Heavy Flavor and Quarkonia in PHENIX

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for the PHENIX collaboration

2nd workshop on advancing the understanding of
non-perturbative QCD using energy flow
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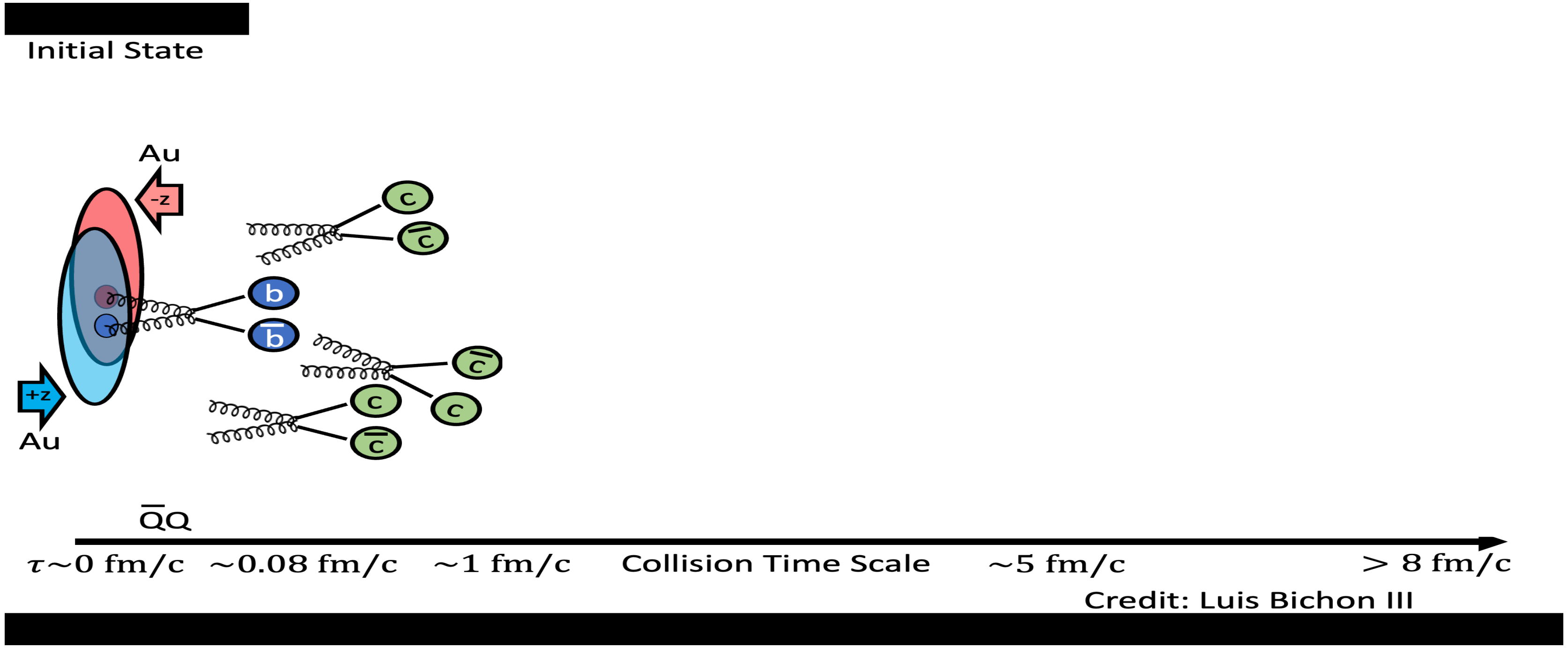
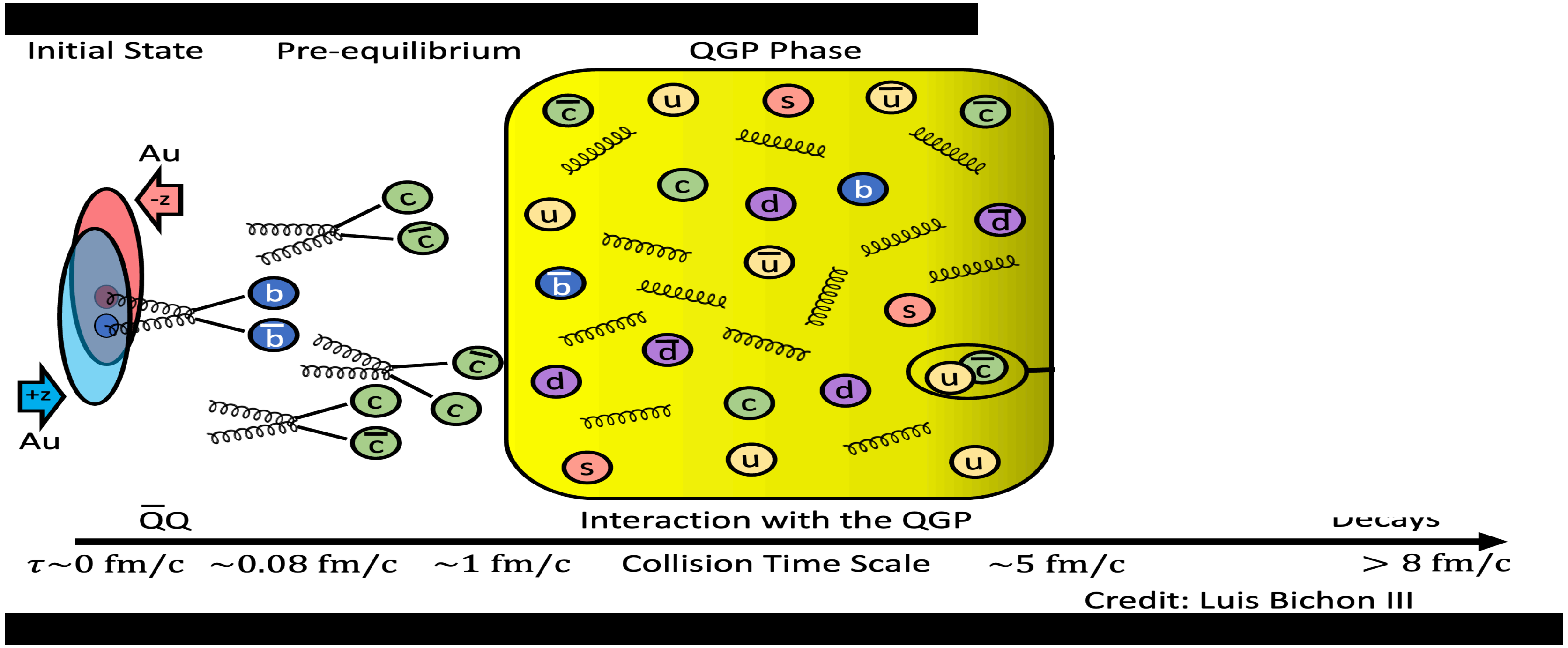
Heavy flavor as a probe of the QGP

- Large mass of heavy quarks —> only produced in initial hard scatterings



Heavy flavor as a probe of the QGP

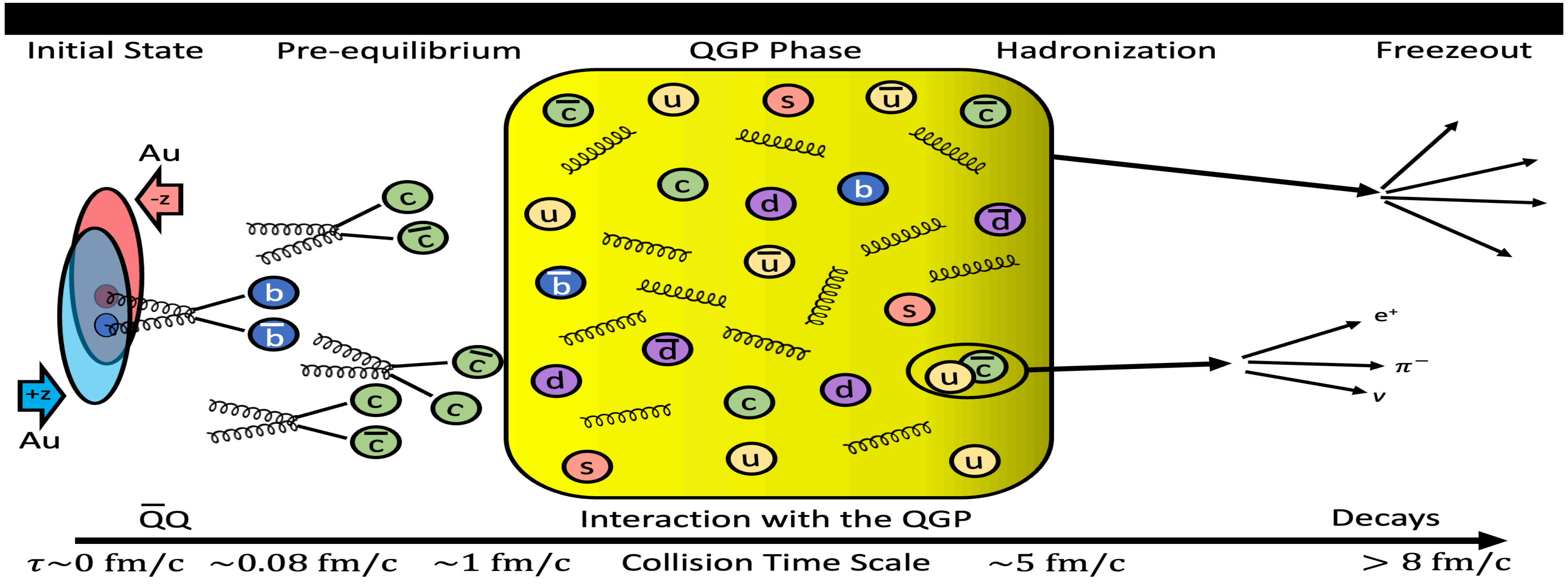
- Large mass of heavy quarks —> only produced in initial hard scatterings
- Energy loss and flow effects as they pass through QGP —> particle yields and angular distributions can be modified by interaction with the QGP



Credit: Luis Bichon III

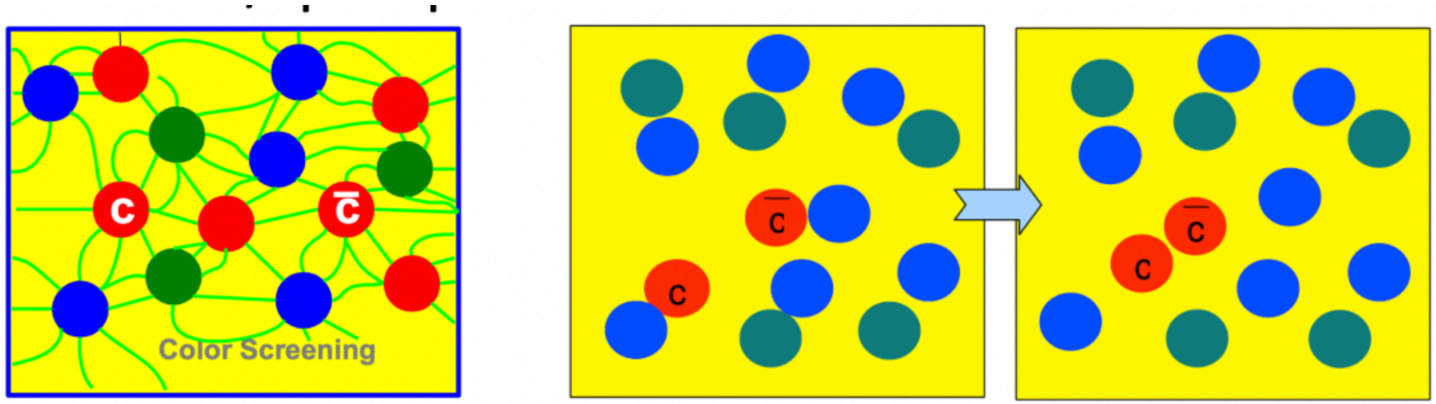
Heavy flavor particles as a probe of the QGP

