A Study of Single Leptons from Heavy Flavor Decays at RHIC as measured by PHENIX

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WWND 2013

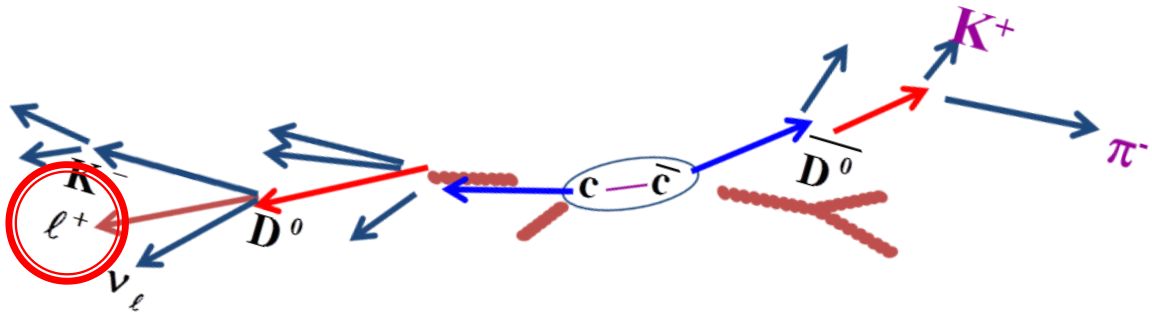
PHENIX

Heavy Quarks (Charm & Bottom)

- Produced by gluon fusion in early stages of collision

$$m_{c,b} > T, \Lambda_{QCD}$$

- Experience full evolution of medium



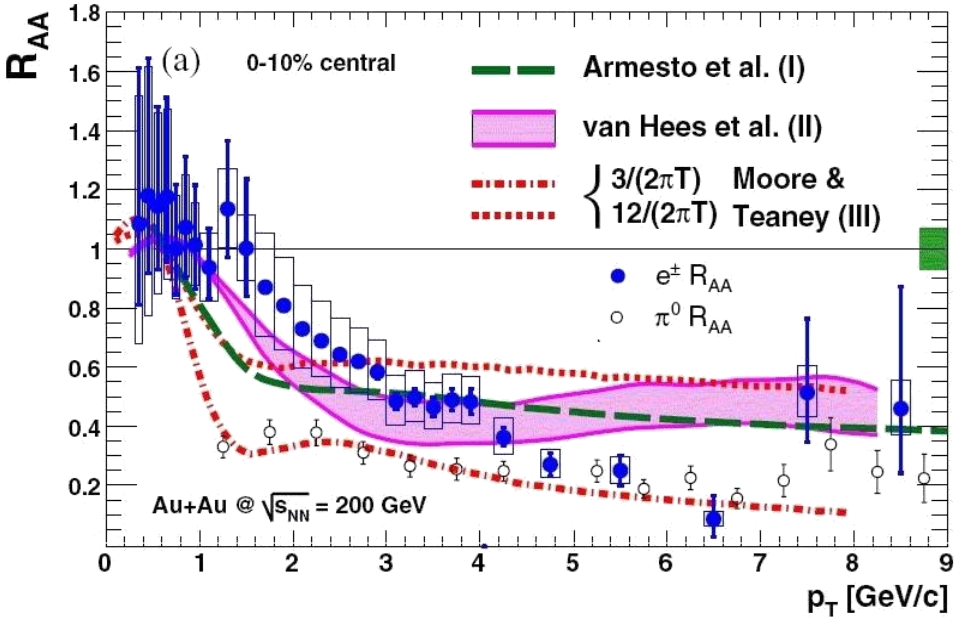
- Measured through semi-leptonic decay
  - Electrons at mid-rapidity
  - Muons at forward/backward rapidity

Expectation

- Heavy quarks expected to lose less energy than light quarks
  - Supression of gluon radiation – "dead cone" effect

$$R_{AA}^{u,d} < R_{AA}^{c} < R_{AA}^{b}$$

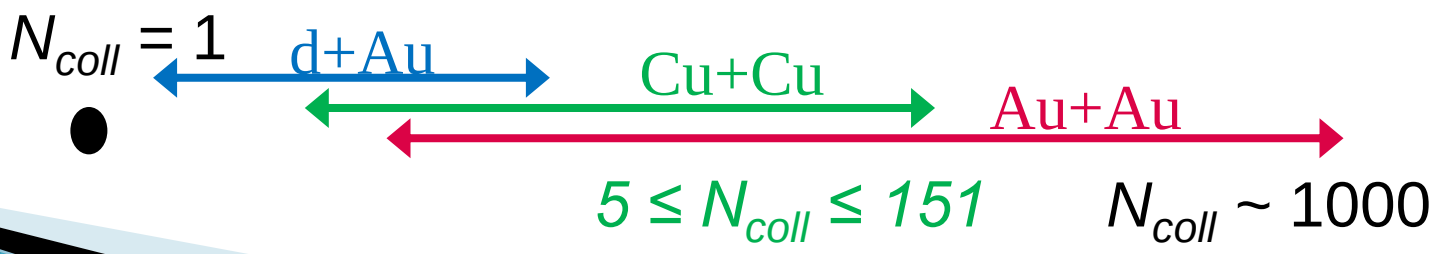
Phys. Rev. Lett. 98, 172301 (2007)



- Large suppression on par with that of the light quarks
- Radiative energy loss insufficient to describe suppression

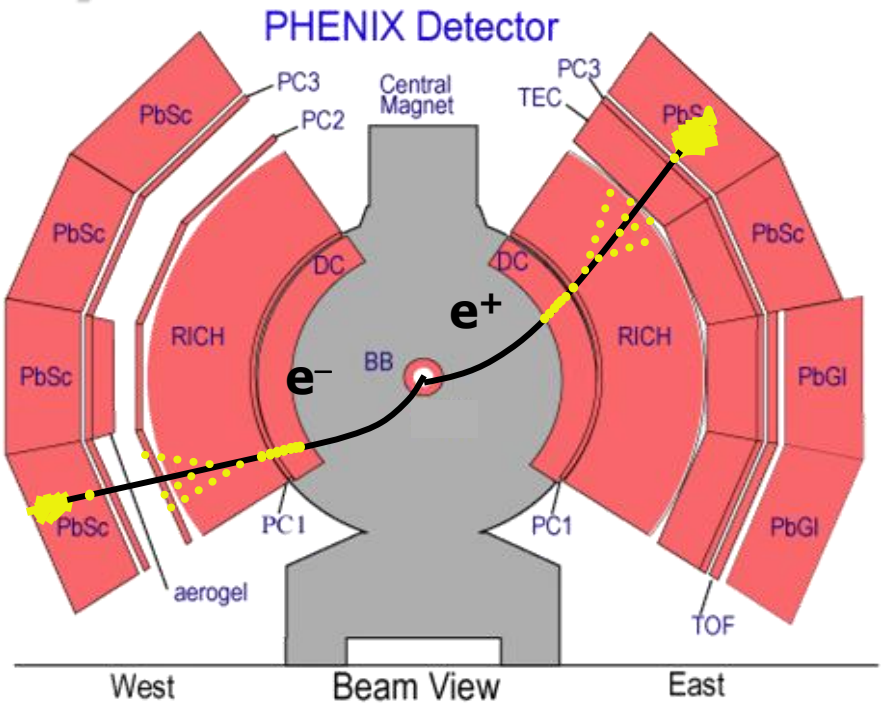
Heavy Flavor at PHENIX

- In p+p collisions
  - Test pQCD calculations
  - Provide baseline for heavy ion collisions
- Heavy Ion (Au+Au & Cu+Cu)
  - Probe effects of the hot medium
- d+Au collisions
  - Study cold nuclear matter (CNM) effects
- Mid vs forward rapidities probe different kinematic regions inside the nucleus



Mid-rapidity heavy flavor

- $e^{\pm}$: $|\eta| < 0.35$
  - DC/PC: tracking
  - RICH: eID
  - EMCal: energy



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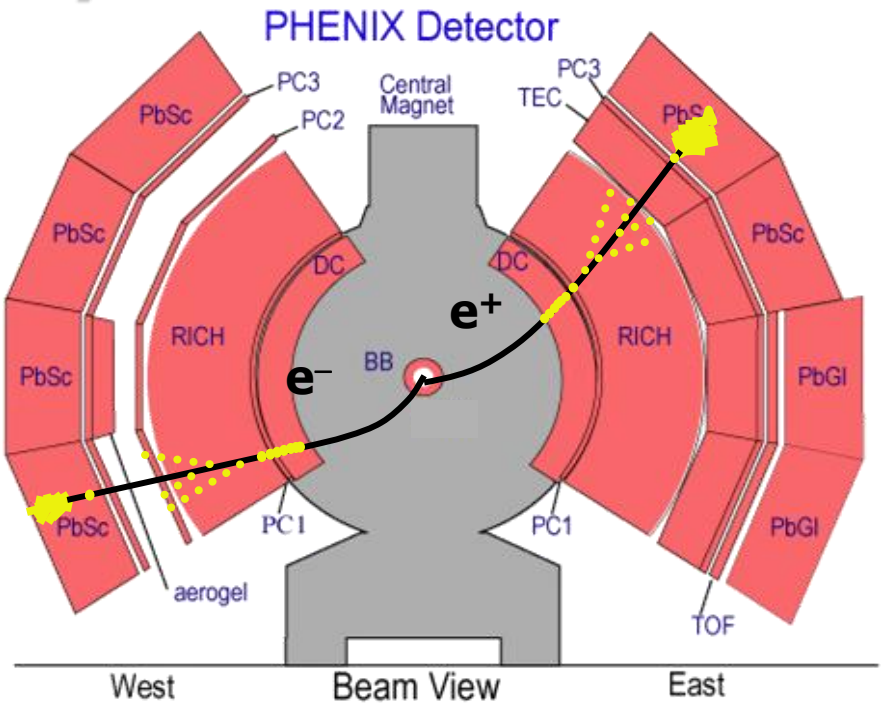
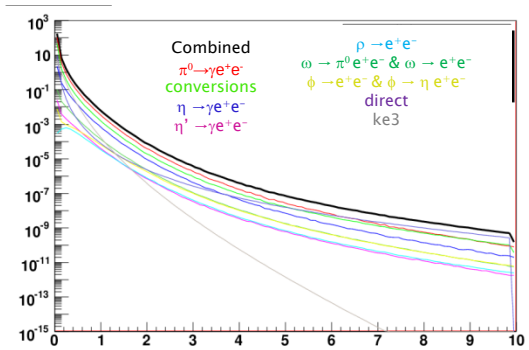
  - EMCal: energy
- Cocktail subtraction
  - π^0 Dalitz largest background: fit to PHENIX data
  - Also includes electrons from conversion γ, direct γ & Ke3 decays
  - Subtract J/Ψ, Y, DY for open heavy flavor
  - Large systematic uncertainties



Central Cu+Cu @ $\sqrt{s_{NN}}$= 200GeV



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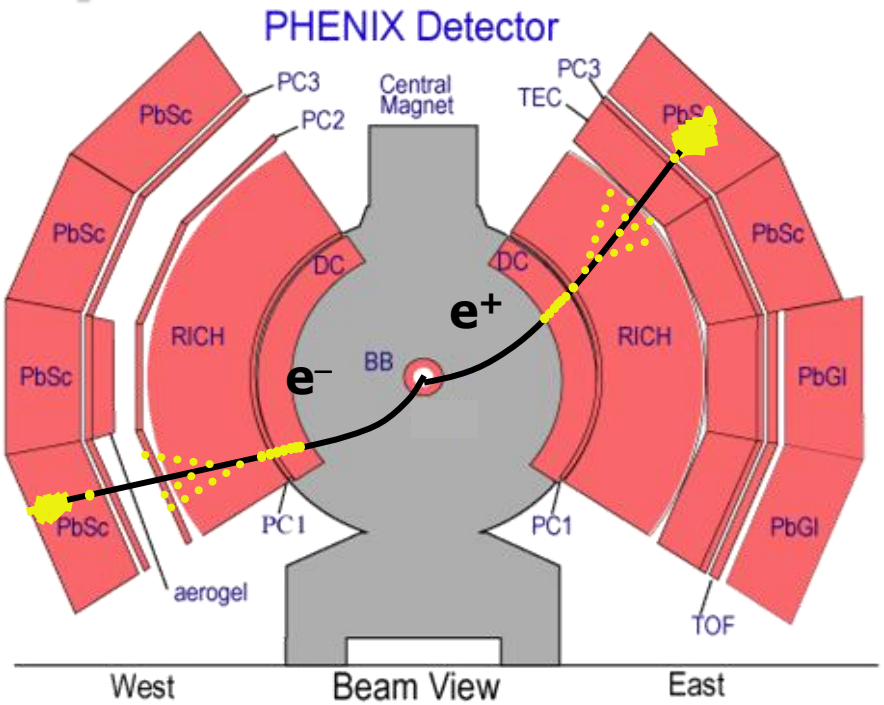
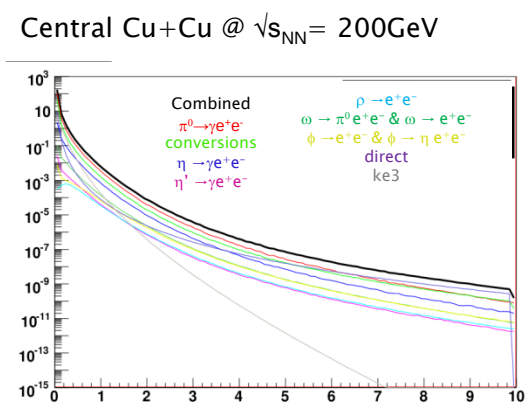




