PHENIX charmonia: What have we learned from d+Au collisions?

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On behalf of the **PHENIX** collaboration

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Heavy quark production in nuclear collisions

Like jets, heavy quarks are an attractive probe of the matter formed in heavy ion collisions because they are produced in **hard processes** that occur only during the nuclear crossing.

Distributions in A+A collisions differ from those in p+p due to:

- Modification of the production cross section in a nuclear target – **cold nuclear matter** (CNM) effects
- Modification of the observed distributions due to interactions with the final state medium – **medium effects**

- Both occur in A+A collisions.
- It has long been assumed that only CNM effects occur in p(d)+A collisions.

A desire to understand CNM effects on heavy quark production leads us to study **p(d)+A** collisions. **But ....**

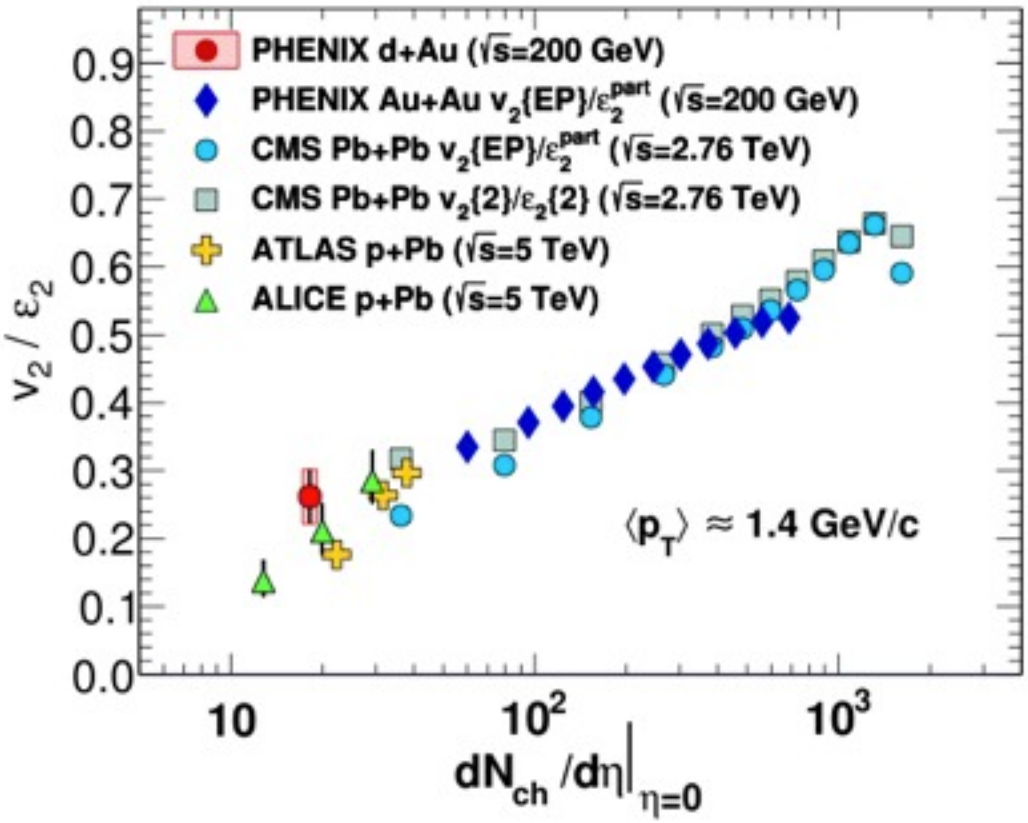
Hot matter effects in (p,d)+A collisions?

CMS, S. Chatrchyan et al., Phys. Lett. B724, 213 (2013), [arXiv:1305.0609 [nucl-ex]].

ATLAS, G. Aad et al., Phys. Lett. B725, 60 (2013 [arXiv:1303.2084 [hep-ex]].

ALICE, B. Abelev et al., Phys. Lett. B719, 29 (2013), [arXiv:1212.2001].

PHENIX, A. Adare et al., Phys. Rev. Lett. (2013), [arXiv:1303.1794 [nucl- ex]].



Substantial long range correlations in p+Pb and d+Au collisions, scales with multiplicity for CM energies differing by up to x25.

Consistent with effects seen in Au+Au and Pb+Pb - which have been attributed to hydrodynamic effects.

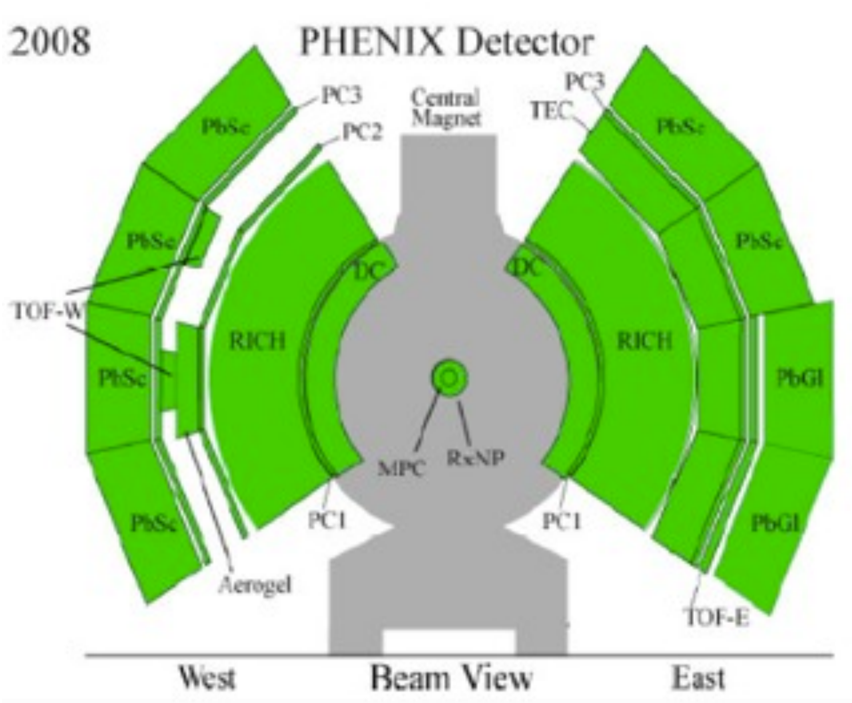
Well described by hydrodynamic calculations, although CGC effects are not ruled out. Raises the possibility that we have hot matter effects in d+Au collisions that might affect our **hard probe** yields.

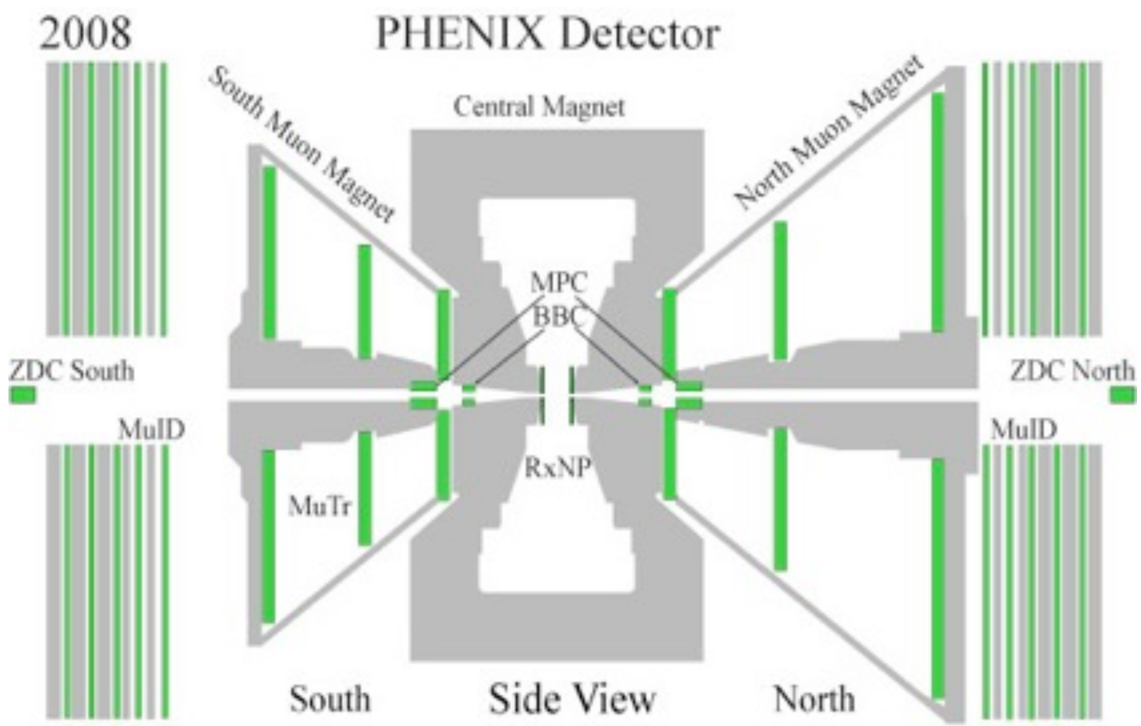
PHENIX charmonium detection

Dielectron measurements at midrapidity and dimuon measurements at forward/backward rapidity cover most of the kinematic region of interest at 200 GeV.

D, B $\rightarrow e^{\pm}$
$J/\psi \rightarrow e^{+}e^{-}$
$-0.35 < y < 0.35$
$\Delta\Phi = \pi$

D, B $\rightarrow \mu^{\pm}$
$J/\psi \rightarrow \mu^{+}\mu^{-}$
$-2.2 < y < -1.2$
$1.2<y<2.4$
$\Delta\Phi = 2\pi$





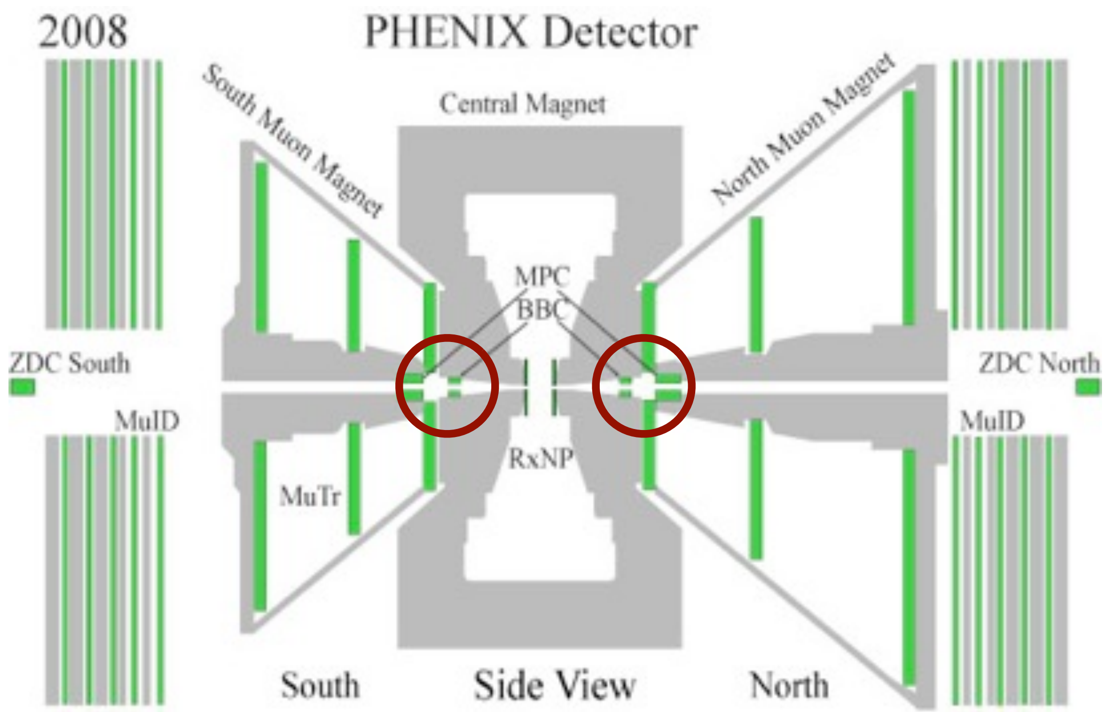
Centrality measurement

The Beam-Beam Counters cover $3.0 < |\eta| < 3.9$.

