Heavy quark production at forward rapidity in d+Au collisions & CNM effects

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Japan-Korea PHENIX workshop
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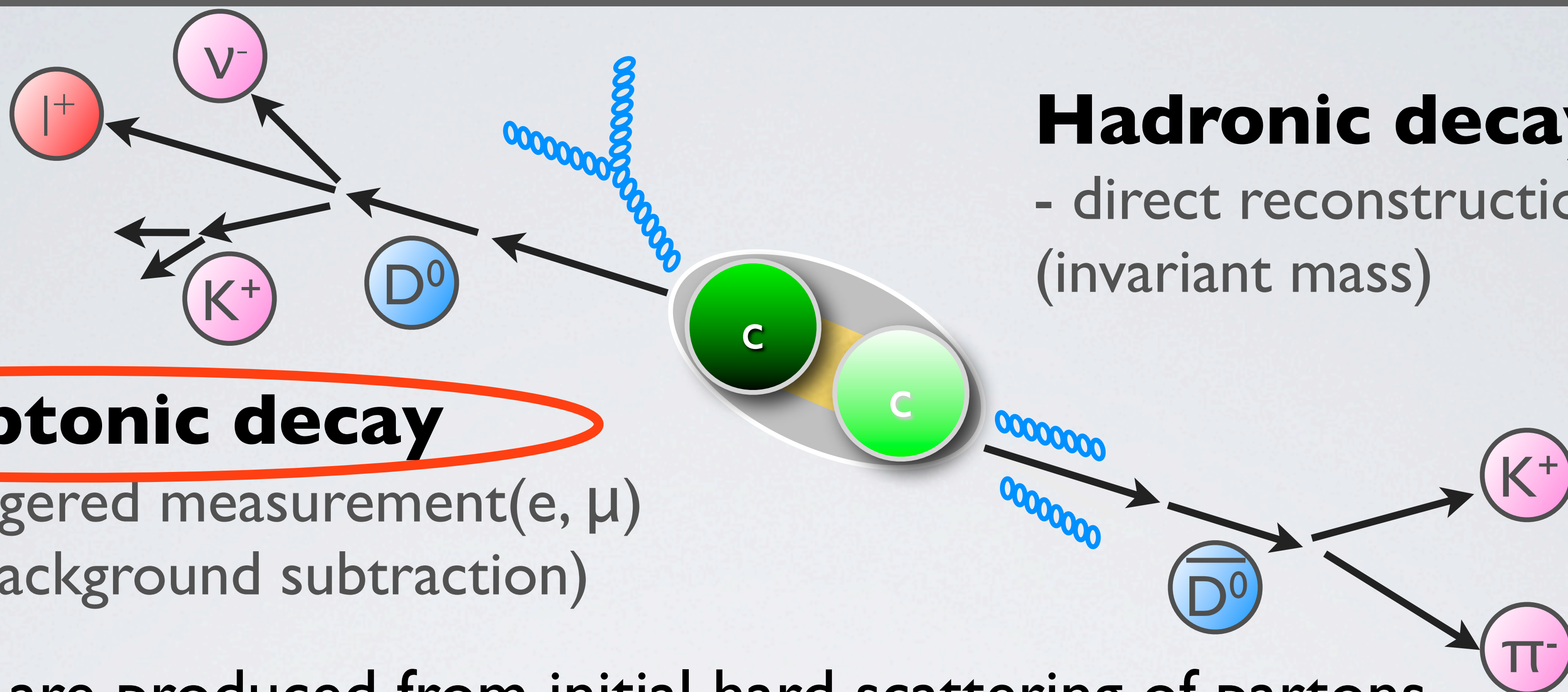
Introduction

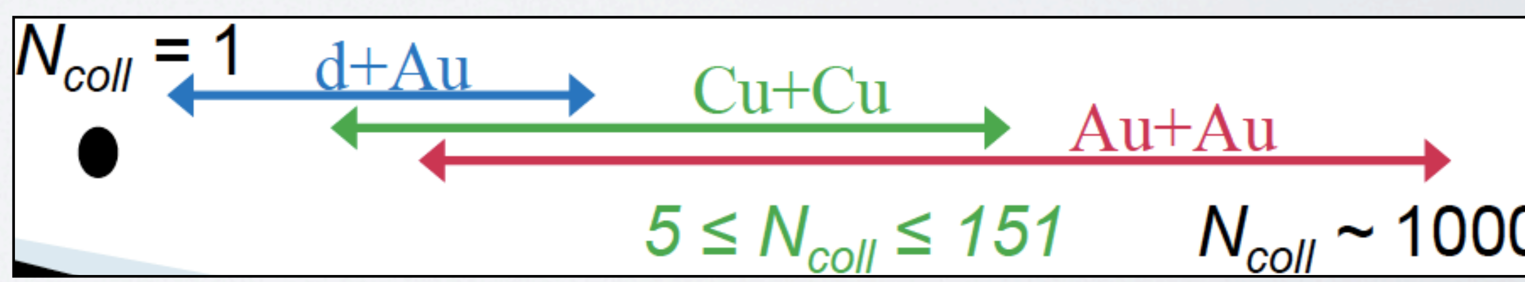


Semi-leptonic decay
- lepton triggered measurement(e, μ)
(statistical background subtraction)

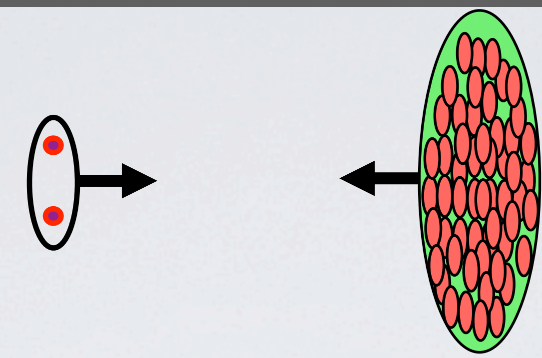
Hadronic decay
- direct reconstruction
(invariant mass)

- Heavy-quarks are produced from initial hard scattering of partons
  - good for studying evolution of medium
  - leading-order process is **gluon fusion** => sensitive to initial nPDF modification

- p+p collisions
  - test pQCD, provide baseline measurements
- d+Au collisions
  - study cold nuclear matter effects
- Heavy-ion collisions
  - probe effects of hot and dense medium



PHENIX backward rapidity
*Au-going side
*$\mathbf{x_1 < x_2}$



PHENIX forward rapidity
*d-going side
*$\mathbf{x_1 > x_2}$

parton of x_1 in d   parton of x_2 in Au

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

- d+Au collisions as a **control experiment**
    - in heavy-ion collisions, both HNM & CNM effects are combined
    - another baseline to interpret and understand the heavy-ion results

d+Au collisions

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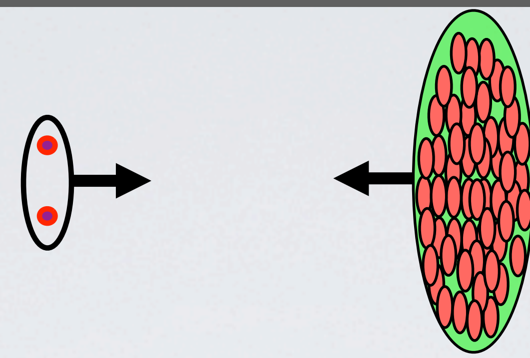

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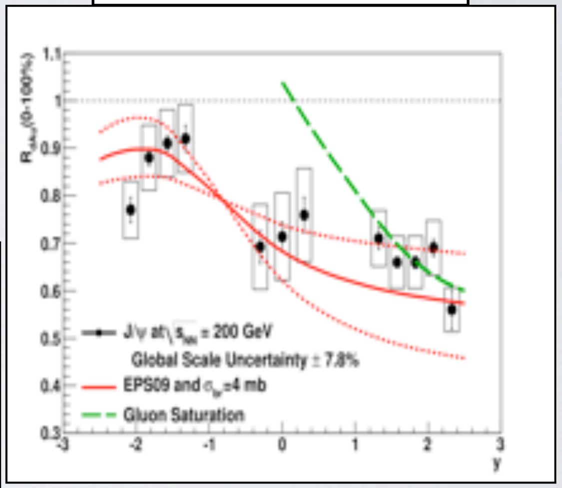
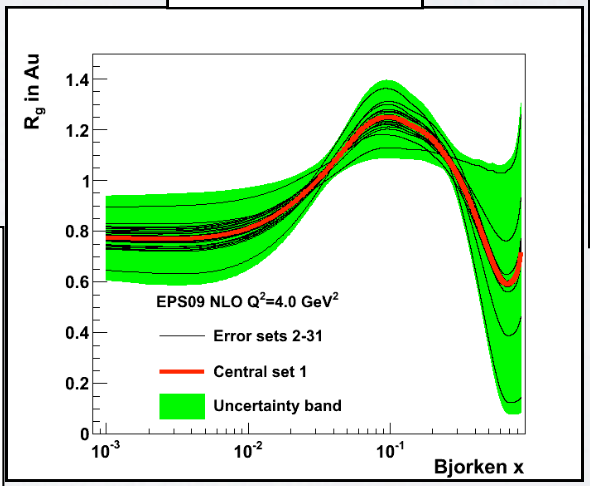
- d+Au collisions as a **control experiment**
  - in heavy-ion collisions, both HNM & CNM effects are combined
  - another baseline to interpret and understand the heavy-ion results

- Cold Nuclear Matter (CNM) effects
  - modification of parton distribution function
  - initial parton energy loss
  - p_T (k_T) broadening (Cronin effect)
  - nuclear break-up (absorption)

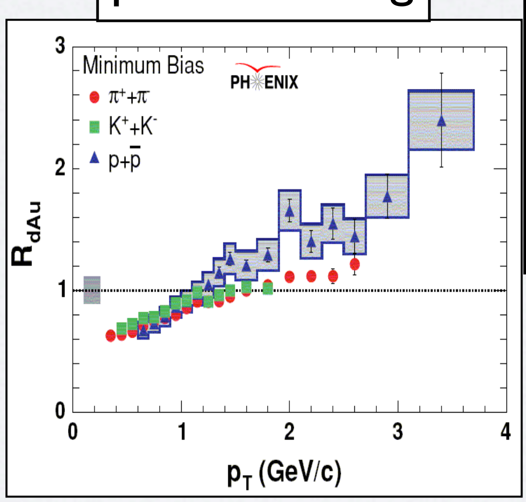
nuclear breakup



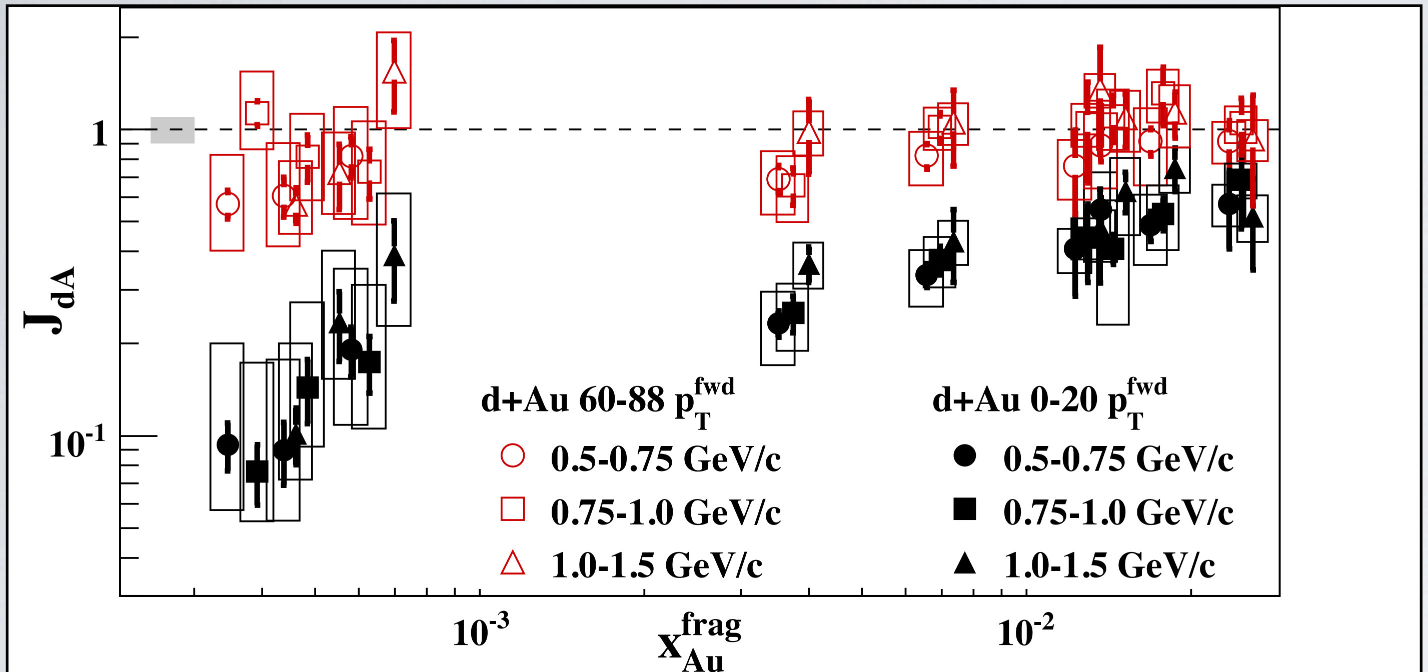
shadowing



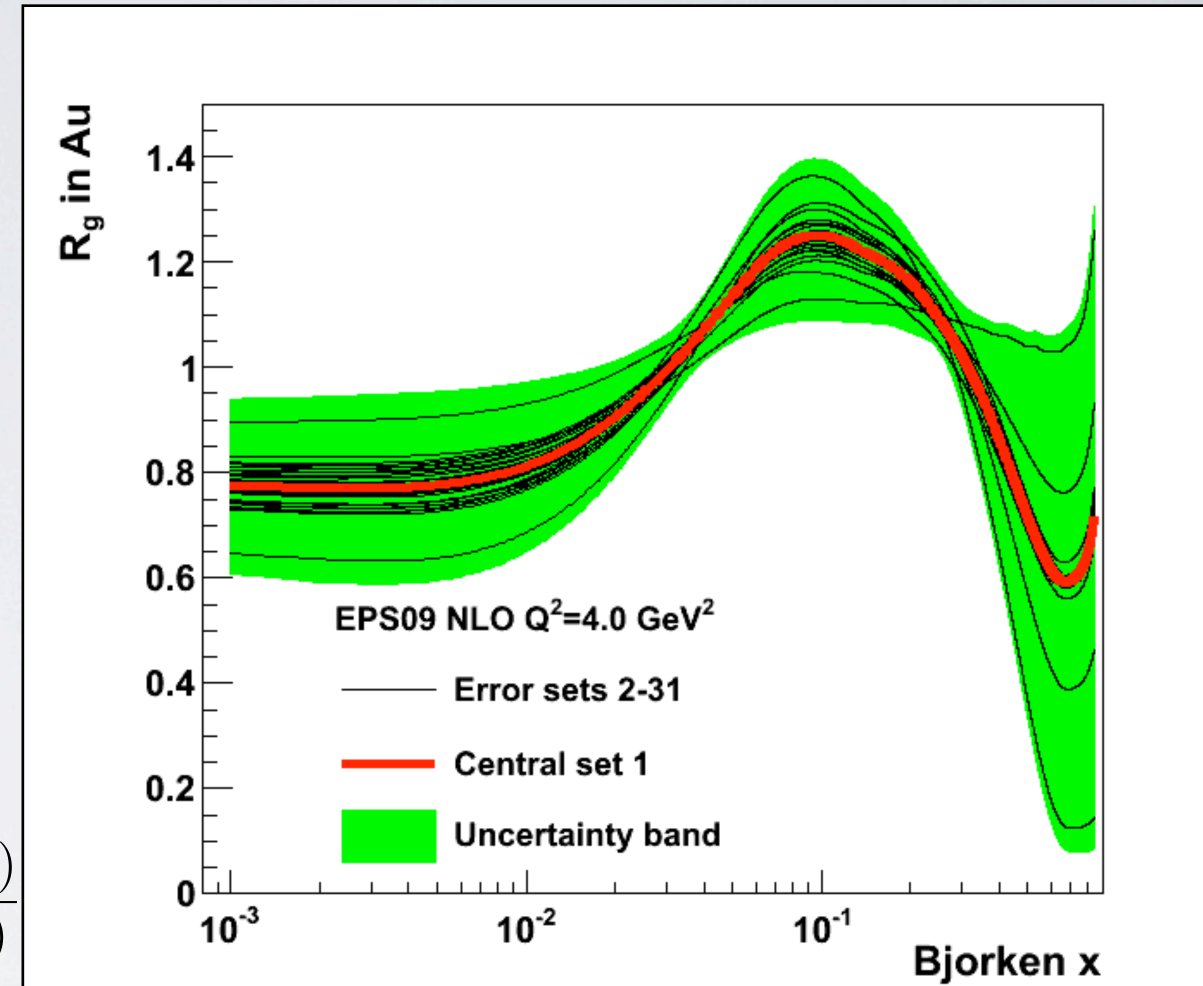
p_T broadening



CNM effects - Nuclear shadowing



Phys. Rev. Lett. 107, 172301 (2011)



