Nuclear matter effects on J/ψ production in Cu+Au and U+U collisions in PHENIX

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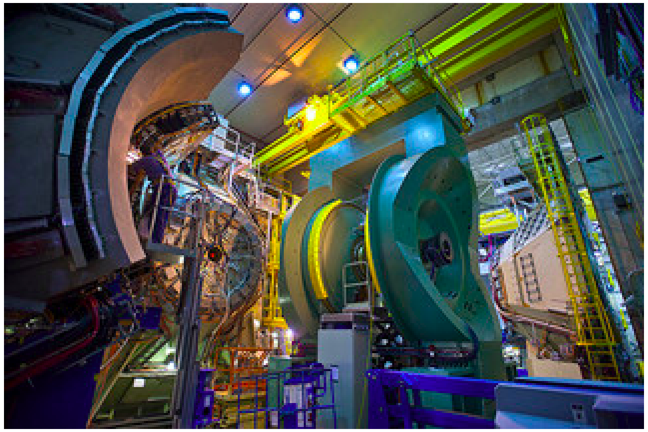


DIS 2014 XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects

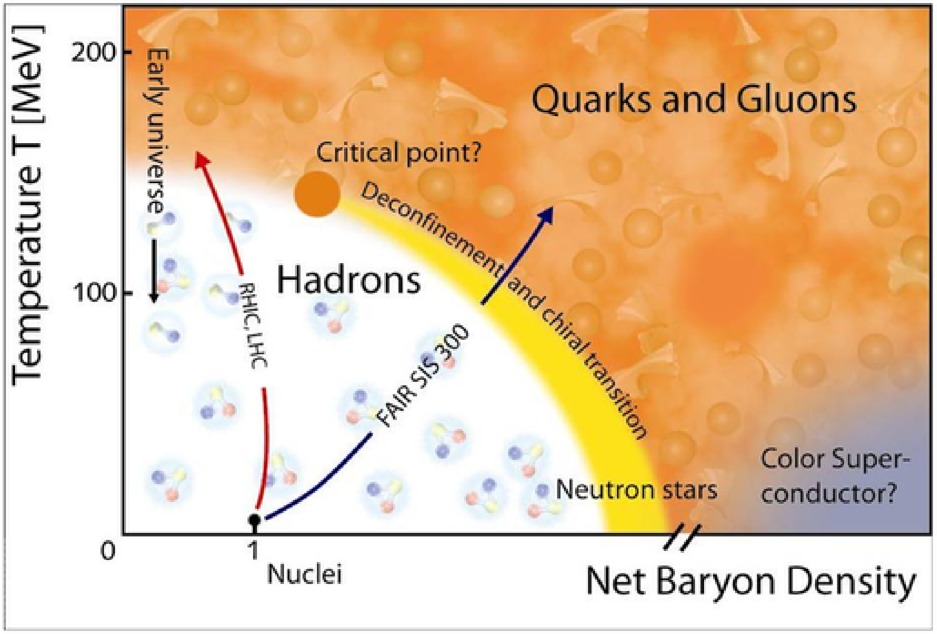
Heavy Ion collisions and QGP

- The hot, dense state of nuclear matter,

  Quark Gluon Plasma

  - deconfined, color charged state of quarks and gluons
  - experimentally achievable with heavy ion collisions
    - High temperature and/or baryon density

QCD phase diagram of nuclear matter



Lattice QCD predictions:

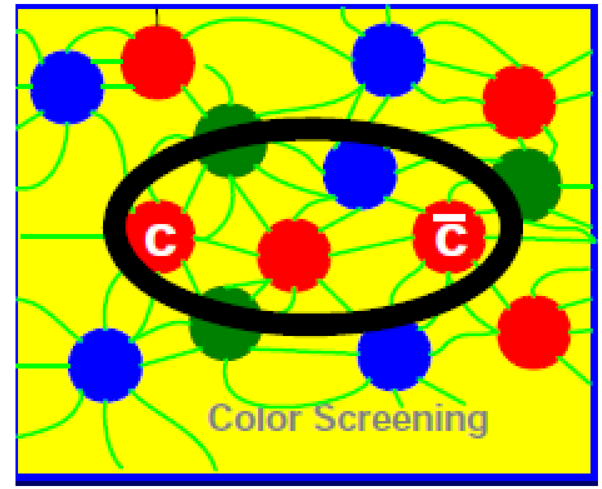
- T_c ~ 170 MeV
- ε_c ~ 1 GeV/fm^3 (>5x Nuclear hadron matter)

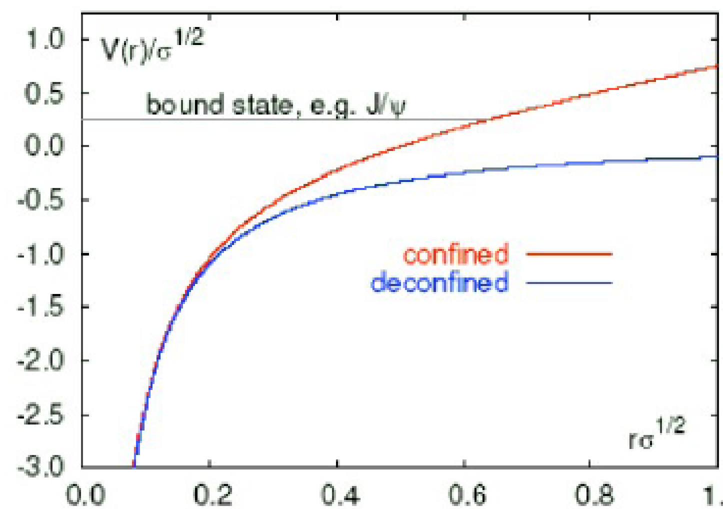
Heavy quarks & Heavy ion collisions

- "*If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region.*"
  - Original idea, *Matsui & Satz,1986*

- The color (Debye) screening modifies the particle potential due to the charge density of the surrounding medium

- Quarkonium potential in the medium becomes shallower
  - With increasing T different $q\bar{q}$ states "sequentially melt"
  - J/ψ becomes unbound → suppression in QGP!





$$V(r) = \sigma r - \frac{\alpha}{r}$$

$$V(r,T) \quad \frac{\sigma}{\mu}\left\{1 - e^{-\mu r}\right\} - \frac{\alpha}{r} e^{-\mu r}$$

What can modify J/ψ production?

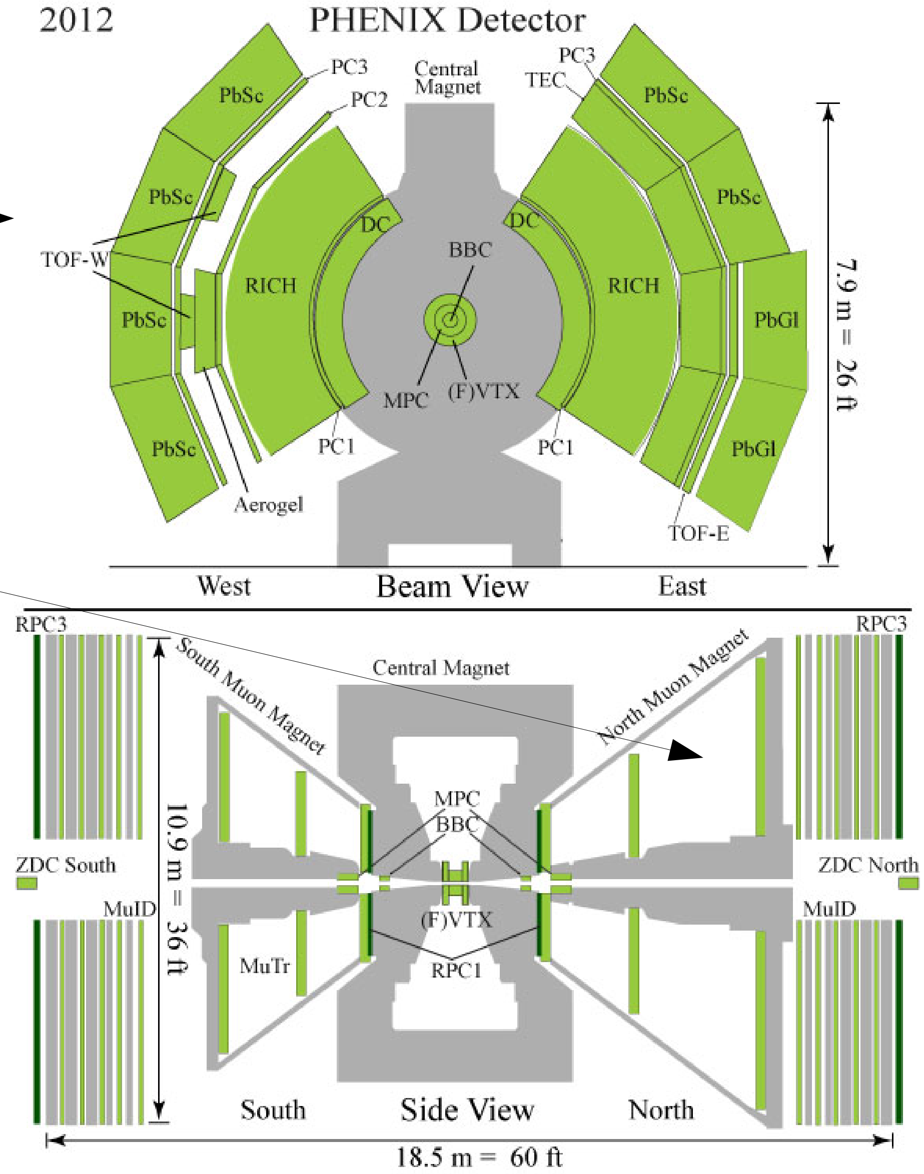
Phenix has good capabilities to measure J/ψ and probe quarkonia deconfinement and other mechanisms which modify its production

- Two main sources:
- Cold nuclear matter effects (CNM)
  - due to the nuclear target (no QGP, systems like d+Au)
- Hot nuclear matter effects (HNM)
  - modification in the created QGP