Detect soft charged particles produced in a collision, and provide:

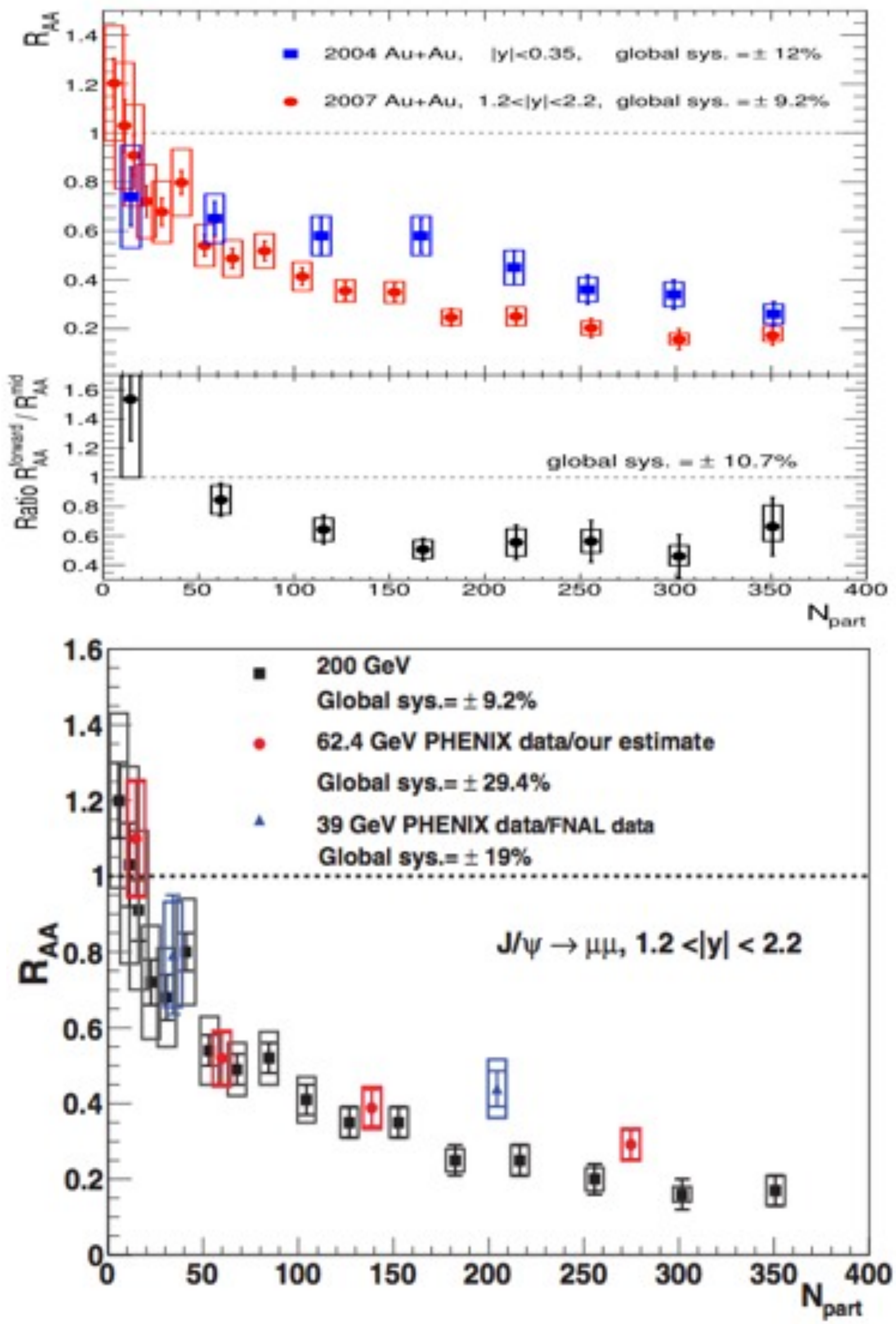
- The minimum bias **event trigger**
- The collision **Z vertex** (from Δt between BBC North and South)
- The collision **centrality** (from the signal size)

In **d+Au** collisions, the signal from only the **Au-going** BBC is used for centrality.



PHENIX J/ψ in A+A collisions

- 200 GeV
  - Au+Au
  - Cu+Cu
  - Cu+Au (preliminary)
  - U+U (preliminary)
- 62.4 GeV
  - Au+Au
- 39 GeV
  - Au+Au



The suppression is:

- Strongest at 200 GeV
- Weaker at 64 GeV
- Weaker again at 39 GeV

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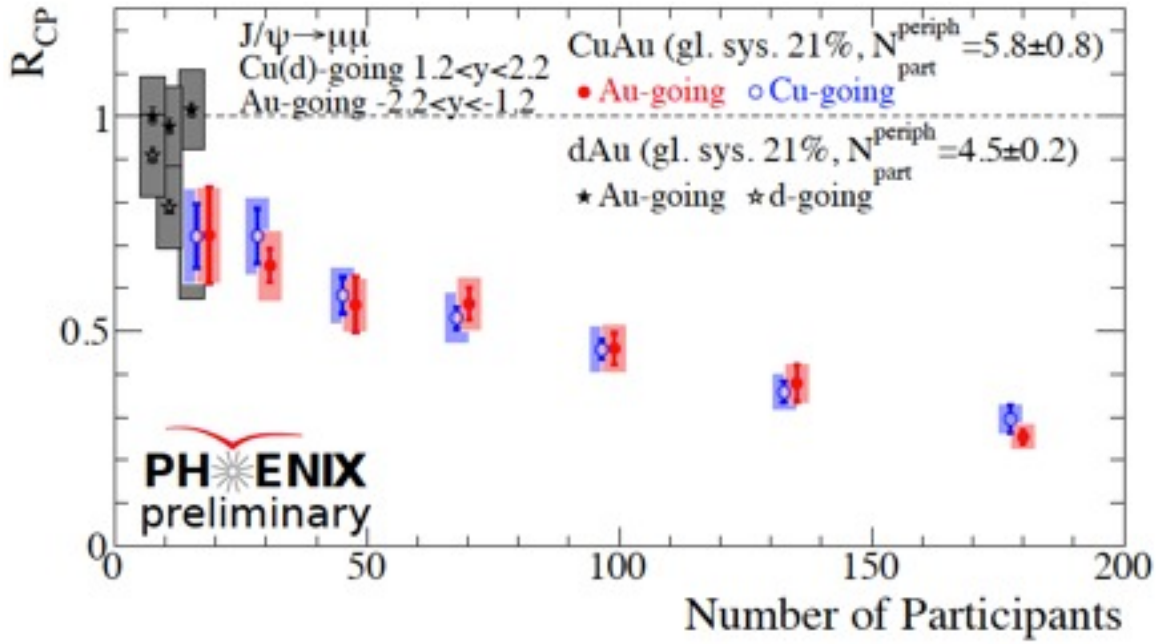
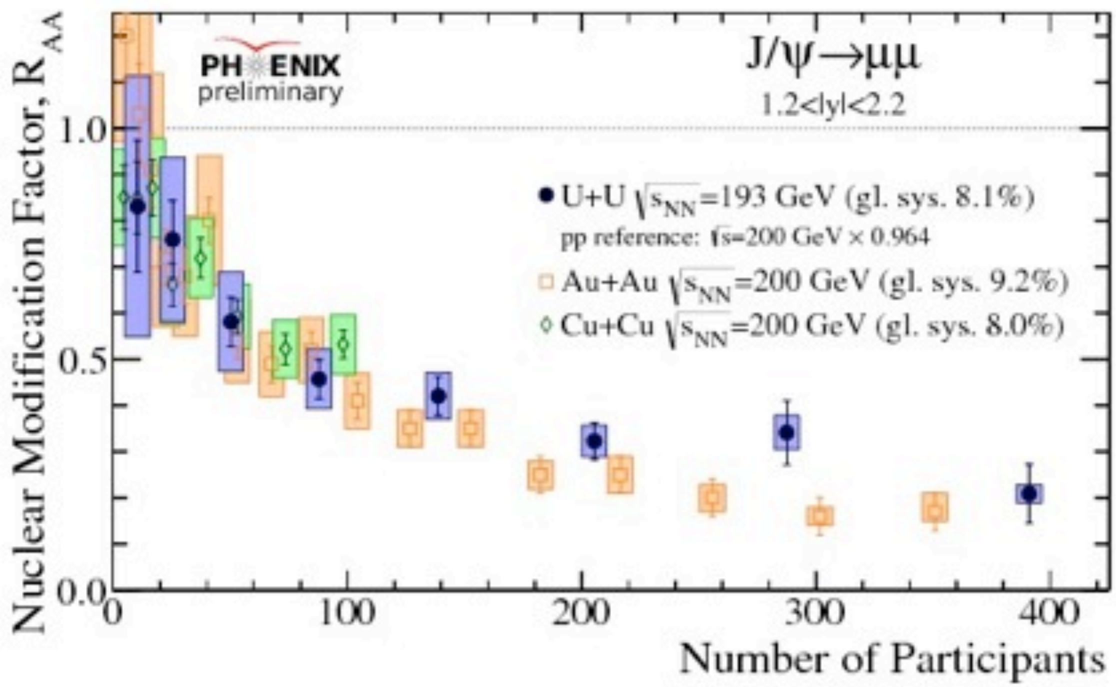




