# Recent heavy flavor measurements by PHENIX experiment

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PHENIX

# Outline

- Brief introduction
  - studying open heavy flavor
  - PHENIX detector

- Heavy flavor measurements by PHENIX
  - remind of HI results
  - d+Au results

- Highlighting the PHENIX results finalized soon

- Summary

# Studying open heavy flavor

- p+p collisions
  - test pQCD calculations
  - baseline for heavy ion collisions

- Heavy ion collisions
  - probe effects of the strongly interacting hot medium

- d(p)+A collisions
  - quantify cold nuclear matter effects

# Studying open heavy flavor

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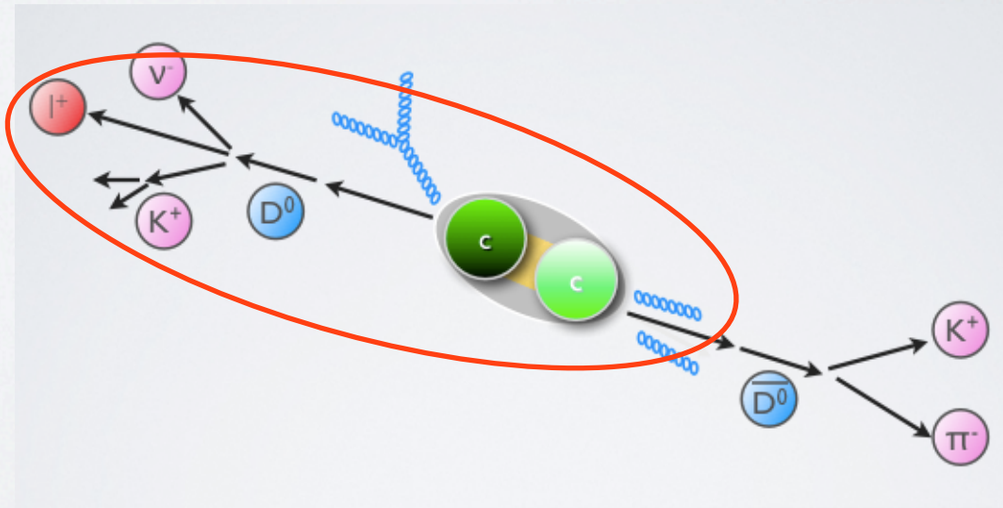
- d(p)+A collisions
  - quantify cold nuclear matter effects

- PHENIX has suitable design for lepton measurements
  - single leptons from open heavy flavor
  - lepton pairs from quarkonia

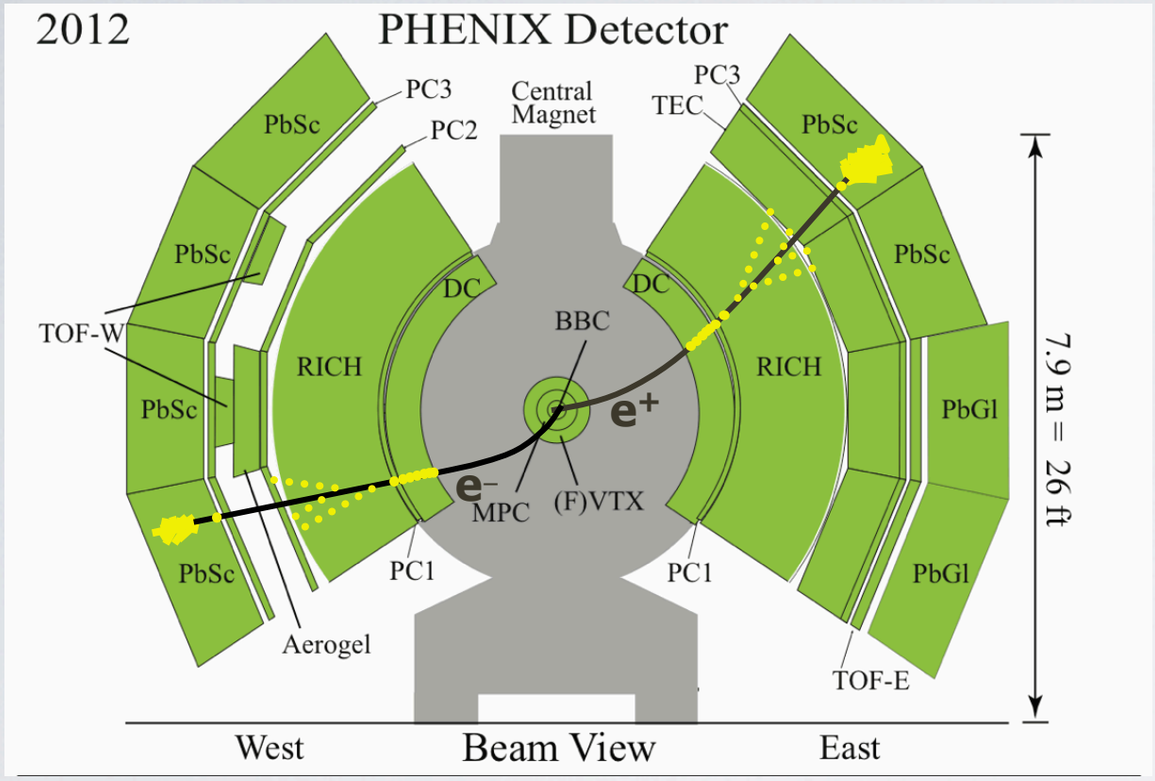
**Semi-leptonic decay**

- lepton triggered measurement(e, μ)
(statistical background subtraction)



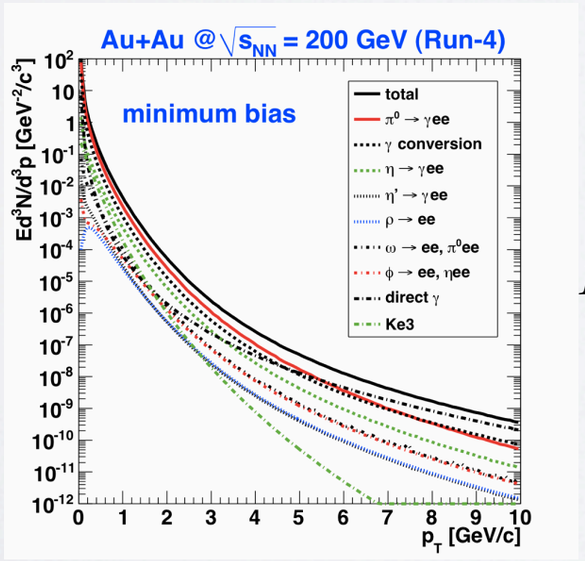

PHENIX

# e measurement @ PHENIX central arm




- kinematic range
  - $|\eta| < 0.35$
  - $\Delta\varphi = \pi$
- Detectors
  - DC & PC for tracking
  - RICH for electron ID
  - EMcal for energy of electron

- Cocktail method
  - simulate photonic background with measured spectra of hadrons
  - large systematics
  - π0 Dalitz
  - conversion γ
  - direct γ & Ke3
  - J/Ψ, Υ, DY




- Converter method
  - using photon converter (1.68% $X_0$)
  - increase photonic background and statistically limited

$$N_e^{conv-out} = N_e^{\gamma} + N_e^{non-\gamma}$$

$$N_e^{conv-in} = R_\gamma N_e^{\gamma} + (1-\epsilon) N_e^{non-\gamma}$$

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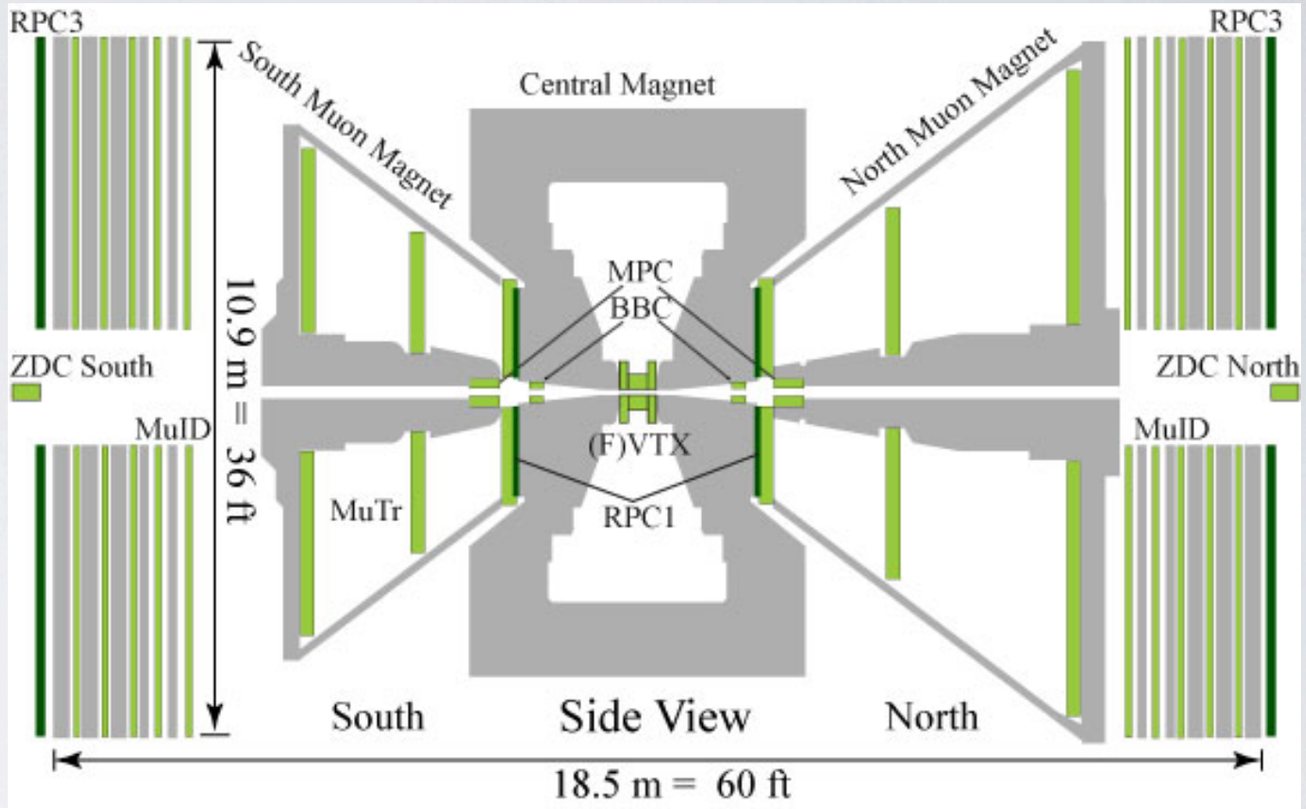
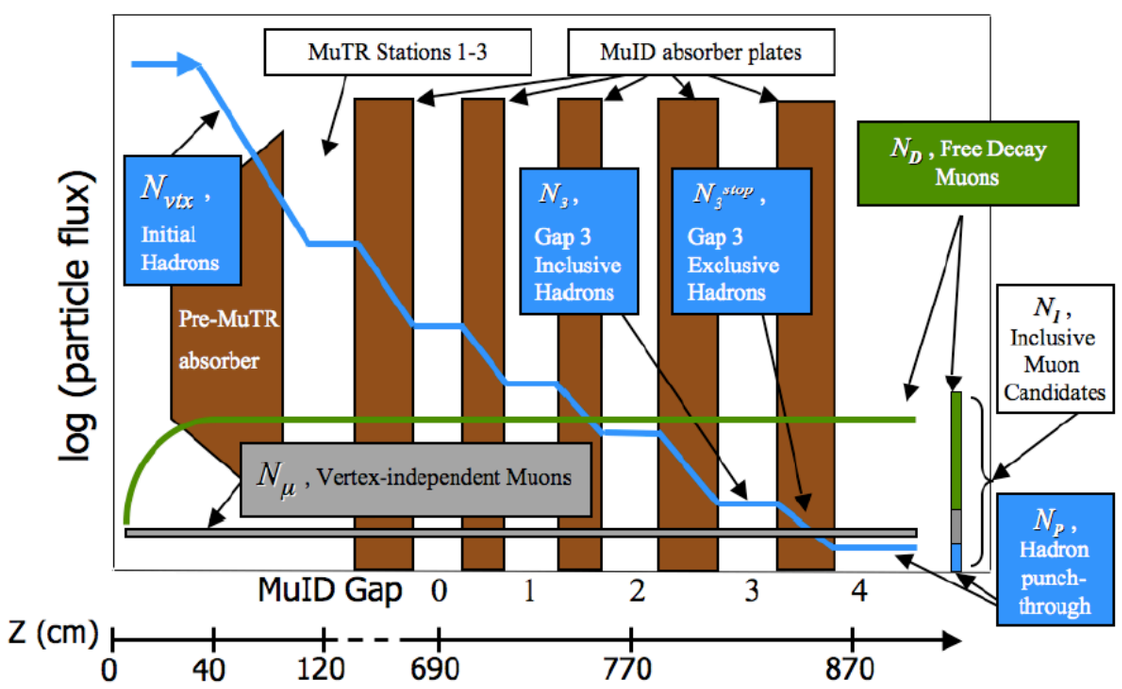
# μ measurement @ PHENIX muon arm

- kinematic range
  - 1.2 < |η| < 2.2 at forward
  - Δφ = 2π

  - ~10λ absorber to reject hadrons
  - Muon Tracker for momentum
  - Muon identifier for hadron/muon separation



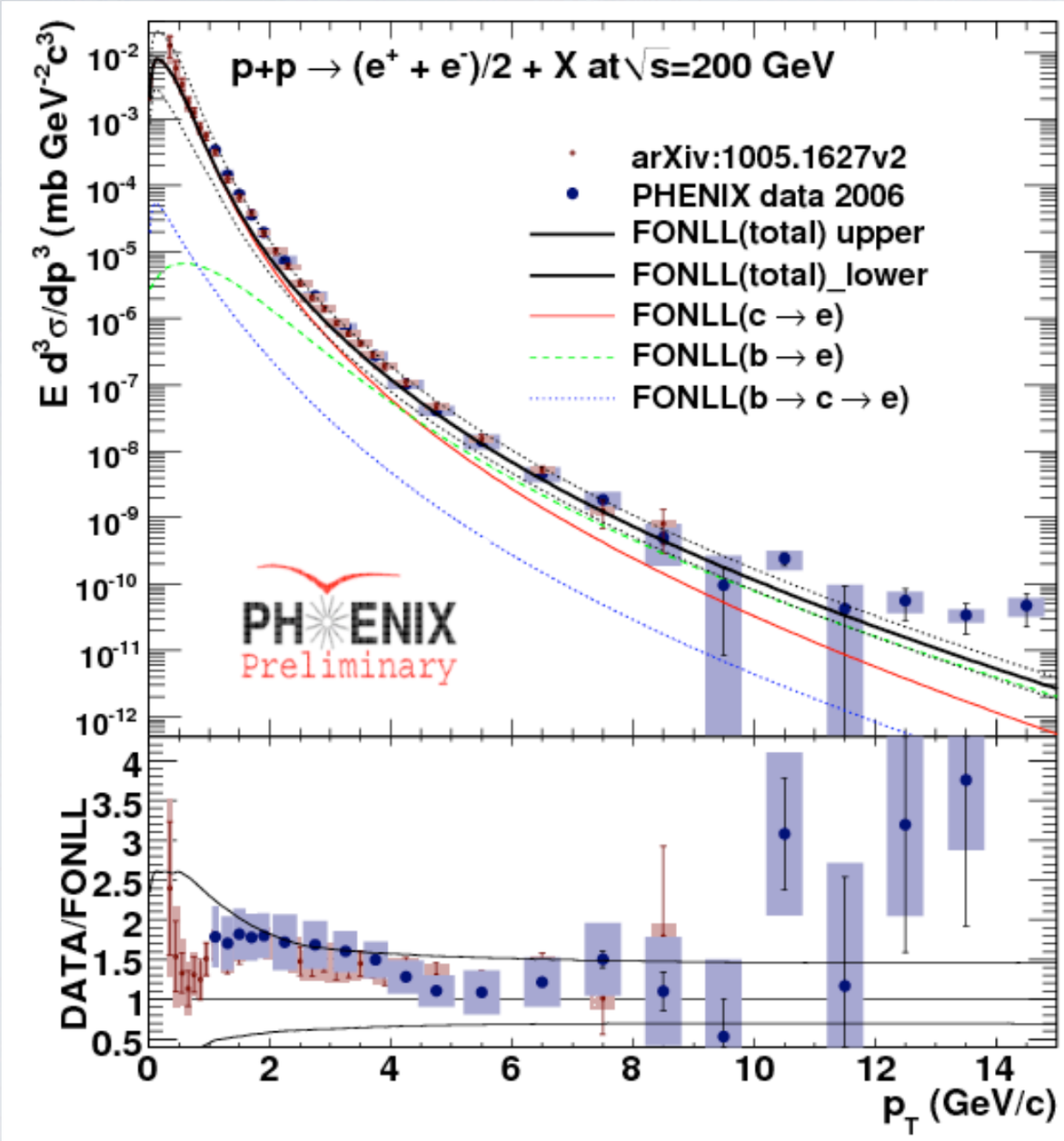




- Main background sources are decay muons from light hadrons and punch-through hadrons.

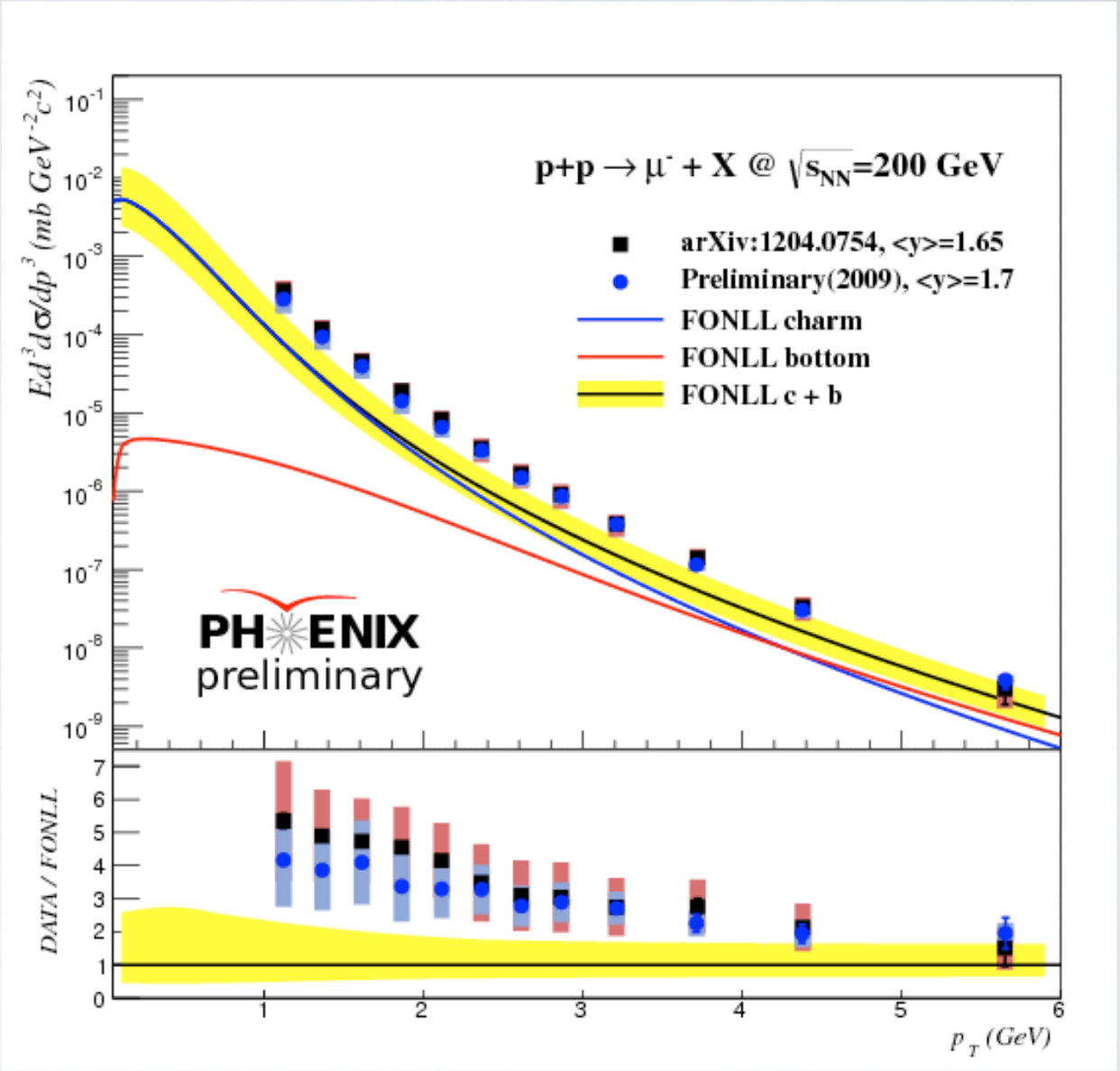
- Full MC simulation of hadron cocktail(π, K, p)
  - Tune to data by using z-vertex dependence of decay muons at MuID Gap 4 and yields of stopped hadrons at MuID Gap 2 and 3

# Heavy flavor in p+p collisions

## mid-rapidity




## forward rapidity




- Extend kinematic range and reduce uncertainties with enhanced statistics and improved analysis techniques

# Quantifying medium effects

- Nuclear modification factor
  - $R_{AA}$ = 1 : No overall modification
  - $R_{AA}$ < 1 : Suppression
  - $R_{AA}$ > 1 : Enhancement