JHP04 (2009)065

$$J_{dA} = \frac{\sigma^{pair}_{dA}/\sigma_{dA}}{\langle N_{coll}\rangle \sigma^{pair}_{pp}/\sigma_{pp}} \propto \frac{f^a_d(x_d) \otimes f^b_A(x_A) \otimes \sigma^{ab\to cd} \otimes D(z_c, z_d)}{f^a_p(x_p) \otimes f^b_p(x_p) \otimes \sigma^{ab\to cd} \otimes D(z_c, z_d)}$$

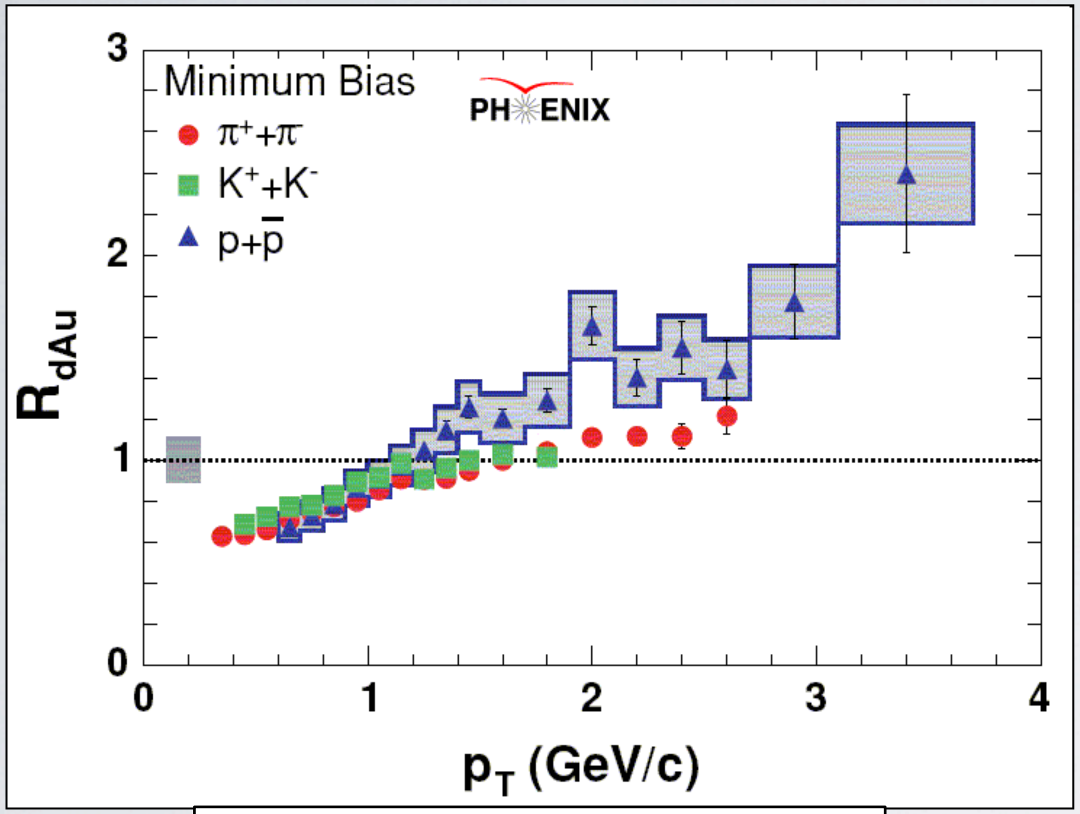
High x in d
mostly valance quarks
weak modification expected

Low x in Au
mostly gluon
strong modification(suppression) expected

$$J_{dA} \sim R^A_G$$

- modification of parton distribution in nuclei
  - shadowing
  - anti-shadowing
  - EMC

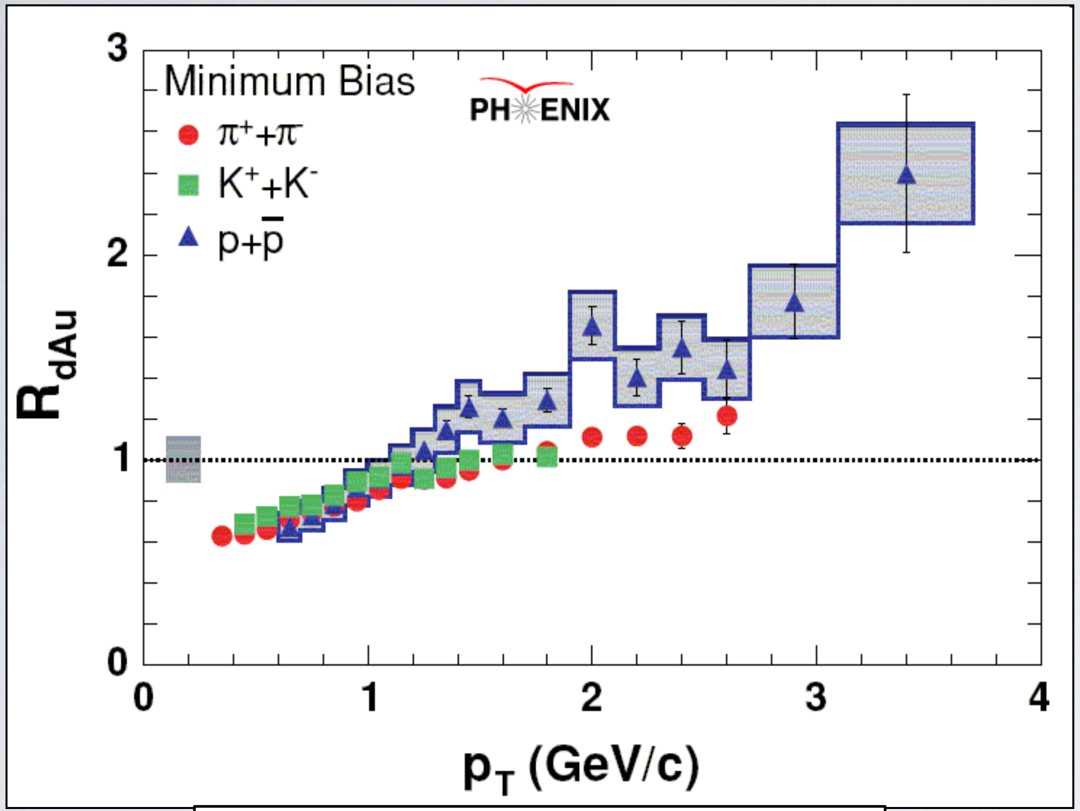
CNM effects - Cronin effect & Nuclear absorption



Phys. Rev. C 74, 024904 (2006)

- Cronin effect
  - p_T broadening due to multiple inelastic scattering of incoming parton before hard scattering
  - baryon enhancement can be explained by recombination model
    *(R. Hwa, et al. nucl-th/0404066)

CNM effects - Cronin effect & Nuclear absorption



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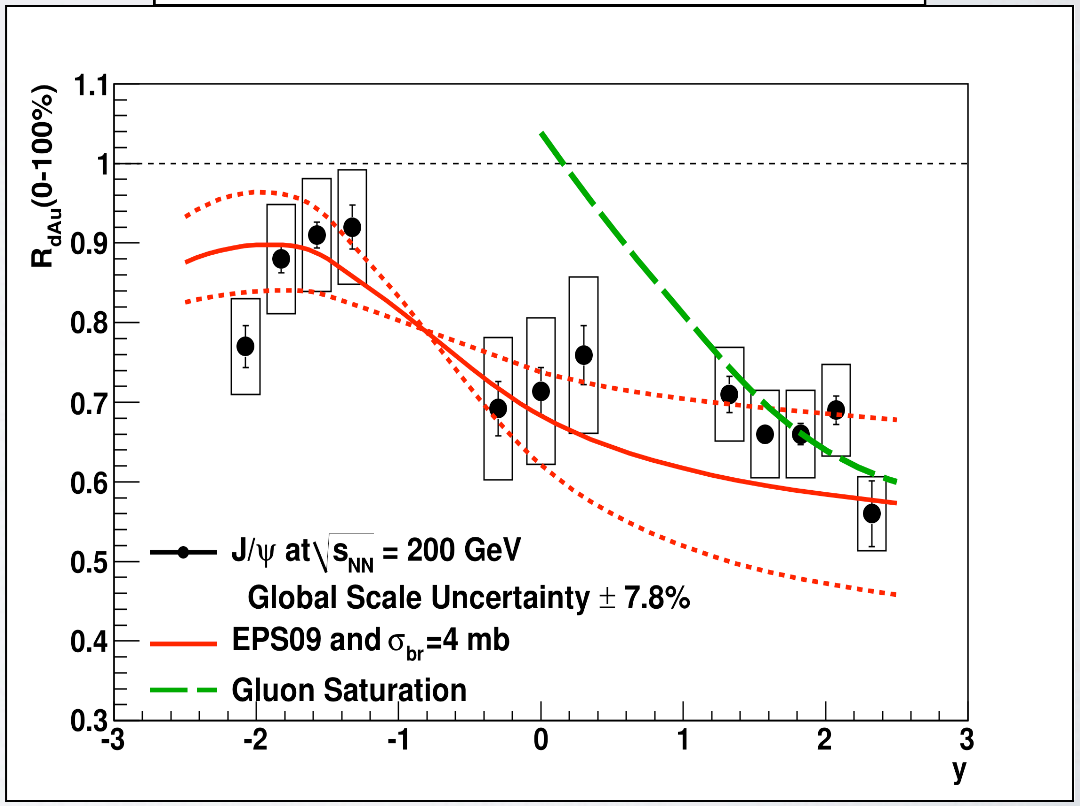
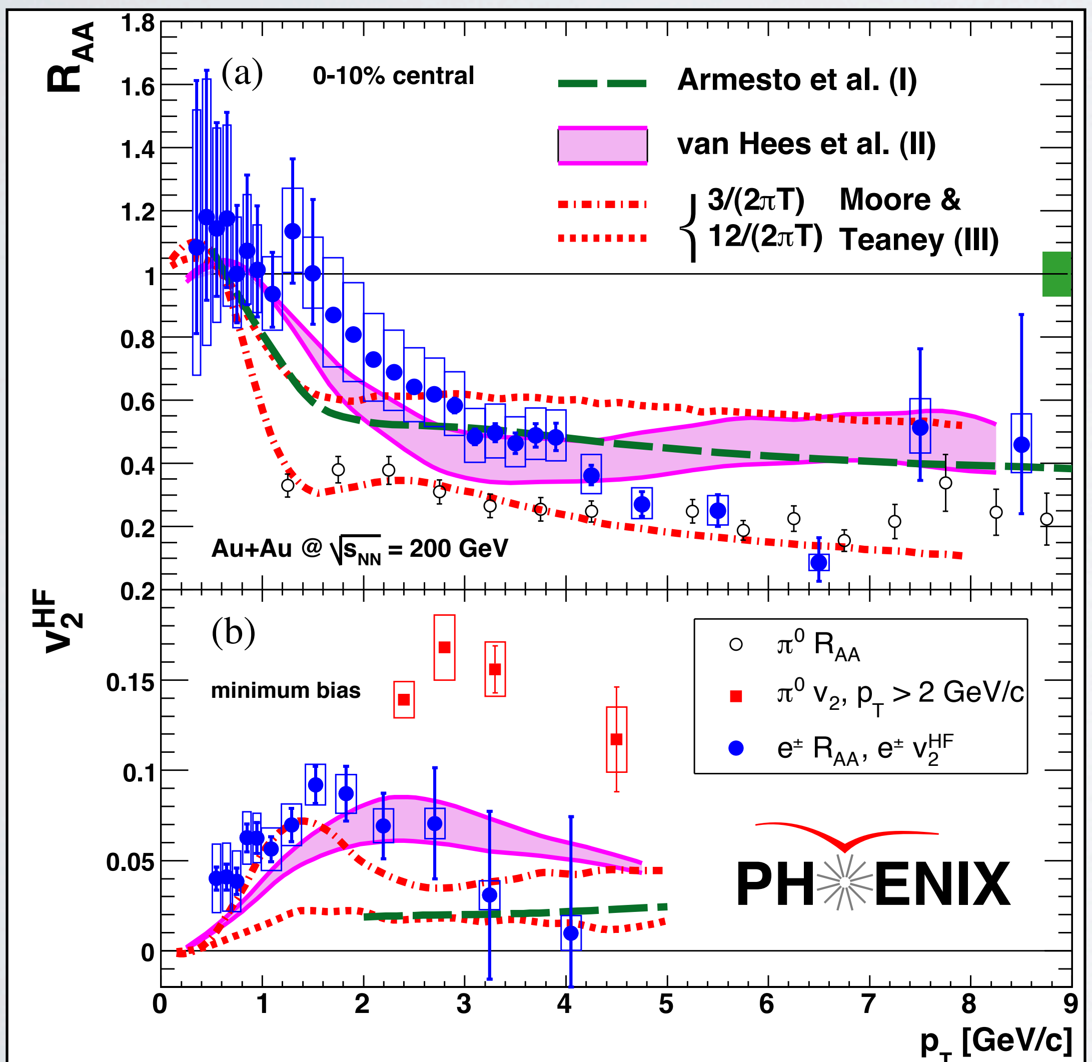


- Nuclear Breakup (Absorption)
  - breaking up quarkonia with CNM
    *nucleus during the crossing
    *co-mover
  - J/ψ are suppressed at all rapidity and in all centrality ranges
  - large difference from open heavy flavor production

Review of heavy-quark results

- In central Au+Au collisions
  - **large suppression** of high p_T heavy-flavor electron
  - **significant v_2**

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



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

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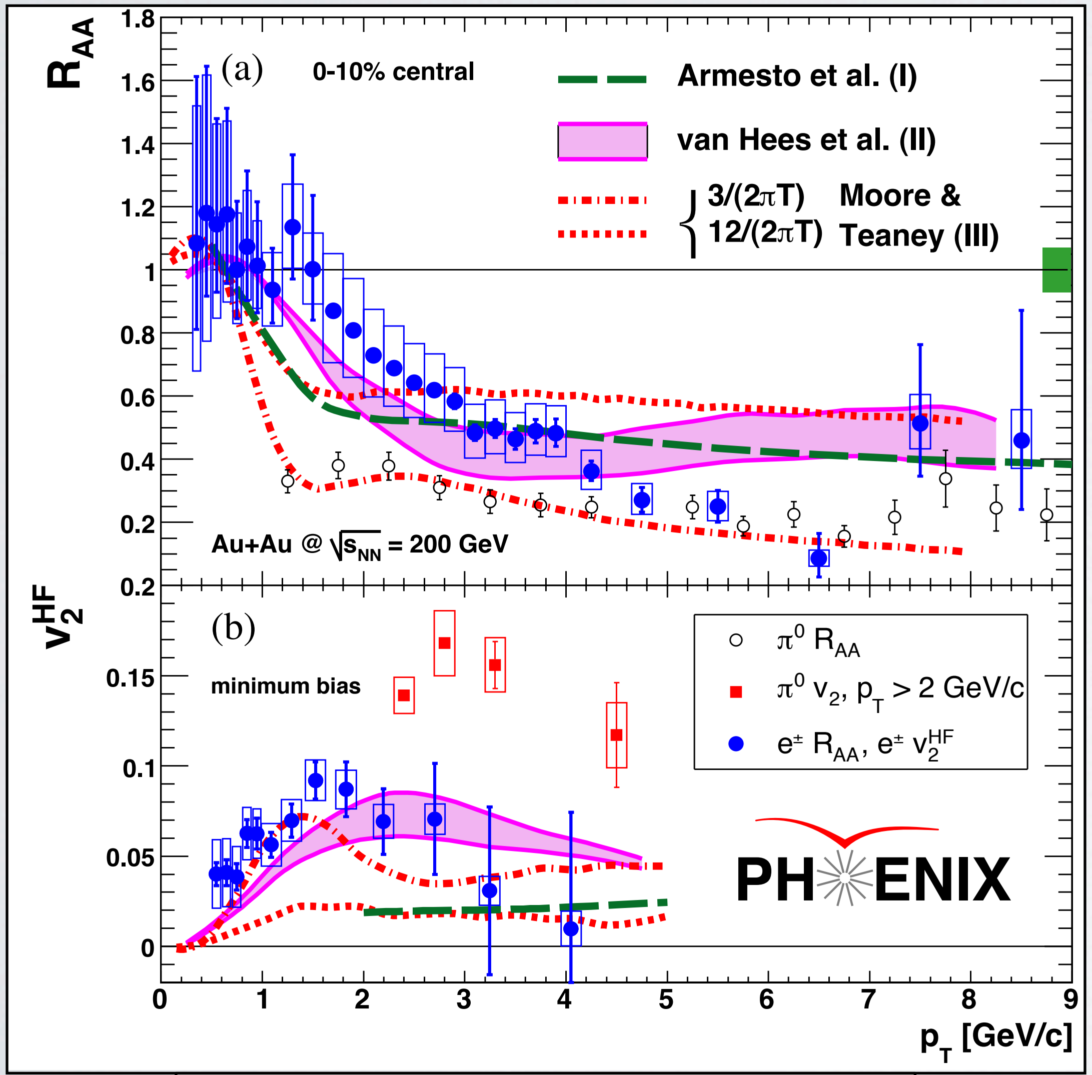
$$R_{AB} = \frac{dN_{AB}}{\langle N_{coll} \rangle dN_{pp}}$$