- Strategy:
  - Measure (then parametrize) CNM effects in p(d)+A
  - A+A collisions will have both CNM+HNM effects
    - “Remove” CNM effects
    - Learn about QGP mechanisms which modify charmonium

J/ψ measurements in Phenix

- Central arms: electrons
  - J/ψ → e+/e-
  - |η|<0.35, $\Delta\phi = \pi$
  - pe>0.2 GeV/c
- Forward rapidity arms: muons
  - J/ψ → μ+/μ-
  - 1.2 <|η|<2.2, $\Delta\varphi = 2\pi$
  - pμ > 1 GeV/c



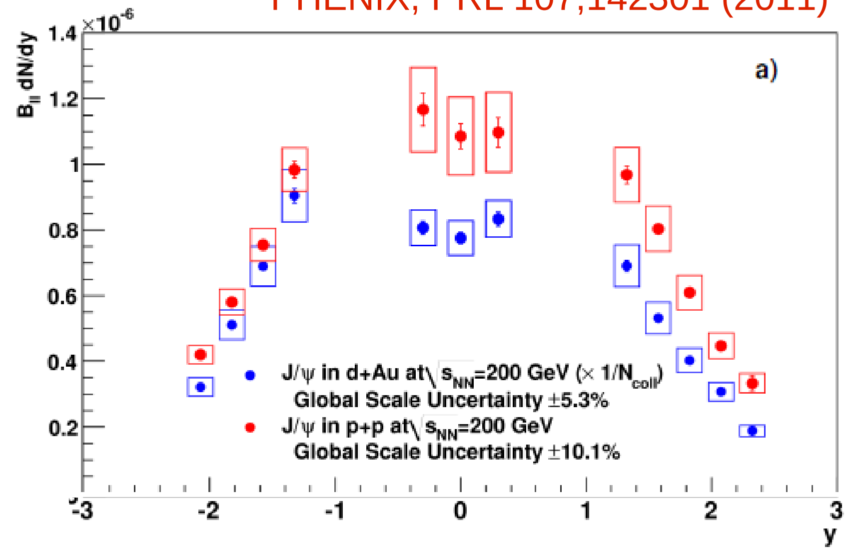
- Broad contribution to the world's J/ψ measurements
  - Large energy range: $\sqrt{s_{NN}}$=39-200 GeV
  - Broad range of collision species p+p, d+Au, Cu+Cu, **Cu+Au**, Au+Au, **U+U**

J/ψ in cold nuclear matter

Phenix d+Au

- d+Au "cold" and asymmetric system
  - Rapidity dependent suppression
    - Compared to pp

PHENIX, PRL 107,142301 (2011)



Quantify suppression in A+B collisions as the ratio of yields in that system to the yield expected from ***binary scaled**** *pp* collisions

$$R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

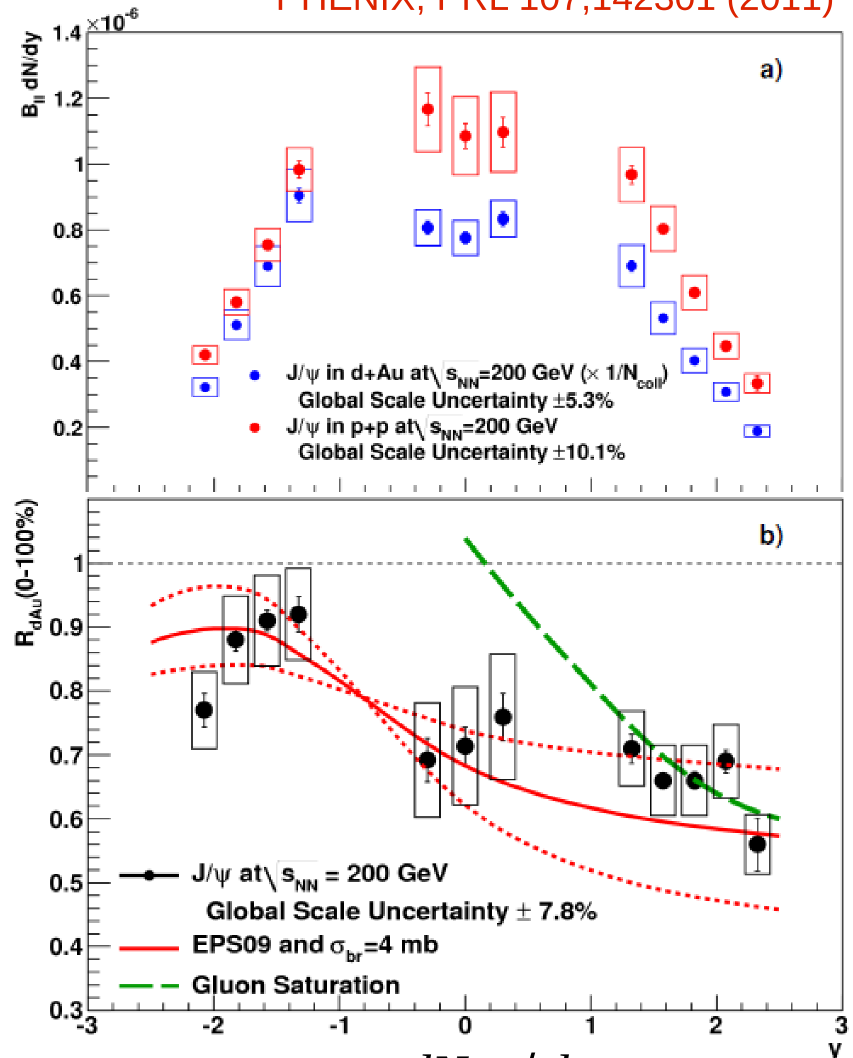
* Binary scaling means the number of hard collisions each nucleon suffers

J/ψ in cold nuclear matter

Phenix d+Au

- d+Au “cold” and asymmetric system
  - Rapidity dependent suppression
    - Compared to pp
- More suppressed at forward (d-going) rapidity
- CNM effects
  - Modification of gluon densities in nucleus → Nuclear modification of pdfs in nuclear target (EPS09)
  - Gluon saturation → Color Glass Condensate

PHENIX, PRL 107,142301 (2011)



$$R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T}$$

J/ψ in cold nuclear matter

- CNM effects
  - Complex admixture of different mechanisms
  - Strongly dependent on rapidity
- Open questions:
  - Can we factorize them?
  - Are there HNM effects in p(d)+Au?
    - Collective phenomenon seen
    - Do they affect J/ψ production?