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

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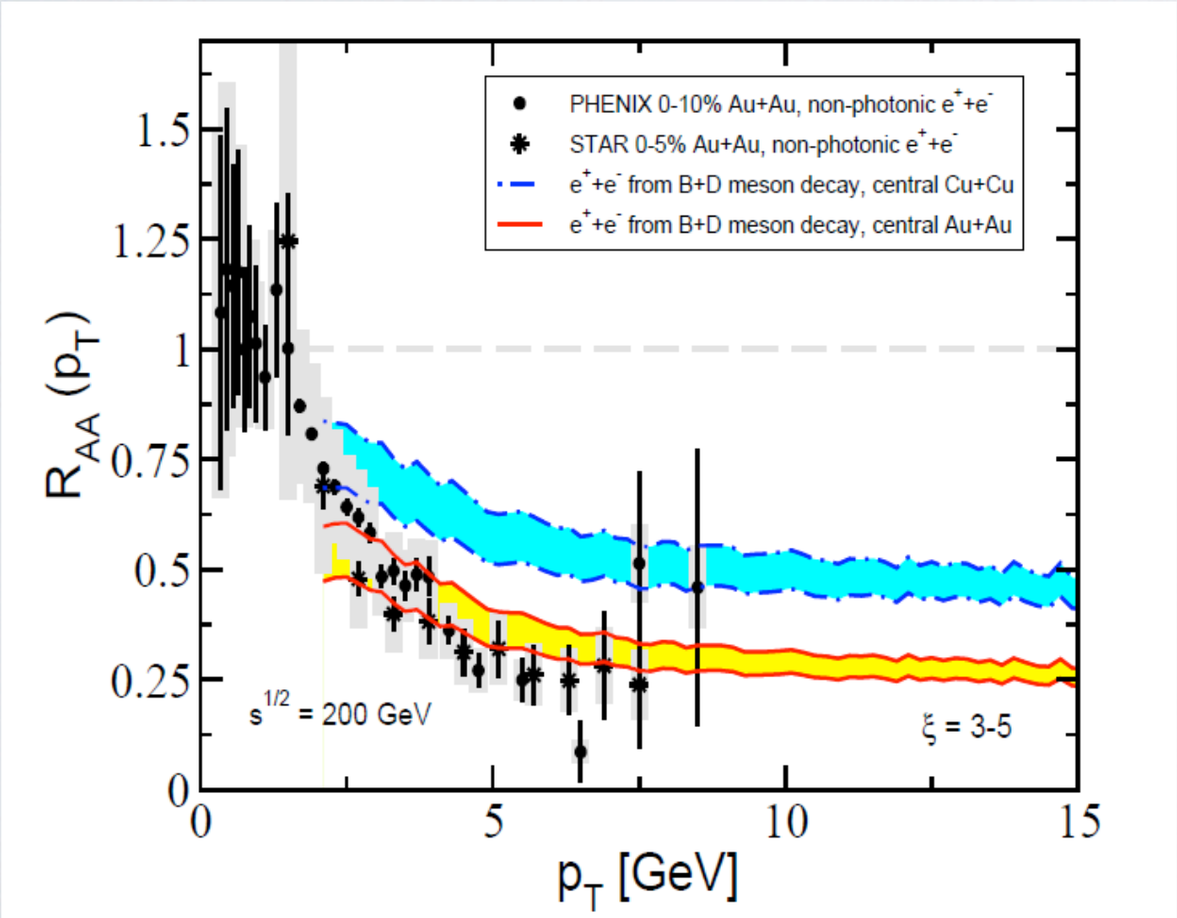
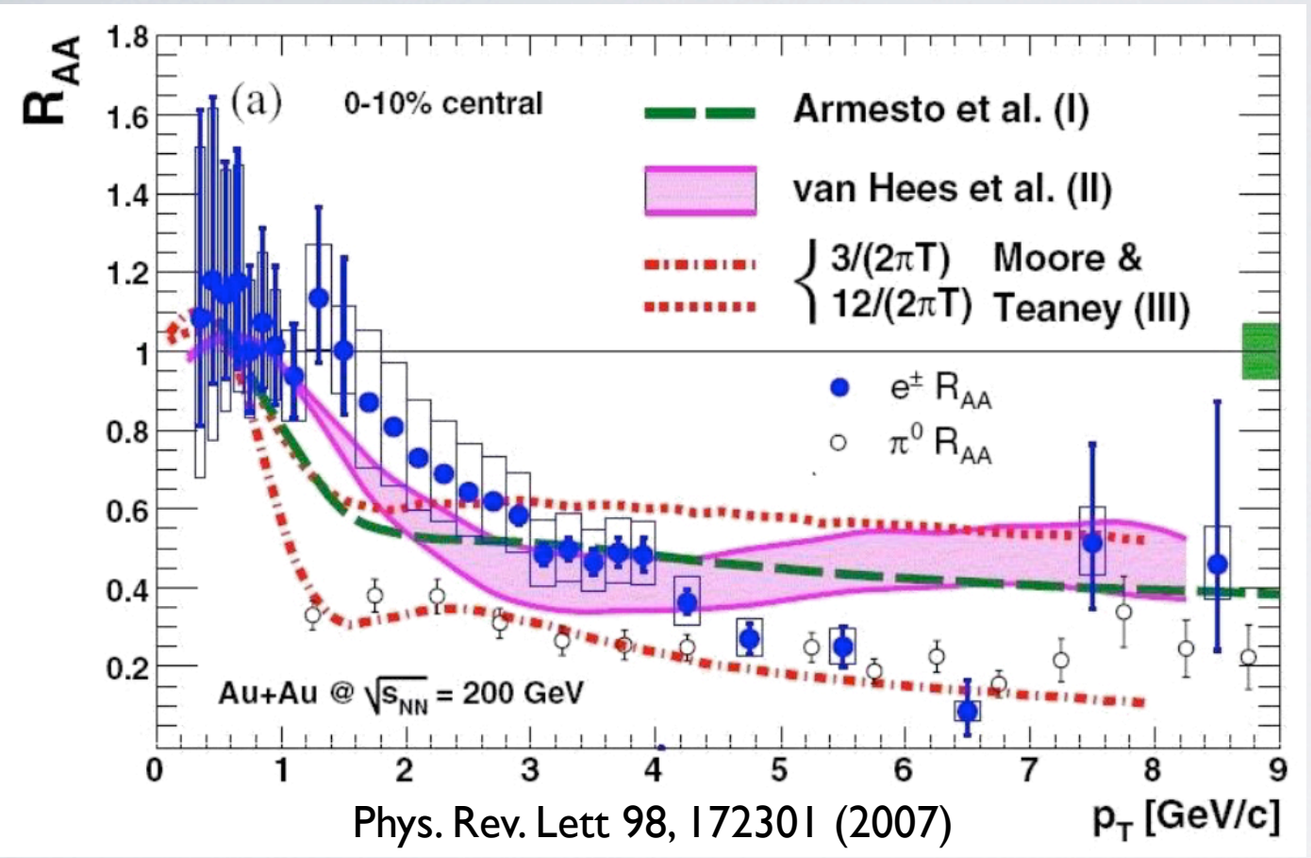



Phys. Rev. C 80, 054902 (2009)

- Theoretical model (Sharma, Vitev and Zhang)
  - radiative energy loss not enough to describe large suppression
  - includes partonic energy loss and collisional dissociation
  - CNM effects such as shadowing, Cronin effect and initial energy loss

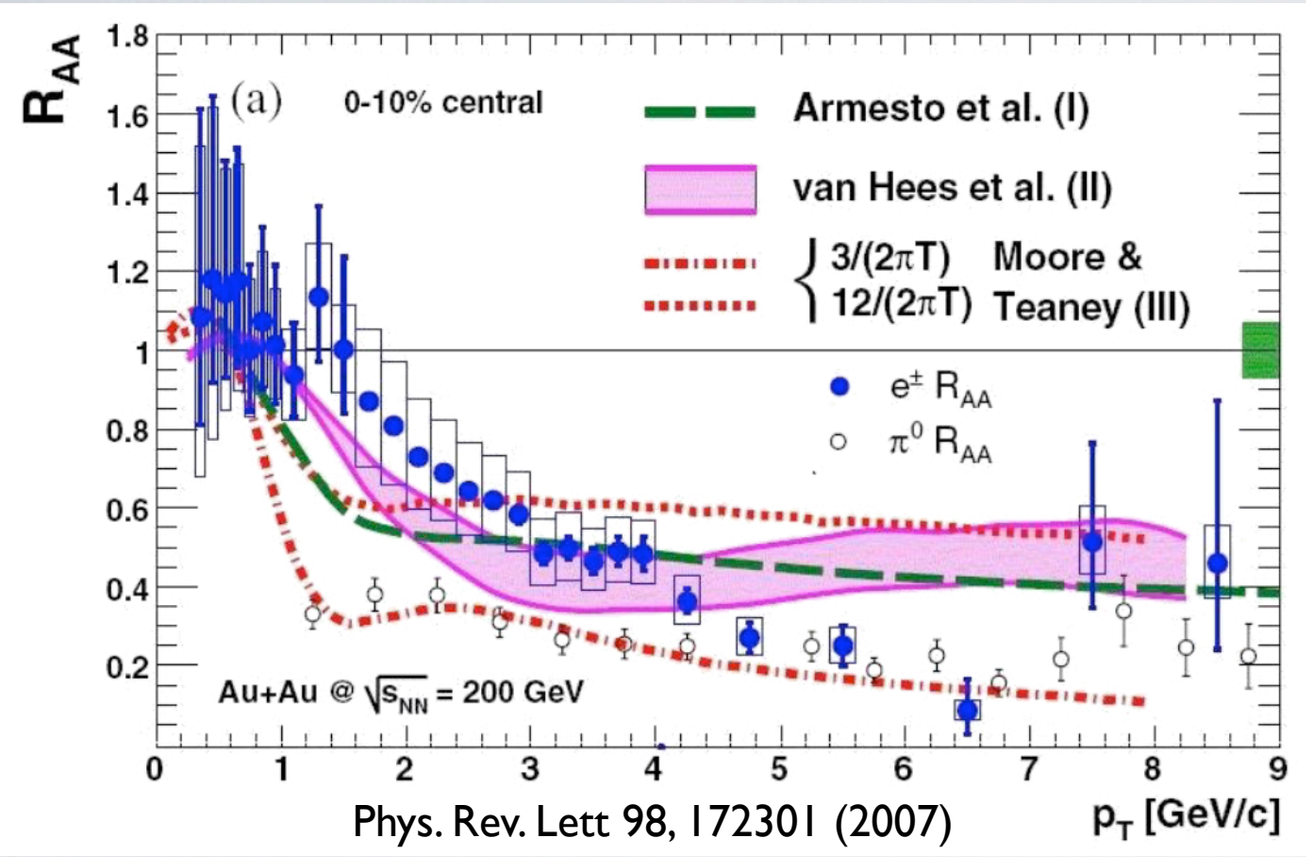
# Heavy flavor in HI collisions

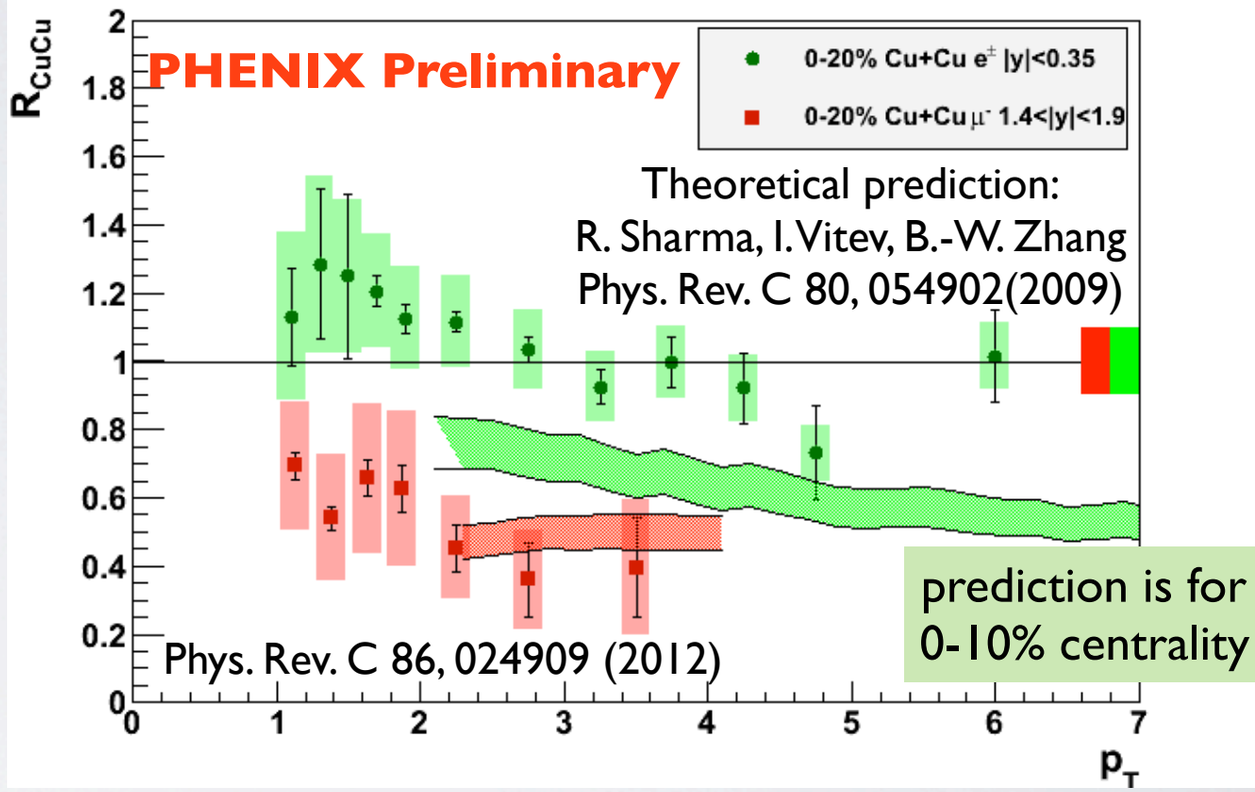


Phys. Rev. Lett 98, 172301 (2007)

- Large suppression in central Au+Au collisions at mid-rapidity

# Heavy flavor in HI collisions

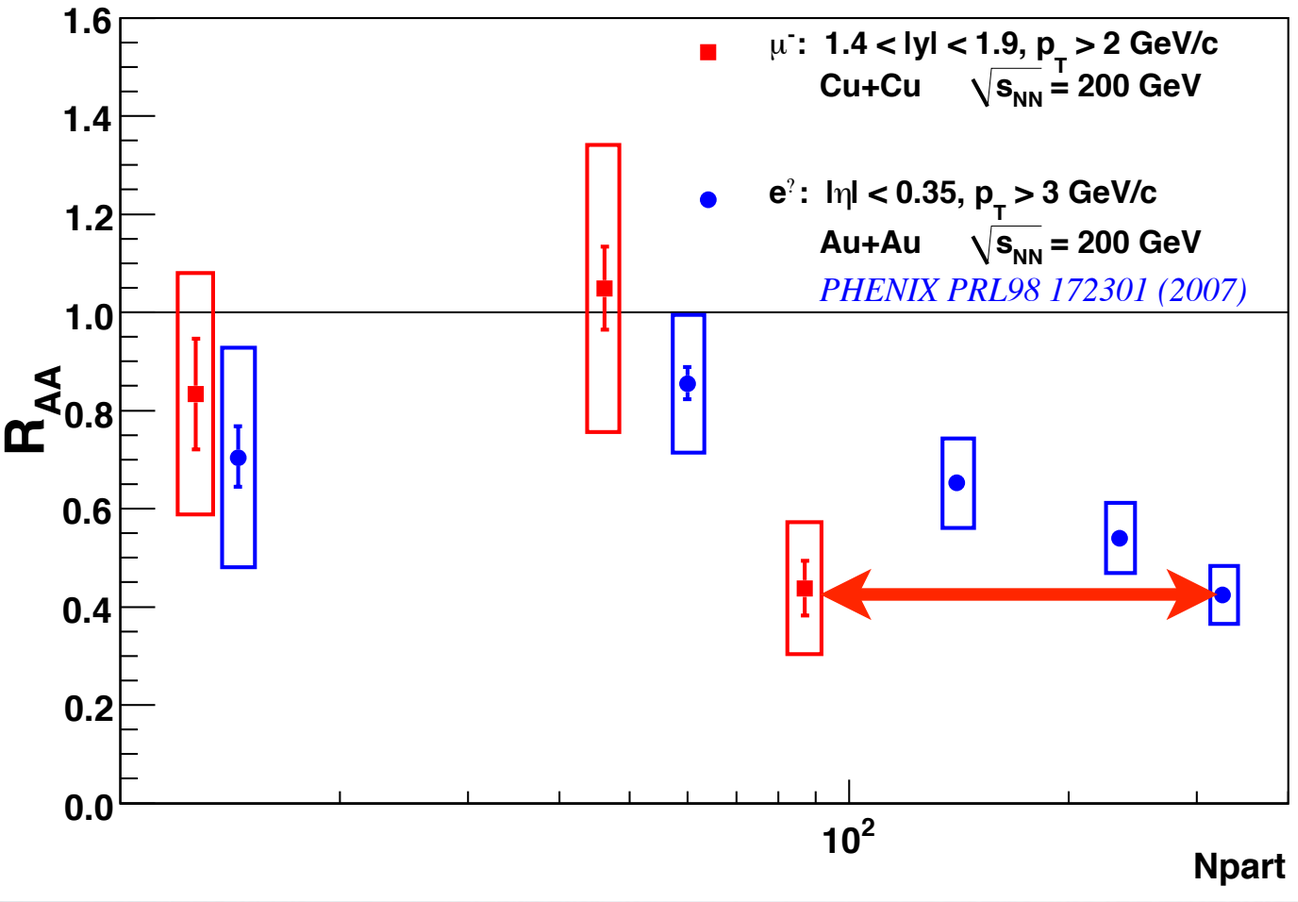


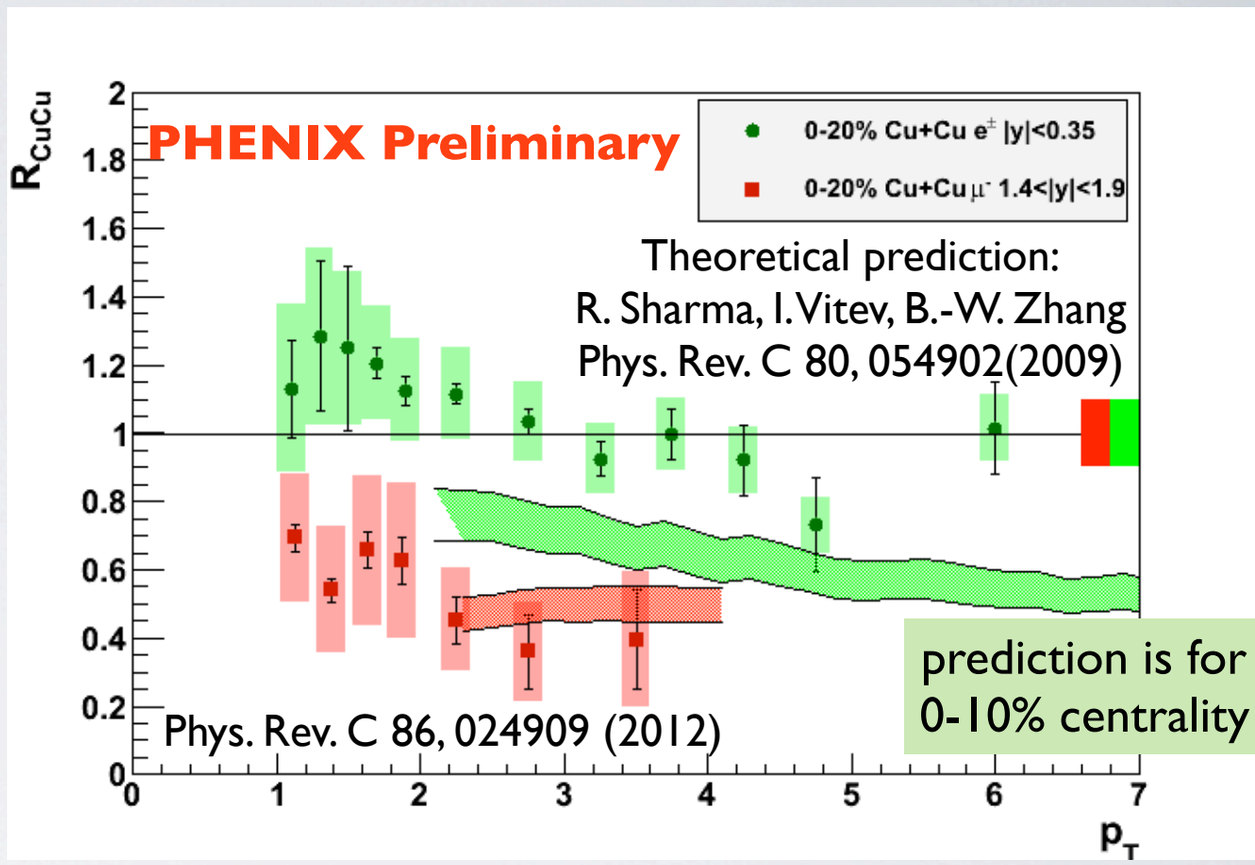




- Large suppression in central Au+Au collisions at mid-rapidity

- The most central (0-20%) Cu+Cu collisions
  - not much suppression at mid, but large suppression at forward
  - well describe suppression at forward rapidity with additional CNM effects (shadowing, initial energy loss)

# Heavy flavor in HI collisions

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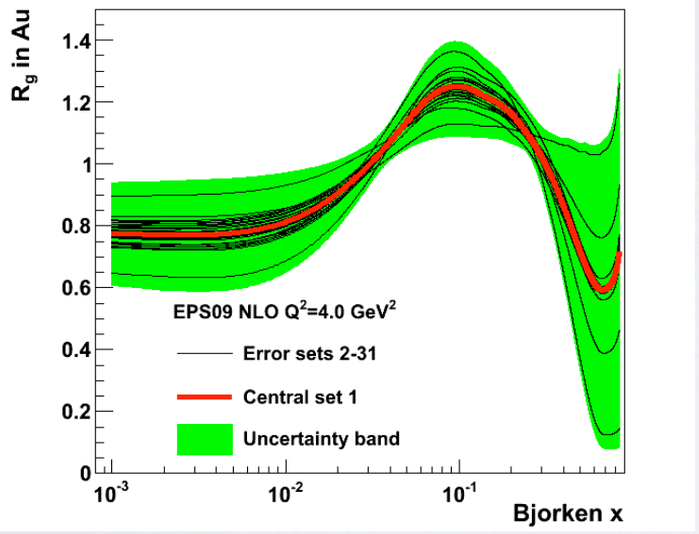
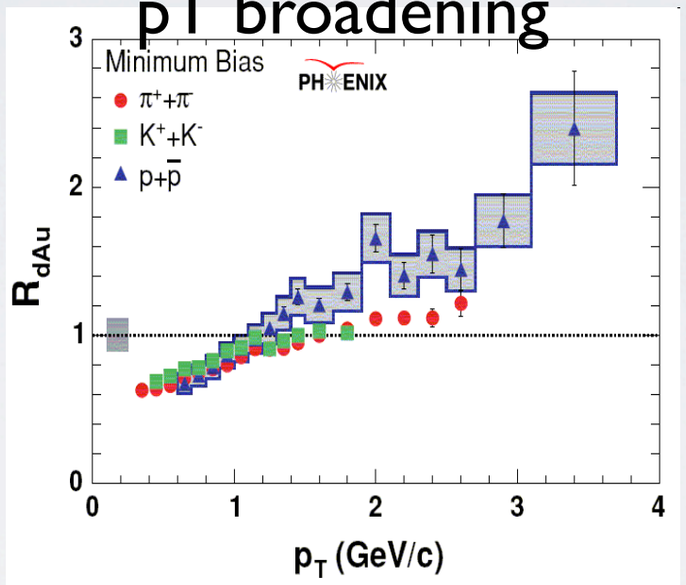
# Cold Nuclear Matter in d+Au collisions

- d+Au collision as a control experiment
  - In heavy ion collision, CNM & HNM effects are mixed
  - baseline measurements with minimal hot nuclear medium