- In d+Au collisions
  - **clear enhancement** in central d+Au collisions at mid-rapidity
    ➔suppression at mid-rapidity is due to HNM effects



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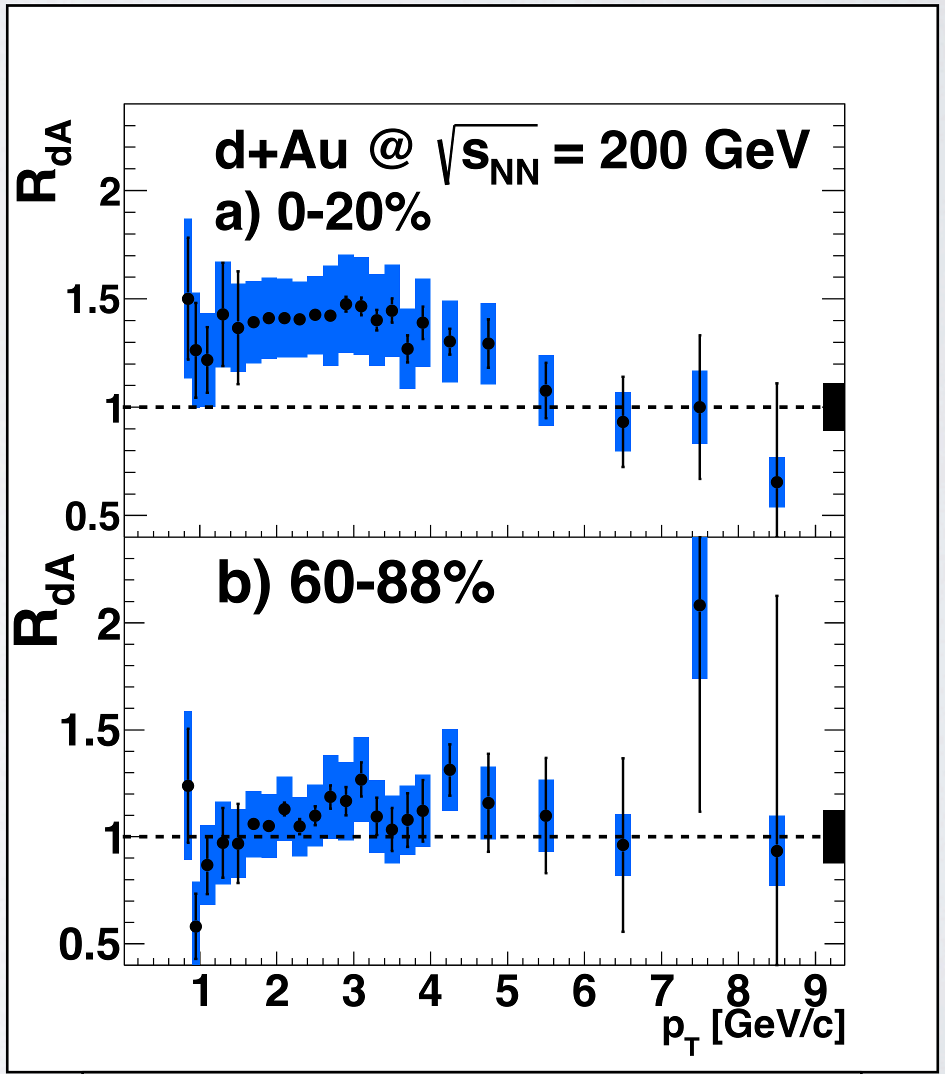
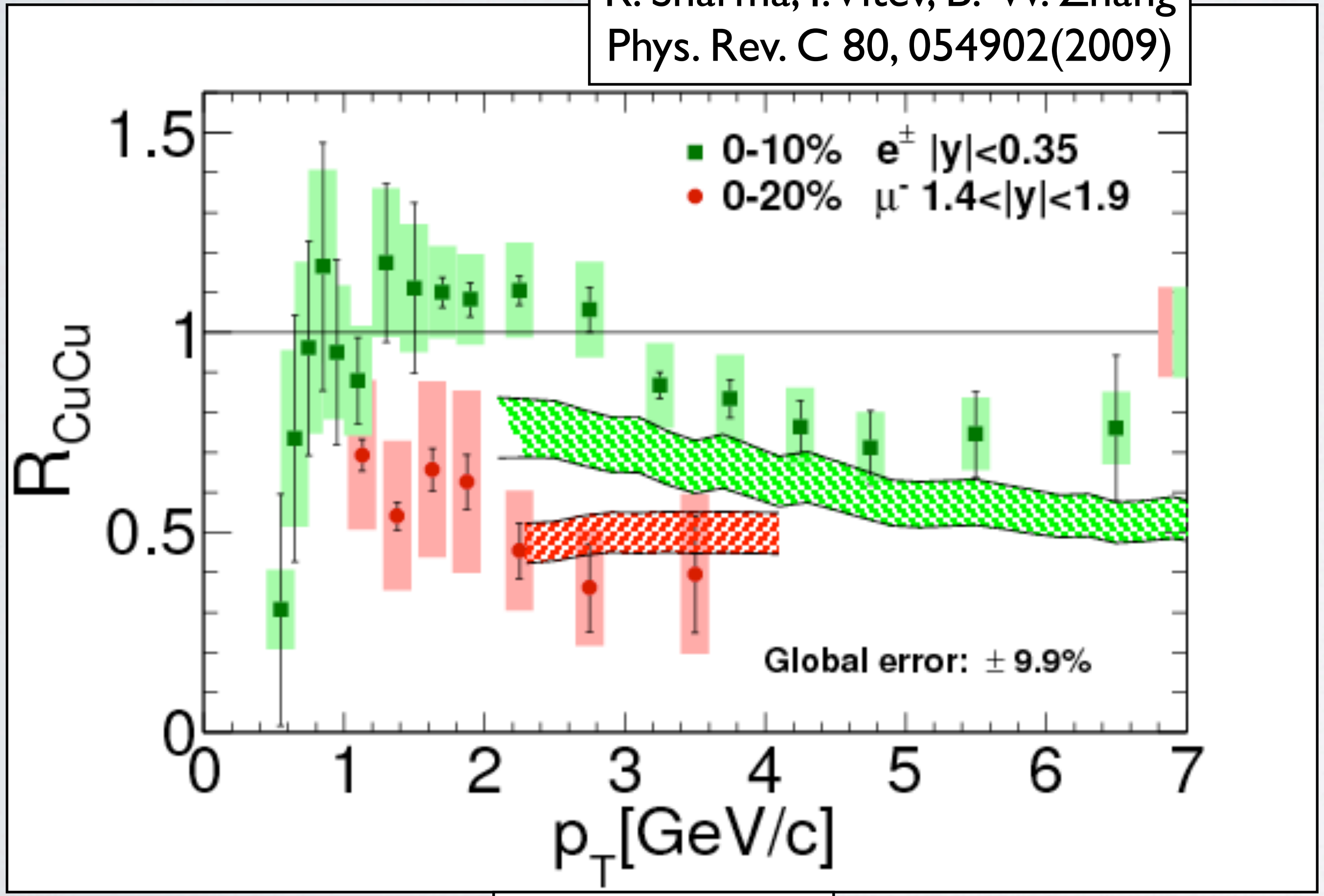


Phys. Rev. Lett. 100, 242301 (2012)

- In central Cu+Cu collisions
  - **small suppression** at mid-rapidity → **CNM & HNM are competing**
  - whereas, **large suppression** at forward rapidity

Theoretical prediction:
R. Sharma, I. Vitev, B.-W. Zhang
Phys. Rev. C 80, 054902(2009)



arXiv:1310.8286

Review of heavy-quark results

- In central Cu+Cu collisions
  - **small suppression** at mid-rapidity → **CNM & HNM are competing**
  - whereas, **large suppression** at forward rapidity
  - similar level of suppressions in **central Cu+Cu at forward** and in **central Au+Au at mid-rapidity** →**large CNM effects at forward?**

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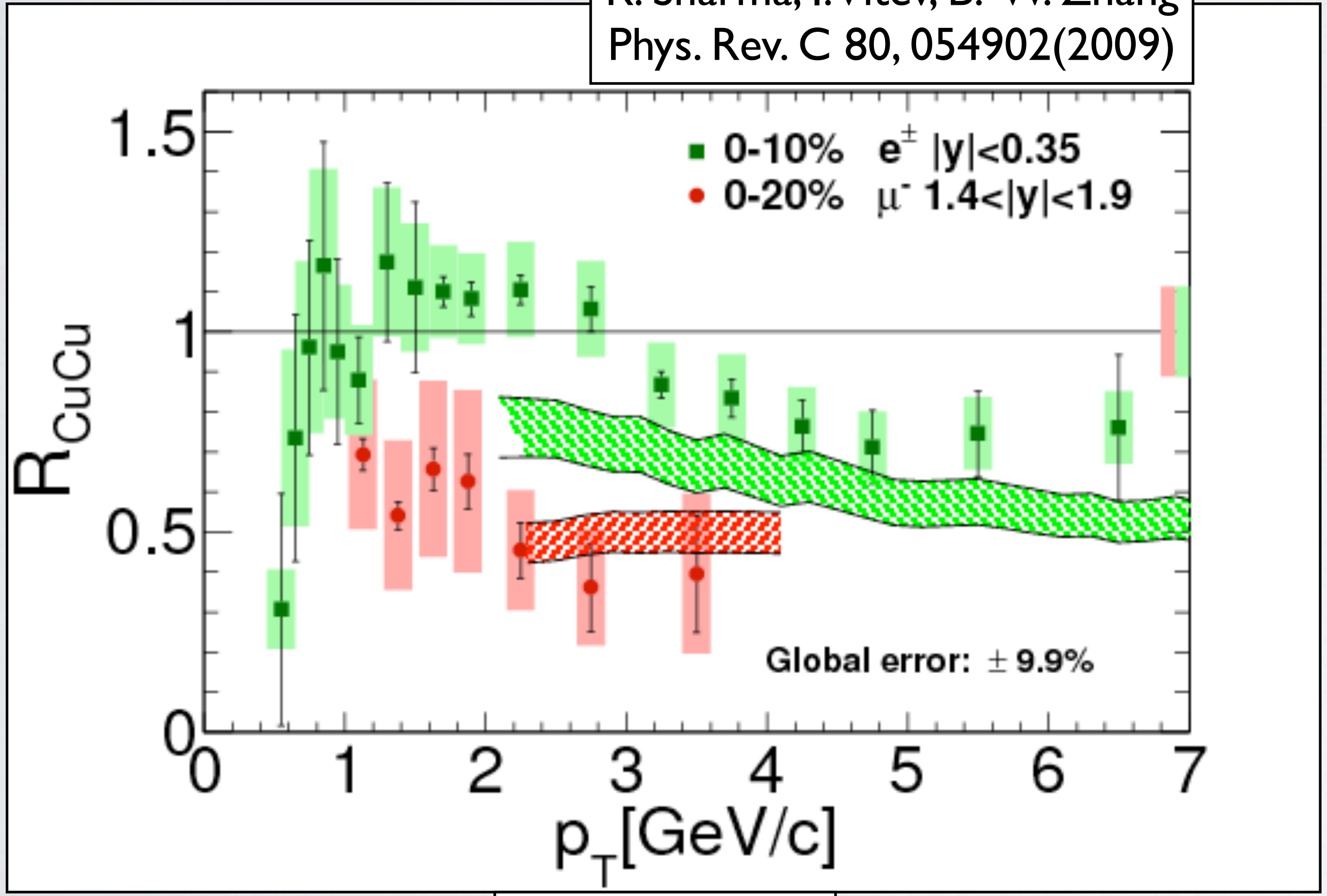
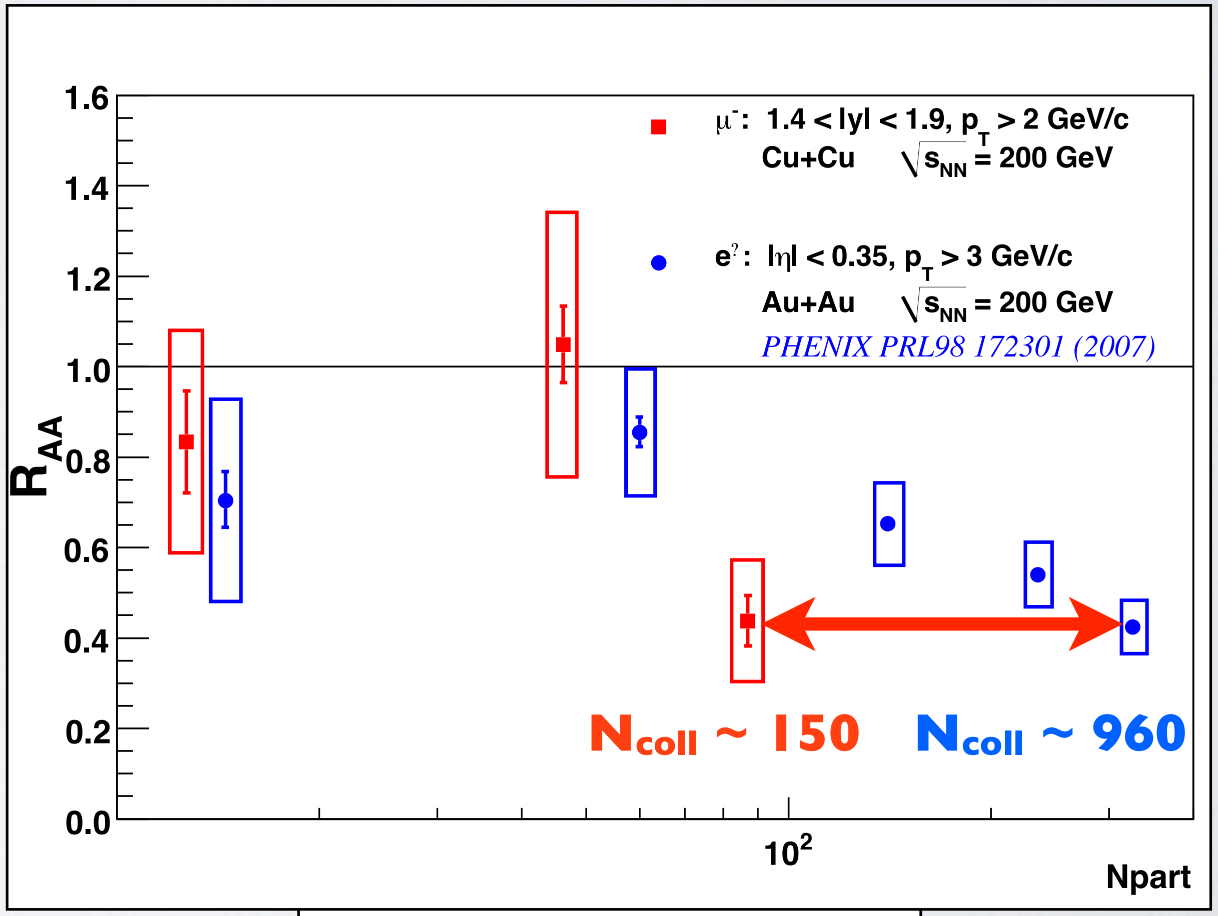


arXiv:1310.8286



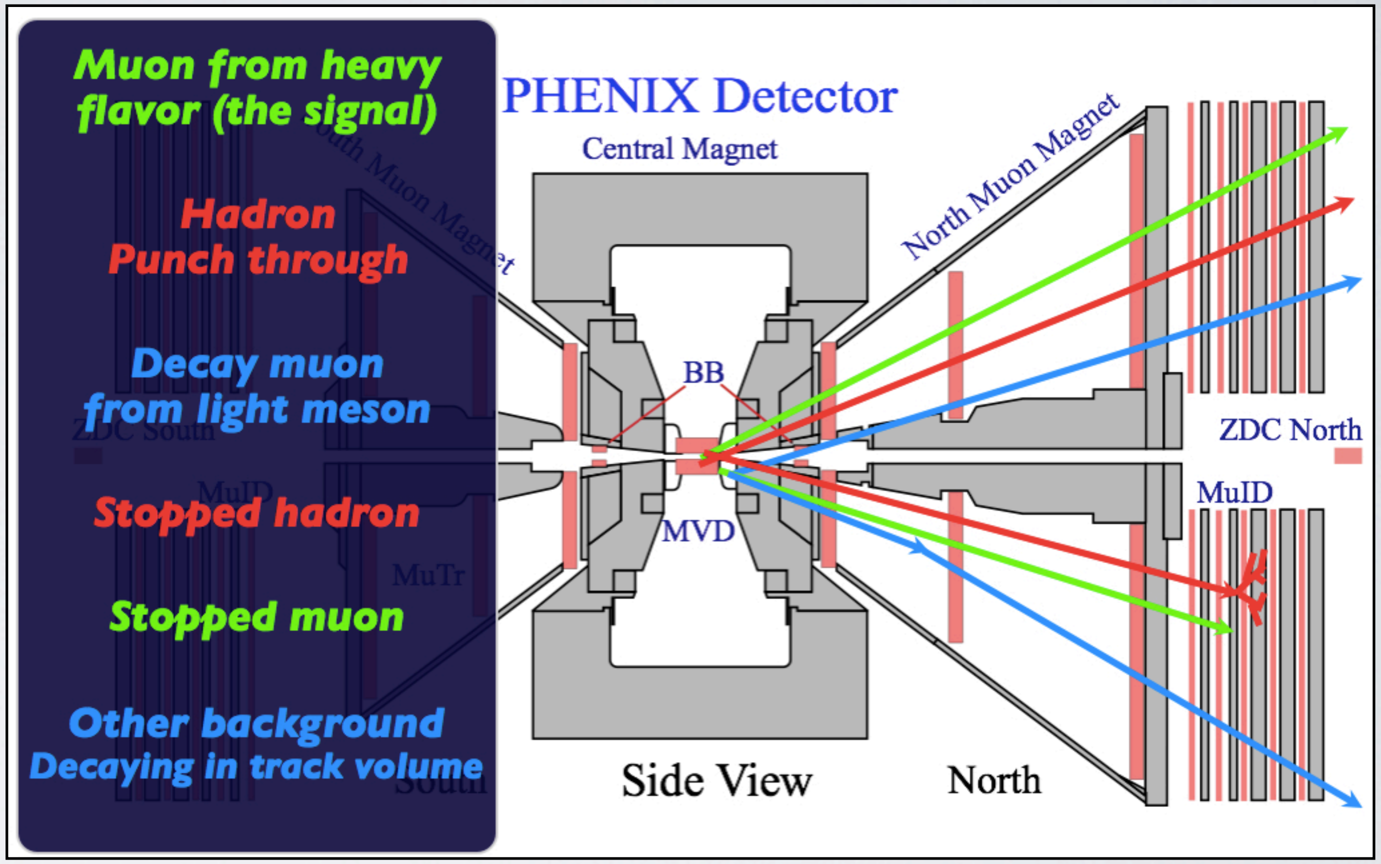
Phys. Rev. C 86, 024909 (2012)