Gluon shadowing / antishadowing

Initial parton energy losss

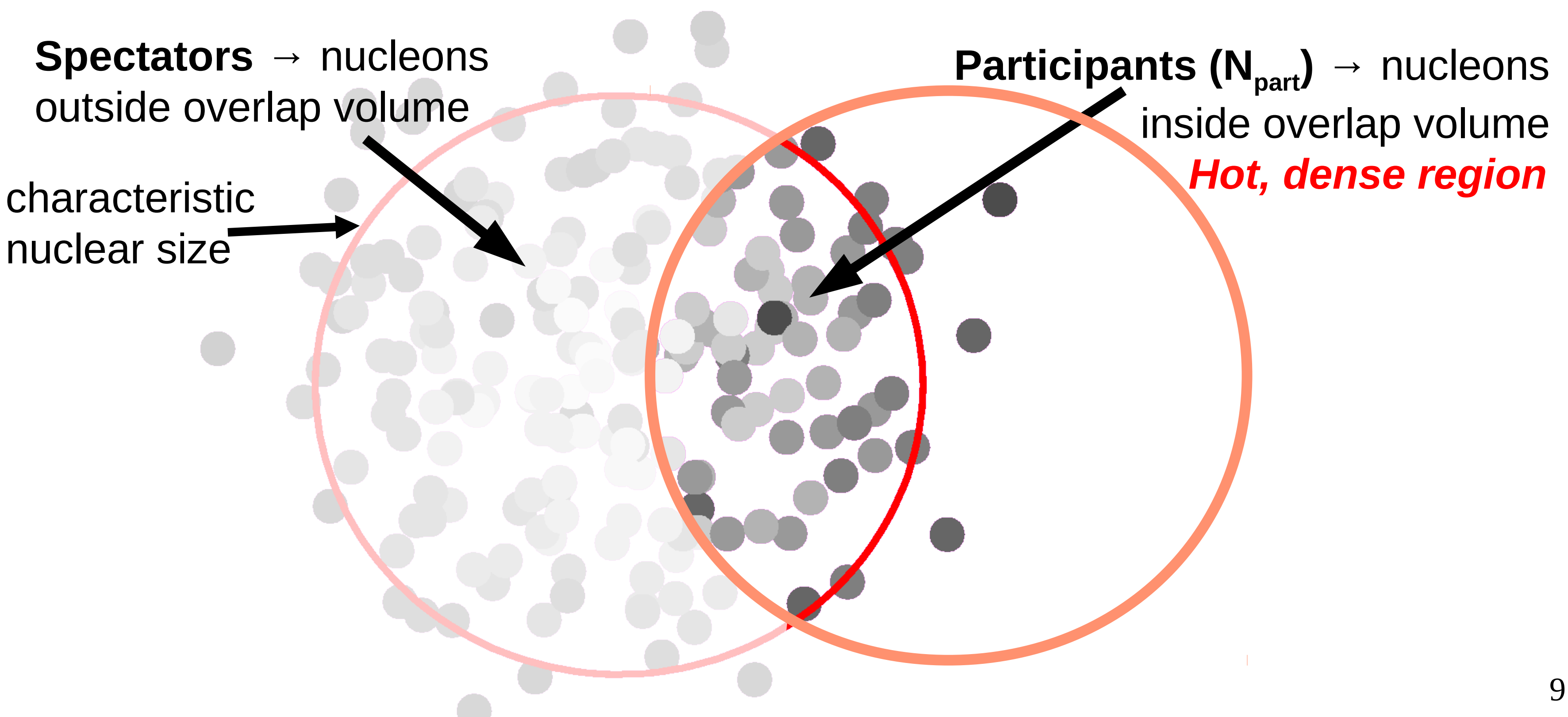
Nuclear transverse momentum broadening

cc-bar breakup in the target nucleus

Gluon saturation

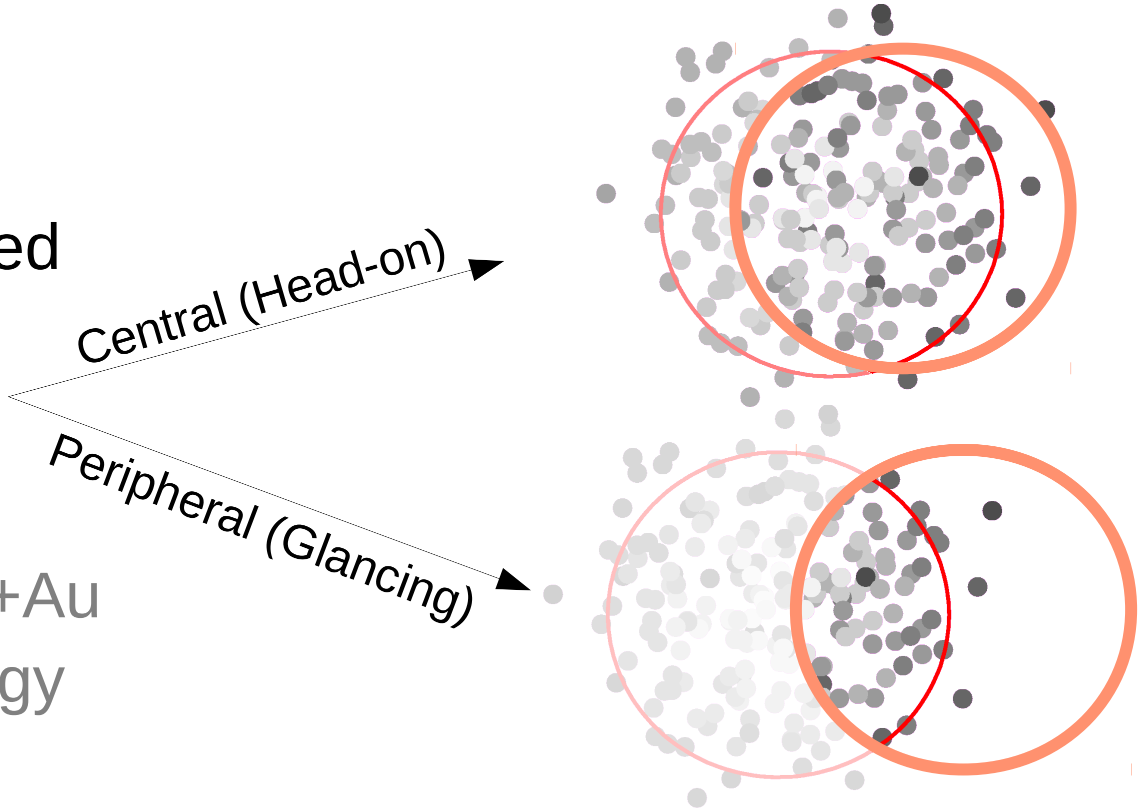
Heavy ion collisions & Hot Nuclear Matter

- HI collision
  - How to control the properties of the created state



Heavy ion collisions & Hot Nuclear Matter

- HI collision
  - How to control the properties of the created state
    - Collision centrality
    - System size
      - e.g. Cu+Cu vs Au+Au
    - Center of mass energy



Heavy ion collisions & Hot Nuclear Matter

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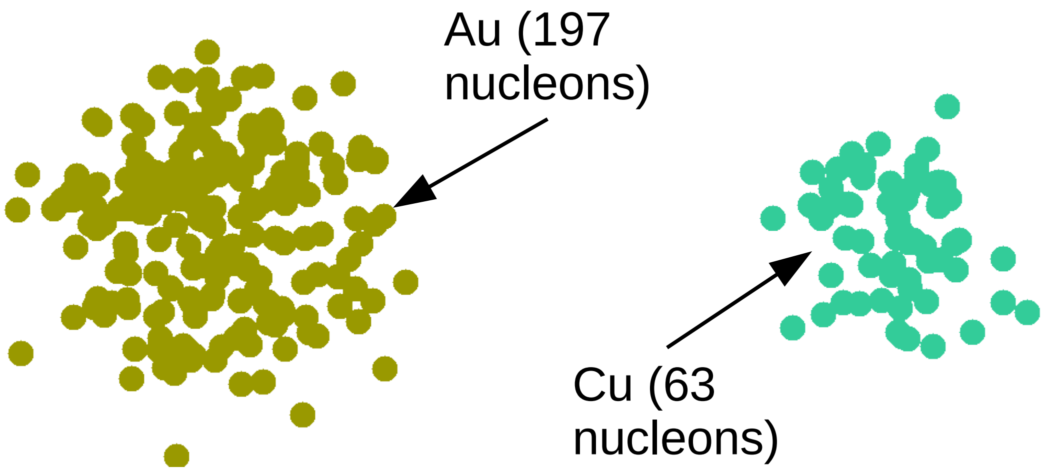
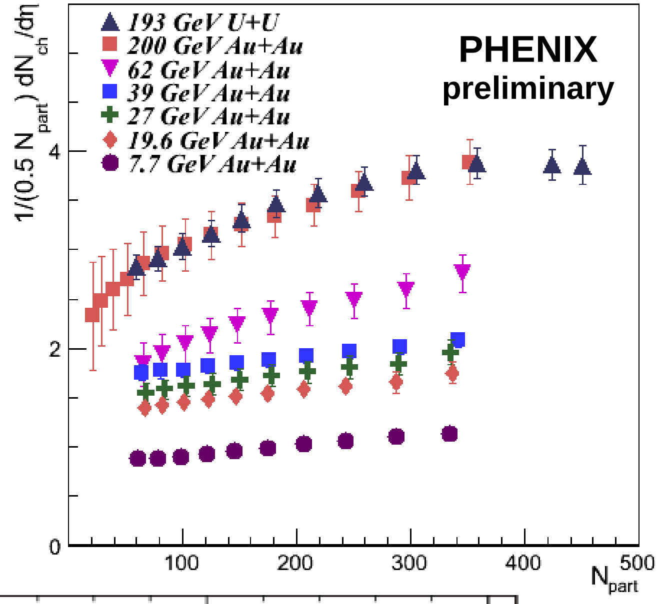
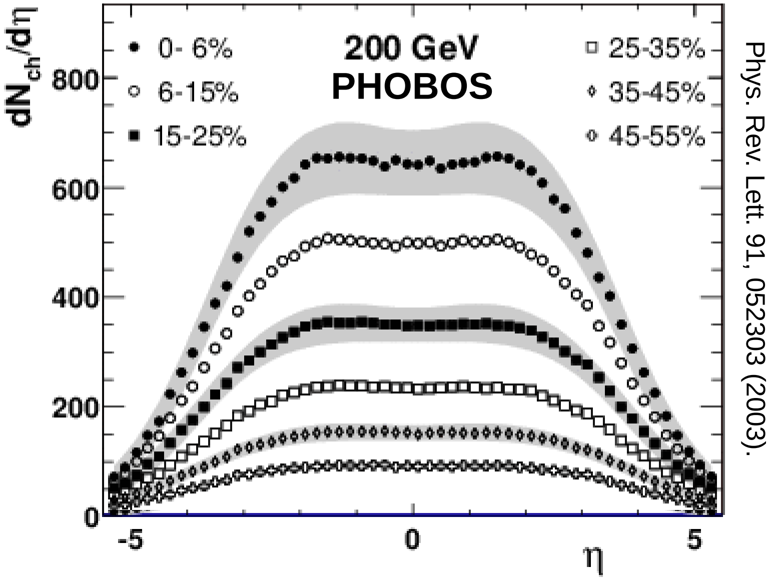


Global particle production & Hot Nuclear Matter

- Charged particle density – measure of the initial energy density of the created state
  - Increases with increasing collision energy.
  - There is an increase for more central collisions at all collision energies.
  - Decreases at higher rapidity.





J/ψ production & Hot Nuclear Matter

- Au+Au measurements in Phenix
  - Energy dependence
  - Rapidity dependence

J/ψ energy dependence

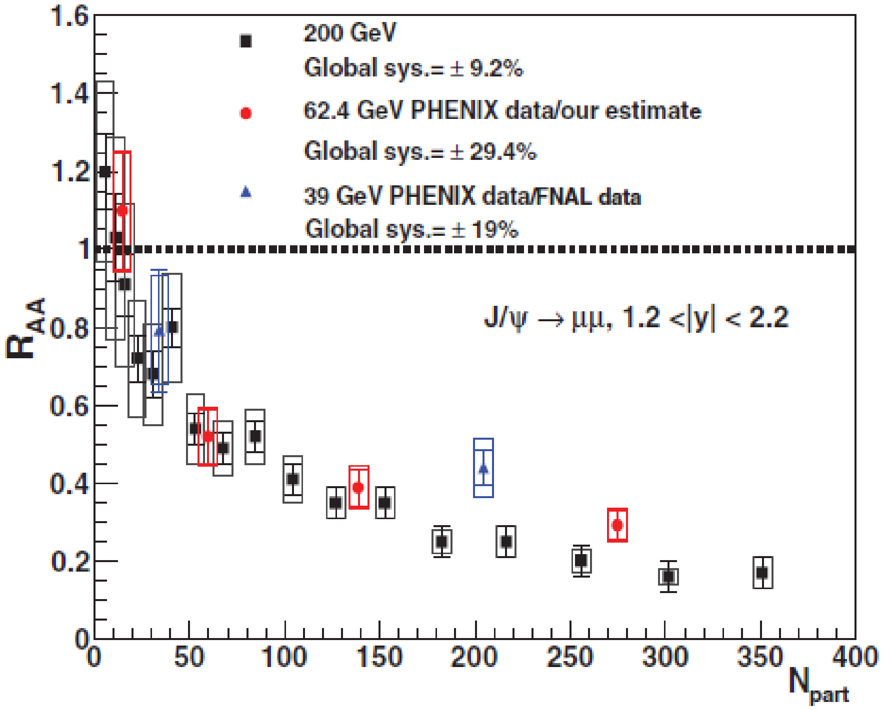
Phenix Au+Au

- Forward rapidity
  - Suppression with respect to pp collisions
  - Suppression increases slightly with increasing energy density (N_{part})
  - Very little, if any, energy dependence