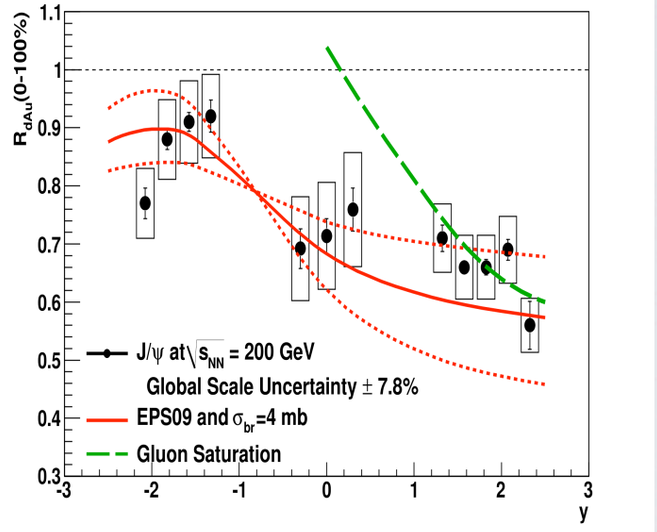
Shadowing




pT broadening




Break up



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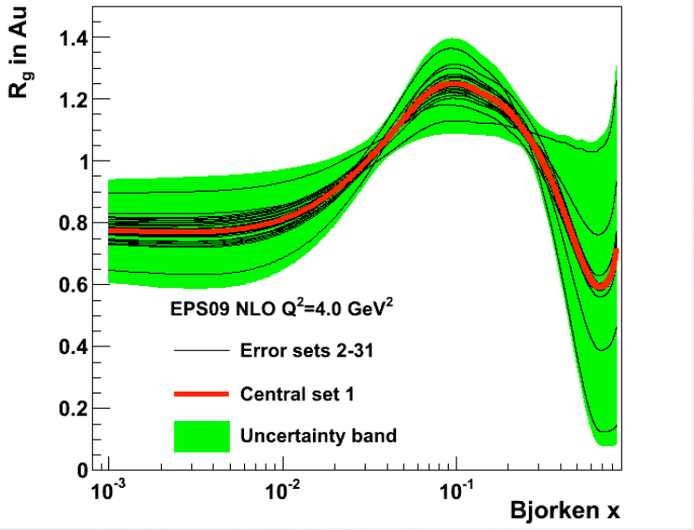


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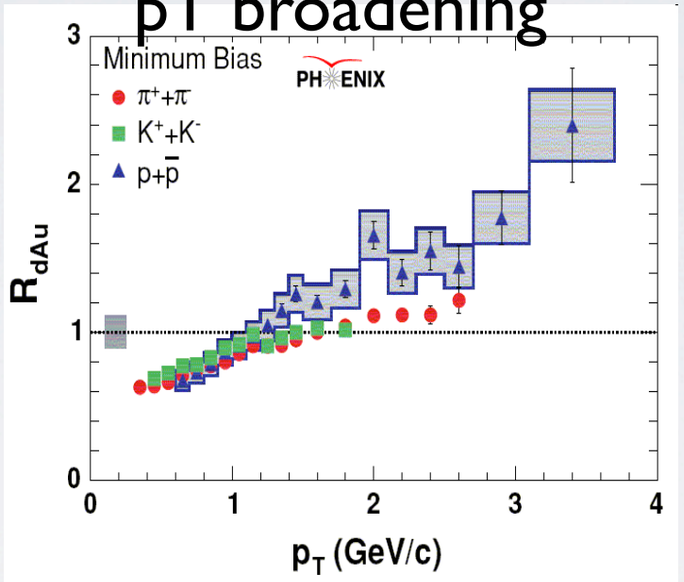


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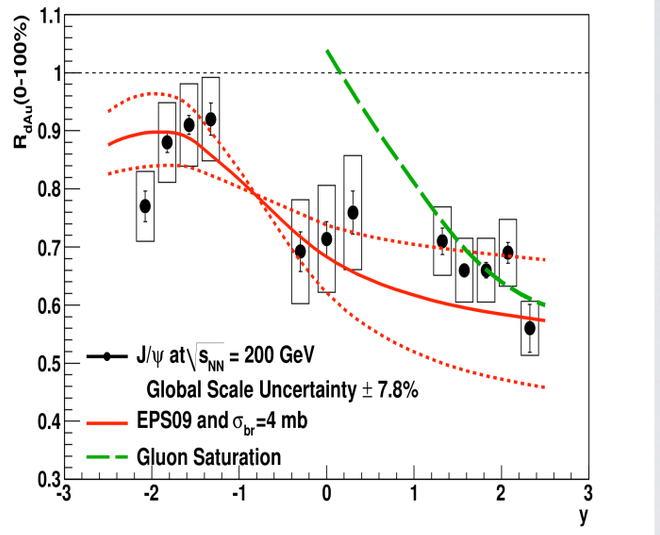
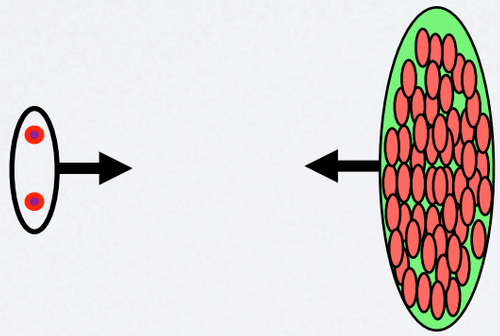



Backward rapidity
*Au-going side
*$x_1 < x_2$



parton of $x_1$ in d

parton of $x_2$ in Au

Forward rapidity
*d-going side
*$x_1 > x_2$

$$x_2 = \frac{Q}{\sqrt{s_{NN}}} e^{-y}$$



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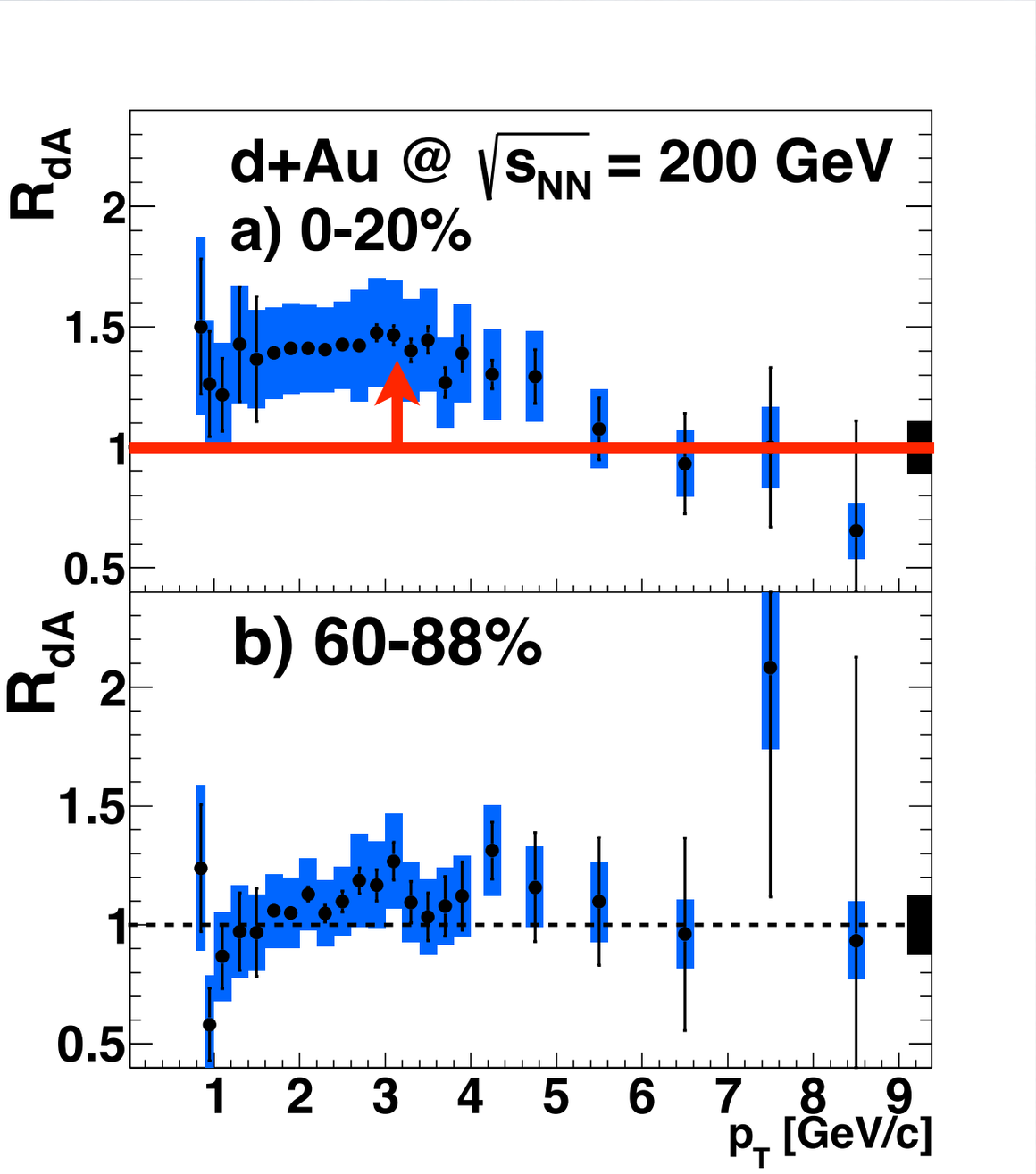
# HF electrons @ mid-rapidity




Phys. Rev. Lett. 109, 242301 (2012)

- $R_{dA}$ ~ 1 in the peripheral collisions
- Large enhancement in the central collision

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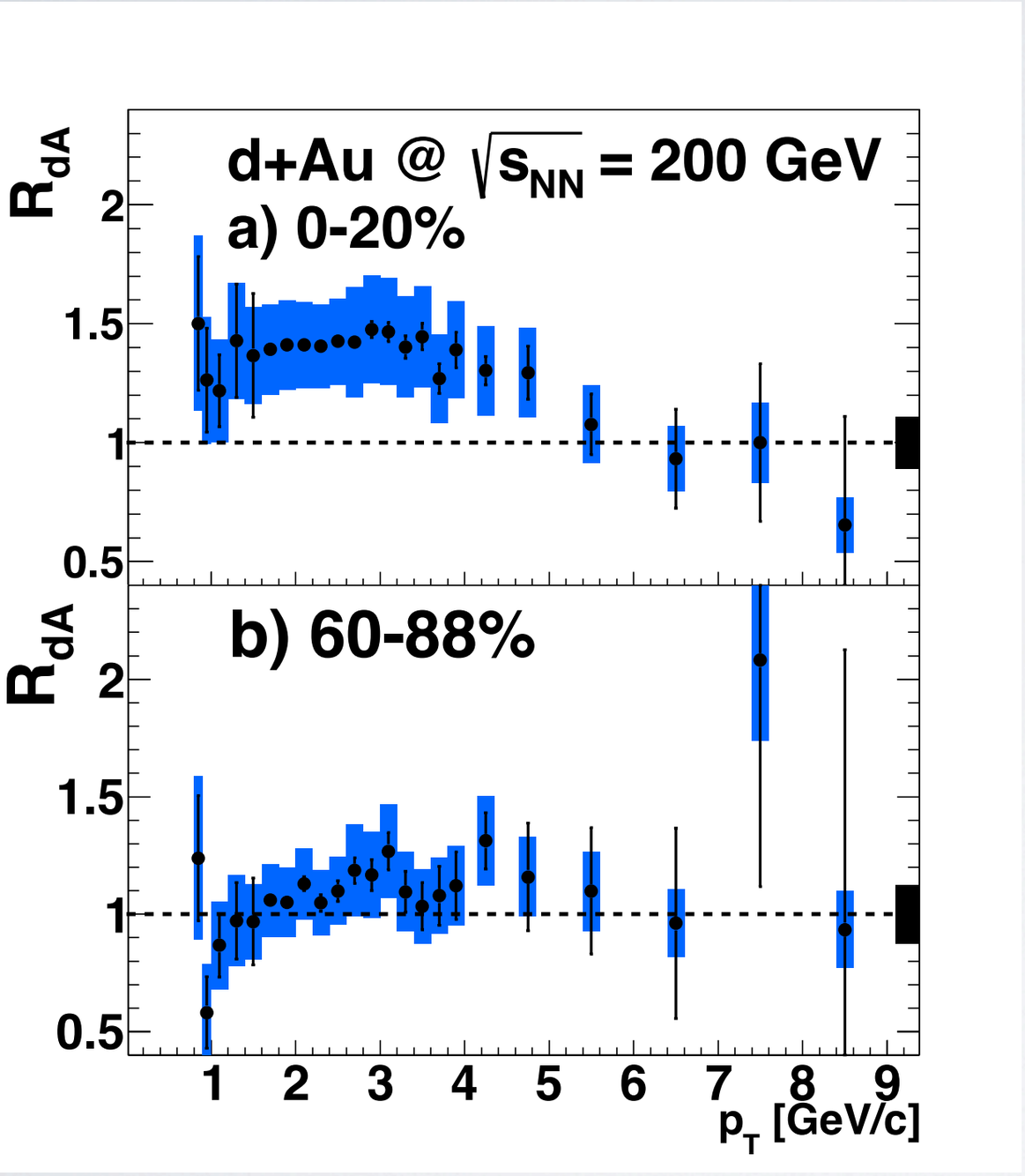
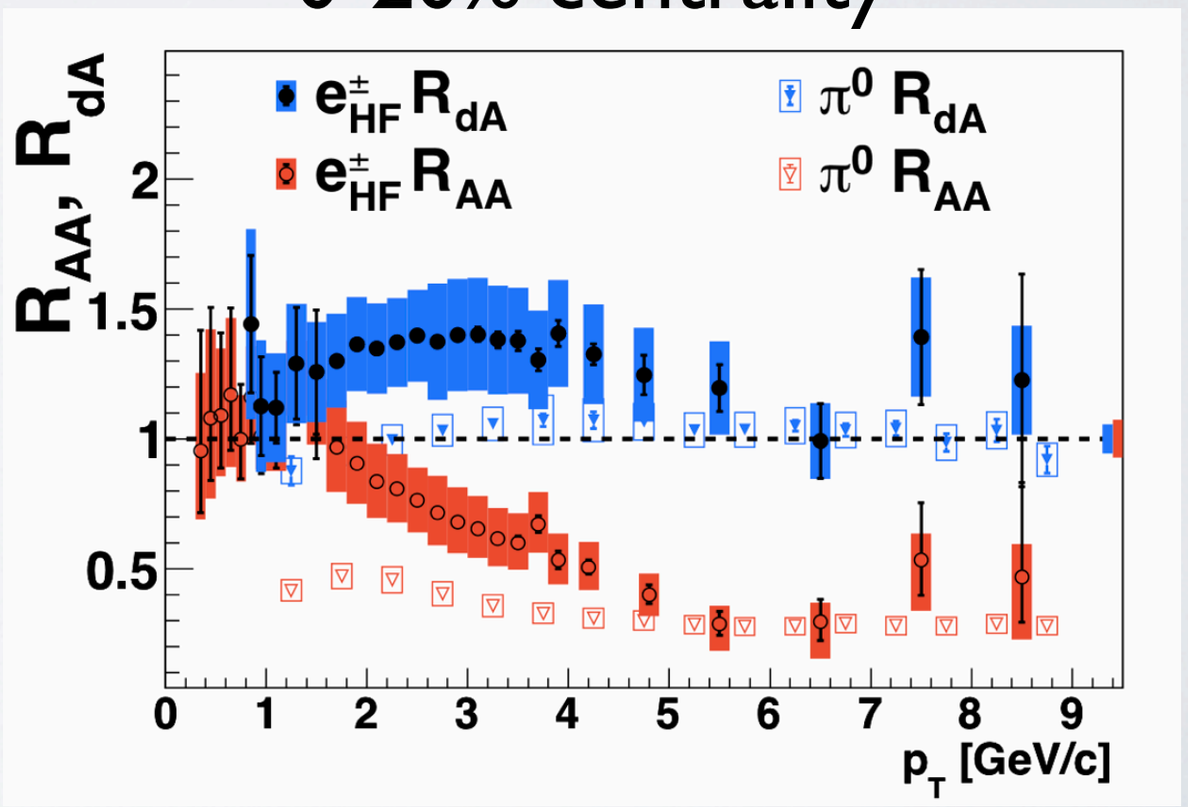



Phys. Rev. Lett. 109, 242301 (2012)

- $R_{dA}$ ~ 1 in the peripheral collisions
- Large enhancement in the central collision
  - HF $R_{dA}$ is larger than $\pi^0$ $R_{dA}$
  - HF suppression in Au+Au is due to the HNM effects

0-20% centrality



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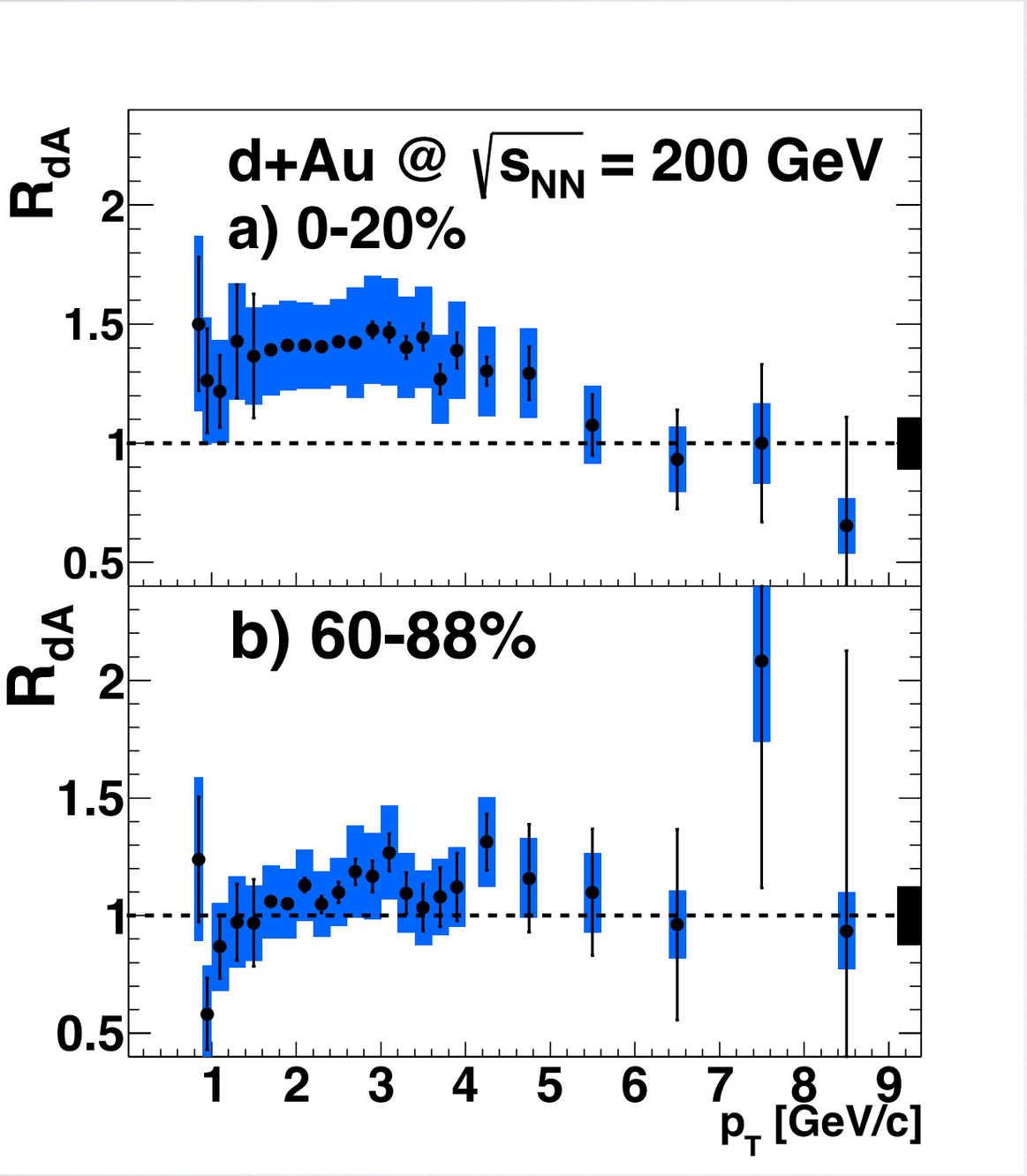


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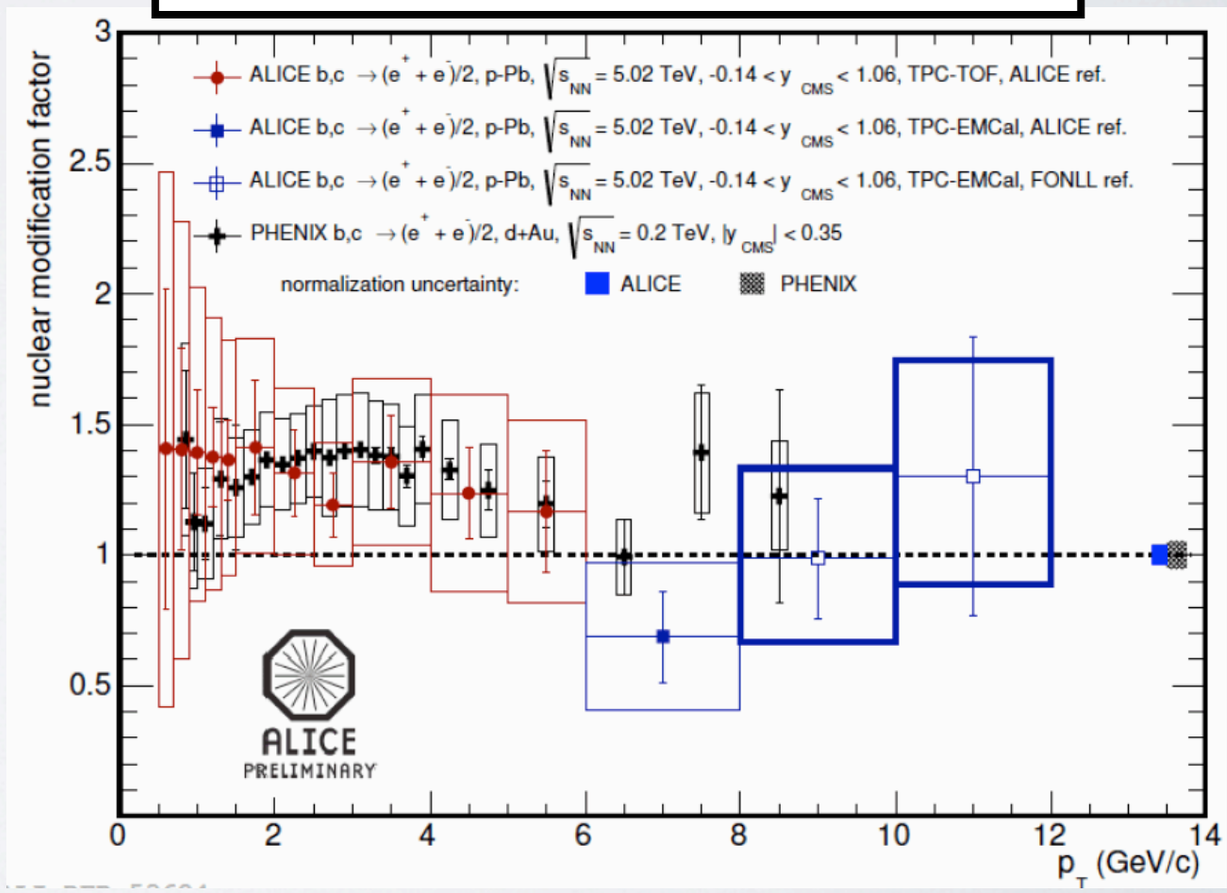
  - H
  the

