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Forward rapidity elliptic flow measurements in PHENIX Au+Au collisions at 200 GeV

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on behalf of the **PHENIX** collaboration

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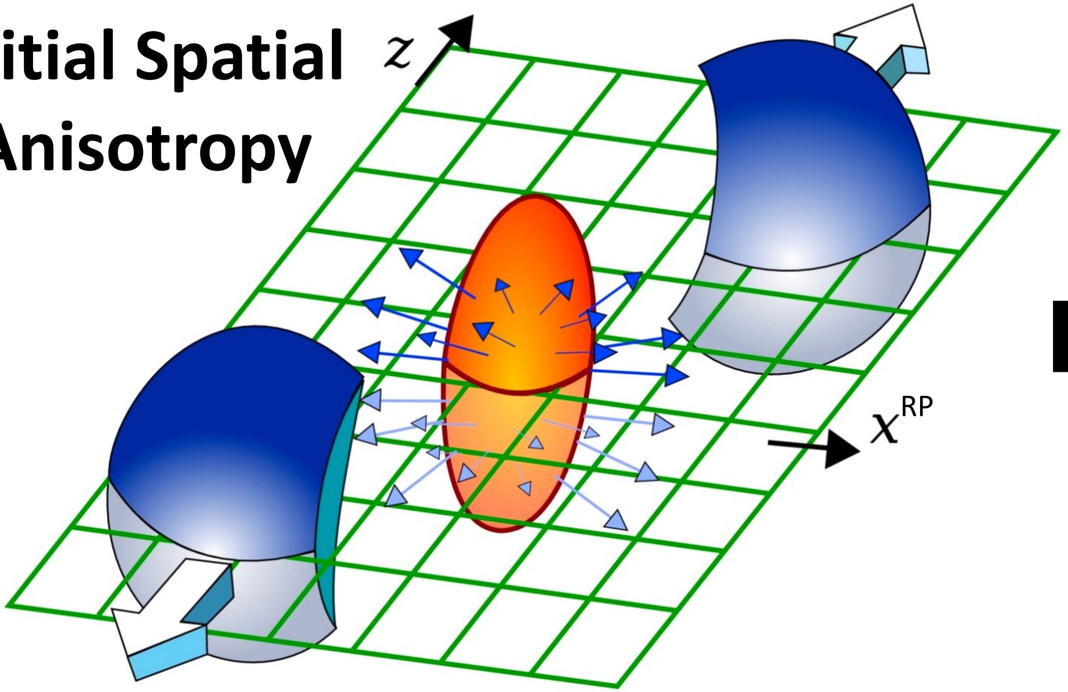
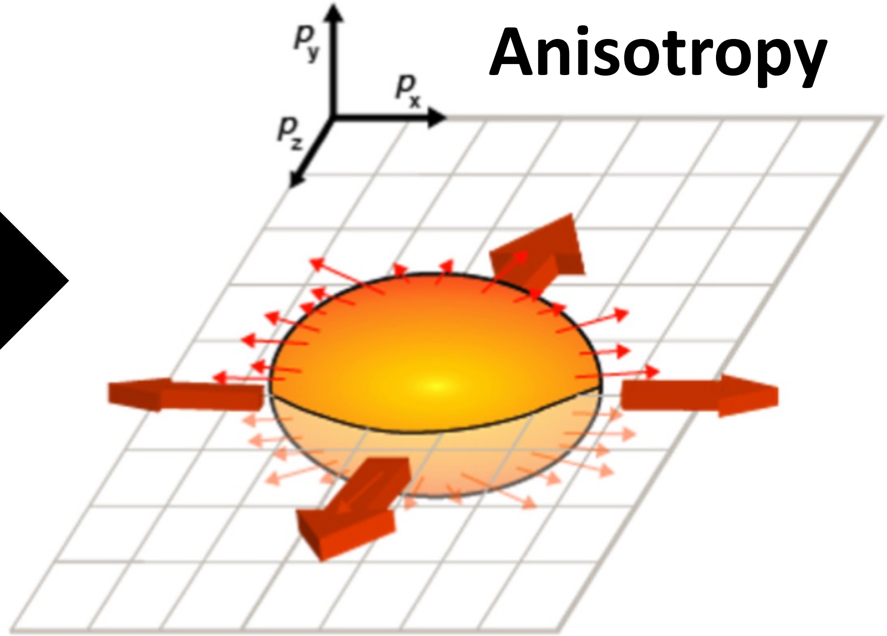
Probing the Quark Gluon Plasma

- QGP is strongly coupled; can be described by hydrodynamics
- Interactions of heavy flavor quarks are still under investigation
- Heavy flavor quarks play a special role due to their large mass

Initial Spatial Anisotropy



Final Momentum Anisotropy



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi p_T}\frac{d^2N}{dy\,dp_T}\left(1+\sum_n 2v_n(p_T)\cos\left[n(\phi-\Psi_{RP})\right]\right)$$

$$v_2 = \langle \cos(2(\phi_i - \Psi_2))\rangle$$

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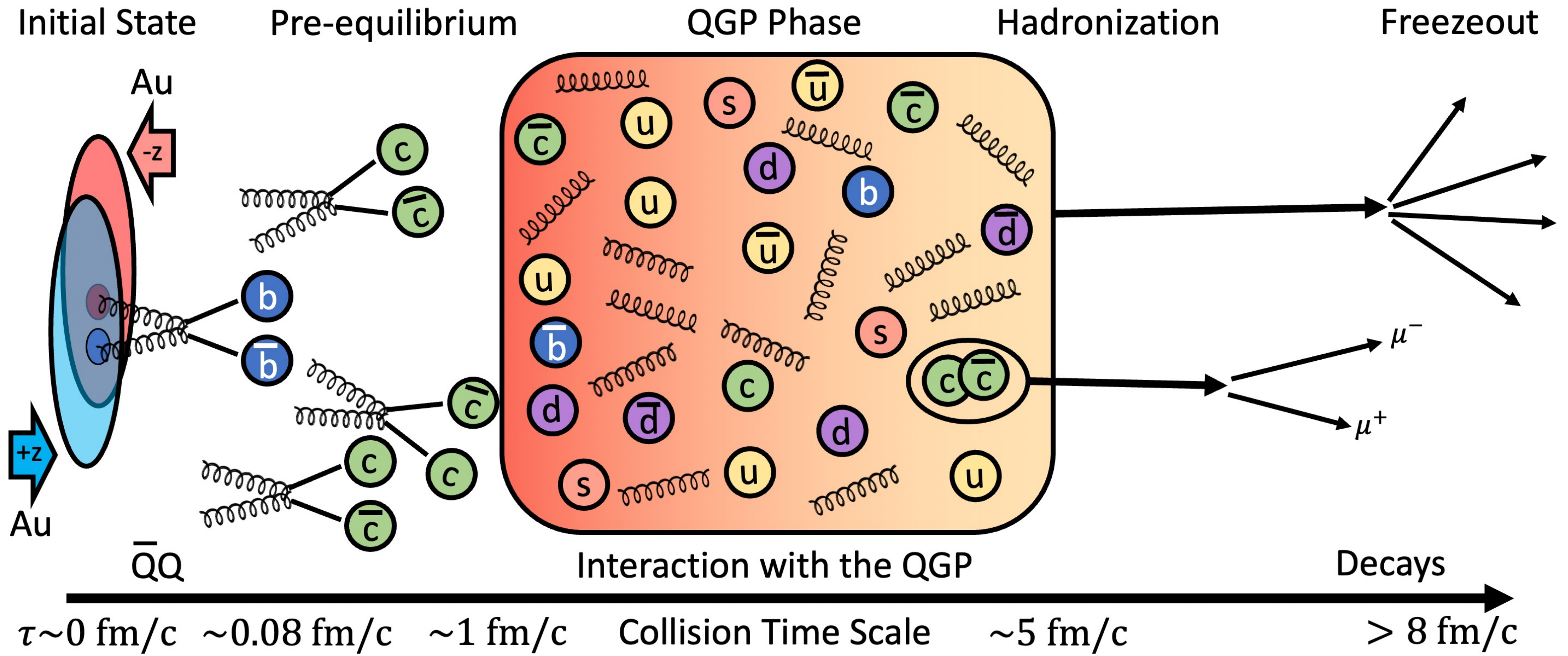
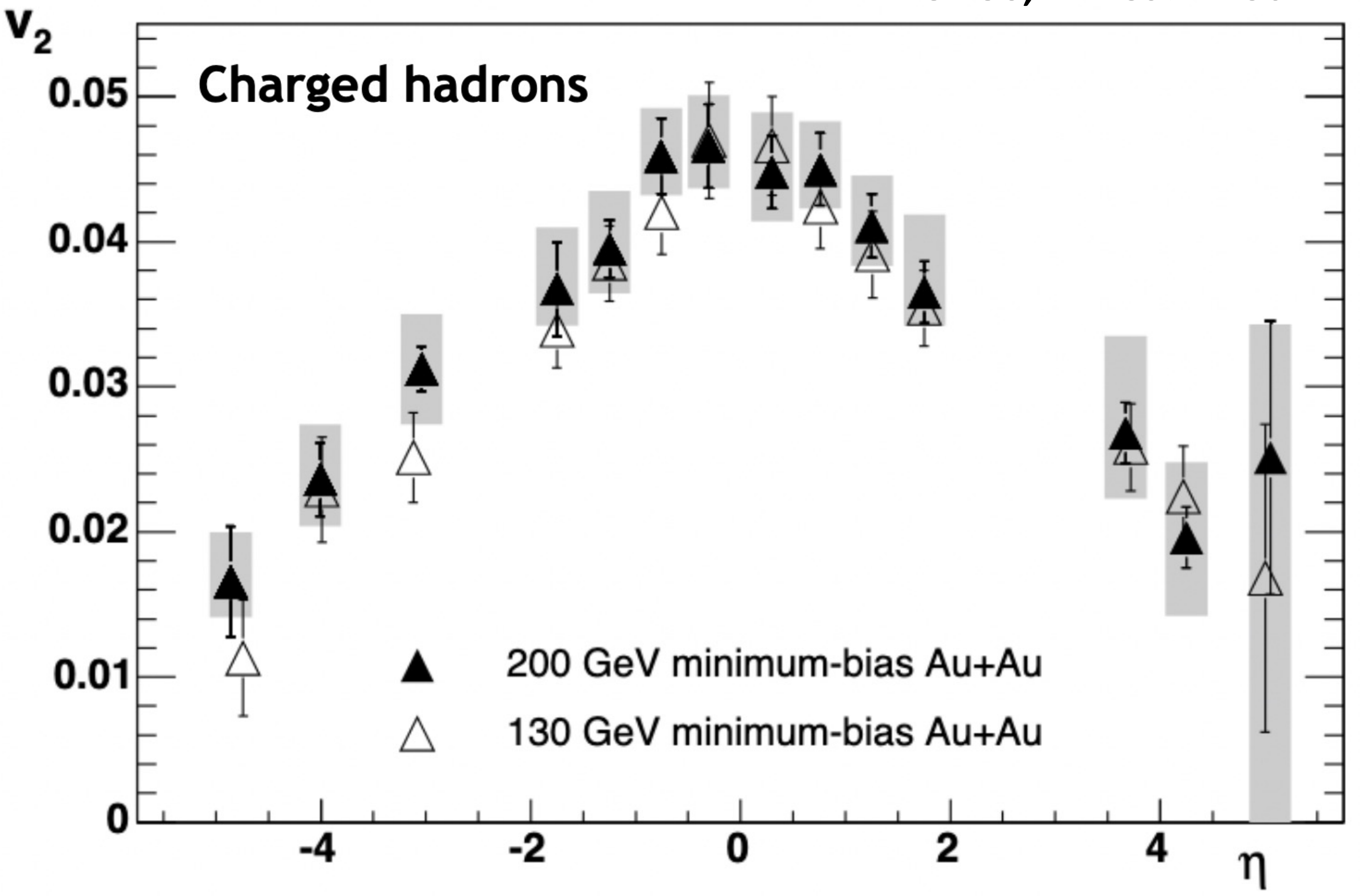


Rapidity dependence of QGP interactions

PHOBOS, PRL 89.222301

- Rapidity dependence of flow gives access to the longitudinal dynamics of the QGP
- Heavy flavor and quarkonia dynamics have rapidity-dependent initial state effects
- **Does rapidity influence heavy flavor v_2?**



The PHENIX Experiment

CENTRAL ARM (Electrons)

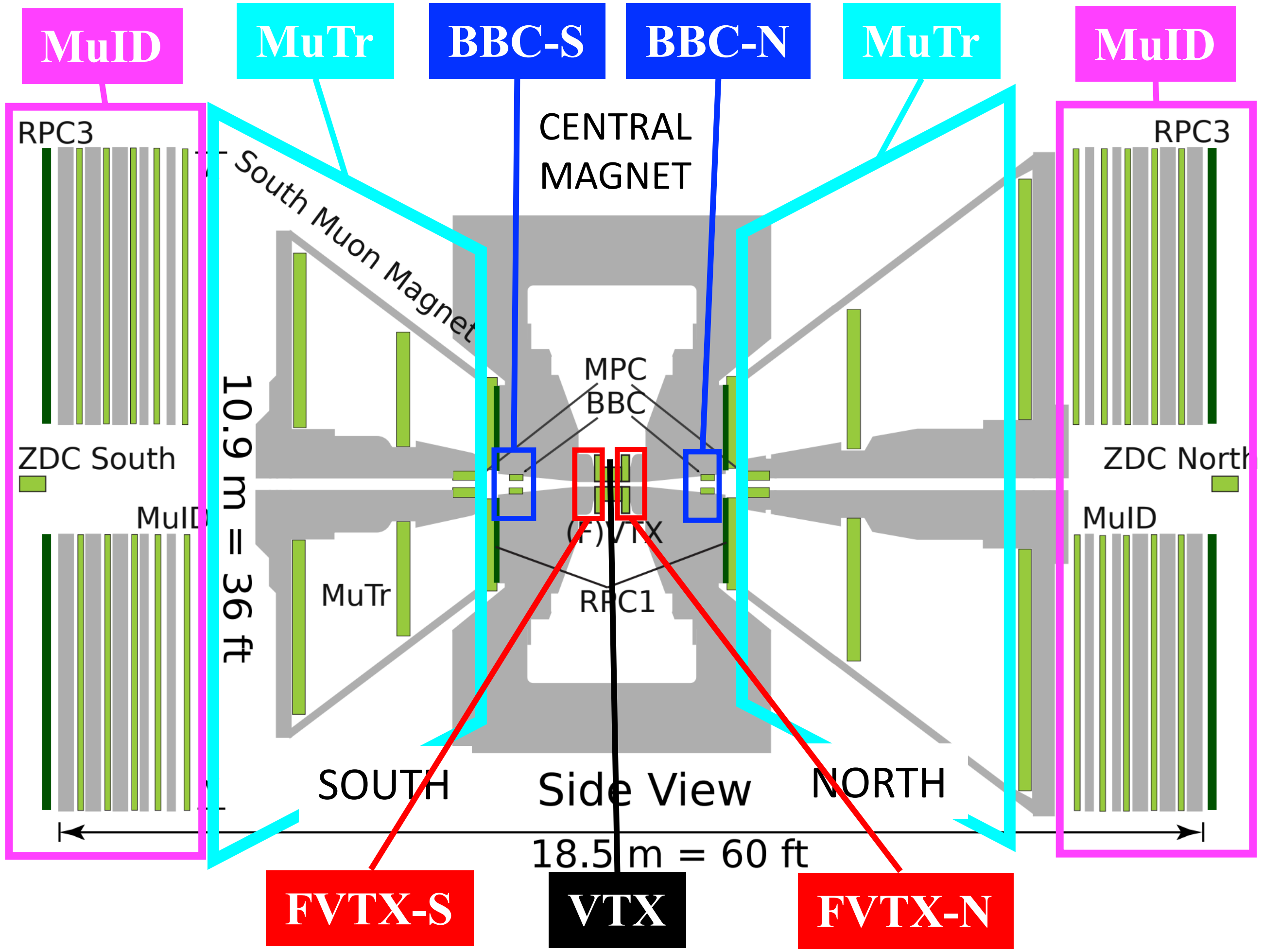
- $|\eta| < 0.35$
- $\Delta\phi = \pi$
- Tracking: DC, PC, **VTX**
- eID: RICH, Emcal

