Recent Quarkonia and Open Heavy Flavor Results from PHENIX

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Moriond 2014

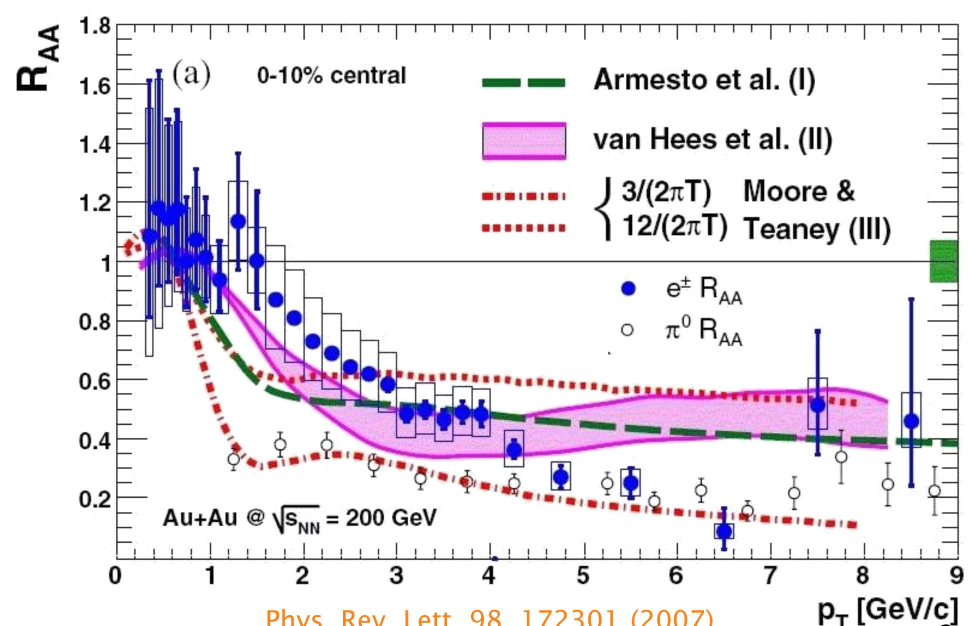
Heavy Quarks in A+A

- Why are heavy quarks interesting? $m_{c,b} > T, \Lambda_{QCD}$
  - produced early & experience full evolution of medium
- Energy loss different
  - "dead cone" effect: suppression of small angle gluon radiation

$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

Nuclear modification factor

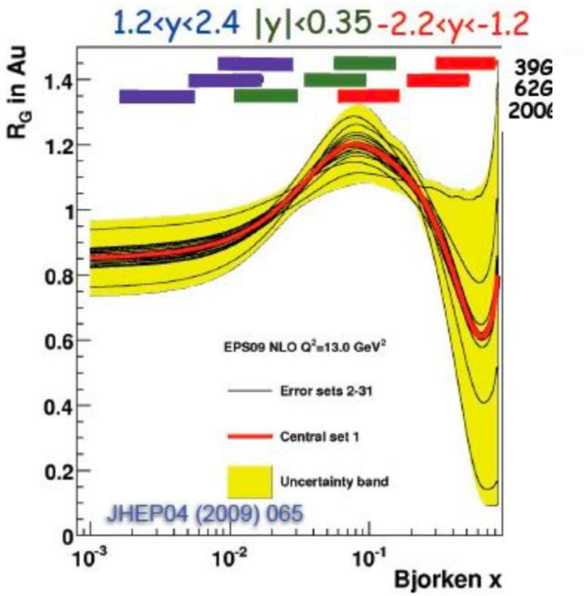
$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$



Phys. Rev. Lett. 98, 172301 (2007)

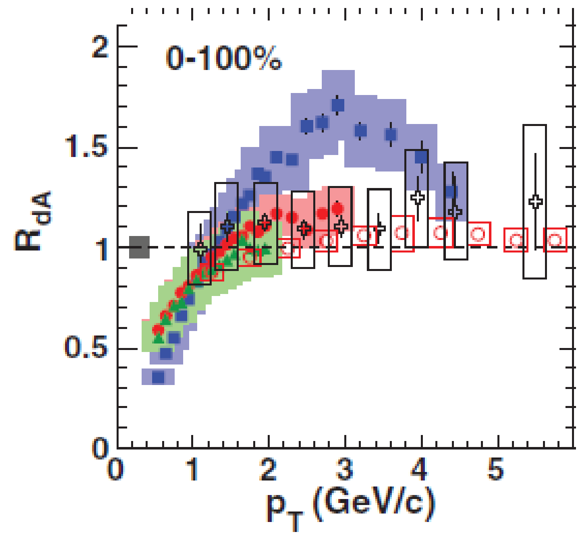
Cold Nuclear Matter Effects

Shadowing



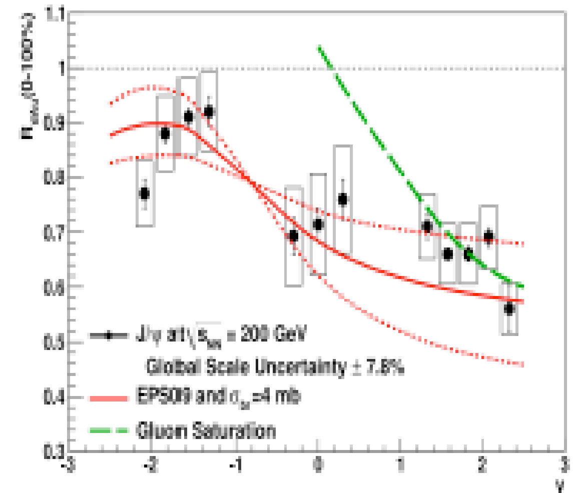
- Modification of the parton distribution functions within nucleus

p_T broadening



- Broadening due to multiple collisions before the hard scattering

Break up



- **Quarkonia only!**: Nuclear absorption, bound state is broken up

Use d+Au to investigate and quantify

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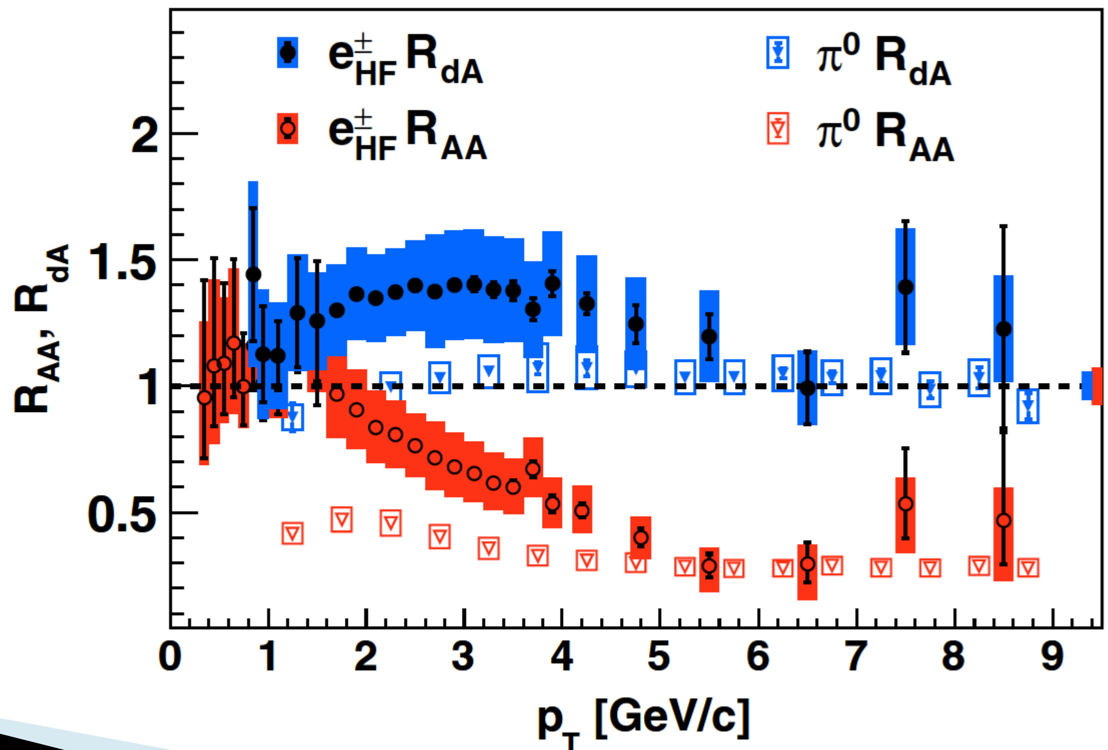
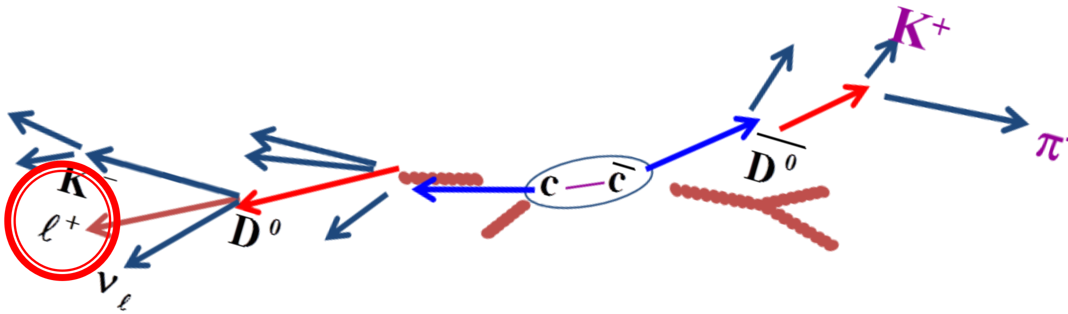
Open Heavy Flavor in d+Au

- Enhanced charm production relative to p+p
- Significant CNM effects…what does this mean for energy loss?