ALICE preliminary in SQM 13'

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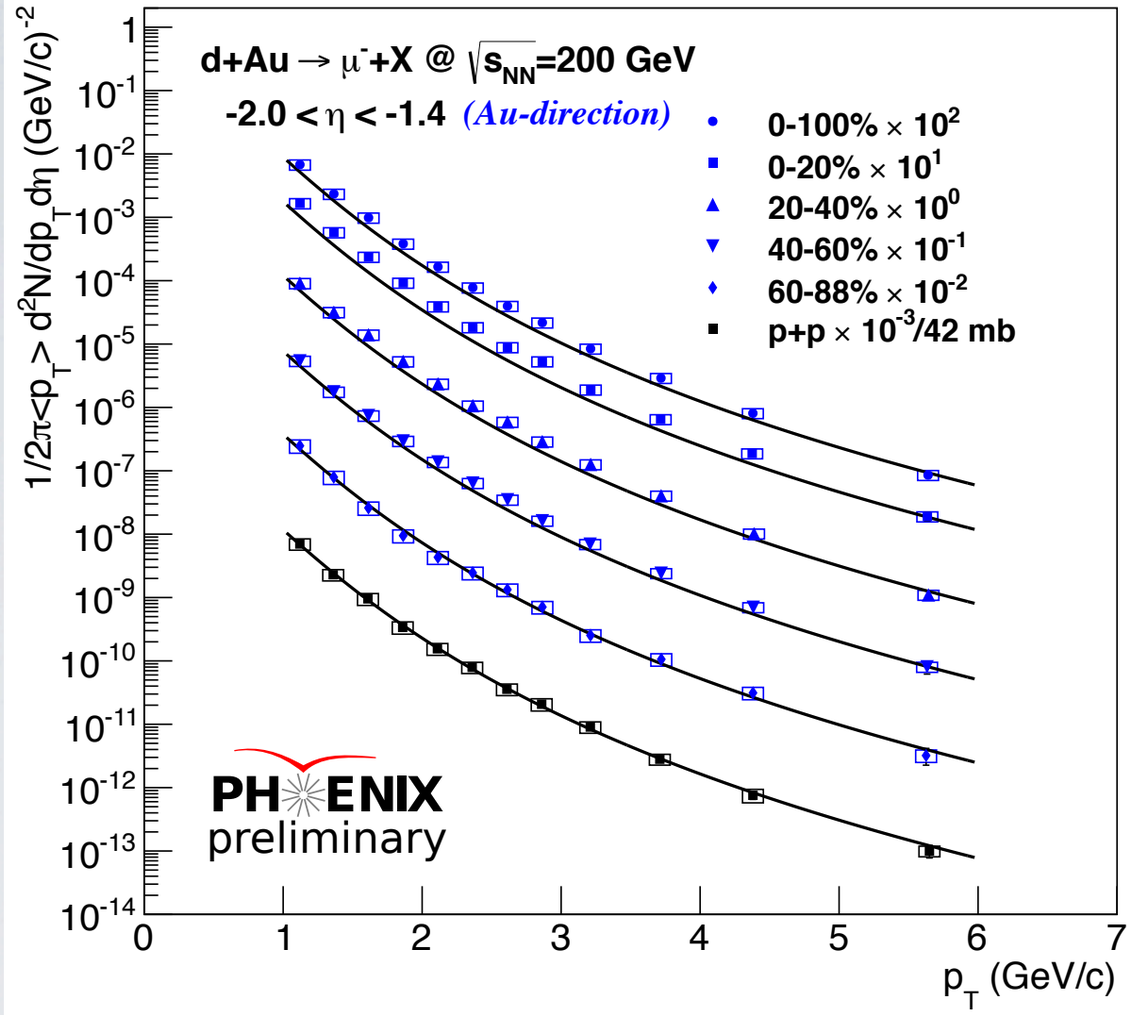
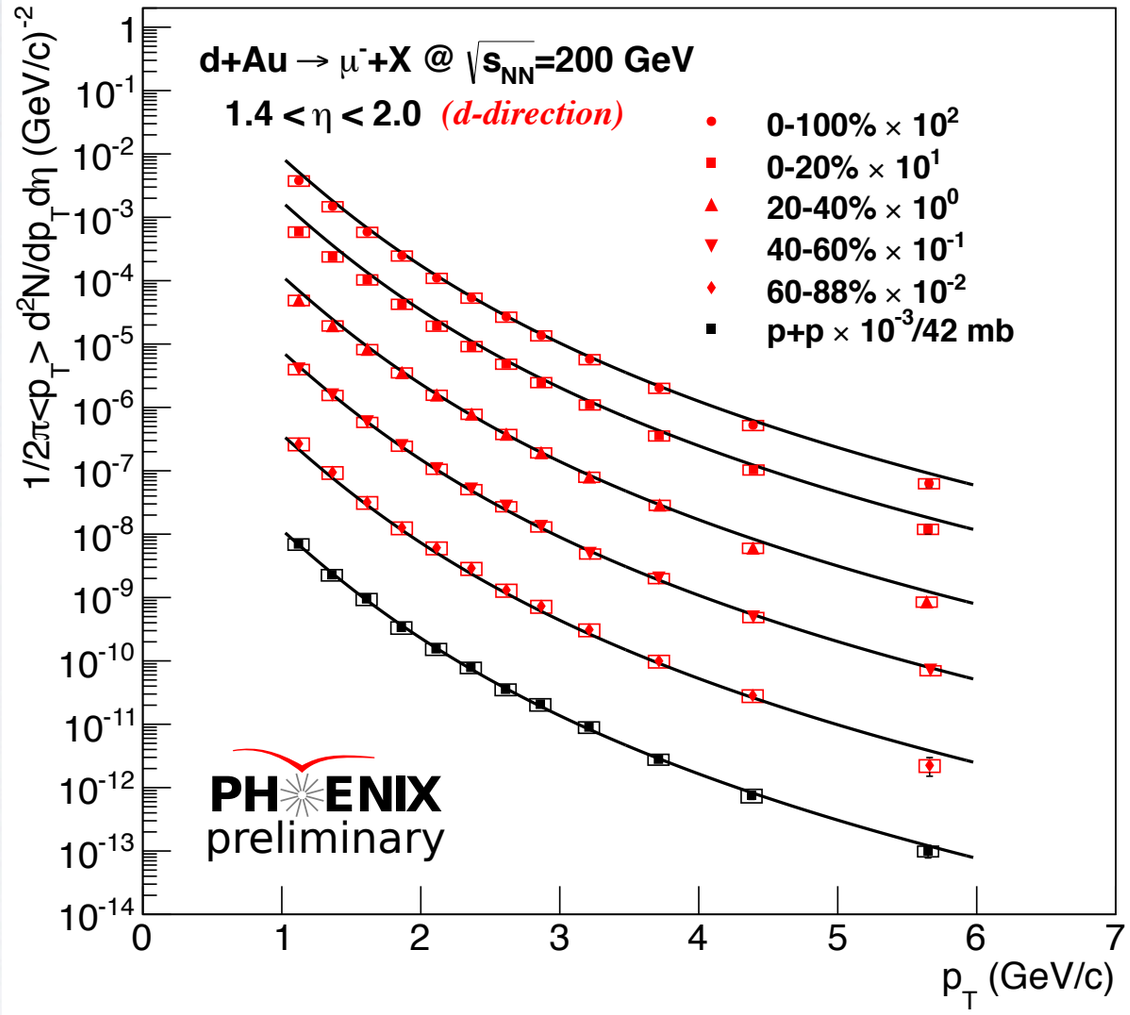
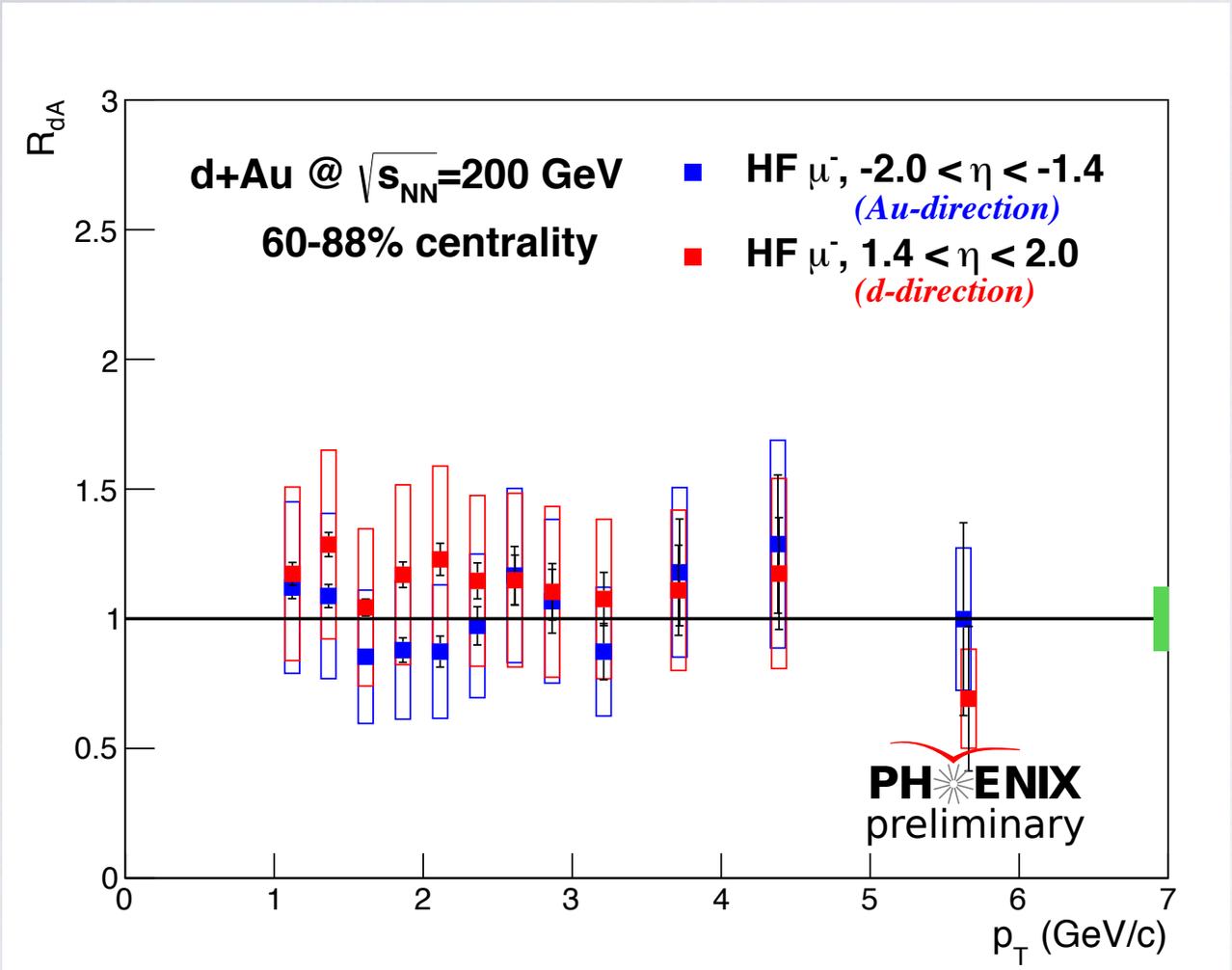
# HF muons @ forward & backward rapidity



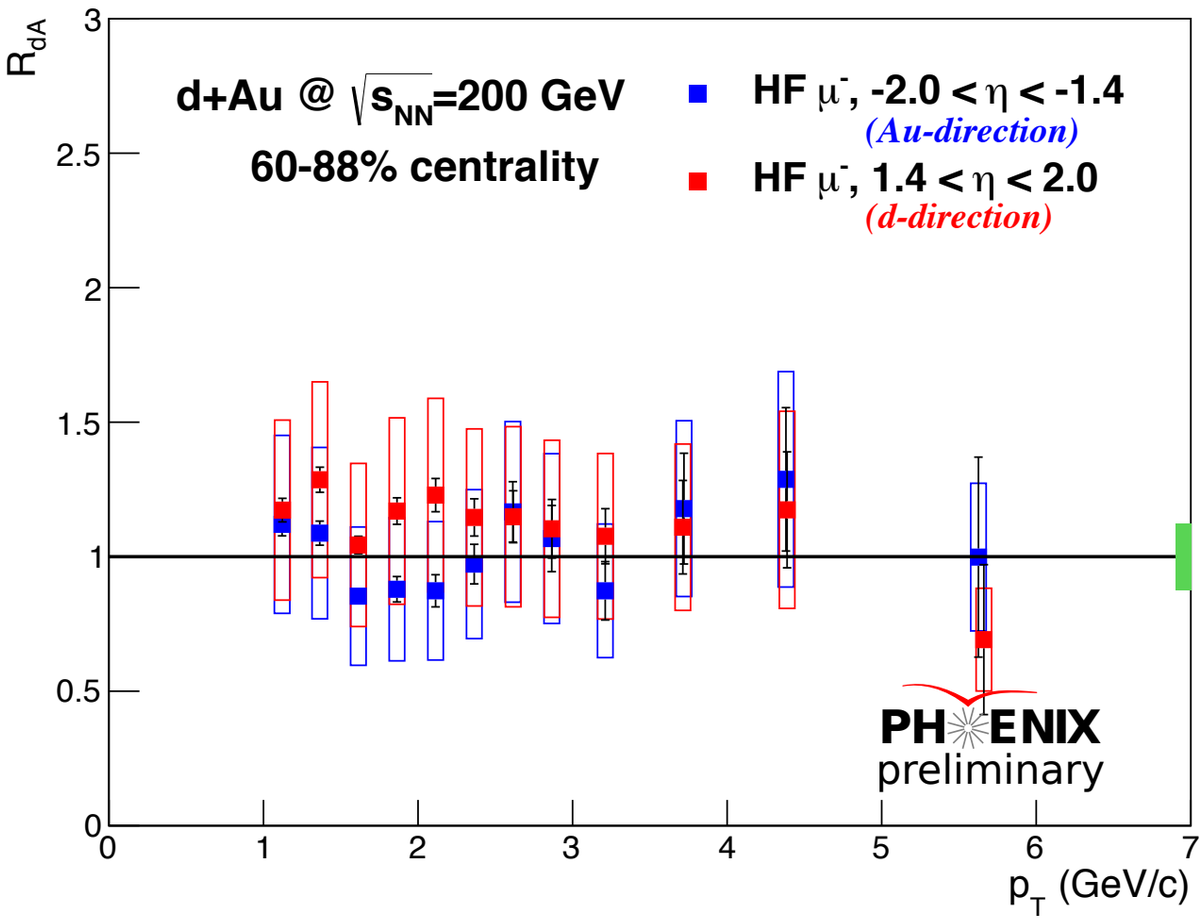

- HF single muons $p_T$ spectra at **backward(Au-direction, left)** and at **forward(d-direction, right)** in d+Au collisions
  - lines are $\langle T_{AB} \rangle$ scaled fit function of spectra in p+p collisions

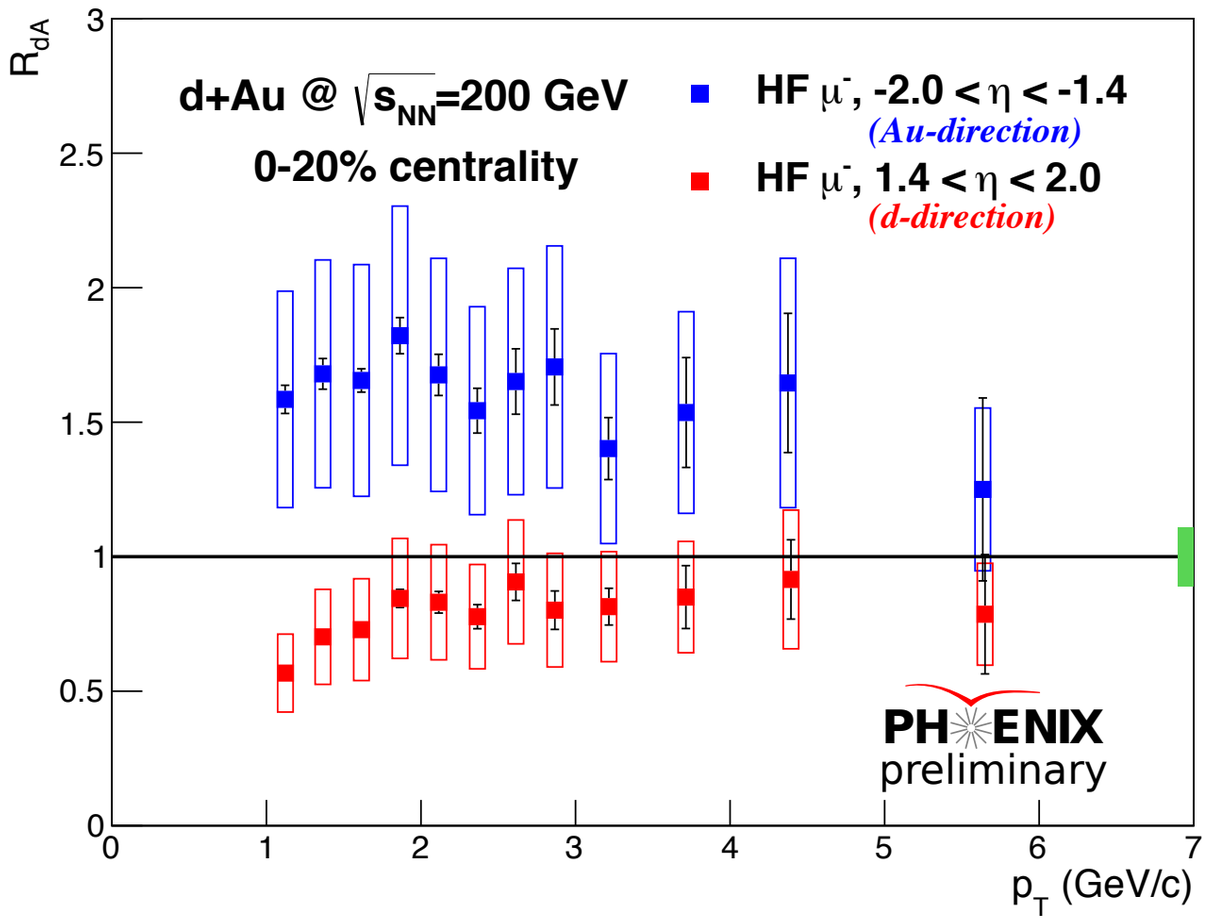
# HF muons $R_{dA}$, peripheral (60-88%)




- No modification at both rapidity ranges in most peripheral collisions

# HF muons $R_{dA}$, peripheral (60-88%) vs. central (0-20%)

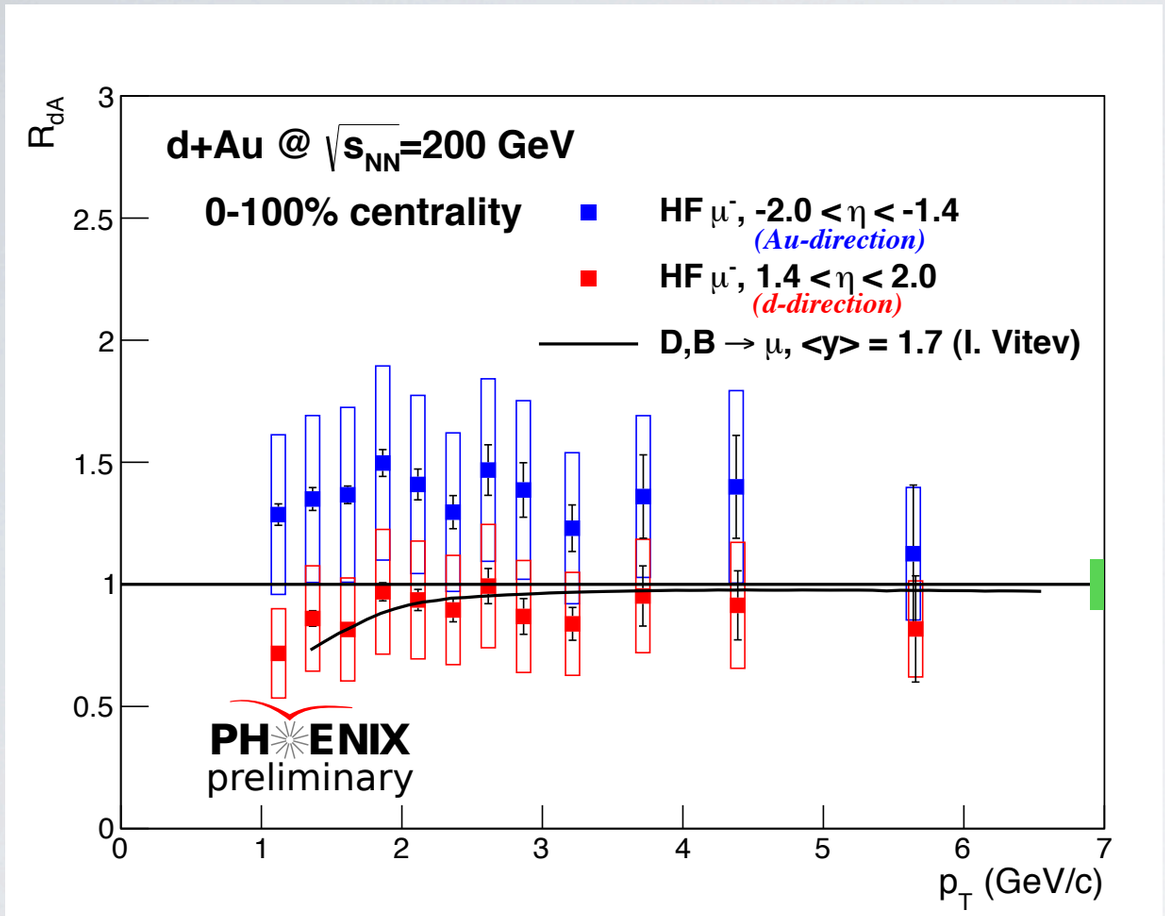



- No modification at both rapidity ranges in most peripheral collisions

- **Enhancement at backward** rapidity and **suppression at forward rapidity** in most central collisions
  - Strong CNM effects in the most central d+Au collisions!