- Large mass of heavy quarks —> only produced in initial hard scatterings
- Energy loss and flow effects as they pass through QGP —> particle yields and angular distributions can be modified by interaction with the QGP
- Heavy flavor particles reconstructed or their semi-leptonic decays —> understanding of heavy quark interaction with QGP medium



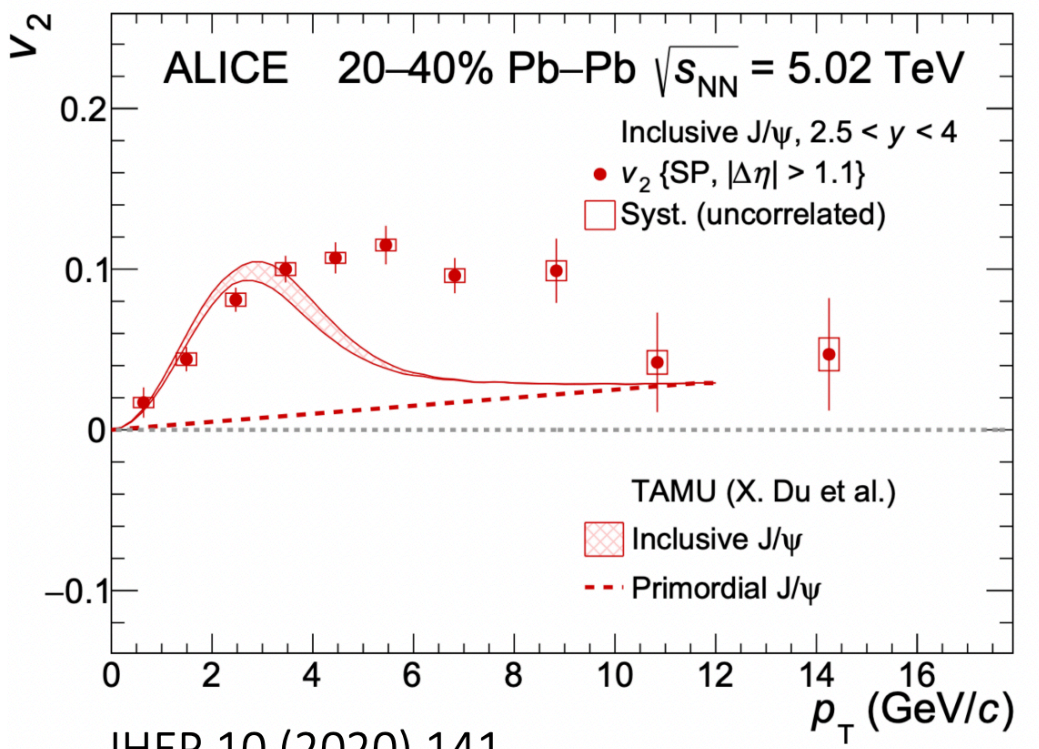
Credit: Luis Bichon III

J/Ψ R_{AA} and v_2 as probes of QGP



- Quarkonium suppression probes T and density of QGP

- Multiple mechanisms for J/Ψ flow
    - Path length dependent dissociation
    - Charm equilibration and J/Ψ regeneration
    - Primordial J/Ψ equilibration – small effect



JHEP 10 (2020) 141

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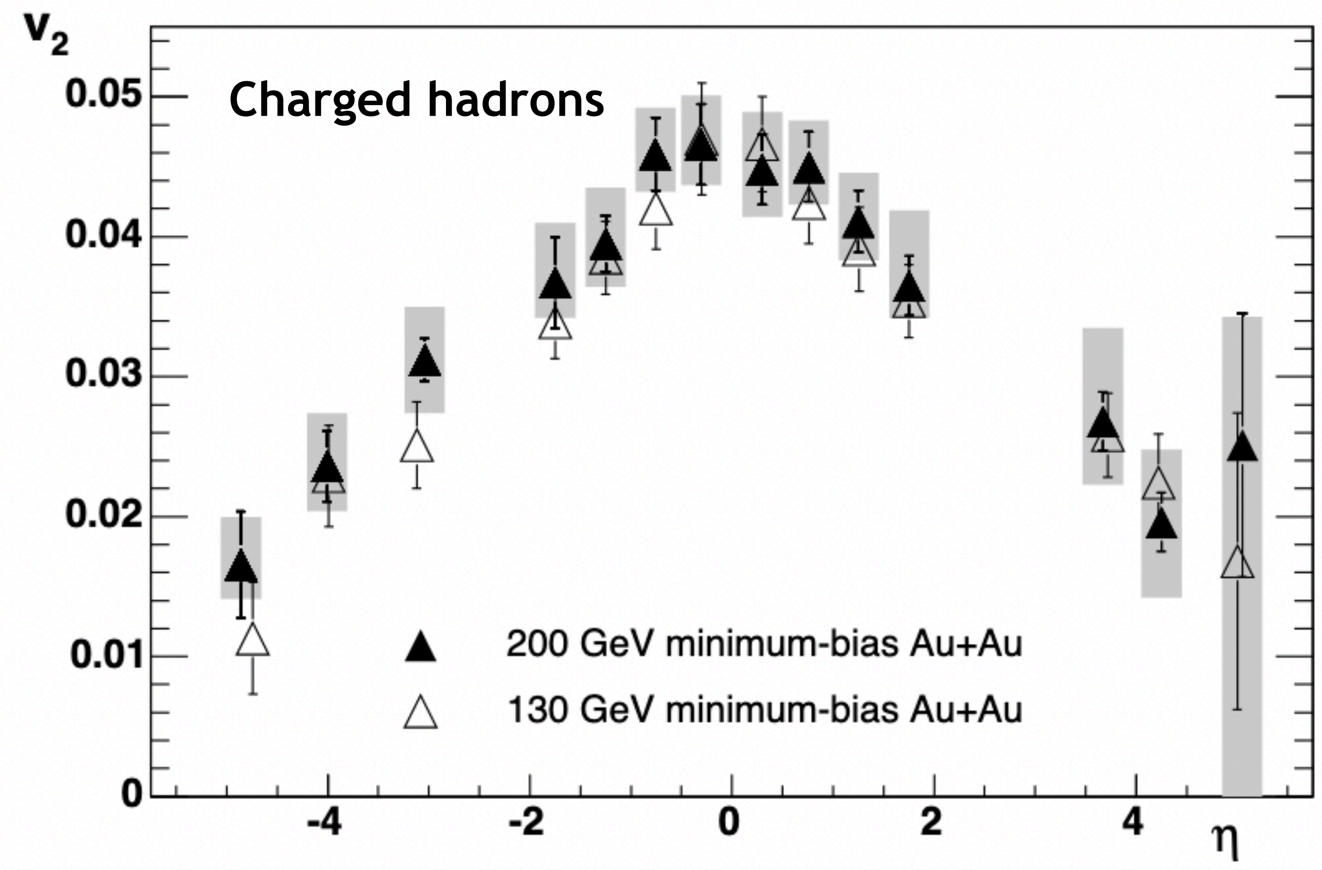
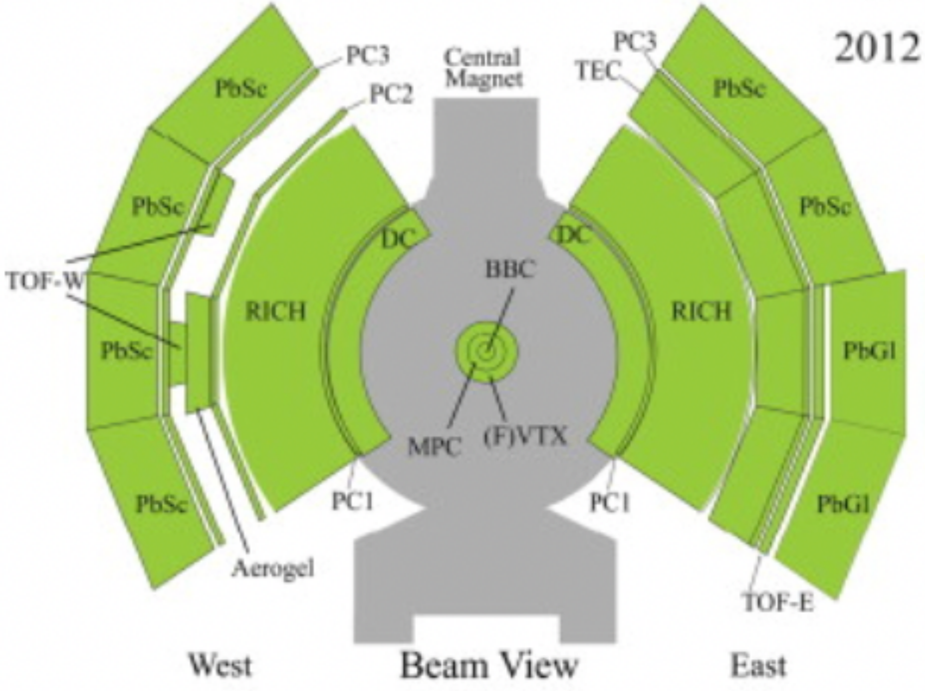
Rapidity dependence of QGP interactions

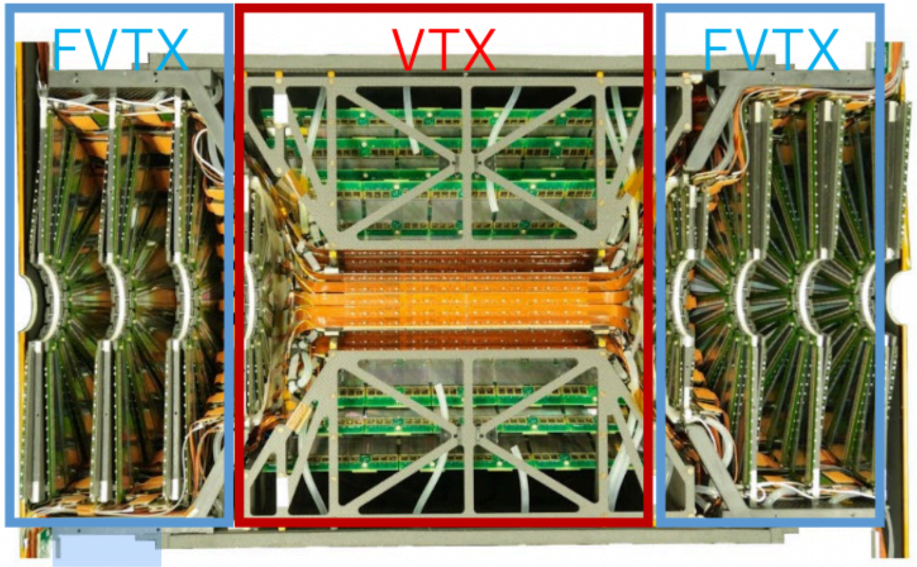
- Rapidity dependence of flow gives access to the longitudinal dynamics of QGP
- Heavy flavor and quarkonia dynamics have rapidity-dependent initial state effects
- PHENIX has unique capabilities at RHIC for separating charm and beauty with decay vertex determination at forward rapidity