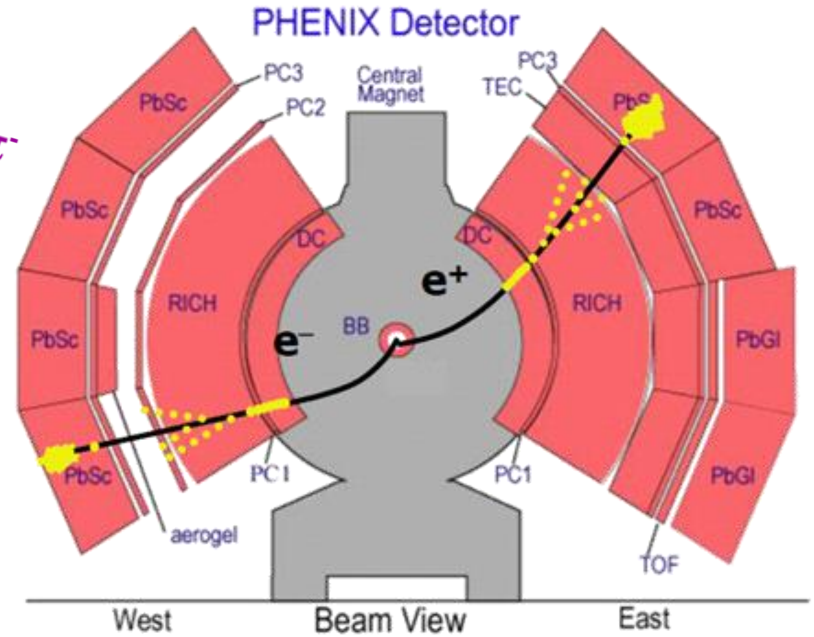


PRL 109, 242301 (2012)

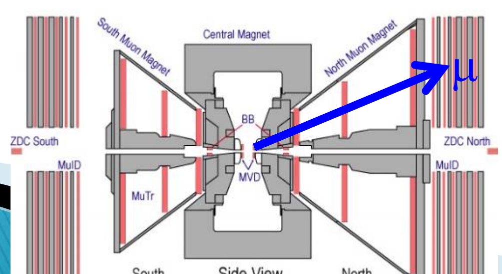
Heavy Flavor at PHENIX



- Open Heavy Flavor
  - Indirectly through semi-leptonic decay
- Quarkonia
  - Natural length & time scales
- Electrons at mid-rapidity
- Muons at forward/backward rapidity

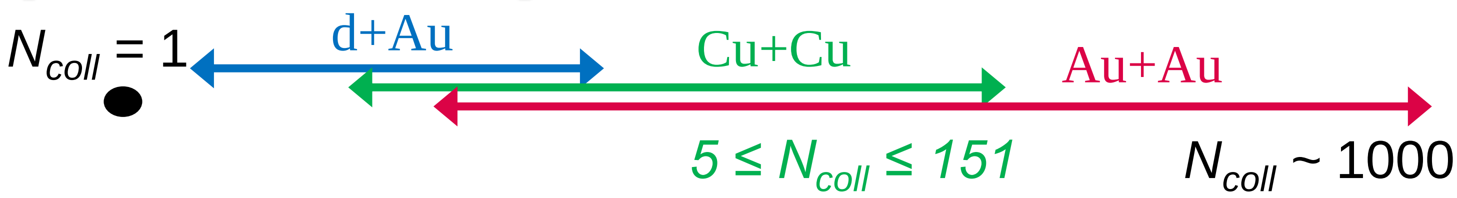


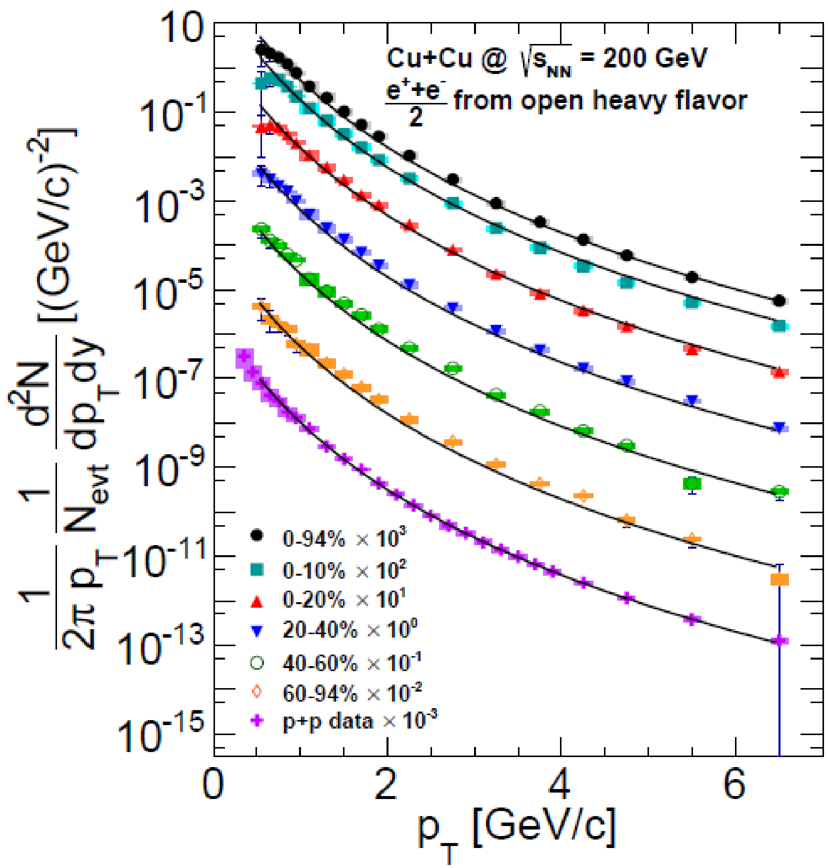
BBC: centrality & trigger
DC: tracking & momentum
RICH: eID
EMCal: energy



arXiv:1310.8286

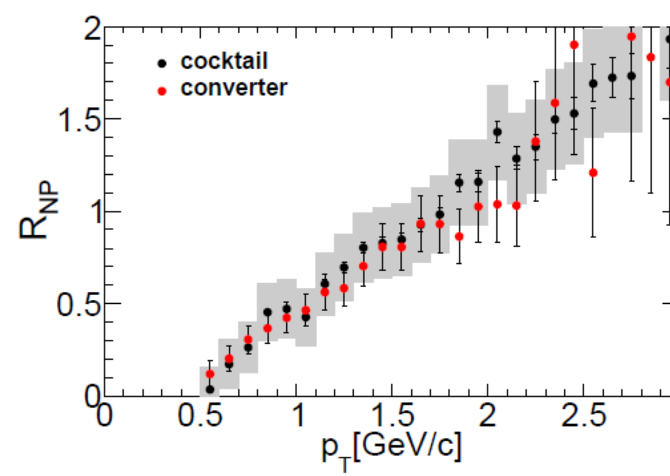
Open Heavy Flavor in Cu+Cu



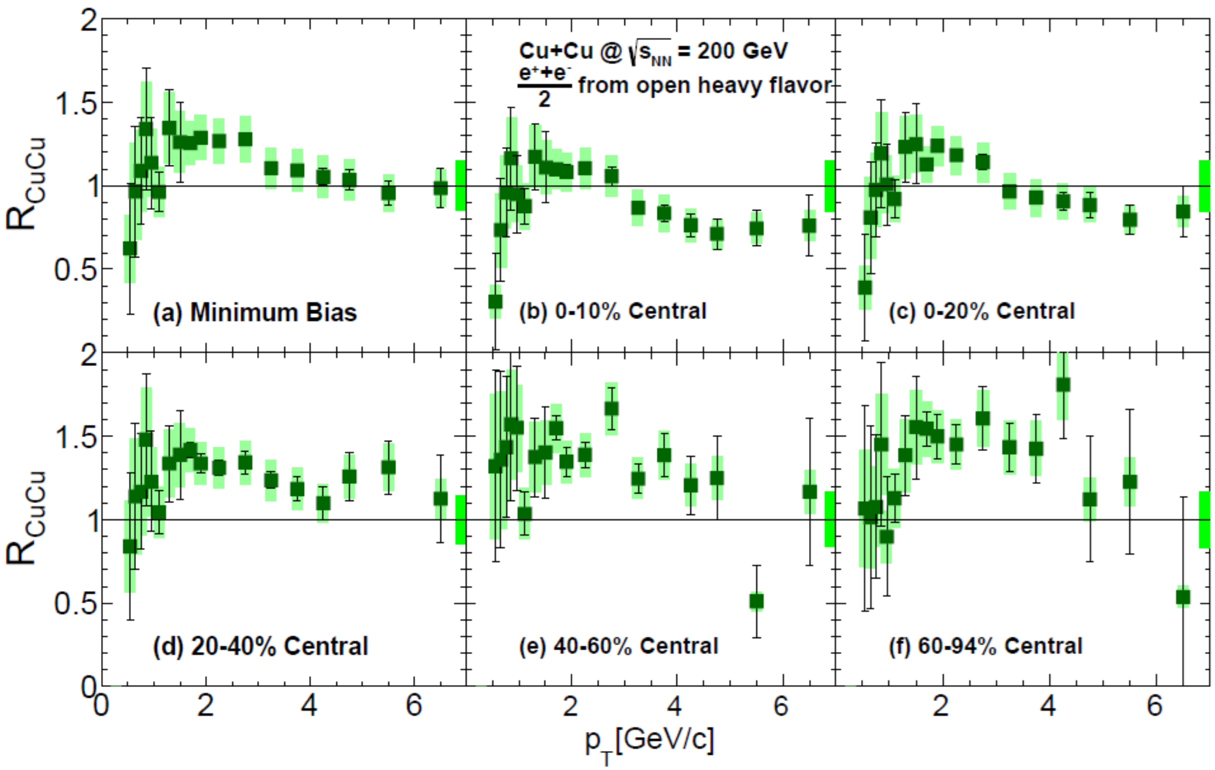


Two independent measurements

- Cocktail: statistically subtract bg electrons (>1GeV/c)
- Converter: increase photonic electrons by a known amount (<1GeV/c)
- Excellent agreement



