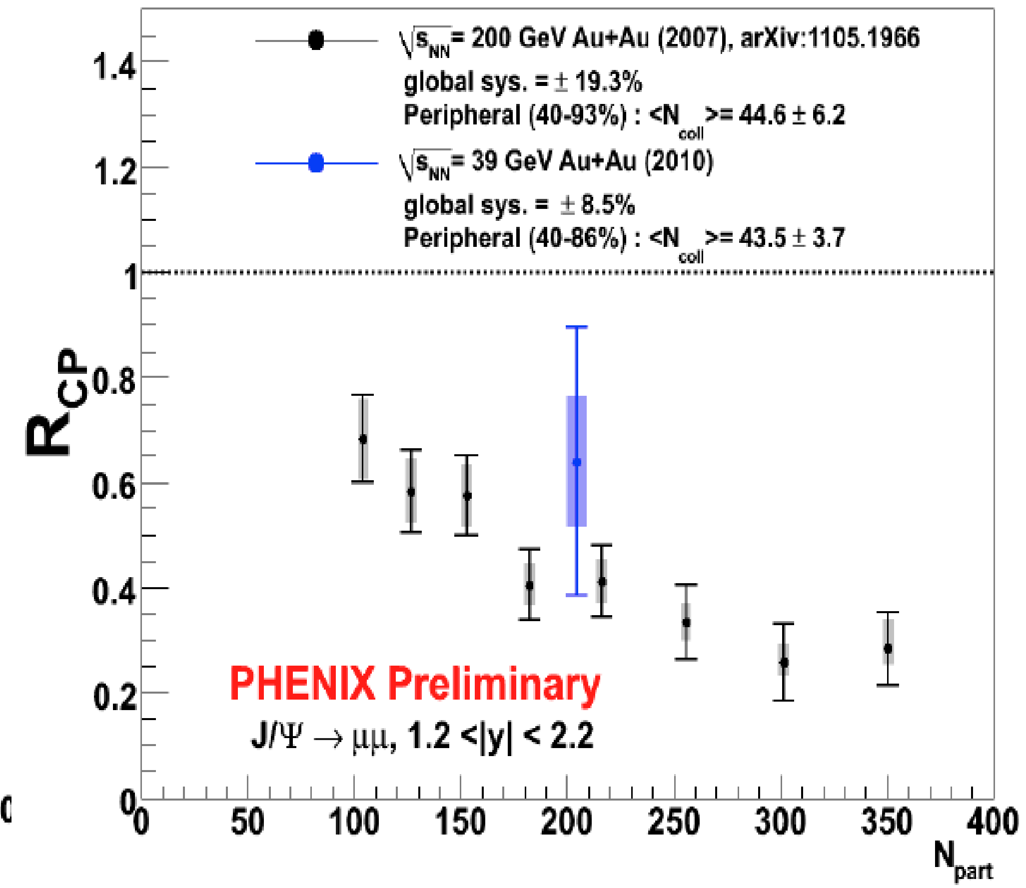
But ....