Single muon analysis

Heavy-flavor muon analysis

- kinematic range
  - $1.2 < |\eta| < 2.2$ at forward
  - $\Delta\phi = 2\pi$

- Absorber to reject hadrons
- Muon Tracker for momentum
- Muon identifier for hadron/muon separation



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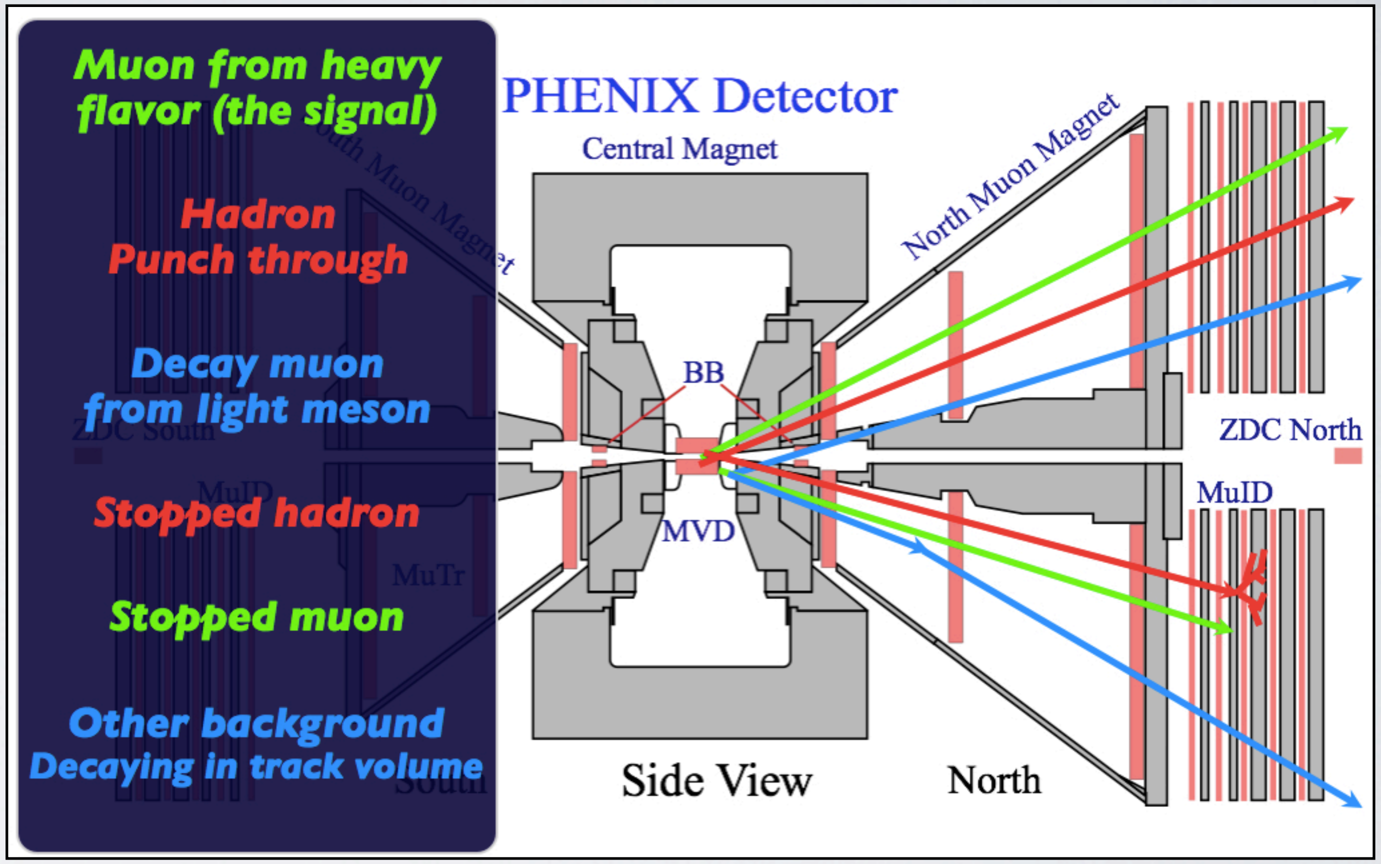
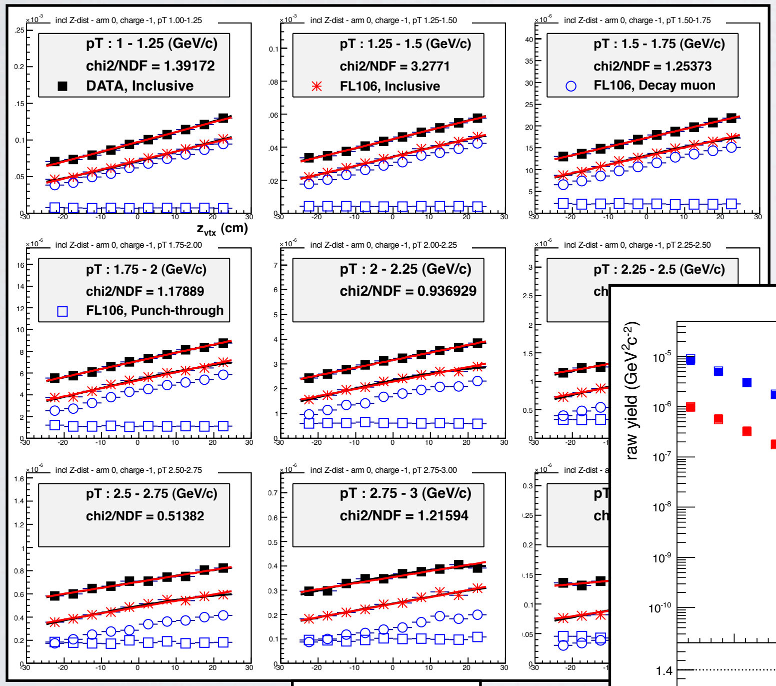
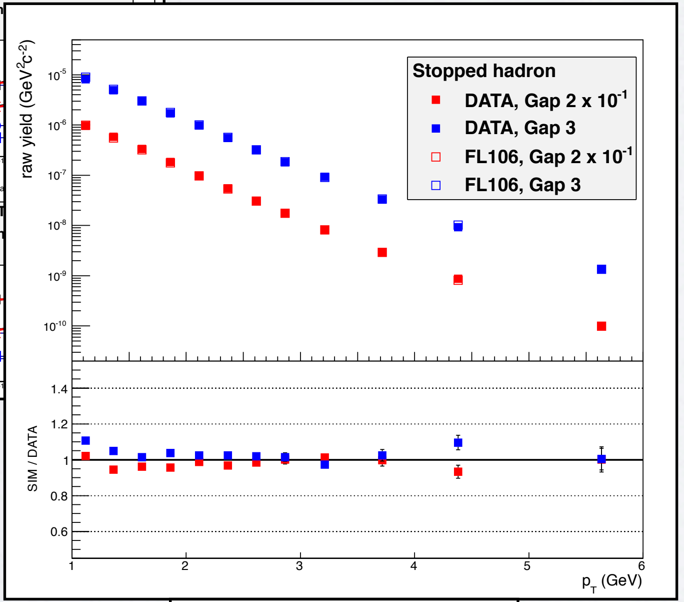




Gap-4

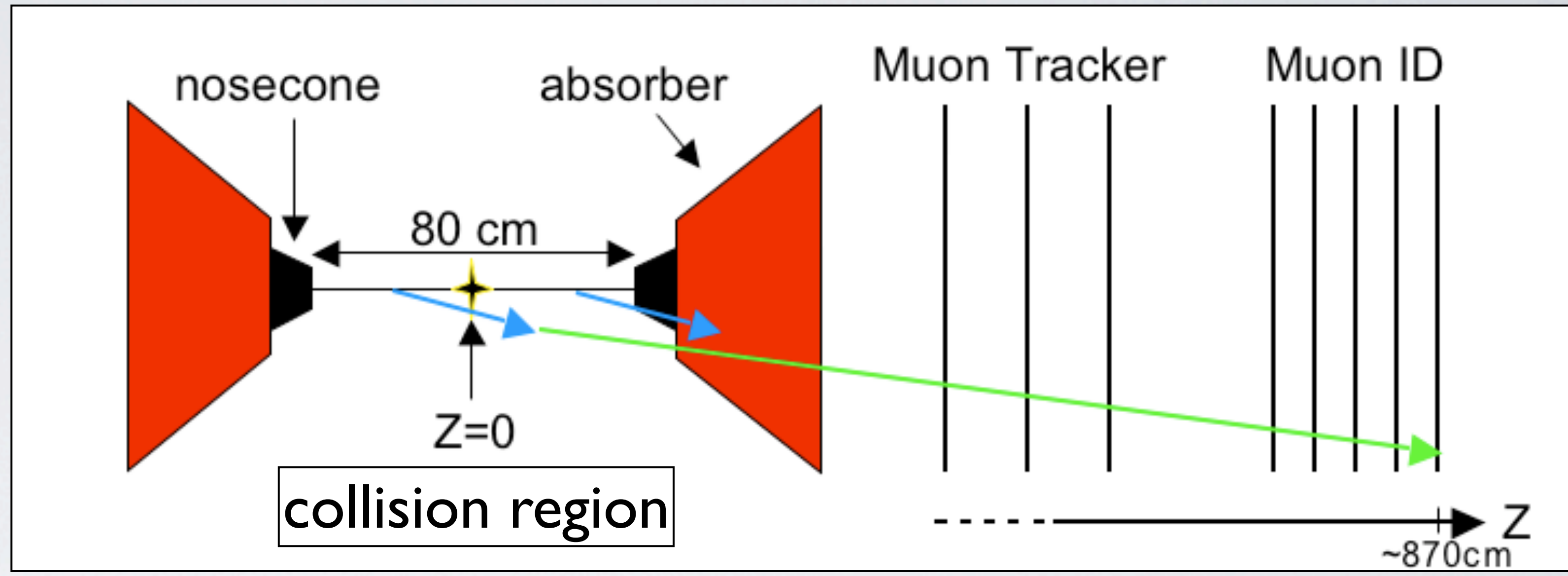


Gap-2 and 3

- Main background sources are **decay muons** from light hadrons and **punch-through hadrons**
  - Full MC simulation of hadron cocktail (π, K, p)
  - Tune MC to data
    ➔ normalized z-vertex slopes at MuID Gap-4
    ➔ stopped hadrons at MuID Gap-2 and 3

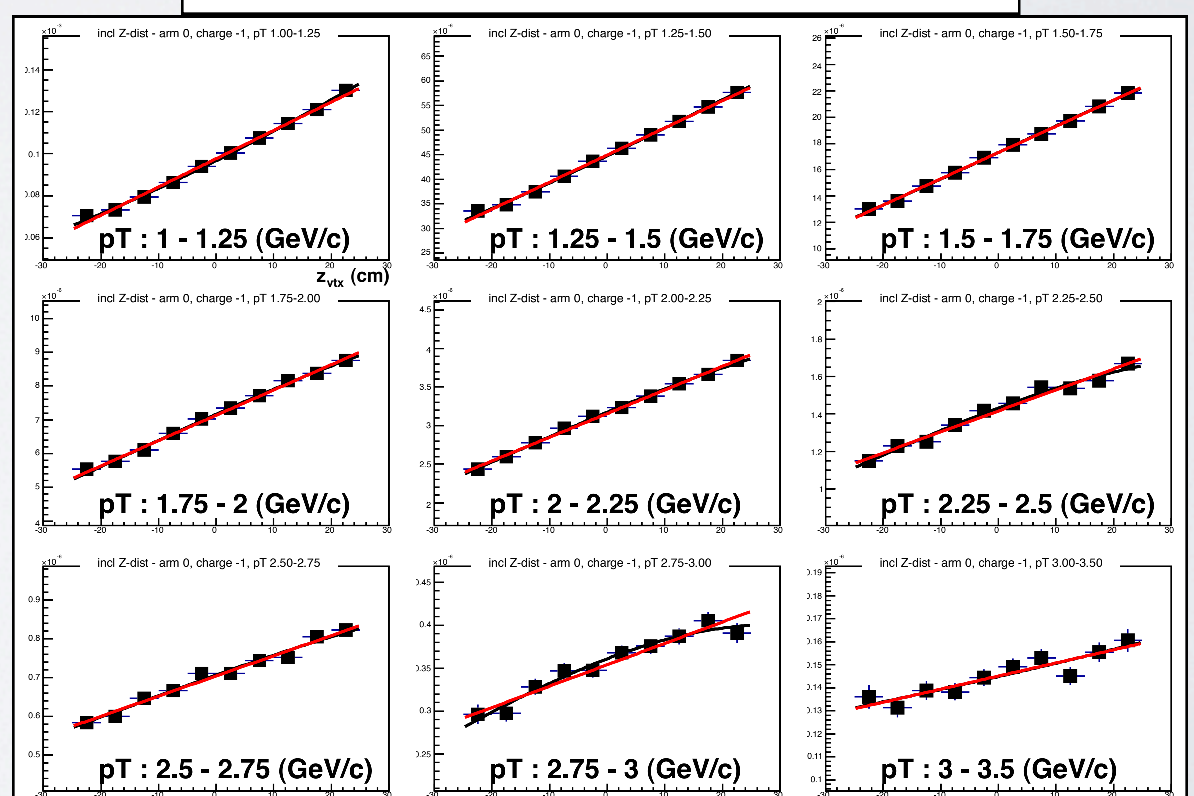
Source of tracks - Decay muon from light hadron

π's : $c\tau$ = 780 cm
K's : $c\tau$ = 371 cm



muons from hadronic decay exhibit a characteristic linear vertex dependence.