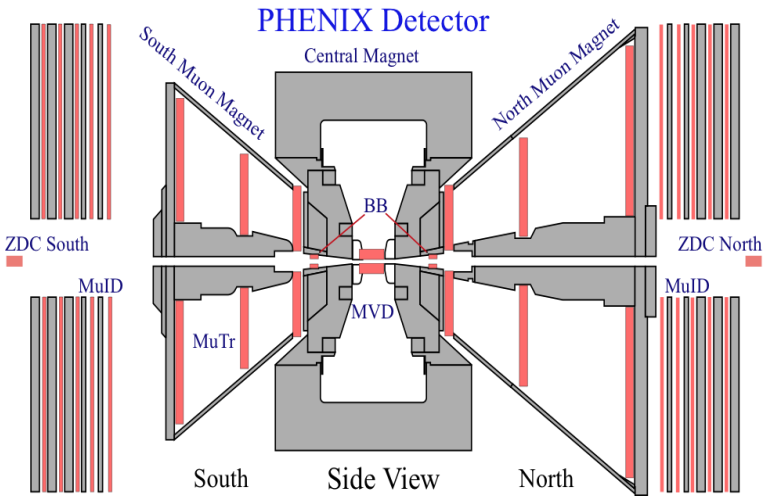
- Converter Method
  - Converter increases photonic yield
  - Statistically limited

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

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

Forward/Backward heavy flavor

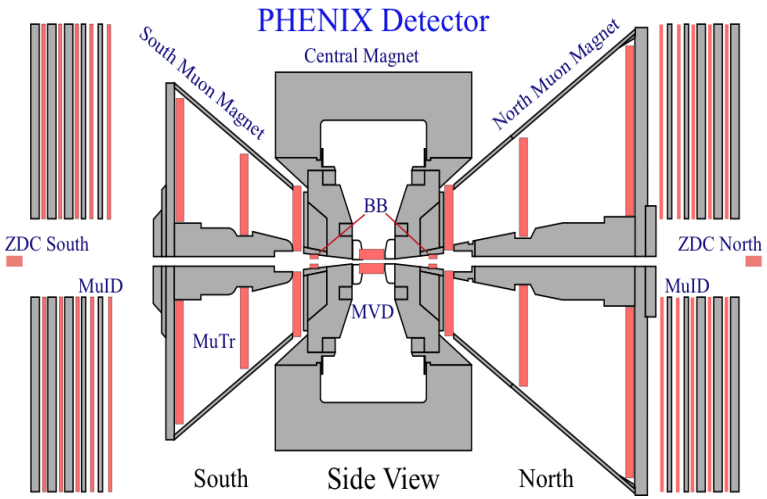
- $\mu^{\pm}$: $1.2 < |\eta| < 2.2$
- Muon candidates
  - Pass through MuTr and all MuID layers



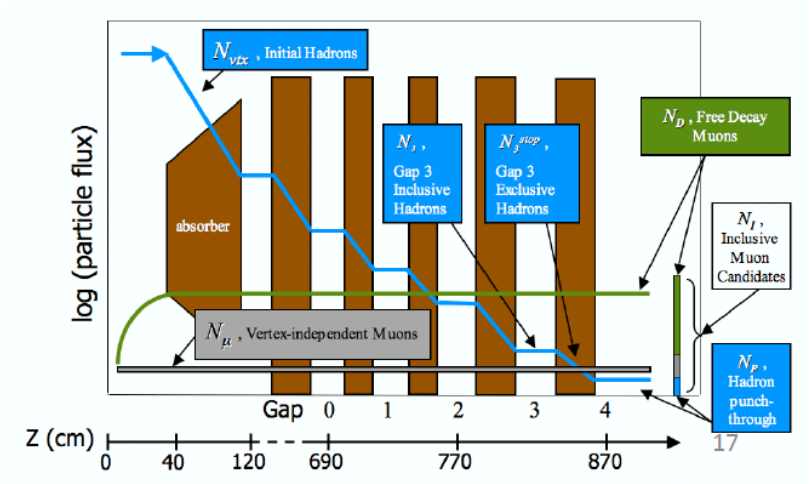
$$\frac{d^2 N_\mu}{2\pi dp_T d\eta} = \frac{1}{2\pi p_T \Delta p_T \Delta\eta} \frac{N_I - N_C - N_F}{N_{evt}\epsilon_{BBC}{}^{cc\to\mu} A\epsilon}$$

Forward/Backward heavy flavor

- $\mu^{\pm}$: $1.2 < |\eta| < 2.2$
- Muon candidates
  - Pass through MuTr and all MuID layers
- Background
  - Decay muons from light vector mesons
  - Punch through hadrons
- Hadron cocktail
  - Data-driven: input tuned to match data distributions
    - Decay muon z-vertex dependence
    - "stopped" hadron spectra

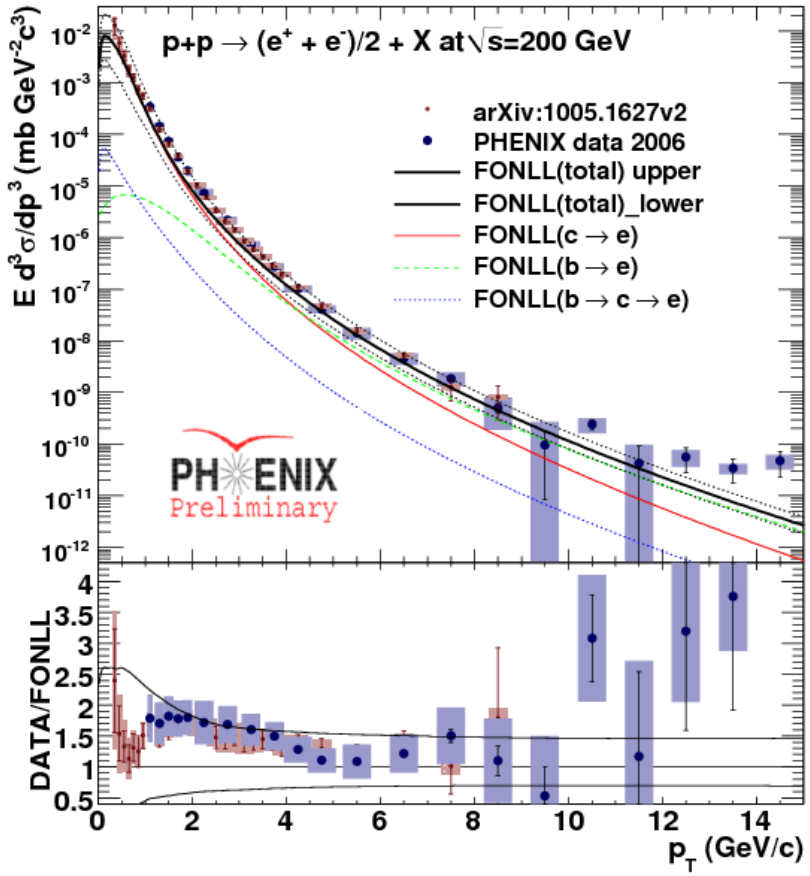


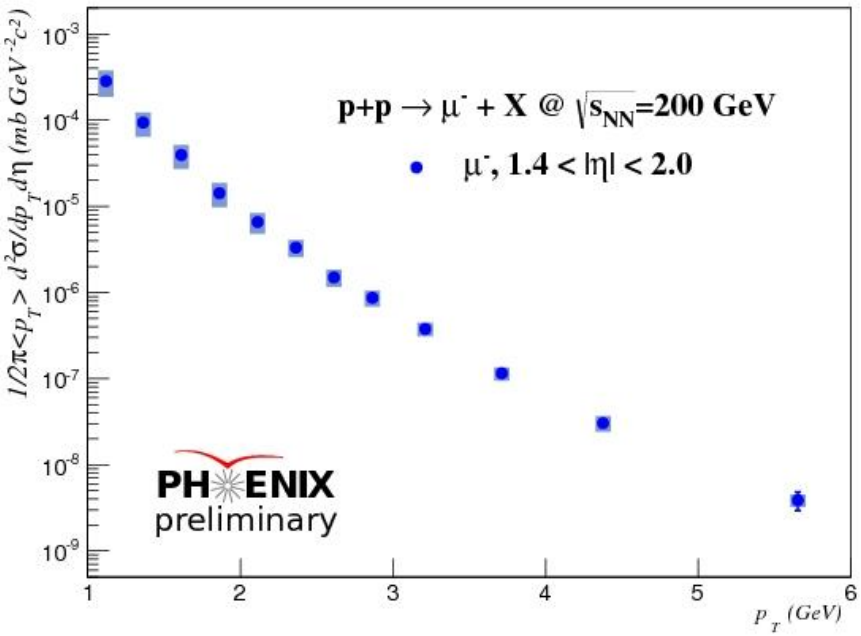
$$\frac{d^2 N_\mu}{2\pi dp_T d\eta} = \frac{1}{2\pi p_T \Delta p_T \Delta\eta} \frac{N_I - N_C - N_F}{N_{evt}\epsilon_{BBC}{}^{cc\to\mu} A\epsilon}$$



Heavy Flavor in p+p collisions

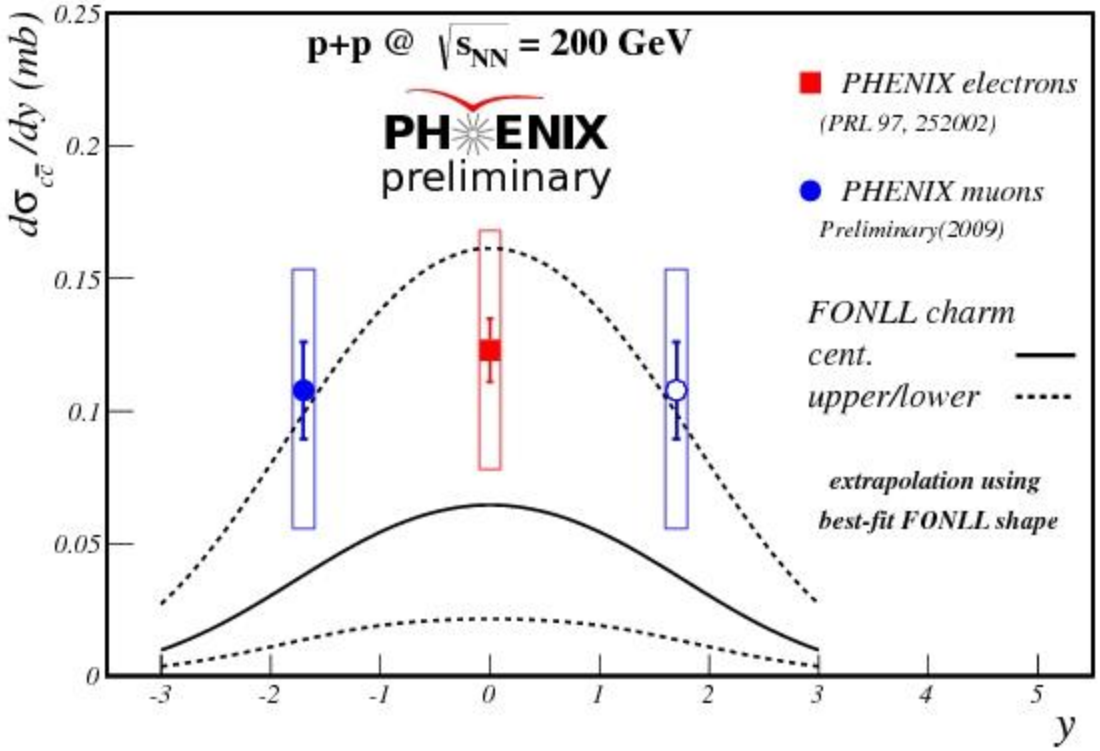
- Combined statistics from 2005 & 2006 p+p runs
- Increased pT range
  - New background subtraction technique





- Extended |η| range
- Smaller systematic errors

Heavy Flavor in p+p collisions



- Extrapolate to $p_T=0$ using FONLL to get charm cross section

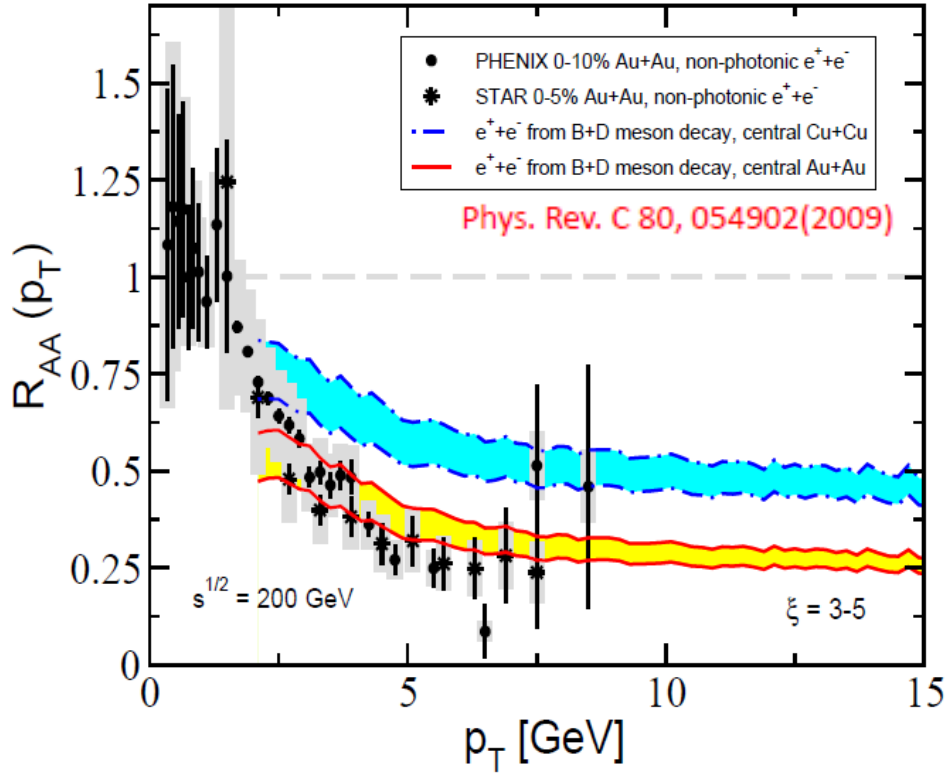
$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0} = 0.123 \pm 9.8\%(stat) \pm 36.5\%(sys)$$