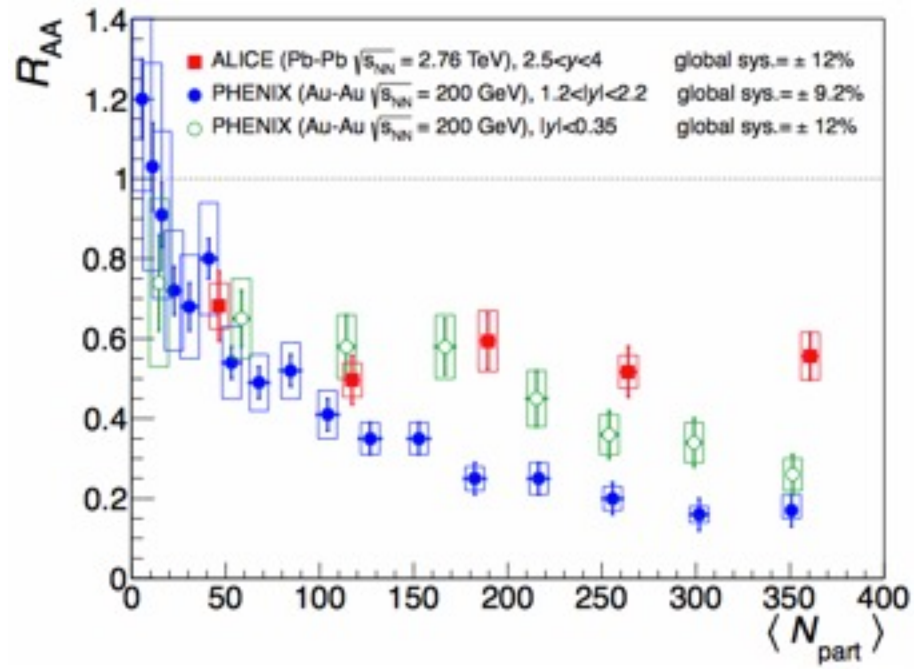
The suppression is:

- Maybe weaker in U+U ??
- similar at forward/backward rapidity for Cu+Au R_{CP}
- Cu+Cu, Au+Au track with N_{part}

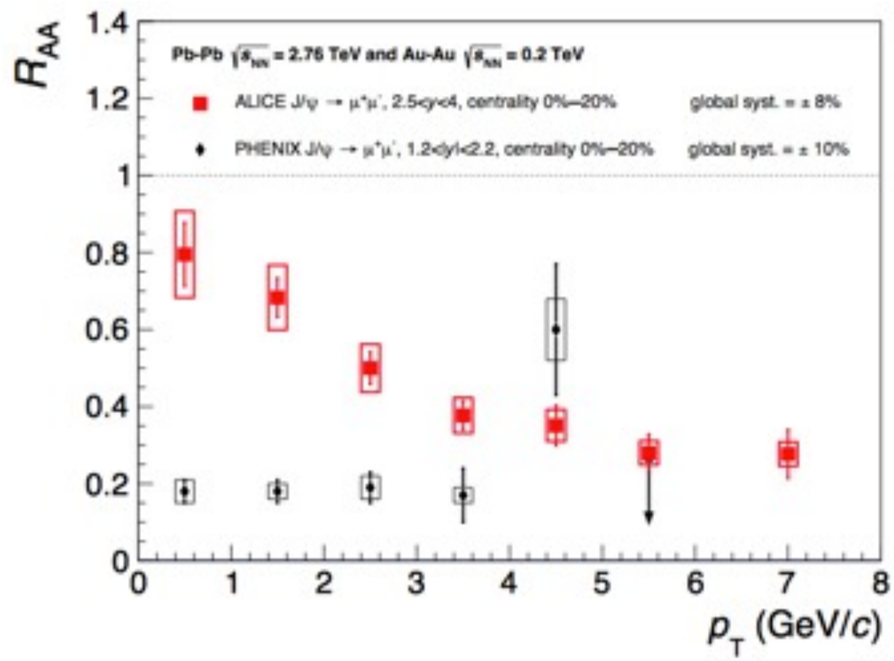
Compared with 2.76 TeV

The ALICE J/ψ results show that at LHC energies the suppression is much reduced (**compare blue and red**).

This is due to a much smaller R_{AA} at low p_T at RHIC energy. Combined with large v_2 at LHC, but not at RHIC, suggests coalescence is important.



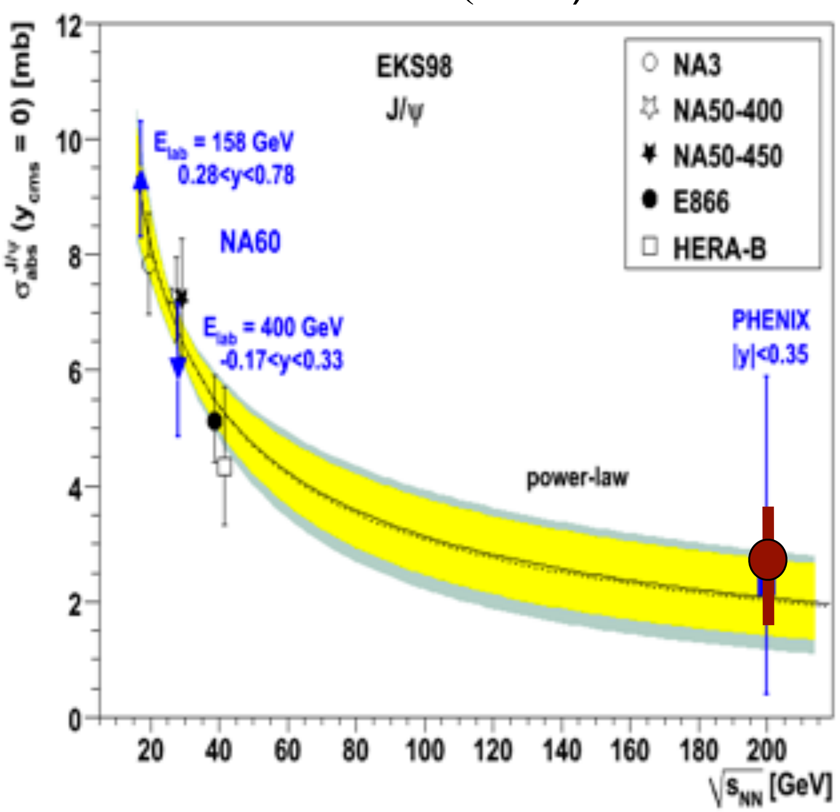
So 200 GeV Au+Au seems to be close to a **minimum of R_{AA}** at low p_T for the J/ψ.



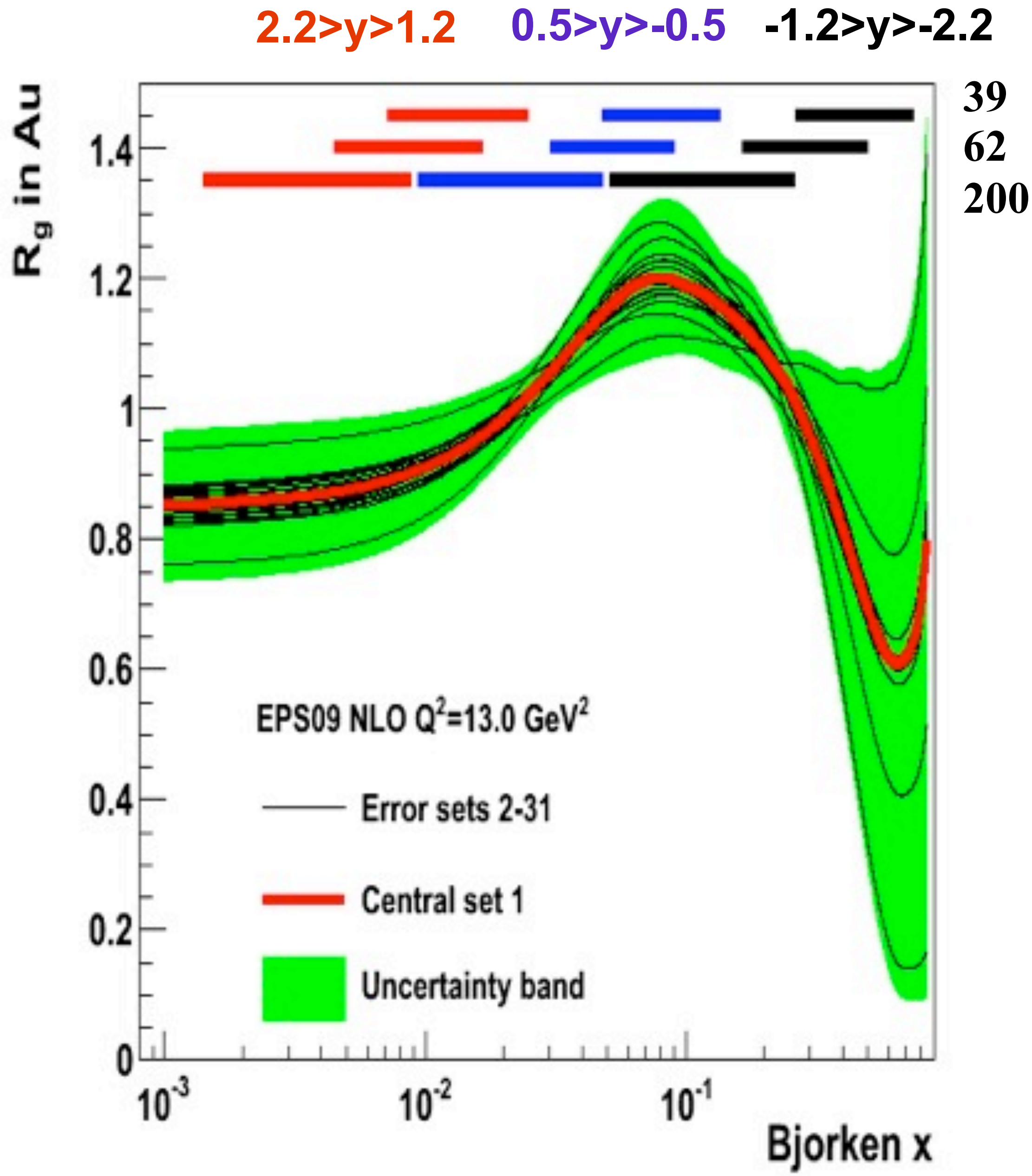
But different collision energy leads to different CNM effects!

Direct comparison of R_{AA} data at different energies and for different systems is inconclusive - CNM effects are known to vary strongly.