PHOBOS, PRL 89 (2002), 222301

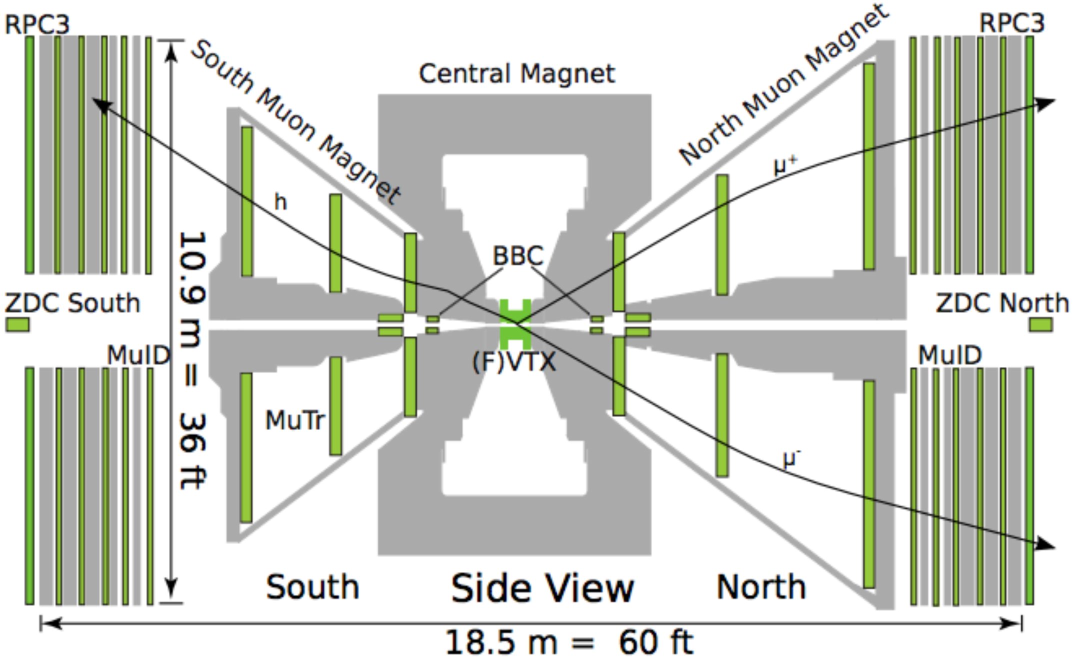


PHENIX detector





- **Central arms:** |y|<0.35
  - electrons, hadrons, and photons
- **Muon arms:** 1.2<|y|<2.2
  - muons and hadrons
- **VTX-FVTX:** Precise HF tracking and ID over full PHENIX rapidity range



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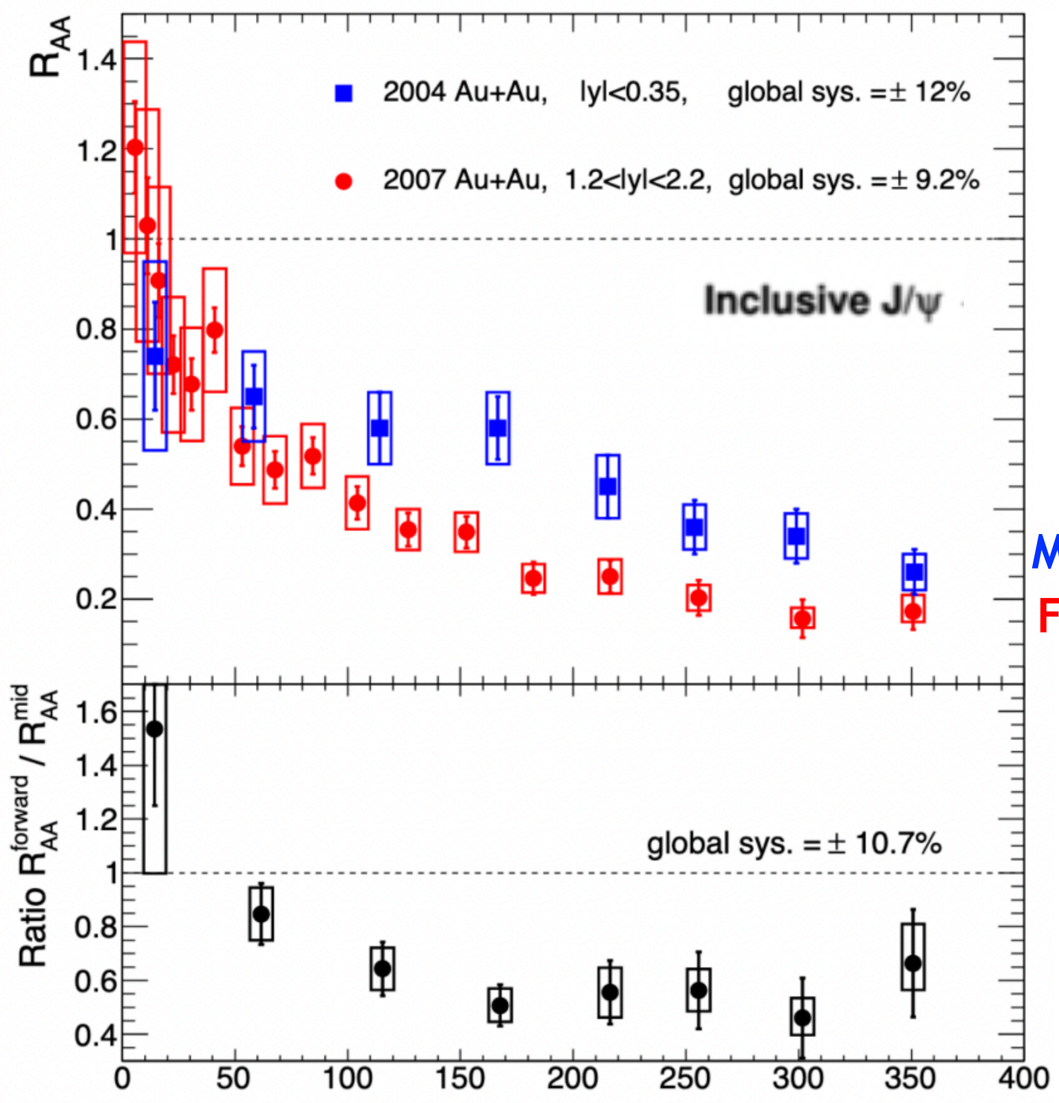
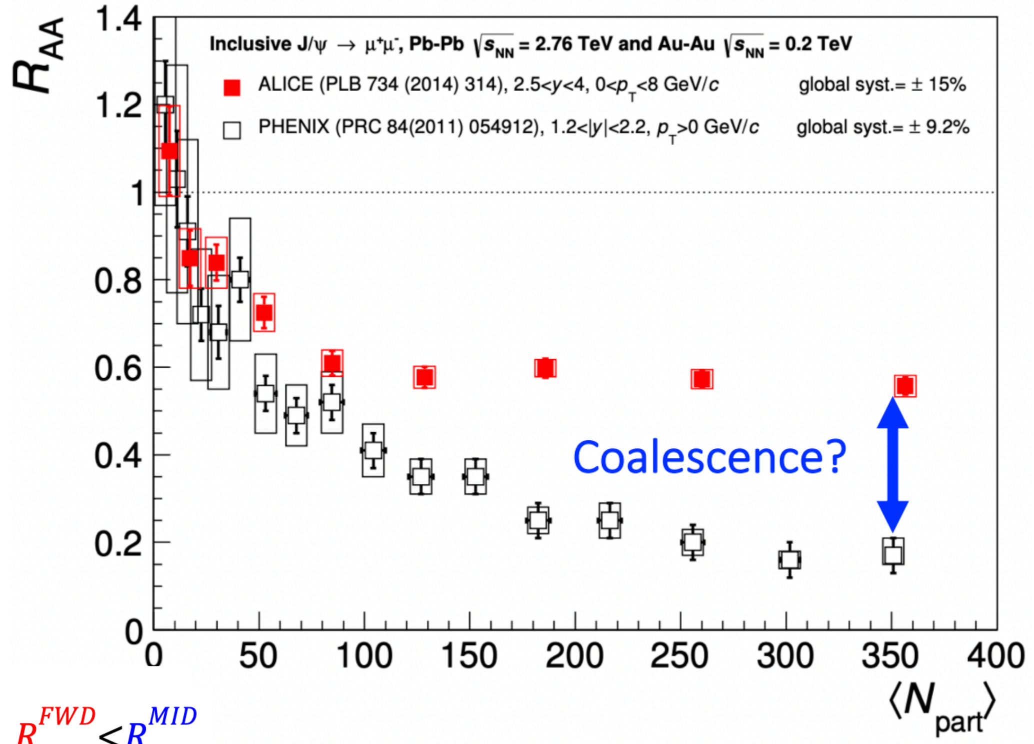
J/Ψ R_{AA} and coalescence



Phys.Rev.C 84 (2011) 054912

Mid-rapidity
Forward



- At RHIC: $R_{AA}^{FWD} < R_{AA}^{MID}$
- LHC vs RHIC: $R_{AA}^{RHIC} < R_{AA}^{LHC}$

➢ Both contrary to expectations of how medium density and temperature influence suppression

- Coalescence can explain these results. Most $c\bar{c}$ pairs are produced at mid-rapidity and ~10x more $c\bar{c}$ pairs at LHC energies