HNM effect

Competing effects of dissociation and regeneration (corrected for CNM)

PHENIX, PRC 86, 064901 (2012)

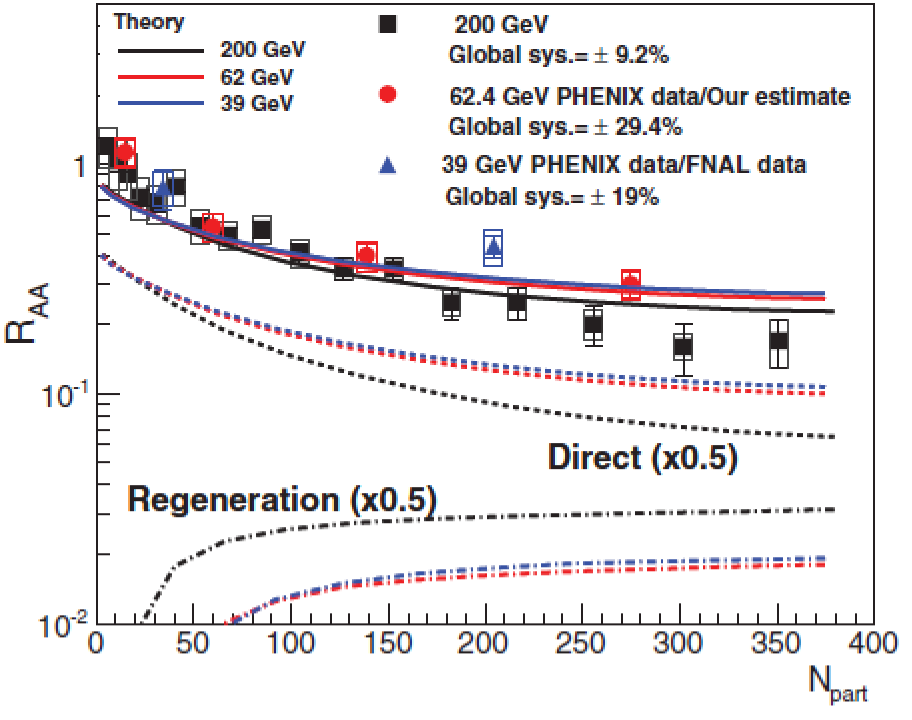


J/ψ energy dependence

Phenix Au+Au

- Forward rapidity
  - Suppression with respect to pp collisions
  - Suppression increases slightly with increasing energy density (N_{part})
  - Very little, if any, energy dependence
- HNM effect
  - Competing effects of dissociation and regeneration (corrected for CNM)

PHENIX, PRC 86, 064901 (2012)



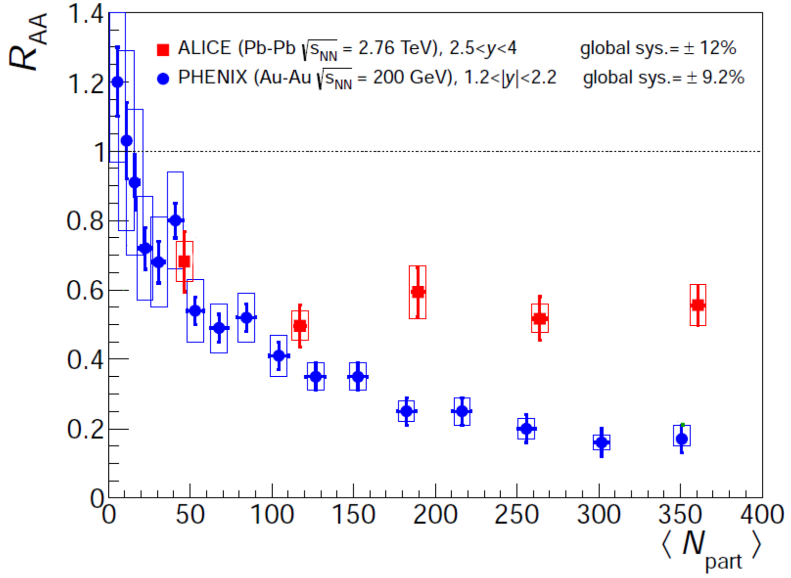
Model: Zhao and Rapp, PRC 82,064905 (2010)

J/ψ energy dependence

Phenix Au+Au

- At LHC
  - Suppression is much reduced

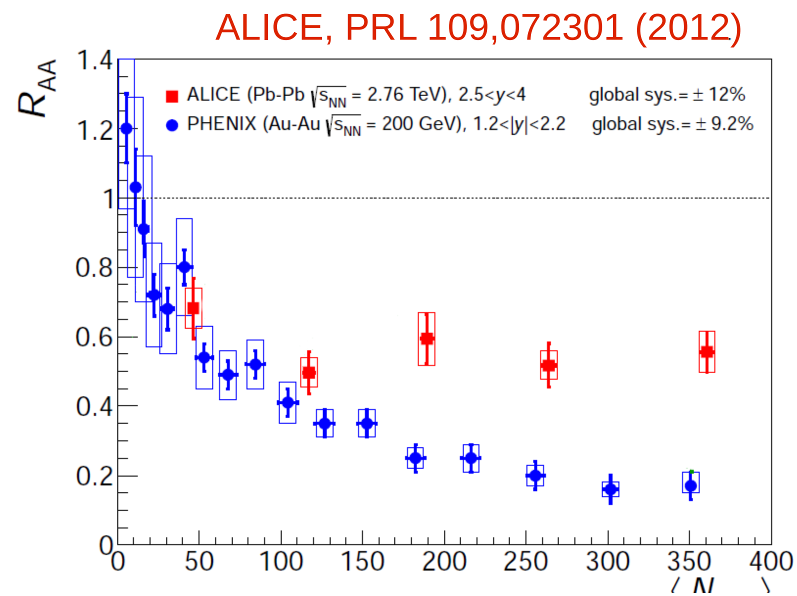
ALICE, PRL 109,072301 (2012)

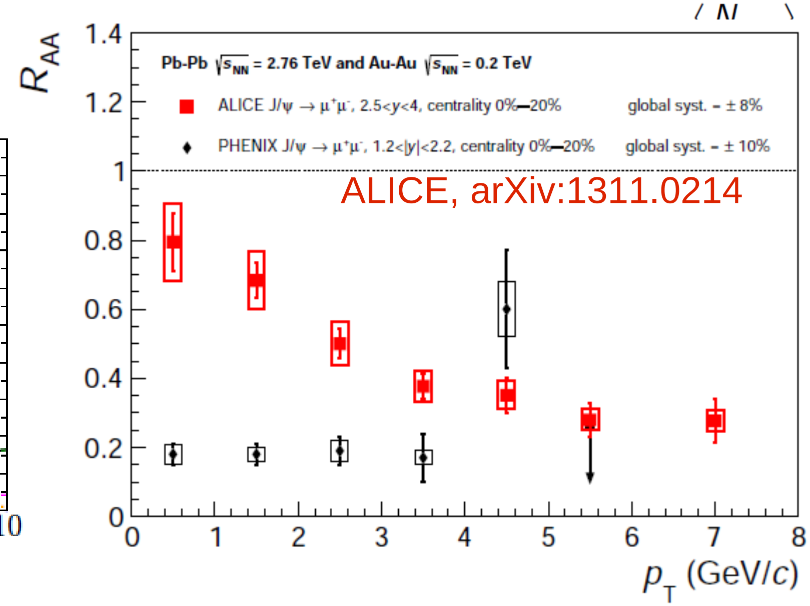


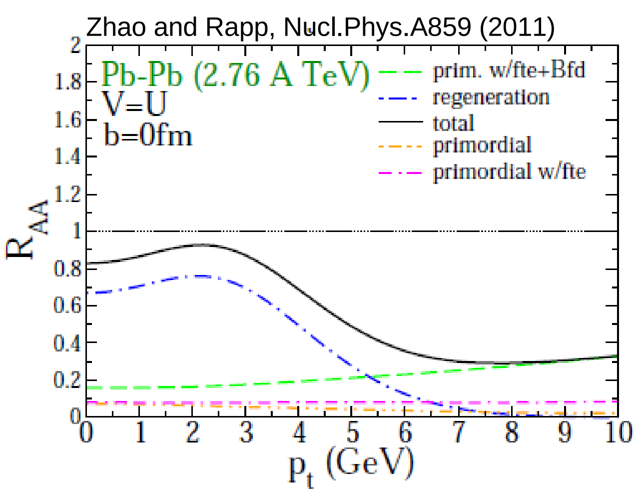
J/ψ energy dependence

Phenix Au+Au

- At LHC
  - Suppression is much reduced
- Recombination (coalescence) important at LHC
  - Smaller R_{AA} at low p_T at RHIC energy
  - Larger v_2 at LHC