Nuclear Modification in Cu+Cu



$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$

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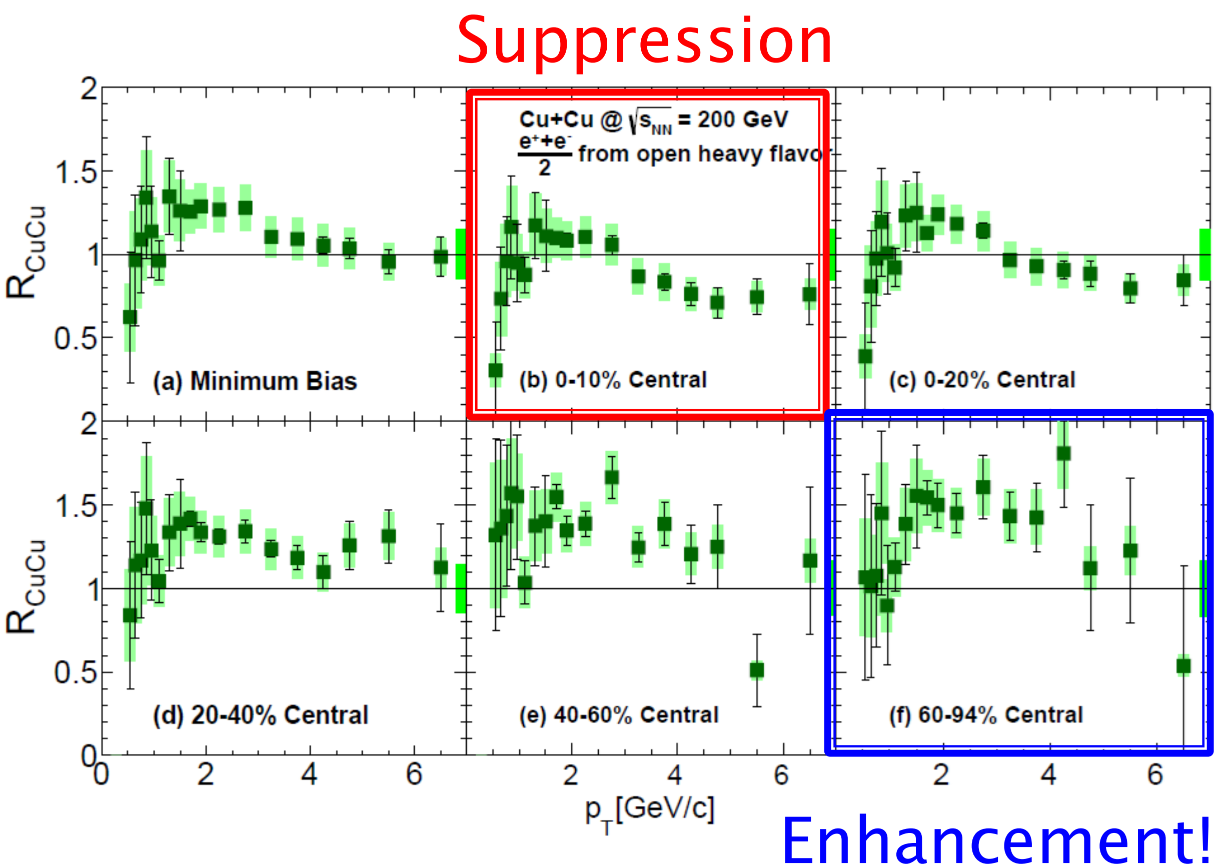

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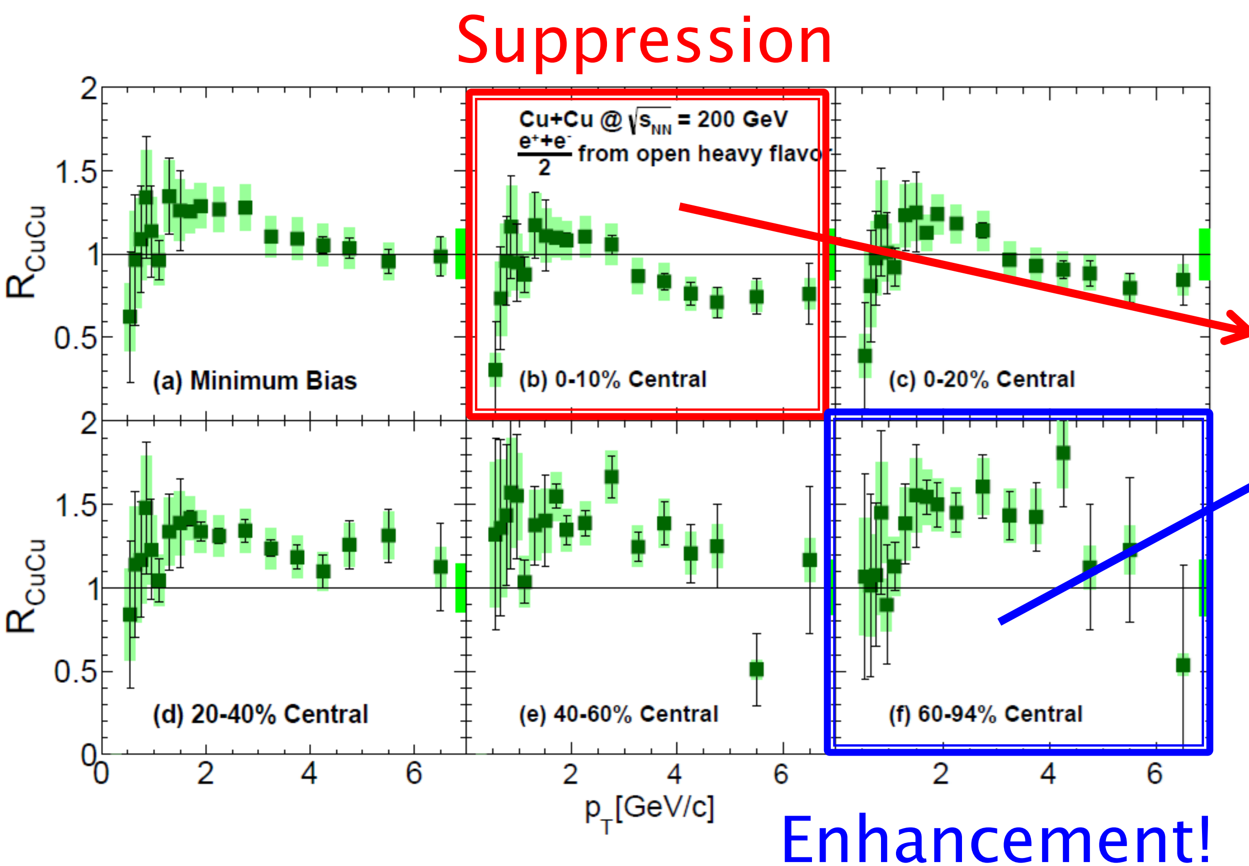
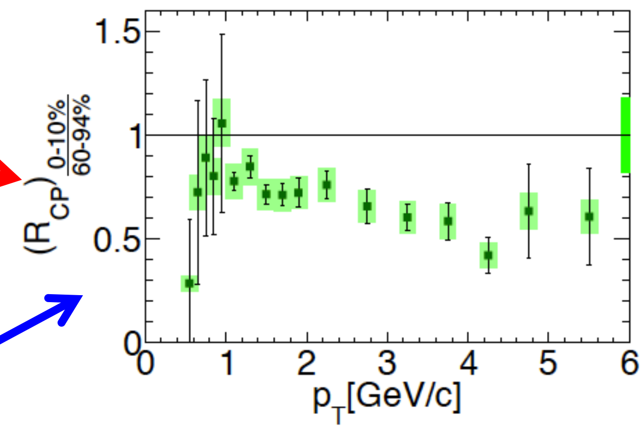




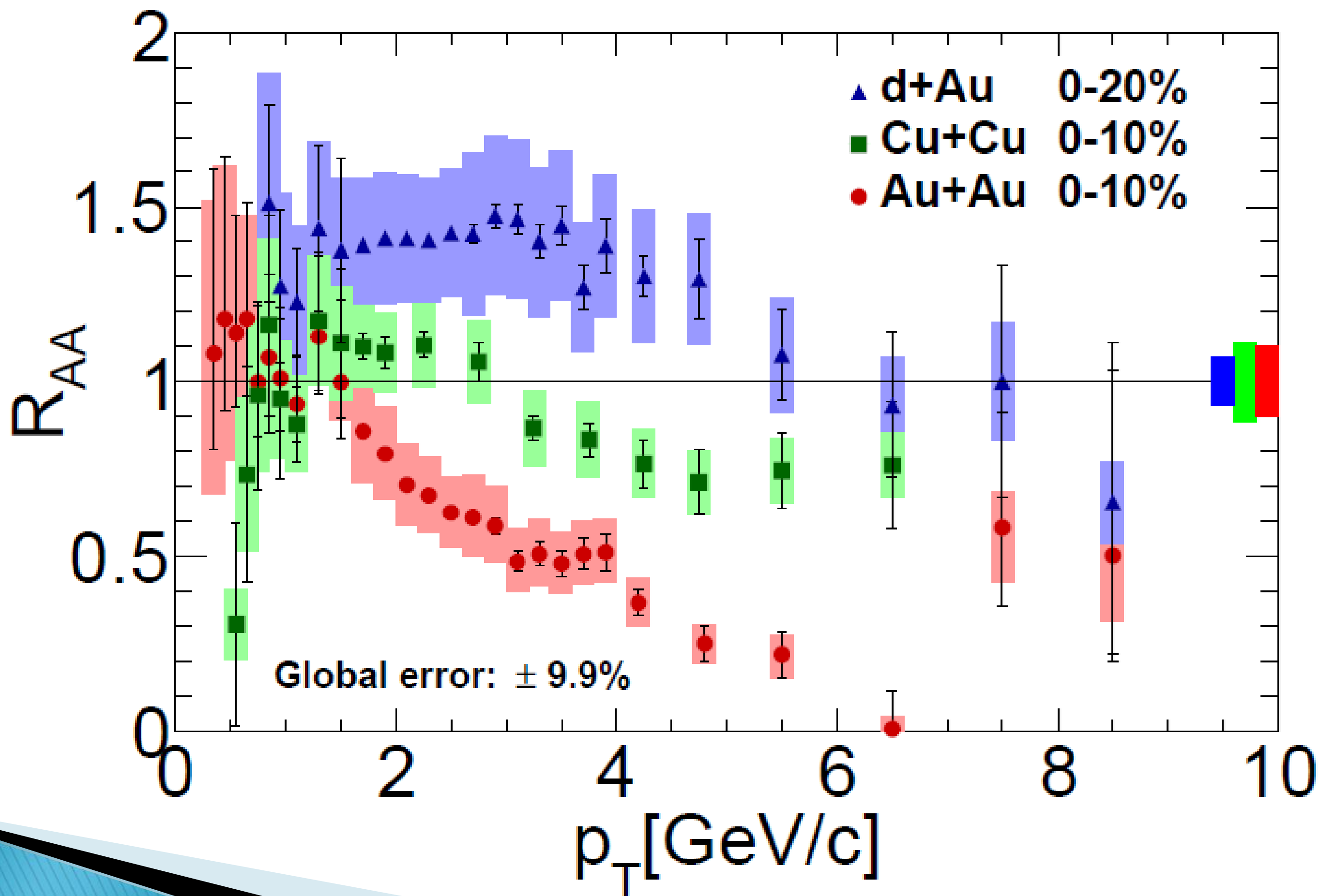
Significant suppression within Cu+Cu system not accounted for with p+p reference