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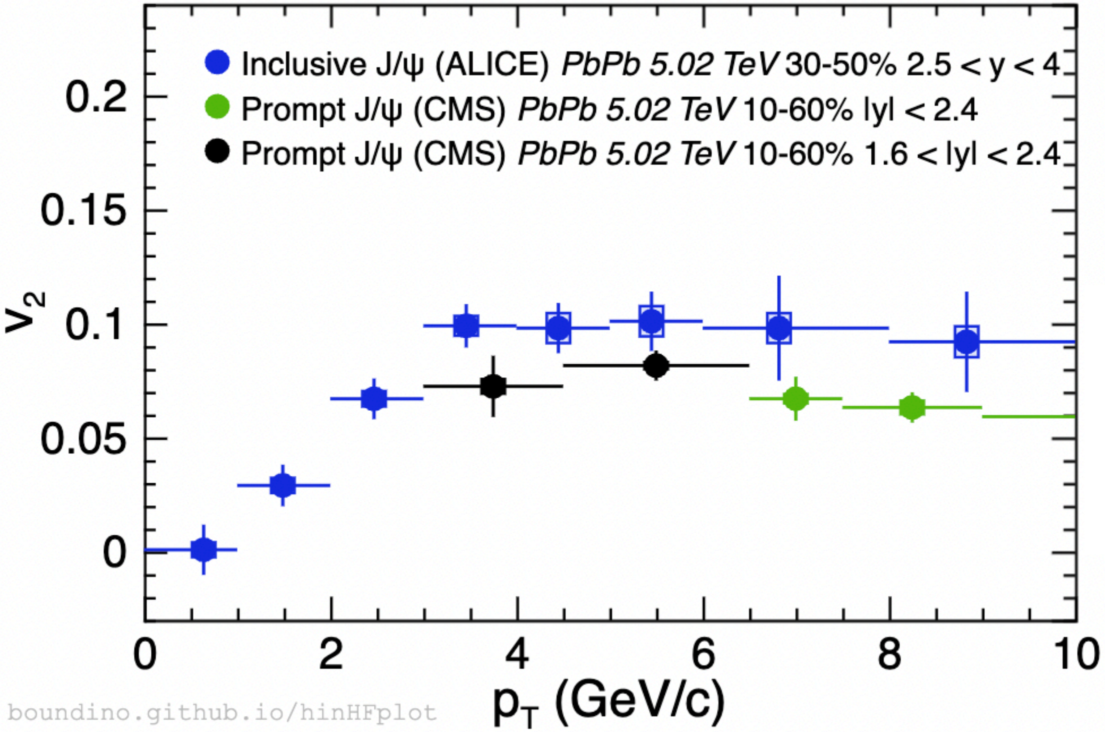
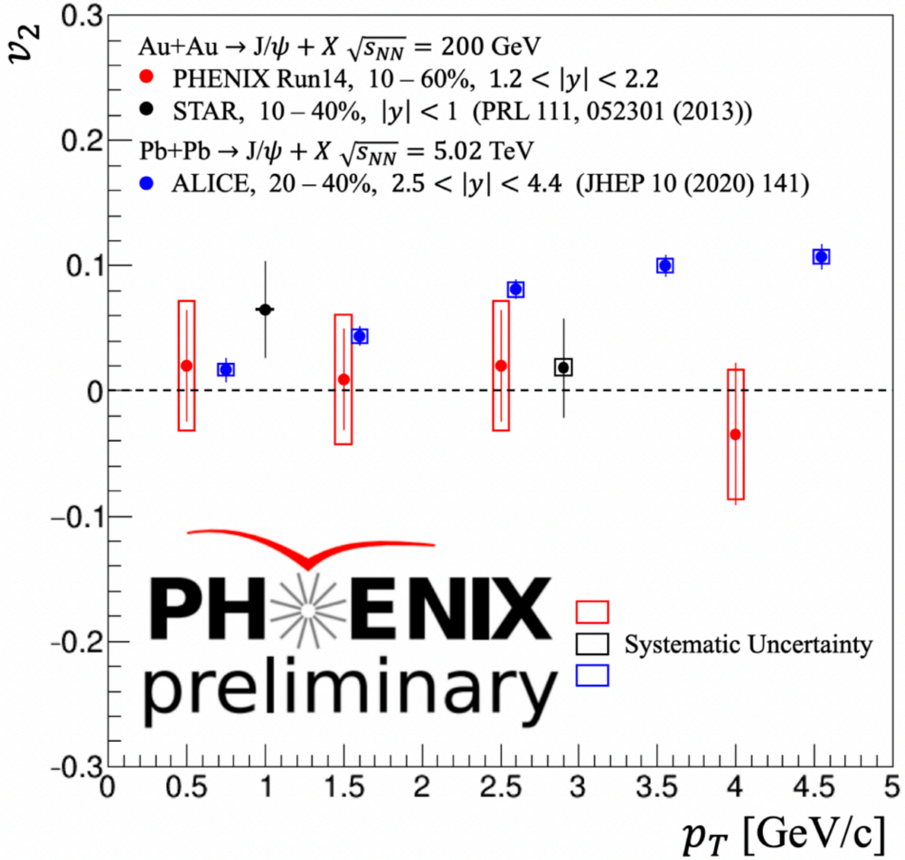
v_2 of J/Ψ at RHIC and LHC





- JHEP 10 (2020) 141
- CMS-PAS-HIN-21-008
- CMS-PAS-HIN-21-008

- At LHC energies, J/Ψ has significant v_2 across rapidity
- At RHIC, v_2 of J/Ψ is consistent with zero both at mid- and forward rapidity

➢ Improvement needed for RHIC results to assess the role of coalescence

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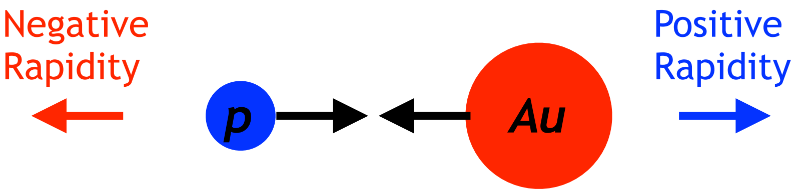
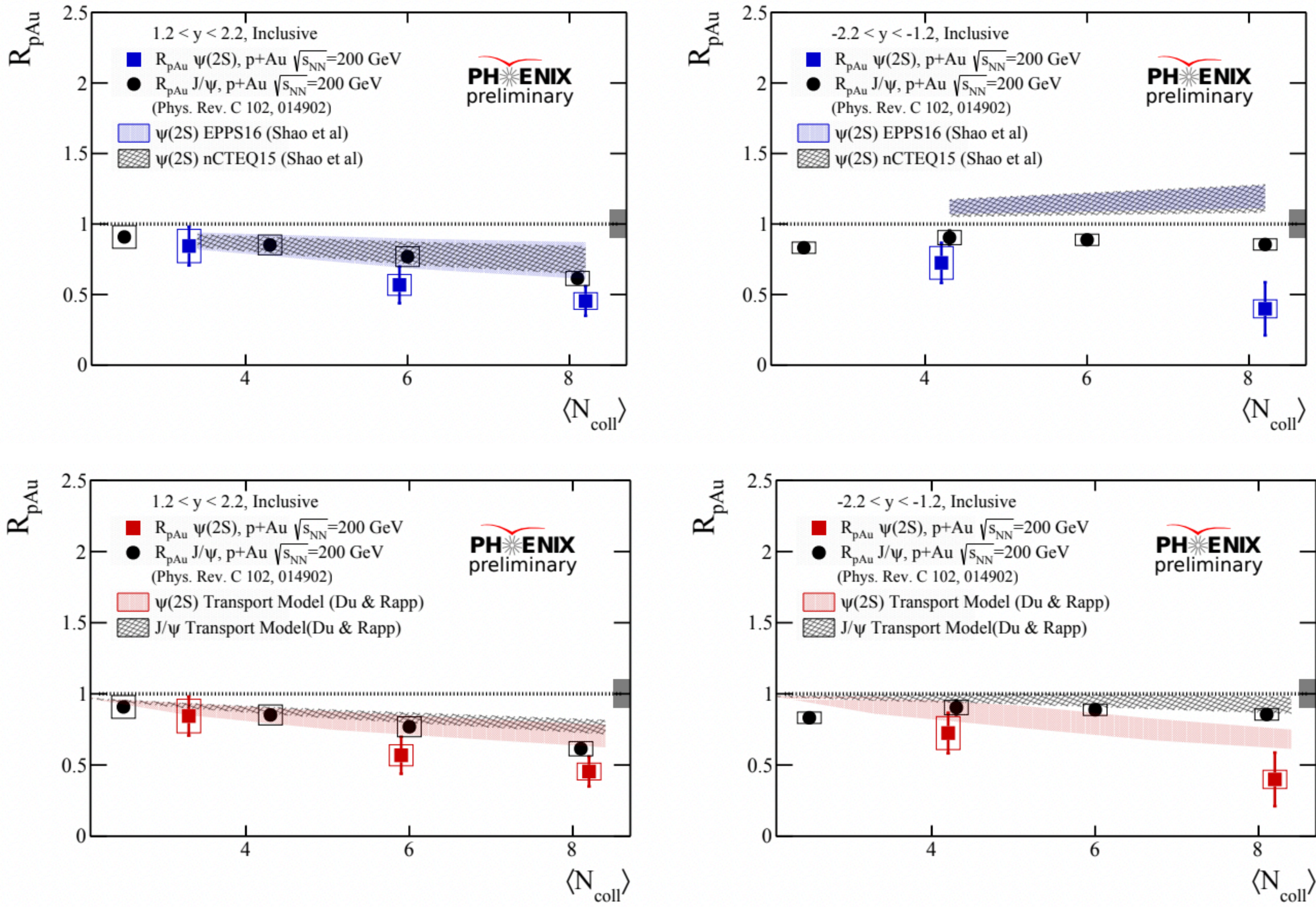
J/Ψ and Ψ(2S) modification

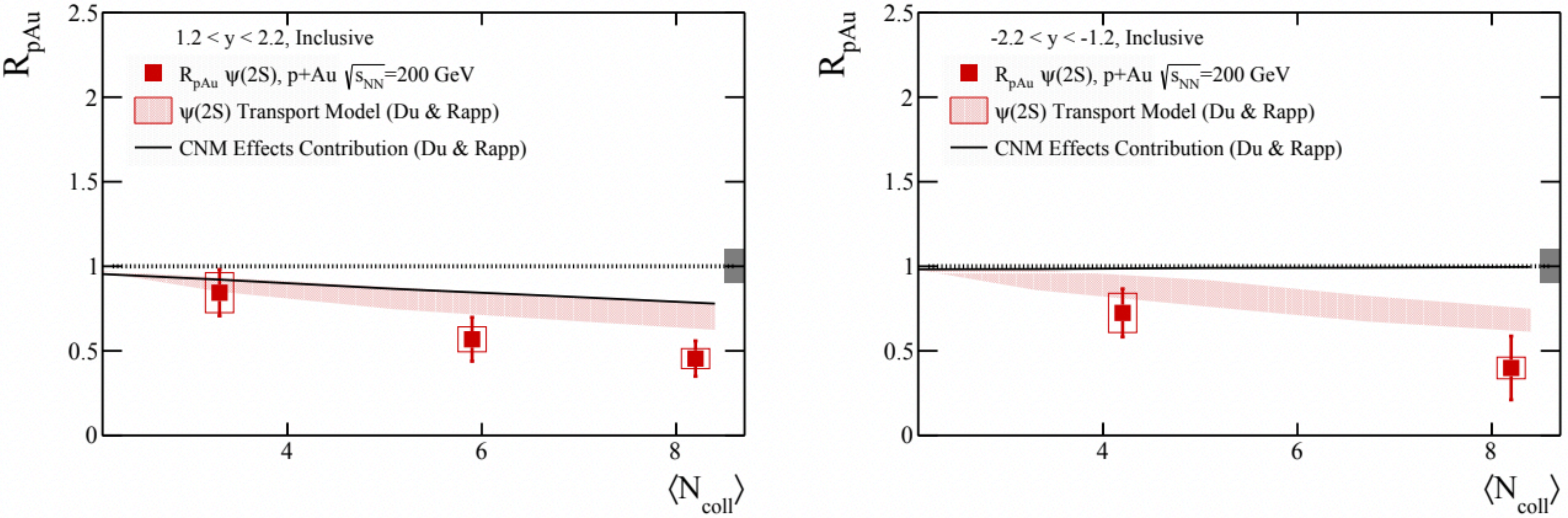


- The modification of J/Ψ and Ψ(2S) at forward rapidity are both reasonably described by models that include cold nuclear matter effects