Normalized vertex distribution

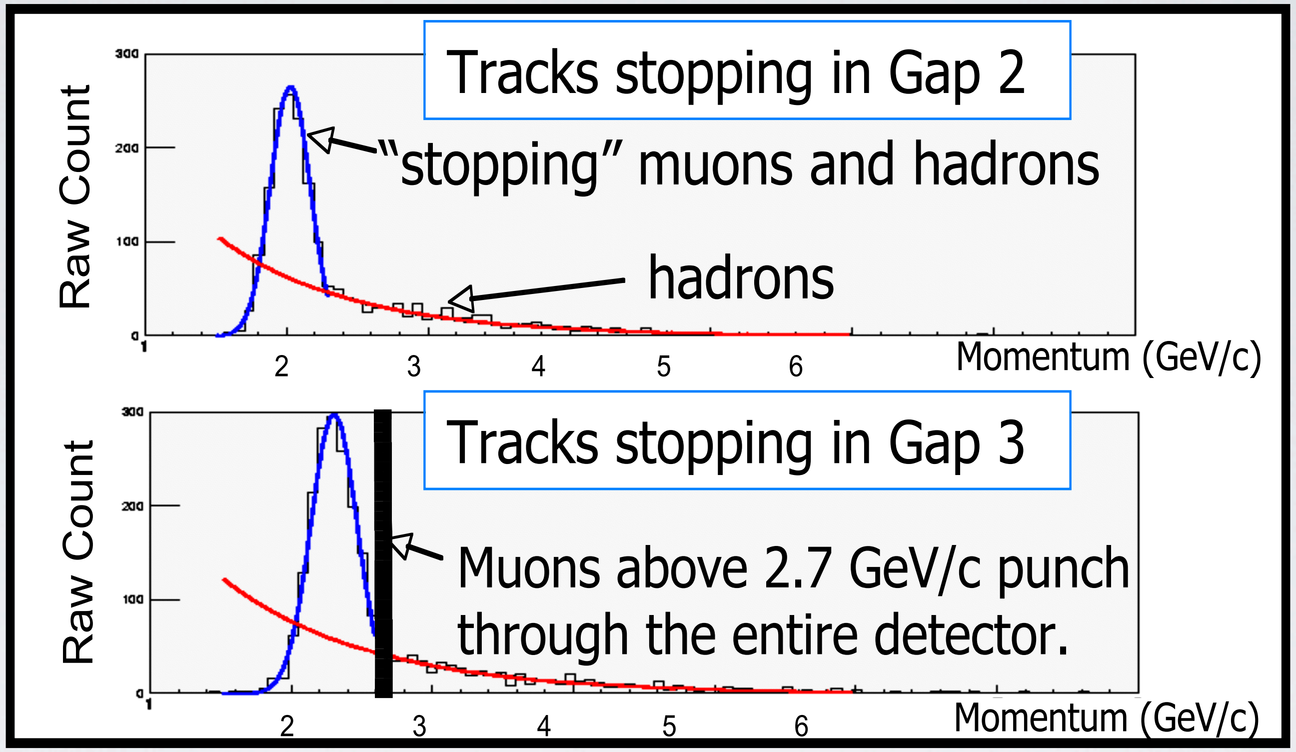


probability of the hadron decay

$$P(\Delta z) = 1 - e^{-\frac{\Delta z}{\gamma c \tau}} \approx \frac{\Delta z}{\gamma c \tau}$$

fit well with linear function

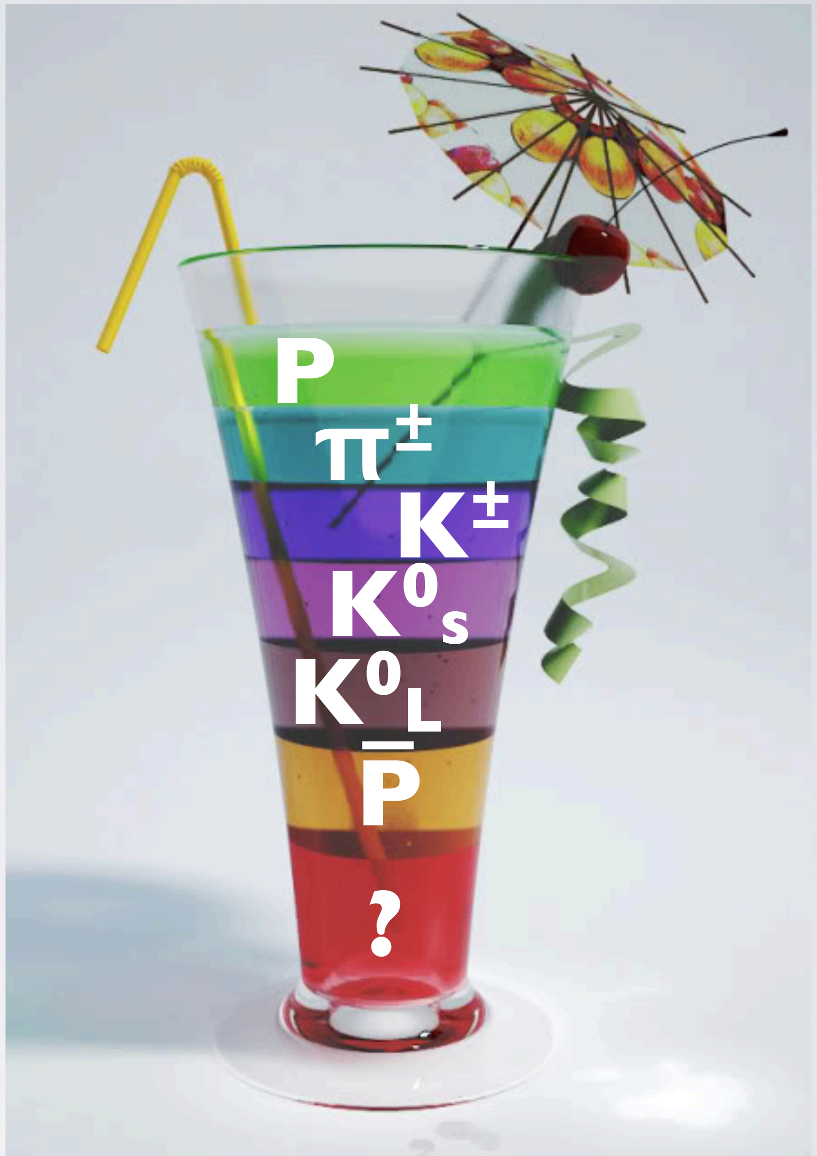
Source of tracks - Stopped & punch-through hadrons



- Stopped hadron at MuID Gap 2 and 3
  - with p_z cut, pure stopped hadrons are collected
  - hadrons at Gap 2 and Gap 3 are important components for matching simulation to data
- Punch-through hadron at MuID Gap 4
  - passing through ~10λ absorber
  - dominant background source at p_T>3 GeV/c (*w/o additional absorber installed in 2010)
  - predictable only by simulation

Background estimation method

- Hadron cocktail
  - limited hadron measurement at forward and backward region
  - estimation of light hadron(π, K, p) production
    *PYTHIA for p+p, HIJING for d+Au
    *tune with measured data at mid-rapidity
  - hadron simulation with modified hadron shower code
  - matching reconstructed cocktail to data
    *stopped hadron at Gap-2 and 3, slope at Gap 4
    *p_T dependent matching for adjustment of incomplete input p_T spectra
  - combined several hadron packages(various nuclear cross section in shower codes)
- Details in PHENIX analysis notes
  - AN1047, AN1079, AN1111



+

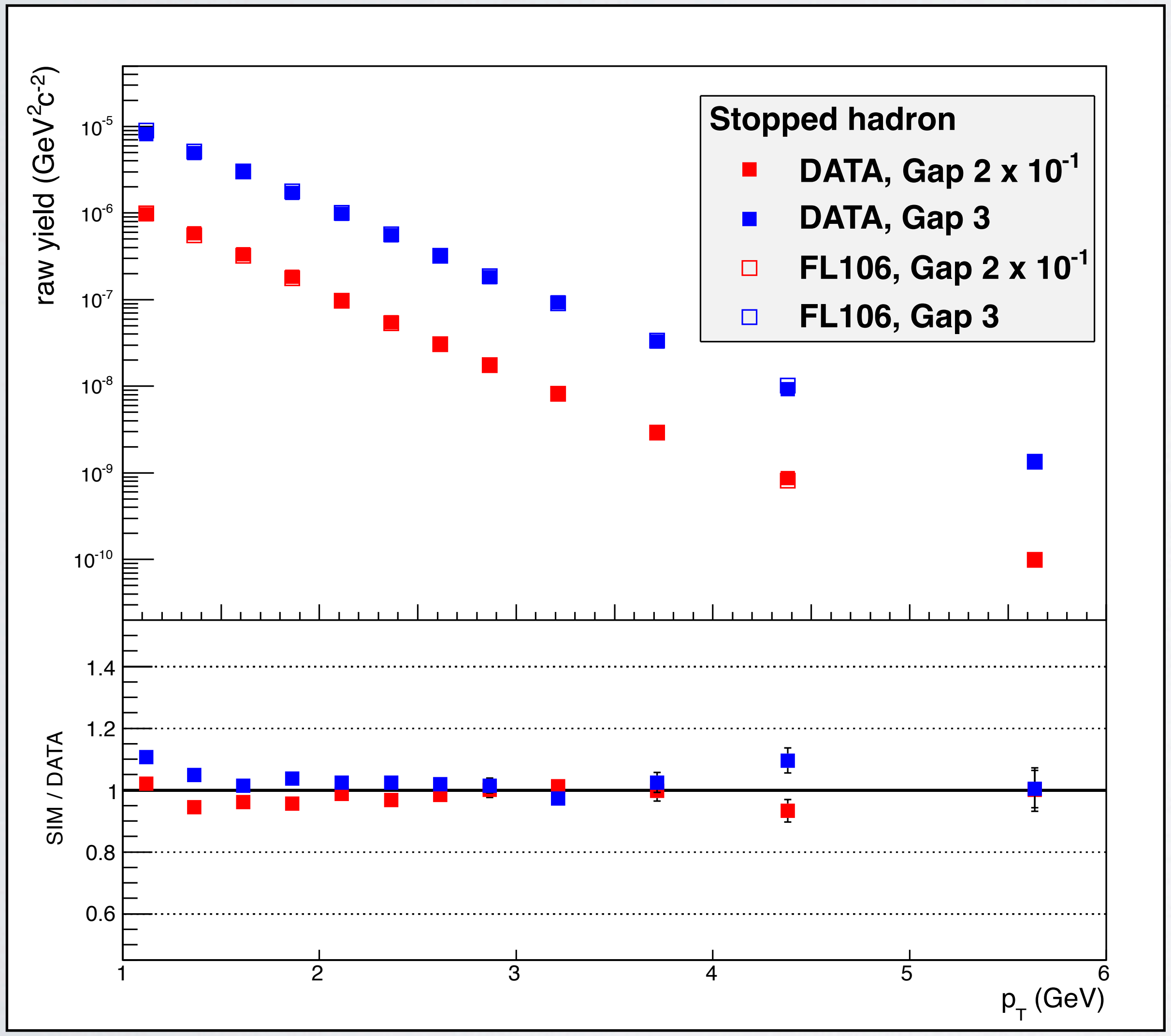
FLUKA

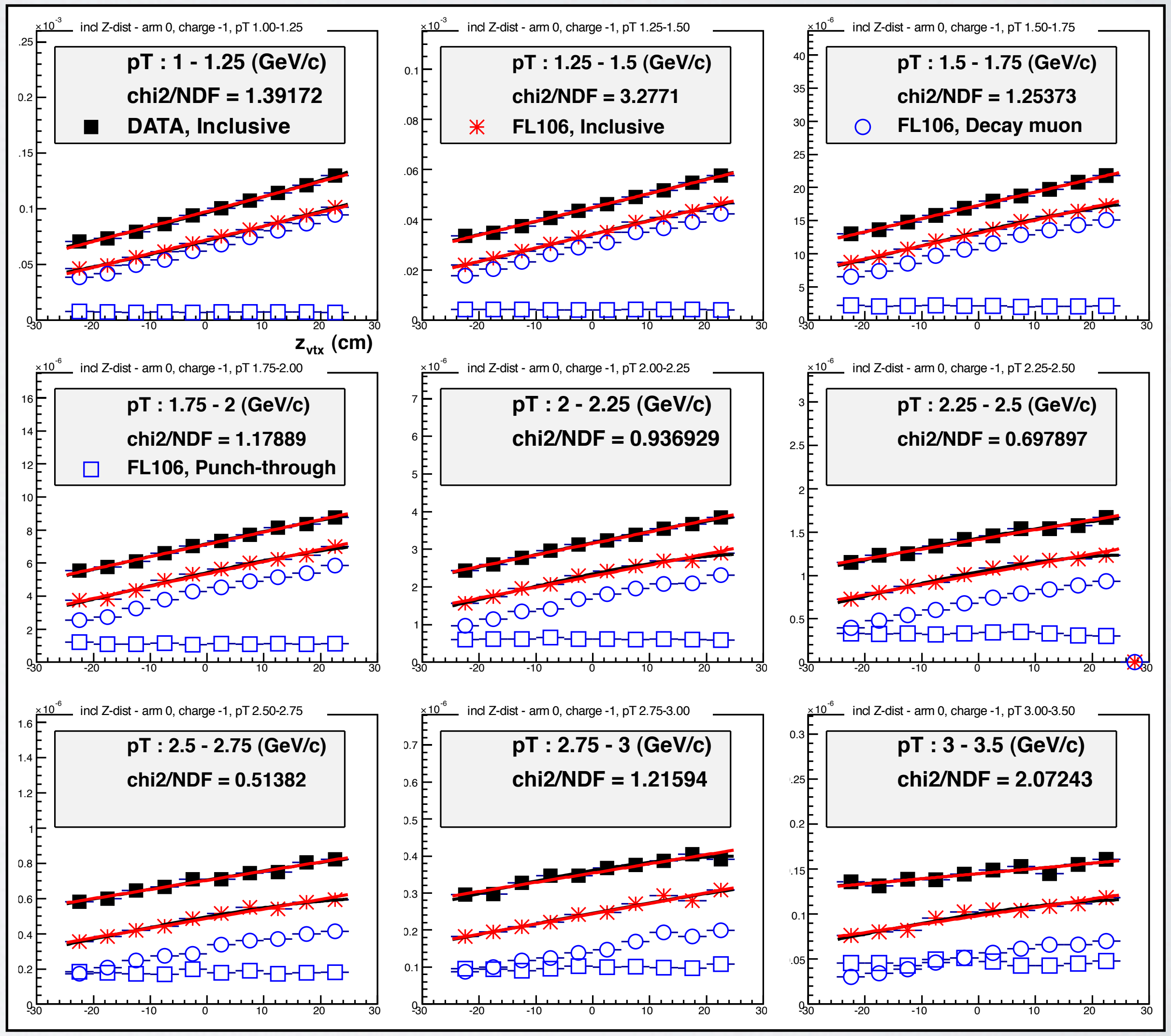
GHEISHA

Tuning the cocktail

- Tune the input hadron information by matching cocktail simulation to data at MuID Gap-2, 3 and 4
  - Qualified hadron packages which show good agreement with data at MuID gaps simultaneously have been used to background estimation

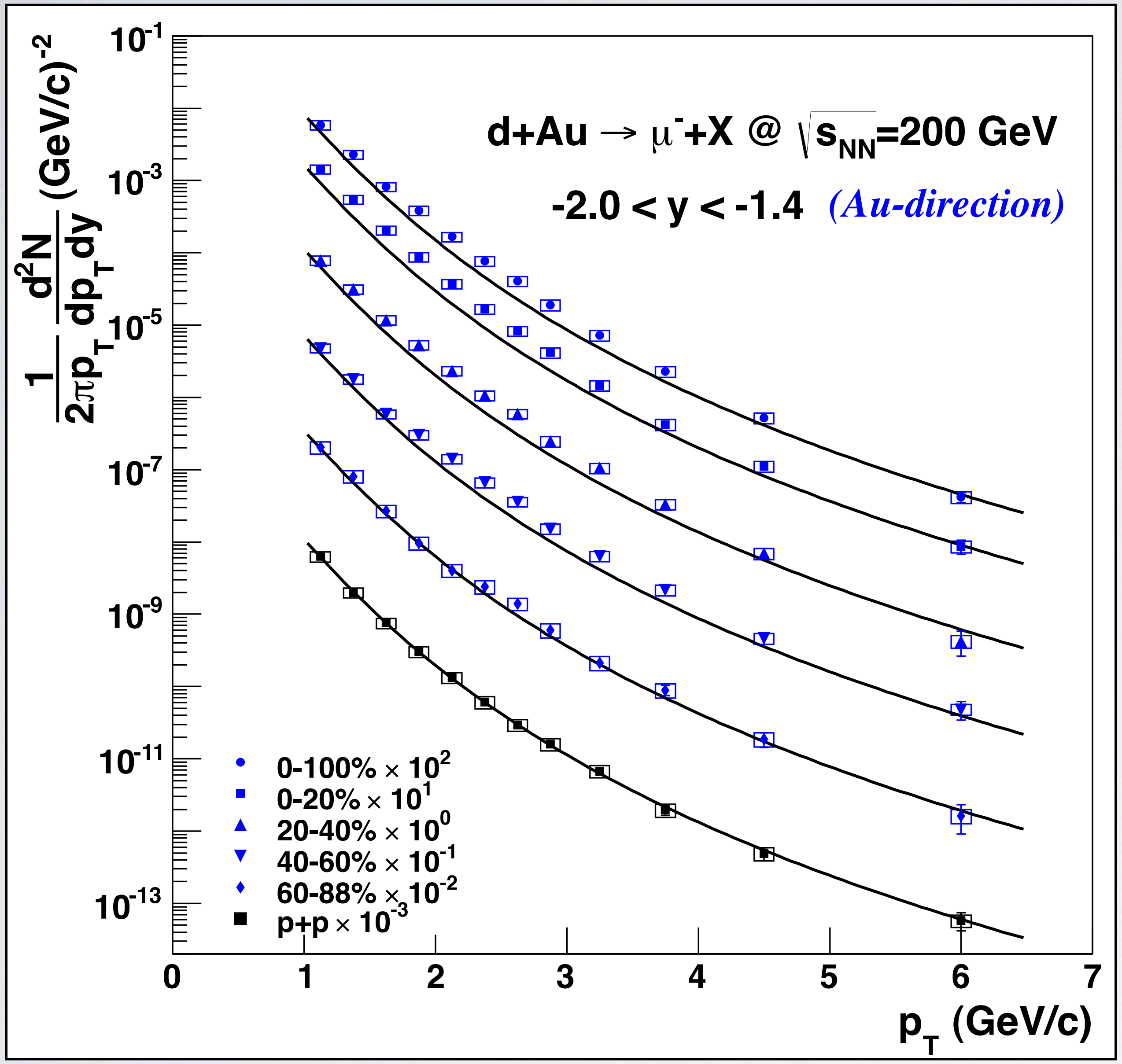
    *(package : a hadron shower code with modified nuclear cross section by a certain fraction)