JHEP 0902:014 (2009)



Approximate PHENIX *x* coverage



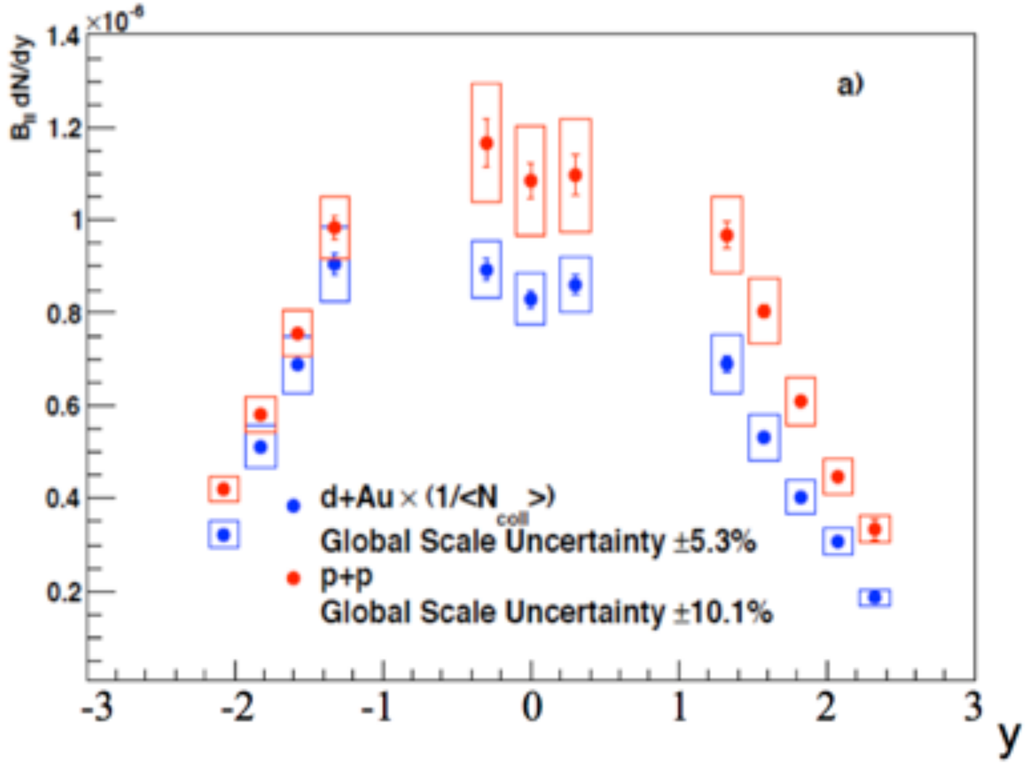
J/ψ measurements in d+Au collisions

Intended as a way to **isolate CNM effects**, charmonium measurements in d+Au collisions turned out to be very interesting in their own right.

The PHENIX measurements cover most of the kinematic region of interest at 200 GeV - important, since the **mix of mechanisms** that modify J/ψ production changes with rapidity.

The modification in d+Au is easily seen in the N_{coll} scaled invariant yield vs rapidity for minbias d+Au and p+p.

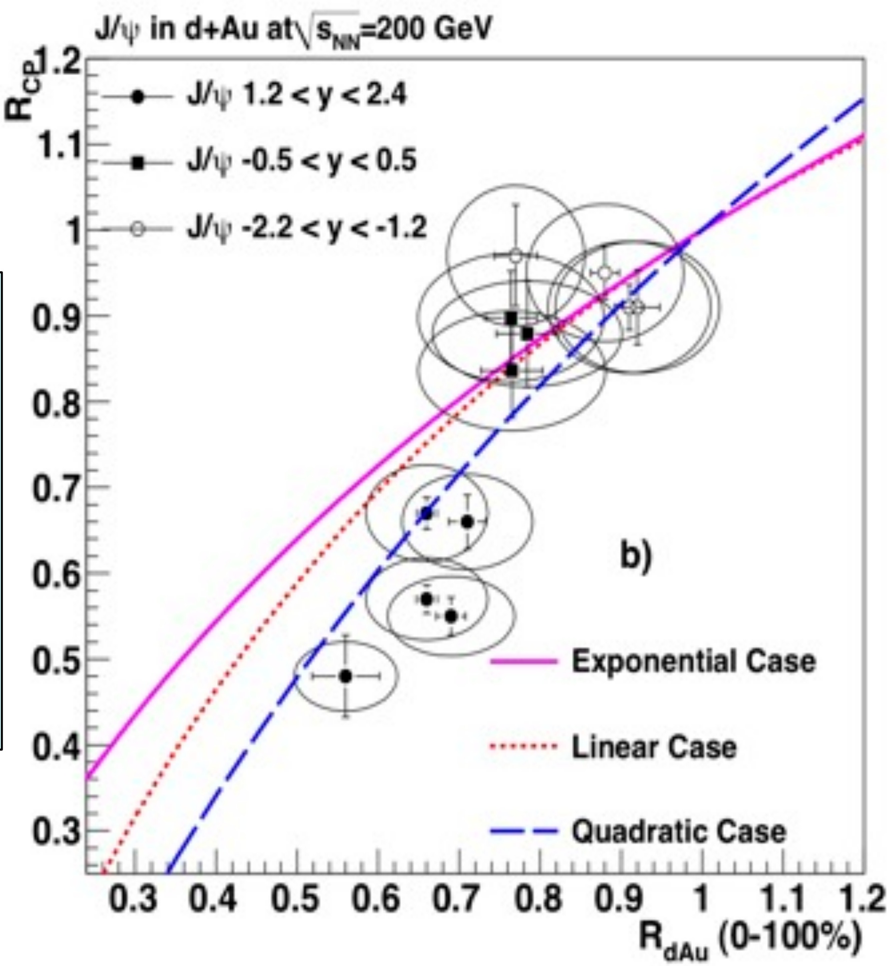
(The middle three points are dielectron measurements, the others are from dimuons.)



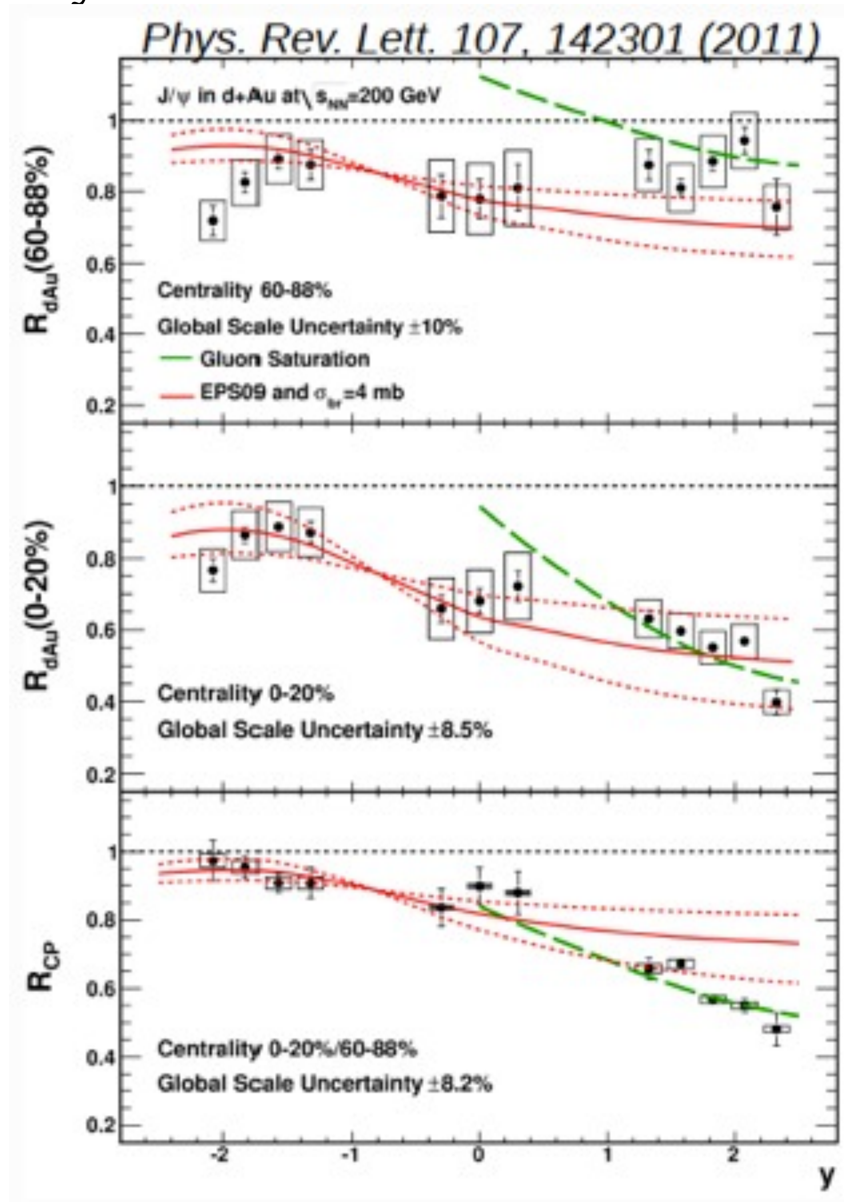
Centrality dependence of J/ψ modification in d+Au

Strong centrality dependence **not** expected from EPS09s or breakup.
CGC model seems to get it at forward rapidity.

Centrality Slope



Overall modification

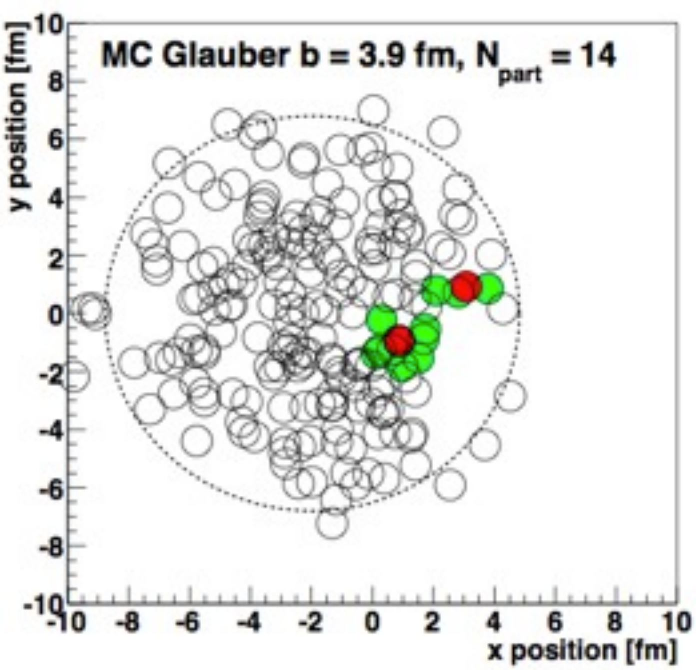


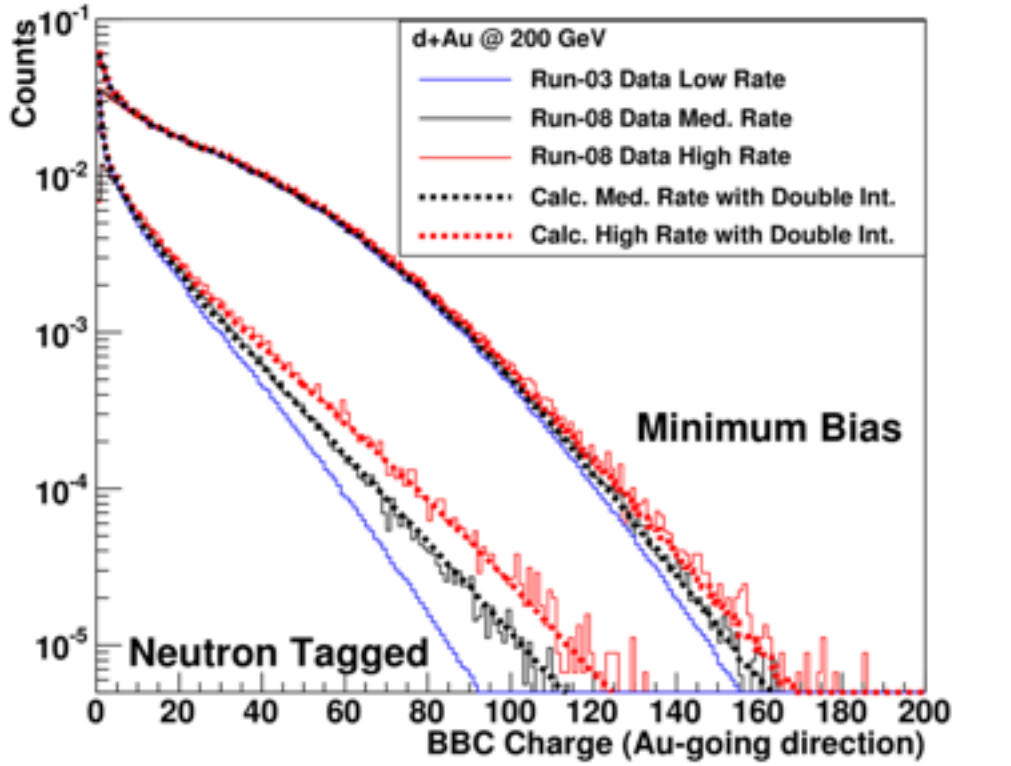
But do we believe the centrality measurement?