$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$

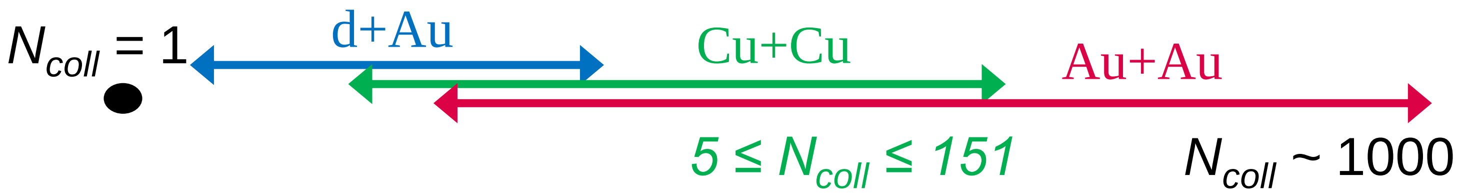
$$R_{\rm cp} = \frac{N_{\rm coll}^{\rm peripheral}}{N_{\rm coll}^{\rm central}} \times \frac{dN_{\rm Cu+Cu}^{\rm central}/dp_T}{dN_{\rm Cu+Cu}^{\rm peripheral}/dp_T}$$

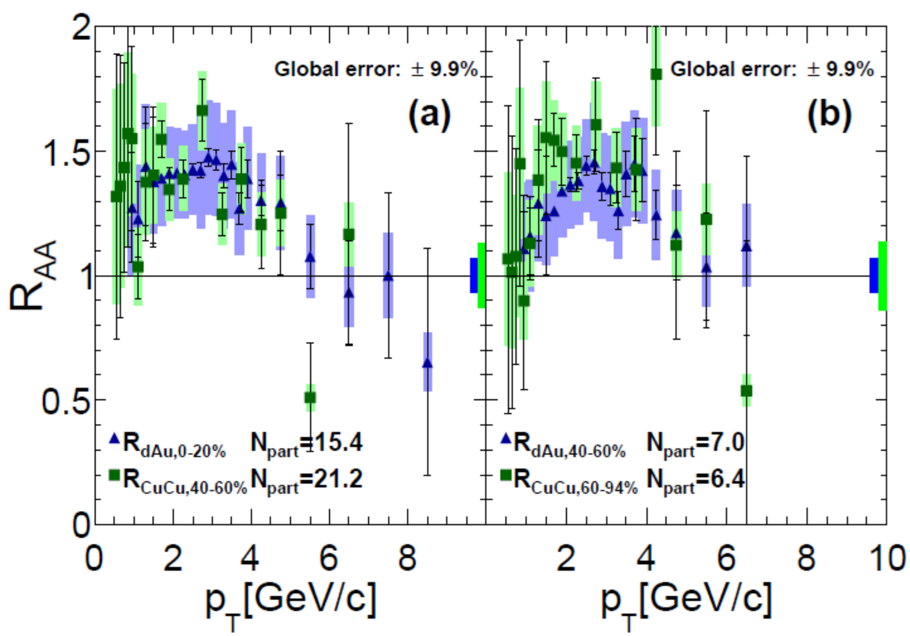
Electrons in d+Au, Cu+Cu, Au+Au

- Hierarchy between the 3 systems

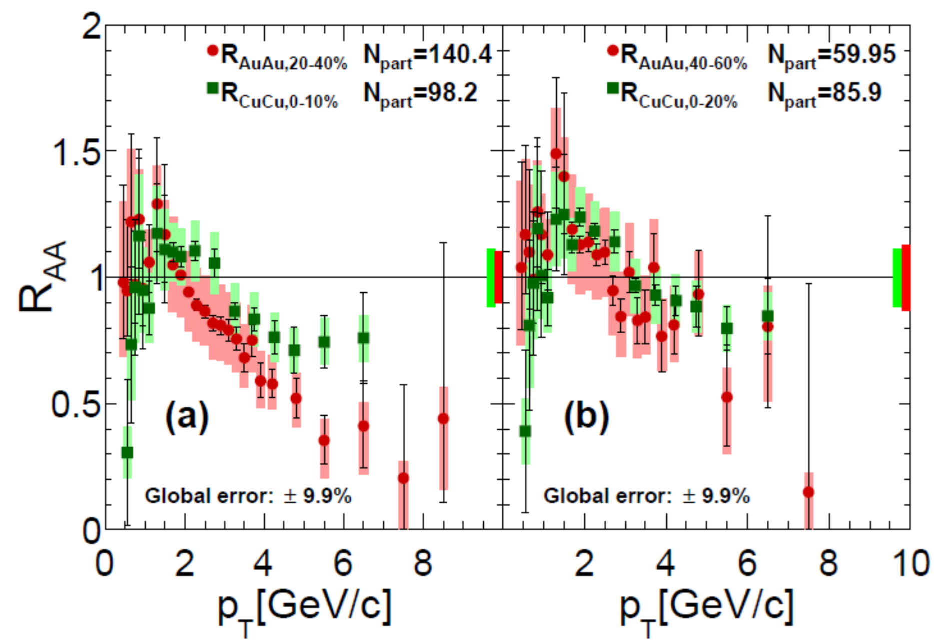


Comparisons Between Systems





PRL 109, 242301 (2012)



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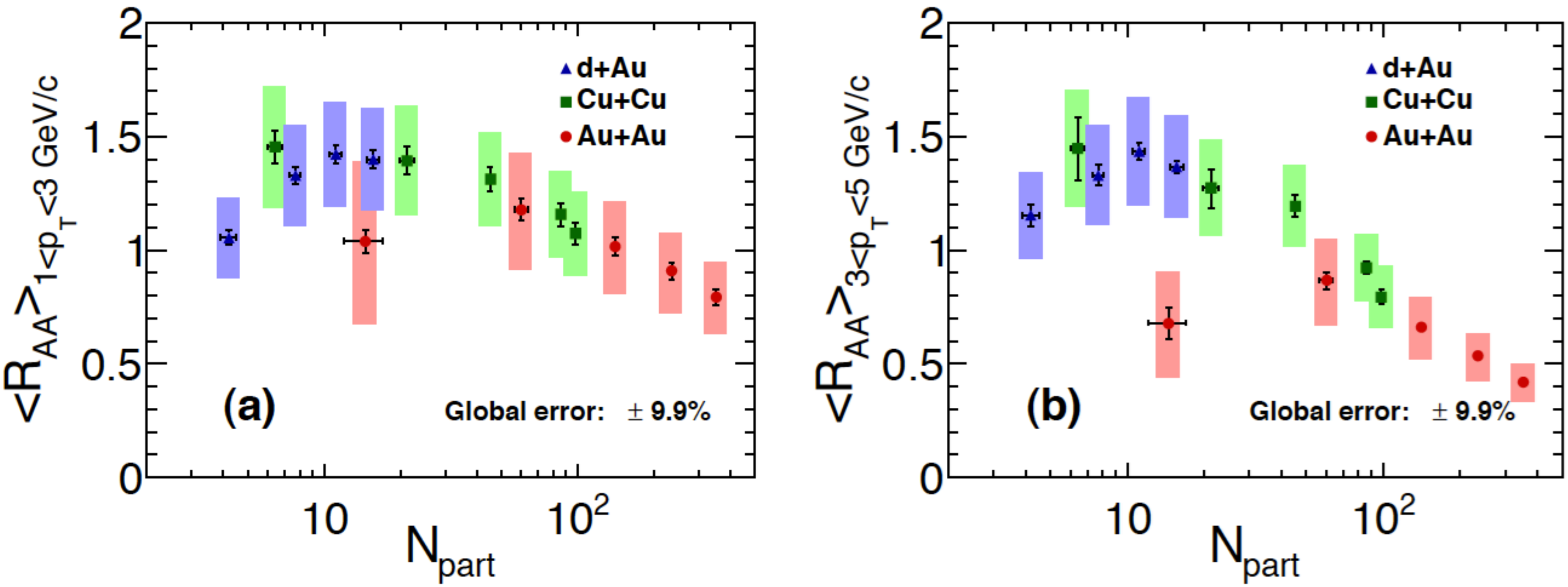
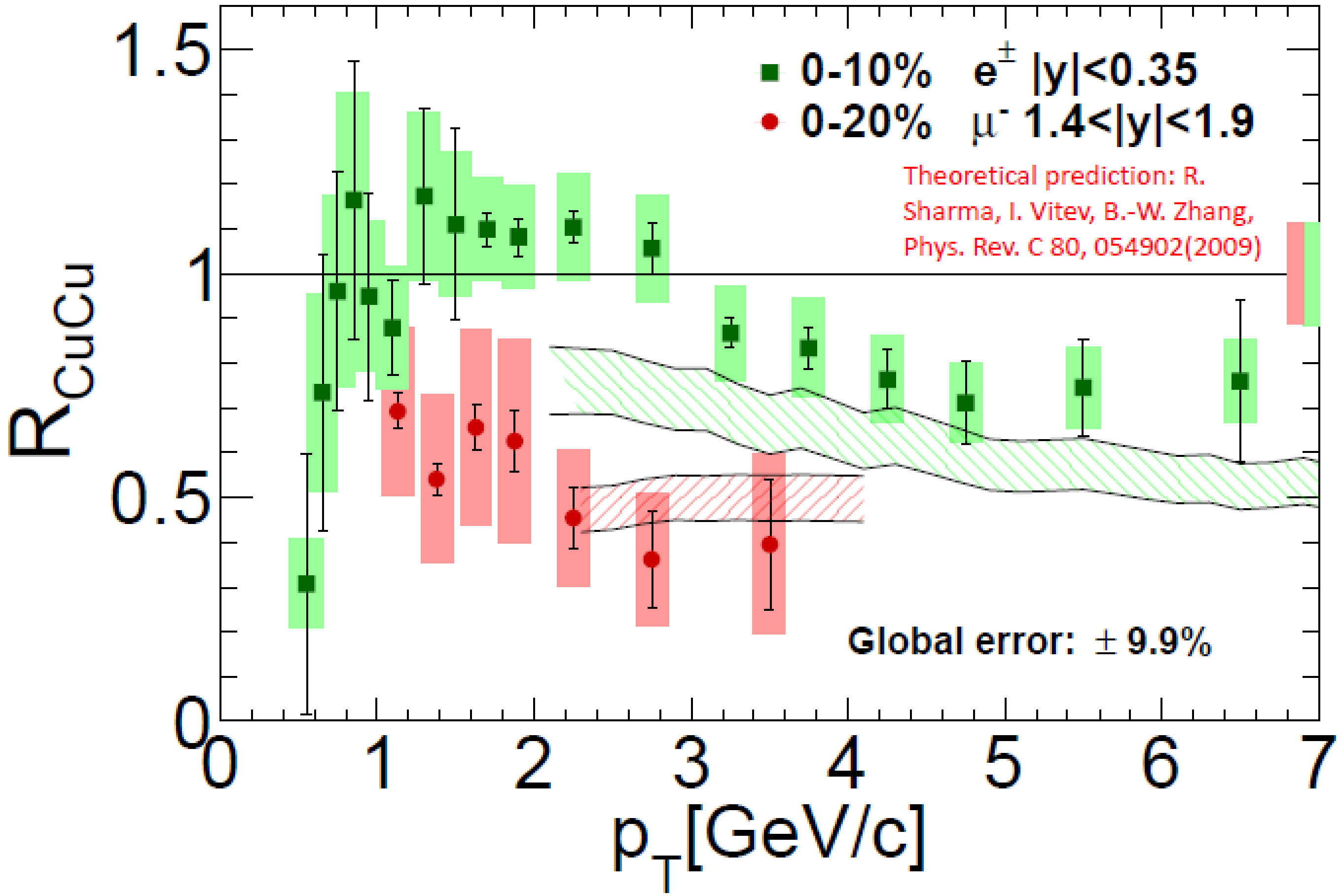
System Size Dependence