BBC (Event Characterization)

- $3.1 < |\eta| < 3.9$
- Centrality, z-vertex and EP determination

FORWARD ARMS (Muons)

- $1.2 < |\eta| < 2.2$
- $\Delta\phi = 2\pi$
- Tracking: MuTr, FVTX
- MuID: Muon Identification detector

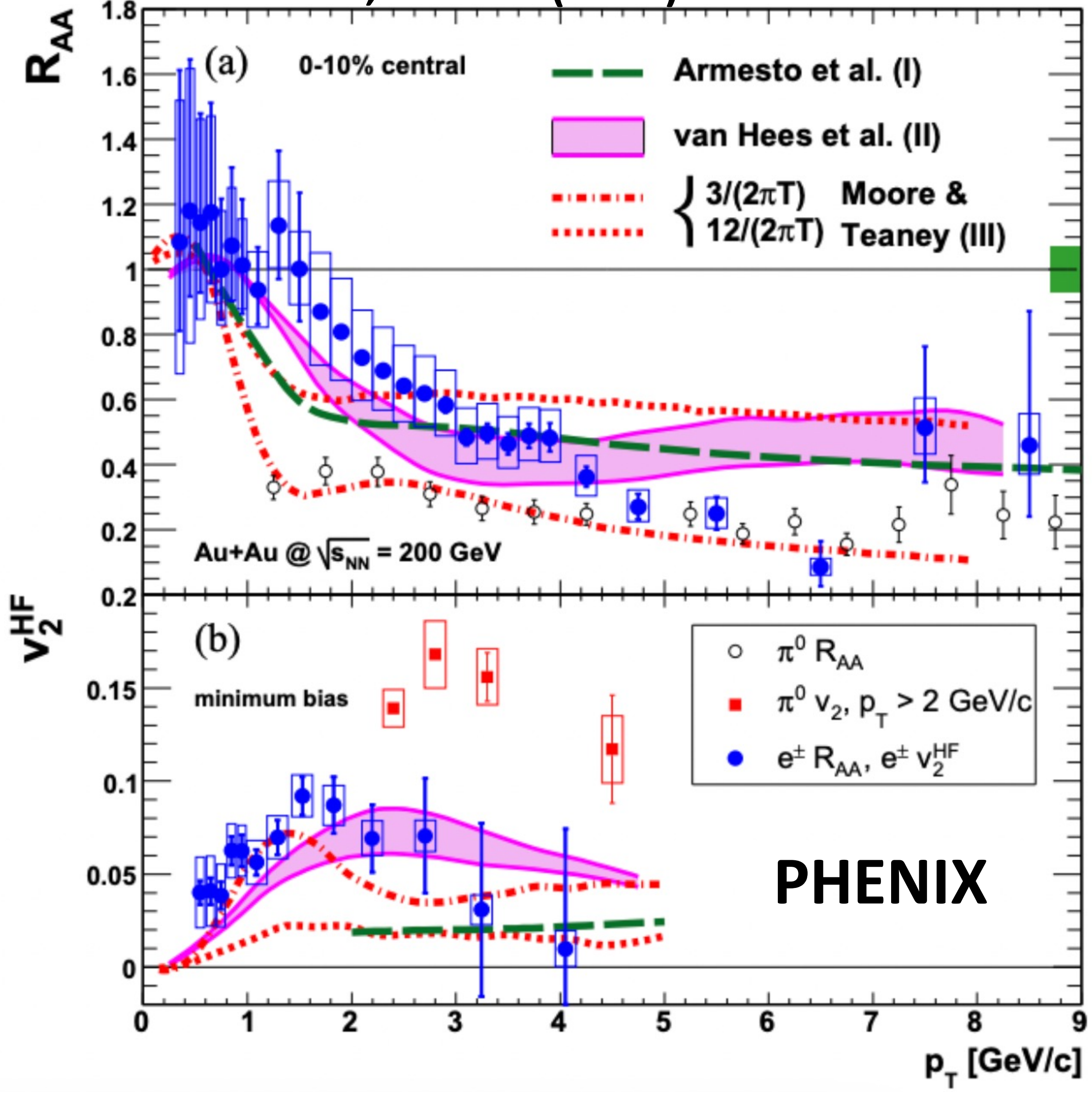


Run 14 Au+Au 200 GeV (19B MB events)
Run 16 Au+Au 200 GeV (15B MB events)

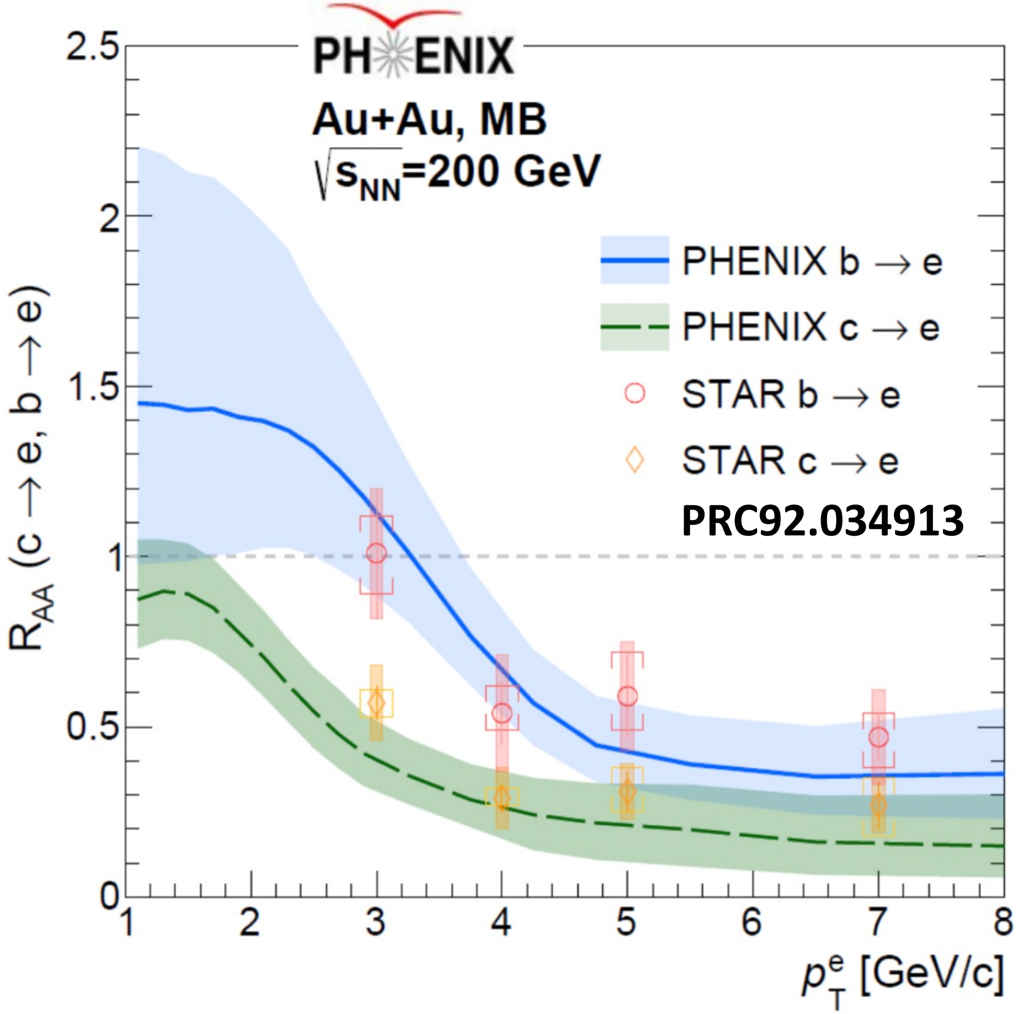
Inclusive HF R_{AA} and v_2

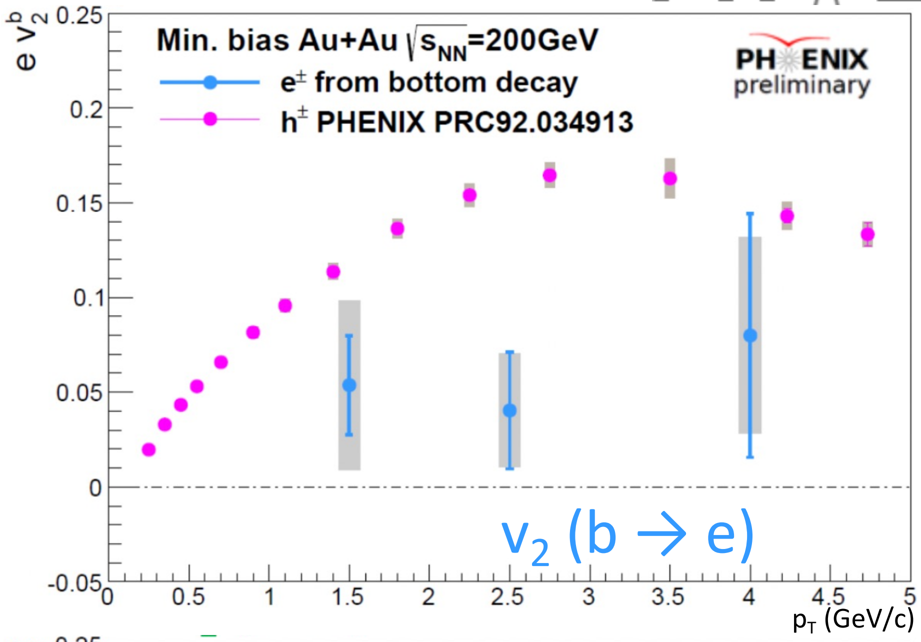
- $e^{\pm}$ from inclusive HF show significant suppression and non-zero v_2
- HF $e^{\pm}$ R_{AA} and v_2 different from neutral pions
  - Indicates mass ordering
- Do *c* and *b* exhibit the same mass ordering behavior?

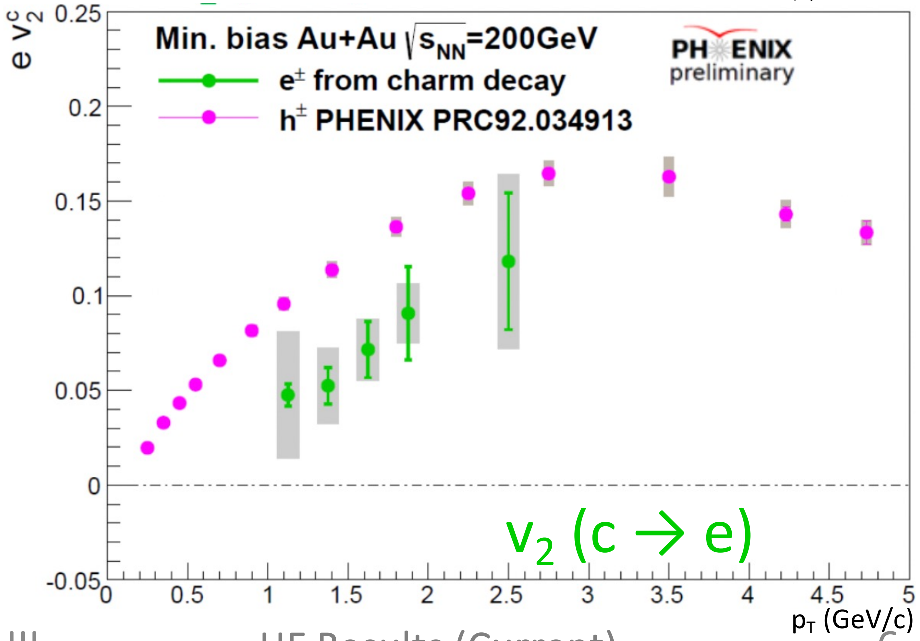
PRL 98, 172301 (2007)