Yes.

Detailed discussion of method used by PHENIX, and comparison with a HIJING study in arXiv:1310.4793.

Conclusion: Bias corrections are fairly small, and under control.





Systematic studies of effective breakup from shadowing corrected data

Method: fit effective σ_{abs} to **shadowing corrected** data.

Effective σ_{abs} extracted for **17.3 to 200 GeV** collisions:

- Lourenco et al., JHEP02, 014 (2009).
- Arnaldi et al. (NA60), Nucl. Phys. A 830, 345C (2009).
- McGlinchey et al., Phys.Rev. C87 (2013) 054910.

Caveats:

- All use **central** EKS98 or EPS09 - ie. nPDF uncertainties ignored.
- Effective σ_{abs} and shadowing **only** are considered.
- Breakup makes no sense on certain time scales (the effective σ_{abs} presumably covers up some other physics then).

Provides **shadowing corrected** effective absorption cross sections that can be systematically compared as a function of kinematics.

Modification versus nuclear crossing time scale

J/ψ breakup by collisions with nucleons makes sense only on time scales larger than the charm pair formation time.

Can we throw some light on reaction mechanisms by looking at J/ψ modification versus **nuclear crossing time τ** for the world's σ_{abs} data?

τ varies with collision energy and **very** strongly with rapidity!

Experiment	$\sqrt{s_{NN}}$ (GeV)	A	$y_{\rm beam}$	$y_{\rm cm}$	L (fm)	$\langle p_T \rangle$ GeV/c	τ (fm/c)
PHENIX	200	Au	5.36	-2.08-2.32	4.36	1.90	0.283 - 0.0035
HERA-B	41.6	W	7.58	0.0	4.26	1.36	0.178
E866	38.8	W	7.44	-0.39-2.1	4.26	1.32	0.283 - 0.024
NA50	29.1	W	6.87	0.0	4.26	1.22	0.258
NA50	27.4	Pb	6.75	0.0	4.44	1.20	0.286
NA3	19.4	Pt	6.06	0.0	4.34	1.14	0.396
NA60	17.3	Pb	5.82	0.3	4.44	1.12	0.339

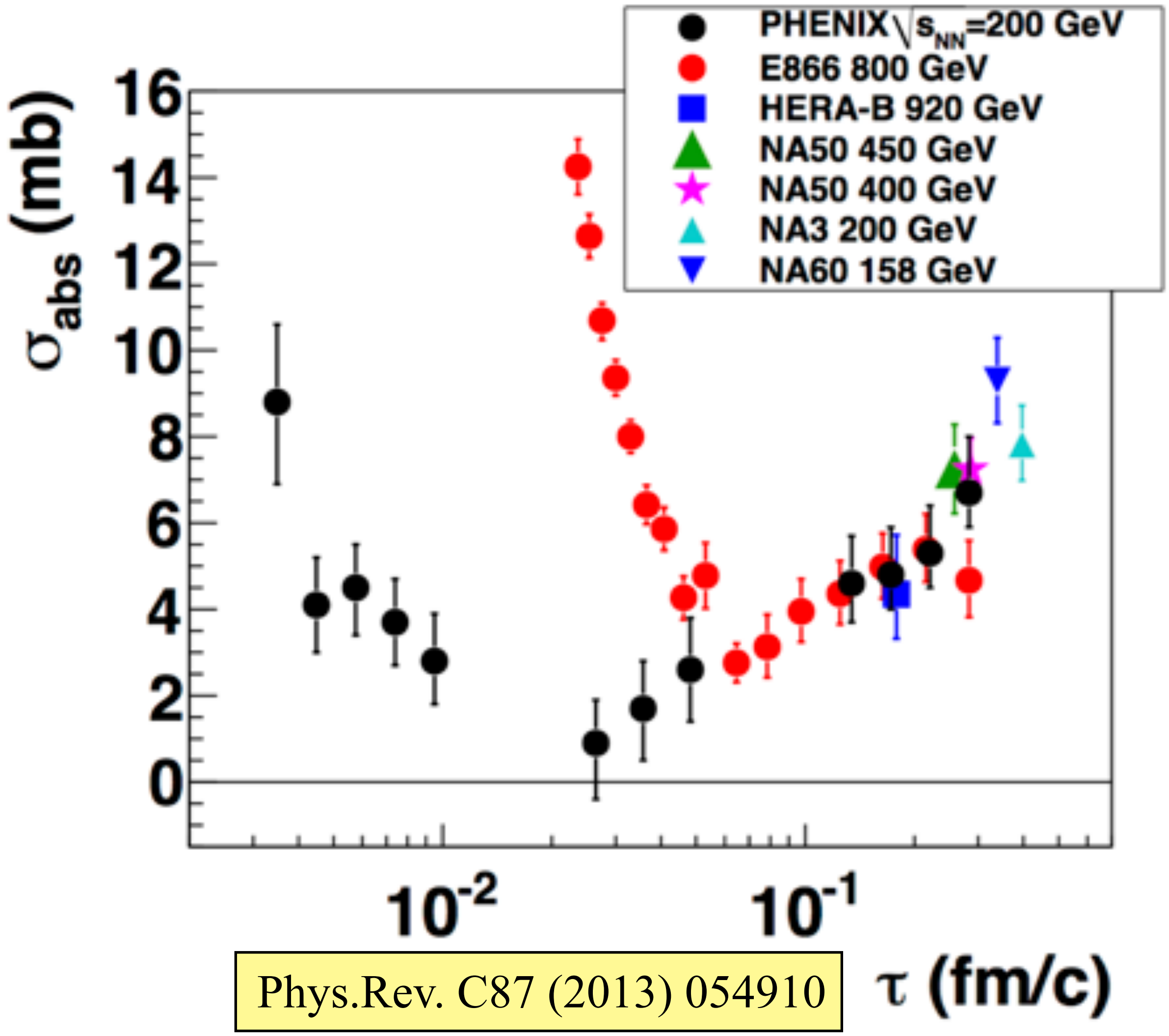
Large range!

$$\tau = \frac{\beta_z L}{\gamma}$$

Modification versus time scale

Shows **scaling** at large τ, but scaling breaks for τ < 0.05 fm/c
- on the order of the charm pair formation time.

Increase of σ_{abs} with τ in scaling region suggestive of **expanding meson**?



Phys.Rev. C87 (2013) 054910

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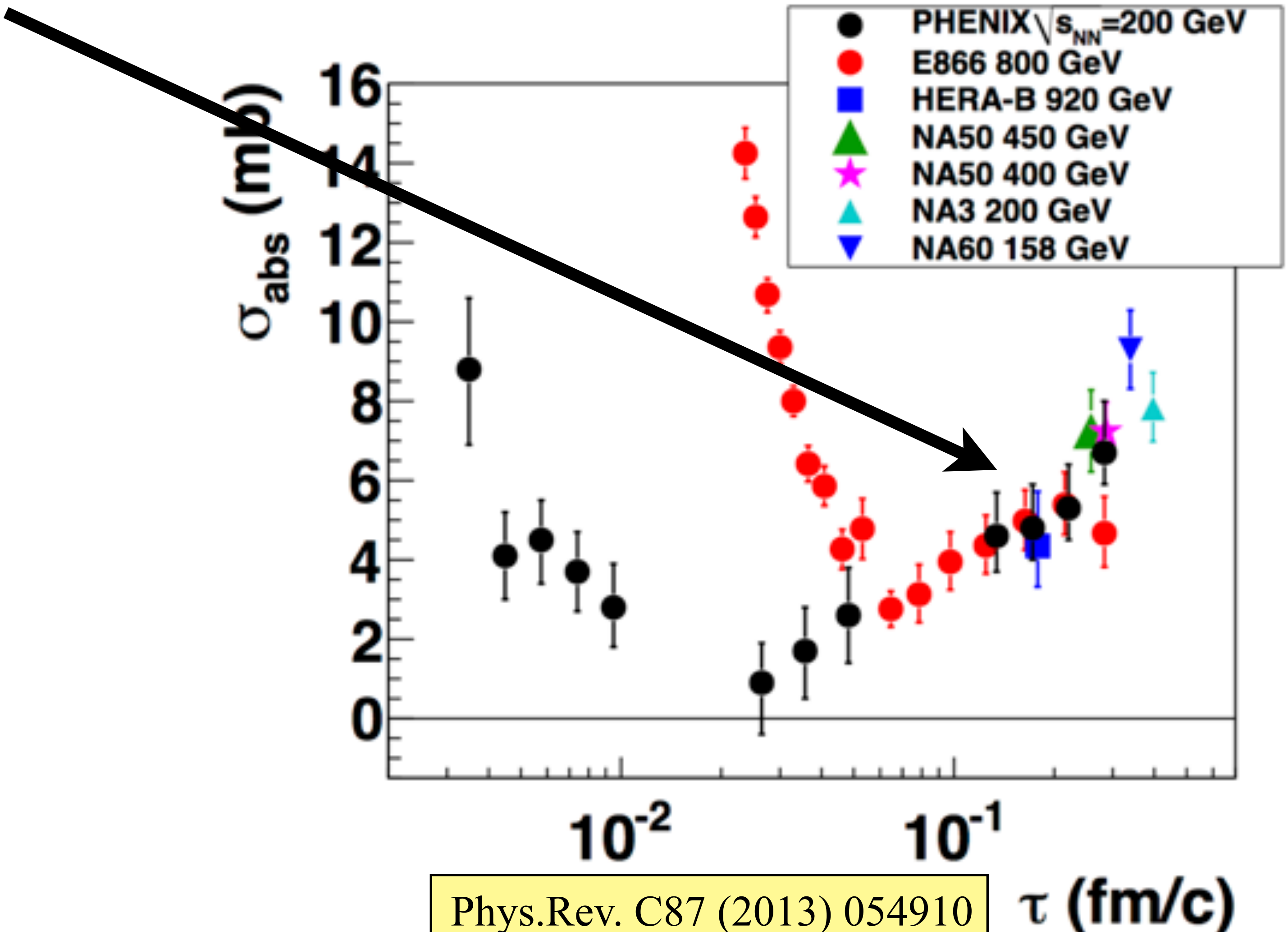