- At backward rapidity there is a clear difference between J/Ψ and Ψ(2S)



Ψ(2S) modification



- At both forward and backward rapidity the contribution from CNM effects alone fails to describe the modification of Ψ(2S)

- **Strong evidence for final state effects in small systems**

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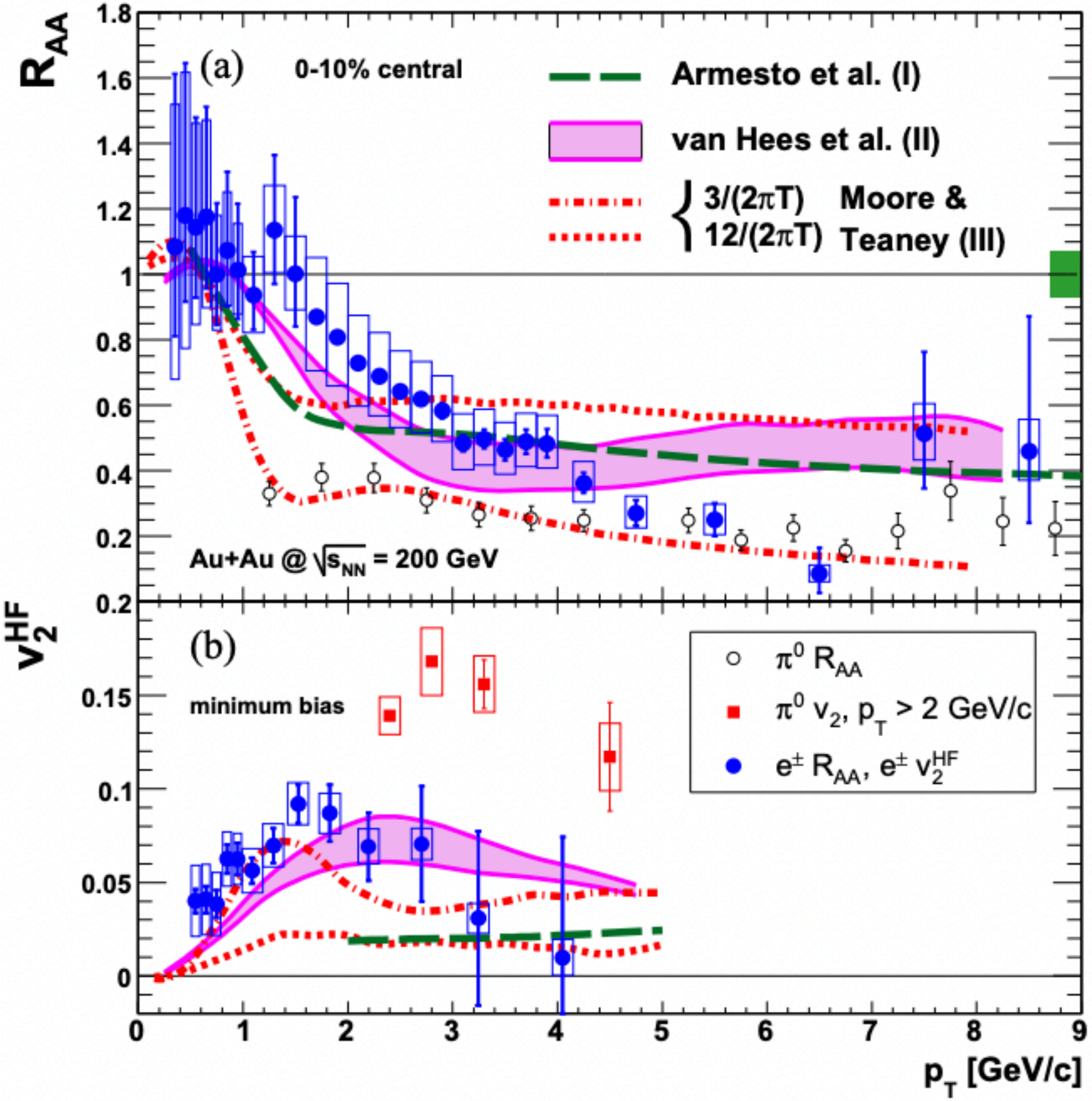
Inclusive heavy flavor v_2 and R_{AA}

- Electrons from inclusive heavy flavor show significant R_{AA} suppression and non-zero v_2
- Both measurements show significant differences compared to neutral pions
  - Indicates mass ordering of particle interactions with QGP
- Do separated *c* and *b* exhibit the same mass ordering behavior?



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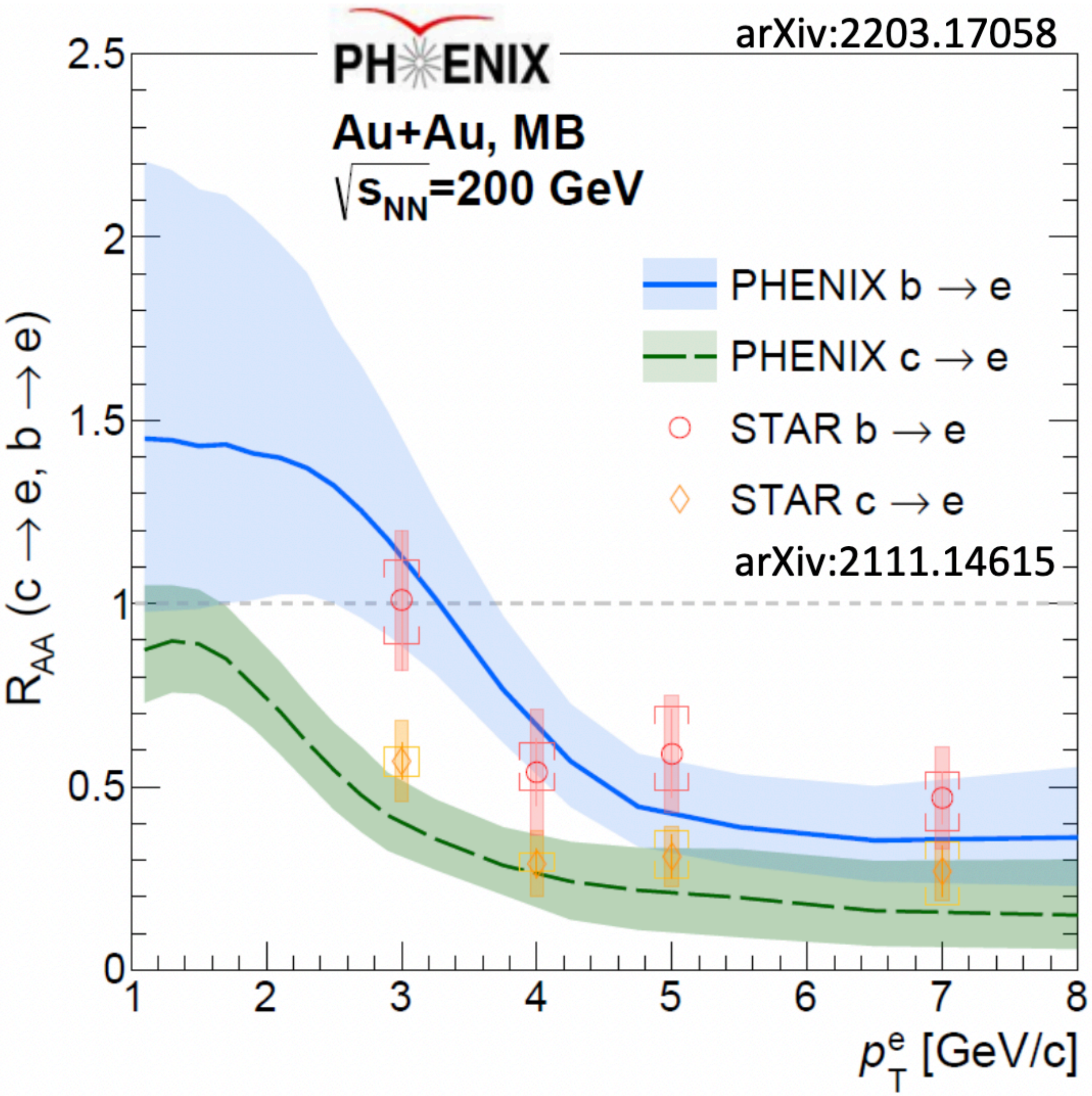
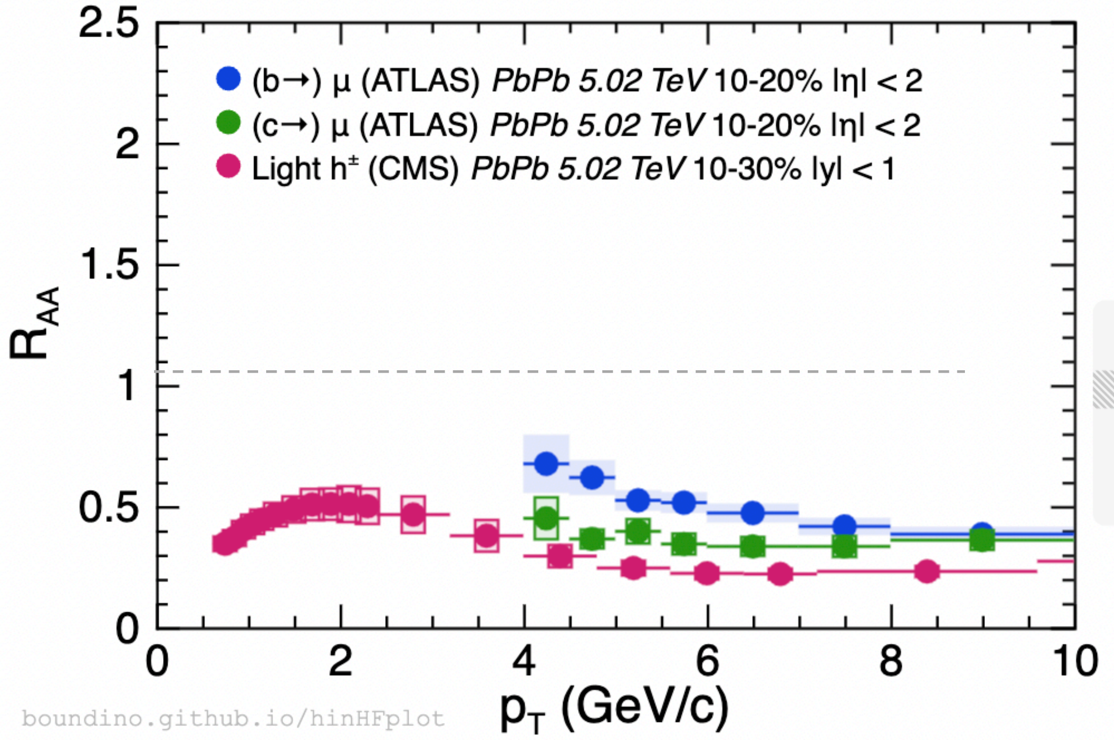
R_{AA} of separated *charm* and *beauty*