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=1.7} = 0.108 \pm 16.7\%(stat) \pm \frac{42.6\%}{48.1\%}(sys)$$

- Consistent with FONLL upper limit

Quantifying Medium effects

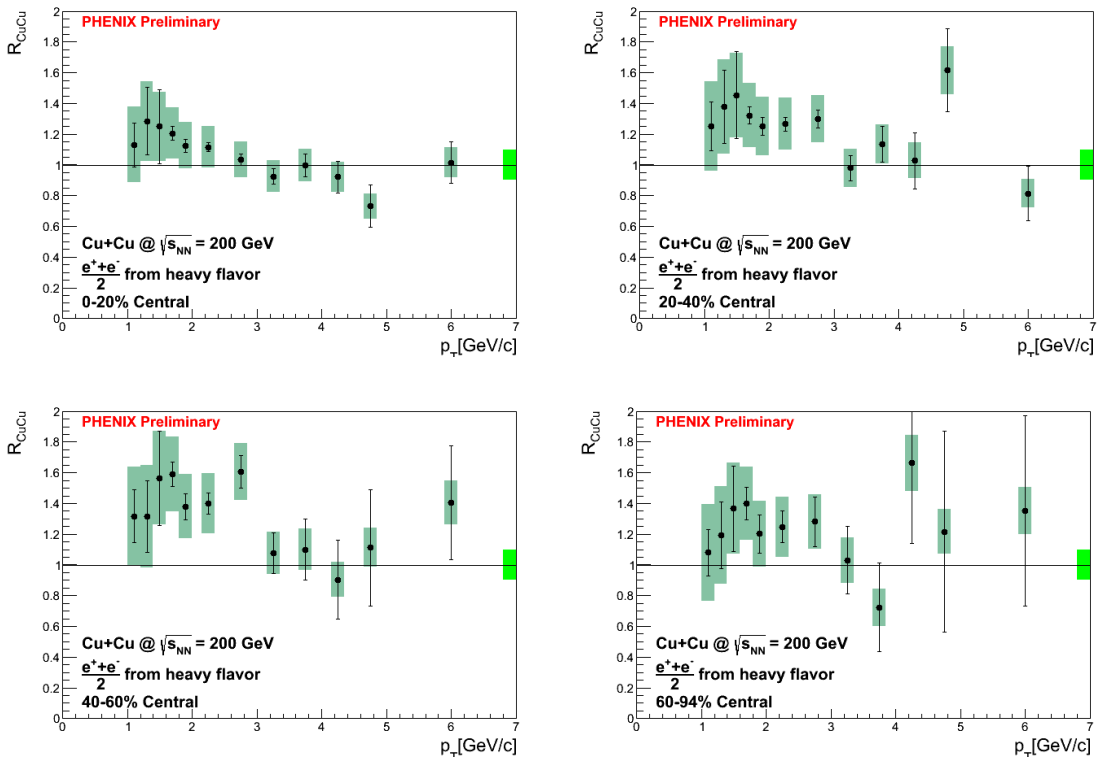
- Nuclear modification factor $R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$
- Radiative energy loss not enough to describe large suppression
- Other energy loss mechanisms added
  - Elastic scattering, dissociation, etc.
- Addition of CNM
  - Nuclear shadowing
  - Parton multiple scattering



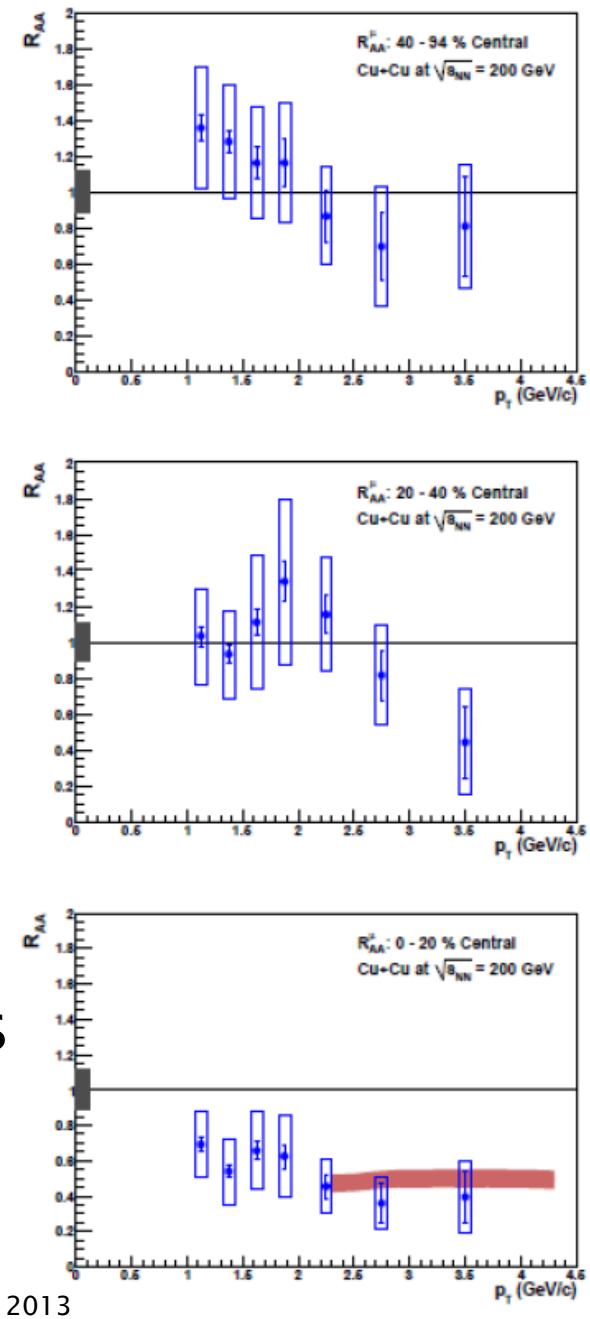
- New model (Sharma, Vitev, & Zhang)
  - Includes partonic energy loss & collisional dissociation
  - Includes CNM effects
- Predictions for mid-rapidity Au+Au & Cu+Cu, and forward Cu+Cu & d+Au

Heavy Flavor in Cu+Cu

Mid: electrons



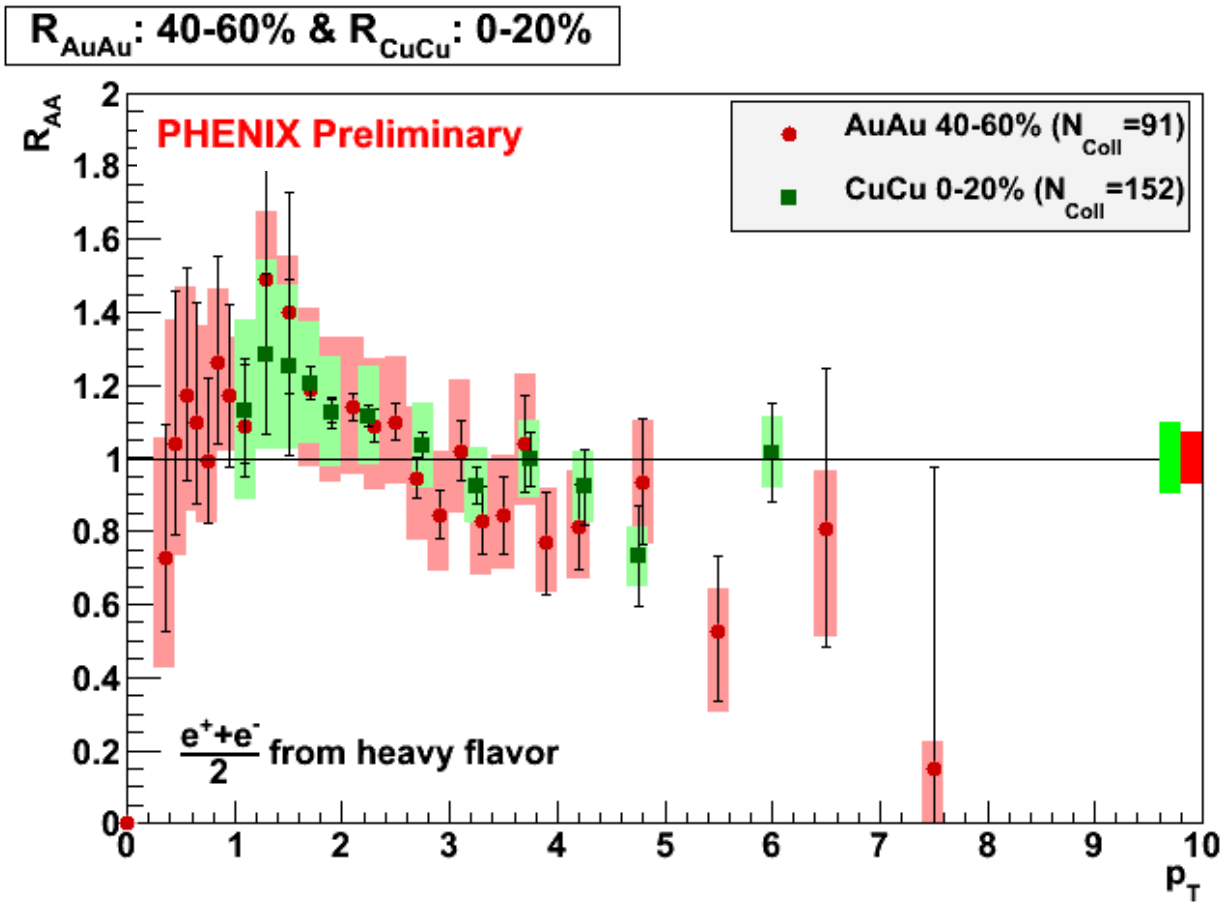
Forward: muons



- Enhancement in mid-central electrons
- Suppression in central muons

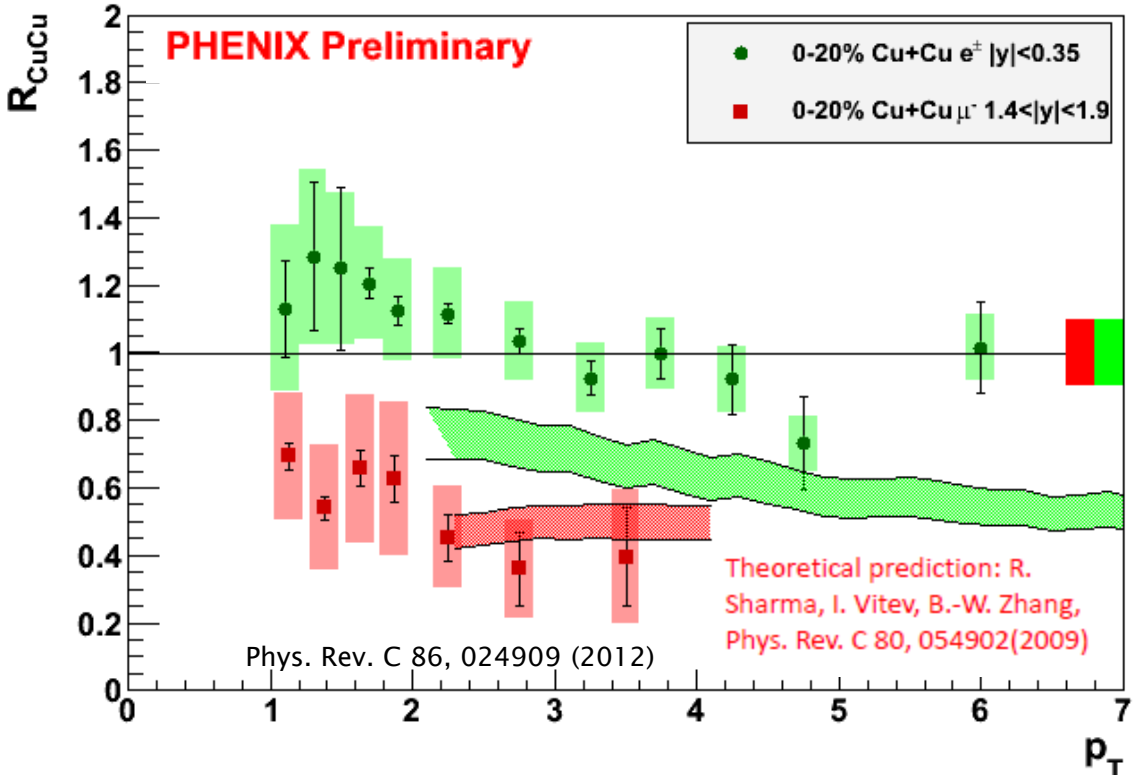
Phys. Rev. C 86, 024909 (2012)