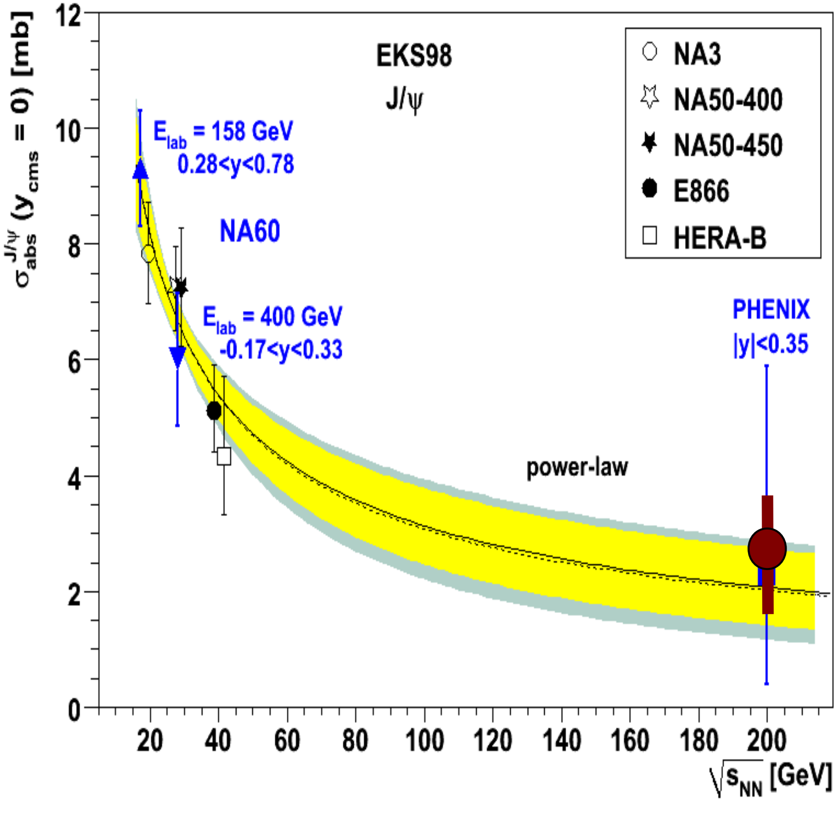


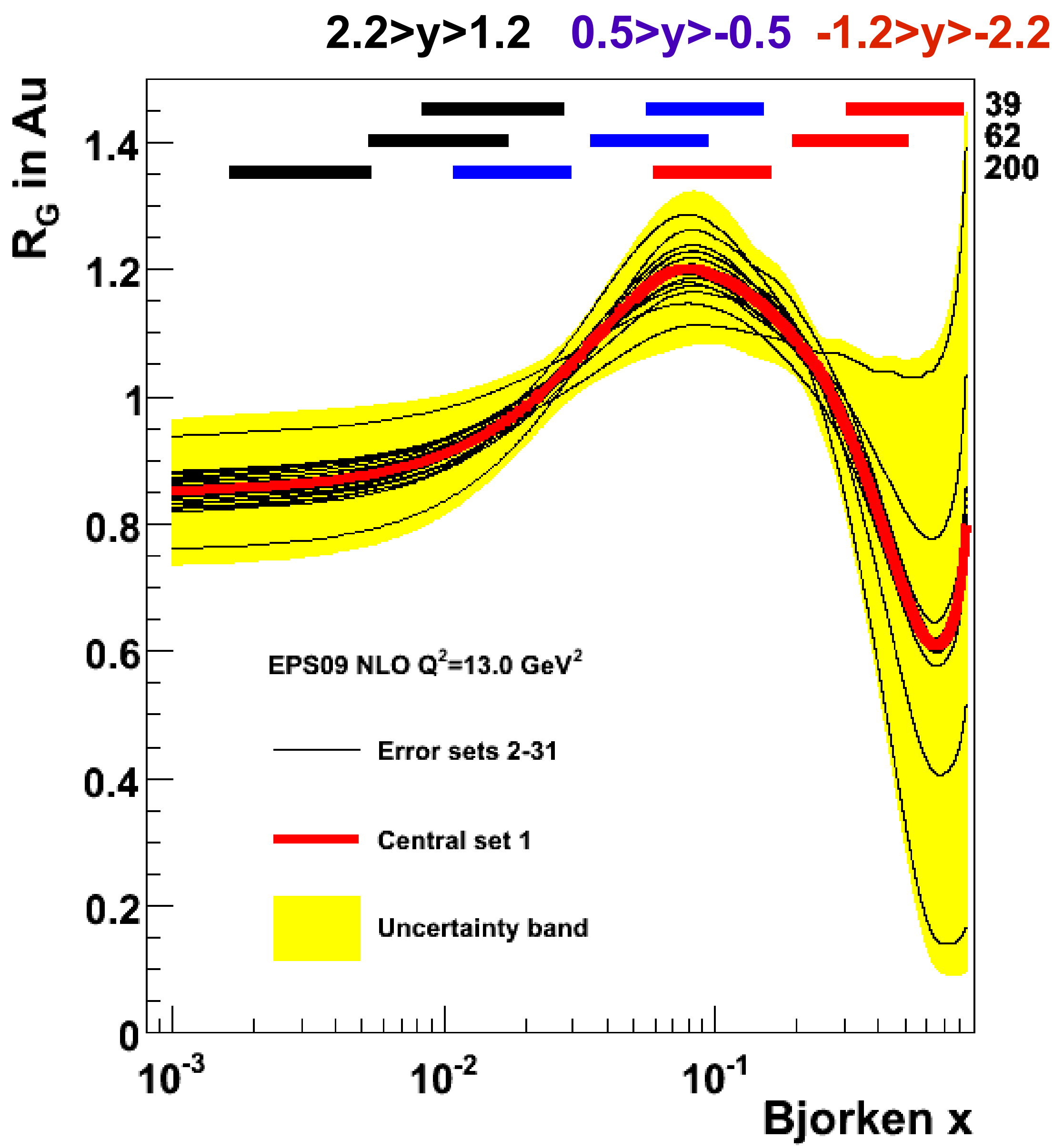


Lower collision energy J/ψ have different CNM effects!

We need to estimate CNM effects at lower energies, until we get low energy d+Au data.

JHEP 0902:014 (2009)