# Comparison to models




- good agreement with the prediction from I.Vitev
  - muon production from D and B meson at <y>=1.7
  - considering shadowing, Cronin effect and initial parton energy loss

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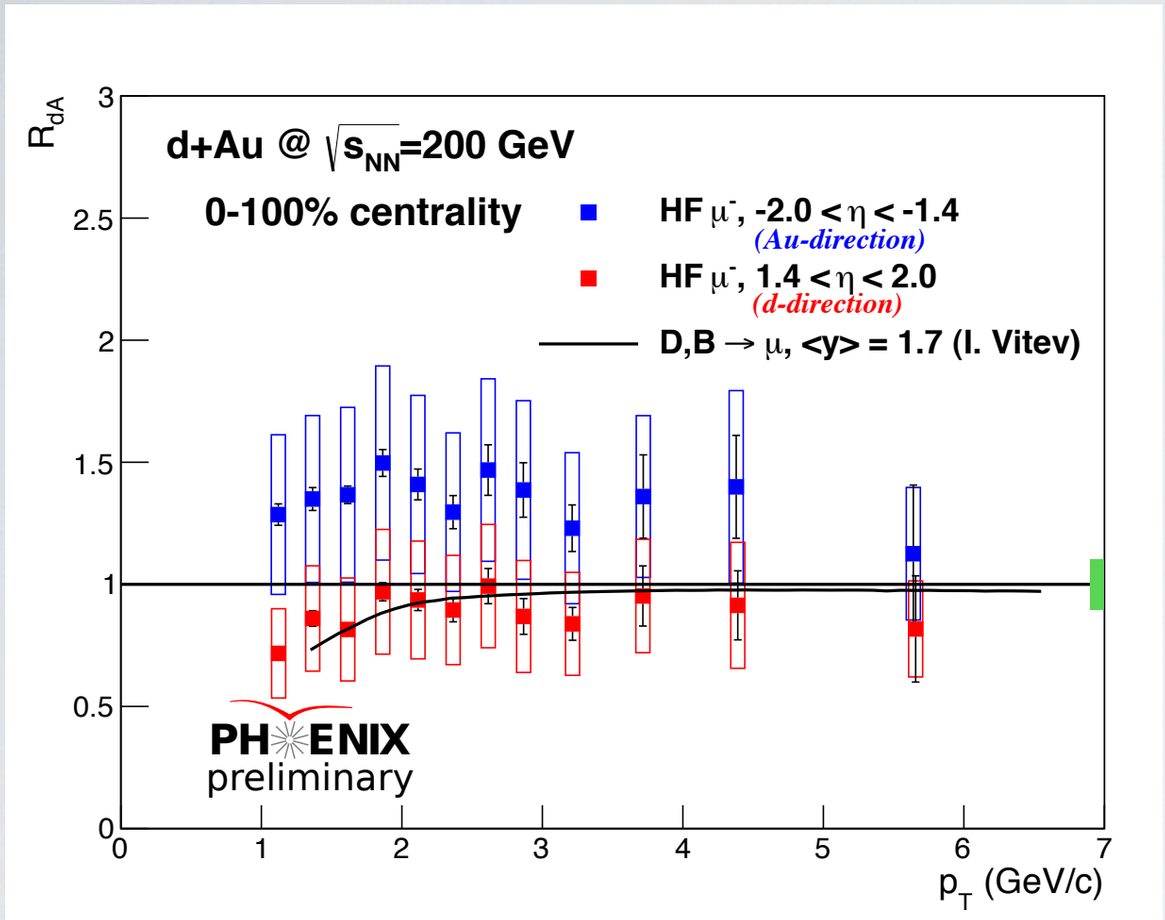


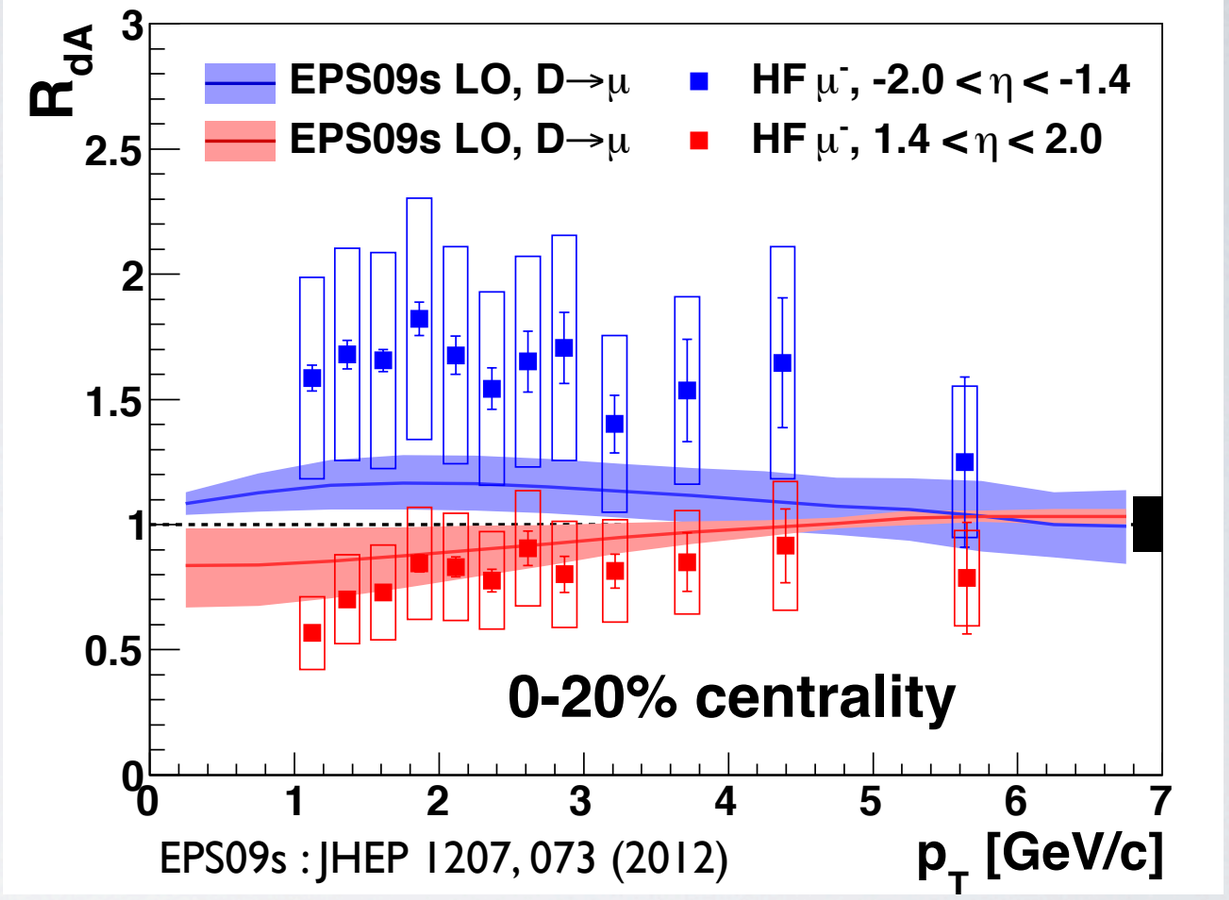


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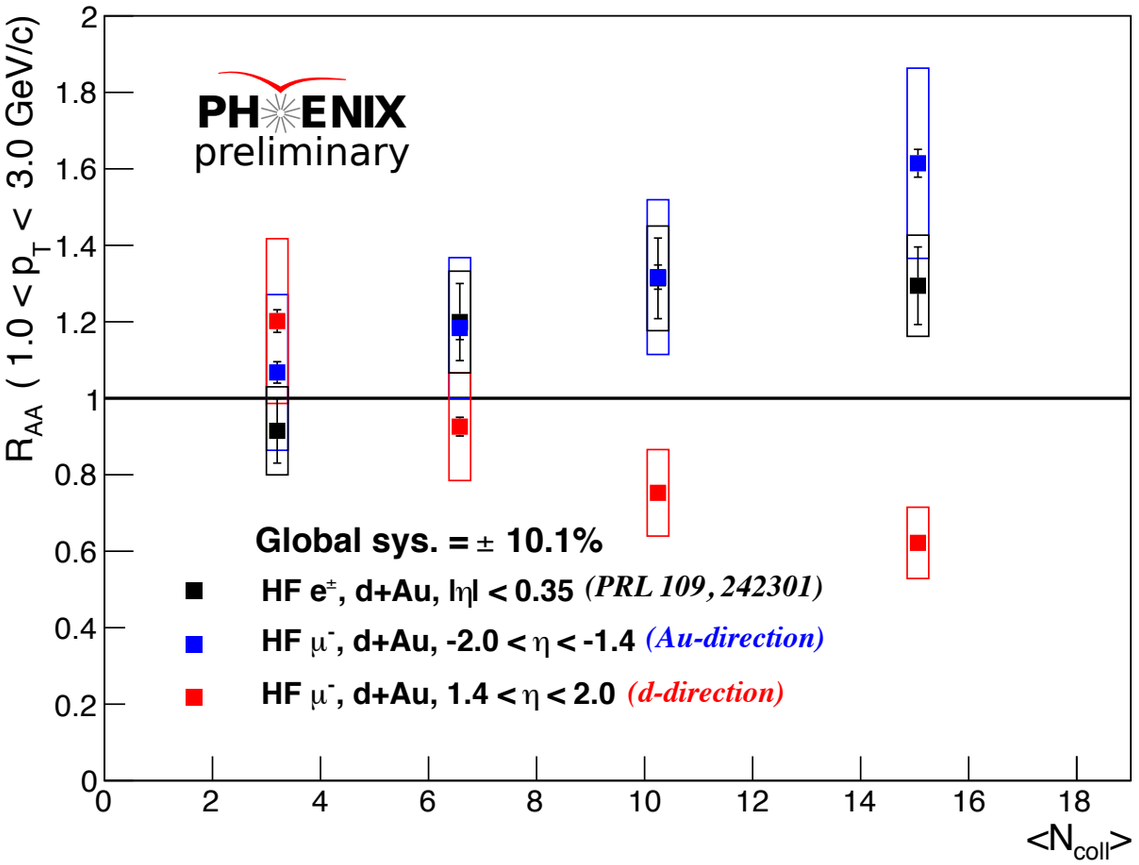
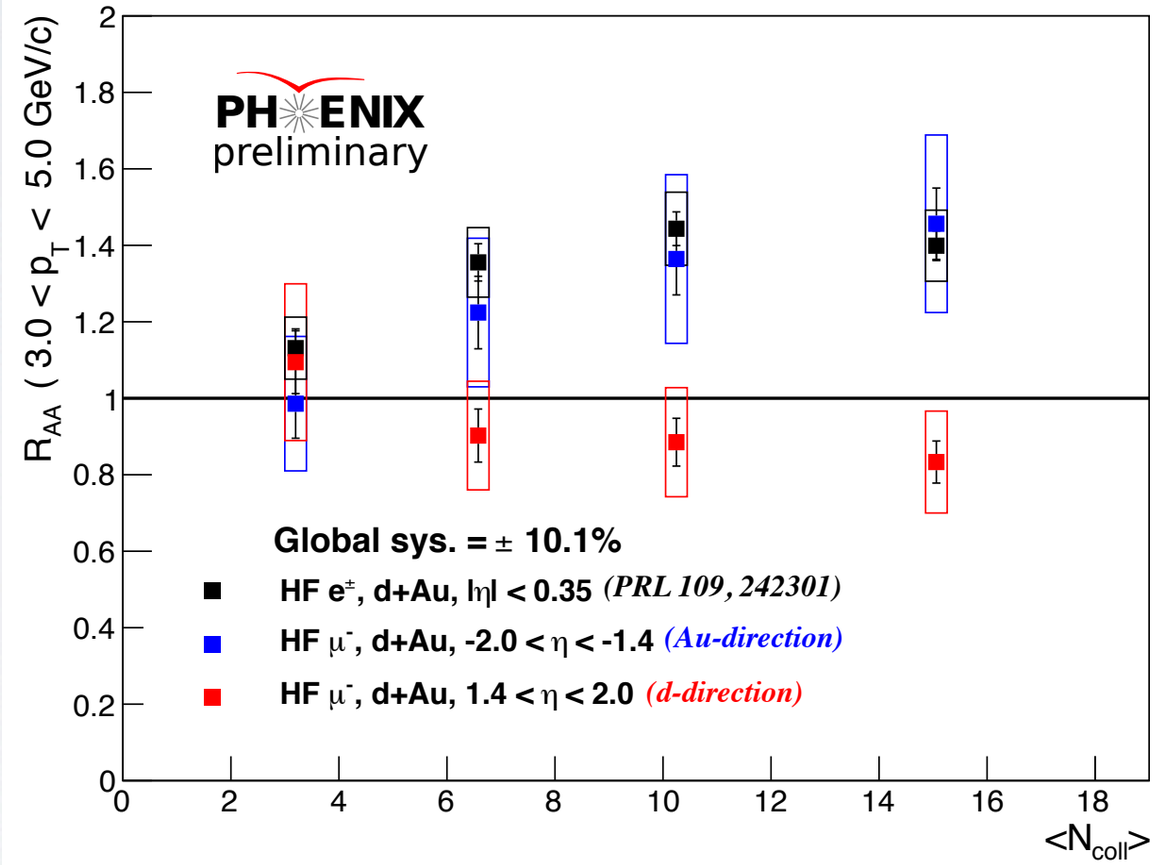
- EPS09s nPDF evaluation with PYTHIA
  - consistent with data at forward rapidity as well

# Rapidity evolution of $R_{dA}$ vs. $N_{coll}$

## $1.0 < p_T < 3.0$ GeV/c

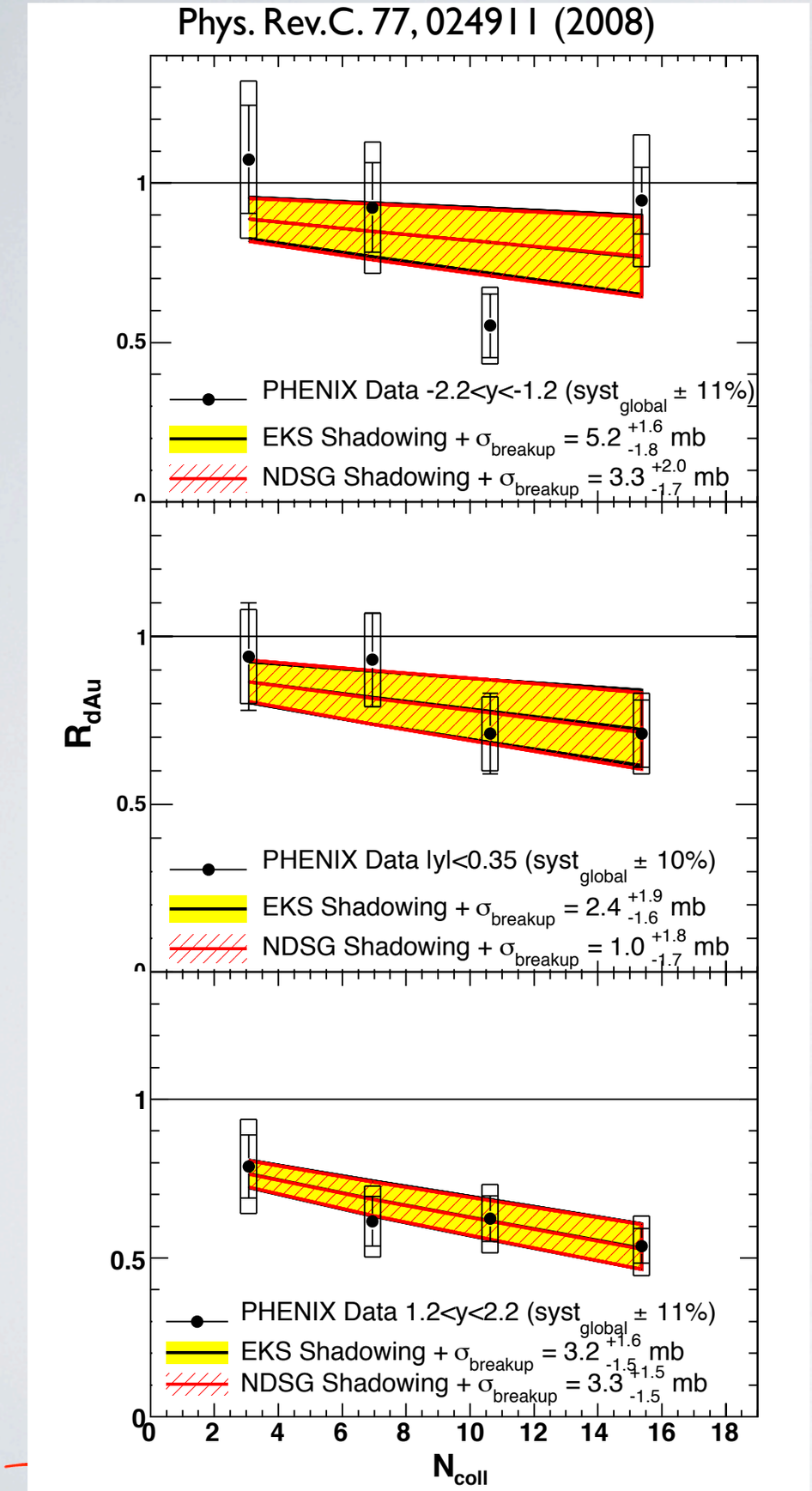


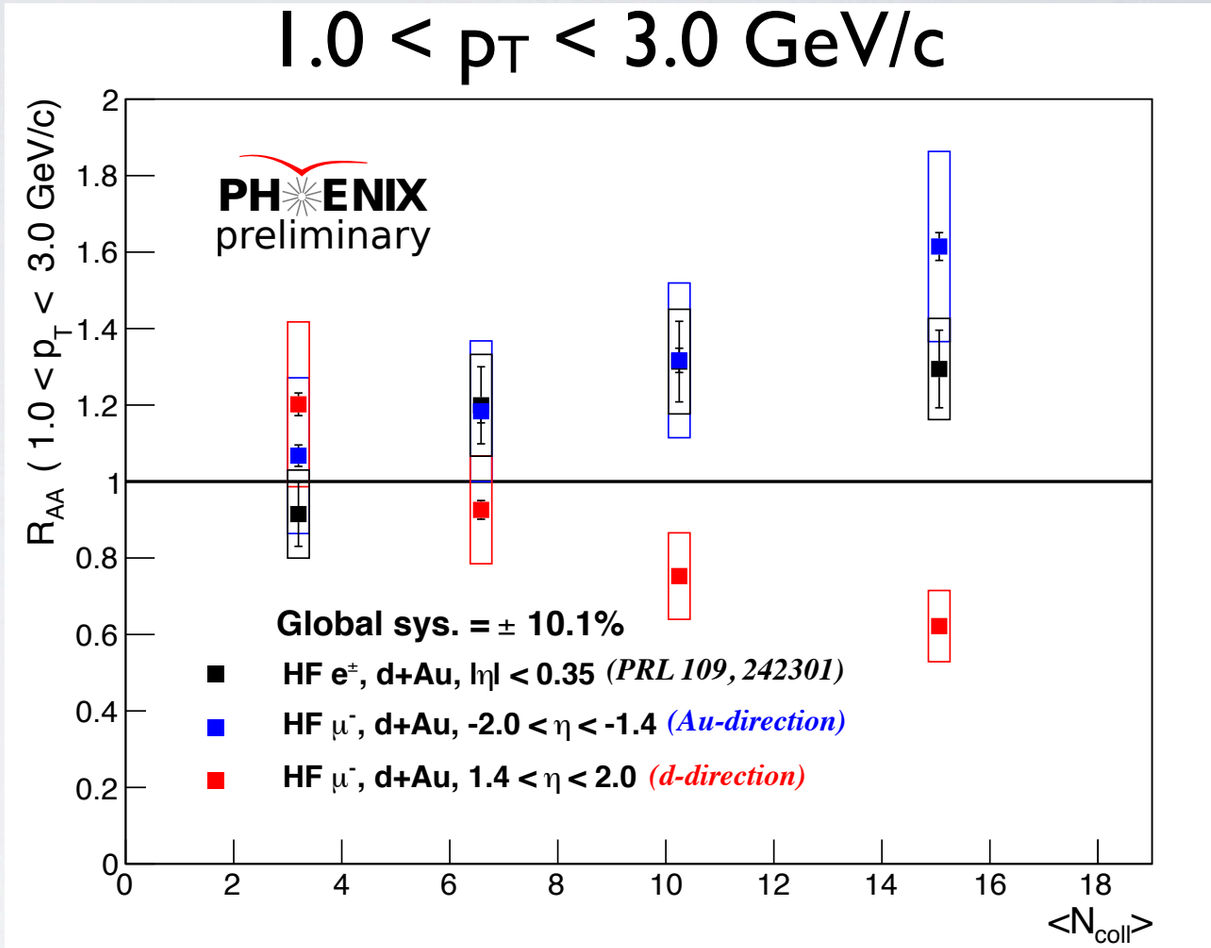

## $3.0 < p_T < 5.0$ GeV/c




- Stronger centrality dependence at low $p_T$ region
  - similar trends at backward and mid-rapidity
  - opposite trend at forward, more suppression as larger $N_{coll}$

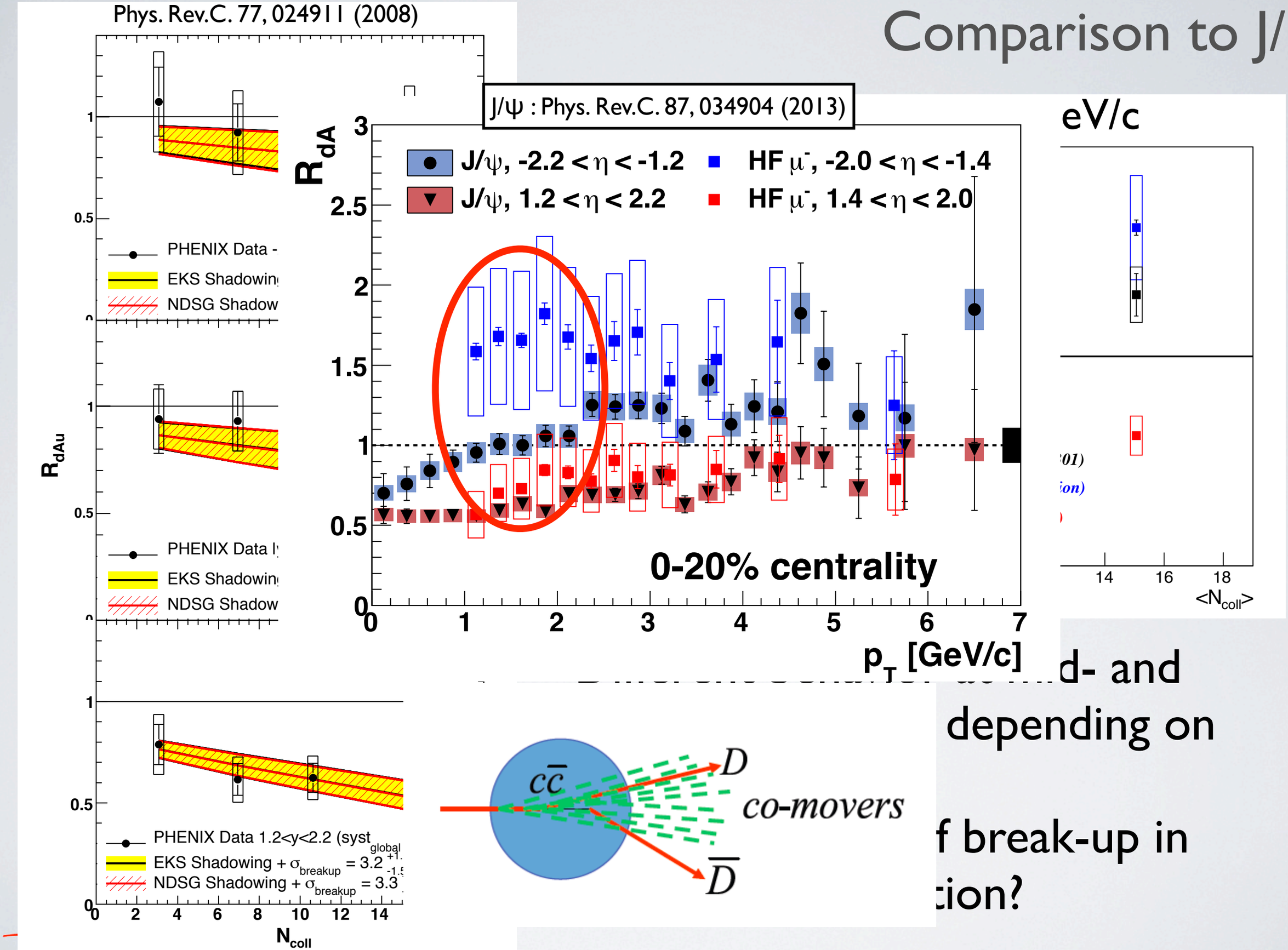
# Comparison to J/ψ




- Different behavior at mid- and backward rapidity depending on centrality
  - significant role of break-up in quarkonia production?