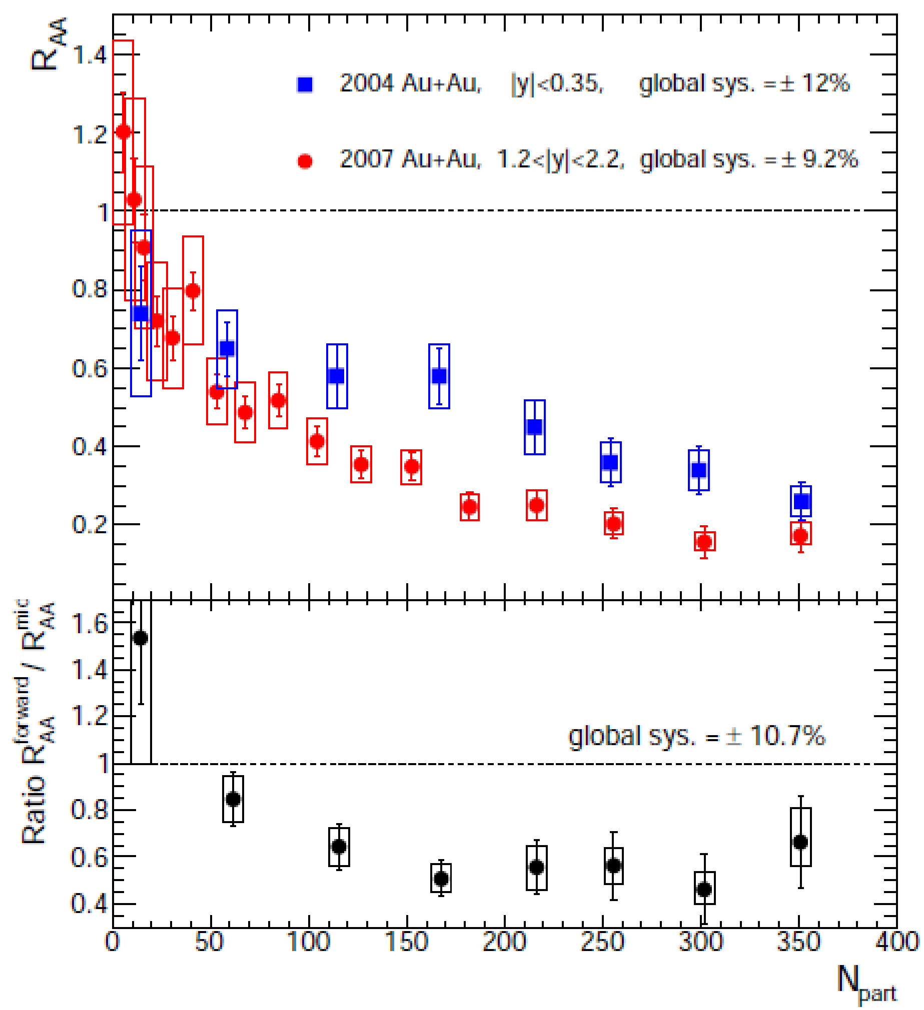




J/ψ rapidity dependence

- Stronger suppression at forward/backward rapidity
  - Does not increase with increasing energy density as seen in charge particle multiplicity
- HNM effects
  - Coalescence
  - CNM effects?

PHENIX, PRC 84, 054912 (2012)



J/ψ in hot nuclear matter

- HNM effects
  - complex admixture of different mechanisms
  - strongly depend on rapidity

- Open questions:
  - Can we factorize CNM effects?
  - *Study new systems*
    - Cu+Au at 200 GeV
    - U+U at 193 GeV

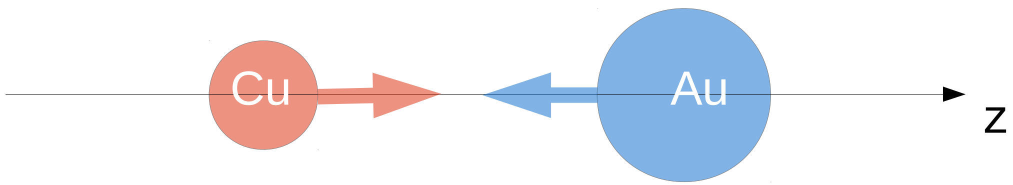
destruction
Color screening
Dynamical destruction
"melting"

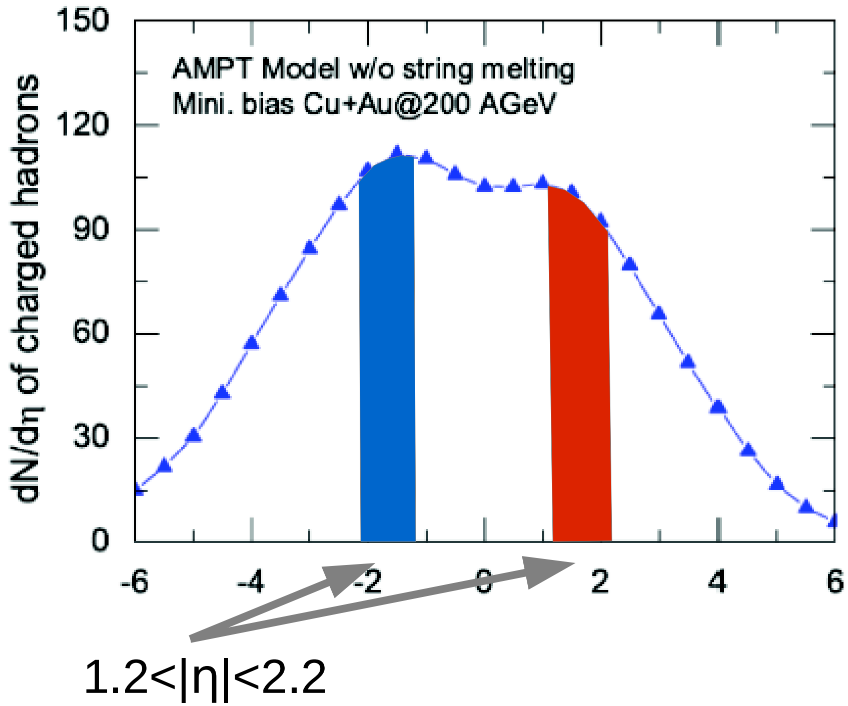
formation
Recombination
Coalescence

property change
Transverse momentum broadening
collective flow
Final state parton energy loss

Cu+Au: asymmetric system

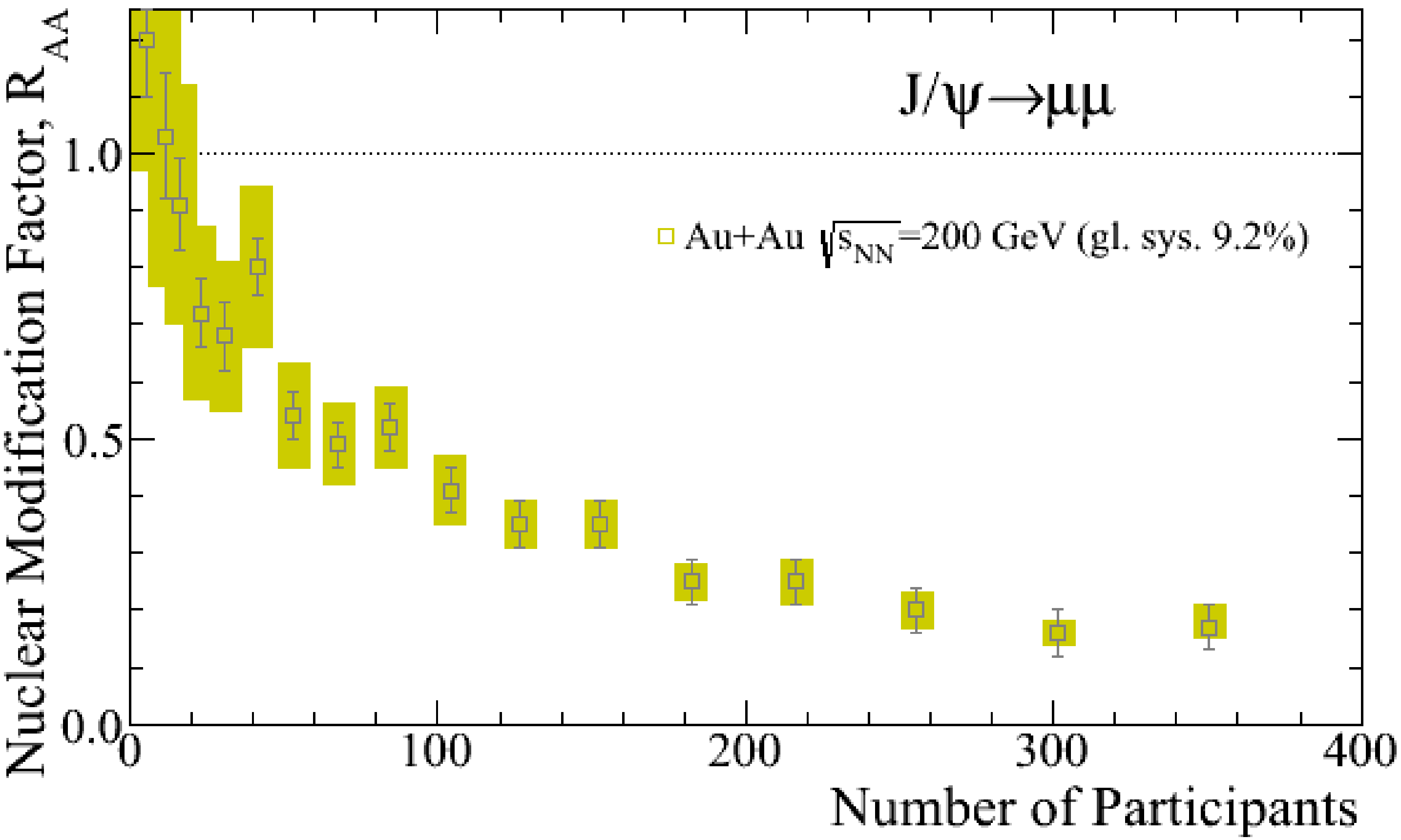
- Forward/Backward asymmetry
  - Along the beam axes
- Adds more variation to the initial state
  - Initial asymmetry → translates into asymmetric distribution of final particle density
- J/ψ expectations in Cu+Au
  - Similar to d+Au
    - CNM effects asymmetric
  - Similar to A+A → added HNM effects
    - But possibly asymmetric