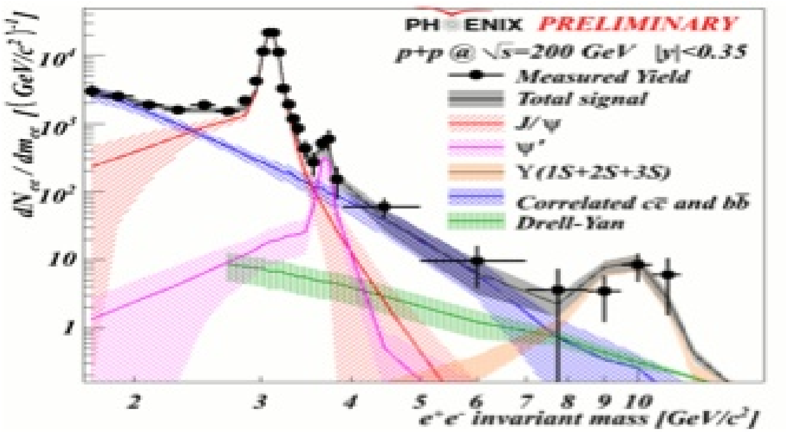


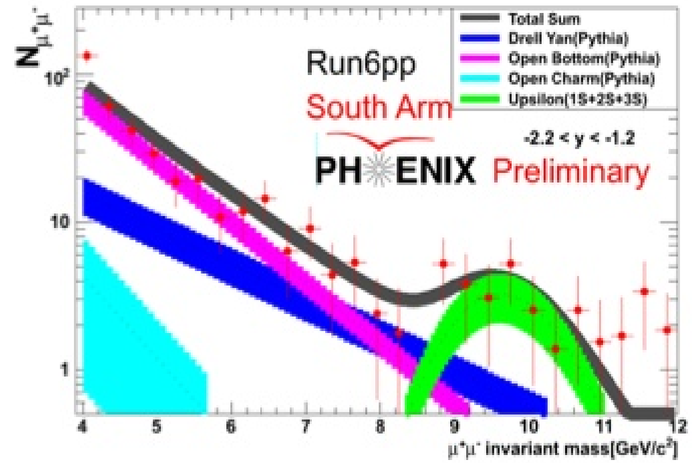
Upsilons

PHENIX Υ(1S+2S+3S) in 200 GeV p+p collisions

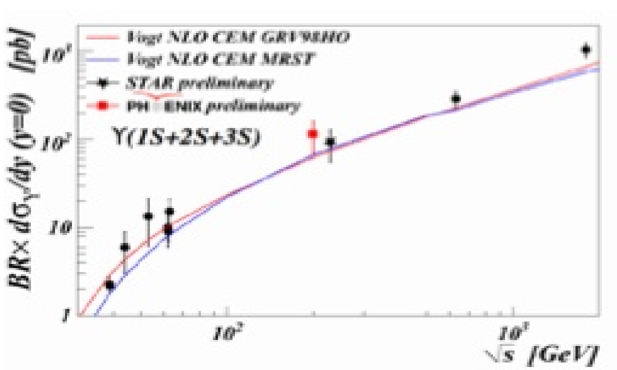
e^+e^- at |y|<0.35