# Comparison to J/ψ







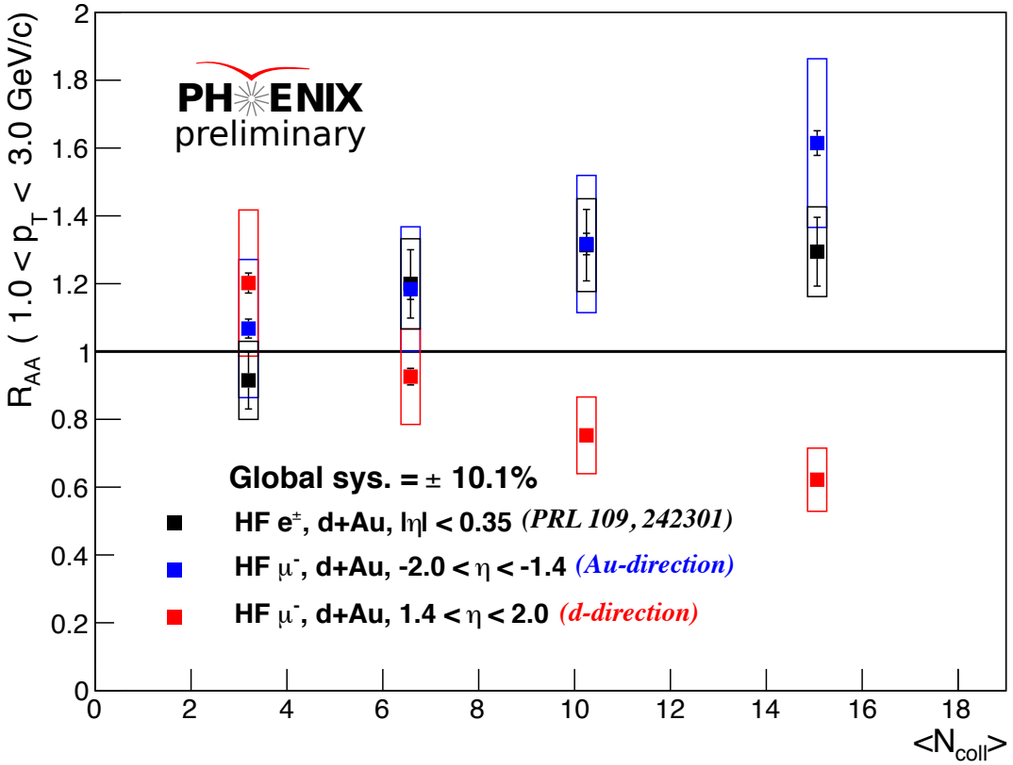
d- and

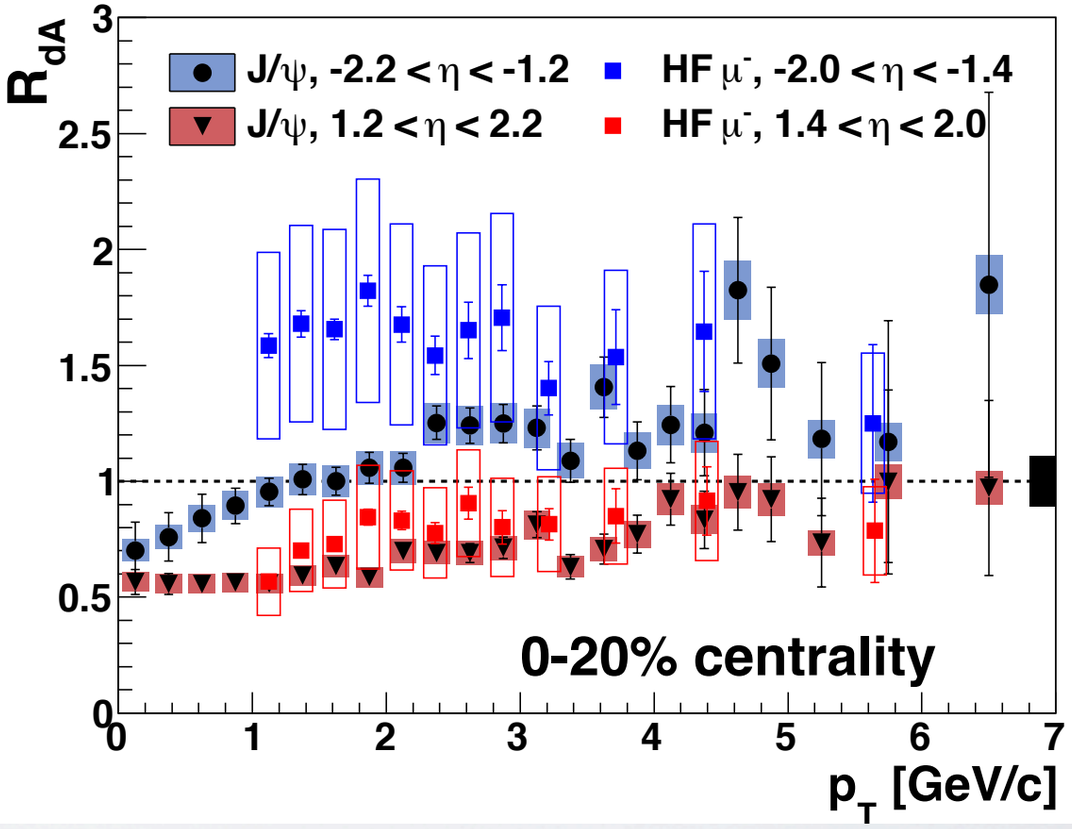
depending on

f break-up in

tion?

# Finalized soon I: HF μ in d+Au (200 GeV) at forward

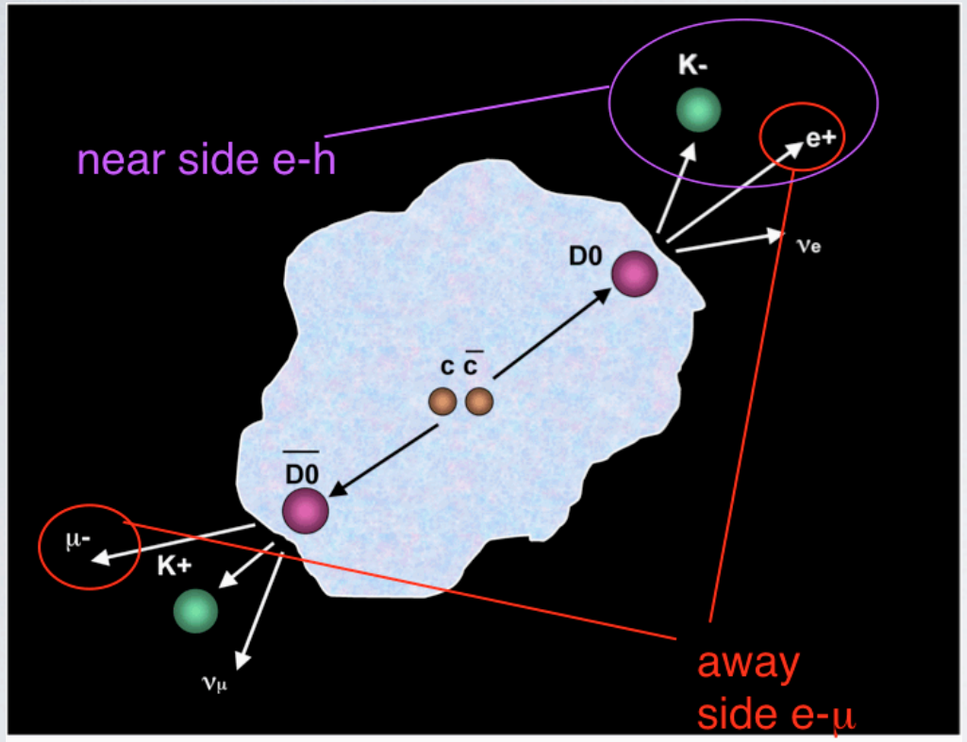


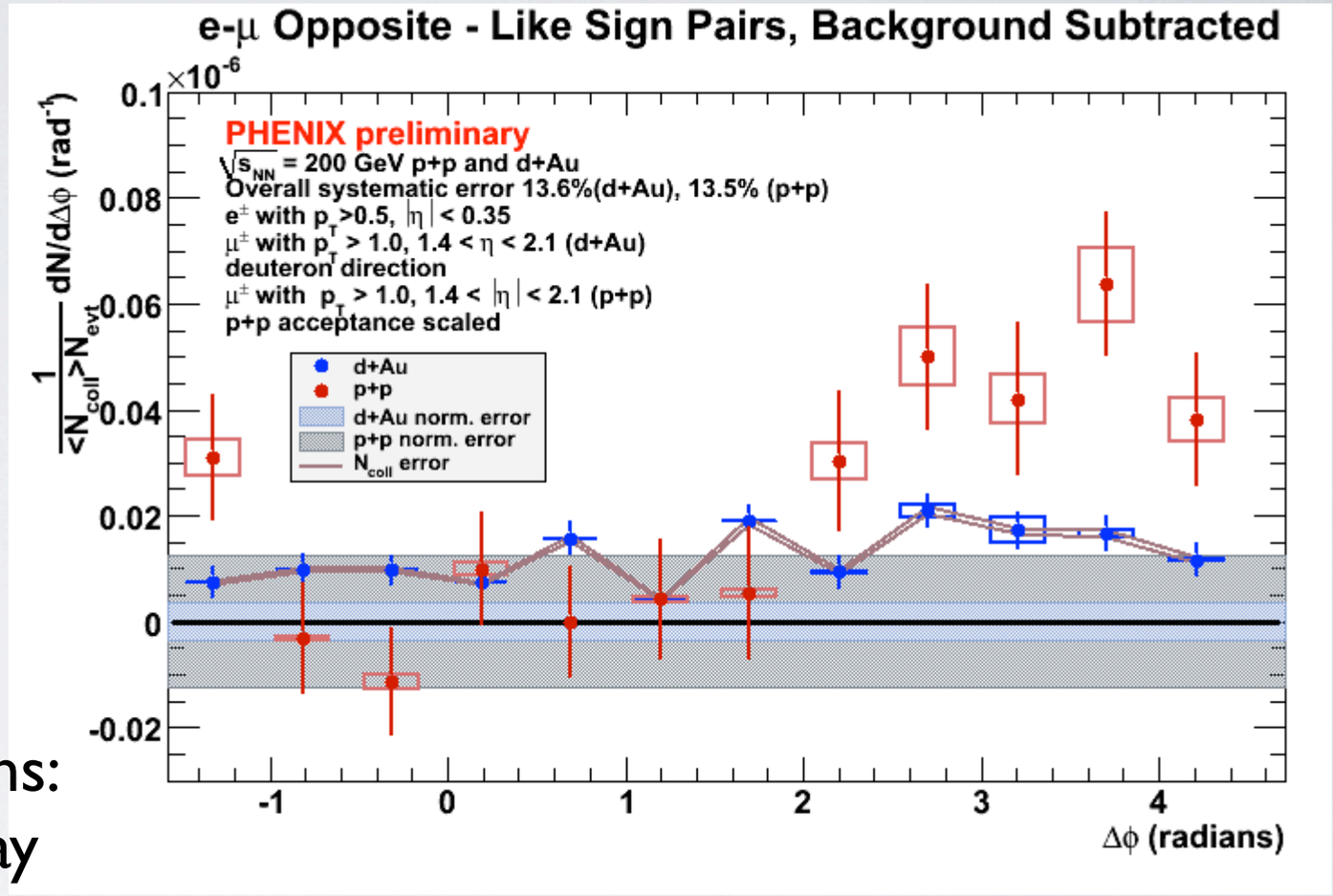




- HF μ production in central d+Au collisions at forward (backward) rapidity is suppressed (enhanced).
  - backward results are consistent with the results mid-rapidity

- Comparison to J/ψ results
  - highlight the role of nuclear break-up cross section in quarkonia production

# Finalized soon II: HF e-μ correlation in d+Au at 200 GeV

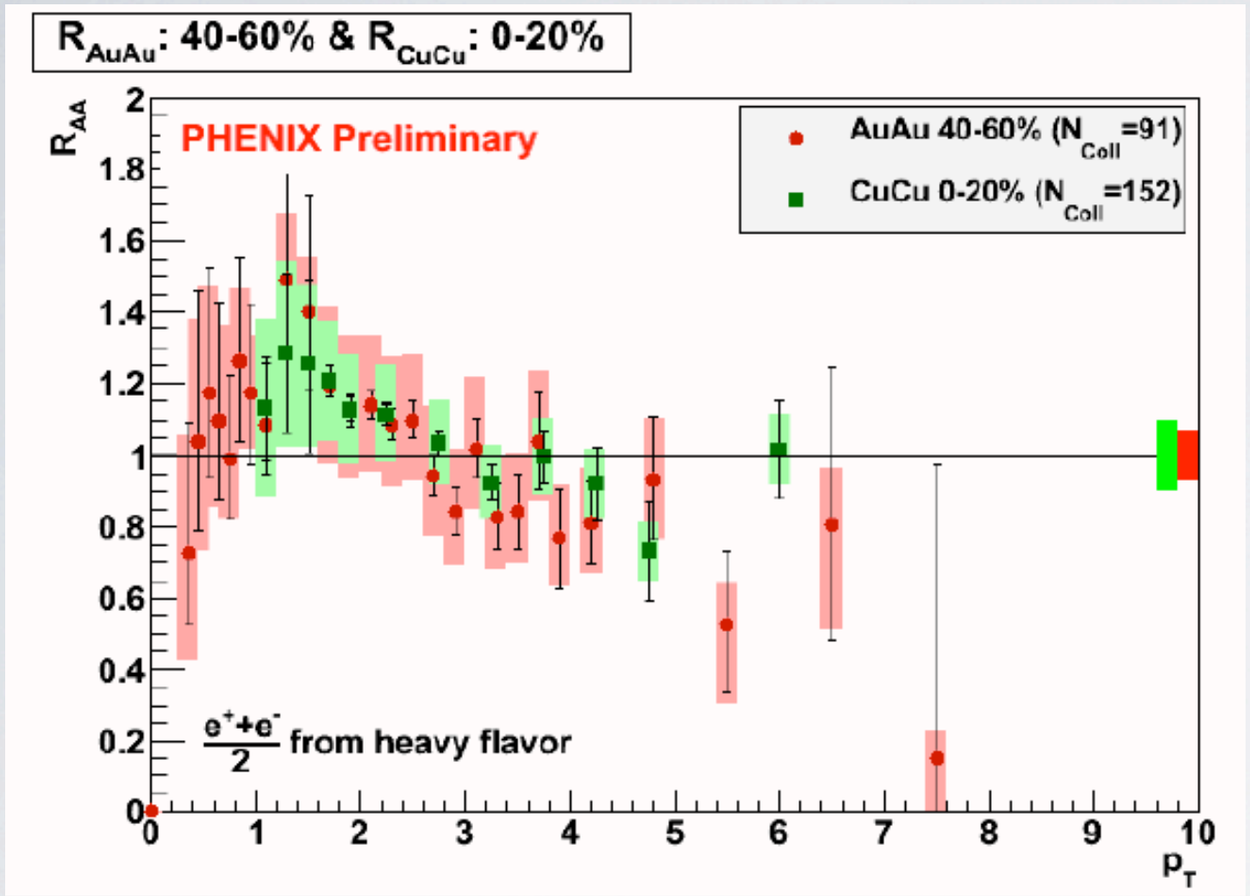


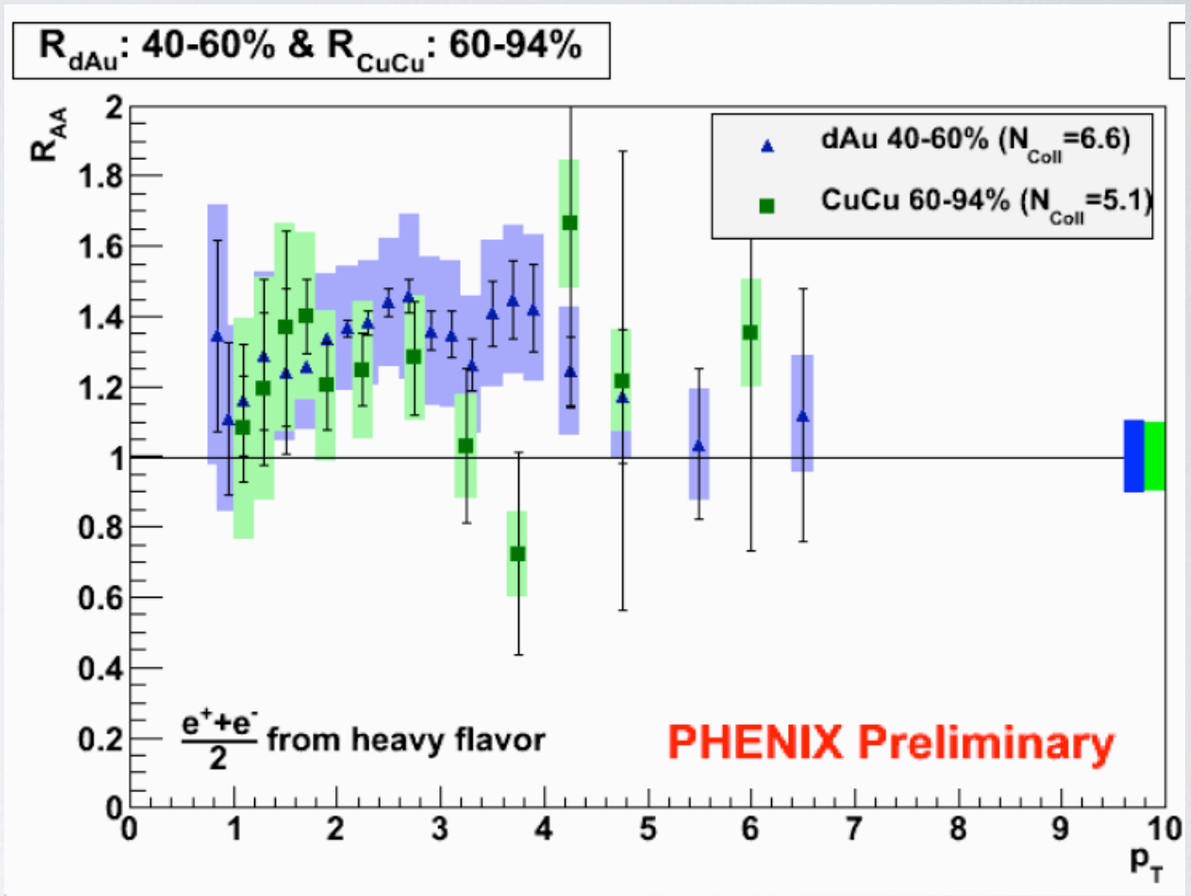




Opposite sign e-μ azimuthal correlations: double semi-leptonic heavy-flavor decay

- Correlation between HF e (mid) and HF μ (forward)
  - In d+Au results at forward rapidity, suppression/de-correlation is shown relative to p+p results.