Heavy Flavor in Cu+Cu



- Au+Au and Cu+Cu agree in similar N_{Coll} regions
- $\langle N_{coll} \rangle_{AuAu} = 91$ & $\langle N_{coll} \rangle_{CuCu} = 152$
- $\langle N_{part} \rangle_{AuAu} = 60$ & $\langle N_{part} \rangle_{CuCu} = 86$

Heavy Flavor in Cu+Cu

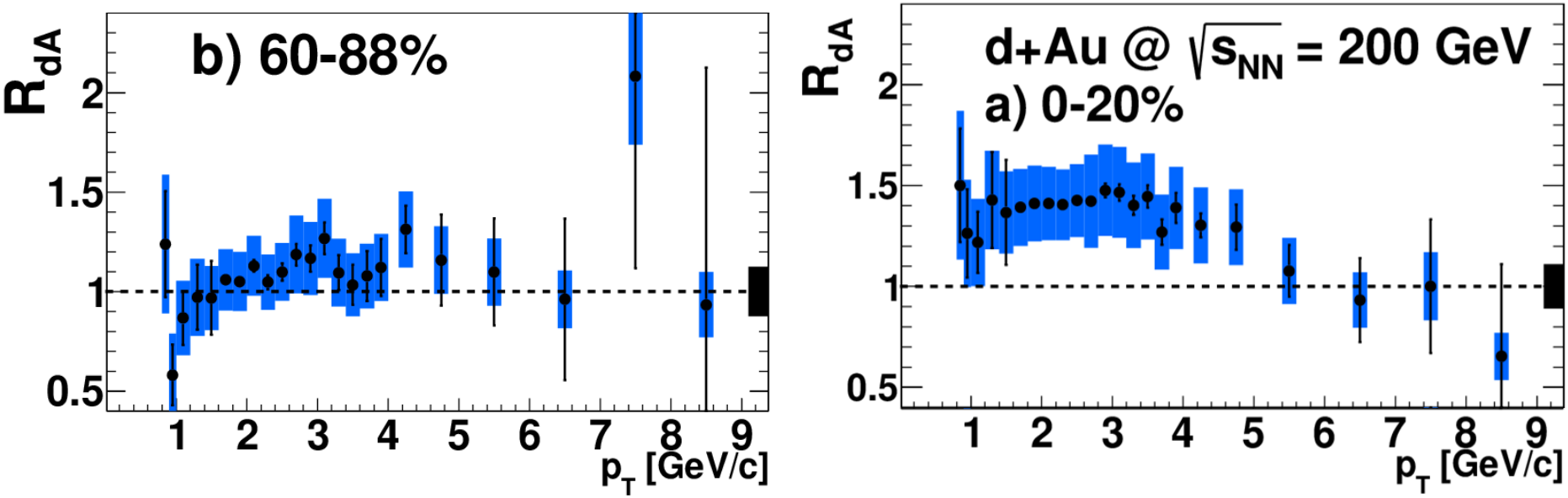


- 0-20% most central heavy flavor electrons and muons
- Suppression in muon yield
  - Additional CNM effects at forward rapidity (shadowing/initial-state energy loss)

Heavy Flavor in d+Au: Electrons

- No hot medium expected
  - Explores CNM effects

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



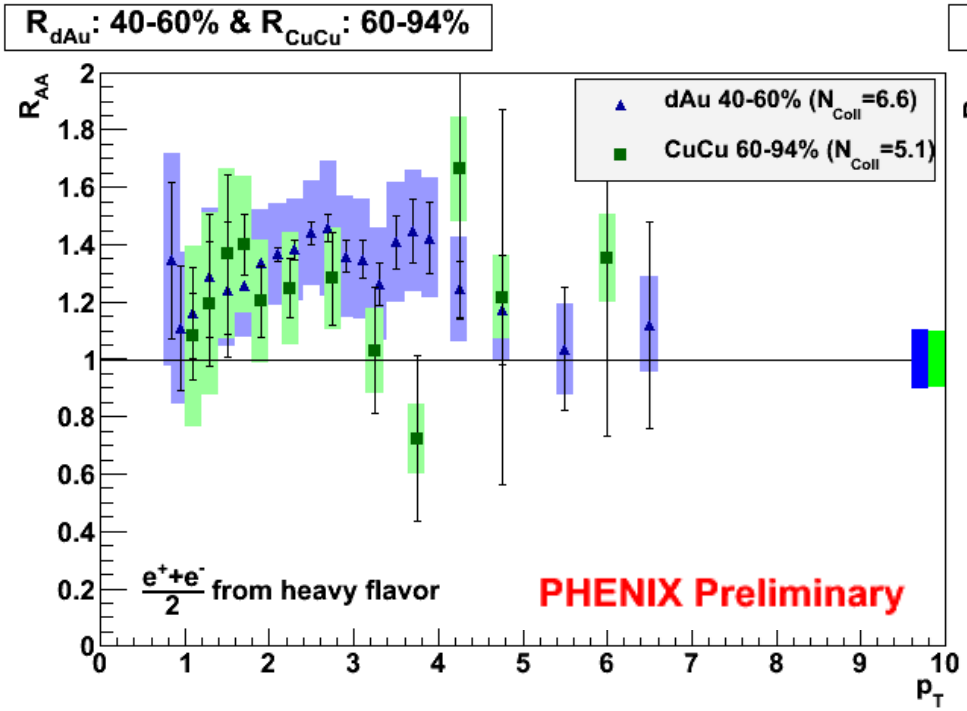
- Consistent with 1 in the most peripheral
- Enhancement as centrality is increased – similar to Cronin effect in hadron production

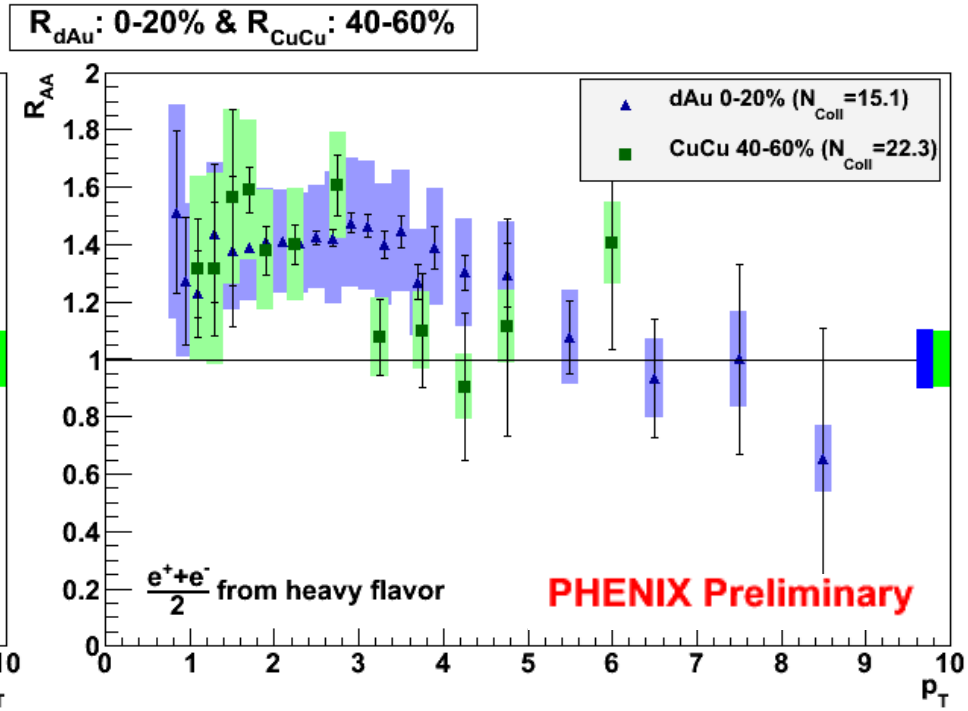
Heavy Flavor in d+Au: Electrons

- d+Au and Cu+Cu consistent in similar N_{coll} region

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

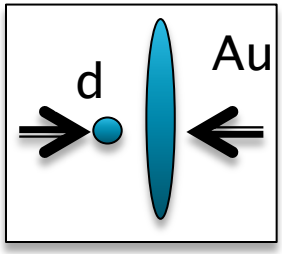
$\langle N_{coll}\rangle_{dAu} = 15.1$ & $\langle N_{coll}\rangle_{CuCu} = 22.3$
$\langle N_{part}\rangle_{dAu} = 15.6$ & $\langle N_{part}\rangle_{CuCu} = 21.2$



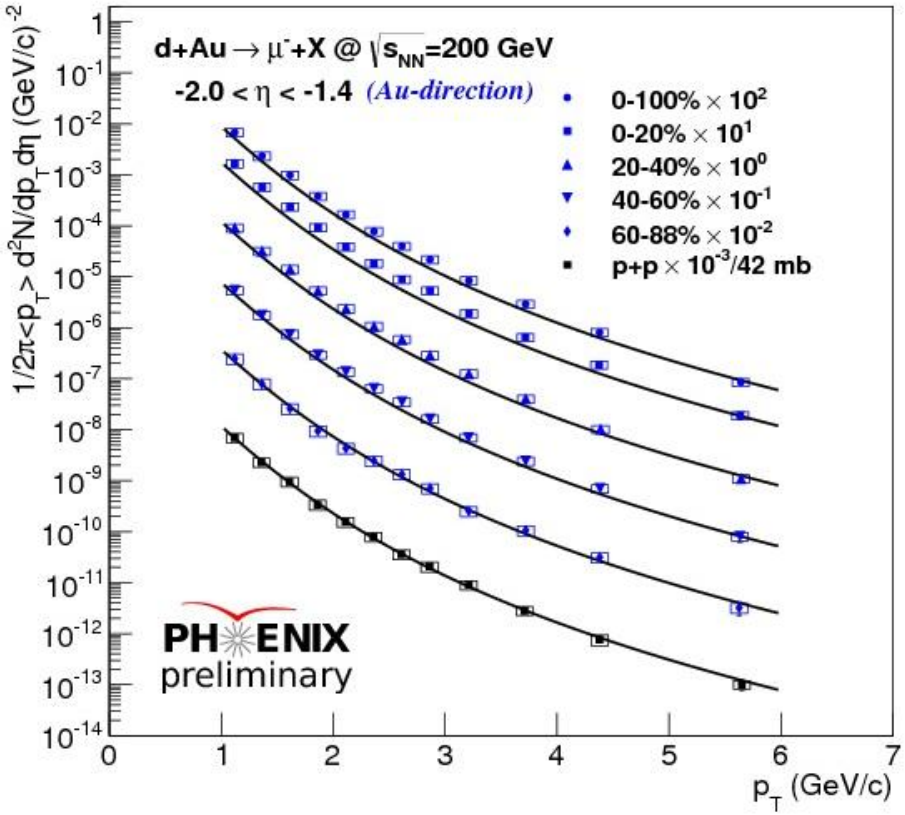


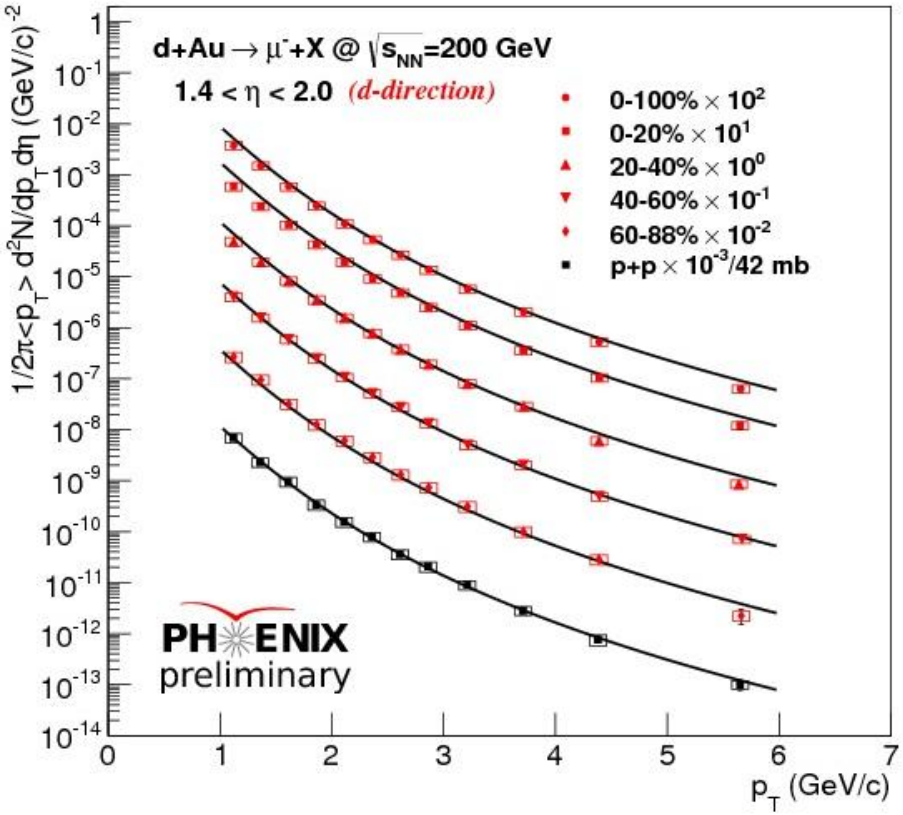
Phys. Rev. Lett. 109, 242301 (2012)