J/ψ in Au+Au *vs* Cu+Au

Phenix Au+Au



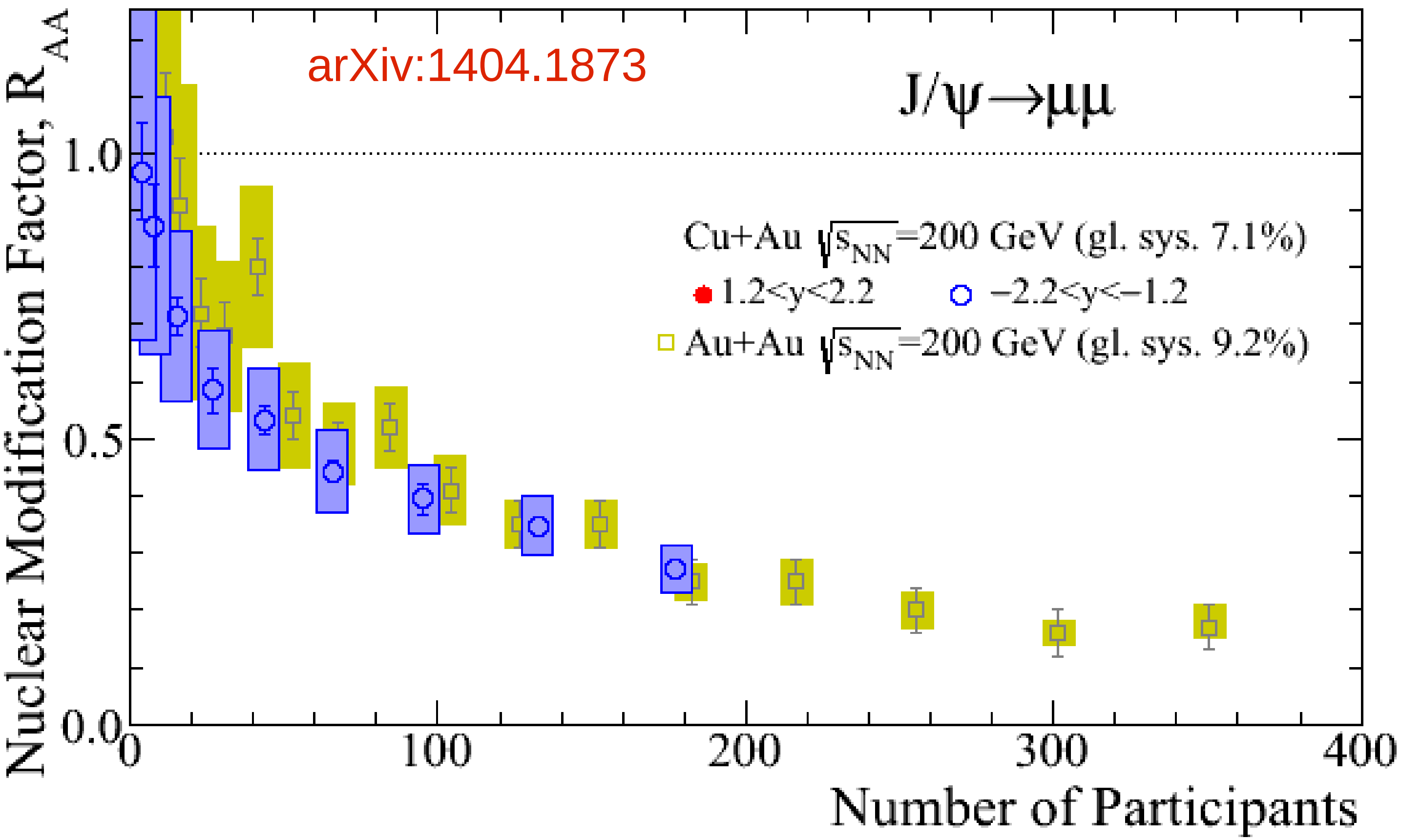
- Au+Au collisions
  - Strong suppression

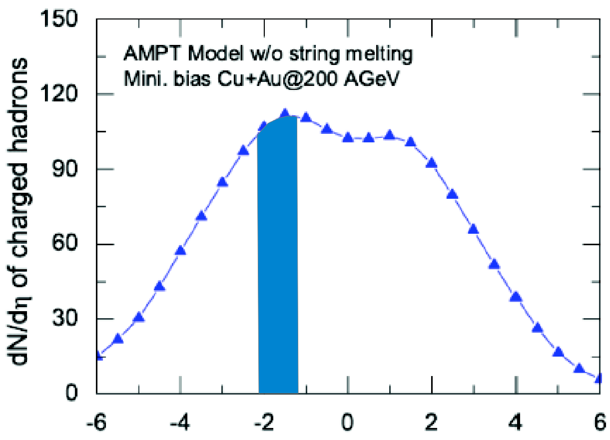
    (with respect to binary scaled pp collisions)

J/ψ in Au+Au *vs* Cu+Au

Phenix Cu+Au

backward rapidity



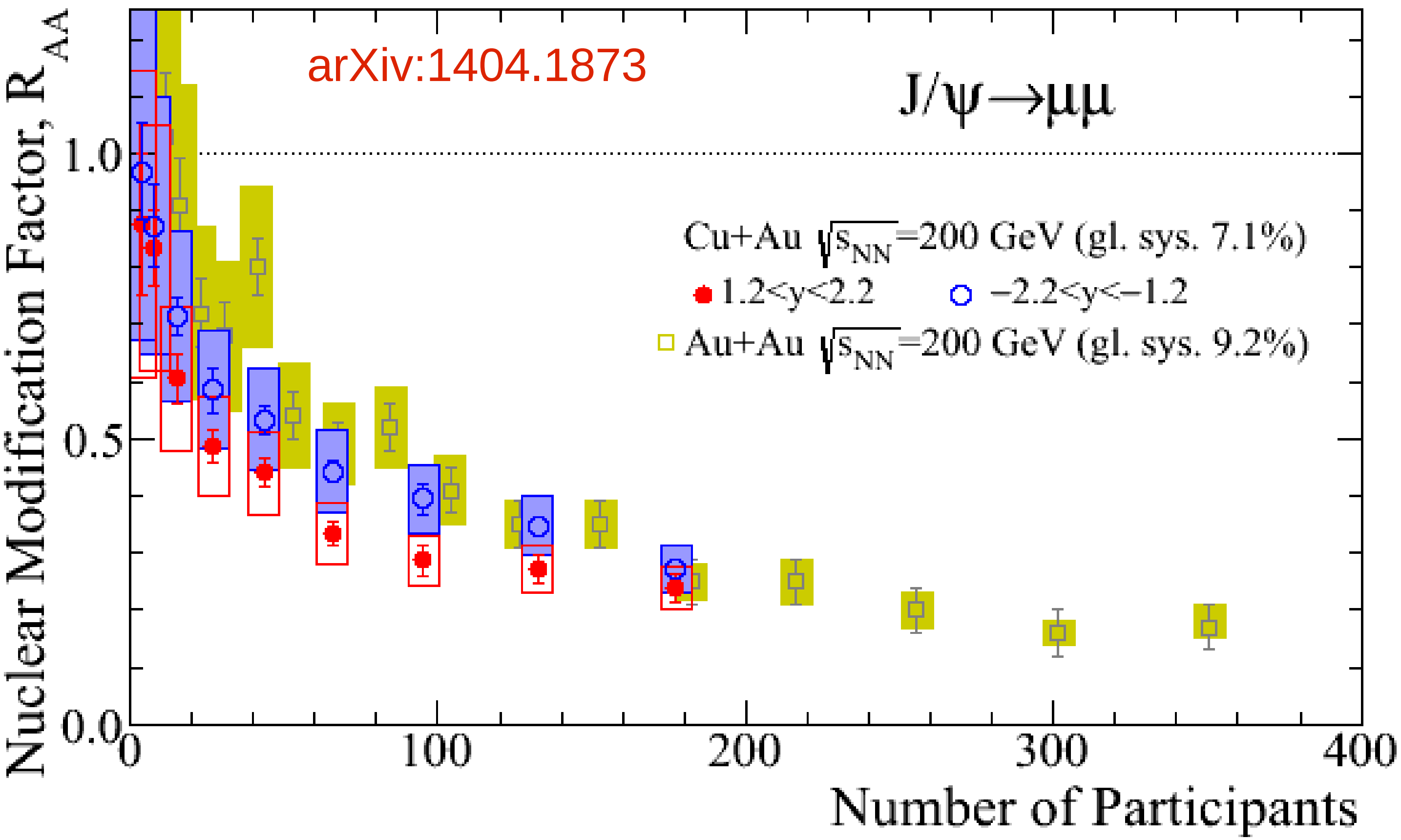


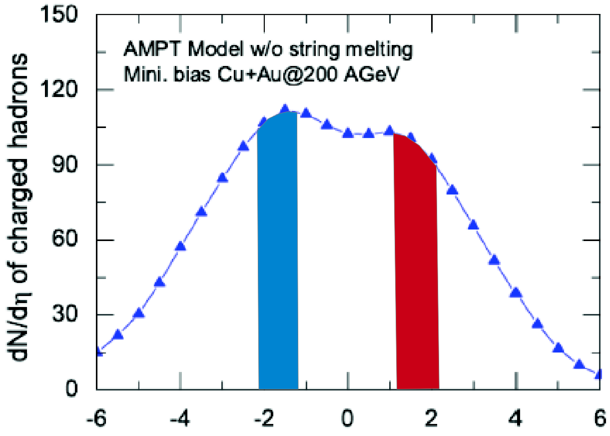
- Cu+Au: Au-going direction
  - Same suppression as in Au+Au at same N_{part}