PLB 829 (2022) 137077 PLB 829 (2022) 137077
JHEP 04 (2017) 039

- Clear mass ordering between b->*l* and c->*l* at RHIC and LHC energies
- R_{AA} measurement of open heavy flavor at forward rapidity will provide further insights

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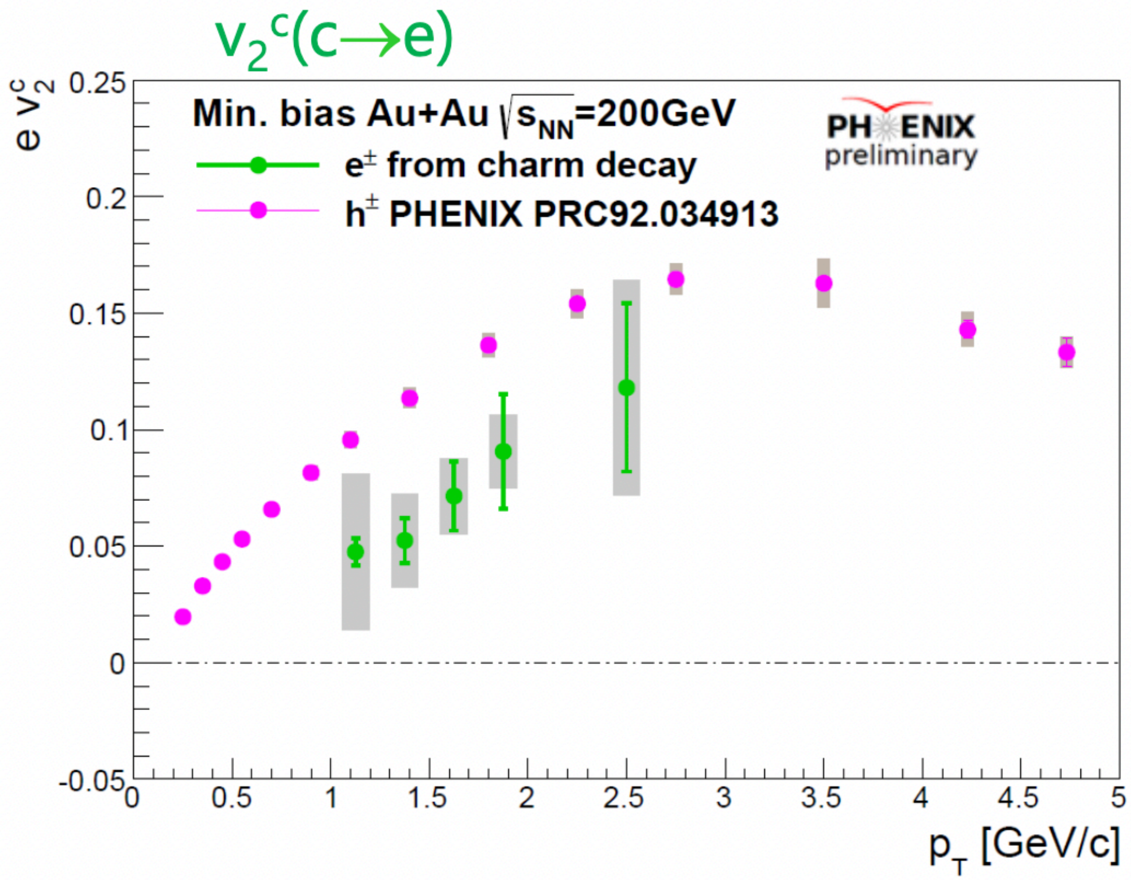
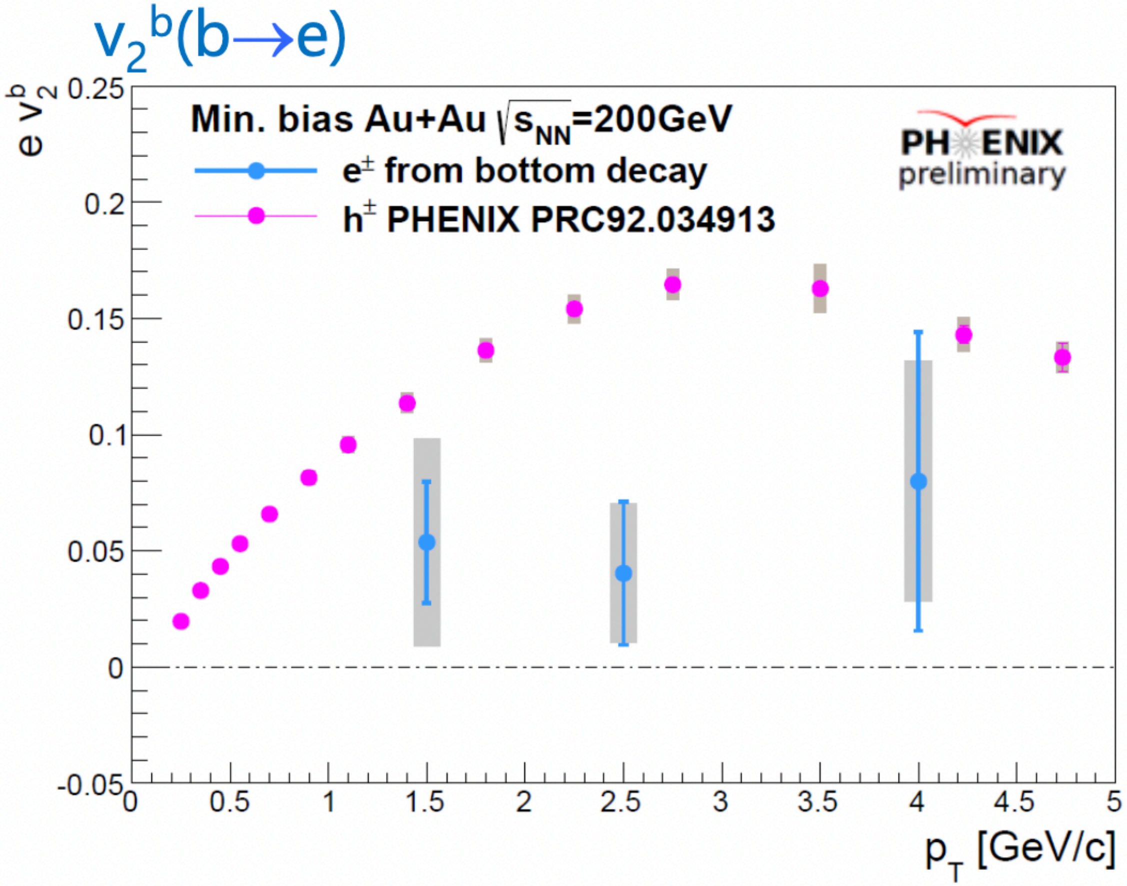
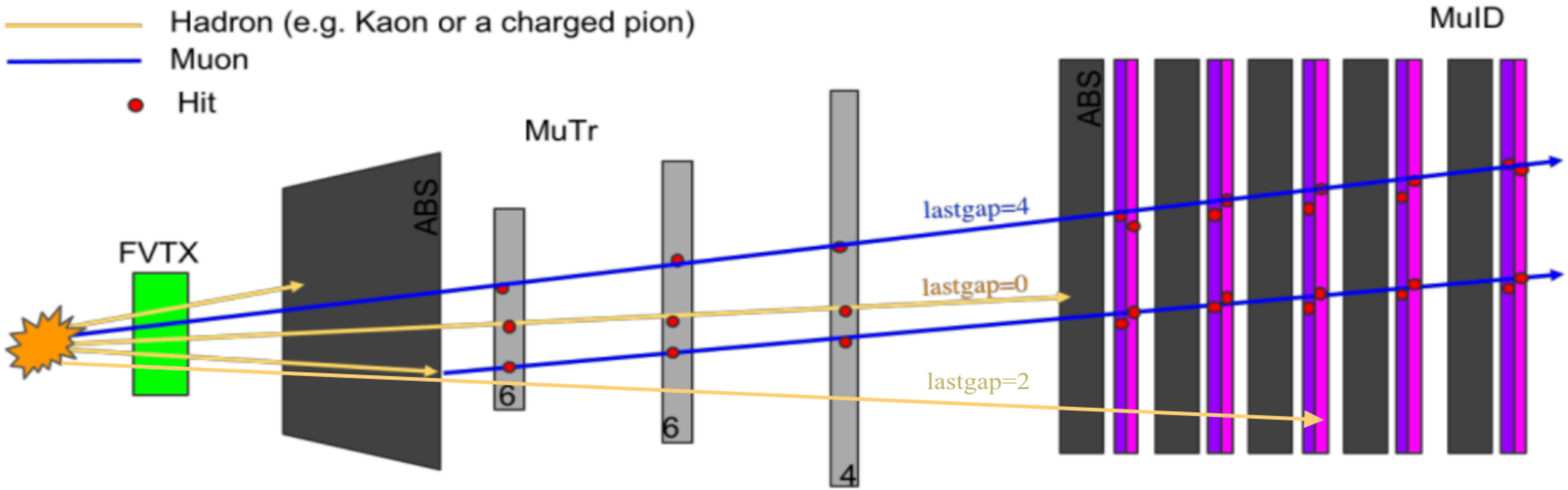
PHENIX separated c and b v_2



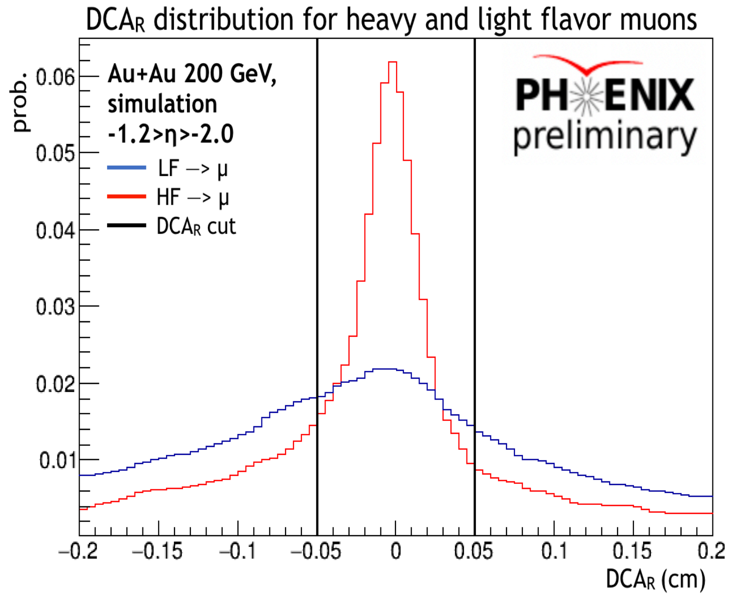


- v_2(c—>e) is positive with ~3.5 sigma and follows trend of charged hadron v_2
- v_2(b—>e) indicates positive with 1.1 sigma
- Mass ordering is seen, as in R_{AA}