Separated Charm and Beauty R_{AA} and v_2

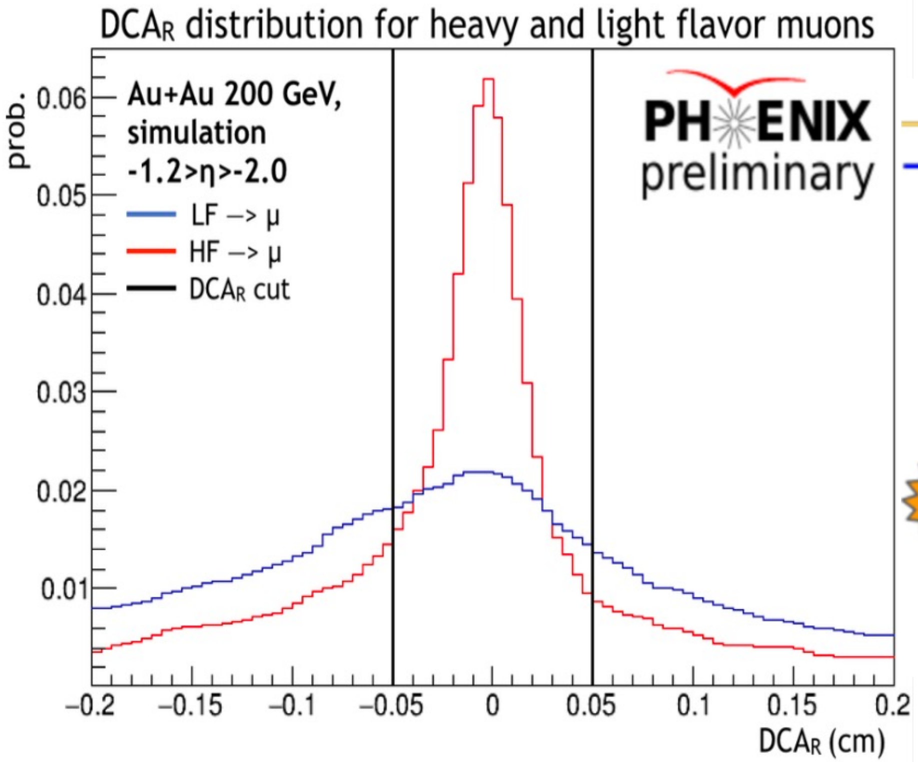


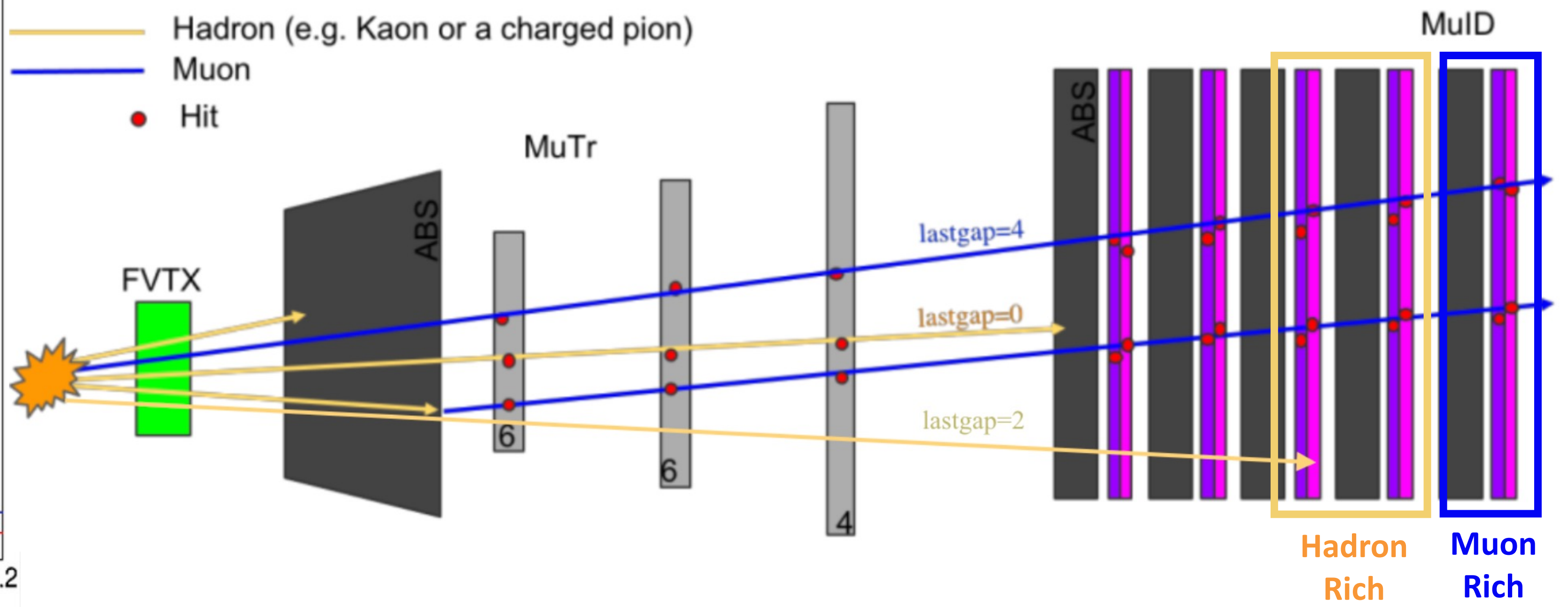




Clear mass ordering observed between ($b \rightarrow l$) and ($c \rightarrow l$) at RHIC for both R_{AA} and v_2

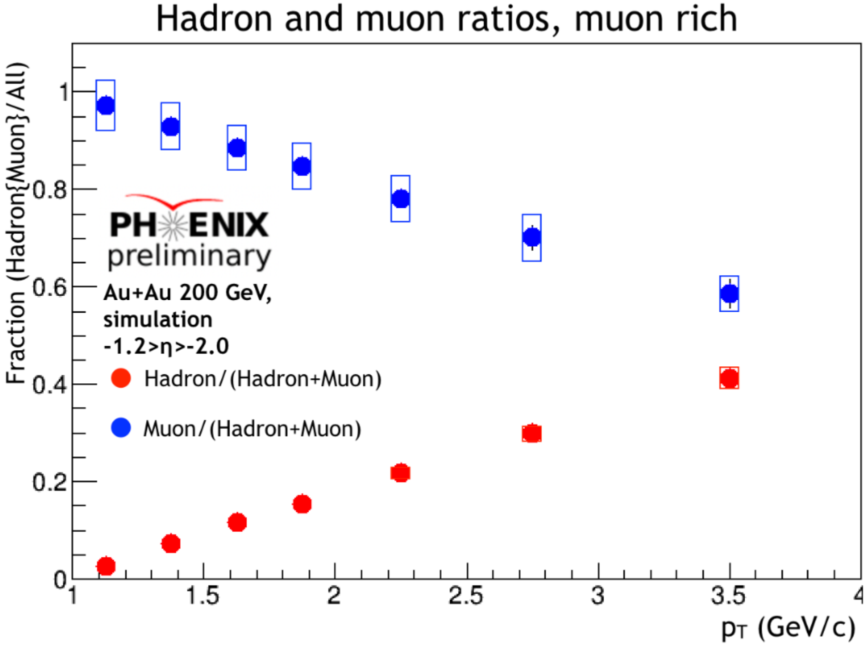
Single Muon Analysis

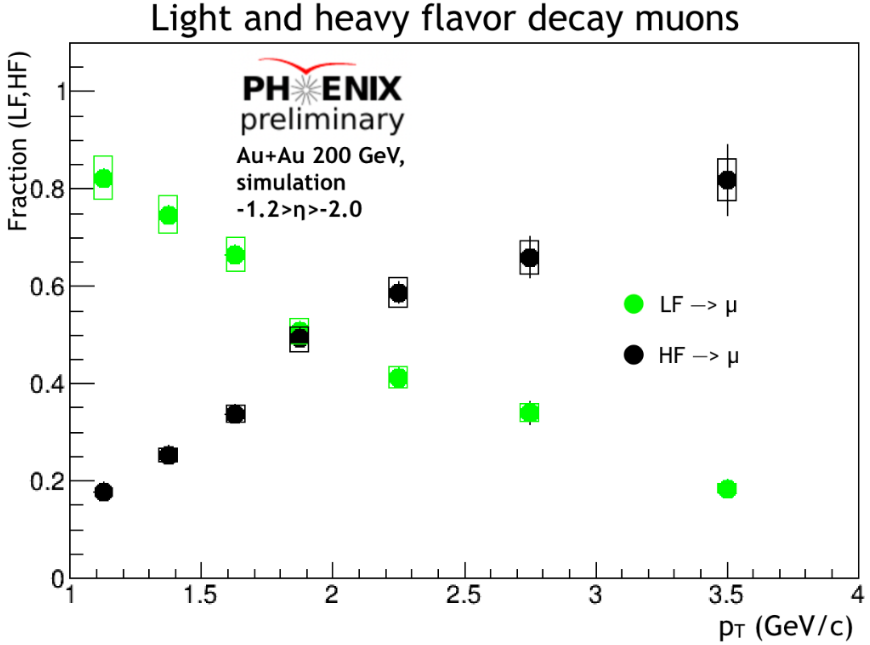


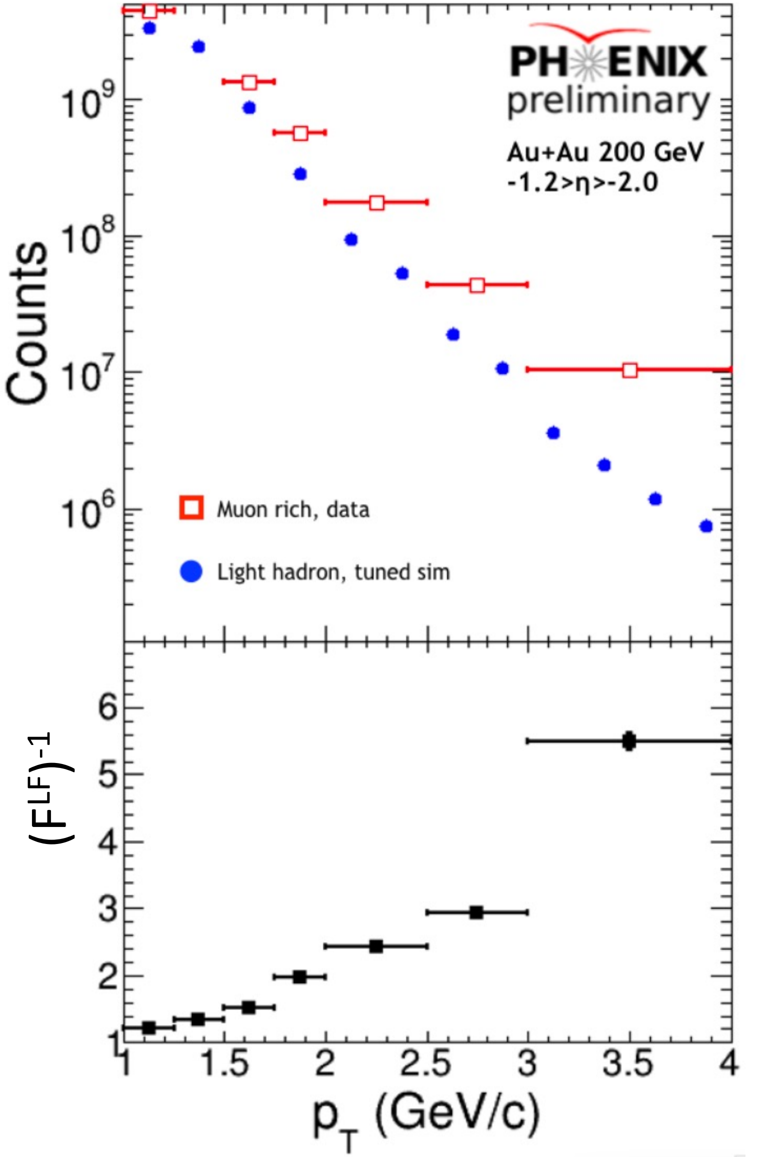


- Track quality cuts to purify muons from heavy flavor
- Extract v_2 for hadrons and inclusive muons
- Tuned MC simulating precise particle ratios to separate muons from light and heavy flavor decays

Heavy-Flavor Extraction



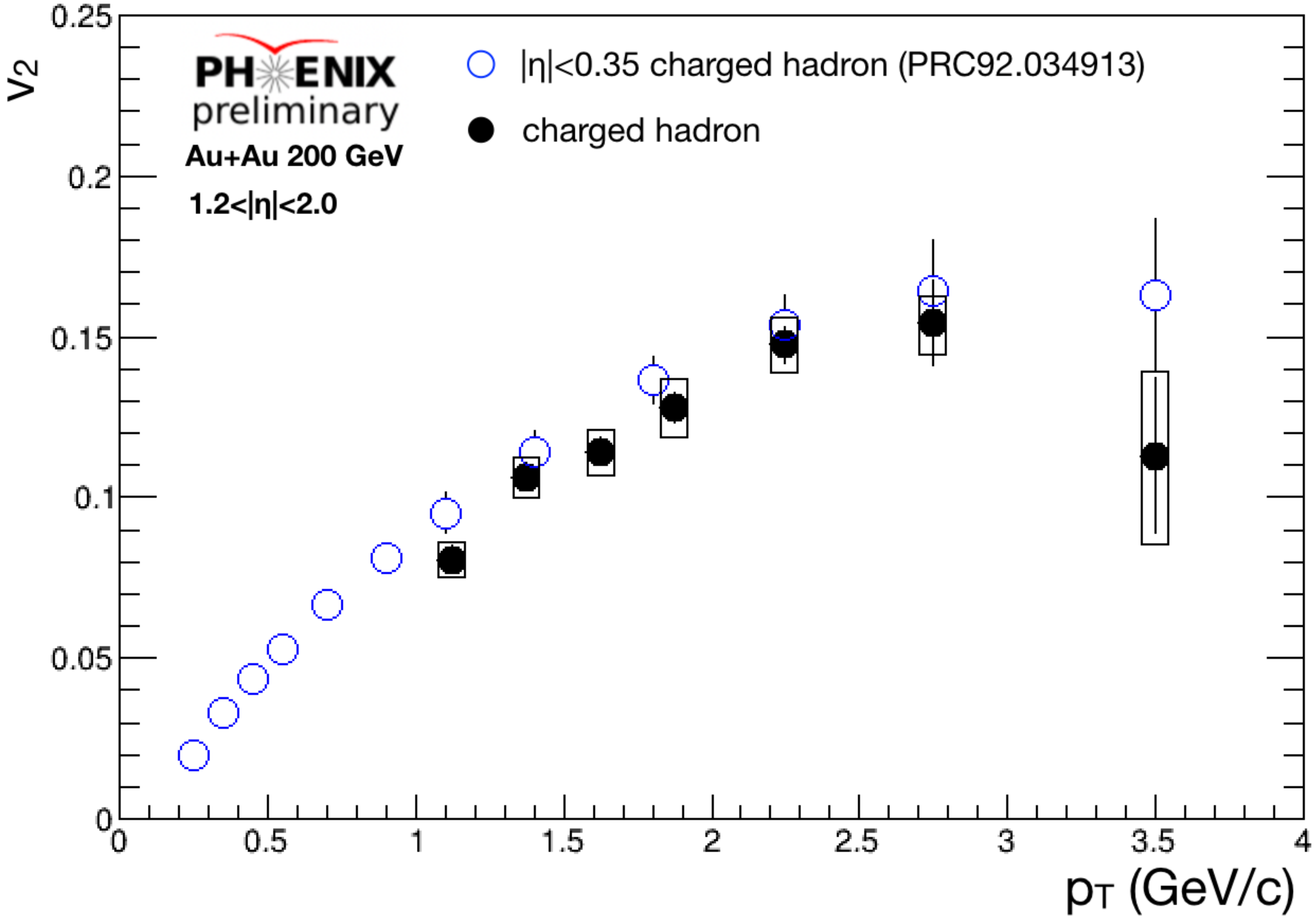




- Using tuned PYTHIA+GEANT4 embedded in real Au+Au events we can extract the inclusive muon fraction
- Extract the HF muon fraction by comparing data to tuned simulation with HF contribution excluded
- Determine heavy flavor muon v_2 in the inclusive muon sample:

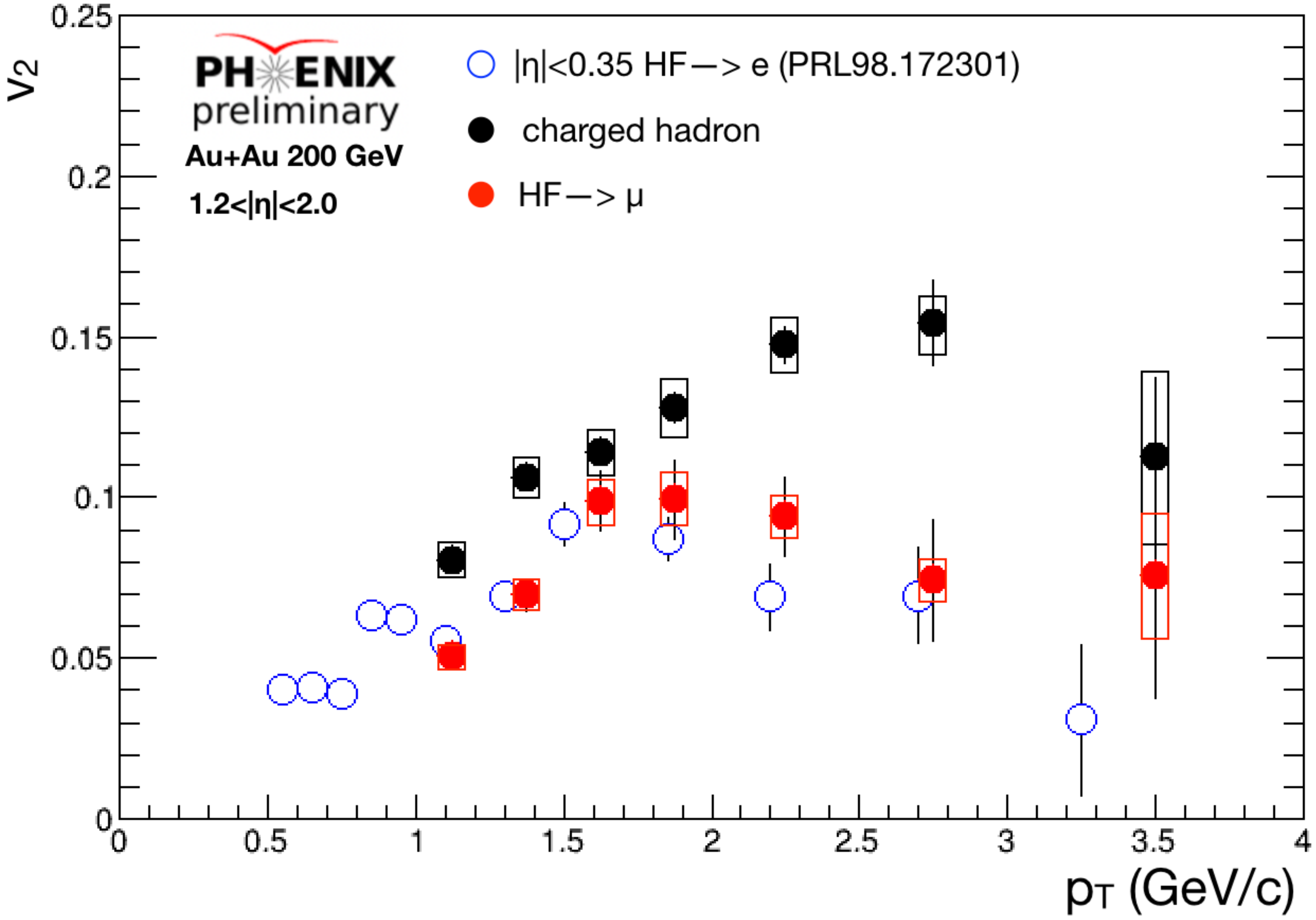
$$v_2^{HF} = \frac{1}{F^{HF}}\left(v_2^{\mu} - (1 - F^{HF})v_2^{LF}\right); \quad F^{HF} = 1 - (F^{LF})$$

PHENIX Charged Hadron v_2 Measurement



- Hint of rapidity-dependence of charged hadron v_2

PHENIX Heavy Flavor v_2 Measurement



- Hint of rapidity-dependence of charged hadron v_2
- Open HF v_2 is consistent with previous PHENIX results at mid-rapidity

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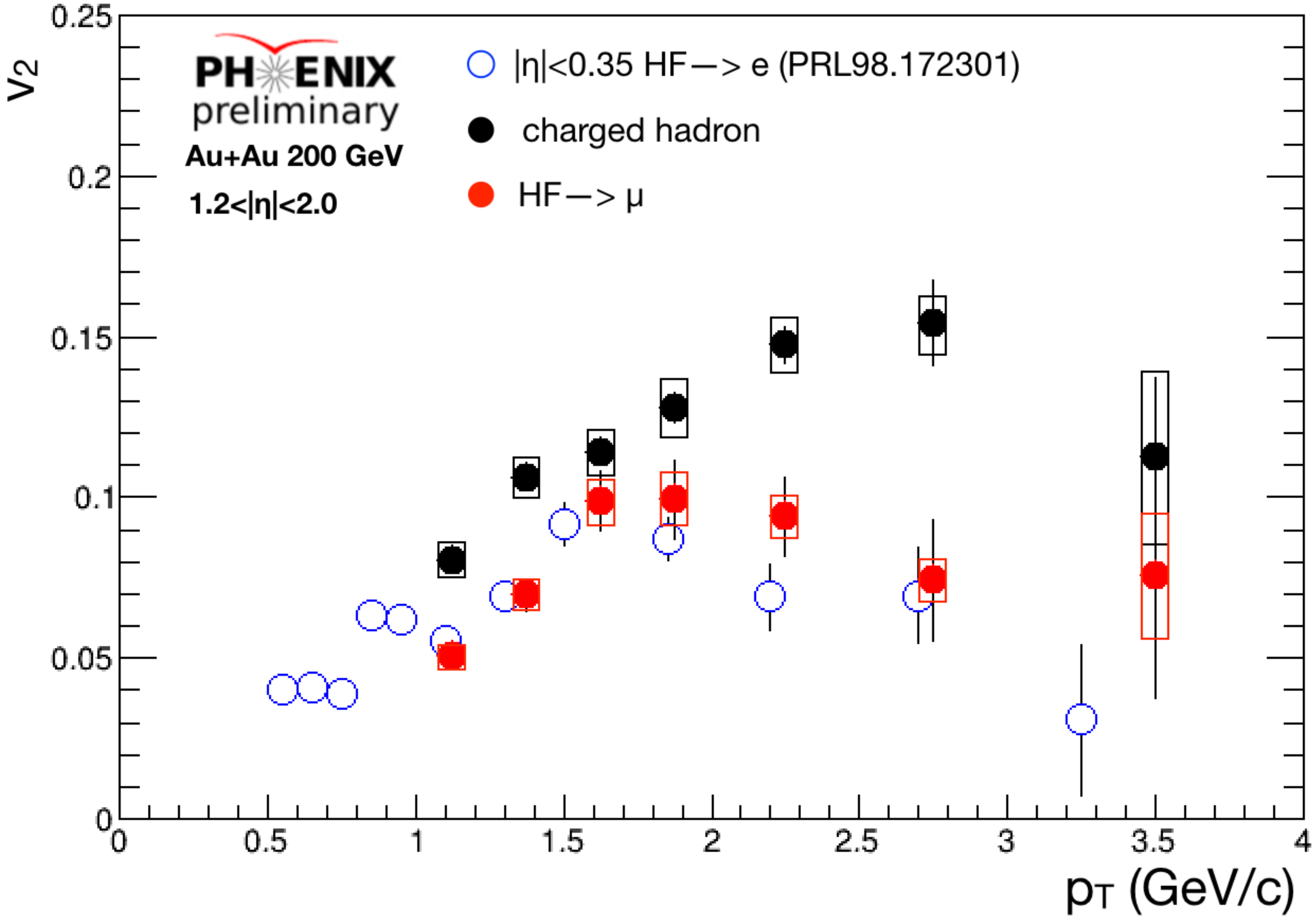
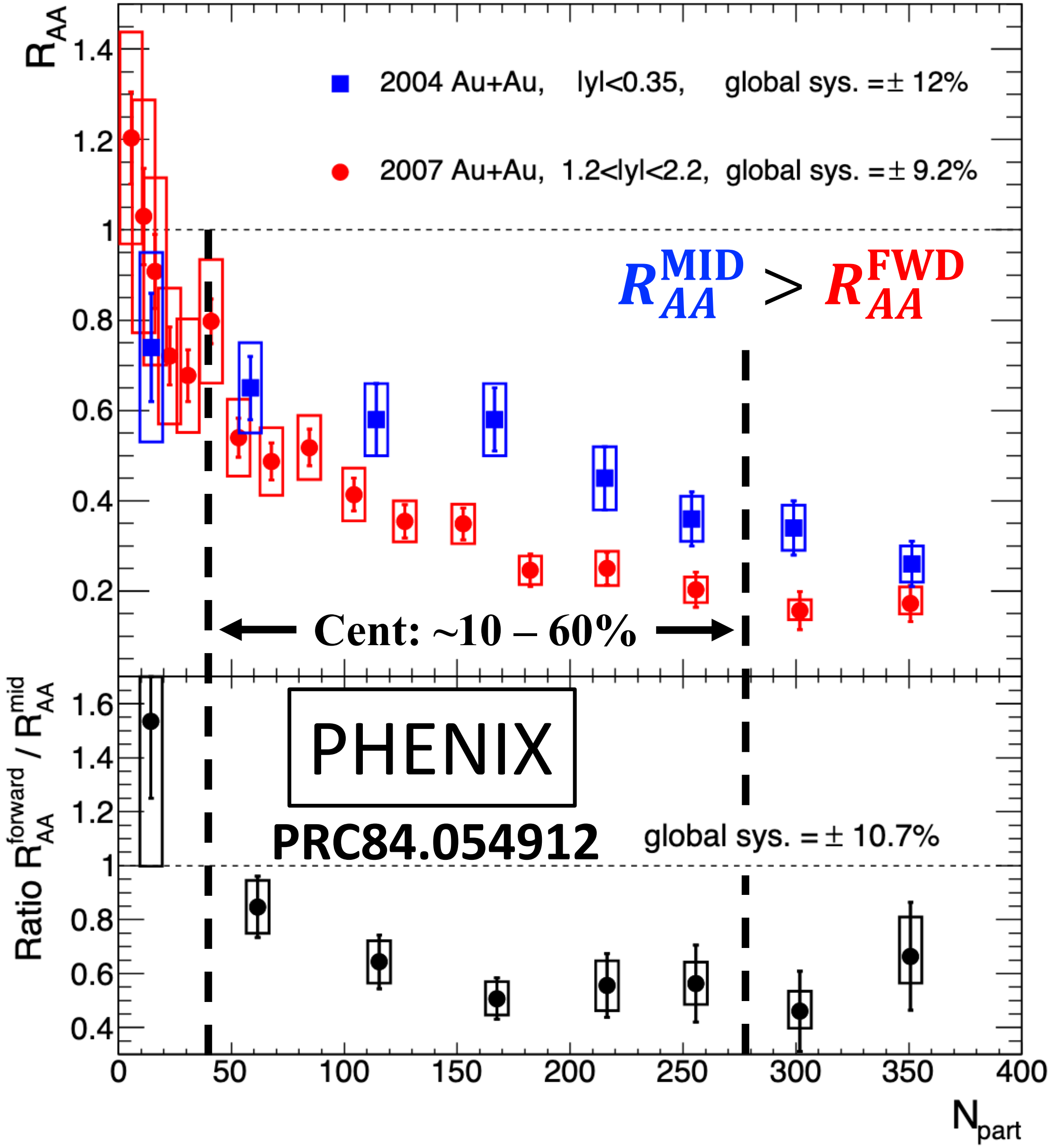
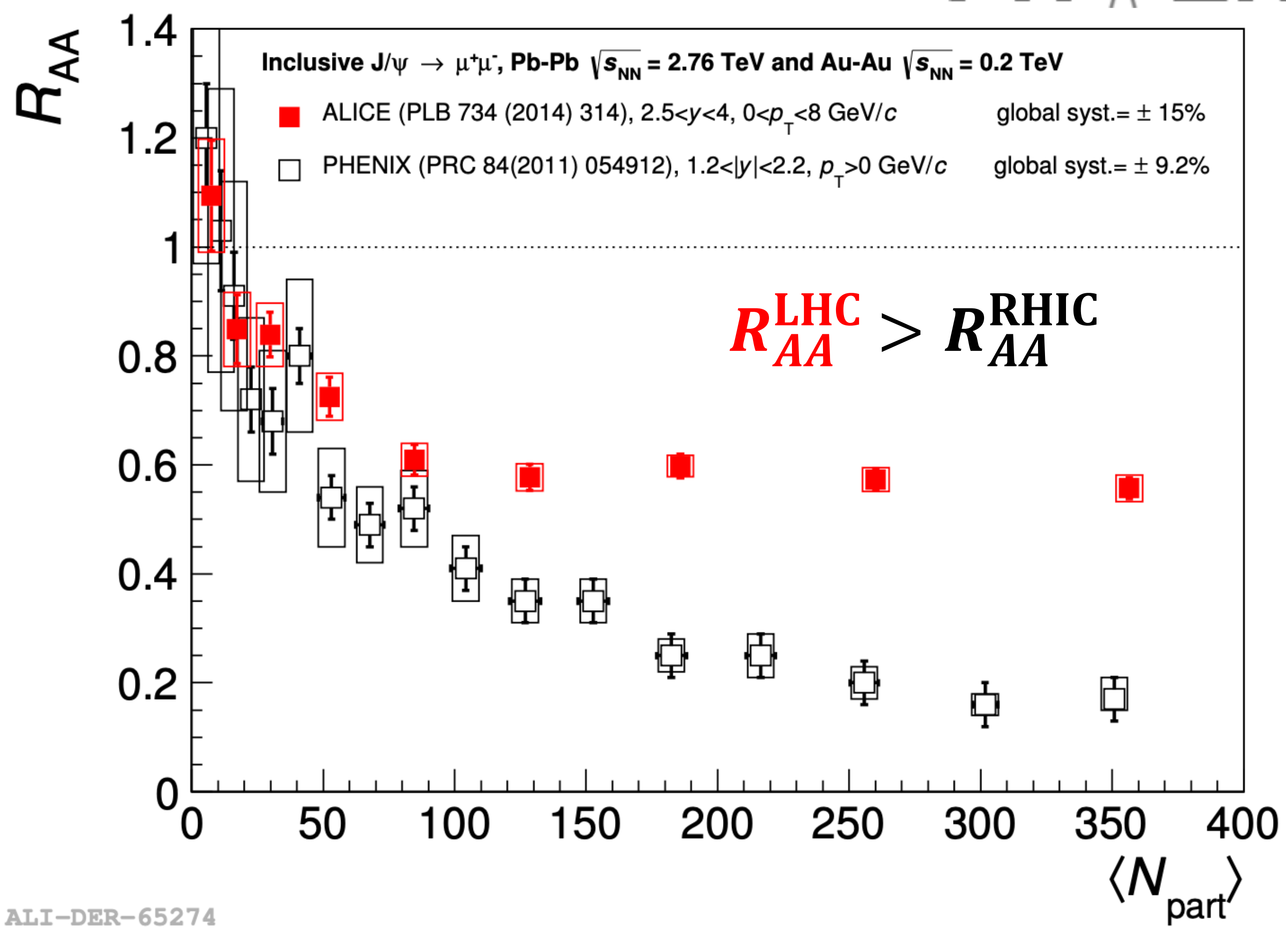