Heavy Flavor in d+Au: Muons

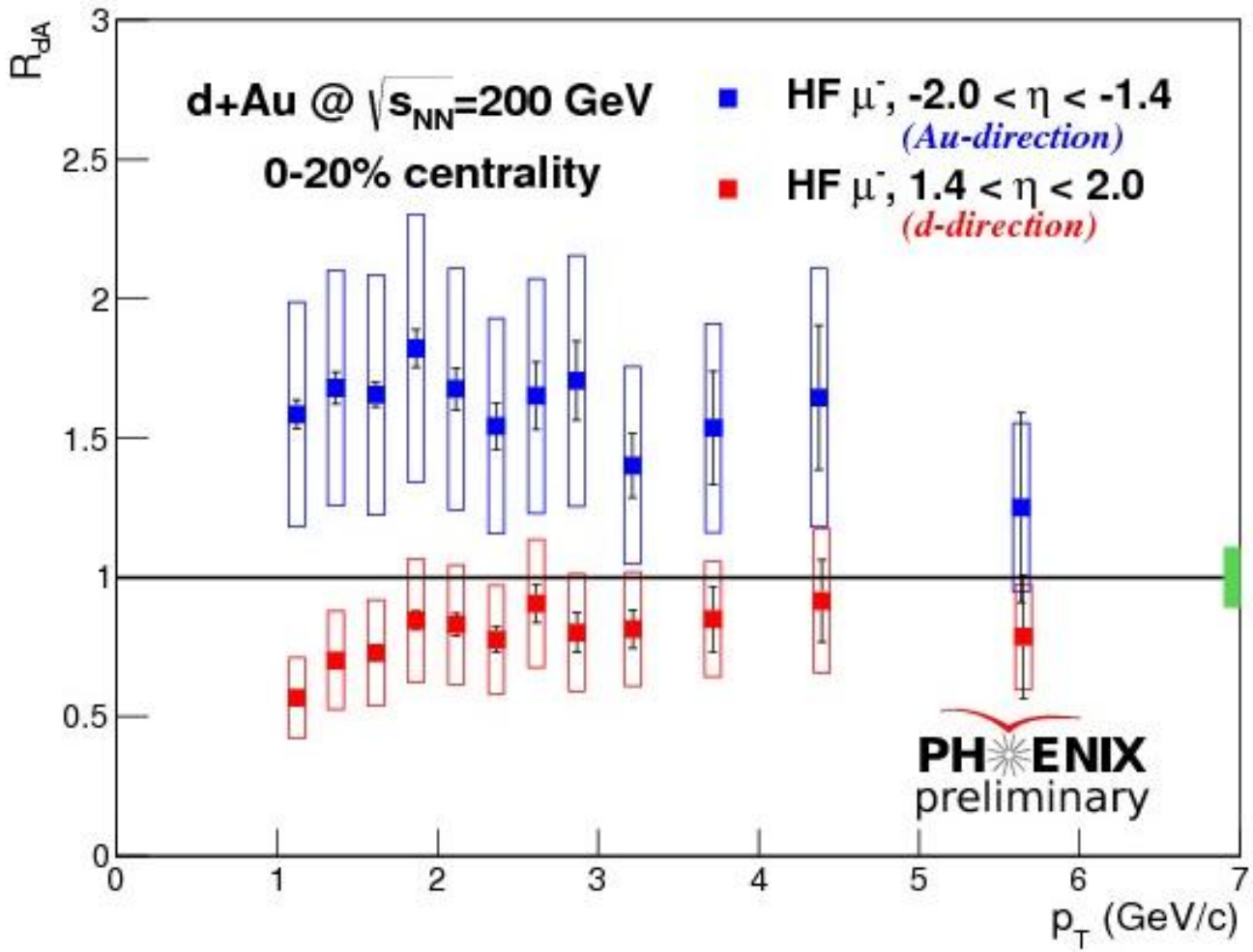


- Asymmetric system
  - Studies different kinematic regions in the nucleus
  - Backward: Au-direction
  - Forward: d-direction