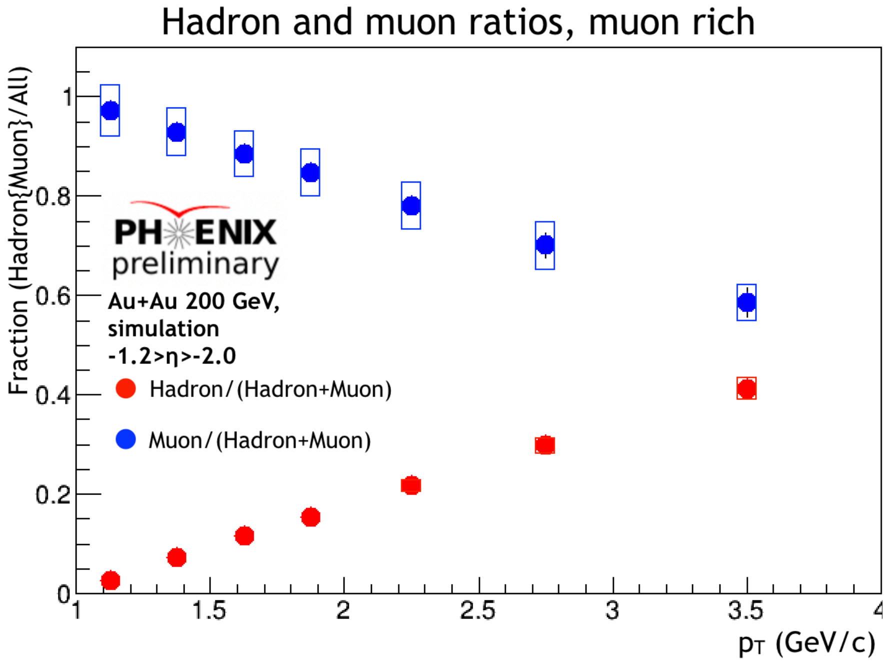
PHENIX muon arm heavy flavor analysis

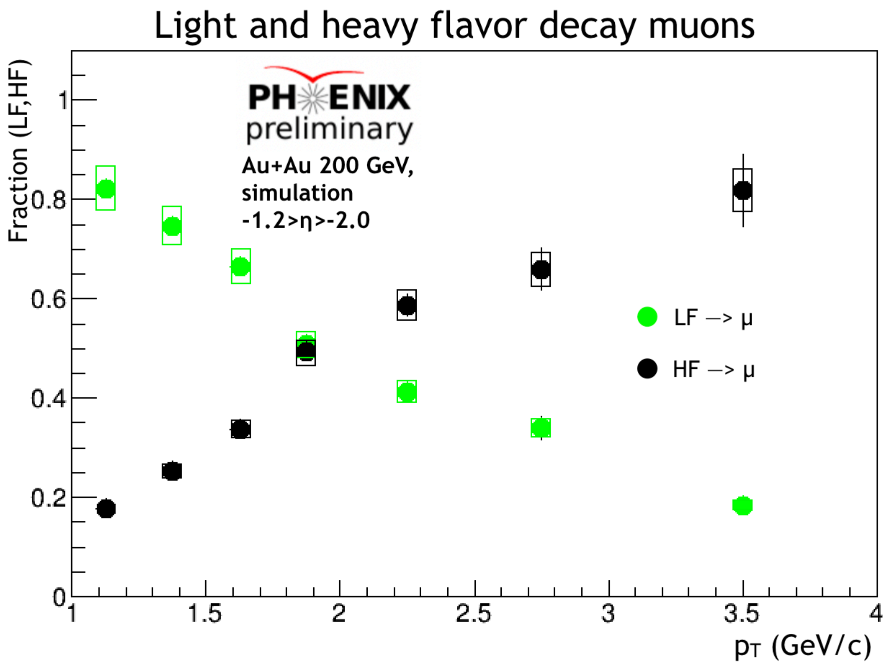


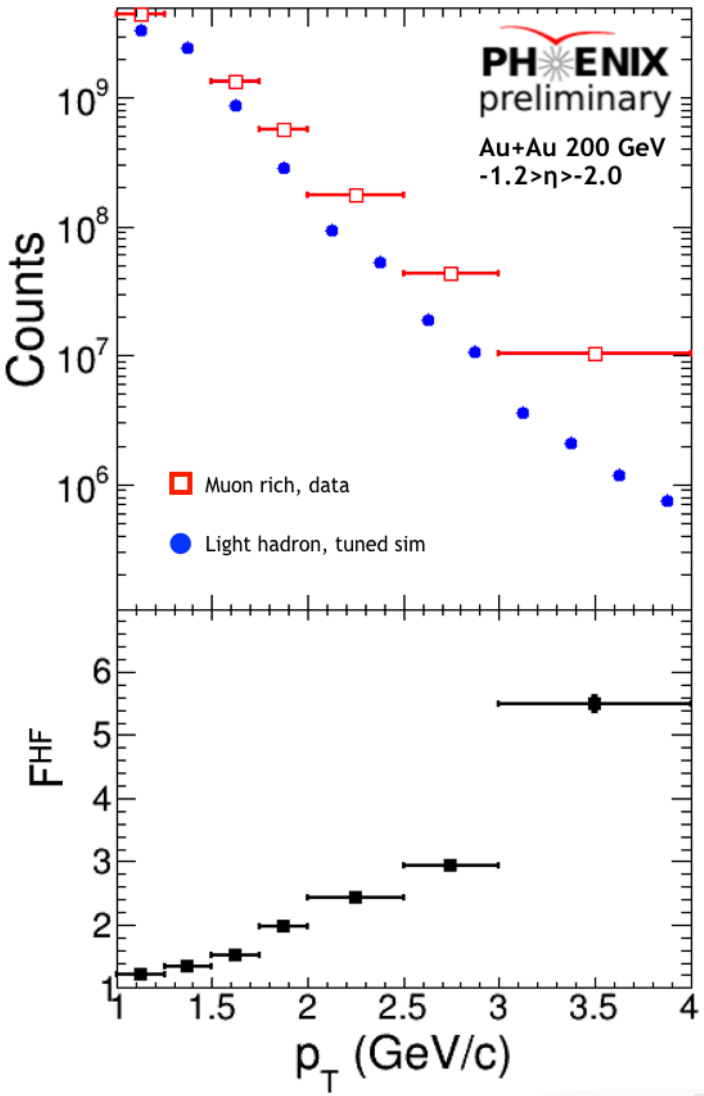
- PHENIX has unique capabilities for forward heavy flavor measurements at RHIC
  - Separation of hadrons and muons (MuID)
  - Secondary vertex determination (FVTX)



Extracting heavy flavor in the muon arms







- Using tuned PYTHIA+GEANT4 embedded in real Au+Au events we can extract the inclusive muon fraction
- Extract the HF muon fraction by comparing data to tuned simulation with HF contribution excluded
- Determine heavy flavor muon v_2 in the inclusive muon sample:

$$v_2^{HF} = \frac{1}{F^{HF}}\left(v_2^{\mu} - (1 - F^{HF})v_2^{LF}\right)$$

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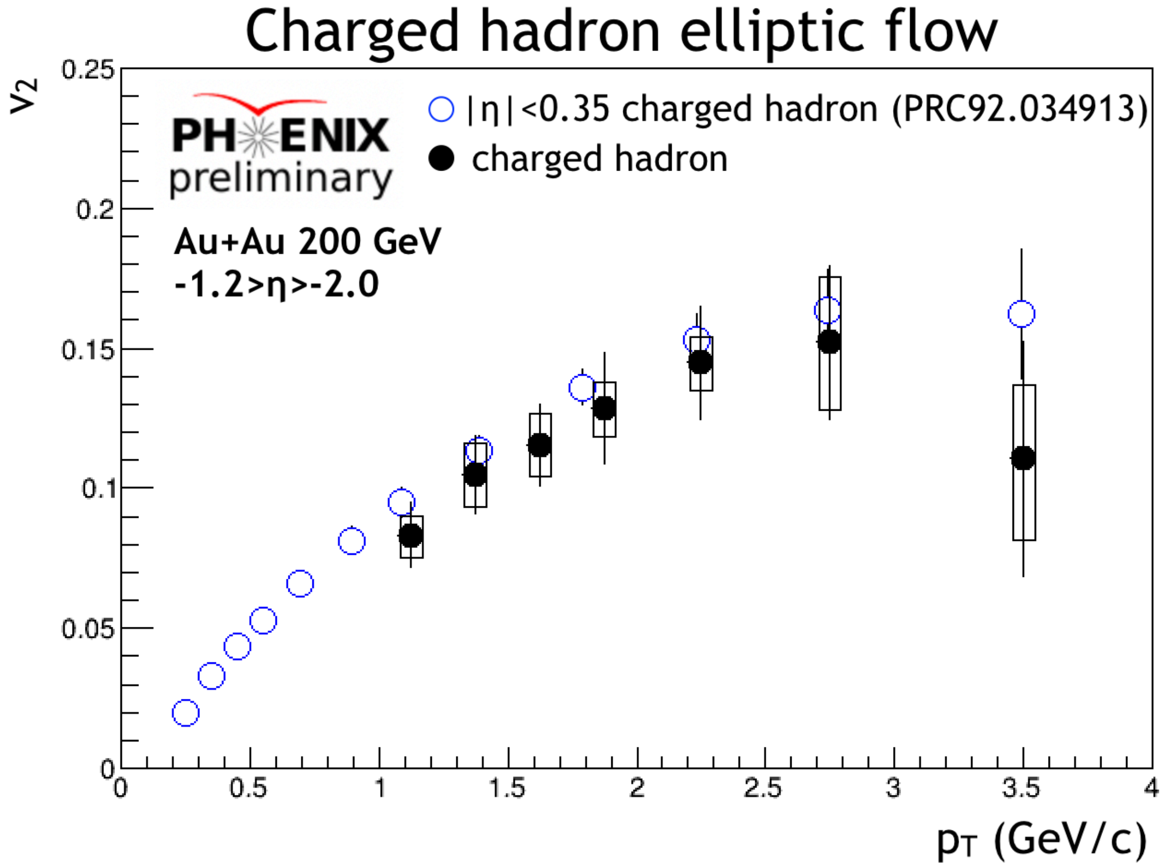
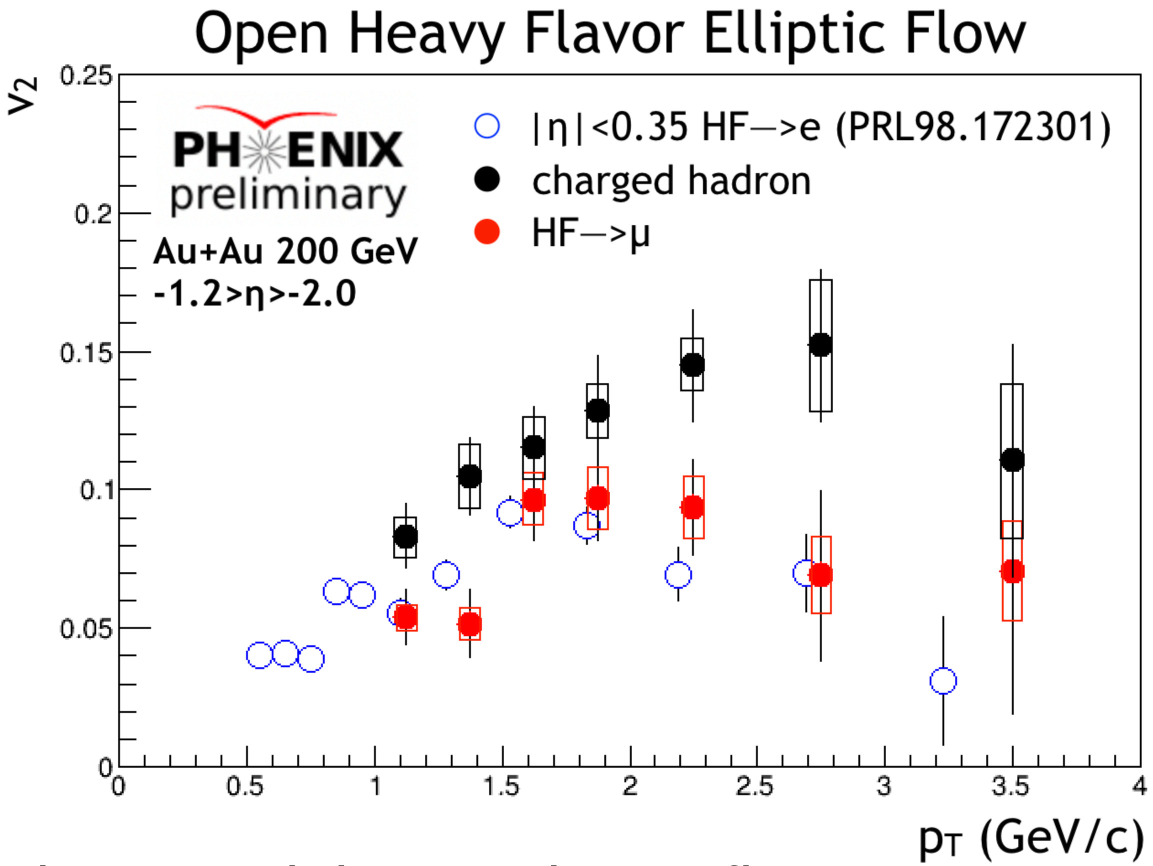
Flow of charged hadrons and heavy flavor muons at forward rapidity