- Hint of rapidity-dependence of charged hadron v_2
- Open HF v_2 is consistent with previous PHENIX results at mid-rapidity
- **HF particles flow with the QGP, but less than charged hadrons**

J/ψ Nuclear Modification (R_{AA})





- **RHIC:** $R_{AA}^{MID} > R_{AA}^{FWD}$
- **Forward:** $R_{AA}^{LHC} > R_{AA}^{RHIC}$

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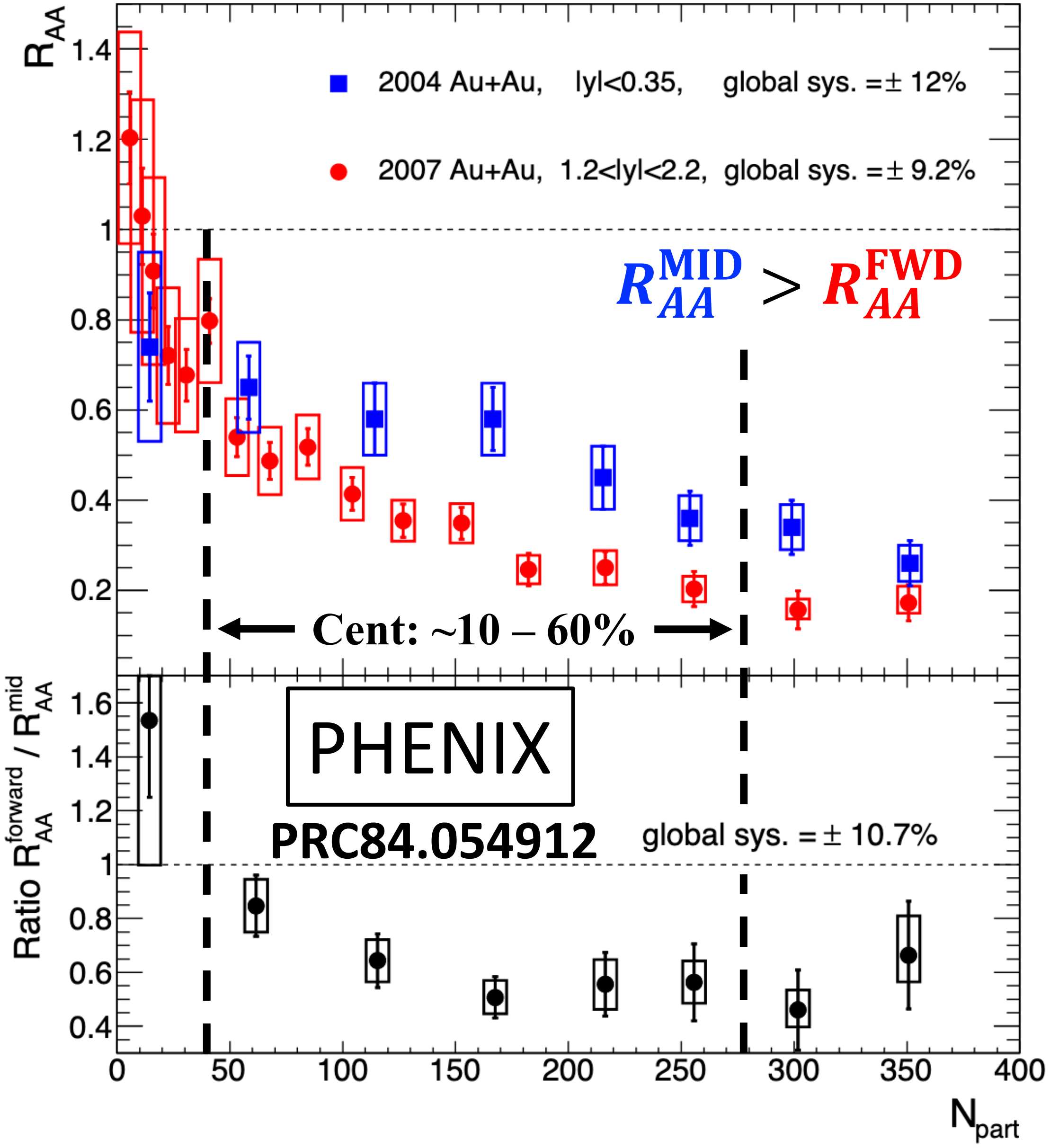
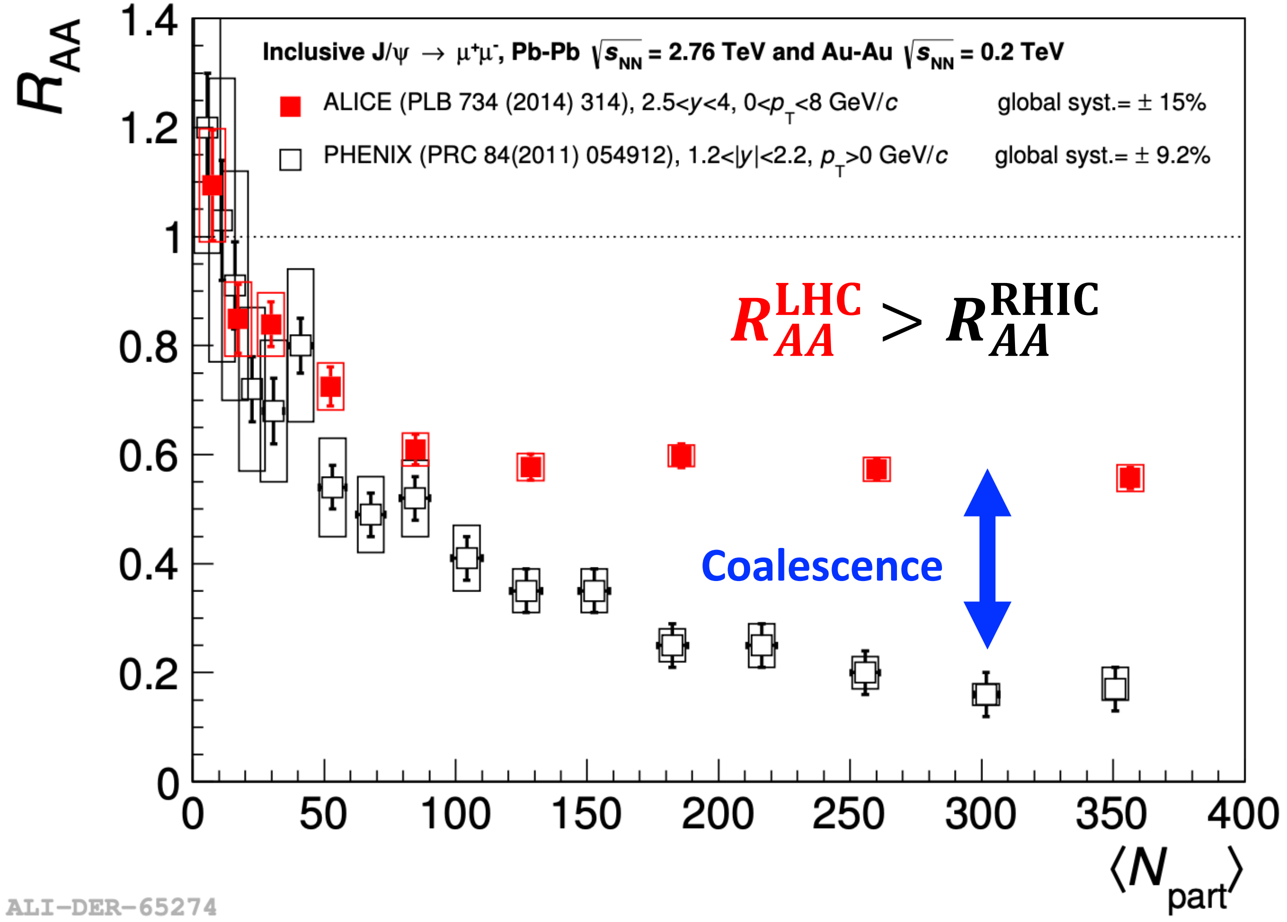
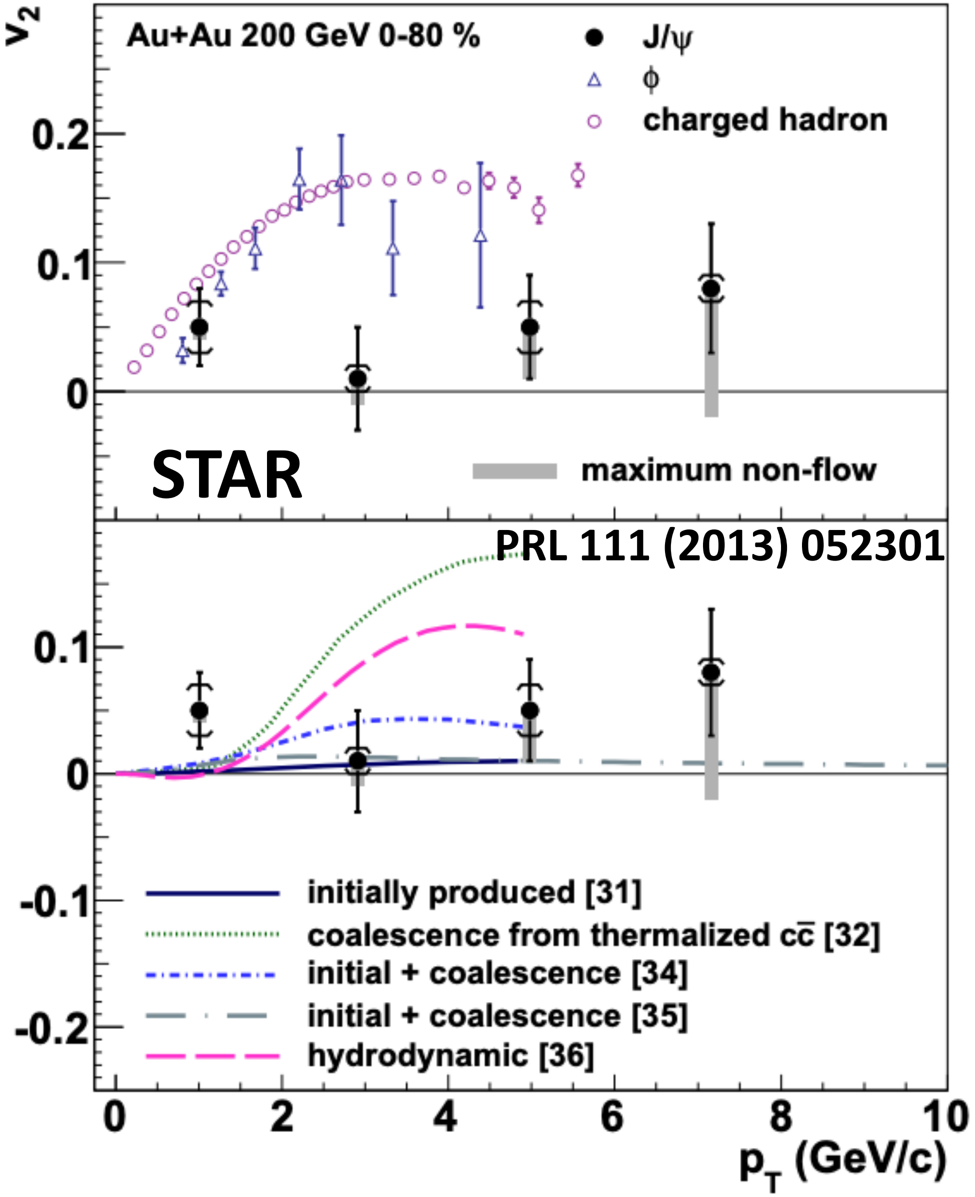
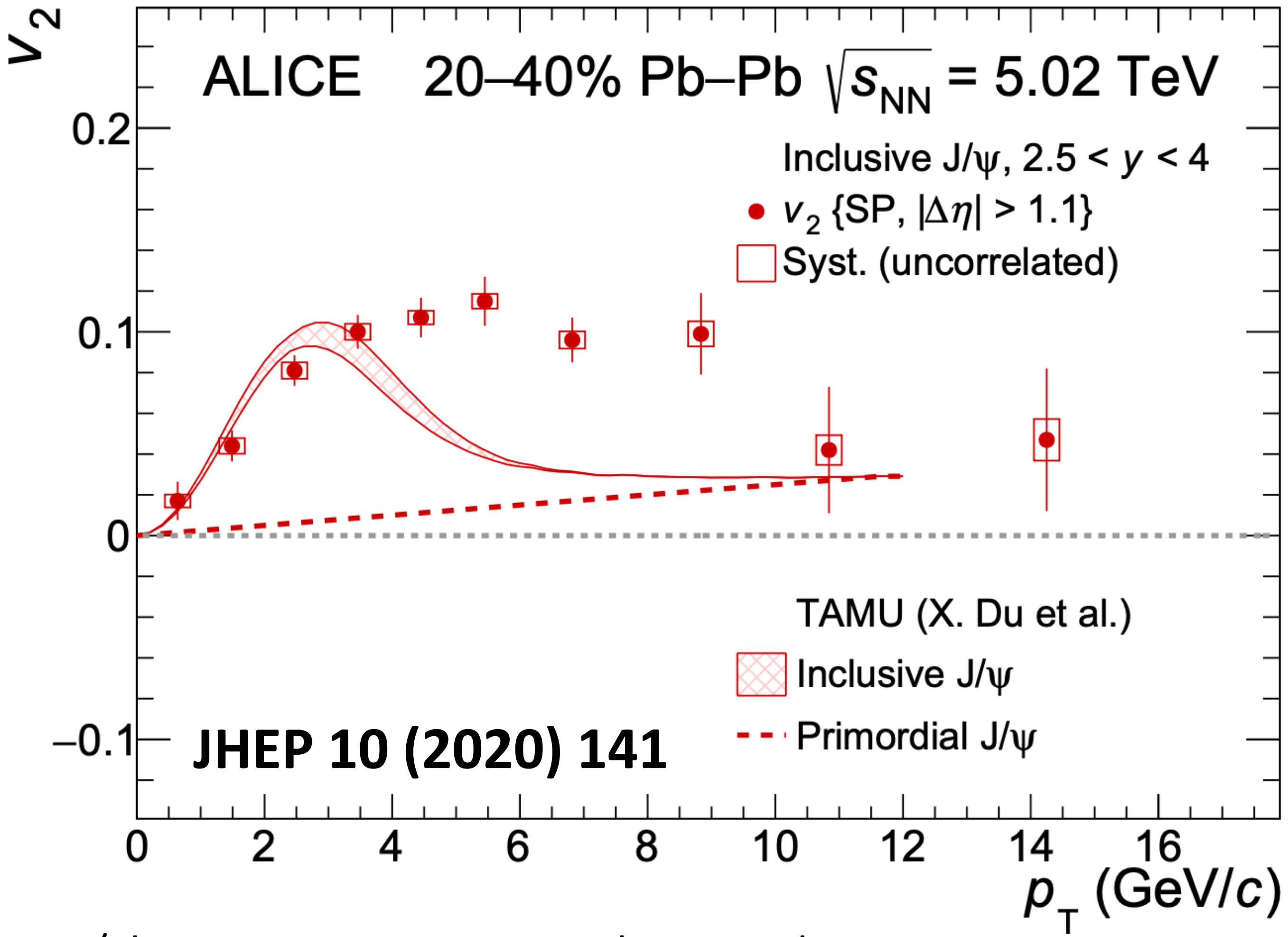