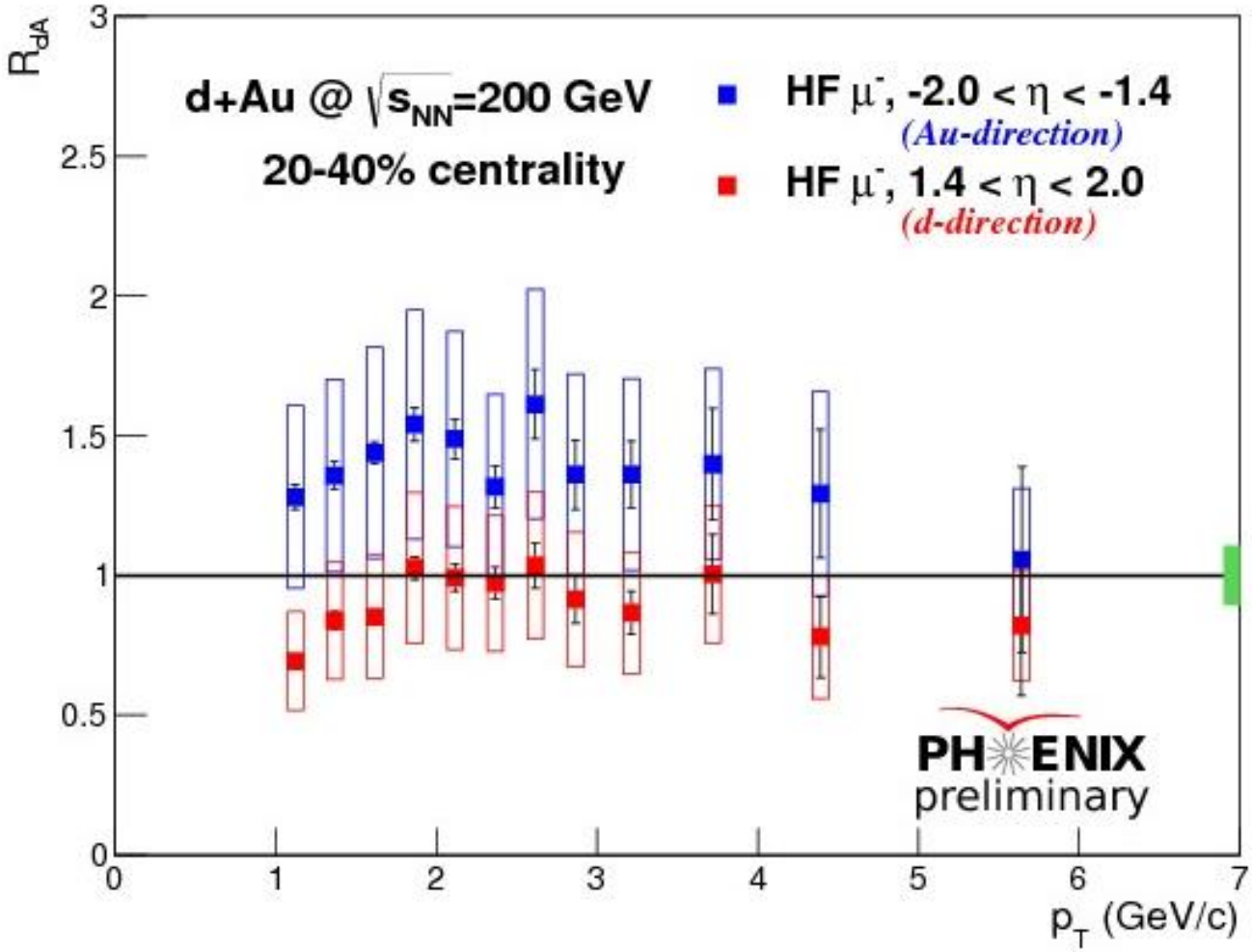




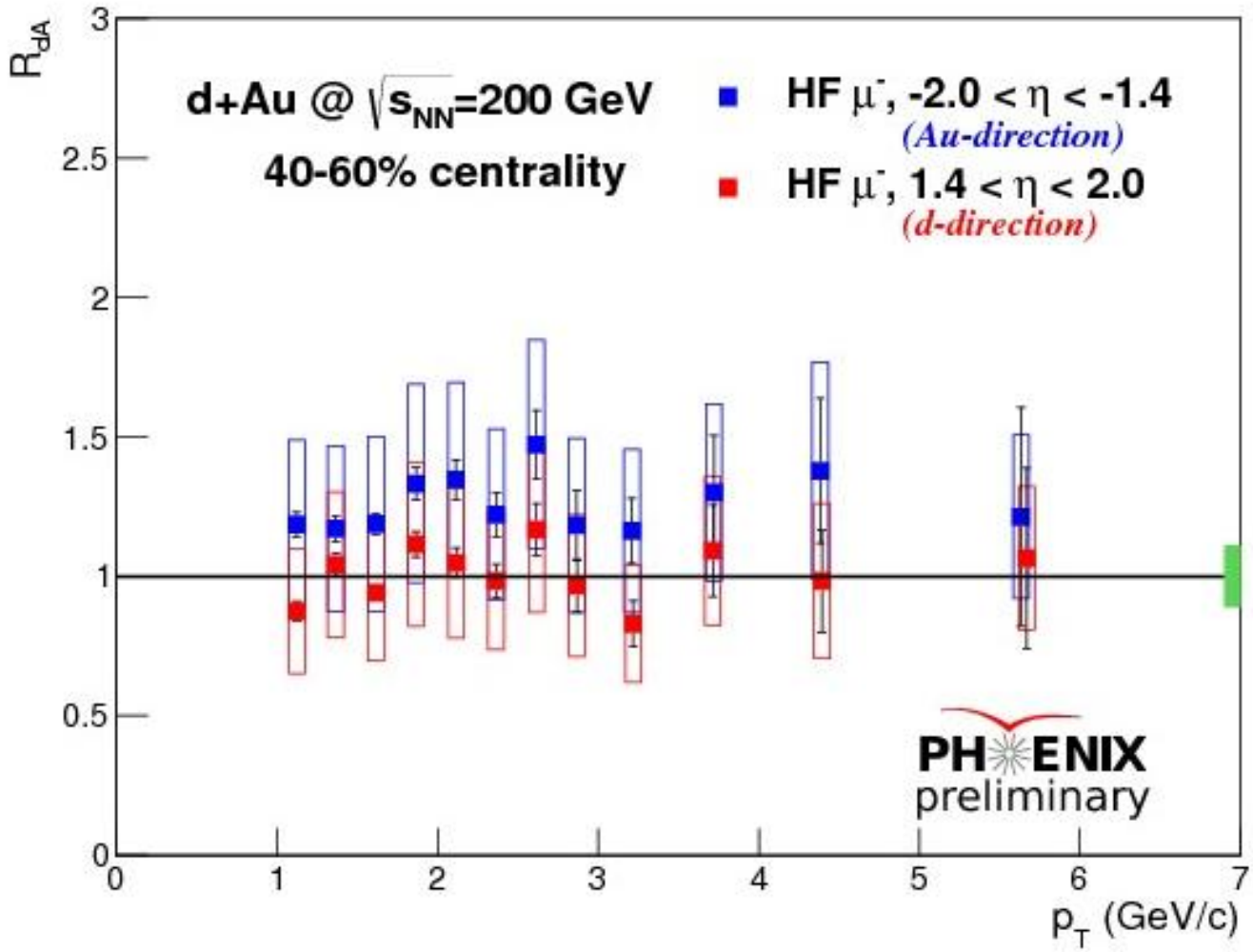
Heavy flavor in d+Au: Muons 0-20%



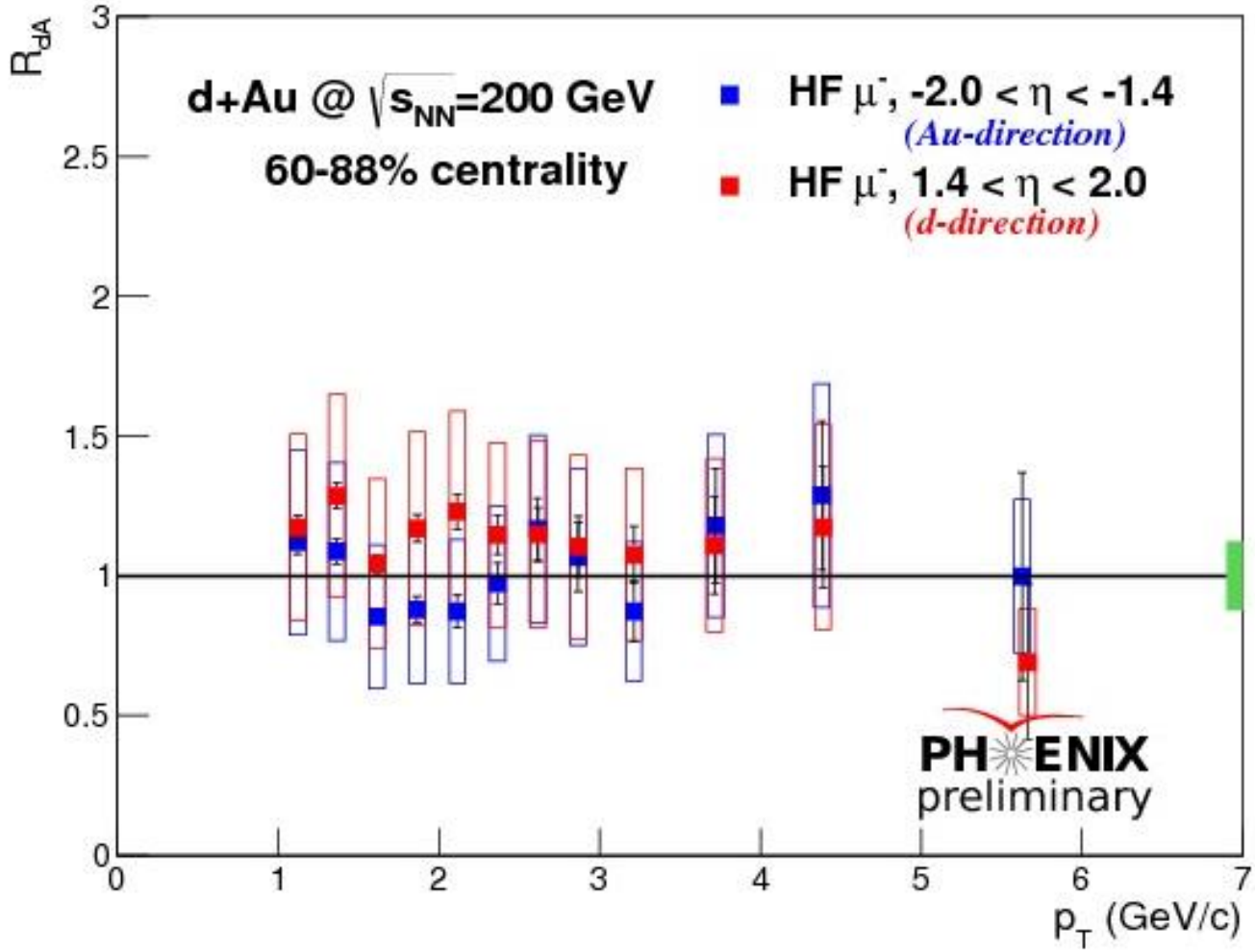
Heavy flavor in d+Au: Muons 20-40%



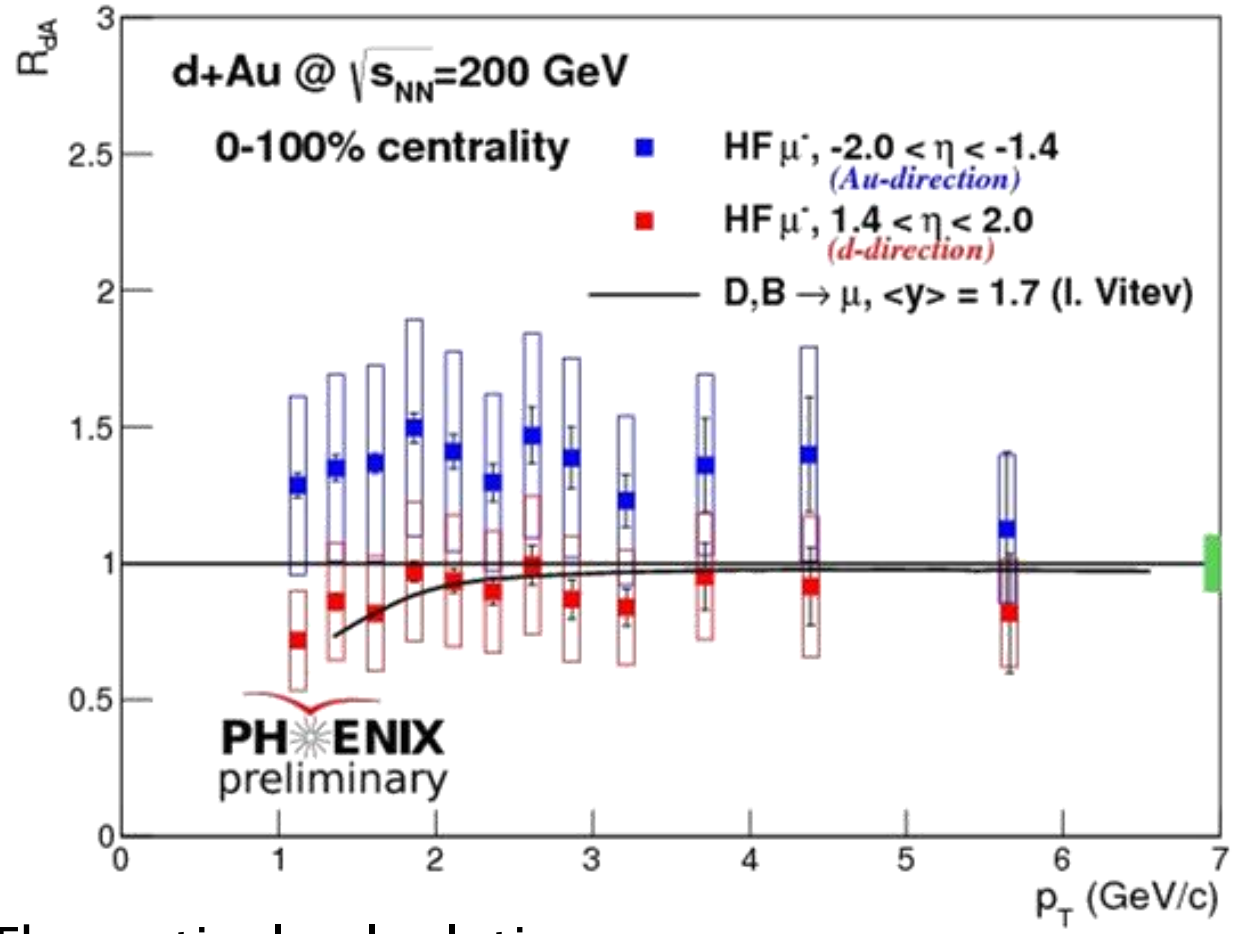
Heavy flavor in d+Au: Muons 40-60%



Heavy flavor in d+Au: Muons 60-88%

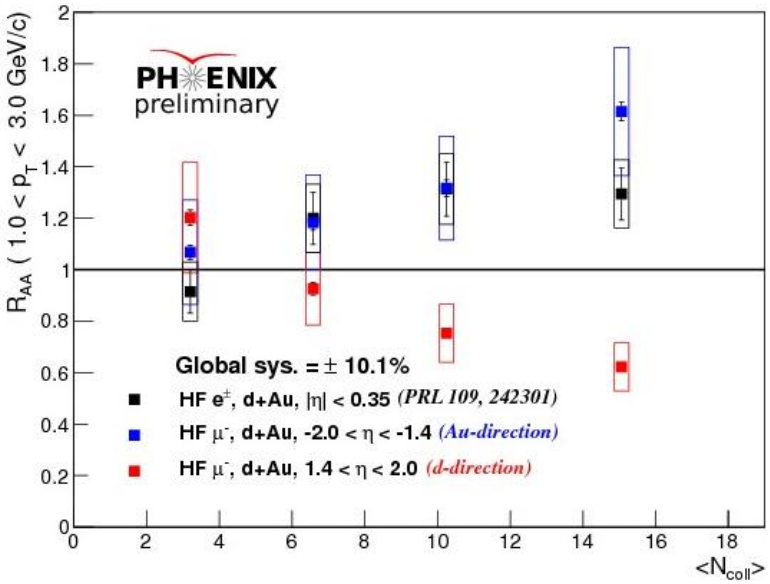


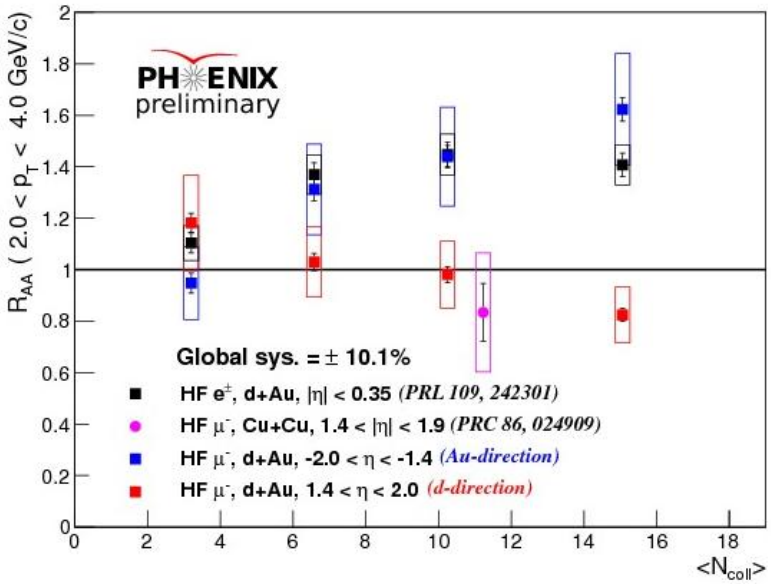
d+Au: Predictions

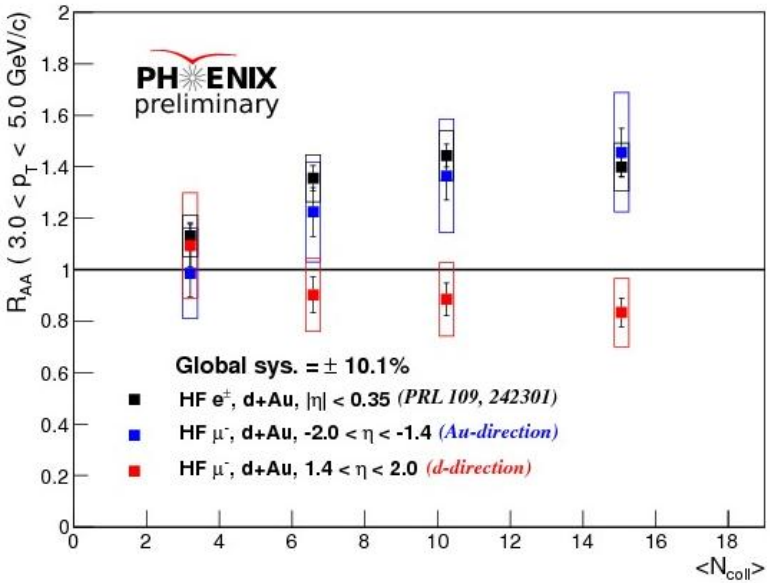


- Theoretical calculation
  - Muons from D & B mesons at <y>=1.7
  - Considers shadowing, initial state energy loss, Cronin

Heavy flavor in d+Au: function of N_{coll}



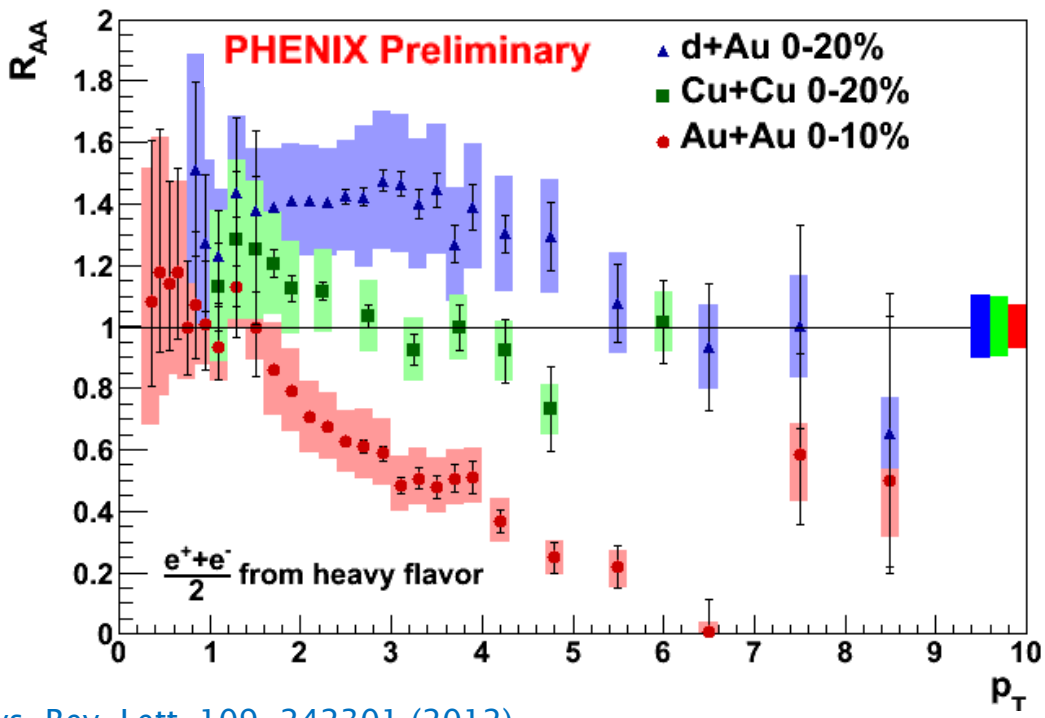




- Centrality dependence more pronounced at low p_T
- Consistent within error in peripheral events