- Hint of rapidity-dependence of charged hadron v_2, while open heavy flavor v_2 results are consistent with PHENIX results at mid-rapidity
- **Takeaway**: heavy flavor particles flow with the QGP, but less than charged hadrons
  - Unlike charged hadrons, no rapidity-dependence for heavy flavor v_2

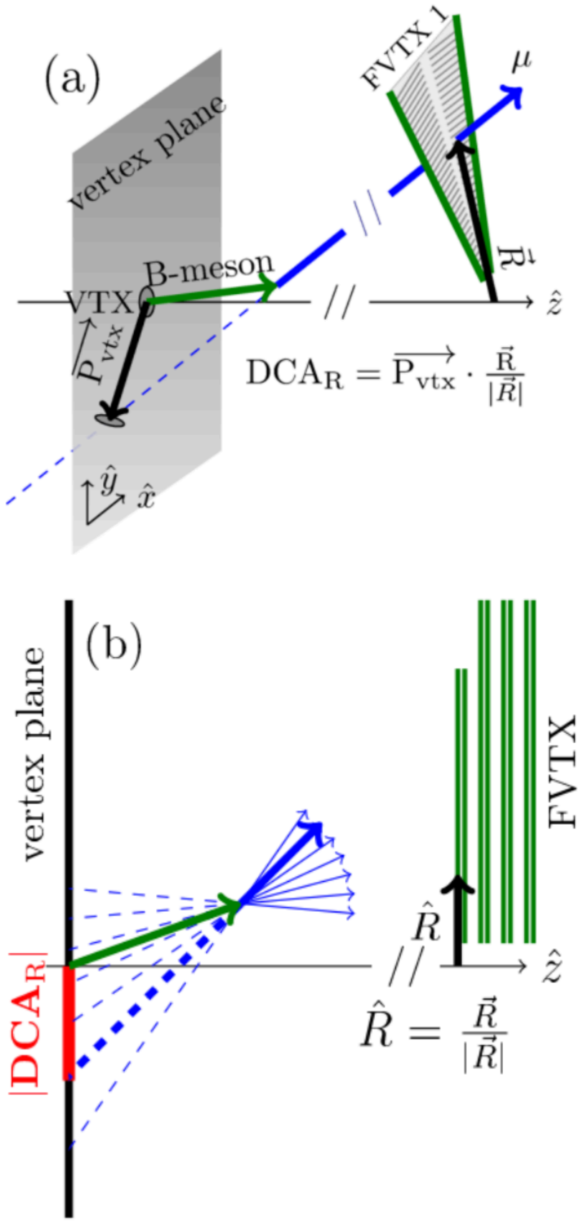
Summary

- PHENIX has many measurements (and ongoing analyses) using heavy flavor as a probe of the unique properties of the QGP
- Coalescence of $c\bar{c}$ pairs could explain the difference between forward and mid-rapidity J/Ψ R_{AA} results
  - J/Ψ v_2 at RHIC has no rapidity dependence, but the results are not yet conclusive (ongoing analysis)
- In small systems HF probes indicate final state effects consistent with QGP formation
- v_2 and R_{AA} light and heavy flavor (*c* and *b)* show mass ordering at mid- and forward rapidity
  - No obvious rapidity-dependence for heavy flavor v_2 at RHIC energies
- Inclusion of the Run16 Au+Au 200 GeV dataset will double statistics for ongoing PHENIX heavy flavor analyses

Back-up

Radial distance of closest approach (DCA_r)

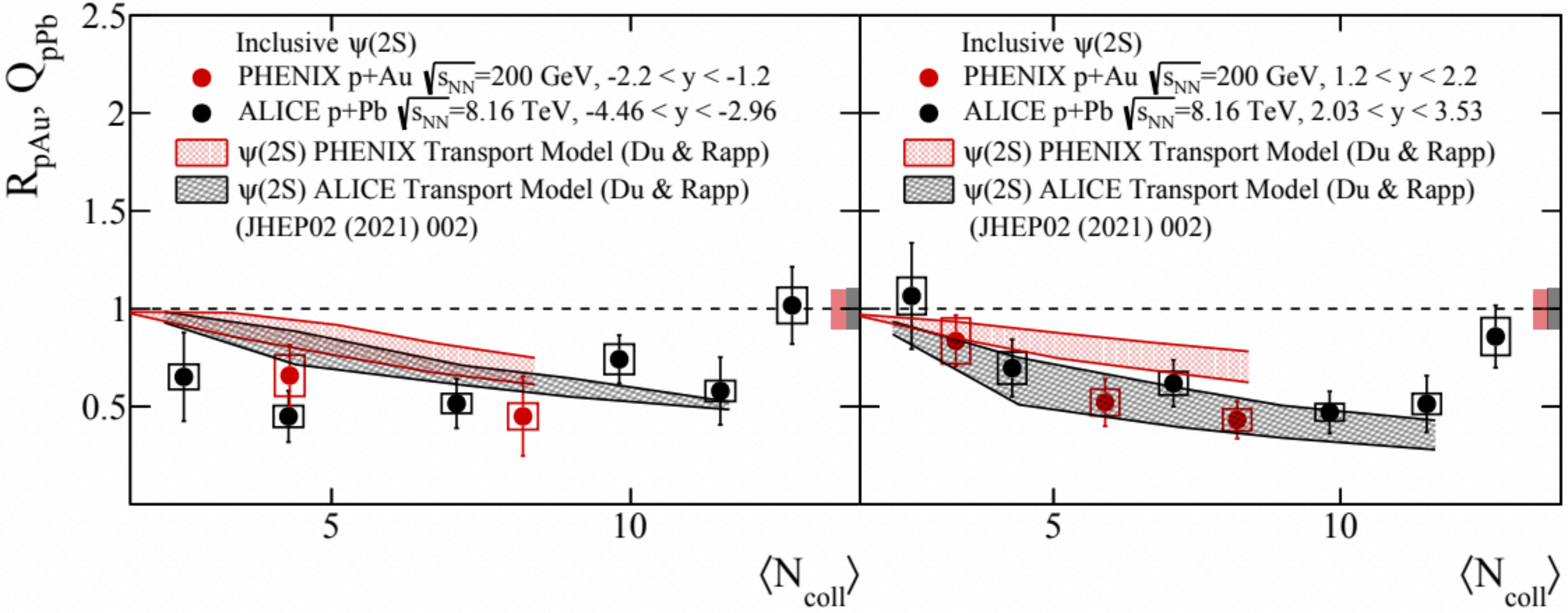
- DCA_r is determined by projecting the particle track determined by the FVTX onto a plane in the z-axis located at the initial collision point
- Essentially this is a measurement of the distance from the primary vertex at which a particle was produced, i.e. for a prompt particle $DCA_r = 0$
- With a precise measurement you can separate detected muons according the particle from which they decayed



3D visualization of DCA_r

r-*z* plane visualization of DCA_r

$\psi(2S)$ Modification at RHIC and LHC



- $\psi(2S)$nuclear modification compared with Du & Rapp Transport Models
  - PHENIX prediction at RHIC energies shown in black
  - ALICE prediction at LHC energies shown in red

Credit: Krista Smith

Cold Nuclear Matter Effects in p+A Systems

❶ **Gluon Shadowing/Anti-Shadowing:**
Modification (suppression/enhancement) of heavy quark cross section due to modifications of the gluon nuclear parton distribution functions (nPDFs) in the target

❷ **Nuclear Absorption:**
The break up of the bound J/ψ (or precursor state) in collisions with other target nucleons passing through J/ψ production point

❸ **Cronin Effect:**
Modification of the J/ψ p_T distribution due to multiple elastic scattering of partons

❹ **Parton Energy Loss:**
The projectile gluon experiences multiple scattering passing through the target prior to J/ψ production, reducing the J/ψ rapidity

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Credit: Krista Smith

Model Overview

nCTEQ15 and EPPS16 NLO (Shao, et. al.) — PRL 121, 052004

- Reweighted using LHC p+Pb data, giving tighter J/ψ constraints

Nuclear Absorption Model — PRC 87, 054910 2013

- Estimated from global fit to world data
- Added to Shao, et. al. at backward rapidity only

EPS09 NLO + Transport Model (Du & Rapp) — JHEP 03, 015

- Includes fireball, MC Glauber for initial conditions
- p_T broadening included
- Backward rapidity: Nuclear absorption added

Credit: Krista Smith