Coalescence effects between charm and anticharm quarks leads to J/ψ regeneration at LHC

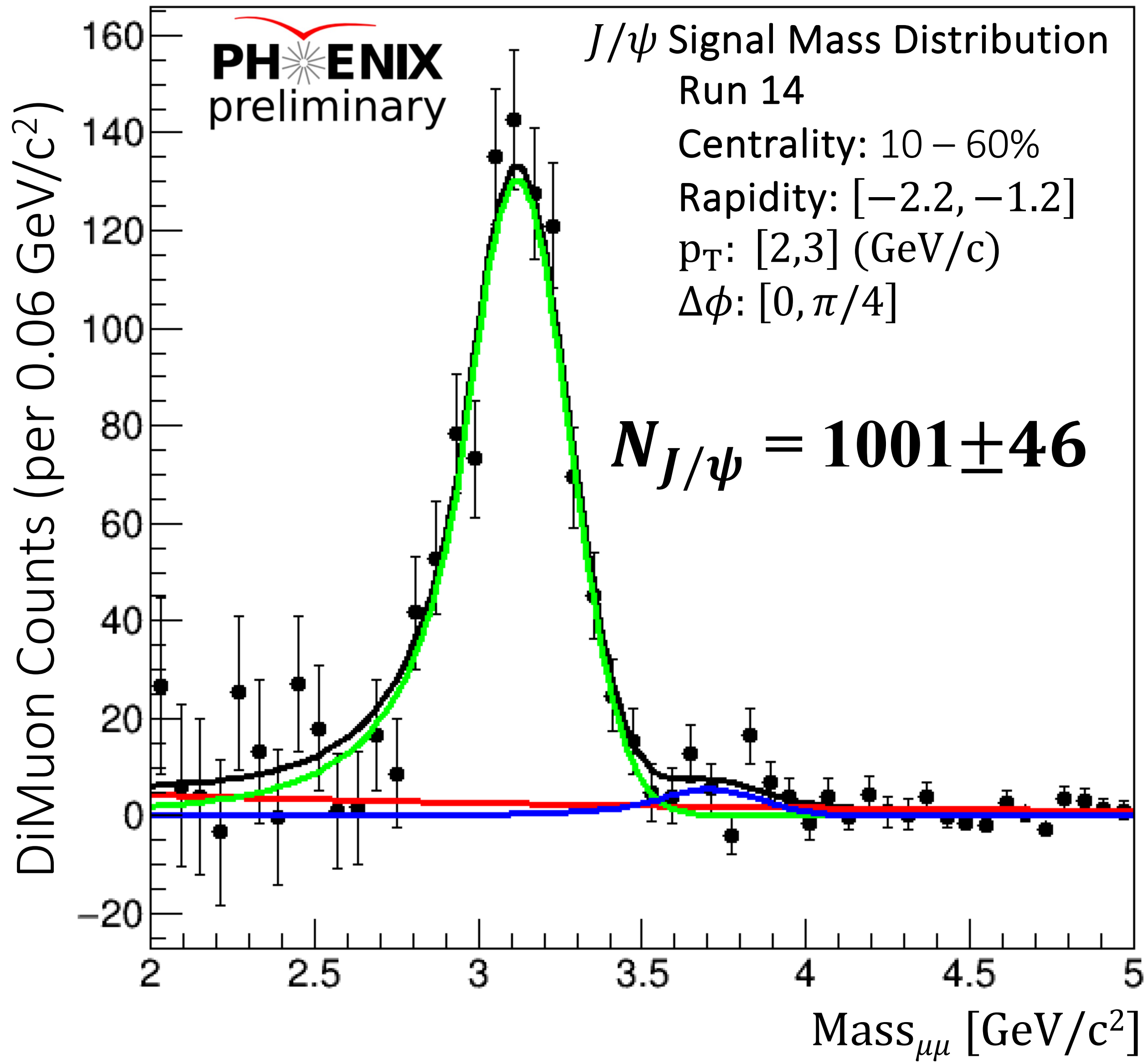
J/ψ Elliptic Flow





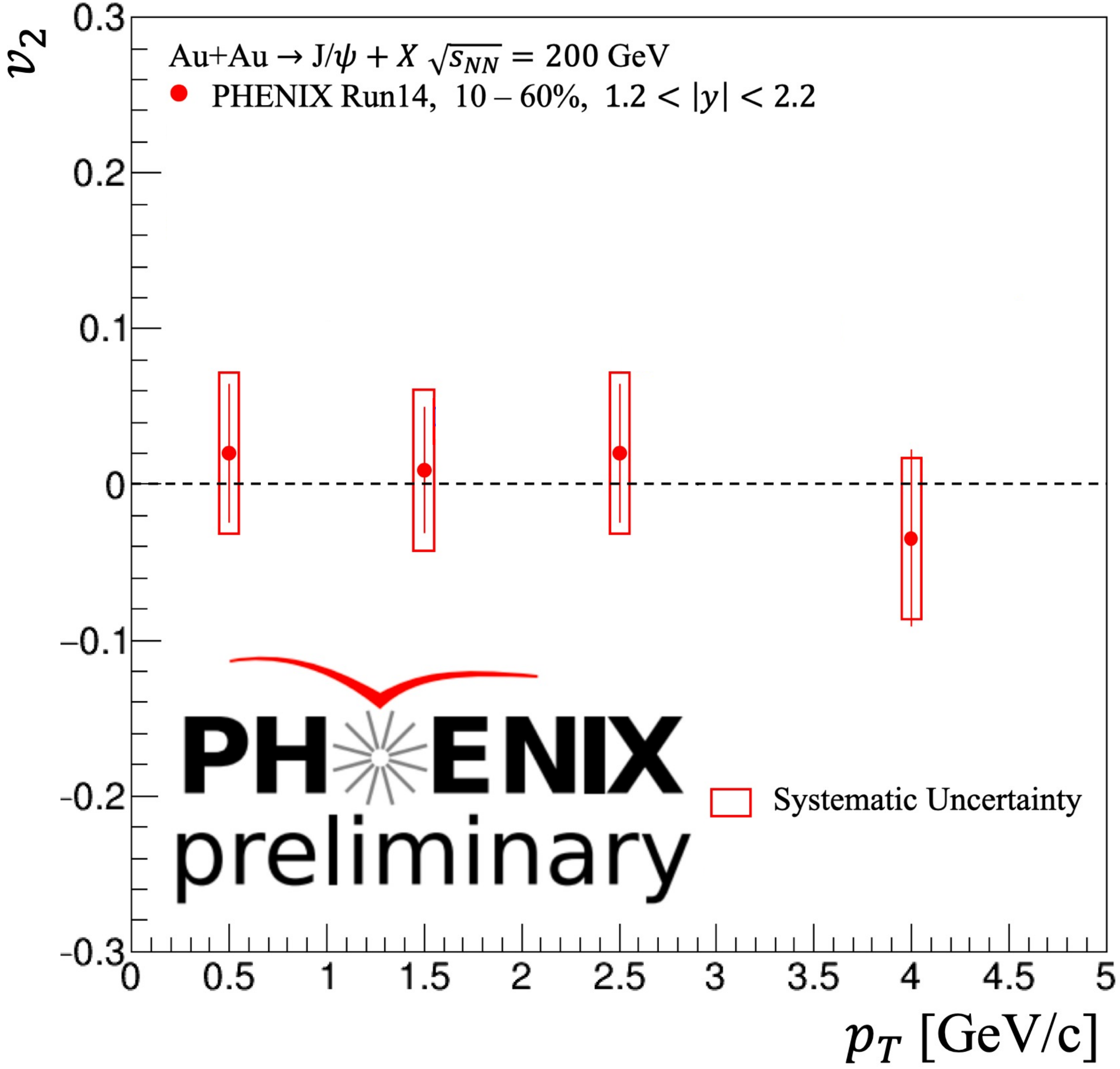
J/ψ v_2 at RHIC inconclusive, however, a significant non-zero v_2 is observed at LHC

J/ψ Signal Reconstruction (J/ψ → μ^++μ^-)



- Candidate J/ψ are reconstructed using dimuon decay channel
- 10-60% centrality will maximize potential v_2 signal
- Measure the J/ψ yield in-plane and out-of-plane to determine v_2

PHENIX J/ψ v_2 Measurement



- PHENIX J/ψ v_2 at forward rapidity is consistent with 0.

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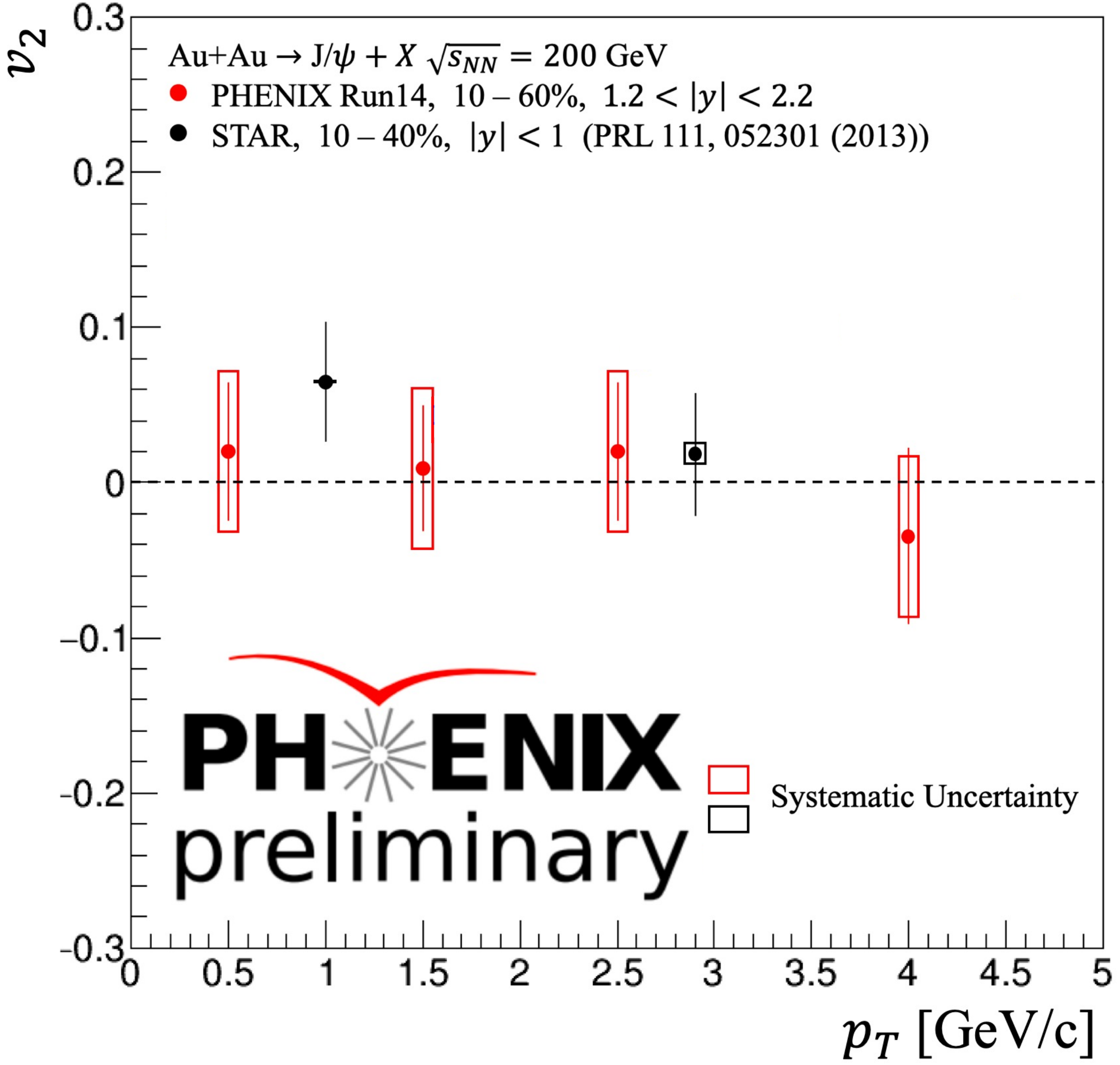