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

- Hierarchy between the 3 systems



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

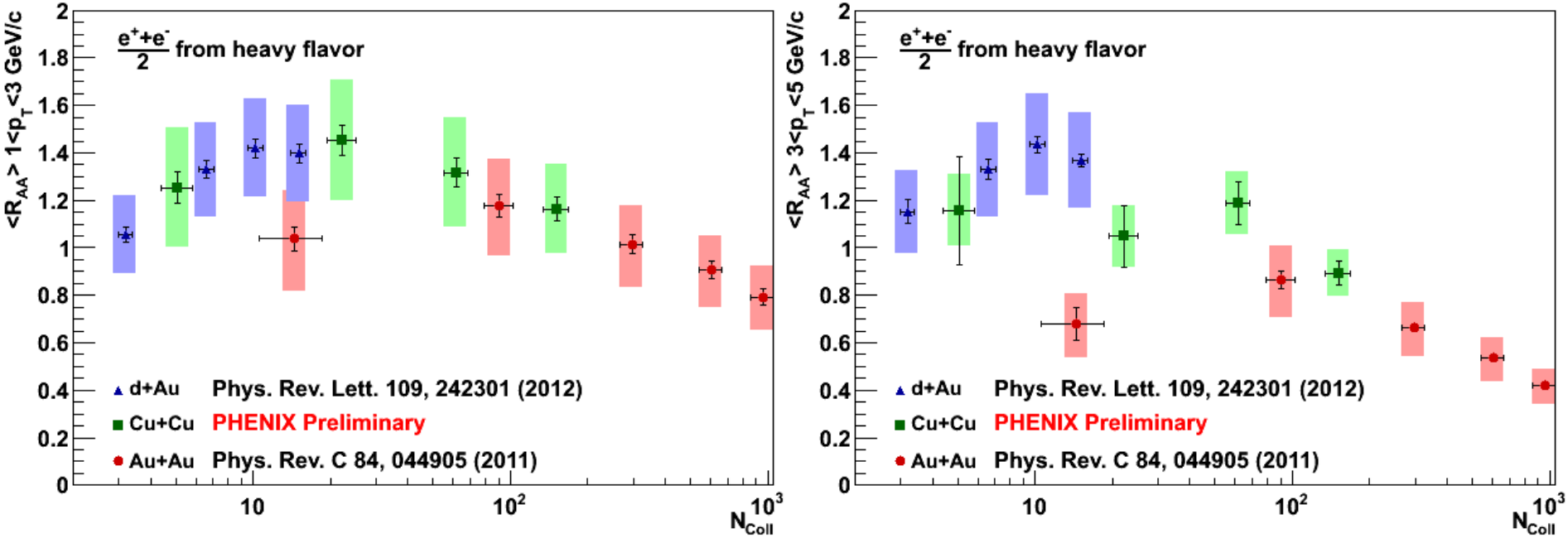
$N_{coll} = 1$ ● ⟷ d+Au ⟷ Cu+Cu ⟷ Au+Au

Phys. Rev. C 84, 044905 (2011)

$5 \leq N_{coll} \leq 151$

$N_{coll} \sim 1000$

$\langle R_{AA} \rangle$ vs N_{Coll}



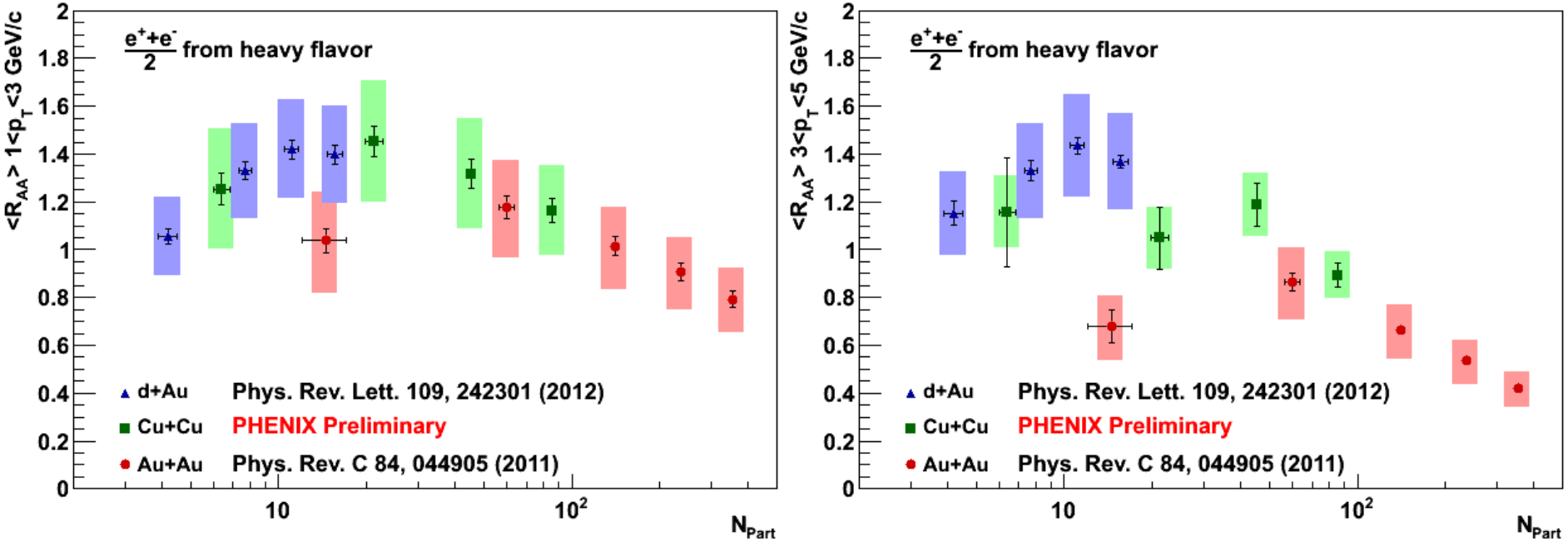
- Move from CNM effects in d+Au/peripheral Cu+Cu to where the hot medium takes over as collision size increases in Cu+Cu and Au+Au systems

Summary

- Cu+Cu
  - Heavy flavor electrons agree with d+Au and Au+Au results – fill in N_{Coll} region
  - Suppression in most central heavy flavor muons – additional CNM effects
- d+Au
  - Enhancement in central open heavy flavor electrons
  - New preliminary heavy flavor muon result
    - Suppression in most central forward (d-going) rapidity
    - Enhancment in most central backward (Au-going) rapidity – consistent with mid-rapidity d+Au electrons
- Theoretical predictions
  - Consistent with forward (d+Au and Cu+Cu) results
  - Consistent with mid-rapidity Au+Au, over predicts suppression in Cu+Cu
  - Would be interesting to make comparison with backward & mid-rapidity d+Au