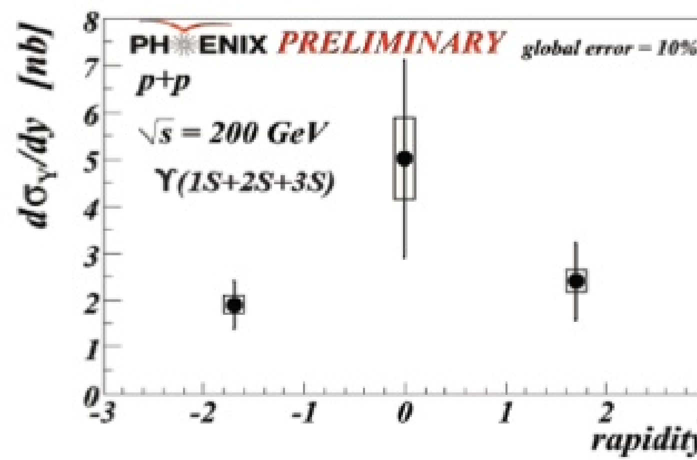
$\mu^+\mu^-$ at 1.2<|y|<2.2



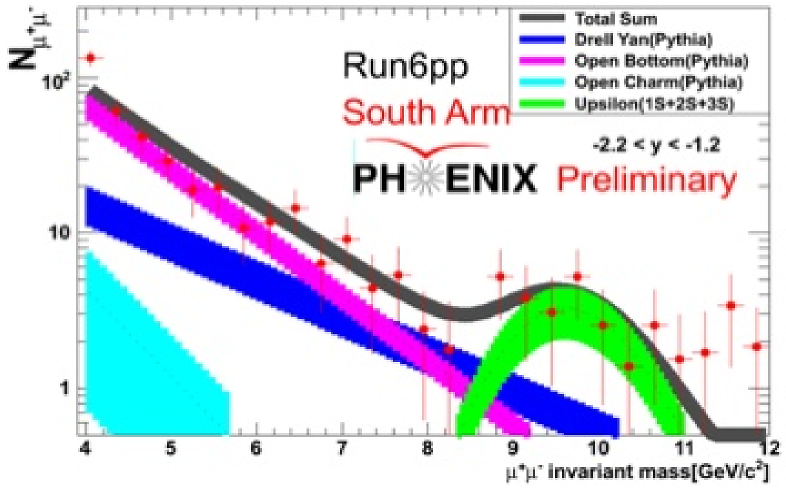


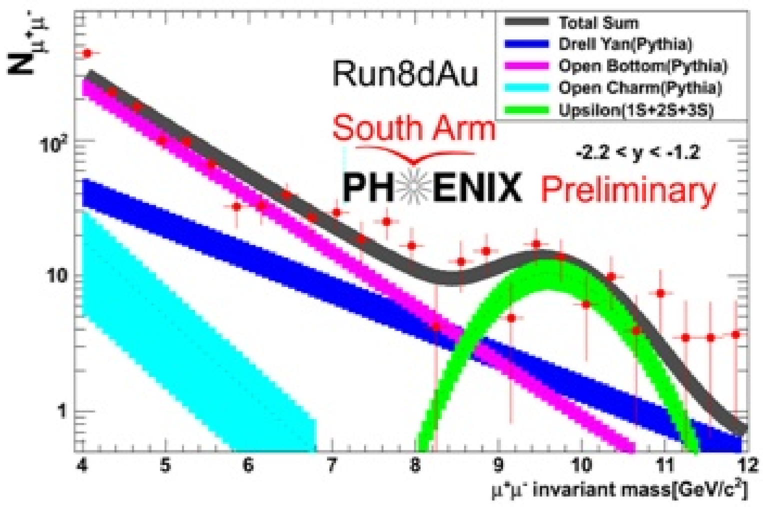
$$BR \times \frac{d\sigma}{dy}\bigg|_{|y|<0.35} = 114^{+46}_{-45}\, pb$$