# Finalized soon III: HF e in Cu+Cu (200 GeV) at mid



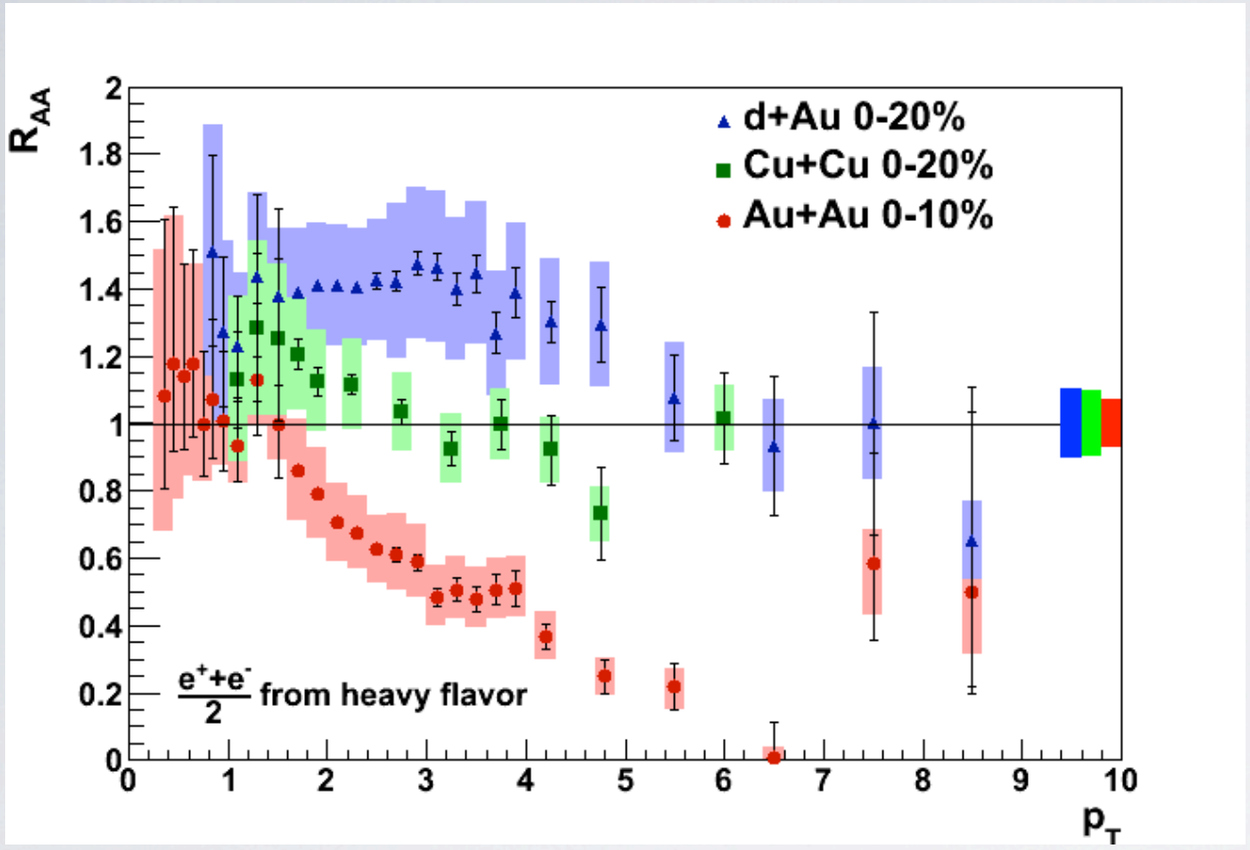



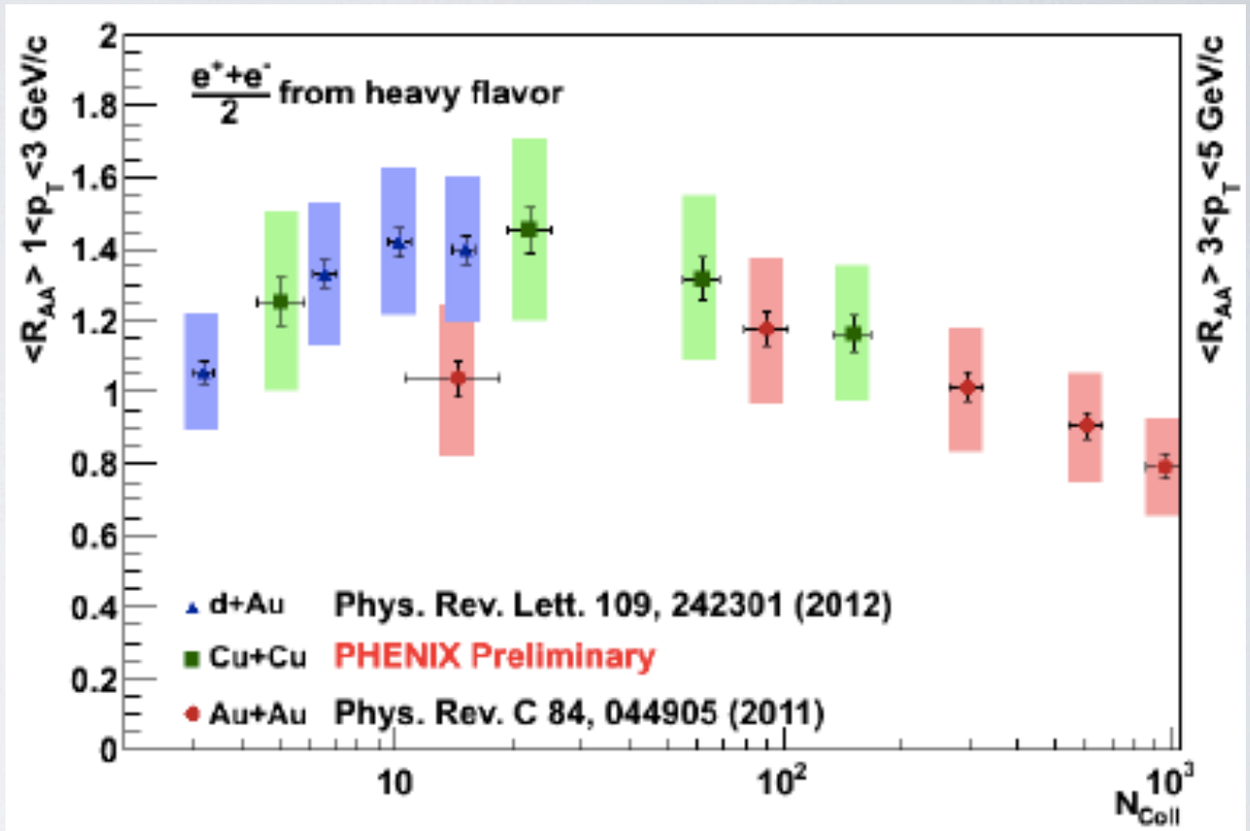

$\langle N_{coll} \rangle_{AuAu} = 91$, $\langle N_{coll} \rangle_{CuCu} = 152$
$\langle N_{part} \rangle_{AuAu} = 60$, $\langle N_{part} \rangle_{CuCu} = 86$

$\langle N_{coll} \rangle_{dAu} = 6.6$, $\langle N_{coll} \rangle_{CuCu} = 5.1$
$\langle N_{part} \rangle_{dAu} = 7.7$, $\langle N_{part} \rangle_{CuCu} = 6.4$

- Cu+Cu results are consistent with Au+Au and d+Au results in similar $\langle N_{coll} \rangle$ regioin

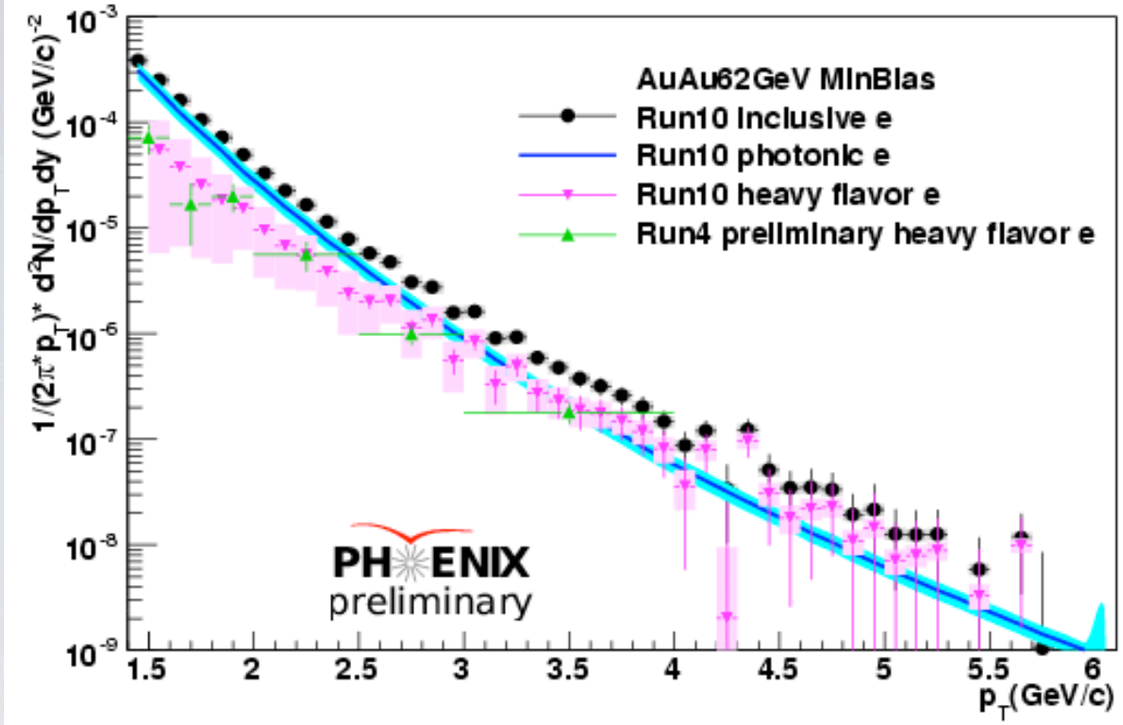
# Finalized soon III: HF e in Cu+Cu (200 GeV) at mid

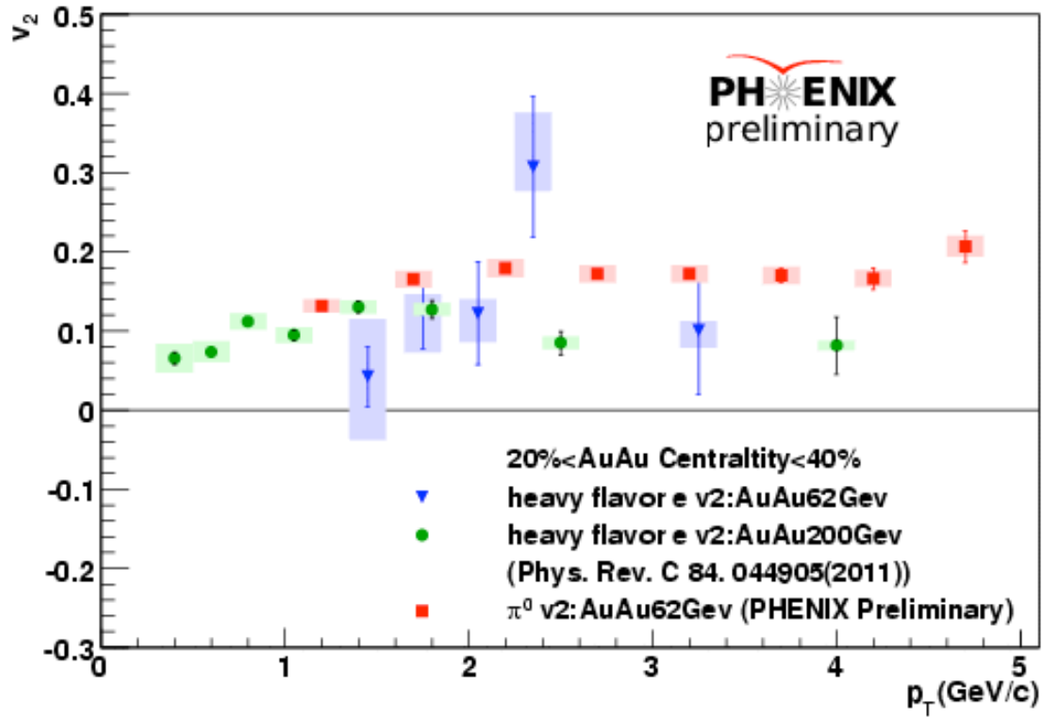



- Cu+Cu $R_{AA}$ is located between $R_{dA}$ and Au+Au $R_{AA}$.
- Smooth take over from CNM effect in d+Au/peripheral Cu+Cu systems to central Cu+Cu/Au+Au systems as collision size increase.

# Finalized soon IIII: HF e in Au+Au (62.4 GeV) at mid



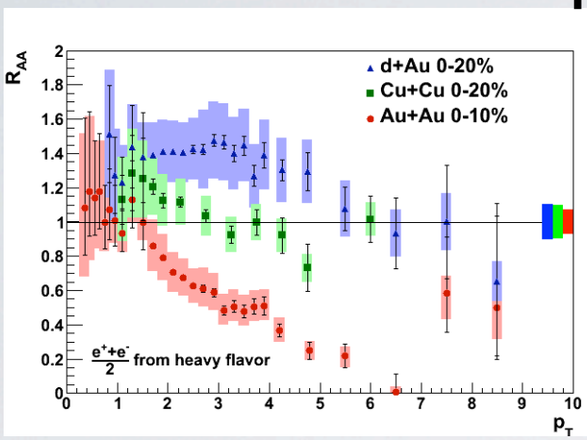



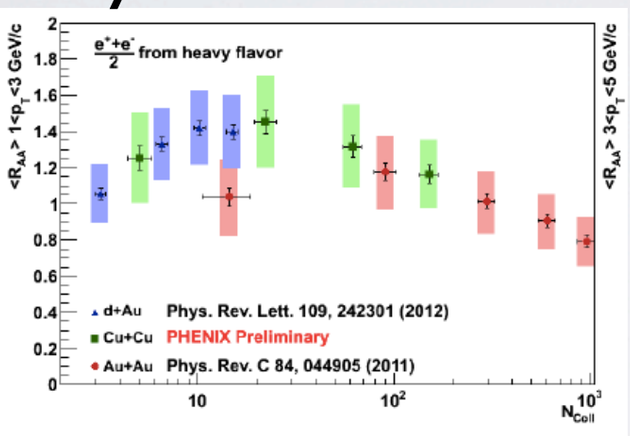

- Non-zero $v_2$ component of HF e in Au+Au collisions at 62.4 GeV
  - consistent with $v_2$ in Au+Au collisions at 200 GeV

# Summary

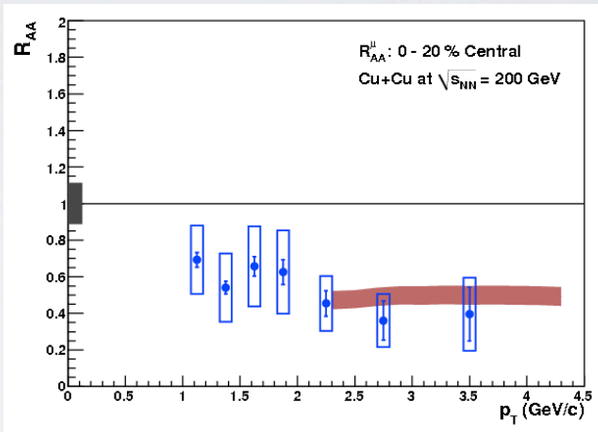
- PHENIX measured open heavy flavors in various collision system
  - many interesting results will be finalized soon

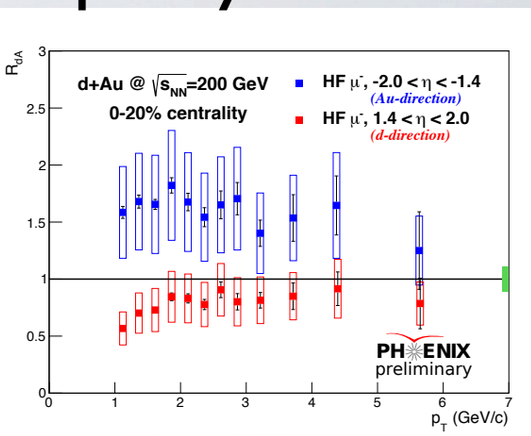
## mid-rapidity




## forward-rapidity



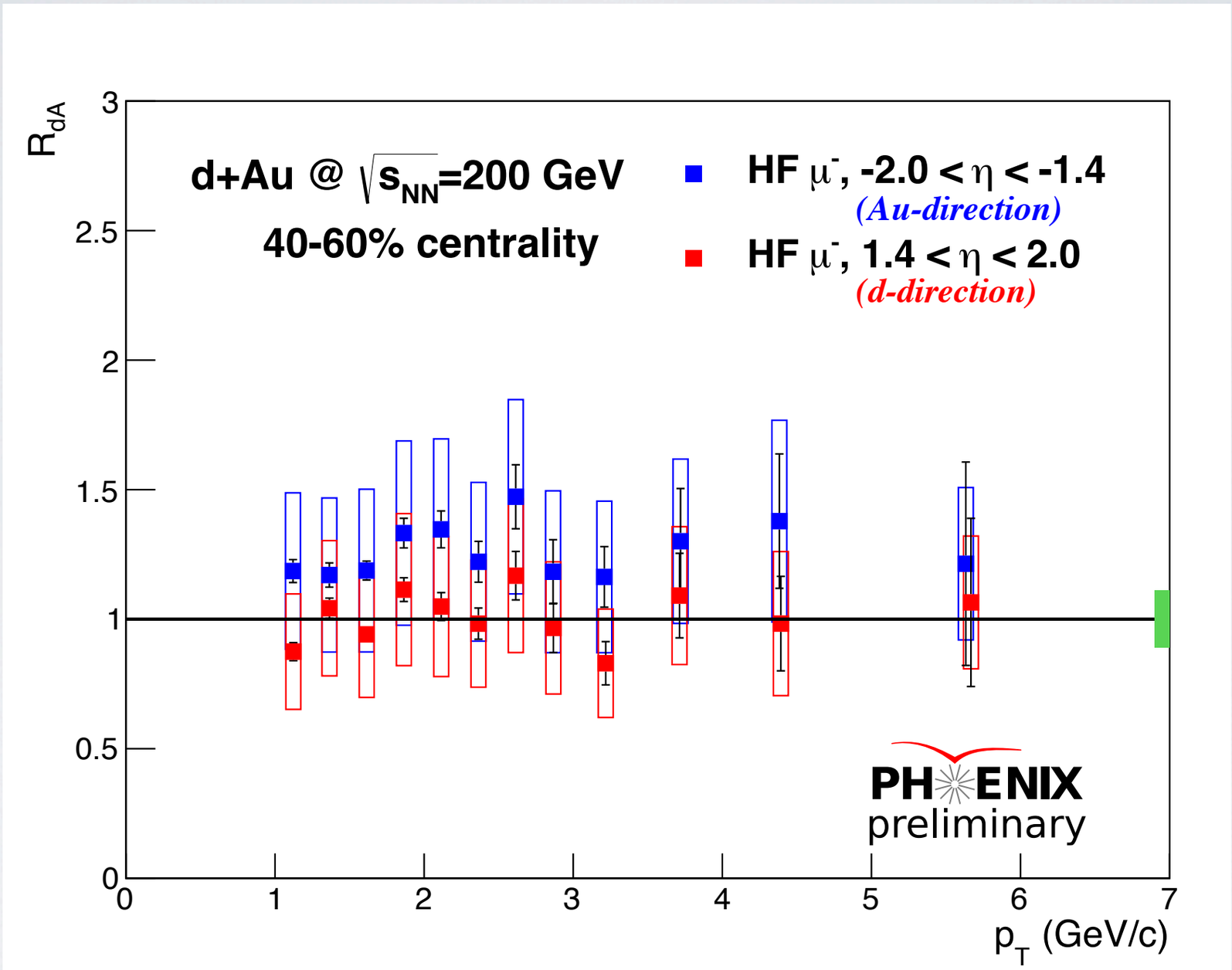




- Theoretical prediction works well!
  - consistent with Au+Au and over predicts suppression in Cu+Cu at mid-rapidity
  - consistent with d+Au and Cu+Cu at forward rapidity

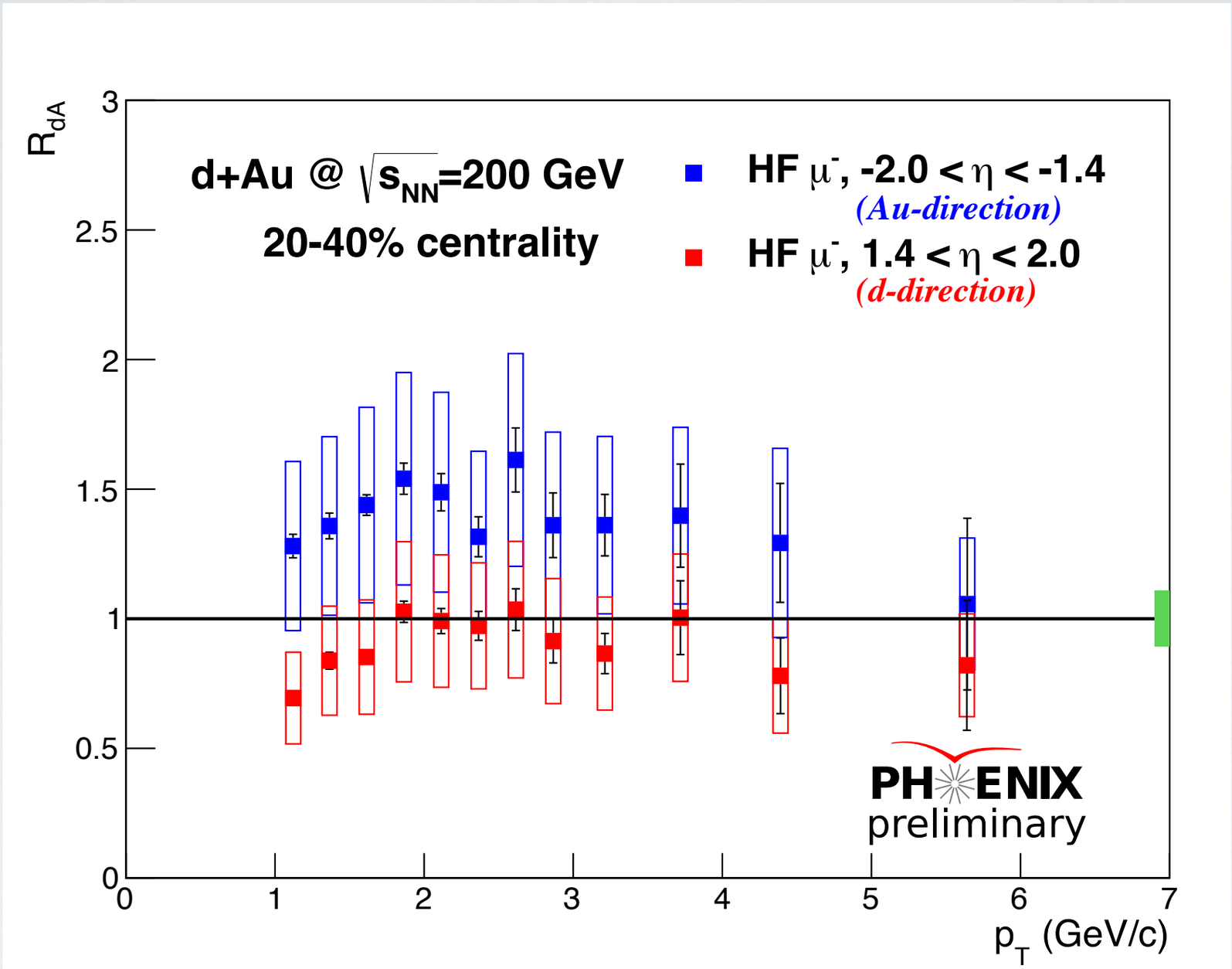
- New PHENIX inner silicon vertex tracker system (VTX & FVTX) provides precise vertex position and allows to separate charm and bottom meson.