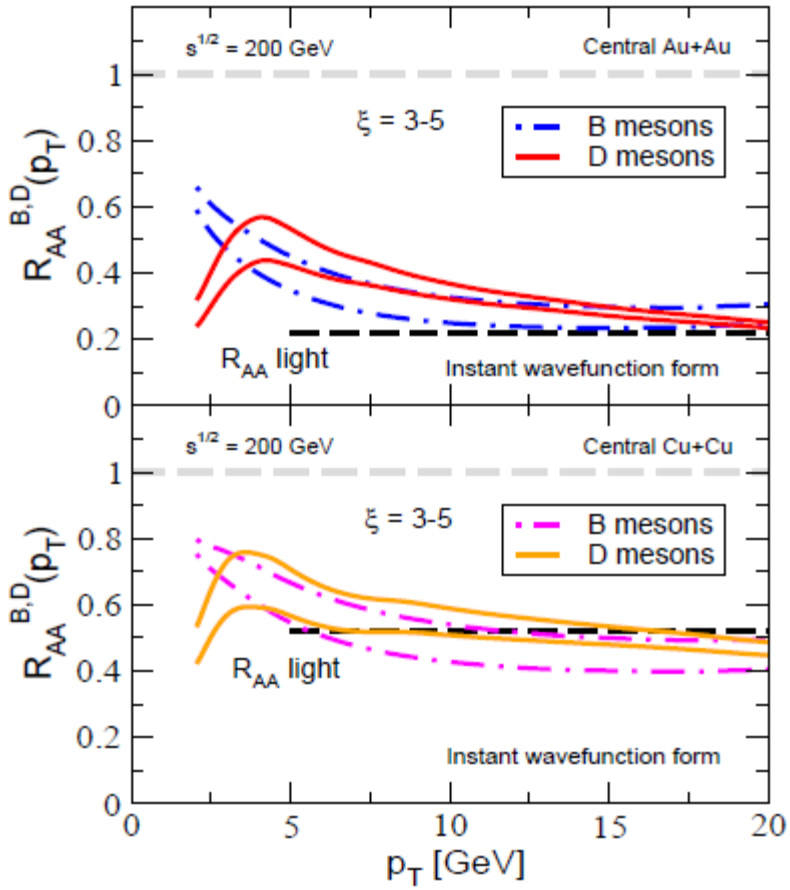
Backup

$\langle R_{AA} \rangle$ vs N_{Part}

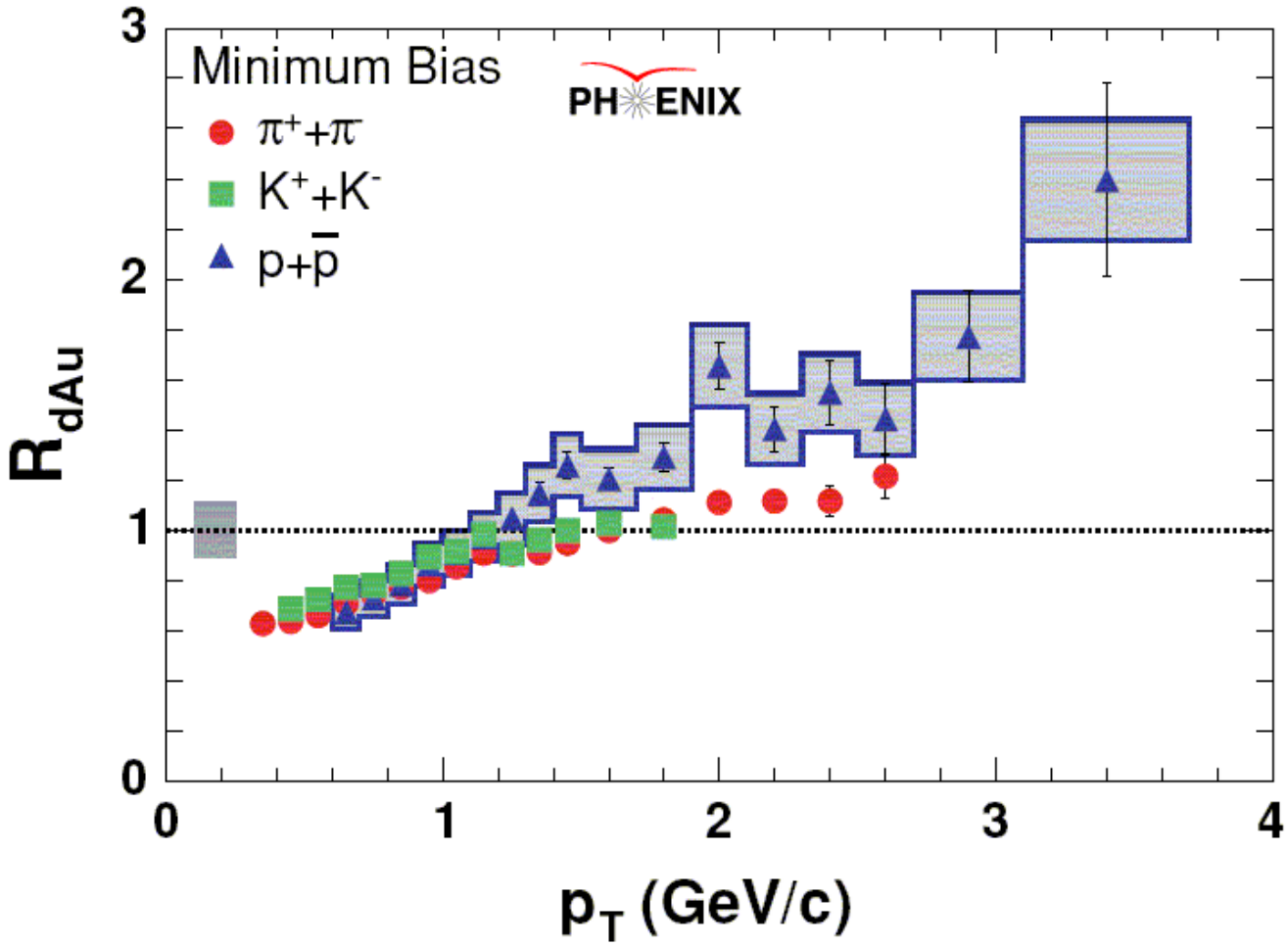


- N_{Part}: rate of soft bulk production

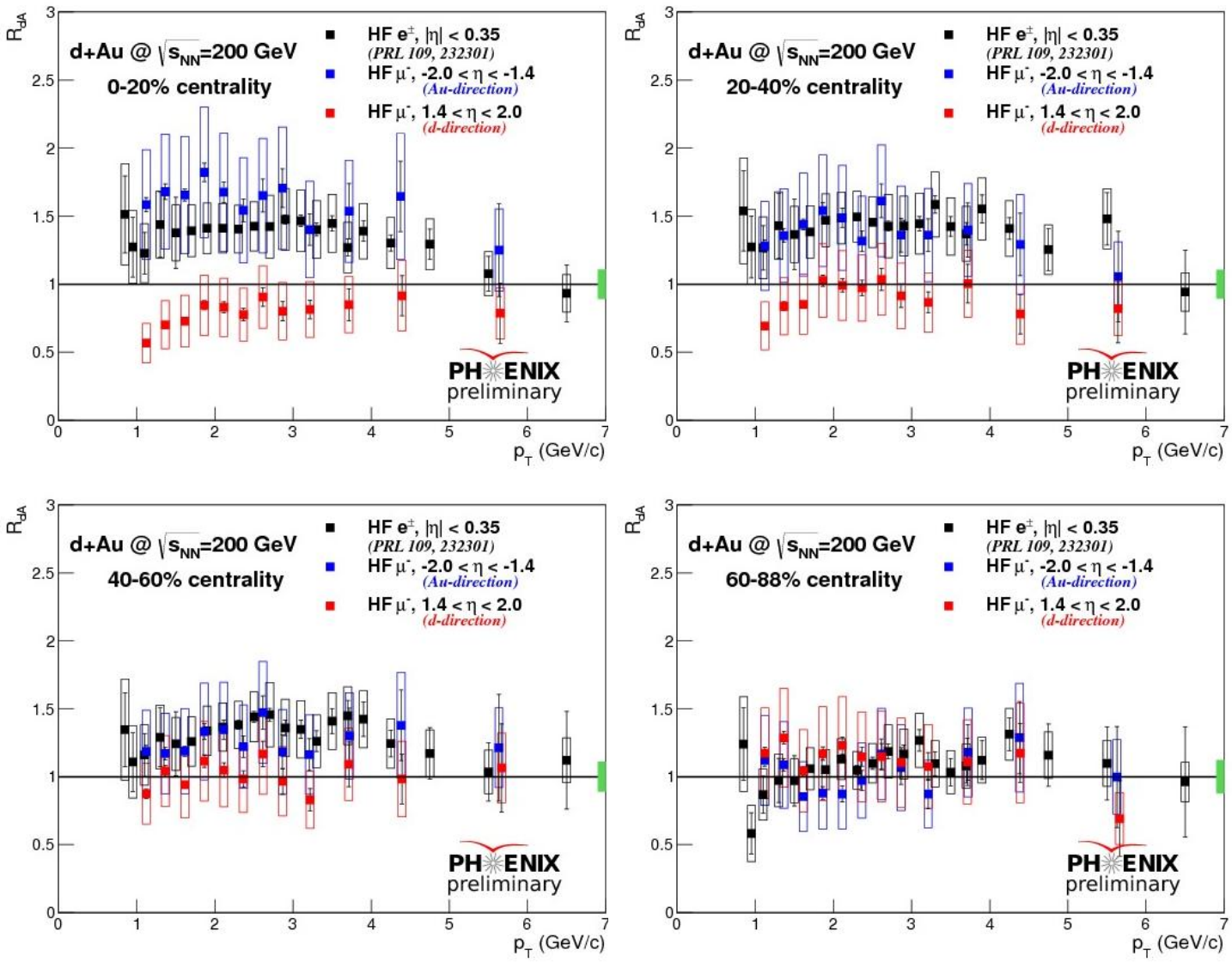
Heavy flavor predictions



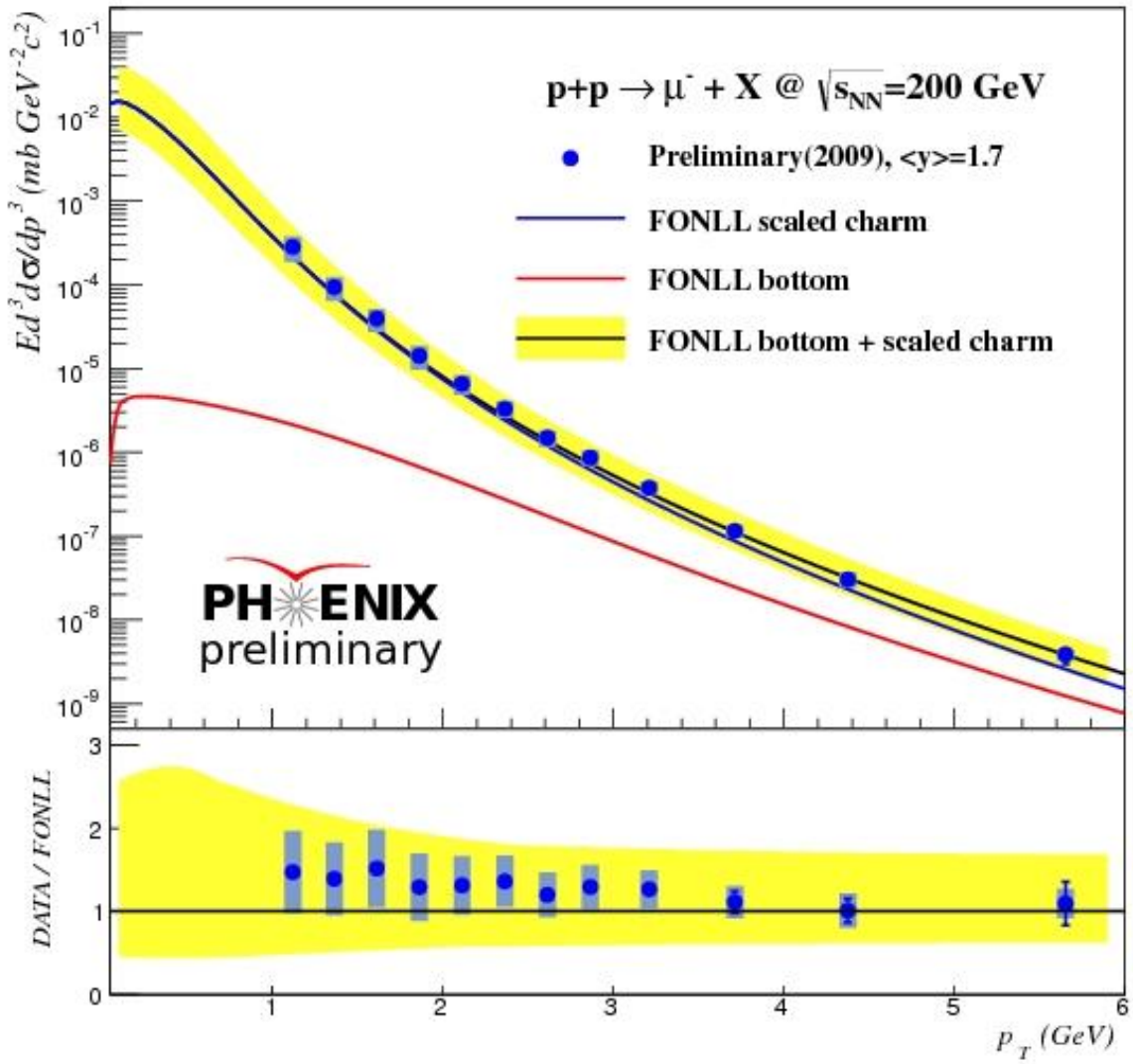
Cronin mass dependence



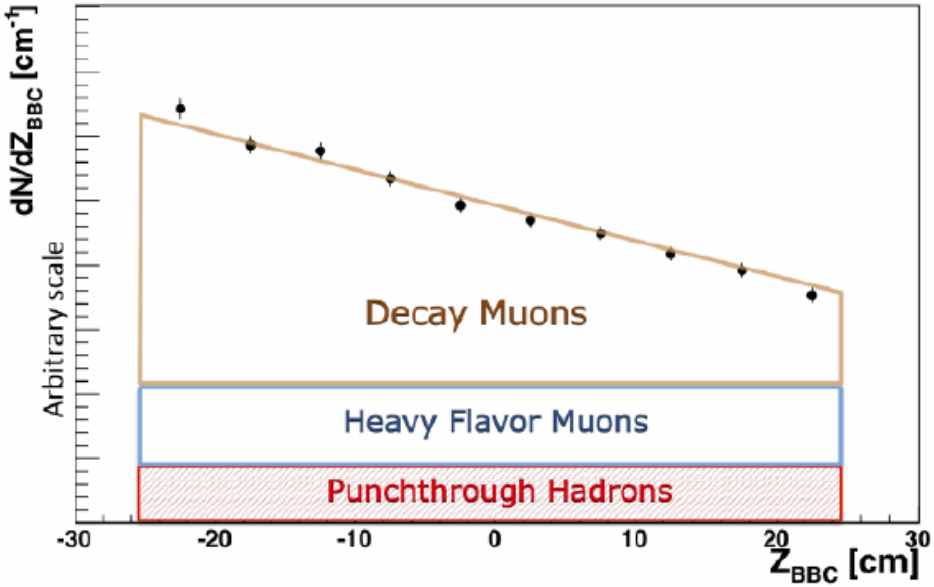
RdAu

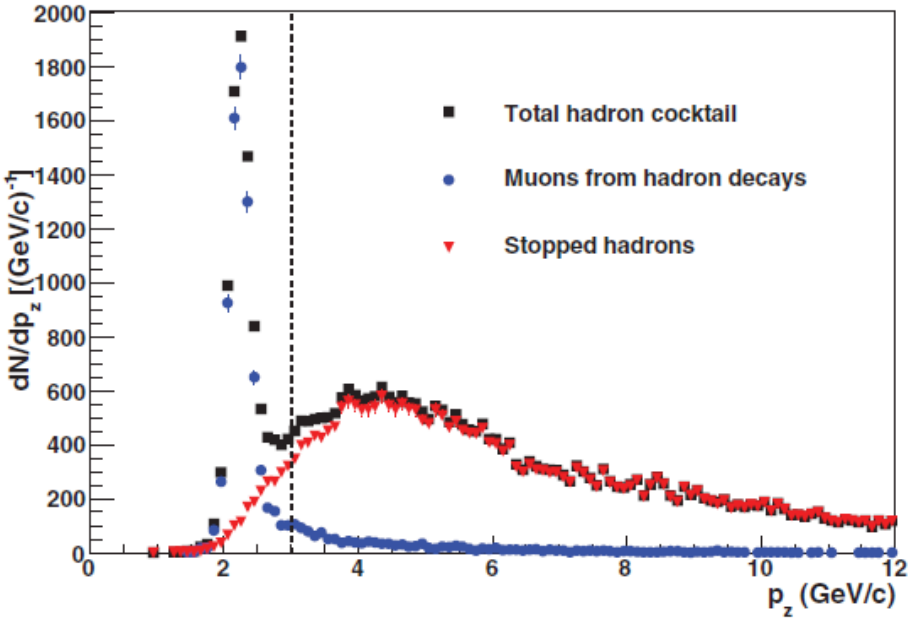

d+Au @ $\sqrt{s_{NN}}$=200 GeV
0-20% centrality
20-40% centrality
40-60% centrality
60-88% centrality
HF e±, |η| < 0.35
(PRL 109, 232301)
HF μ±, -2.0 < η < -1.4
(Au-direction)
HF μ±, 1.4 < η < 2.0
(d-direction)
PHENIX
preliminary
R_{dA}
p_T (GeV/c)

p+p muons

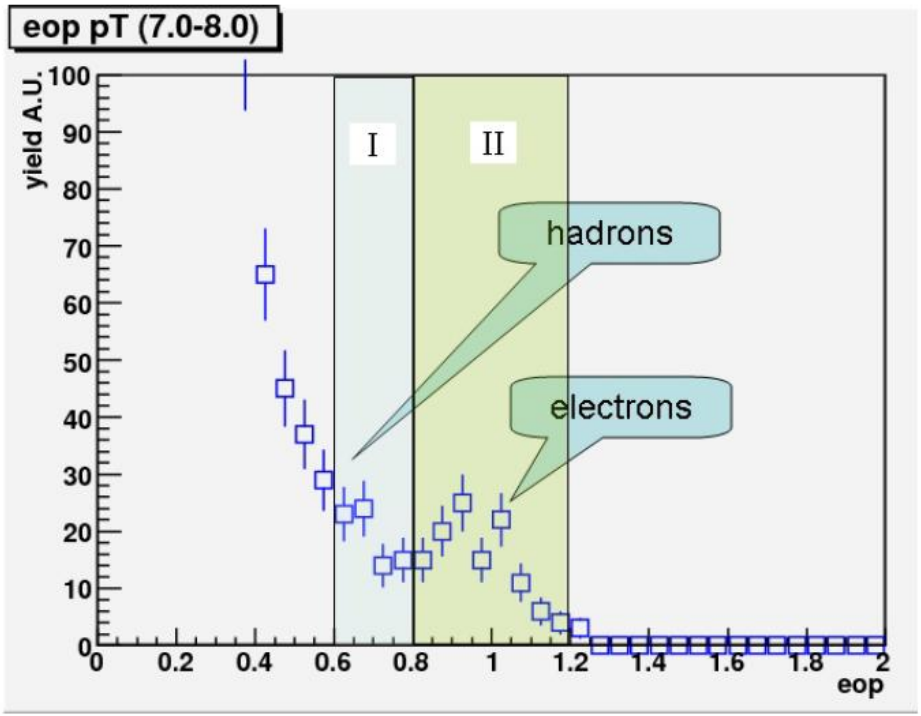

p+p → μ⁻ + X @ √s_NN=200 GeV
Preliminary(2009), <y>=1.7
FONLL scaled charm
FONLL bottom
FONLL bottom + scaled charm
PHENIX
preliminary
Ed³dσ/dp³ (mb GeV⁻²c²)
DATA / FONLL
p_T (GeV)

Muon background





Background subtraction for p+p electrons



$$R = \frac{\int_{0.8}^{1.2} \left[\frac{E}{p}\right]_{\pi}}{\int_{0.6}^{0.8} \left[\frac{E}{p}\right]_{\pi}}$$

$$N_e = \int_{0.8}^{1.2} \left[\frac{E}{p}\right]_{all} - R_{\pi} \int_{0.6}^{0.8} \left[\frac{E}{p}\right]_{all}$$