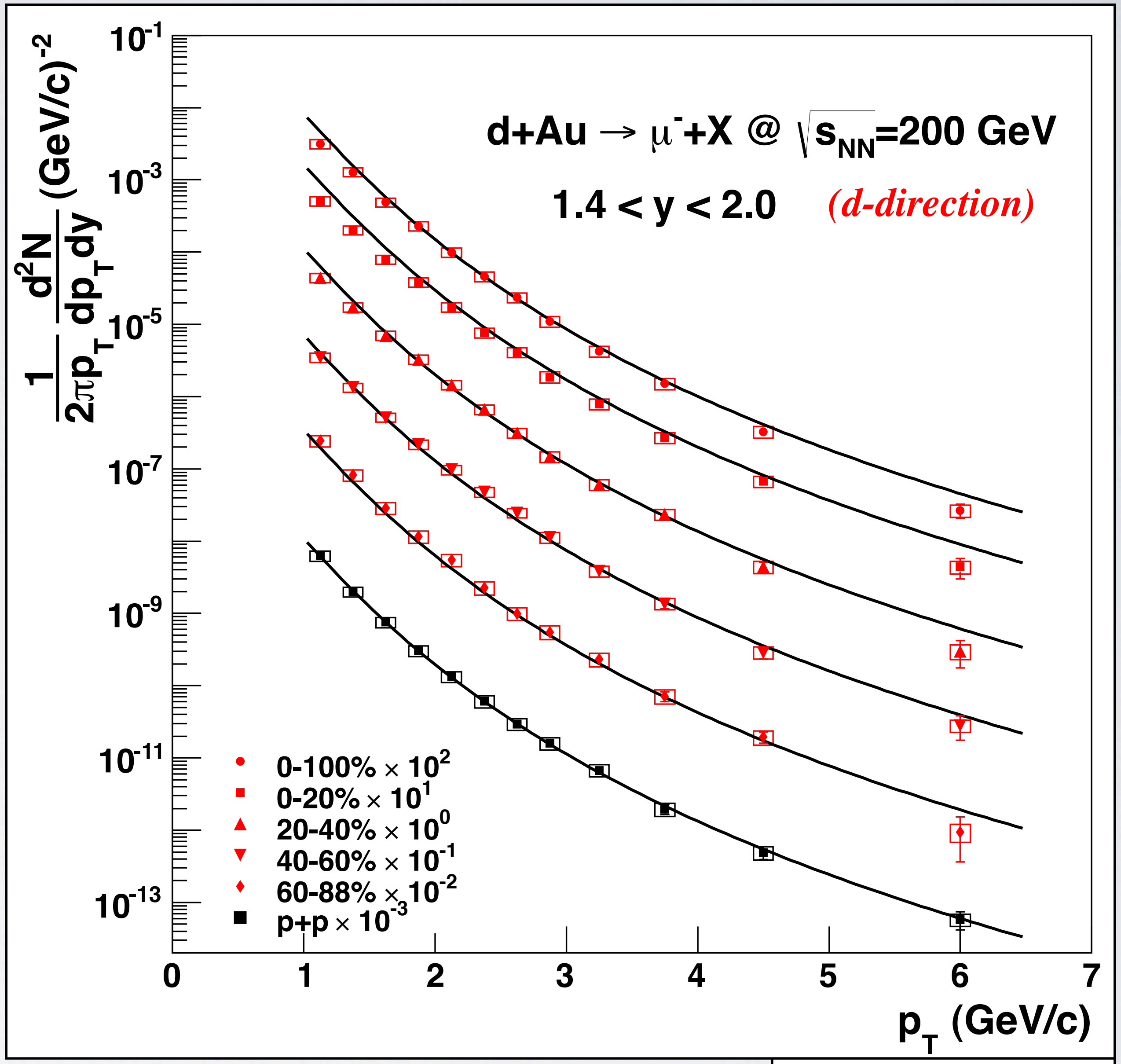




Results

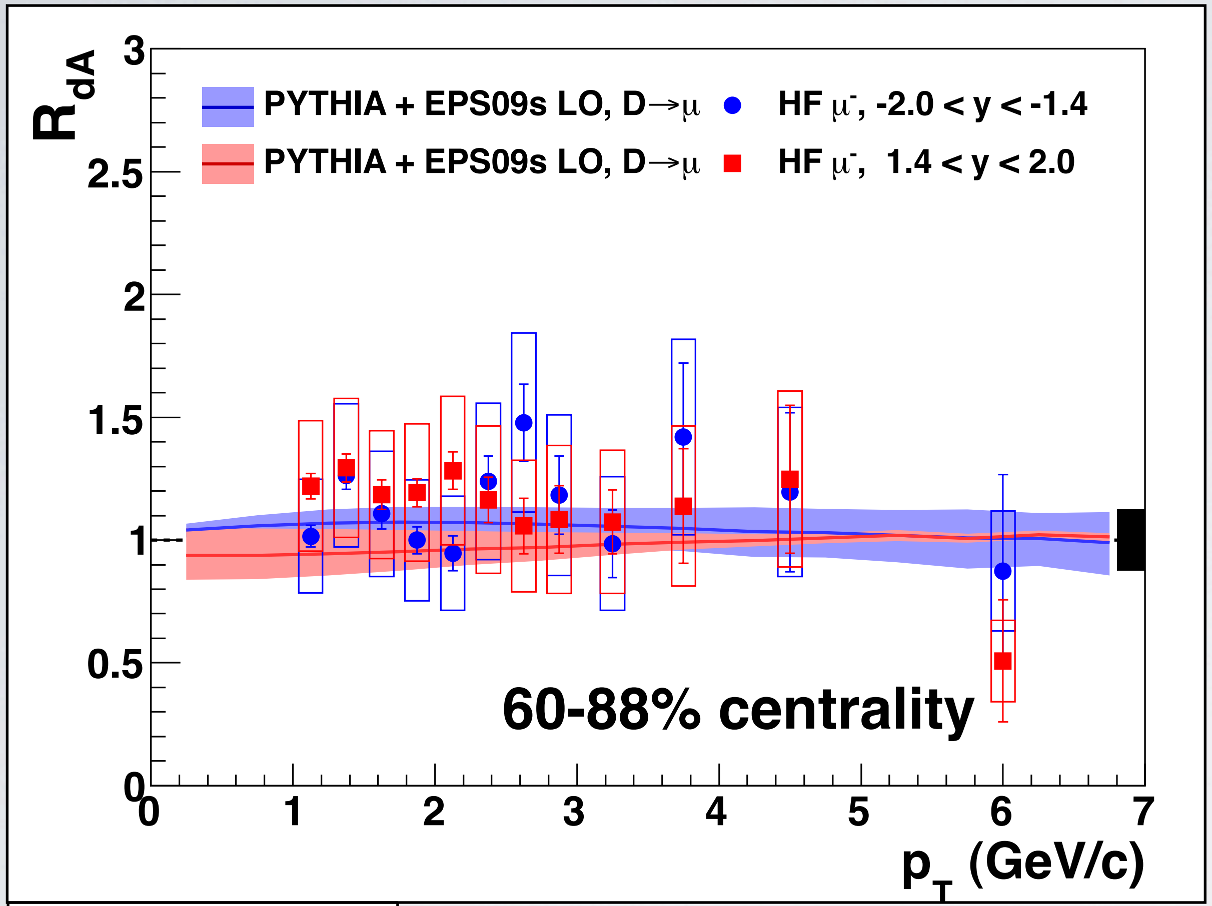
HF muon p_T spectra





arXiv:1310.1005

- Invariant yield of heavy-flavor muon in d+Au collisions at sqrt(s_{NN})=200 GeV
  - lines are scaled fit functions of the p+p results by the average number of binary collision corresponding centrality class

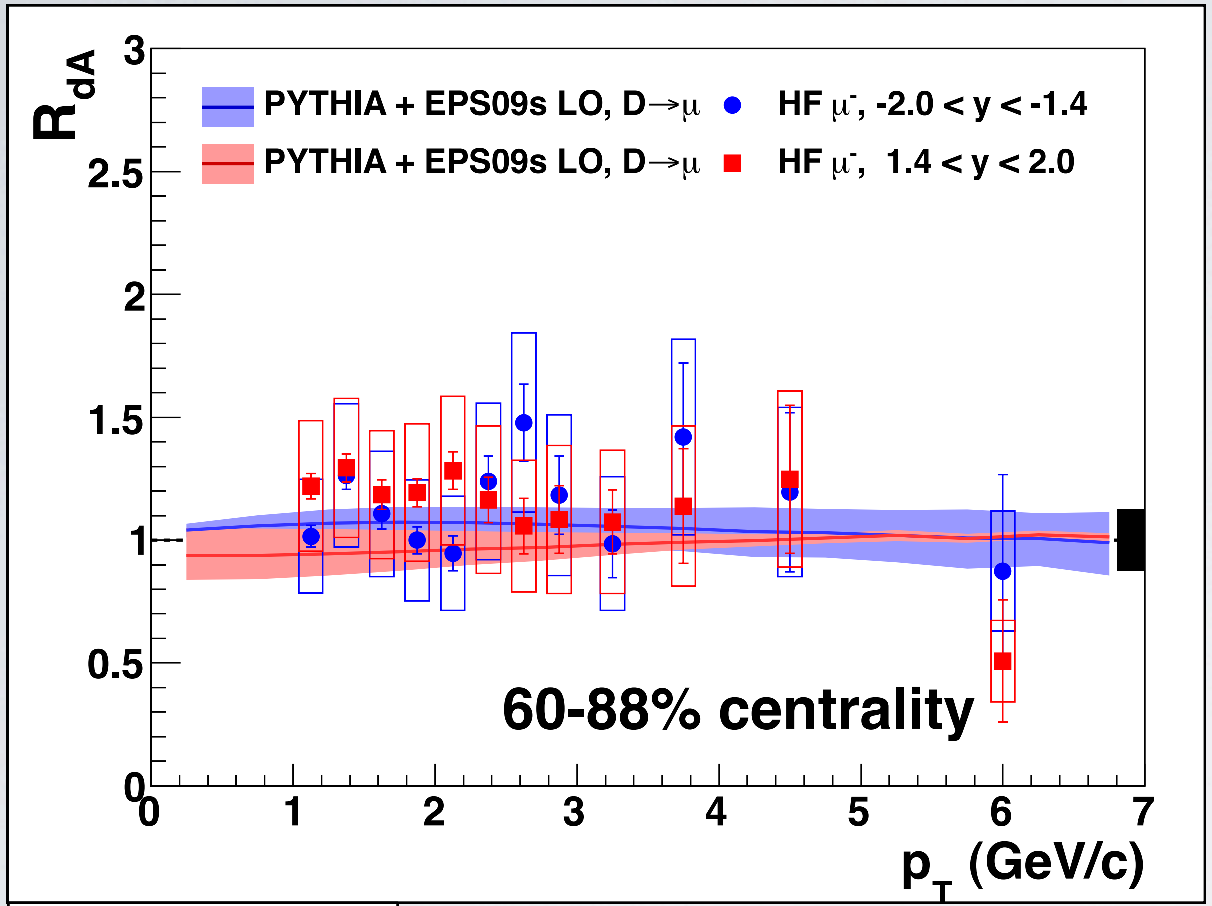


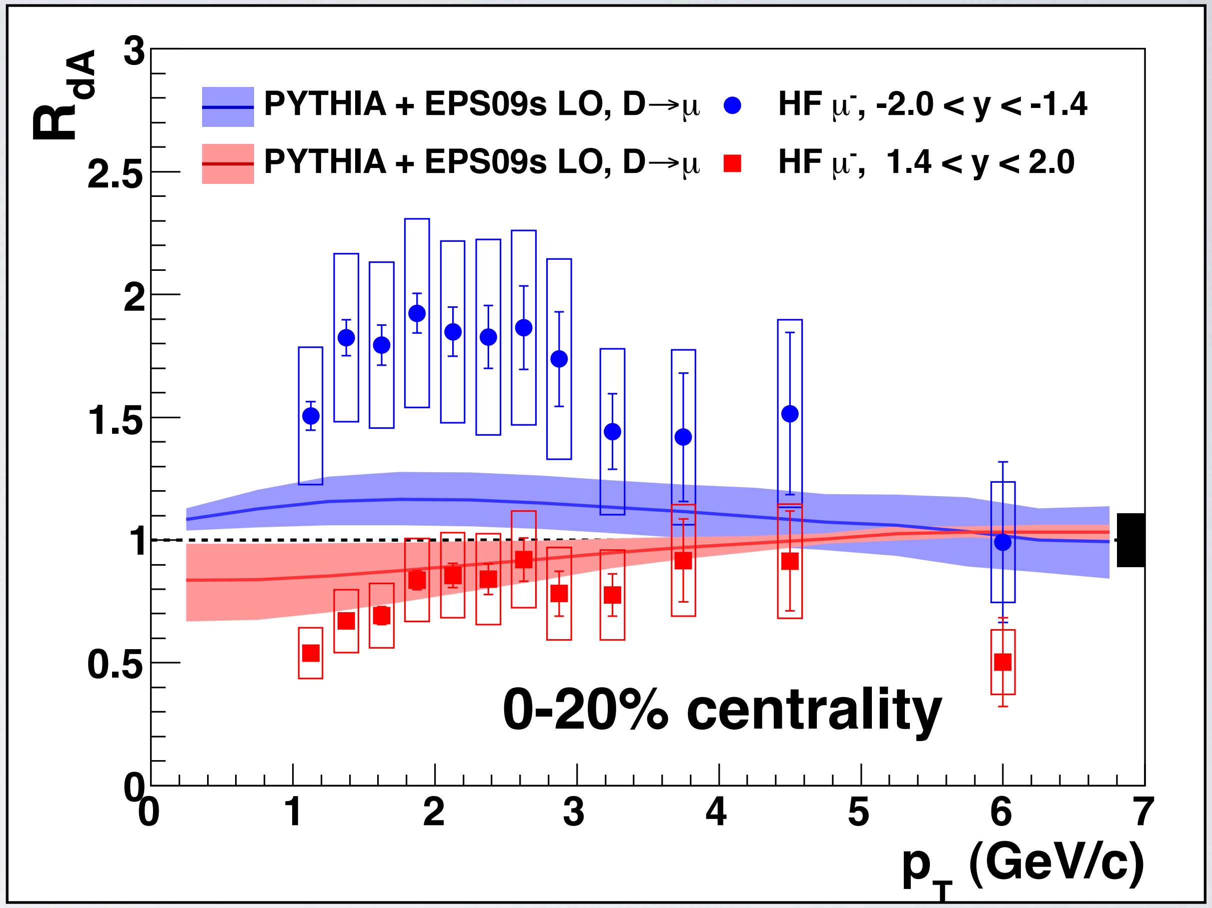
arXiv:1310.1005

- No modification at both rapidity ranges in most peripheral collisions

$$R_{dA} = \frac{dN^{\mu}_{dAu}}{\langle N_{coll} \rangle dN^{\mu}_{pp}}$$

HF muon $R_{dA}(p_T)$

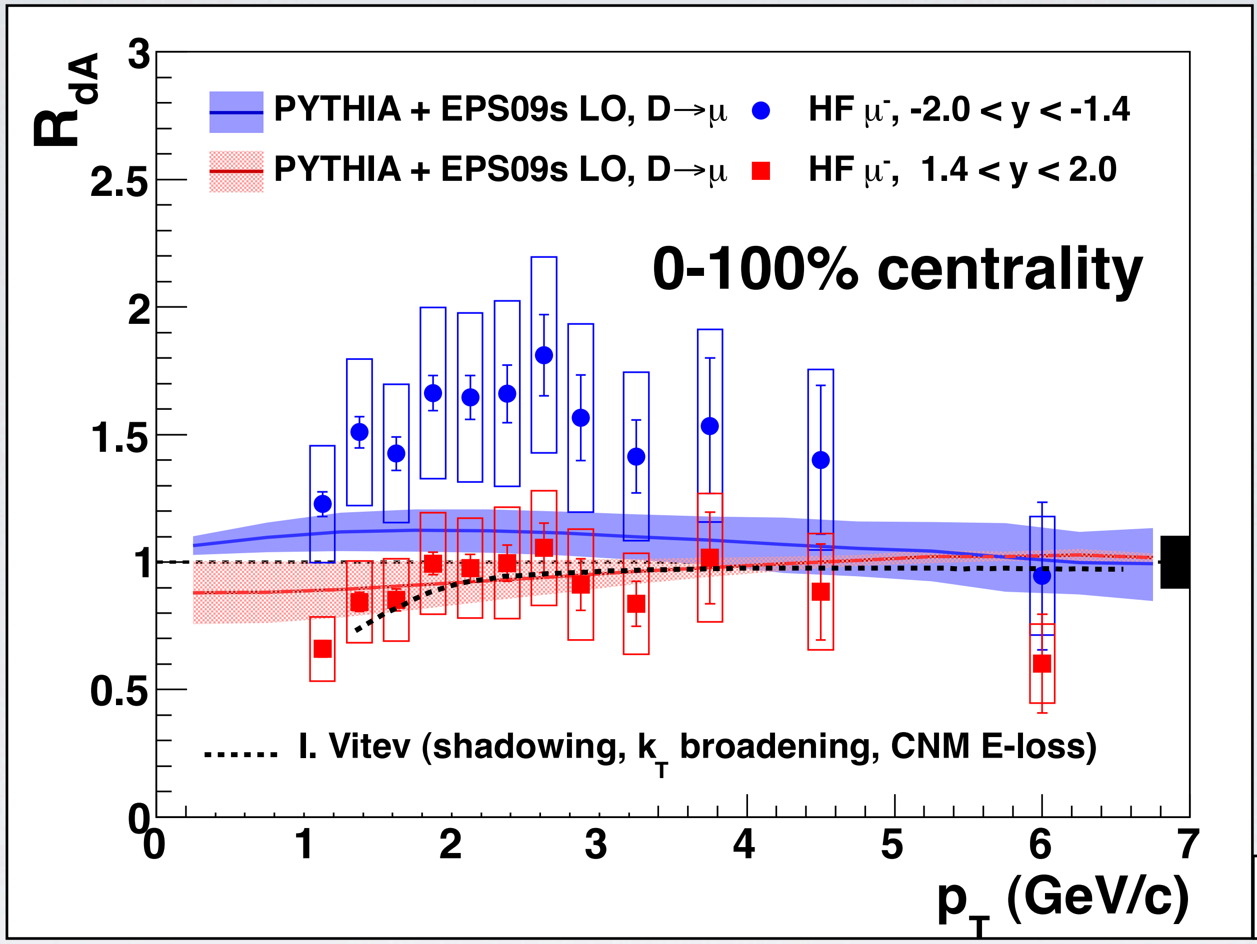




arXiv:1310.1005

- No modification at both rapidity ranges in most peripheral collisions
- **Enhancement at backward** rapidity and **suppression at forward** rapidity in most central collisions