# Back up

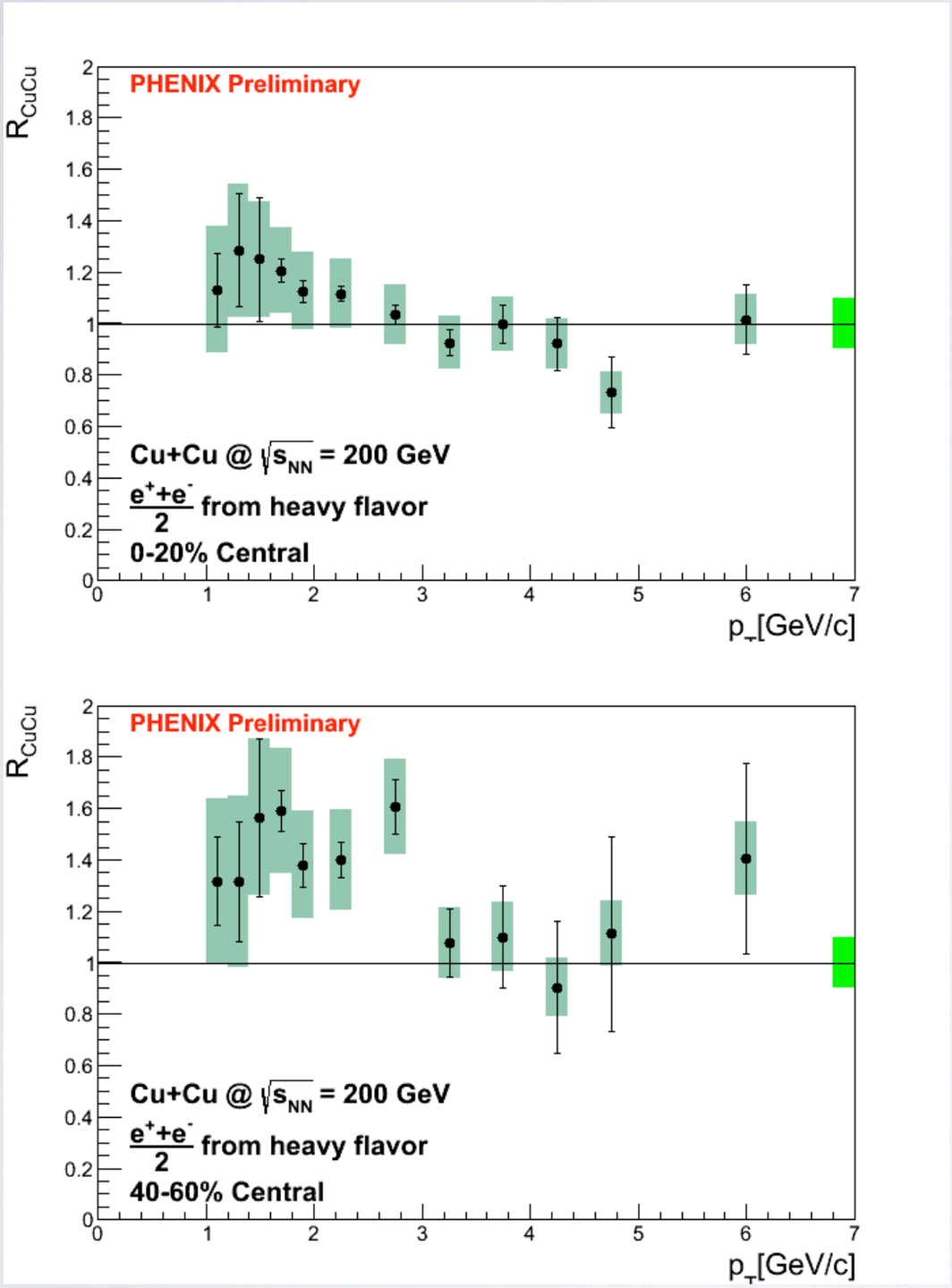
# Heavy flavor muons $R_{dA}$, 40 - 60%

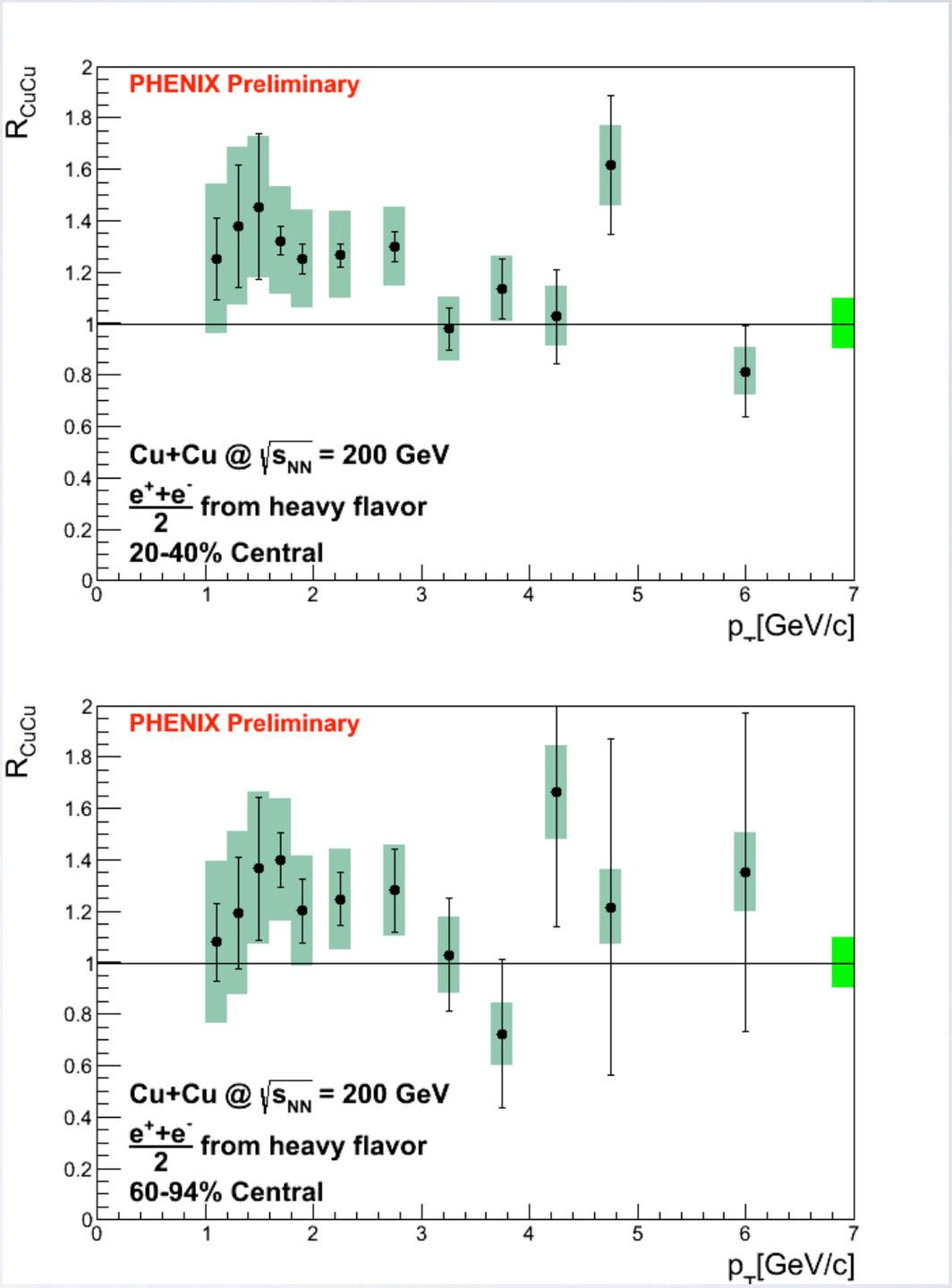


# Heavy flavor muons $R_{dA}$, 20 - 40%

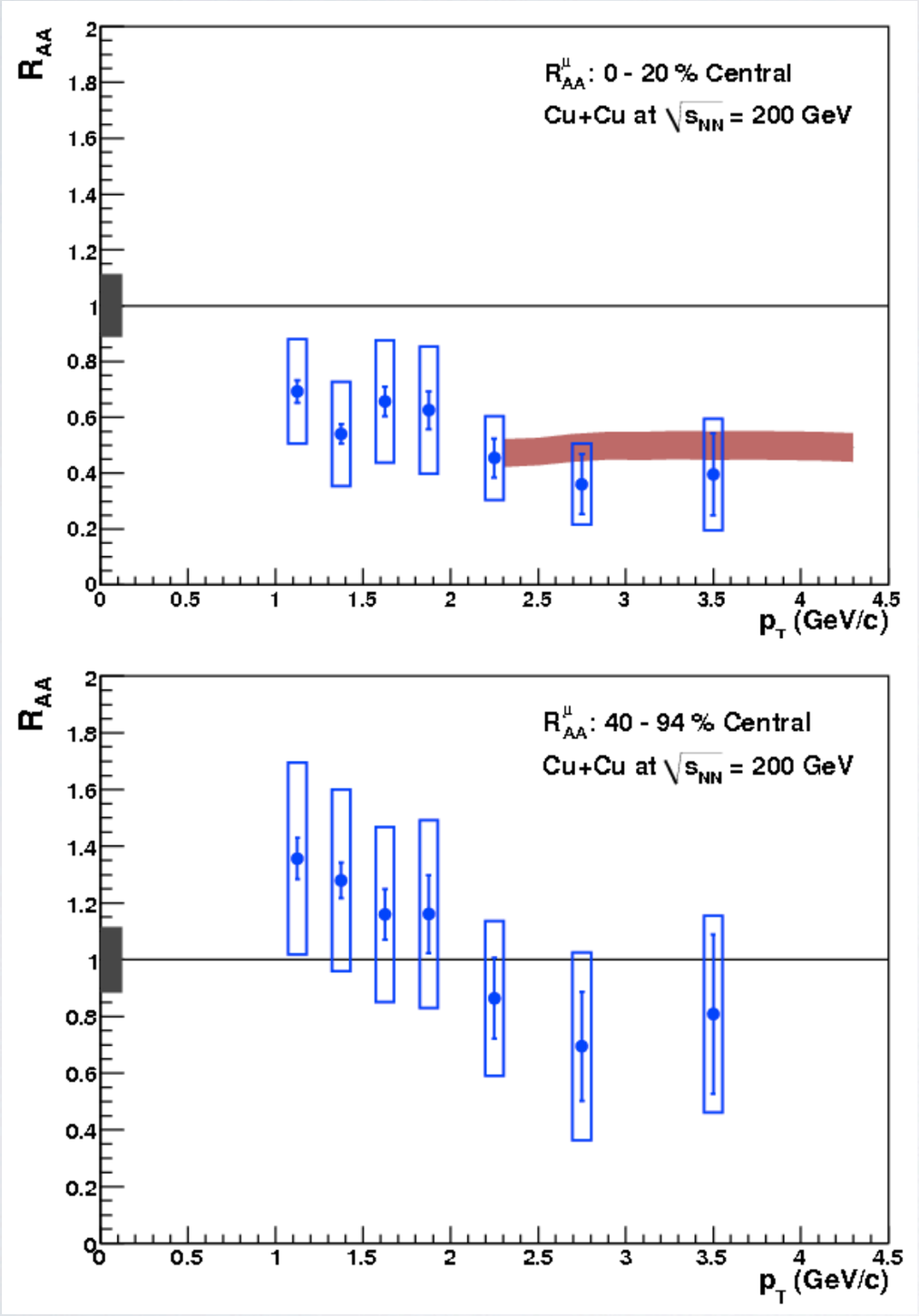


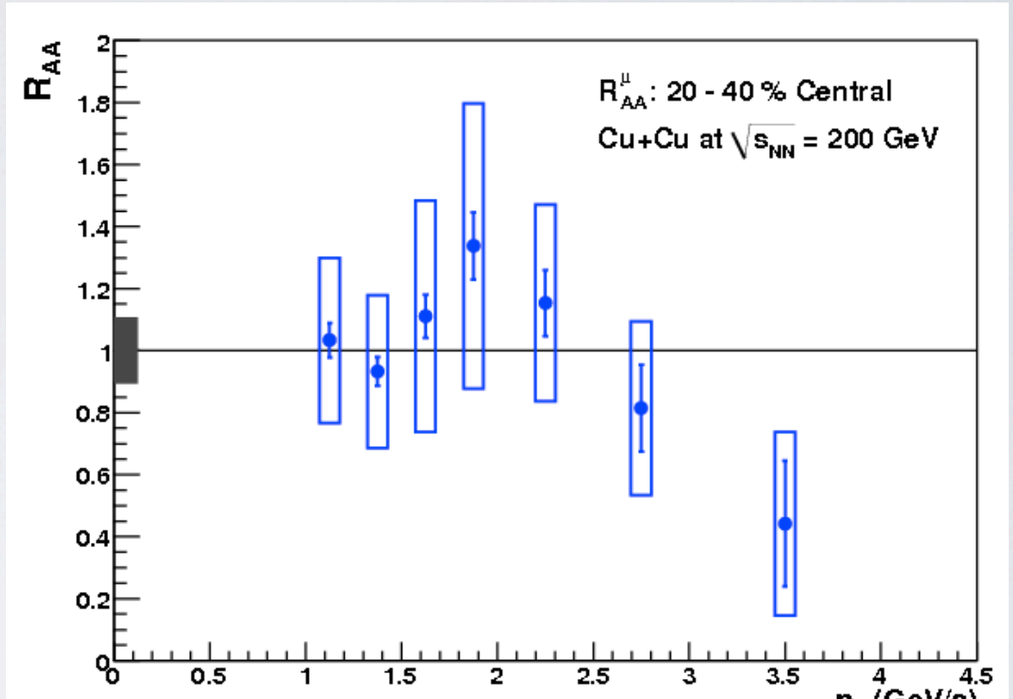
# Heavy flavor electrons $R_{AA}$ at mid-rapidity



# Heavy flavor μ $R_{AA}$ at forward-rapidity

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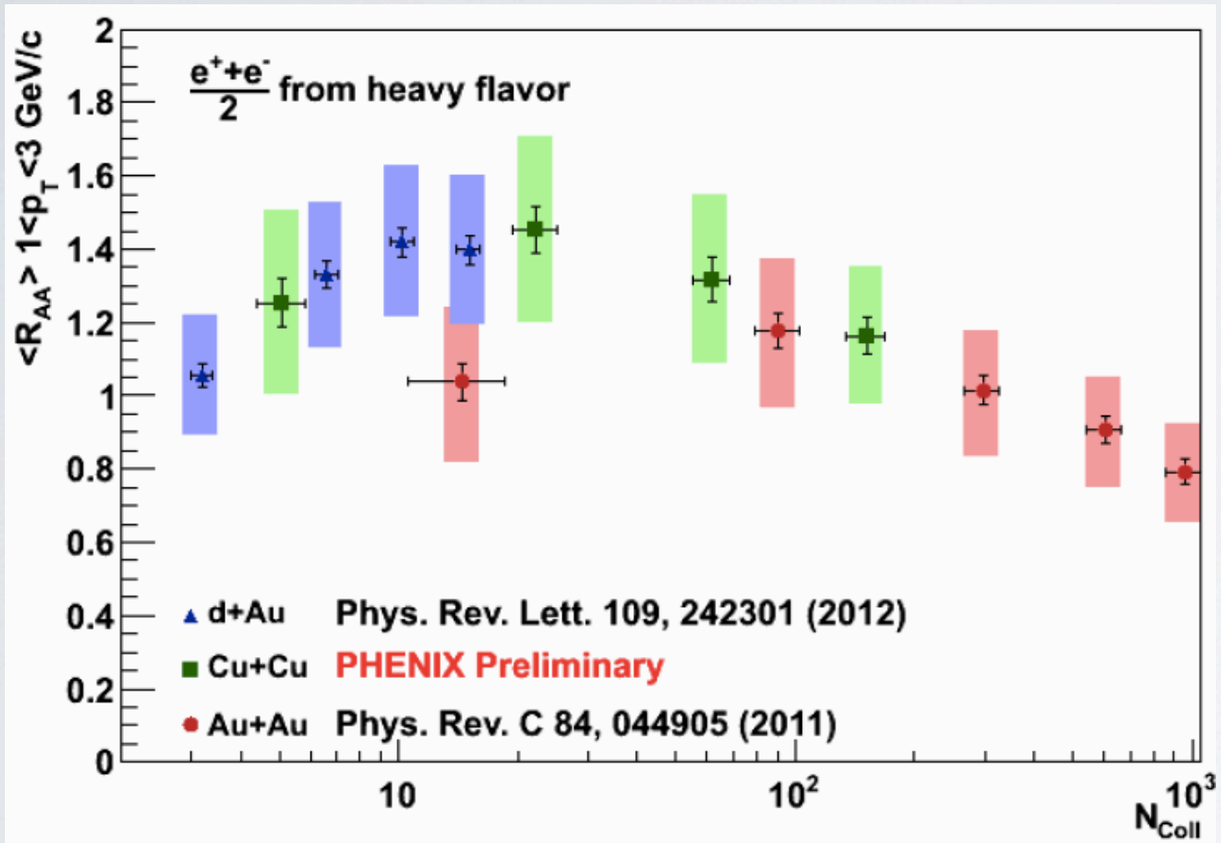
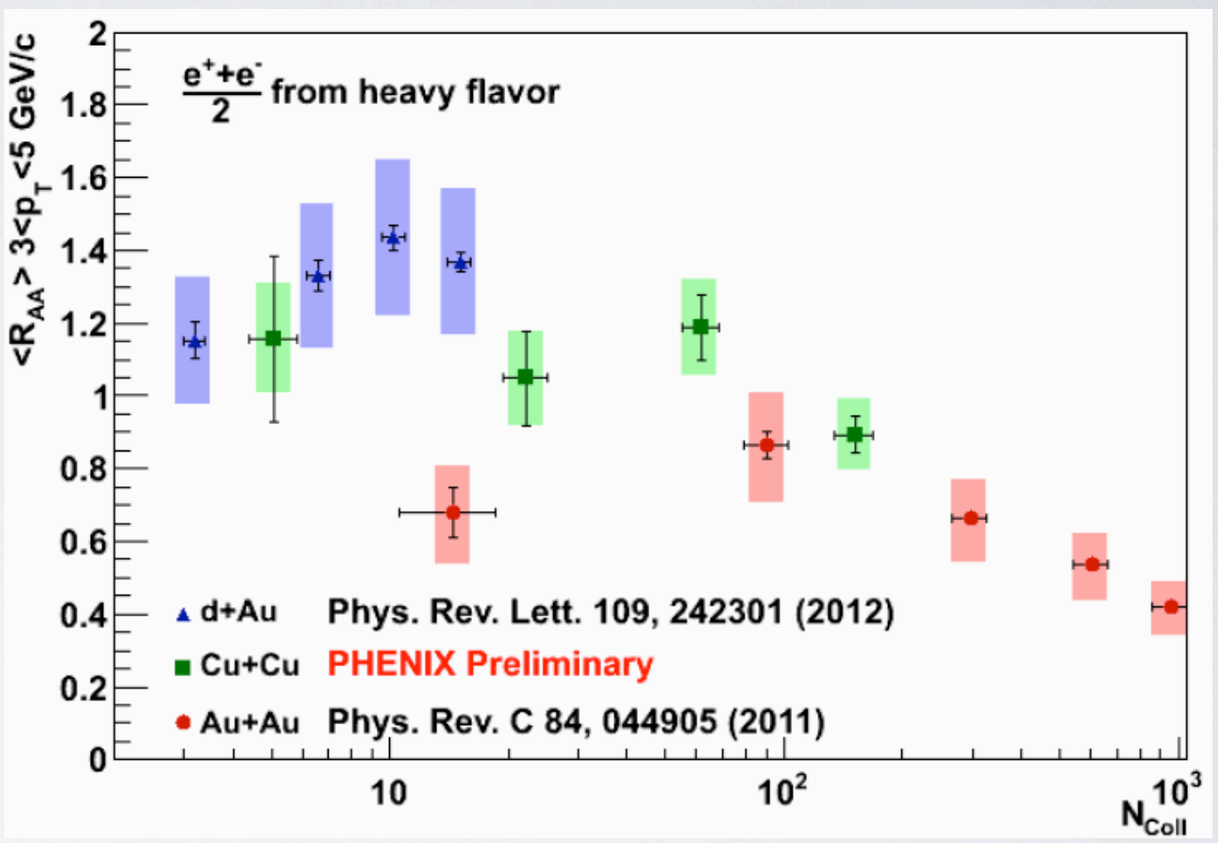
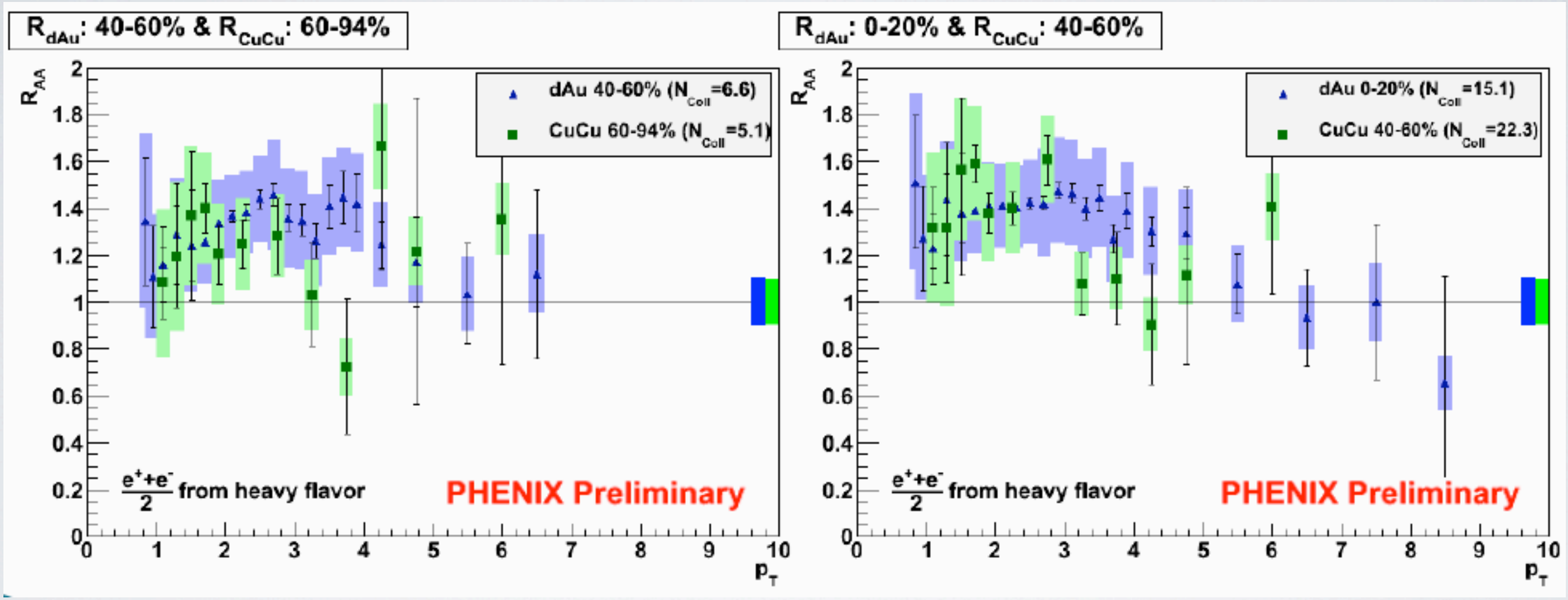
# $R_{AA}$ vs. $N_{coll}$ at mid-rapidity






# comparison between d+Au and Cu+Cu