Phys.Rev. C87 (2013) 054910

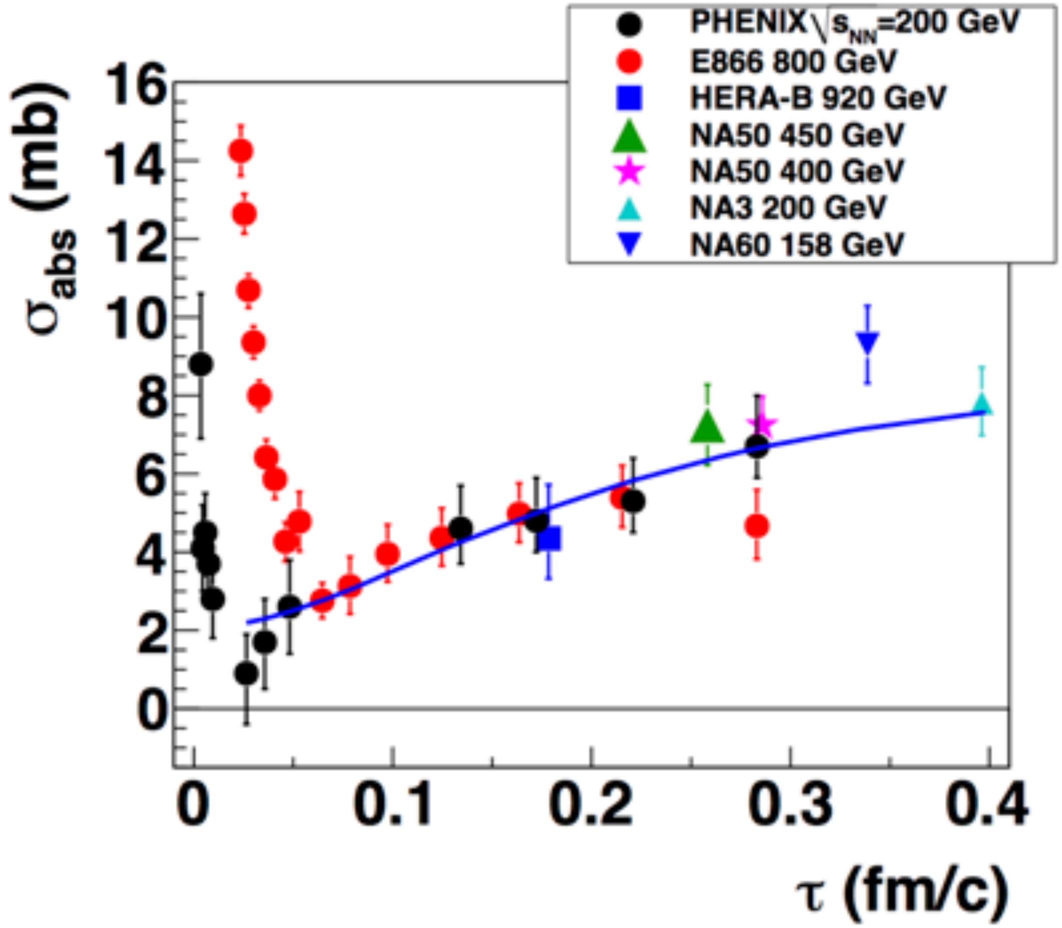
Modification vs time scale - PHENIX backward rapidity data

Scaling behavior at large τ consistent with a model of a **color neutral charm pair** expanding inside the nucleus (Arleo et al., Phys. Rev. C 61 (2000) 054906) fitted to shadowing corrected data (McGlinchey et al., Phys.Rev. C87 (2013) 054910).

Nice fit to large τ data.

The behavior for **τ < 0.05 fm/c** is clearly due to other physics.

Makes sense: for τ < 0.05 fm/c there is no physical meson before the charm pair leaves the target.



J/ψ vs HF lepton modification in d+Au collisions

Comparison of p_T dependence of J/ψ modification with that for **open HF** leptons is instructive (**Matt Durham's** talk, today)

Caveat: Different kinematics!

The J/ψ suppression at **backward rapidity** is much stronger than for HF.

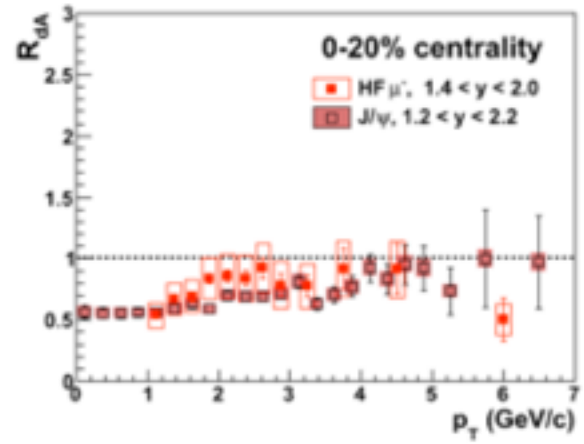
- Implies J/ψ is suppressed **beyond** the underlying HF production.

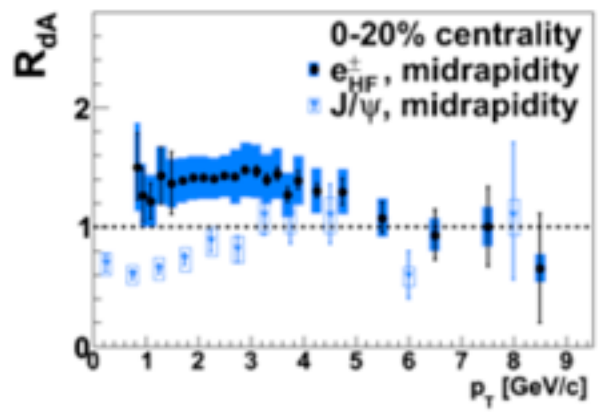
At **forward rapidity** they are similar.

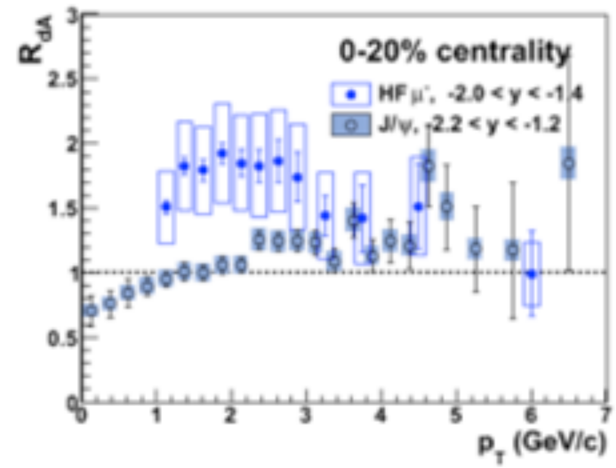
- Implies J/ψ suppressed at forward rapidity **because** the underlying HF is suppressed.

Consistent with

- Breakup at backward rapidity
- A process like energy loss of a colored dipole in CNM at forward rapidity.



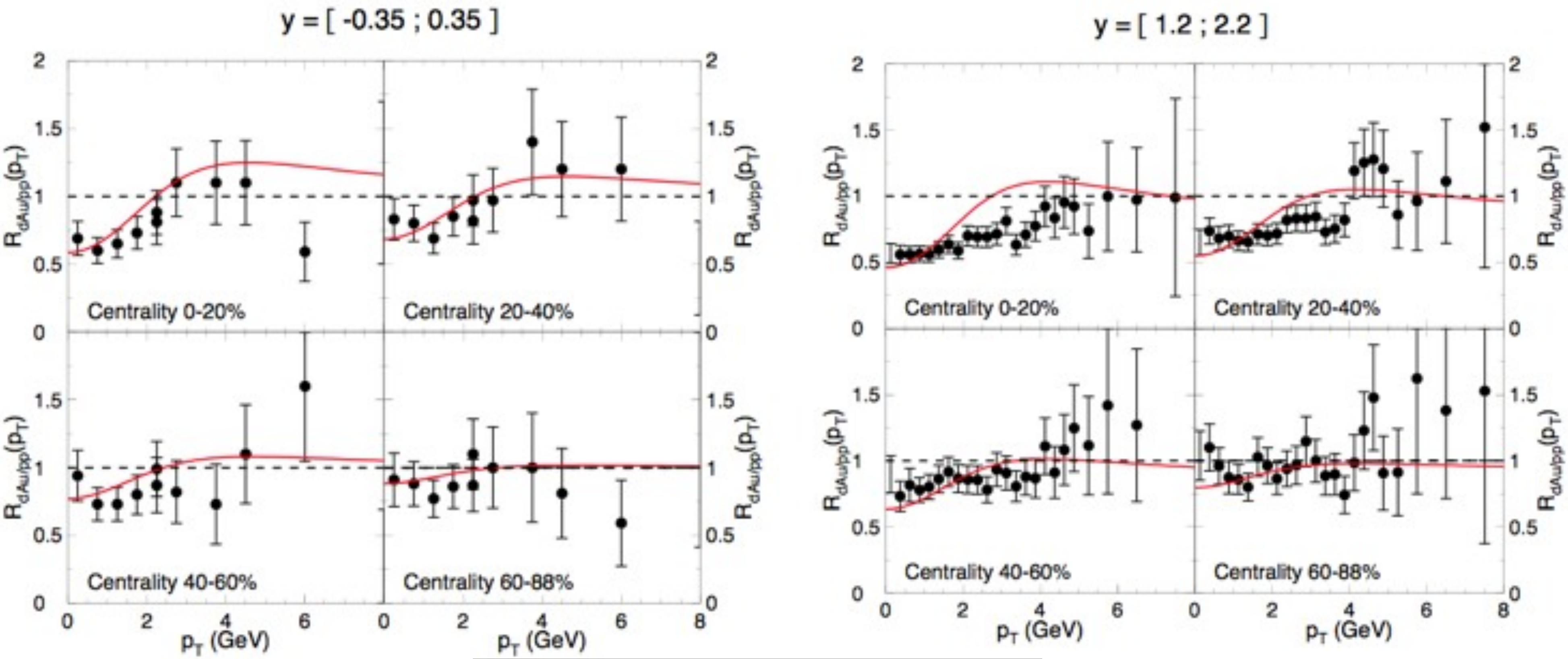




J/ψ modification at forward rapidity in d+Au

Models of parton radiative energy loss (Arleo et al., JHEP 1305 (2013) 155; Sharma and Vitev, Phys.Rev. C87 (2013) 044905) and absorption (Kopeliovich et al., Nucl.Phys. A864 (2011) 203; Ferriero et al., Few Body Syst. 53 (2012) 27).

These seem to describe J/ψ data over a **broad CM energy range**.