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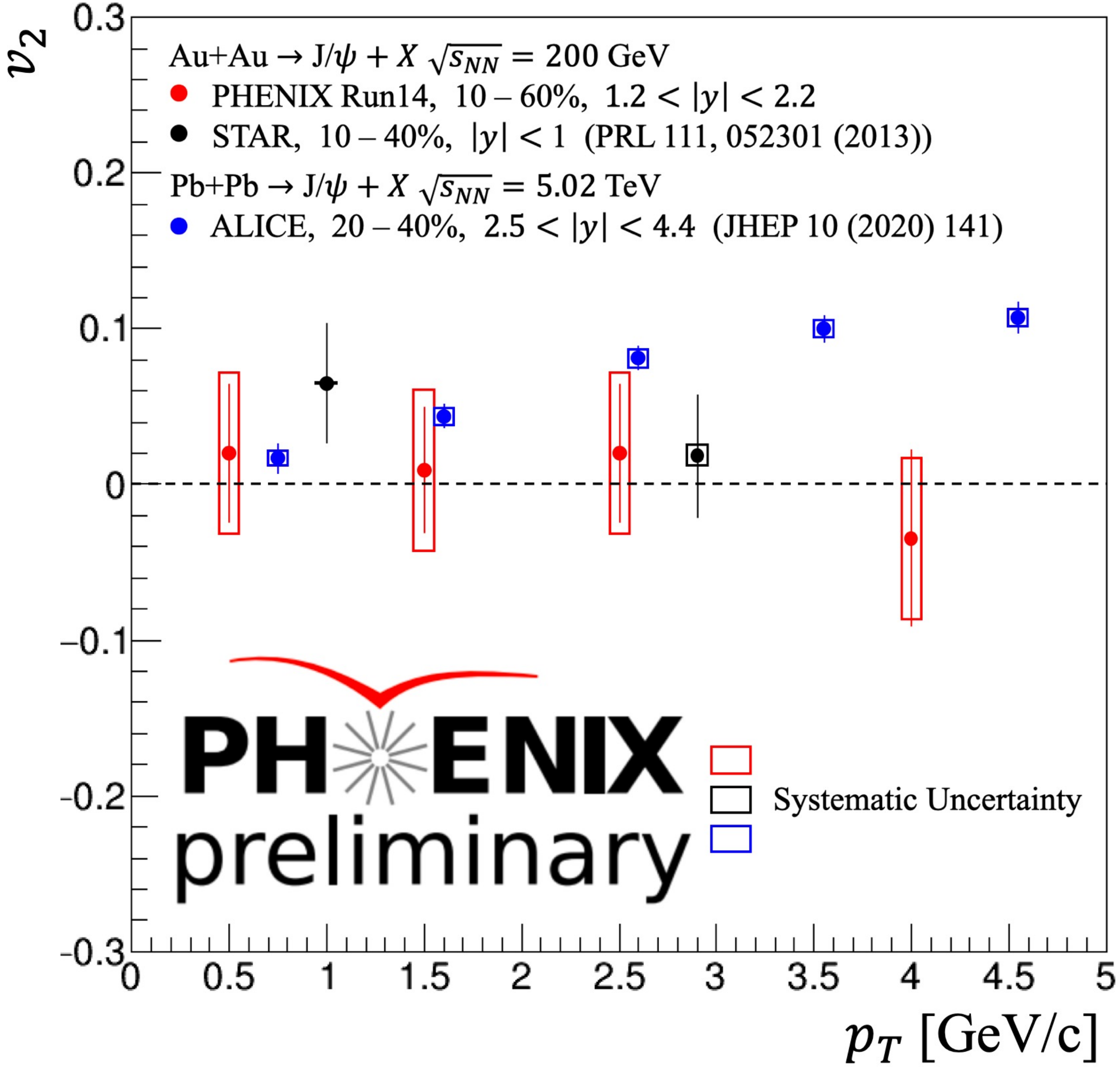

- PHENIX J/ψ v_2 at forward rapidity is consistent with 0.
- Forward and mid-rapidity results at RHIC are consistent, but the uncertainties are large
- The ALICE nonzero result is different from our measurement.

Summary and Outlook

Midrapidity:

- $R_{AA}^{b} > R_{AA}^{c}$
- $v_2^h > v_2^c > v_2^b$

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Forward Rapidity [unique coverage for PHENIX]:

- $h^{\pm}\ v_2$ results consistent, but may hint at a rapidity dependence
- Muons from heavy flavor decays flow ($v_2^{HF} > 0$)
- Open heavy flavor flow is consistent between rapidity regions at RHIC

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Midrapidity:

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Forward Rapidity [unique coverage for PHENIX]:

- $h^{\pm}\ v_2$ results consistent, but may hint at a rapidity dependence
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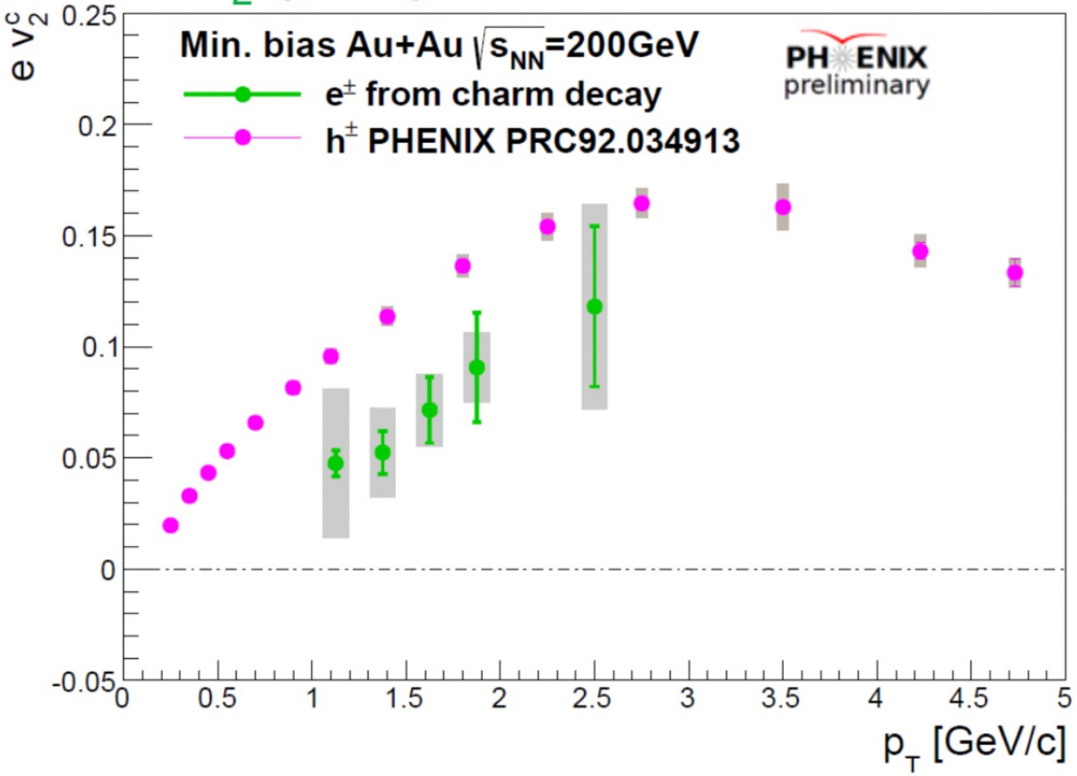
- PHENIX forward rapidity J/ψ v_2 is consistent with 0
- J/ψ v_2 measurements are consistent between rapidity regions at RHIC
- The ALICE result is distinctly different than our measurement

Backup Slides

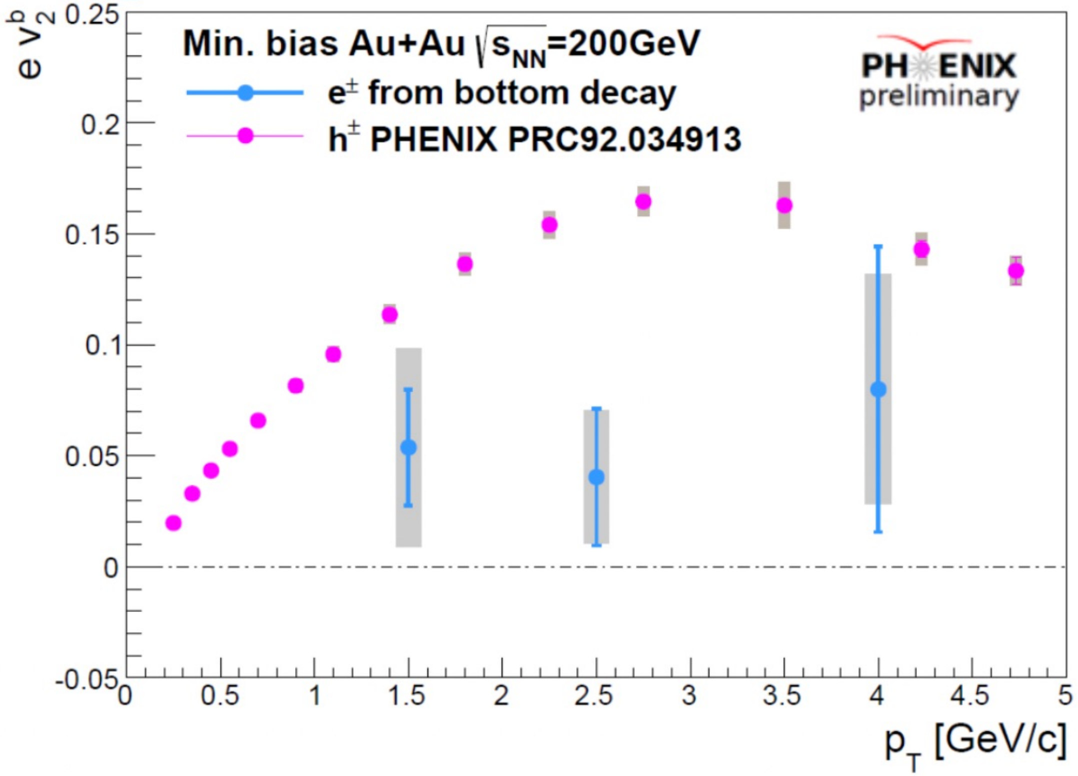
PHENIX Separated c and b v_2

PHENIX

$v_2^c(c \rightarrow e)$



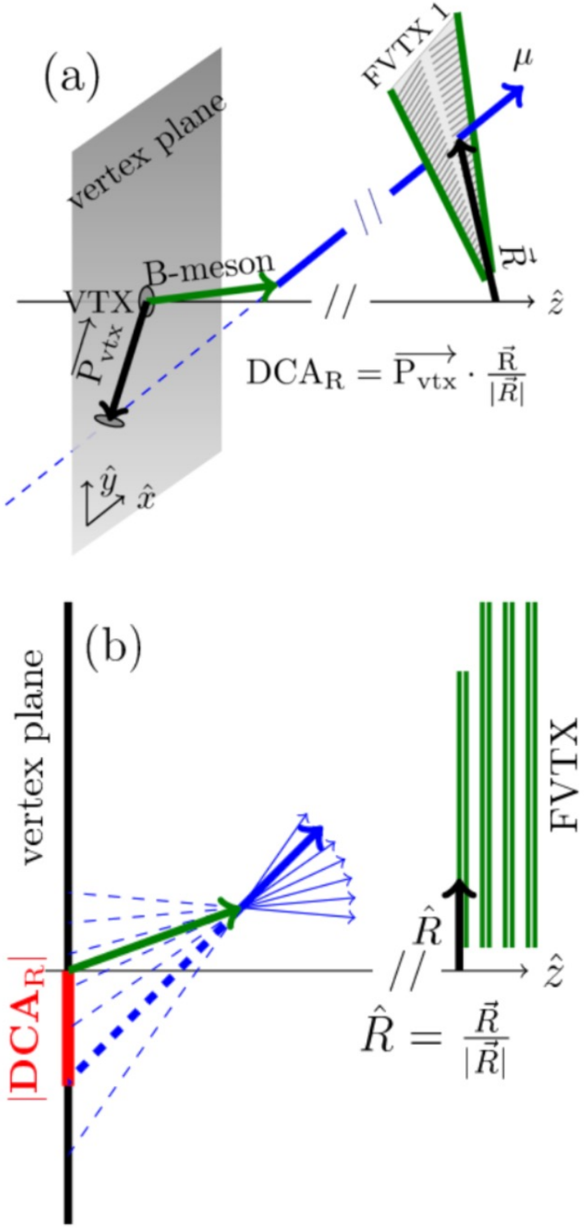
$v_2^b(b \rightarrow e)$



- $v_2(c \rightarrow e)$ is positive within $\sim 3.5\sigma$ and follows trend of hadron charged v_2
- $v_2(b \rightarrow e)$ appears positive within $\sim 1.1\sigma$
- Mass ordering is seen similar to R_{AA} measurements

Radial Distance of Closest Approach

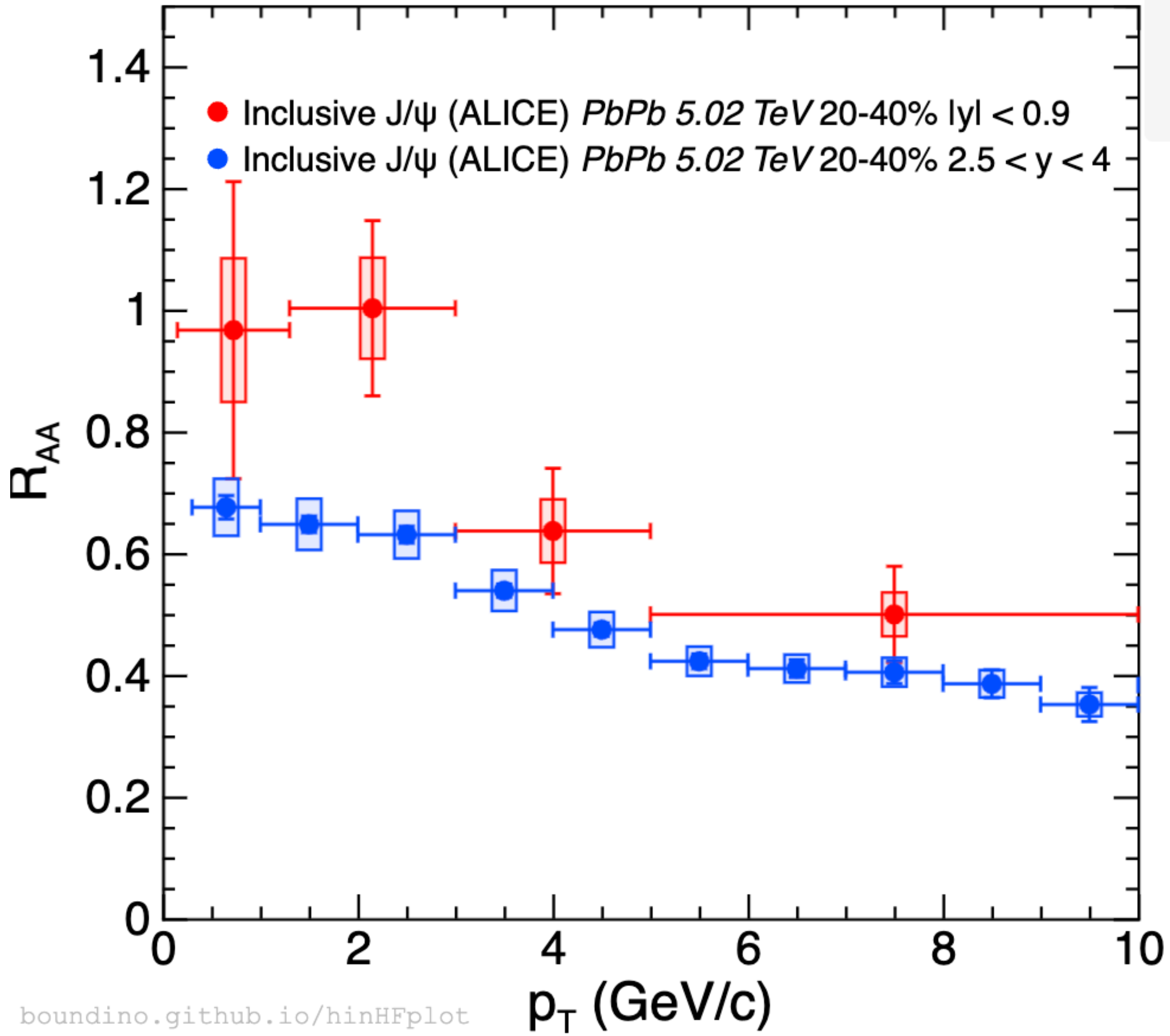
- DCA_r is determined by projecting the particle track determined by the FVTX onto a plane in the *z*-axis located at the initial collision point
- Essentially this is a measurement of the distance from the primary vertex at which a particle was produced, i.e. for a prompt particle $DCA_r = 0$
- With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