PHENIX Υ(1S+2S+3S) in 200 GeV d+Au collisions

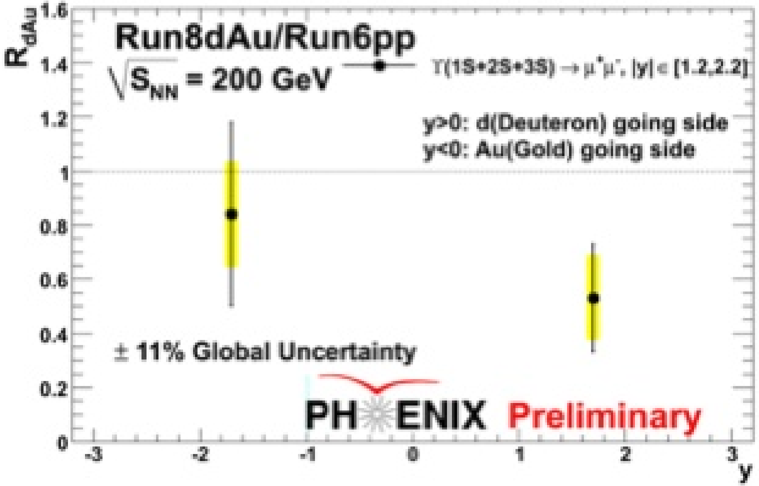




Run 6 pp, Run 8 d+Au Υ(1S+2S+3S)→$\mu^+\mu^-$

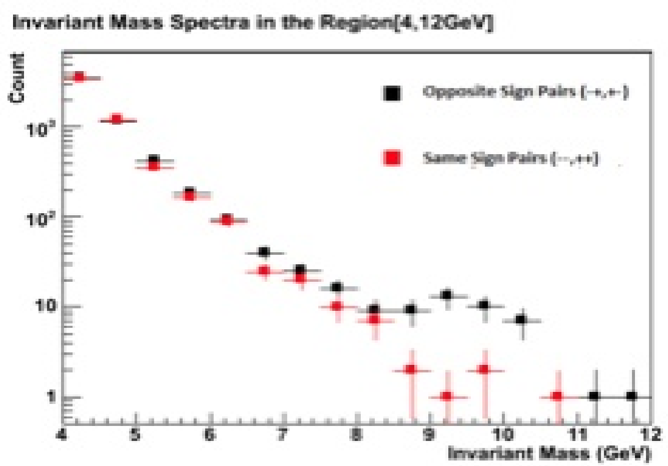
R_{dAu}= 0.84±0.34(stat.)±0.20(sys.), y [-2.2,-1.2]

R_{dAu}= 0.53±0.20(stat.)±0.16(sys.), y [1.2, 2.2]



PHENIX Υ(1S+2S+3S) in 200 GeV Au+Au collisions

Run 10 200 GeV Au+Au data show a significant signal for the combined Υ(1S+2S+3S)→e^+e^- at midrapidity.



R_{AA} coming soon!

Focus of measurements in the next 5 years or so

The introduction of the VTX detector (Run 11) and FVTX detector (Run 12) will allow **separated D and B** semileptonic decay measurements within the rapidity range $-2.2 < y < 2.2$ for p+p, d(p)+Au, and Au+Au collisions.