- CNM effects in d+Au/peripheral Cu+Cu to where HNM takes over as collision size increases in Cu+Cu & Au+Au systems



N_{part} = Number of participants

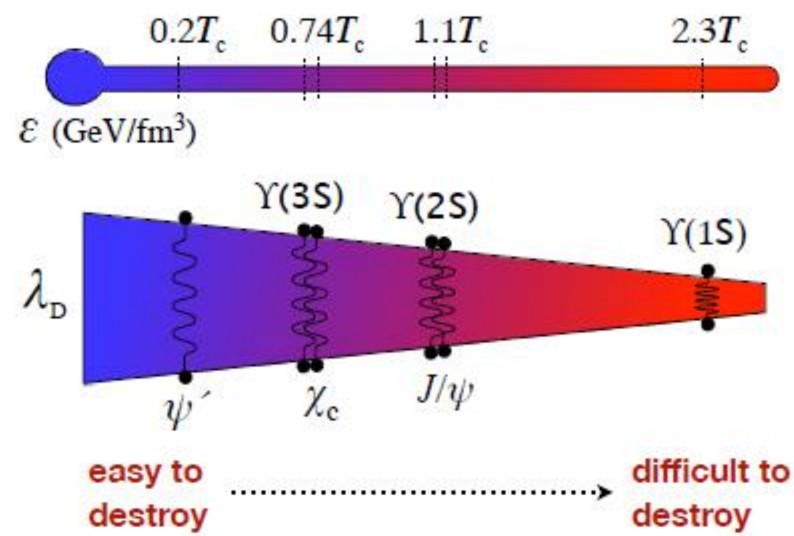
Theoretical Description

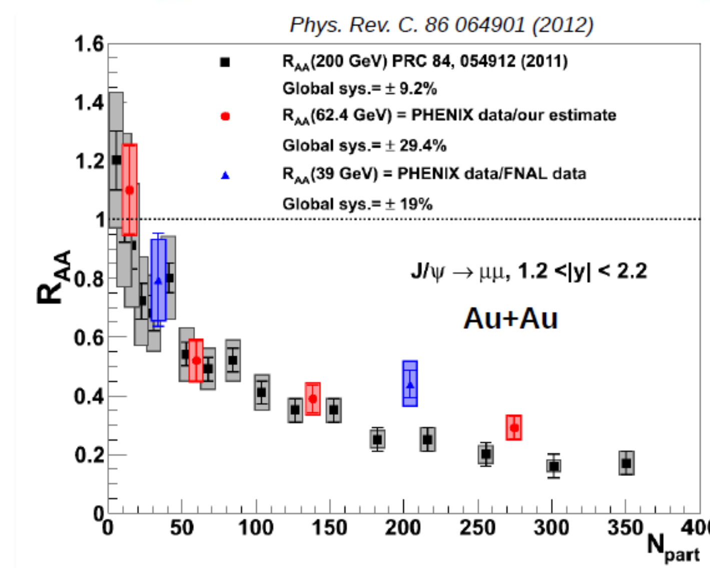


- More suppression in muon yield
  - Additional CNM effects at forward rapidity (shadowing/initial state energy loss)

Quarkonia Suppression

- Predicted "smoking gun" for QGP
  - Medium screening dissolves bound state hadrons
  - Remaining states reveal peak temp
- Not so simple…
  - CNM effects
  - Recombination
    - Bind after QGP
  - Feed-down contamination
    - Lower mass states produced

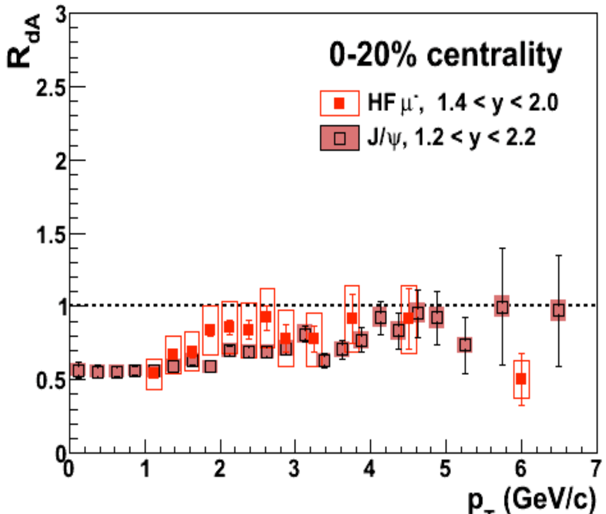




CNM effects on Quarkonia in d +Au

- Same initial state effects (CNM) as open HF, but…
  - Quarkonia also has breakup effects
  - Different decay kinematics

- Forward rapidity
  - Similar dependence
  - Same underlying mechanism



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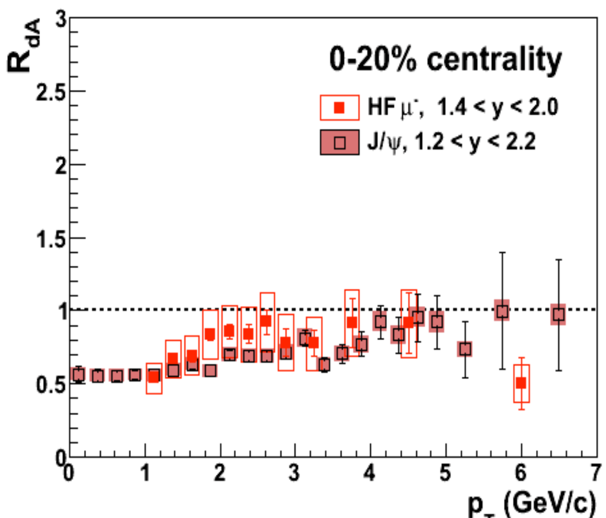
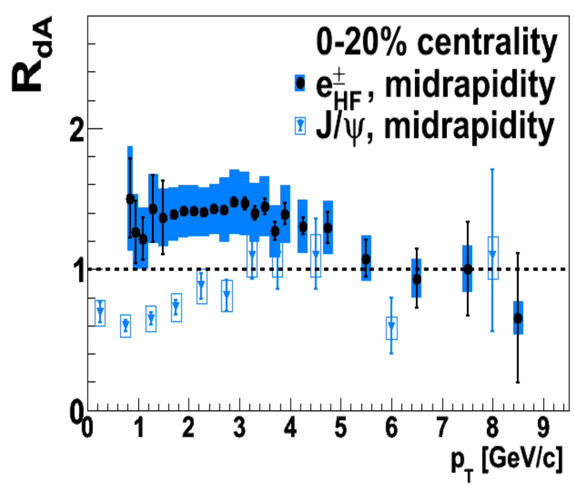
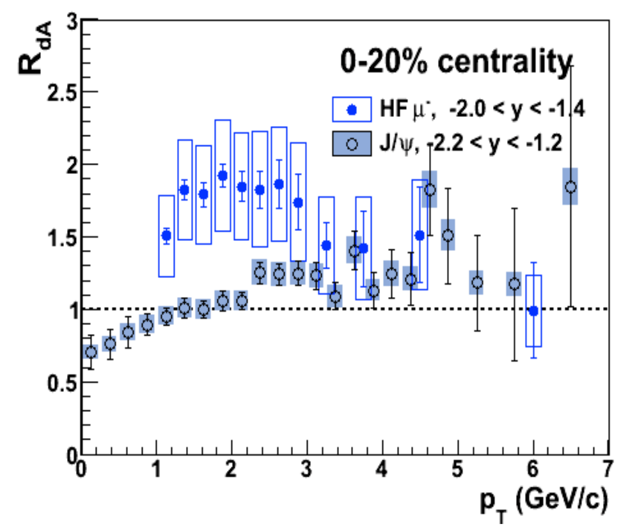
  - Similar dependence
  - Same underlying mechanism