Arleo et al. JHEP 1305 (2013) 155

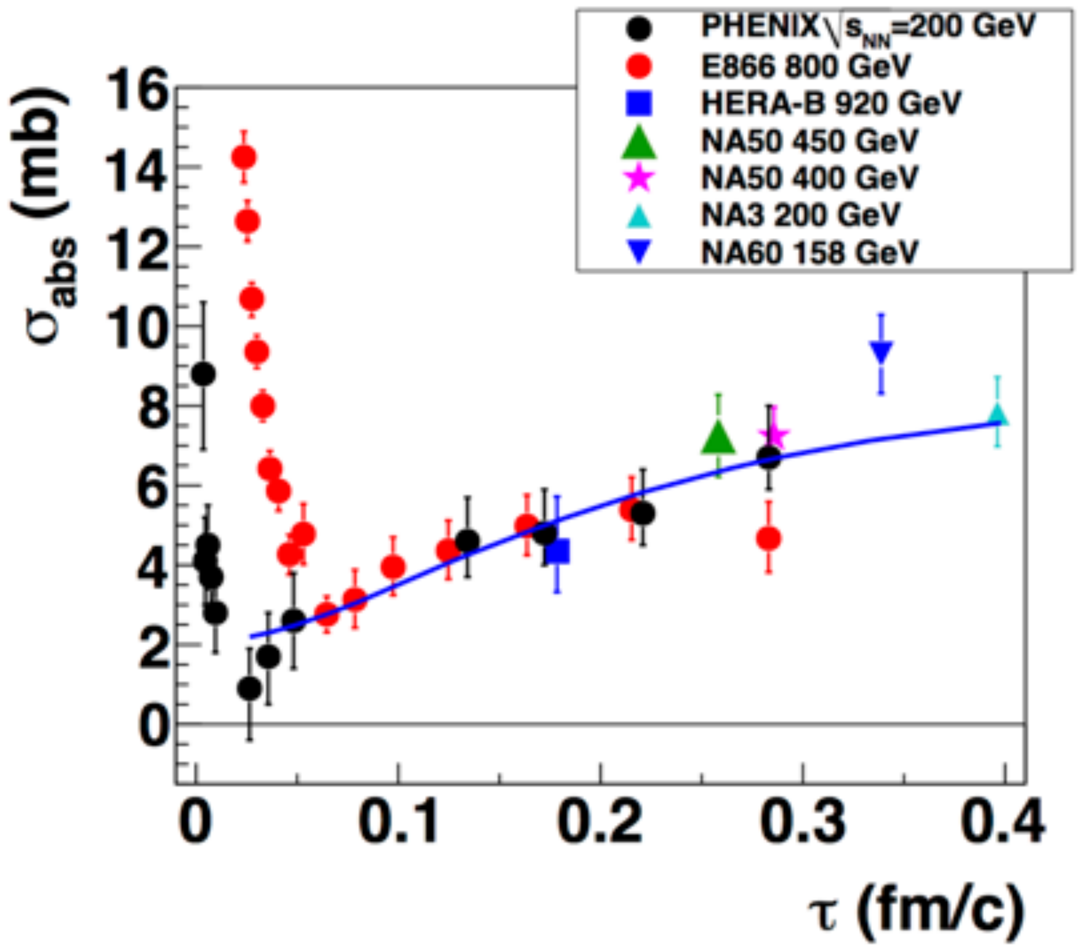
Do hot matter effects modify J/ψ R_{AA} in d+Au?

Hot matter effects in d+Au and p+A collisions should destroy the scaling at large τ between the PHENIX and lower energy data.

Scaling seems to hold - argues that hot matter effects are ≲ the uncertainties on the σ_{abs} extracted from inclusive J/ψ data.

But inclusive J/ψ data are not very sensitive to the suppression of the weakly bound psi' (only ~10% feed down).

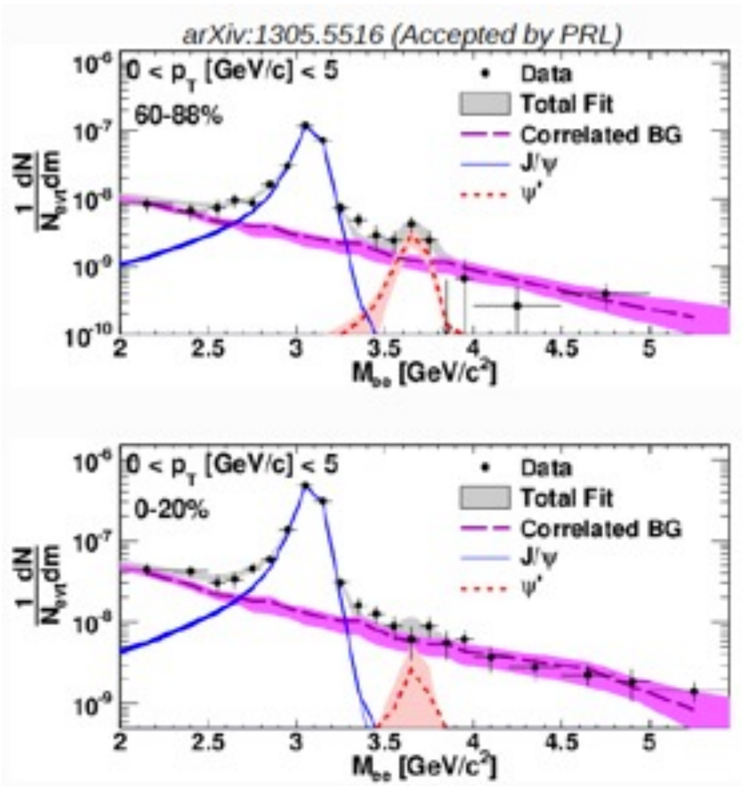
Perhaps the ψ' might show an effect?

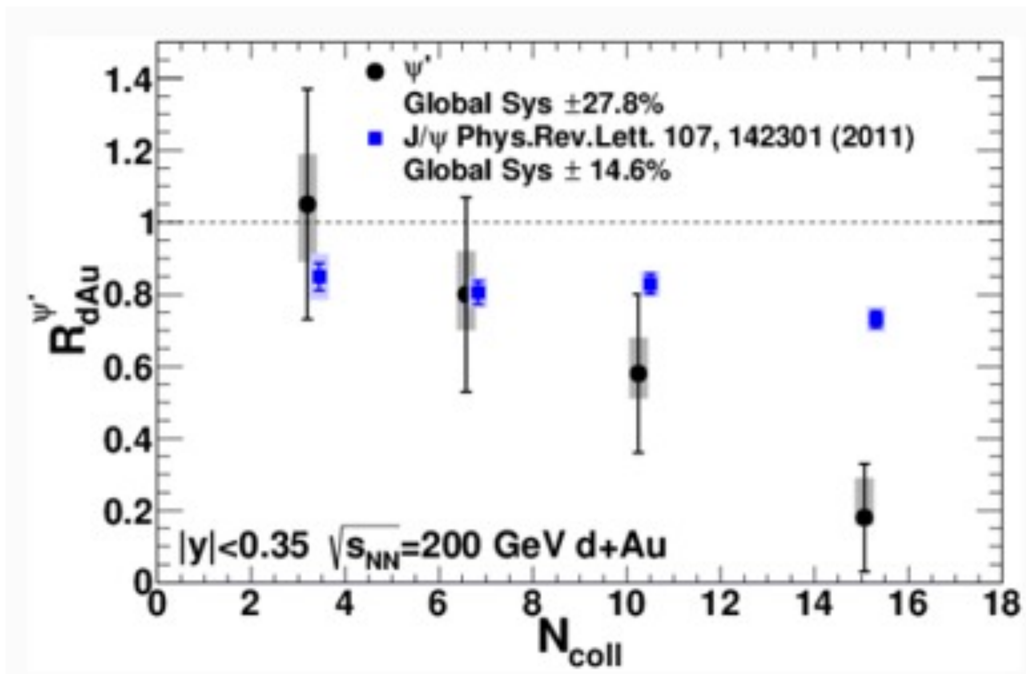


ψ’ modification at midrapidity

Very recently **finalized** PHENIX measurement of ψ’ R_{dAu} at midrapidity (arXiv:1305.5516, PRL in press).

ψ’ suppression in central collisions is very strong relative to J/ψ suppression!





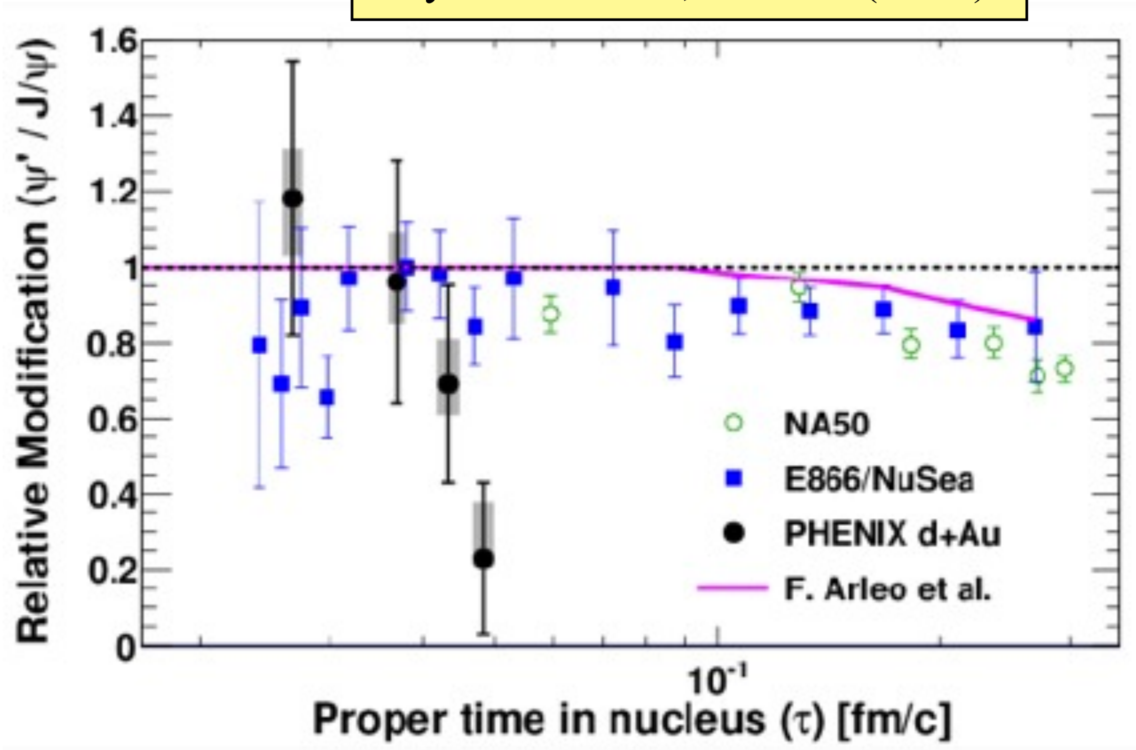
What were we expecting?