These measurements are of interest both for studying heavy quark energy loss in the medium, and for investigating nuclear target (CNM) effects.

The VTX and FVTX will also improve the momentum/mass resolution, helpful for some quarkonium measurements – will allow **ψ' separation** in the muon arms, for example.

We need to tie together forward measurements using different hard probes! Do they all tell the same story?

Longer term: sPHENIX

For **quarkonia**, the goal has always been the **characterization of the Debye screening length as a function of temperature**. This has turned out to be far less straightforward than initially expected, for three reasons:

- Strong CNM effects in the data
- Feed-down effects from higher states
- The need to consider coalescence of quark pairs

These complications have to be addressed by a combination of measurements that fully characterize the CNM and feed-down effects, models of the collision dynamics, and **data covering a broad range of initial temperatures**.

The **upper table** shows a grid of possible quarkonium states and initial medium temperatures.

The red stars show which measurements require upgraded PHENIX.

The **lower table** shows which of the needed measurements have been done (or will soon be done).

$\sqrt{s_{NN}}$	T/T_C	J/ψ	Ψ'	χ_C	Υ(1S)	Υ(2S)	Υ(3S)
62	1.5	*	*	*			
200	2.0	*	*	*	*	*	*
2760	3.5	*	*	*	*	*	*

√sNN	Species	J/ψ	Ψ'	χ_C	Υ(1S)	Υ(2S)	Υ(3S)
62	Au+Au	Y					
	d+Au						
	p+p						
200	Au+Au	Y					
	d+Au	Y					
	p+p	Y					
2760	Pb+Pb	Y			Y	Y	Y
	p+Pb						
	p+p	Y			Y	Y	Y

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2760	3.5	*	*	*	*	*	*

Nail down coalescence, after CNM corrections

√sNN	Species	J/ψ	Ψ'	χ_C	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
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	d+Au						
	p+p						
200	Au+Au	Y					
	d+Au	Y					
	p+p	Y					
2760	Pb+Pb	Y			Y	Y	Y
	p+Pb						
	p+p	Y			Y	Y	Y

Conclusions - 1

The J/ψ R_{dAu} data require a **shadowing centrality dependence** at forward rapidity that is **stronger than linear,** implying that the onset of gluon saturation effects occurs suddenly as the impact parameter decreases.

The Run 8 J/ψ R_{dAu} data strongly constrain CNM modification vs rapidity and p_T. They will allow hot matter effects in Au+Au to be isolated at mid and forward/backward rapidity. That work is ongoing.

New J/ψ RCP data at 62 GeV show similar suppression to the 200 GeV data – but we need to **estimate CNM effects** to quantify the comparison.