- Mid/backward rapidity
  - More suppressed than open HF
  - J/ψ can break up

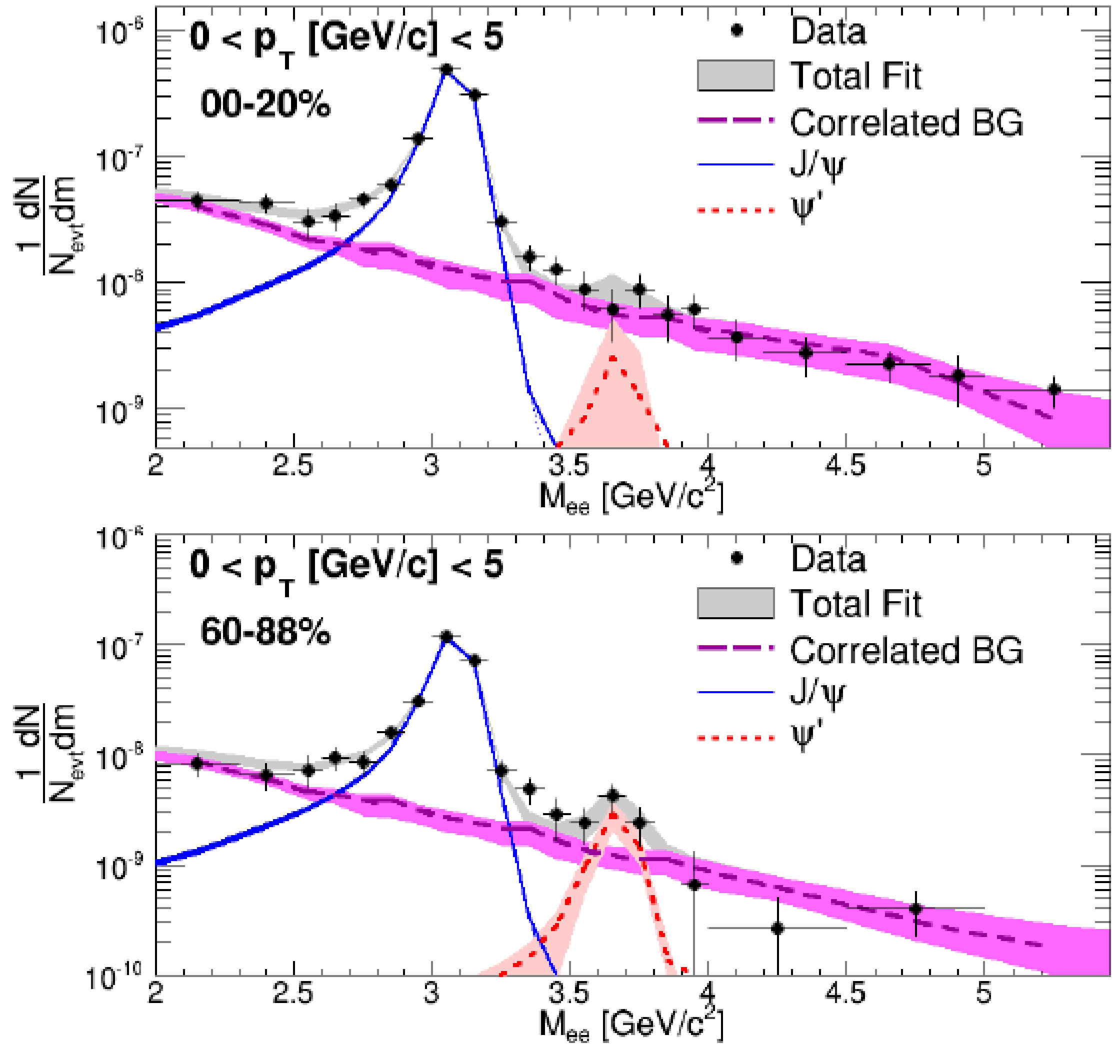






Other Quarkonia States – ψ' in d+Au

- CNM dominates
- ψ' suppressed in central
- Breakup could be more important (binding energy ~10x less than J/ψ)
- Any A+A measurement may be from regeneration only



Phys. Rev. Lett. 111, 202301 (2013)

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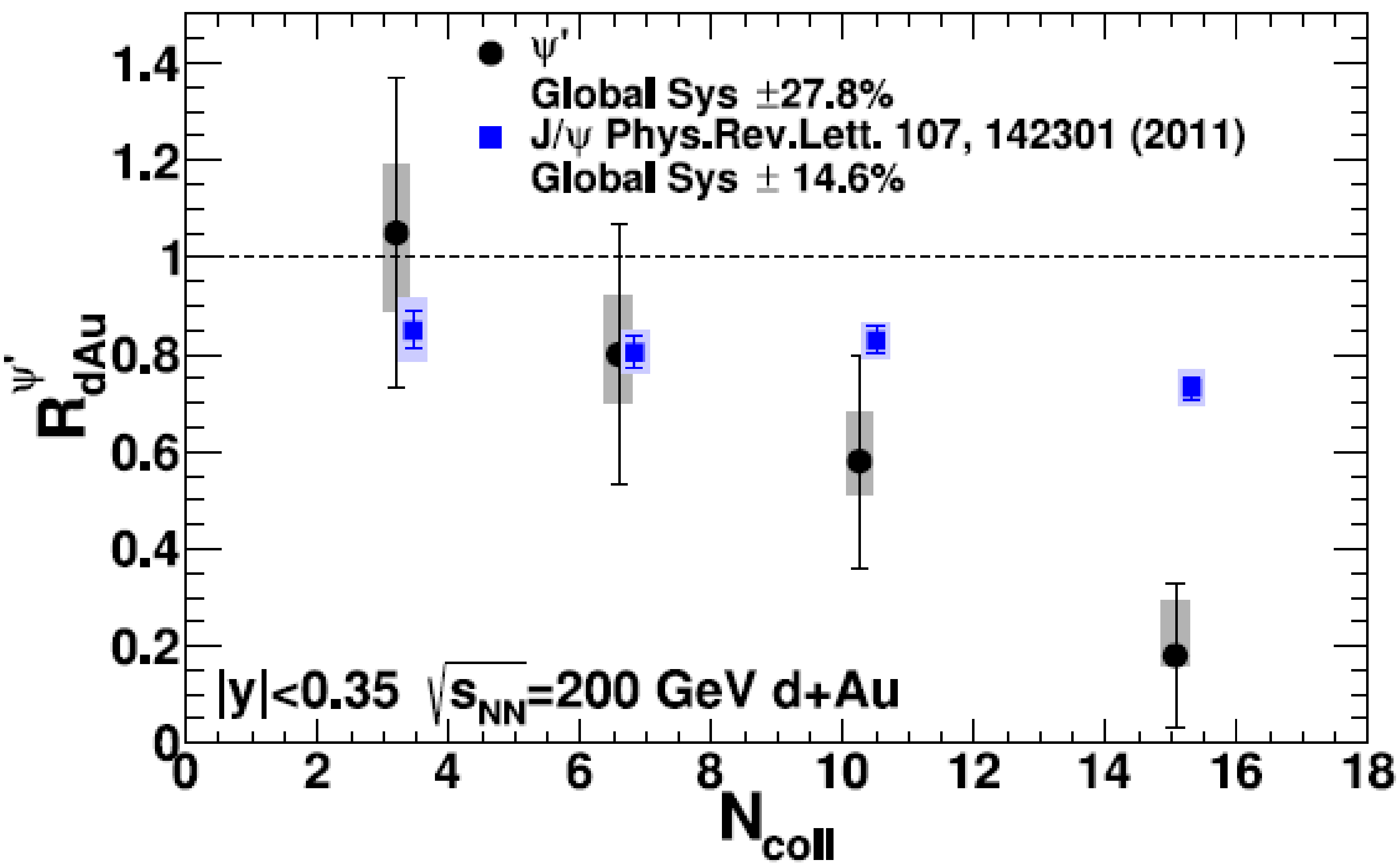
Nuclear Modification



- ψ' much more suppressed than J/ψ

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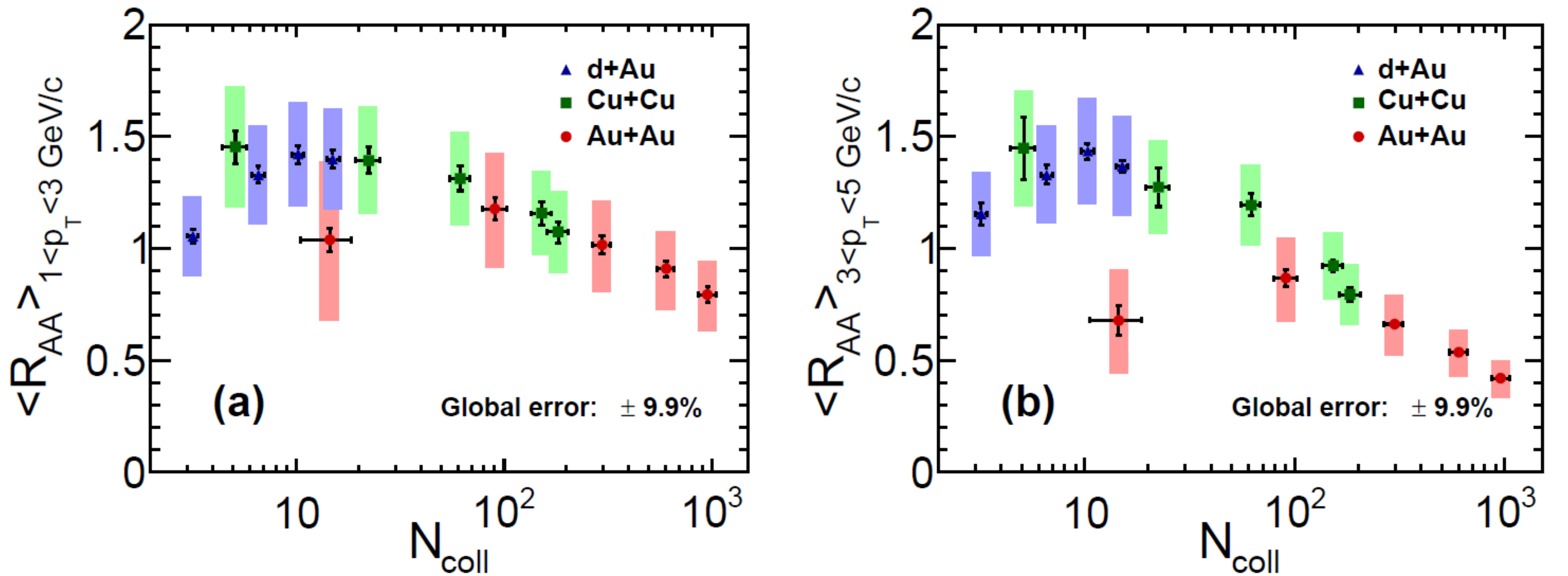
Summary

- Open heavy flavor electrons in Cu+Cu system show both suppression and enhancement effects similar Au+Au and d+Au
- ψ' is ~3x more suppressed than J/ψ in d+Au central collisions

- CNM are different and important for both open heavy flavor & quarkonia
  - Important for the interpretation of suppression

Backups

<RAA> vs Ncoll

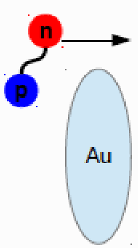


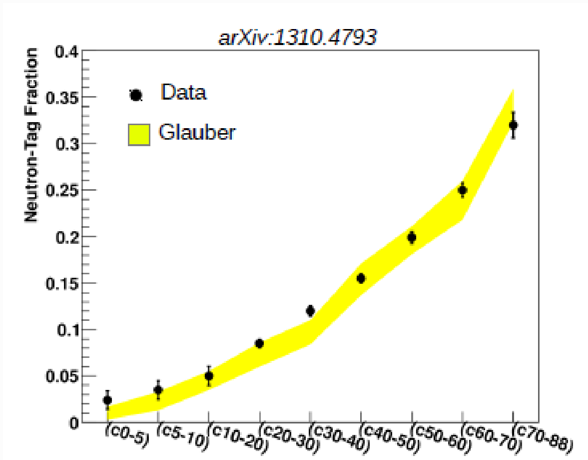
(a)
d+Au
Cu+Cu
Au+Au
Global error: ± 9.9%
$\langle R_{AA} \rangle_{1<p_T<3\ GeV/c}$
N_{coll}
(b)
d+Au
Cu+Cu
Au+Au
Global error: ± 9.9%
$\langle R_{AA} \rangle_{3<p_T<5\ GeV/c}$
N_{coll}

Understanding Geometry in d+Au

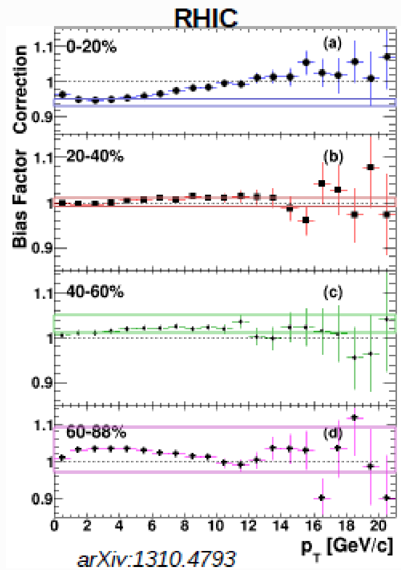
Measure fraction of events with a neutron in the ZDC.