If ψ’ suppression was due to breakup of a colorless expanding meson by nucleons, it should be **identical to the J/ψ suppression**:

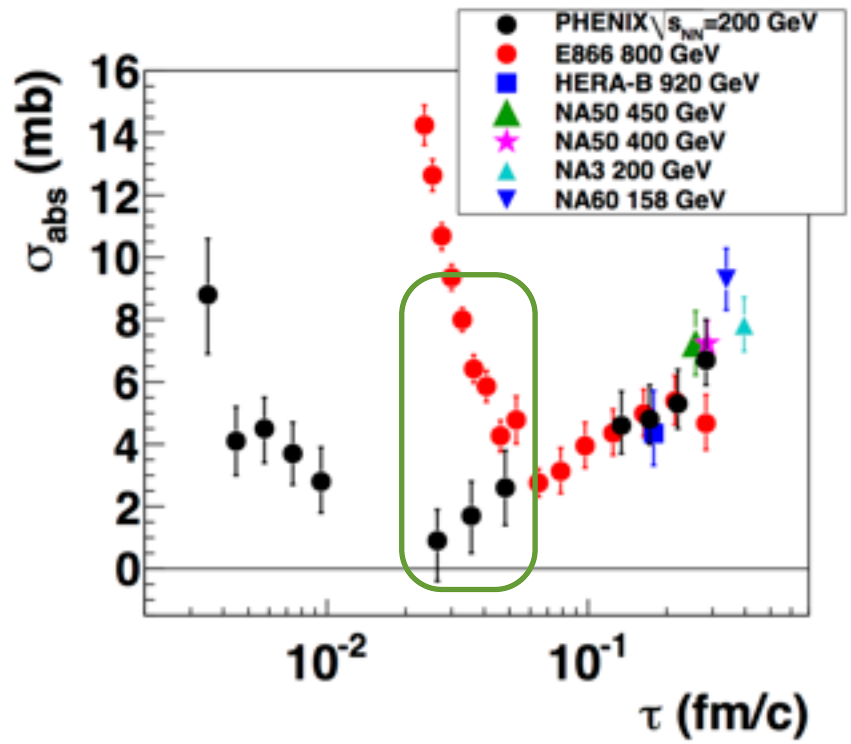
- At y=0 at 200 GeV, τ is so short the final meson size difference between J/ψ and ψ’ does not come into play.

Calculation by F. Arleo, et al., Phys. Rev. C 61, 054906 (2000)

ψ’ suppression is clearly not due to breakup alone.

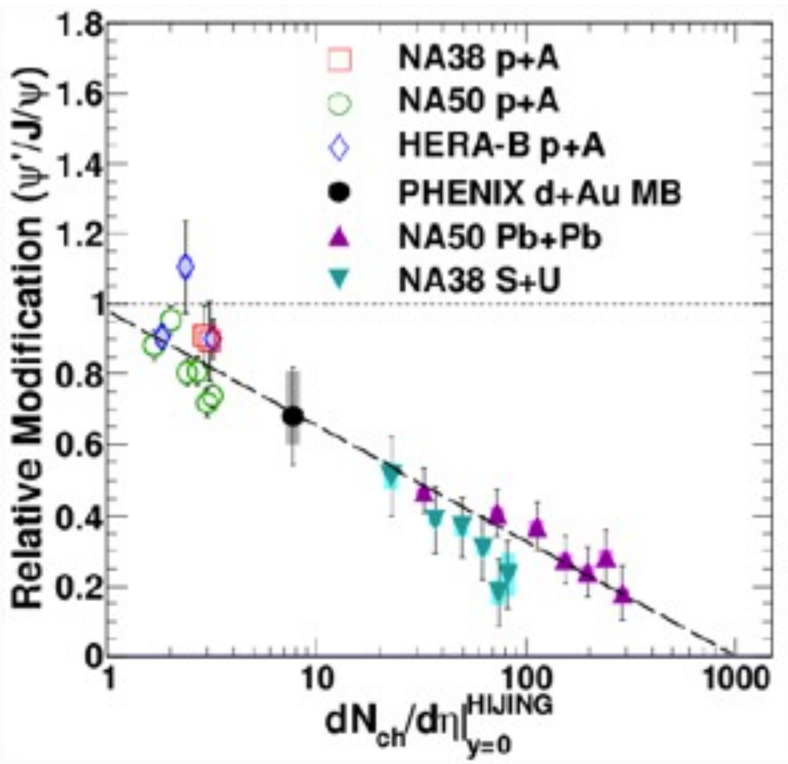


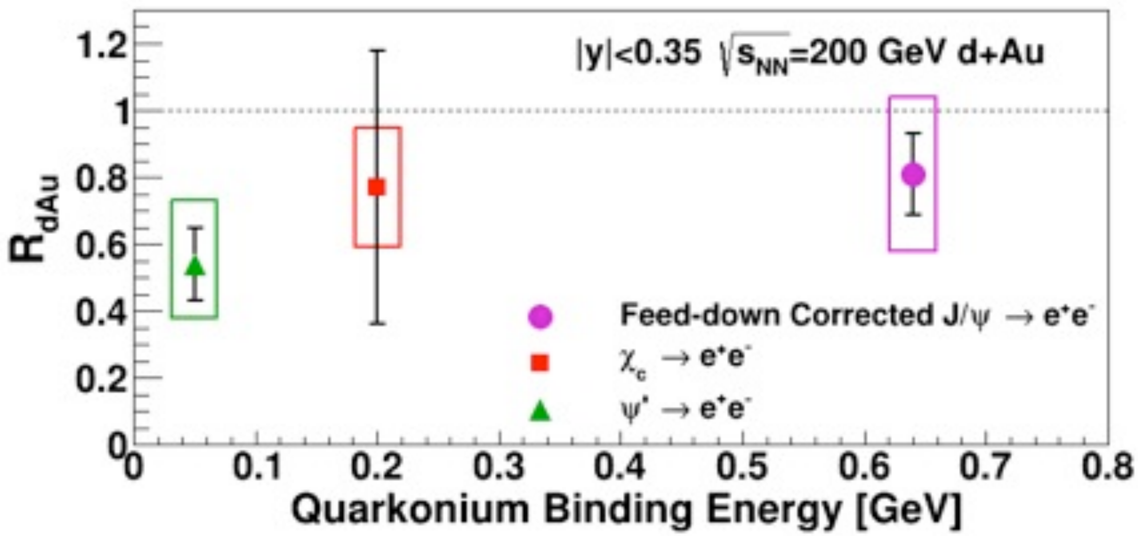
Possible explanations?



Inclusive J/ψ suppression at midrapidity varies strongly with collision energy.

But there seems to be a systematic increase of ψ' to J/ψ **relative** modification with multiplicity.
- hot matter effect?





Conclusions

CNM effects at **forward** and **backward** rapidities reflect very different mechanisms, correspond to different crossing time scales.

The **backward** rapidity PHENIX inclusive J/ψ data seem consistent with shadowing plus breakup of a color neutral physical meson. They do not show evidence of large hot matter effects.

The **forward** rapidity PHENIX and E866 data show large suppression that is clearly not related to breakup, perhaps E loss.

The **midrapidity** data fall in a region where it is not clear what the mechanism is. But all CNM effects are **smaller** at midrapidity.

- - - Comparison to open HF leptons seems consistent with all of that.

Midrapidity is probably the best place to isolate hot matter effects in A+A, because CNM effects are minimal.

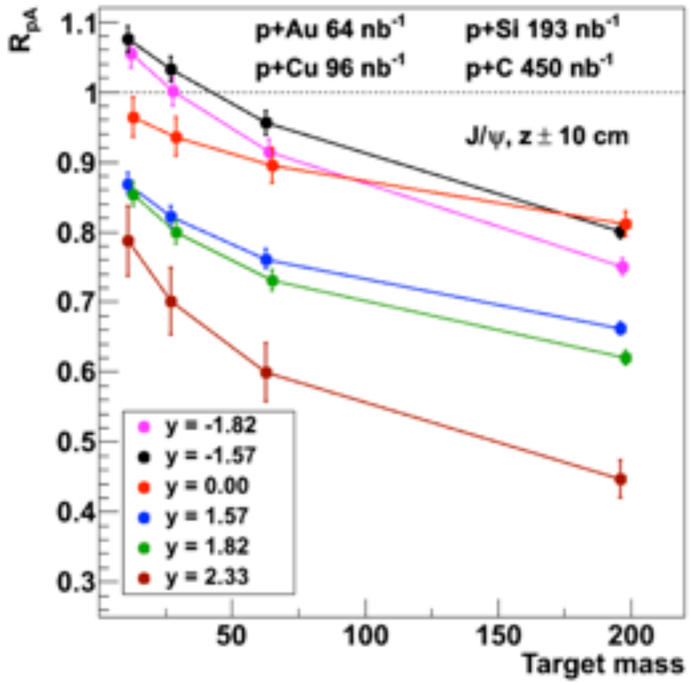
The **ψ'** is much more strongly suppressed than expected from breakup. Perhaps hot matter effects, combined with weak binding?

Backup

Upcoming: p+A with PHENIX

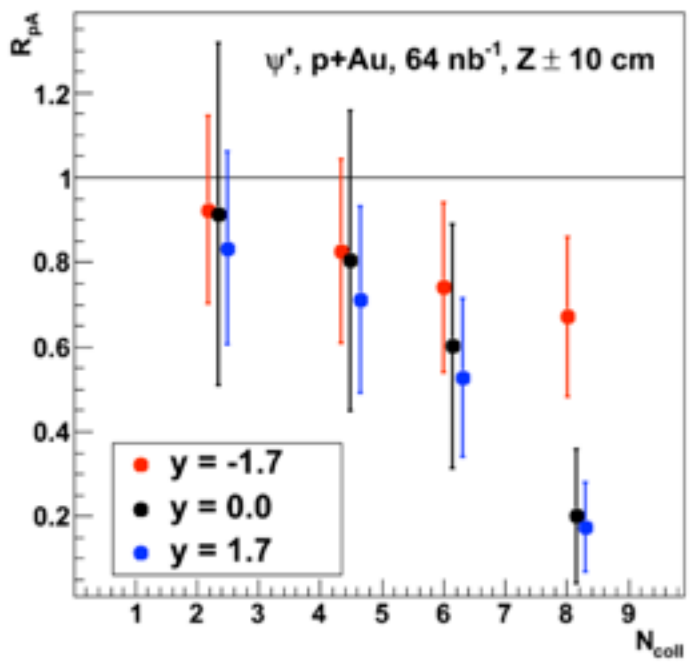
J/ψ in p+(Au, Cu, Si) at 12 rapidities

- Measure J/ψ R_{AA} vs centrality for p+(Au, Cu, Si).
- Study CNM effects vs mass at 200 GeV.
- Compare varying centrality with varying mass.



ψ' in p+Au at forward, mid, backward y

- Vary mix of CNM effects on ψ' production.
- Feasible only in p+Au case due to statistical precision.



Longer term: sPHENIX

For **quarkonia**, our major goal has always been the **characterization of the Debye screening as a function of temperature**.

The SPS, RHIC and LHC J/ψ results have already shown the value of high quality **data covering a broad range of initial temperatures**.

The proposed large acceptance **sPHENIX** detector, which is designed as a **jet detector**, will also – with added tracking and electron ID, make good **separated Upsilon measurements**.