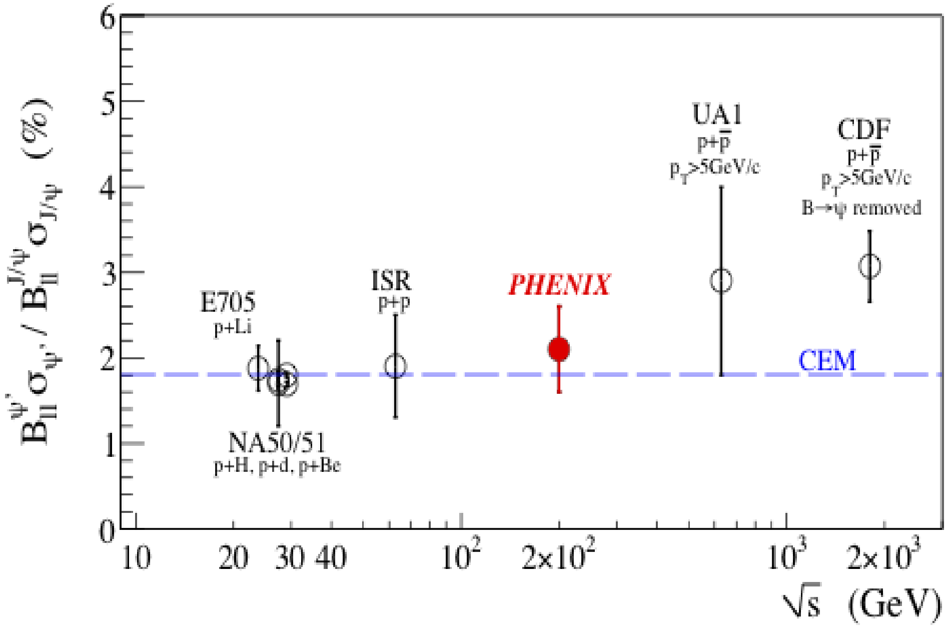
Conclusions - 2

The heavy flavor program for the next 5 years will be dominated by the new capabilities brought by the VTX and FVTX silicon detectors.

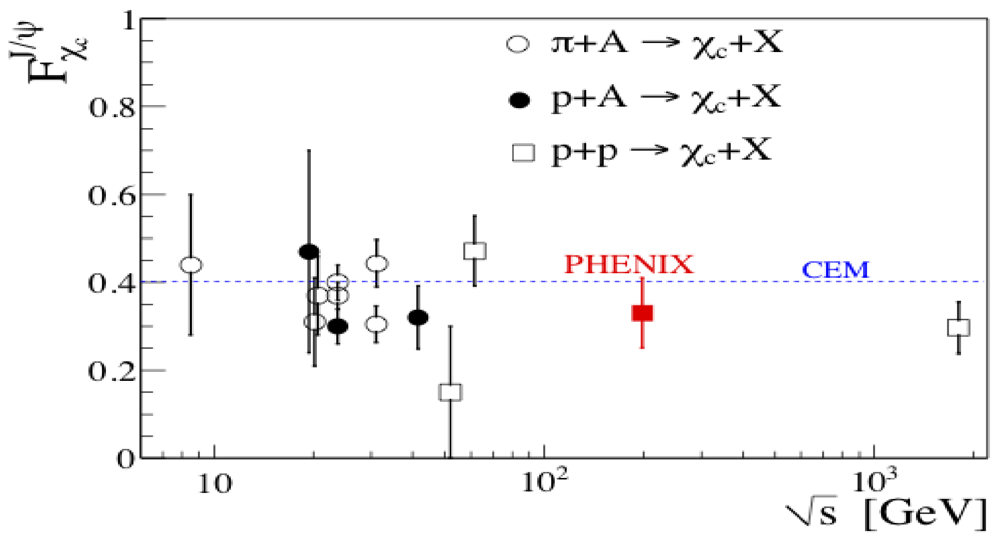
Bringing together p(d)+A heavy flavor measurements with the VTX/FVTX over a wide rapidity range **and** forward measurements using other hard probes (MPC-EX) should provide an excellent data set for studying the gluon modification at low x in nuclei **as a function of impact parameter**.

Beyond 5 years, the opportunity exists with **sPHENIX** to (along with the LHC experiments) build a data set that will allow us to characterize the Debye screening length in hot nuclear matter as a function of temperature.

Backups



6
5
4
3
2
1
0
UA1
p+p̄
p_T>5GeV/c
CDF
p+p̄
p_T>5GeV/c
B→ψ removed
ISR
p+p
PHENIX
E705
p+Li
CEM
NA50/51
p+H, p+d, p+Be
10
20
30
40
10^2
2×10^2
10^3
2×10^3
$\sqrt{s}$ (GeV)
$B_{ll}^{\psi'}\sigma_{\psi'} / B_{ll}^{J/\psi}\sigma_{J/\psi}$ (%)



$F_{\chi_c}^{J/\psi}$
1
0.8
0.6
0.4
0.2
0
π+A → χ_c+X
p+A → χ_c+X
p+p → χ_c+X
PHENIX
CEM
10
10^2
10^3
$\sqrt{s}$ [GeV]