Compares well with expectations from Glauber model.





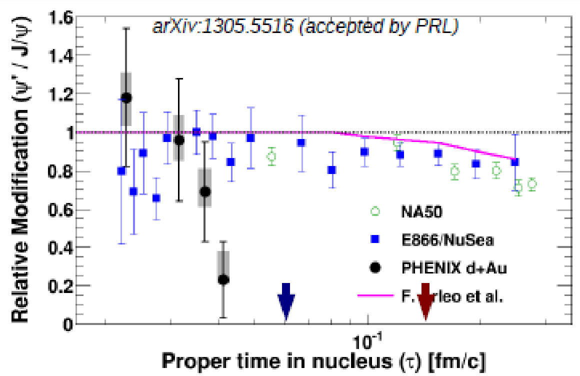
Understanding Geometry in d+Au



- Large interest in correlations between the process of interest and the measured centrality (i.e. bias factors)
- Determined using data+Glauber model
- **Included in PHENIX 2003 & 2008 d+Au results.**
- Now test results using HIJING
- Minimal p_T dependence at RHIC for p_T<10 GeV.
- **Good agreement with Glauber results**.

~5% Effect at RHIC!

τ Dependence of Suppression



Low energy results described by increased nuclear breakup due to expanding cc pair.

cc formation time ~ 0.05 fm/c
J/ψ formation time ~ 0.15 fm/c

Increased nuclear breakup can not explain RHIC results, the cc crosses the nucleus too quickly!

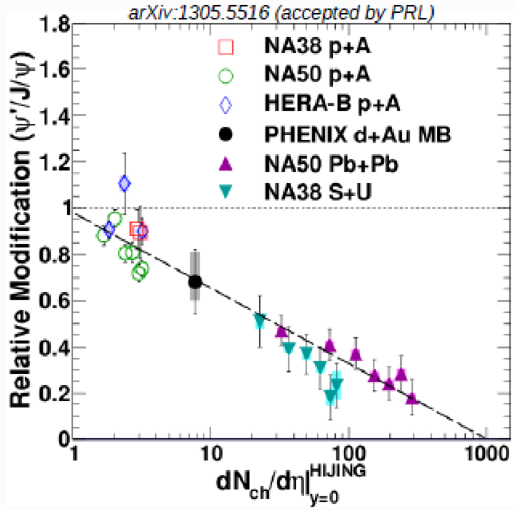
Need either an initial state effect that differs at very short time scales, or perhaps a long-range final state effect

Relative Modification

Relative modification ψ'/(J/ψ) vs midrapidity multiplicity for SPS p+A, RHIC d+Au and SPS A+A

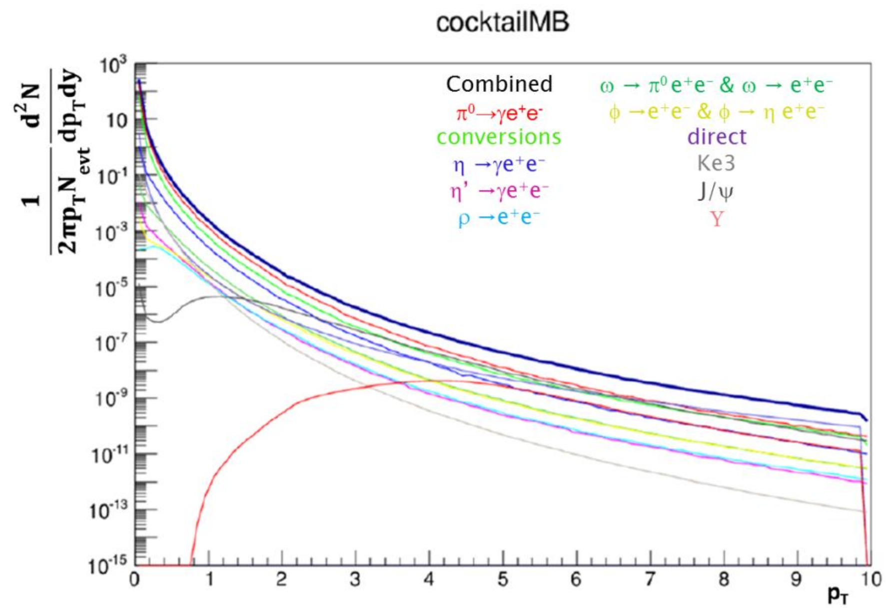
Results seem to follow a common trend.

ψ' more effected by presence of a medium in d+Au?



Cocktail Method

- π^0 Dalitz largest background: fit to PHENIX data
  - All other light mesons are m_T scaled and normalized to meson/pion ratio at high momentum
- Cocktail includes electrons from conversions, Ke3 decays and direct photons
- J/ψ, Υ and Drell Yan also added
- Large systematic uncertainties



$$p_T \rightarrow m_T = \sqrt{p_T^2 + \left(M_{meson}^2 - M_{\pi^0}^2\right)}$$

- $\pi^0 \rightarrow \gamma e^+ e^-$
- $\eta \rightarrow \gamma e^+ e^-$
- $\eta' \rightarrow \gamma e^+ e^-$
- $\rho \rightarrow e^+ e^-$
- $\omega \rightarrow \pi^0 e^+ e^- \,\&\, \omega \rightarrow e^+ e^-$
- $\varphi \rightarrow \eta e^+ e^- \,\&\, \varphi \rightarrow e^+ e^-$

η/π^0	0.48 ± 0.03
η'/π^0	0.25 ± 0.075
ρ/π^0	1.00 ± 0.30
ω/π^0	0.90 ± 0.06
ϕ/π^0	0.40 ± 0.12

Converter Method

- Converter wrapped around beam pipe for a number of runs
  - Increases photonic yield
- Statistically limited

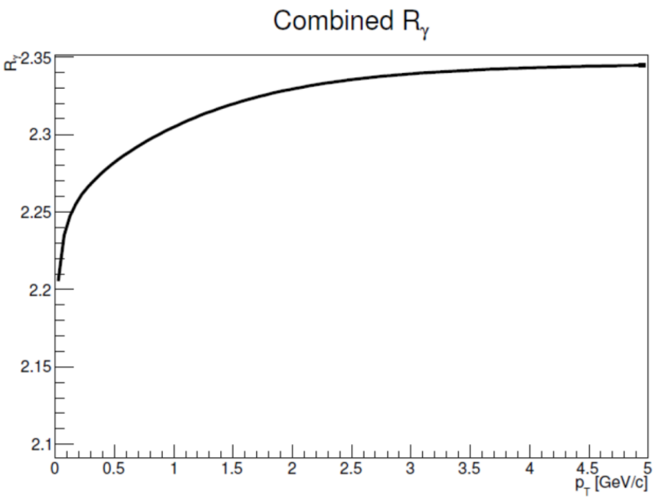
$$N_{inc} = N_\gamma + N_{non-\gamma}$$

$$N_{inc}^C = R_\gamma N_\gamma + (1-\epsilon)\, N_{non-\gamma}$$

$$N_{non-\gamma} = \frac{R_\gamma N_{inc} - N_{inc}^C}{R_\gamma - 1 + \epsilon}$$

$$N_\gamma = \frac{N_{inc}^C - (1-\epsilon)\, N_{inc}}{R_\gamma - 1 + \epsilon}$$

- R_γ and ε found in simulation

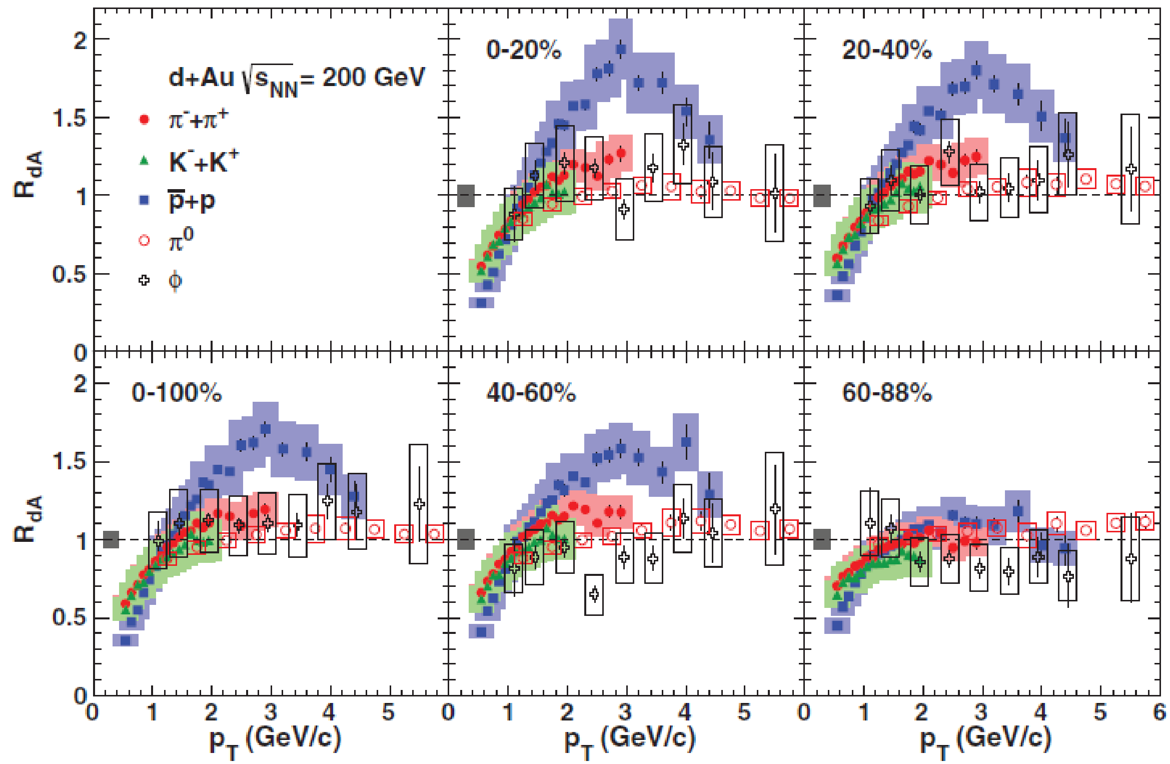


$\varepsilon = 2.1\% \pm 25\%$

Cronin Effect

- Enhancement more structured than expected
- kT boosts to partons before scattering
  - Doesn't explain mass dependence

PHYSICAL REVIEW C 88, 024906 (2013)