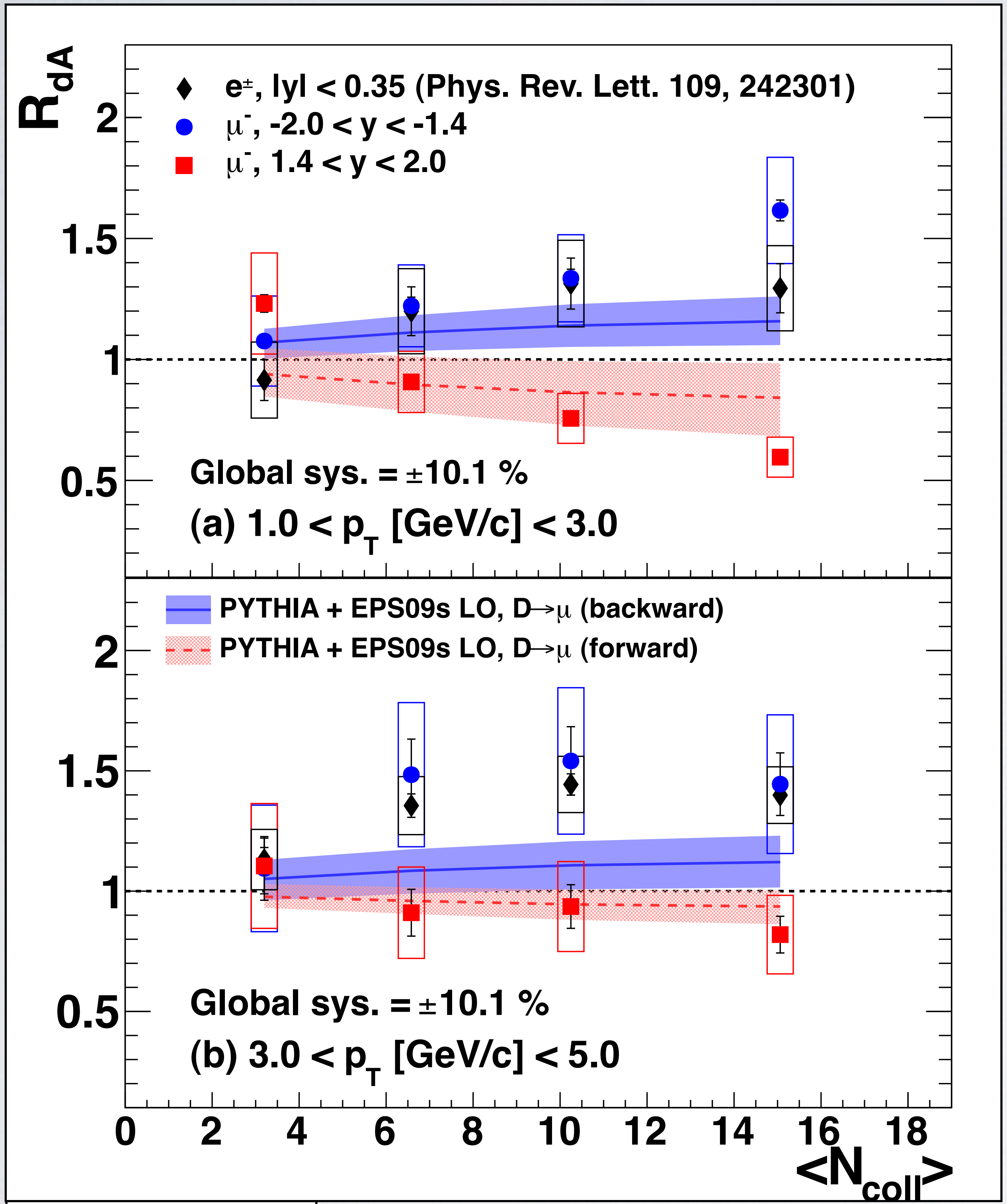
$$R_{dA} = \frac{dN^{\mu}_{dAu}}{\langle N_{coll} \rangle dN^{\mu}_{pp}}$$



arXiv:1310.1005

- pQCD calculation
  - CNM effects including shadowing, p_T broadening, and energy loss
  - good agreement with the data at forward rapidity

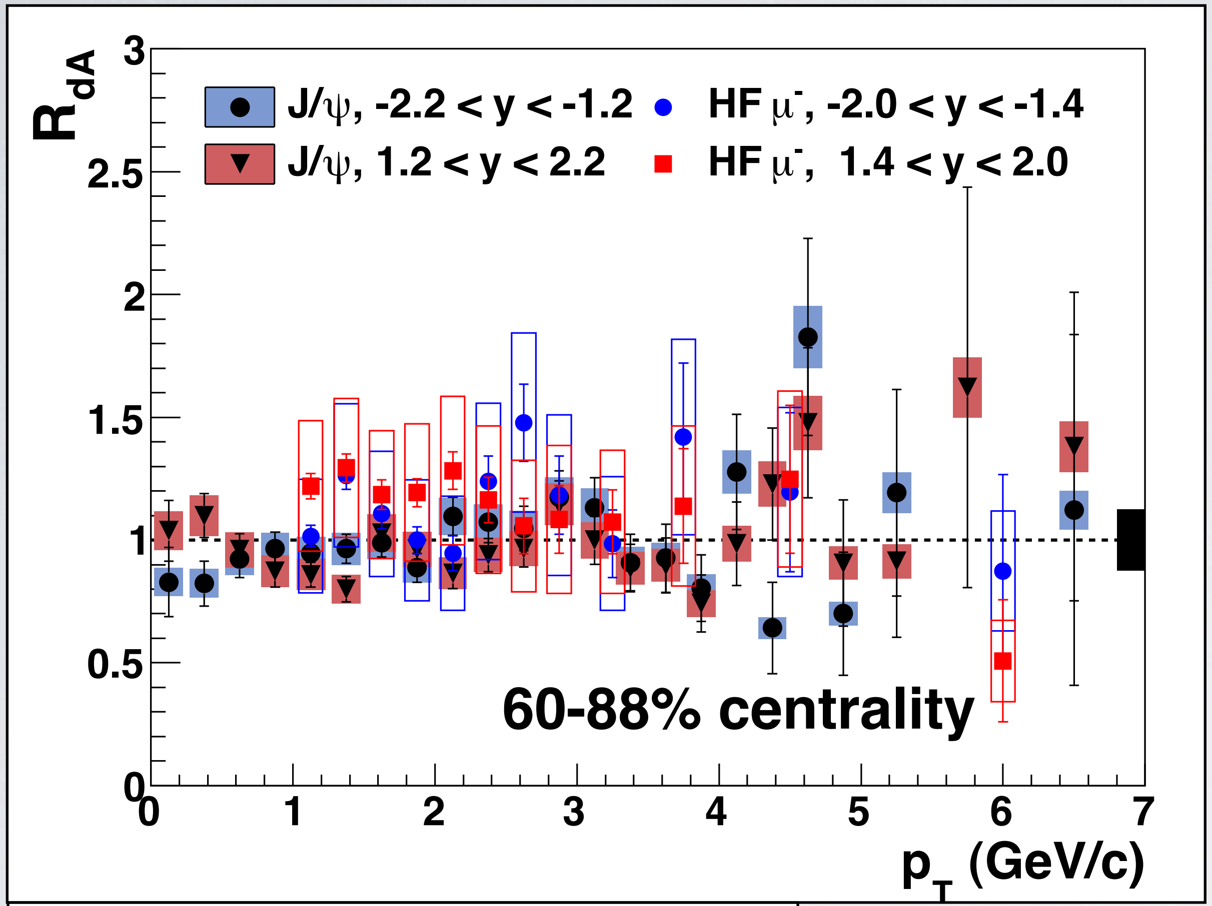
- prediction based on EPS09s (spatial dependent) nPDF set
  - calculate modification with x and Q^2 of D→μ from PYTHIA
  - well describe the data at forward rapidity
  - but fail to reproduce the results at backward rapidity



arXiv:1310.1005

- RdA as a function of $<N_{coll}>$ in two p_T ranges
  - stronger CNM effects with increasing centrality at both rapidity ranges
  - enhancement at backward rapidity is similar to that in HF electron at mid-rapidity
  - EPS09s calculation shows similar trends, but underestimate the difference between forward and backward rapidity

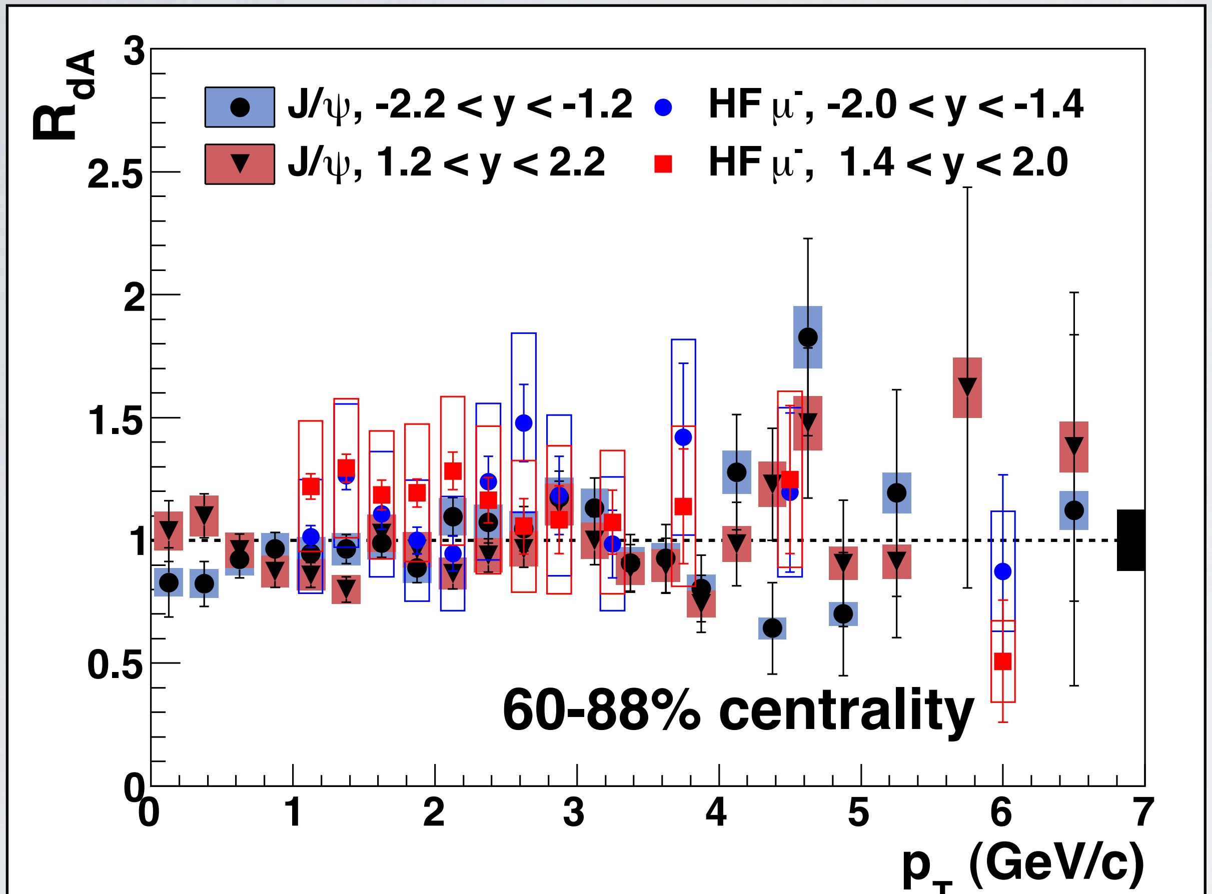
HF μ vs. J/ψ

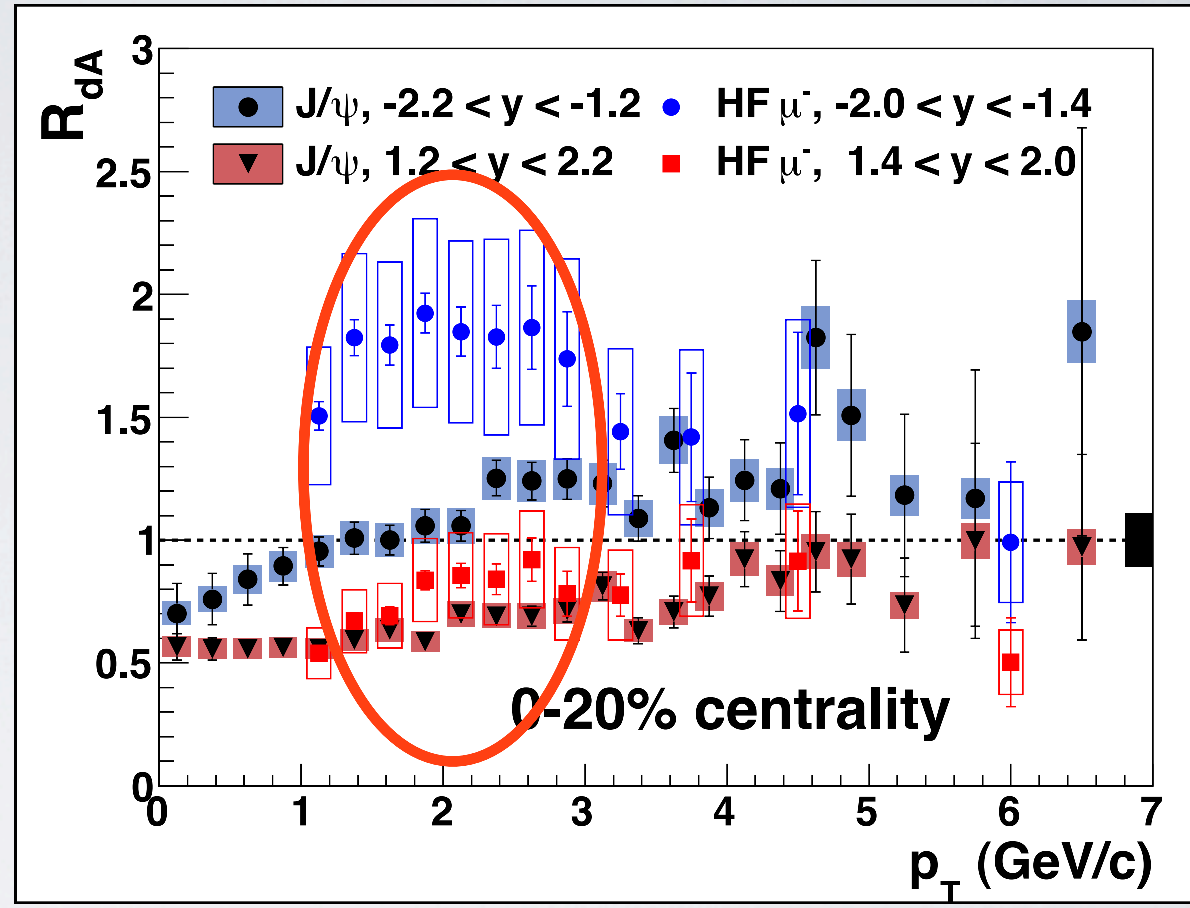


J/ψ : Phys. Rev. C 87, 034904 (2013)