J/ψ in Au+Au *vs* Cu+Au

Phenix Cu+Au

forward rapidity



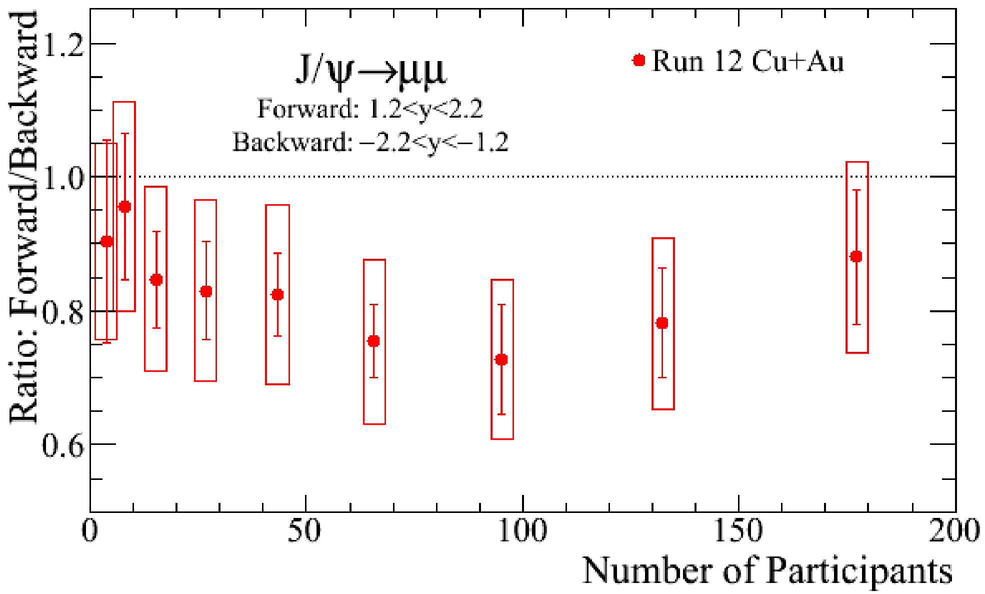


- Cu+Au: Cu-going direction
  - Less suppression than in Au+Au at same N_{part}

Cu+Au CNM effects

ratio forward/backward

Ratio ~ 20% for non-peripheral data



CNM effects → asymmetric in rapidity

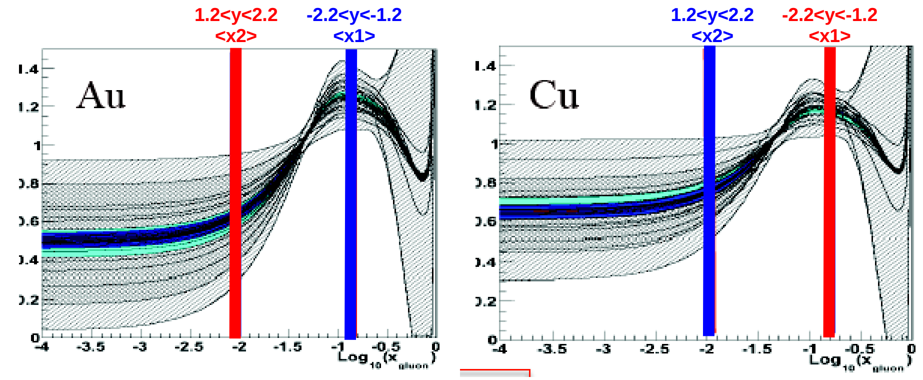
Forward CNM effects (Cu-going)

- gluon modification
  - J/ψ probes gluons at high-x in Cu, low -x in Au
- dynamical processes
  - Eloss, J/ψ short crossing proper time in Au
  - $c\bar{c}$ breakup by nucleon collisions, long crossing proper time in Cu

Backward(Au-going)

- Reversed CNM effects

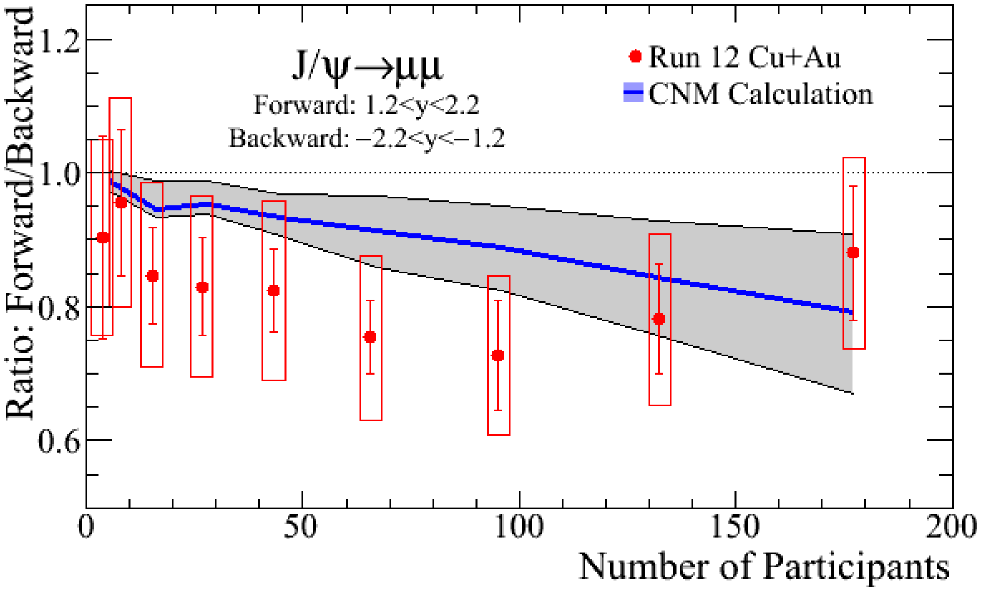
Rg



Cu+Au CNM effects

- CNM calculation
  - only includes shadowing
  - Uses EPS09 nPDF and 4 mb effective cross section at all rapidities
  - Shadowing effect comparable with data
  - Has same sign as data

J.Nagle, A.Frawley, L.Levy, M.Wisocky, PRC 84 044911 (2011)



- Not considering other mechanisms, e.g. color screening, which will increase the ratio

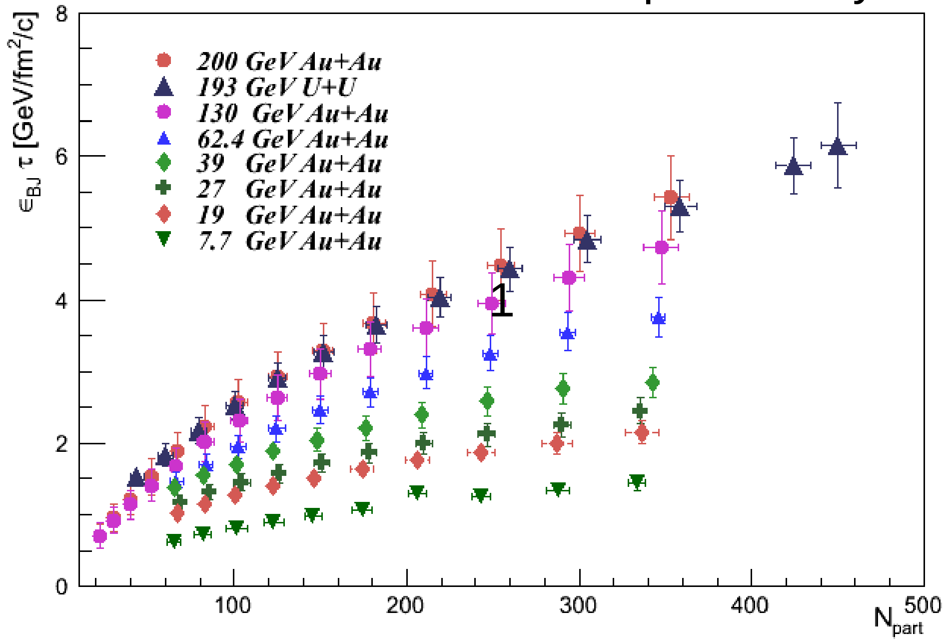
U+U: larger system

- New RHIC energy density record in U+U collisions

  e_B = 6.15 GeV/fm^2/c.

- Moderate increase from central Au+Au to very central U+U (20%)
  - Some expected up to 55% for tip-tip orientation
    - PRL 94, 132301 (2005)

Phenix preliminary



Upper U+U point 1% most central, all other 5% centrality bins

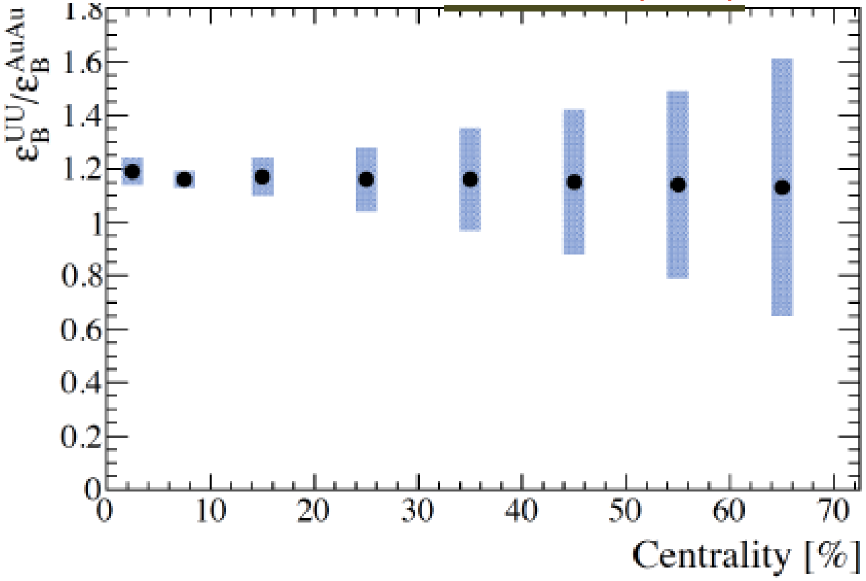
$$\epsilon_B = \frac{1}{\tau S_\perp}\frac{dE_T}{dy}$$

J/ψ in U+U predictions

- The higher energy density (15-20% expected in this model)
  - should lead to stronger suppression due to color screening
- Larger N_{coll} (than in Au)
  - Should lead to increased charm by statistical coalescence
- Both effects in opposite direction

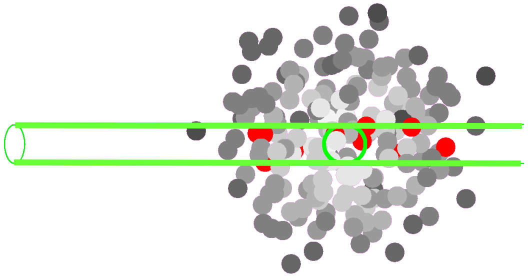
- CNM: gluon shadowing is expected to be similar for U+U and Au+Au

D.Kikoła, G.Odyniec, R.Vogt, PRC 84, 054907 (2011)