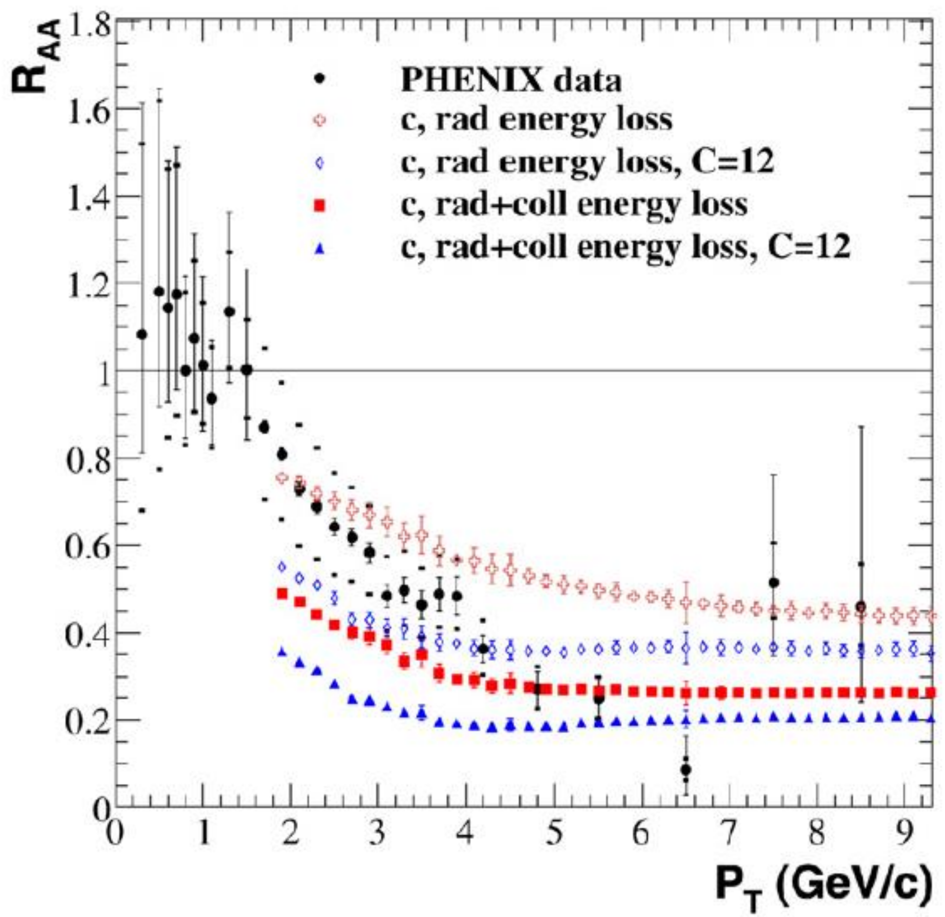


Baryon enhancement

- Can suppress e_{HF} production
  - Smaller branching ratio for charmed baryons
- No charmed baryon measurements at RHIC

$$\mathcal{C} = \frac{(N_{\Lambda_c,\bar{\Lambda}_c}/N_D)_{AA}}{(N_{\Lambda_c,\bar{\Lambda}_c}/N_D)_{pp}}$$

G. Martínez-García et al. / Physics Letters B 663 (2008) 55–60



Radiative & Collisional energy loss

- Intial radiative energy loss calculations under predict suppression
- Collisional energy loss should also be included

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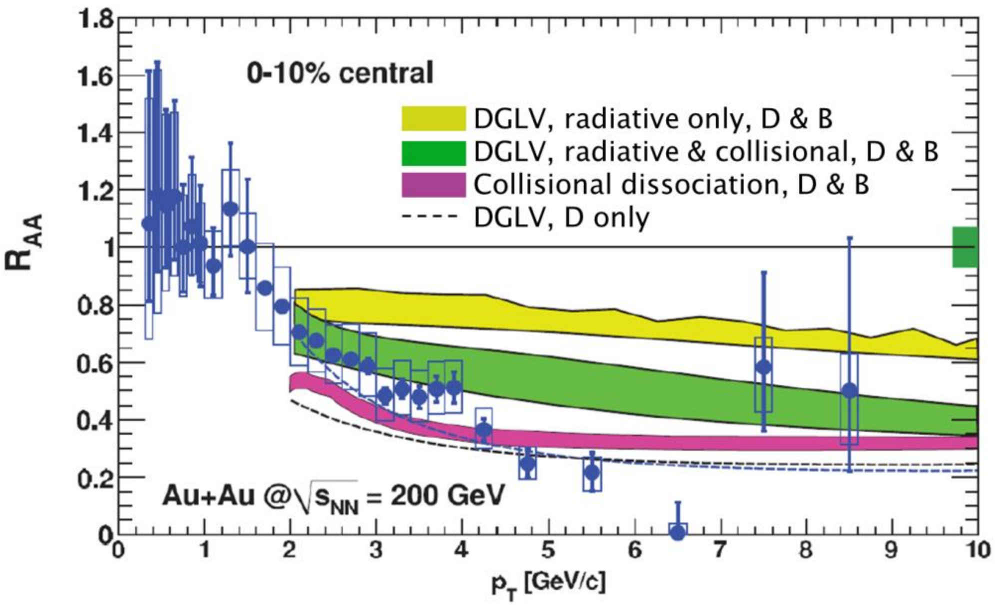
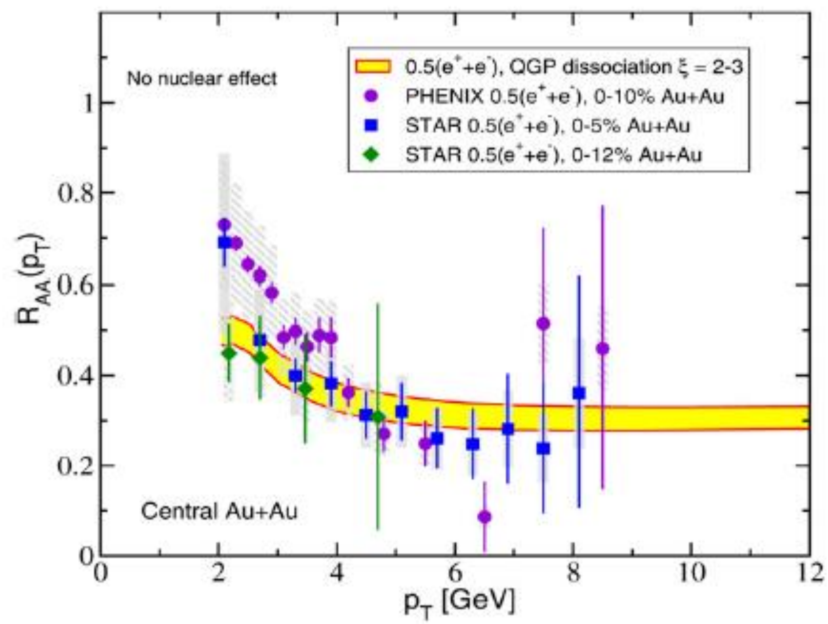


Dissociation

- D & B meson dissociation
  - Light meson formation time > length of QGP
  - Heavy meson formation time < length of QGP
  - Has been successful for heavy flavor
    - Very sensitive to formation times of hadrons and QGP
    - Persists longer for B

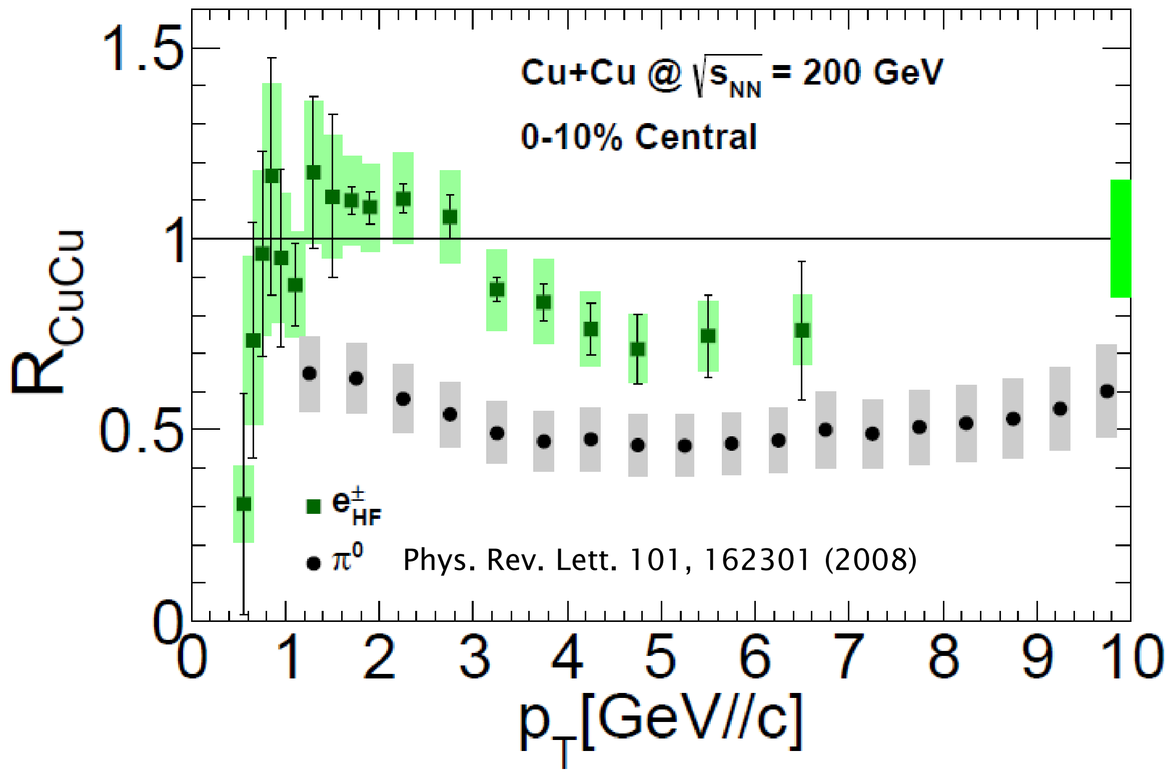
$$\tau_{\text{form}} = \frac{\Delta y^+}{1+\beta_Q}, \quad \beta_Q = \frac{p_Q}{E_Q}.$$

$$\Delta y^+ \simeq \frac{1}{\Delta p^-} = \frac{2z(1-z)p^+}{\mathbf{k}^2 + (1-z)m_h^2 - z(1-z)m_Q^2}$$



A. Adil, I. Vitev / Physics Letters B 649 (2007) 139–146

Light & Heavy Flavor in Cu+Cu



- $R_{AA}^{light} < R_{AA}^{heavy}$
- Suggests the initial state effects on the light and heavy quarks are different