- In the most peripheral collision
  - **all R_{dA} ~ 1**

HF μ vs. J/ψ





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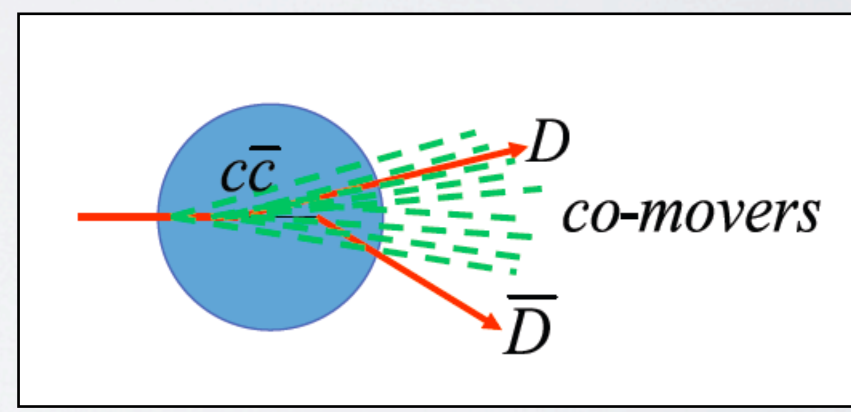


- In the most peripheral collision
  - **all R_{dA} ~ 1**
- In the most central collision
  - R_{dA} of HF muon and J/ψ are still consistent
  - However, **large difference at backward rapidity**
  - charm production is enhanced but **J/ψ is significantly absorbed due to nuclear breakup** inside dense co-movers at backward rapidity

Summary

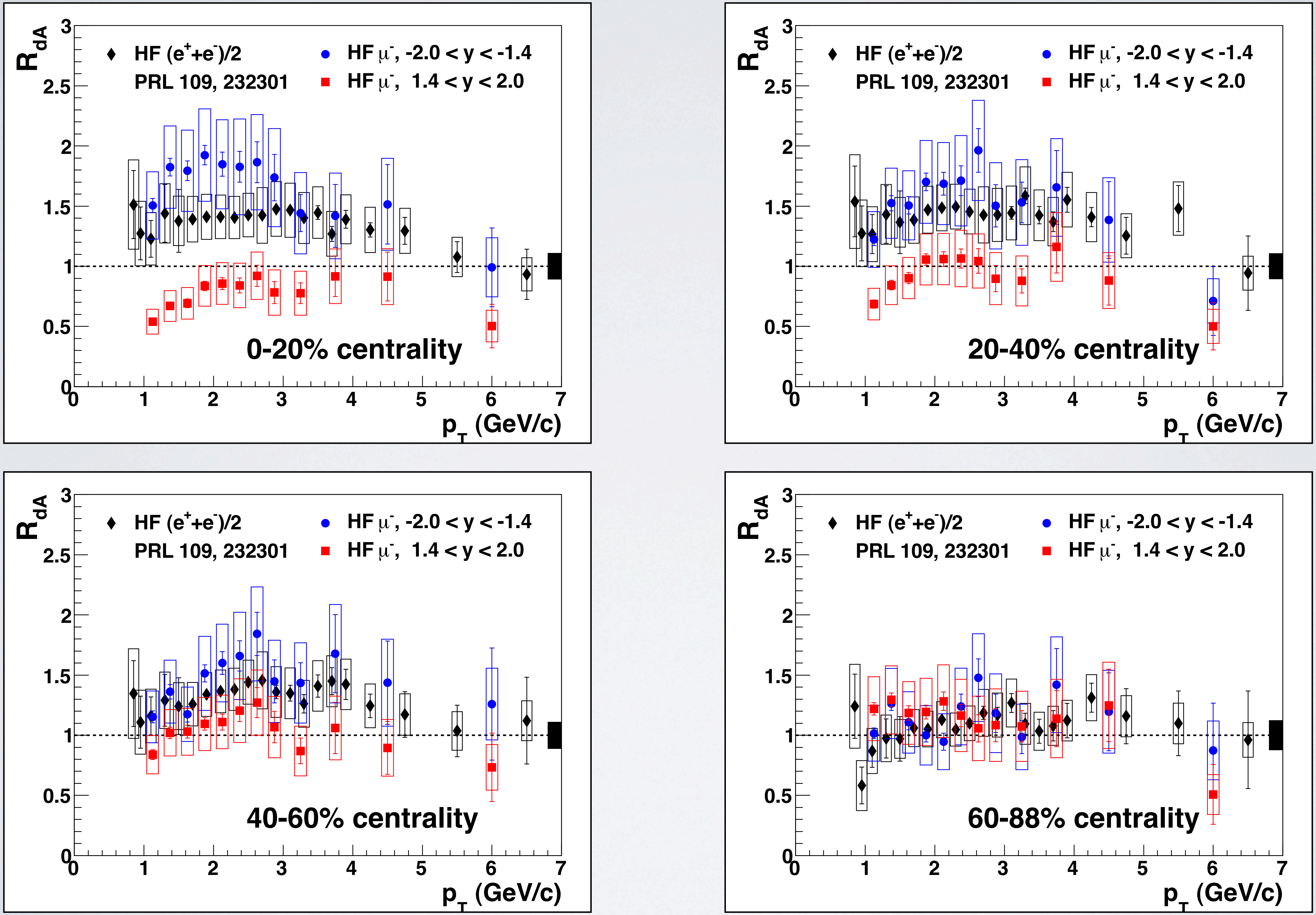
- Heavy-flavor muon production in d+Au collisions
  - **suppression at forward** rapidity
  - **enhancement at backward** rapidity
  - indicate **important role of nuclear break-up in J/ψ** production
  - pQCD calculation well reproduce the forward data
  - EPS09s nPDF prediction underestimate the difference between forward and backward rapidity
  - these results were submitted to Phys. Rev. Lett. (arXiv:1310.1005)

- Further analysis are going on
  - asymmetric heavy-ion collisions (Cu+Au)
  - low energy Au+Au collisions at 39 & 62 GeV

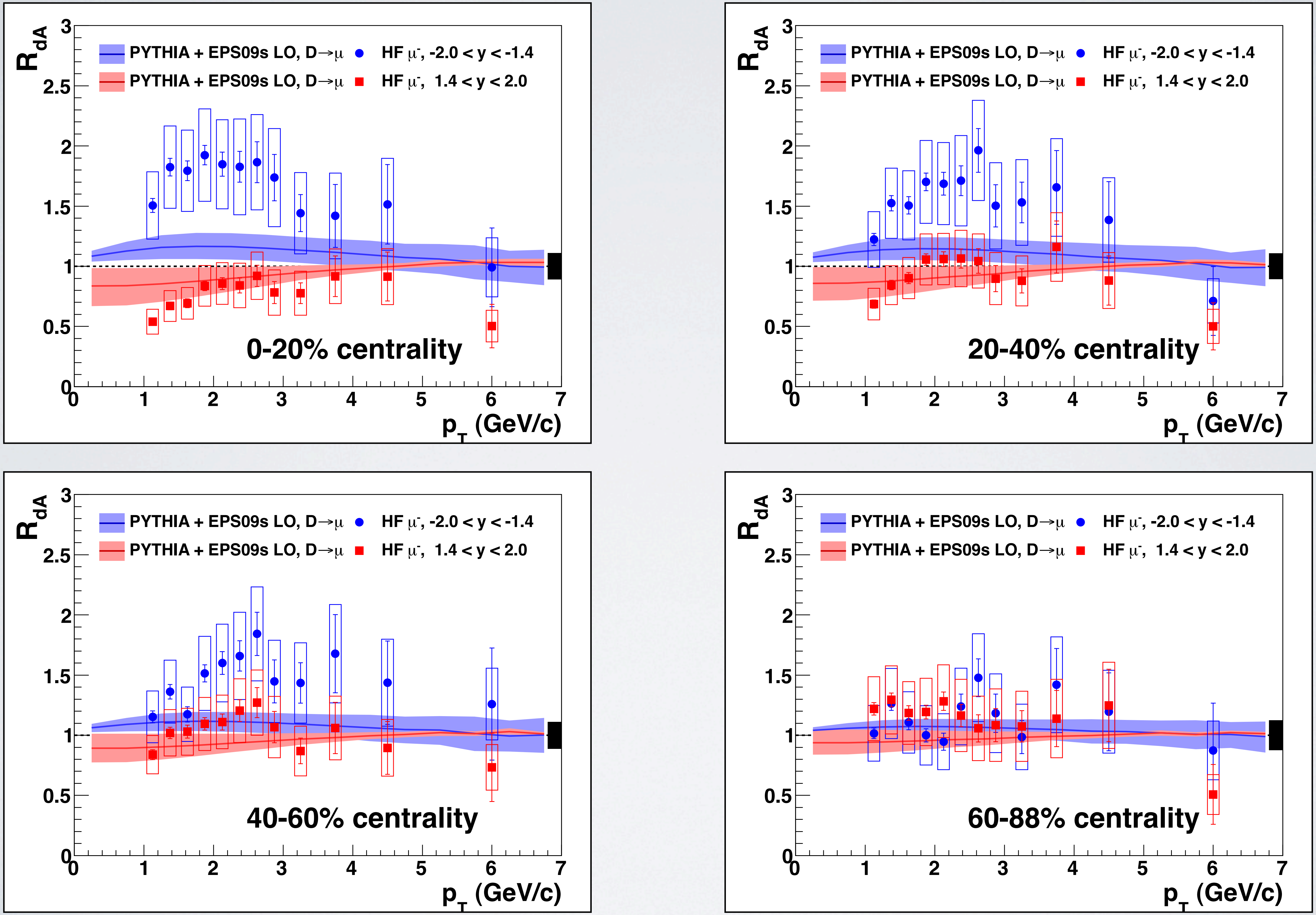
- New PHENIX inner silicon vertex tracker system (VTX & FVTX) provides precise vertex position and allows to separate charm and bottom meson.

Back up

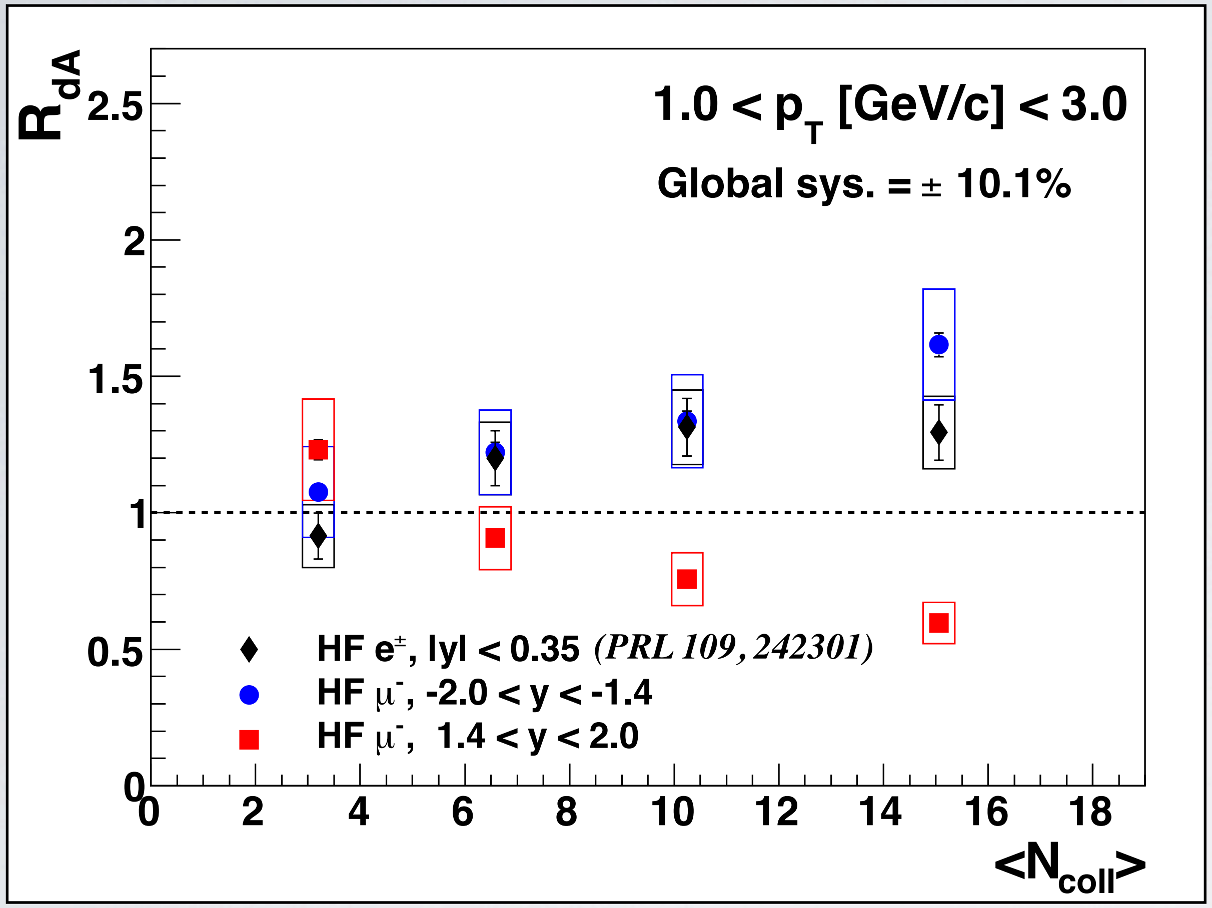
Comparison of $R_{dA}(p_T)$ with HF e at y=0

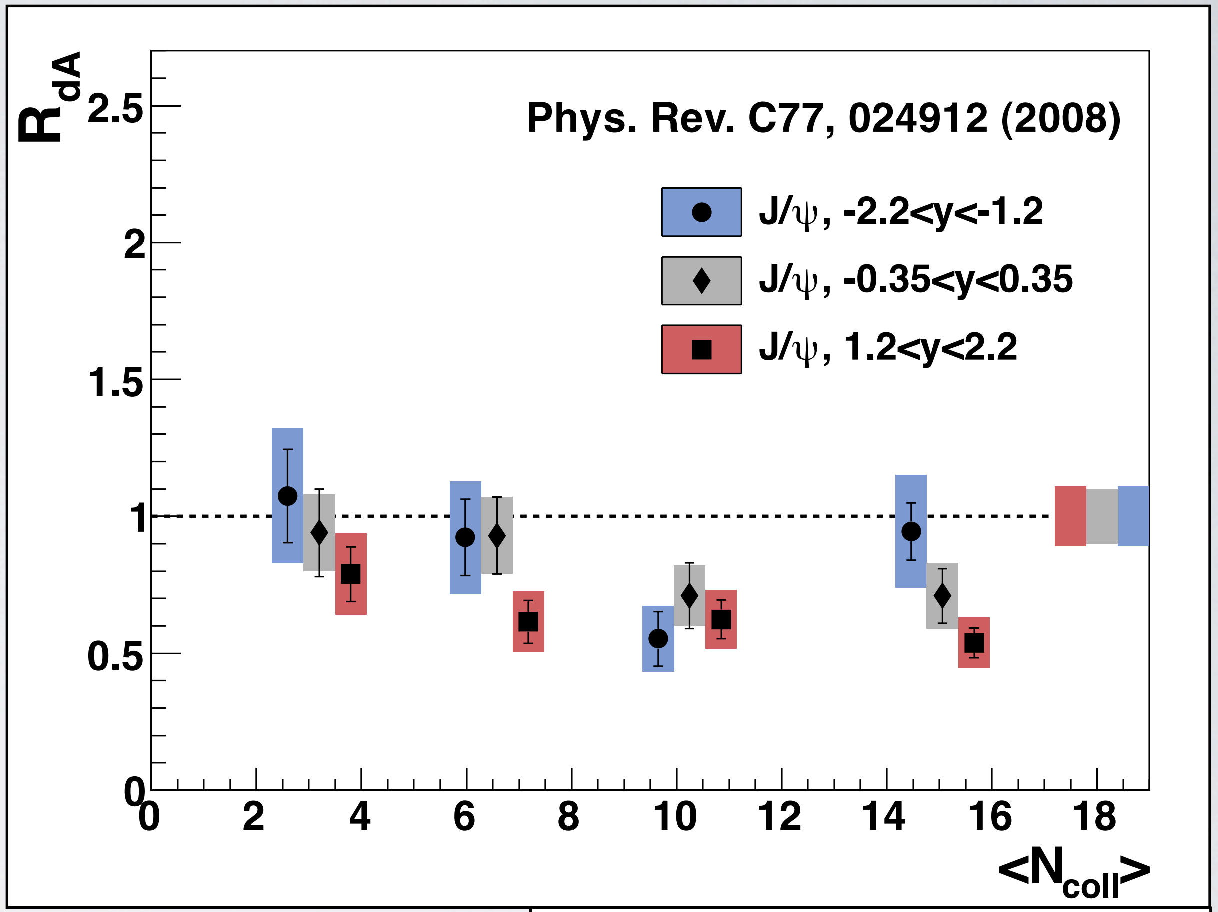


Comparison to EPS09s calculations



HF μ vs. J/ψ I





Phys. Rev. C 77, 024912 (2008)

- R_{dA} as a function of <N_{coll}>

  - R_{dA} of J/ψ are suppressed at all rapidity ranges

  ⇔ only R_{dA} at forward rapidity are suppressed in case of HF muon

  *caveat : J/ψ integrated over the entire p_T range

-J/ψ suppression at forward probably is related to the suppression of charm production predicted by nuclear shadowing

-at mid- and backward rapidity imply large effects of nuclear breakup