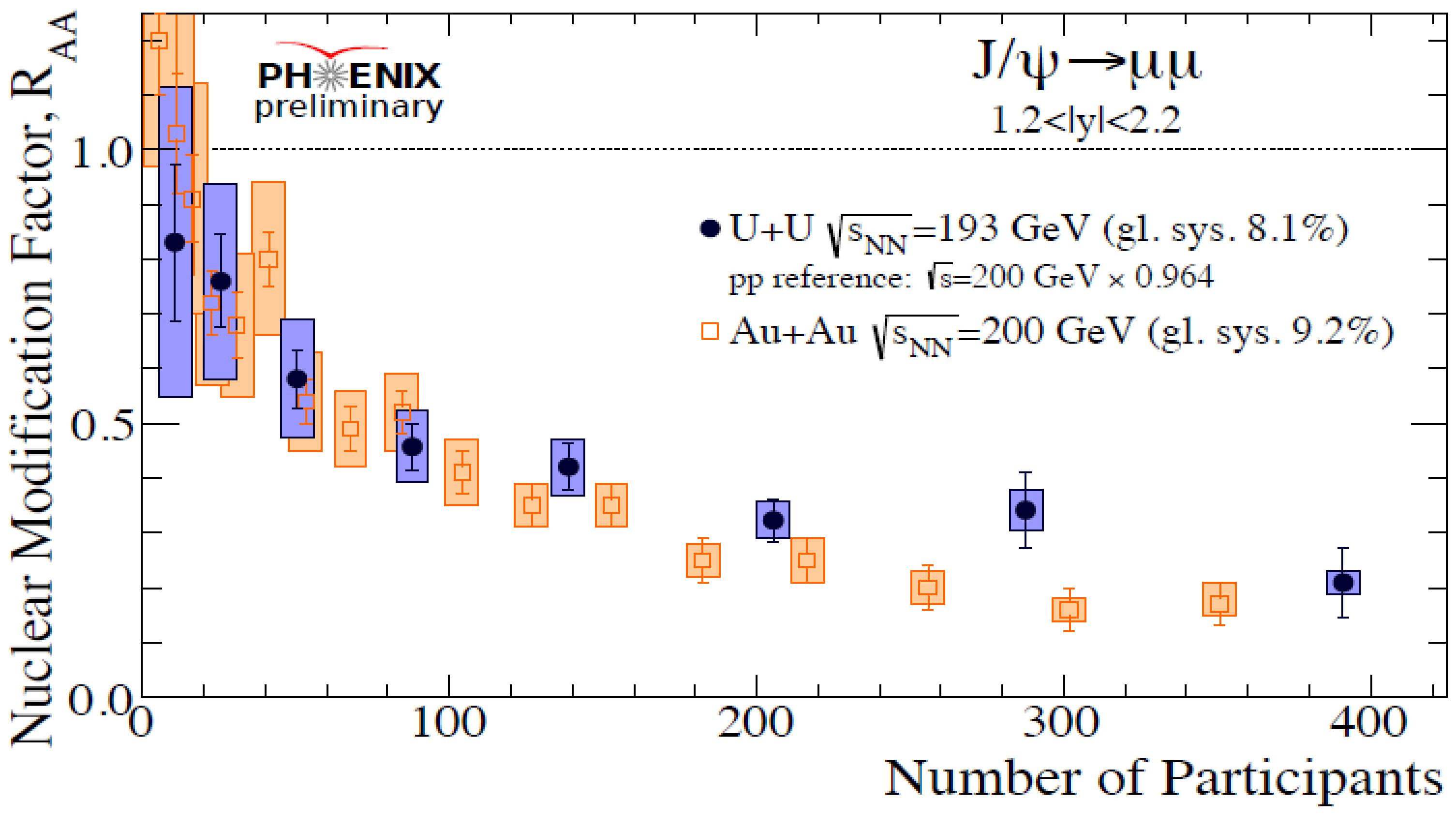


$$N_{J/\psi}^{stat} \propto N_c^2$$

N_{coll} – number of binary nucleon-nucleon collisions



J/ψ in U+U



Weaker suppression in central collisions in U+U?
Higher coalescence?

Conclusions

- Phenix has measured the J/ψ production in two new collision systems
  - Cu+Au
    - adds variation in the studied initial geometry.
    - shows significantly stronger J/ψ suppression in the Cu-going direction, consistent with the direction and magnitude expected from differences in EPS09 shadowing between Cu and Au.
  - U+U
    - a larger system than Au+Au.
    - J/ψ suppression seems to be slightly less than Au+Au at the same rapidity for central data.

Backup

Charmonium measurements in A+A

There is now a long history of studying charmonium in A+A collisions.

$\sqrt{s_{NN}}$ (GeV)	Species	Rapidity	Experiment
17.3	Pb+Pb, In+In	$0 < y < 1$	NA50,NA60
19.4	S+U	$0 < y < 1$	NA38
64, 39	Au+Au	$-2.2 < y < -1.2$ $1.2 < y < 2.2$	PHENIX
193	U+U	$2.2 < \|y\| < 1.2$	PHENIX
200	Au+Au, Cu+Cu	$2.2 < \|y\| < 1.2$ $\|y\| < 0.5$	PHENIX
200	Cu+Au	$-2.2 < y < -1.2$ $1.2 < y < 2.2$	PHENIX
2760	Pb+Pb		ALICE

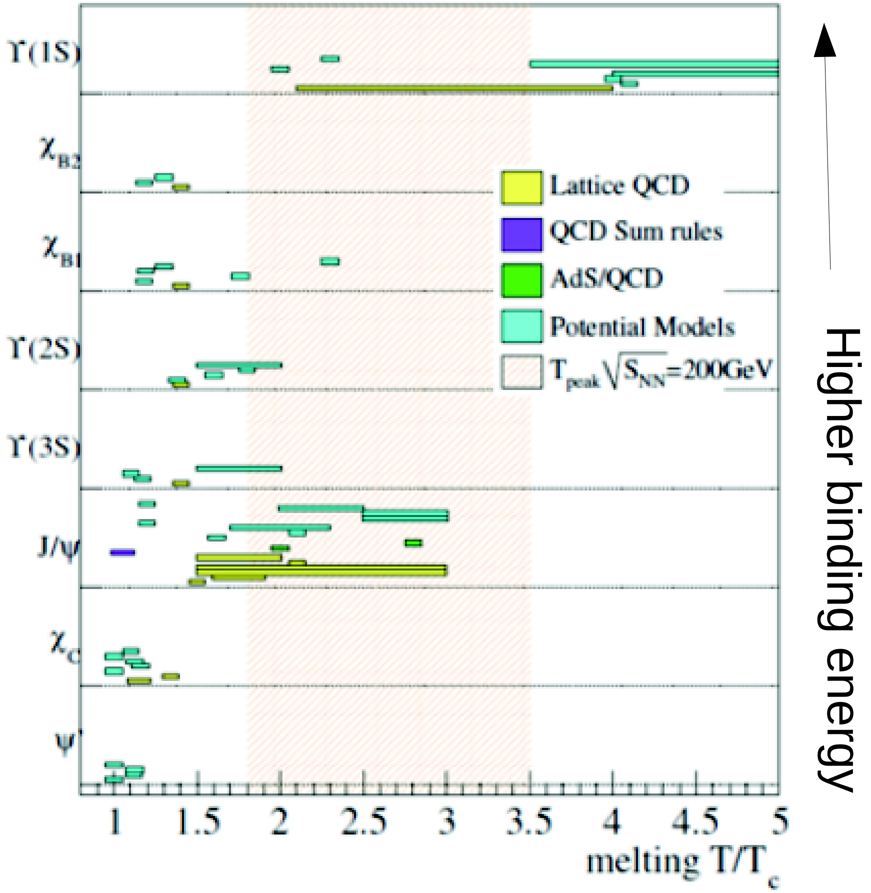
Heavy quarks & Heavy ion collisions

- Heavy quarks are produced during the collision of two nuclei – important probe
- Any modification in their production with respect to pp
  - Signal a deconfined state, QGP

    (*Matsui & Satz PLB 178, 416(1986))*

    Different charmonium states have different binding energy

    Suppression of given state – QGP "thermometer"
- In this talk
  - *Look at how J/ψ production is modified in heavy ion collisions in Phenix*



Quarkonium binding and dissociation

review by L. Kluberg and H. Satz, arXiv:0901.3831

- Cornell confining potential for qq-bar at separation distance r
  - σ=0.2 GeV^2 (string tension), α~π/12
- In vacuum (T=0), the free energy of the cc-bar is F_0 and the distance for string breaking is r_0
- With increasing T
  - Early string break up, until reaching Tc
- In the QGP, the Debye screening radius rD(T) decreases with increasing T.
  - for rD(T) < r(cc-bar) the system becomes unbound → suppression compared to charmonium production without QGP.

$$V(r) = \sigma\, r - \frac{\alpha}{r}$$

state	J/ψ
mass [GeV]	3.10
ΔE [GeV]	0.64
ΔM [GeV]	0.02
r_0 [fm]	0.50

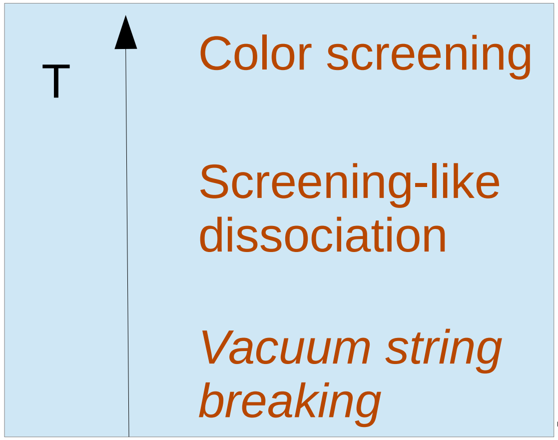
$$F(r) \sim \sigma r$$

$$F_0 = 2(M_D - m_c) \simeq 1.2 \text{ GeV};$$

$$r_0 \simeq 1.2 \text{ GeV}/\sigma \simeq 1.5 \text{ fm},$$

$$V(r,T)\ \frac{\sigma}{\mu}\left\{1 - e^{-\mu r}\right\} - \frac{\alpha}{r} e^{-\mu r}$$

rD~1/μ



Free energy of qq-bar pair

The screening radius can be computed using potential models or solving QCD on the lattice

Color screening free energy
F1(T)= U(T) – T S(T)

J/ψ is bound by 640 MeV

J/ψ disappears for T > 1.6 Tc

Phys.Rev. D. 71.114510