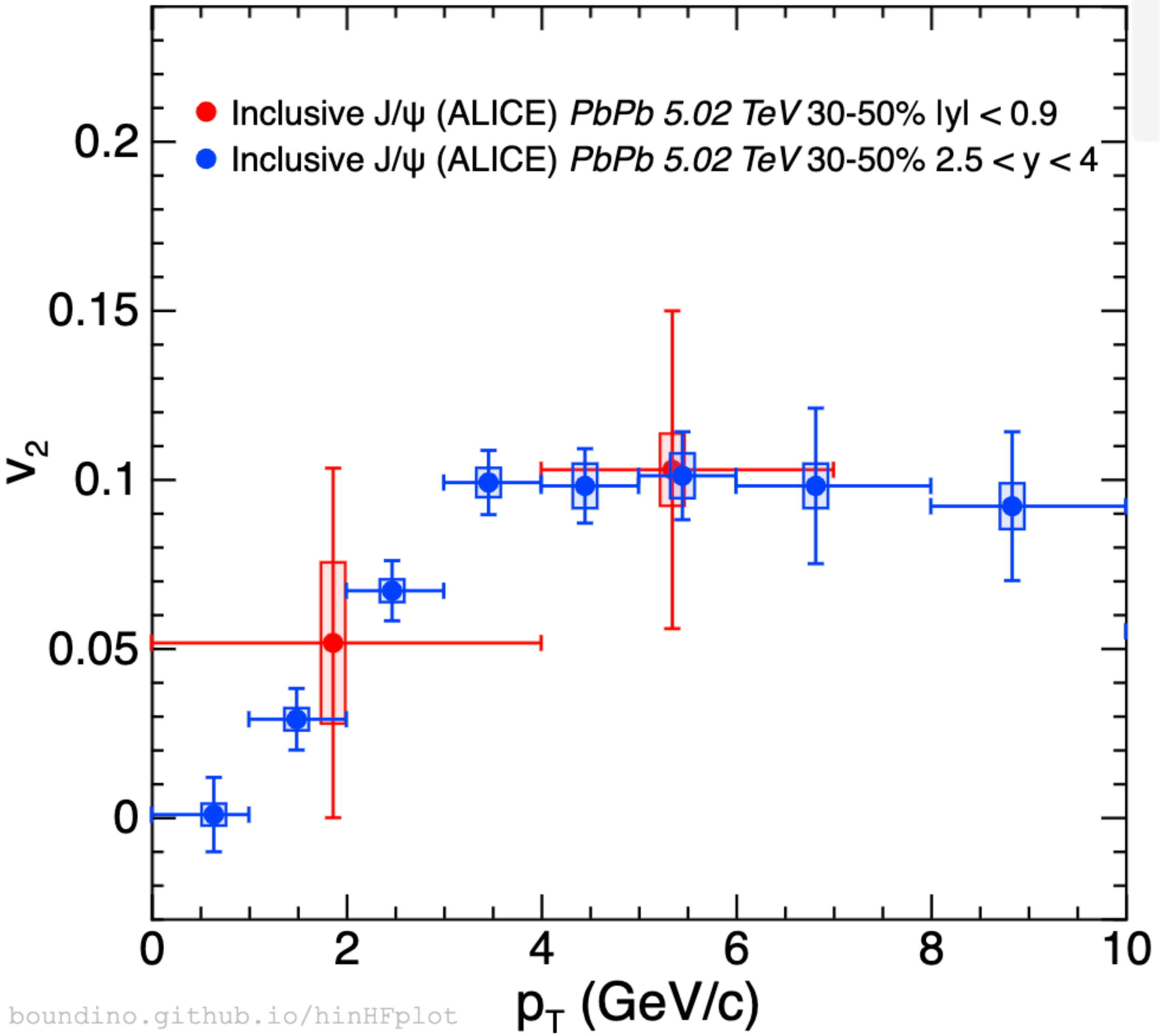


3D visualization of DCA_r

***r-z* plane visualization of DCA_r**

LHC J/ψ R_{AA} and v_2

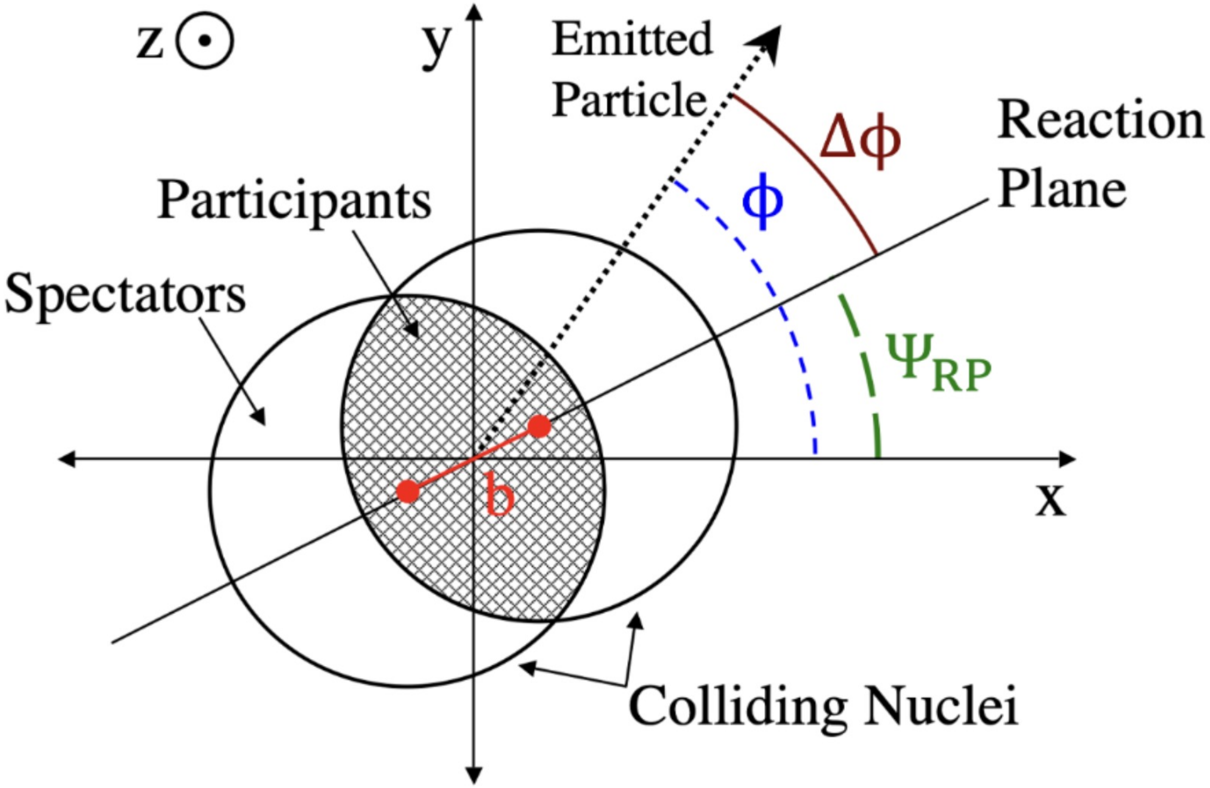


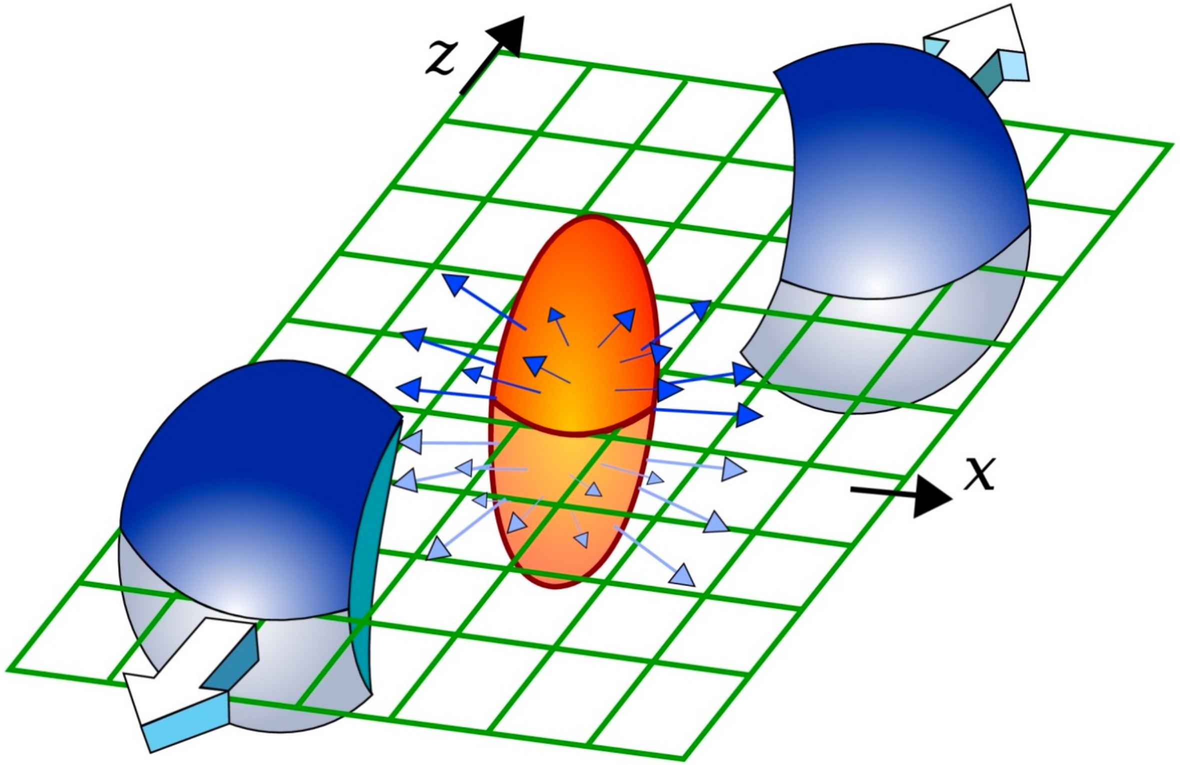


Anisotropic flow mechanisms

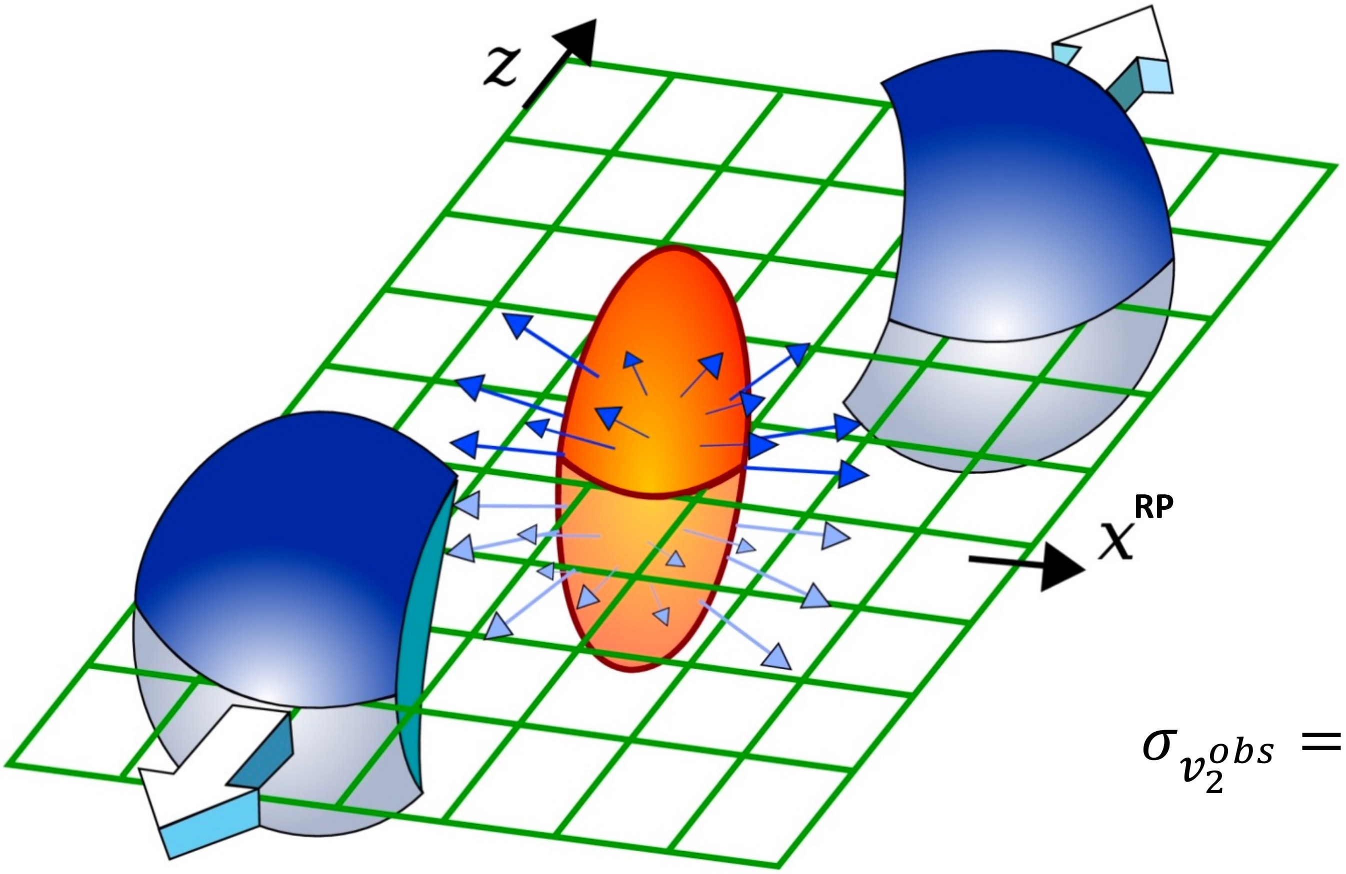
- Path-length dependent dissociation
- Charm equilibration and J/ψ regeneration
- Primordial J/ψ equilibration

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi p_T}\frac{d^2N}{dy\,dp_T}\left(1+\sum_n 2v_n(p_T)\cos\left[n(\phi-\Psi_{RP})\right]\right)$$





Event plane method: In/Out Ratio



In/out ratio method (for v_2):

$$\Delta\phi = \phi - \Psi_2$$

In-plane and out-of-plane counts:

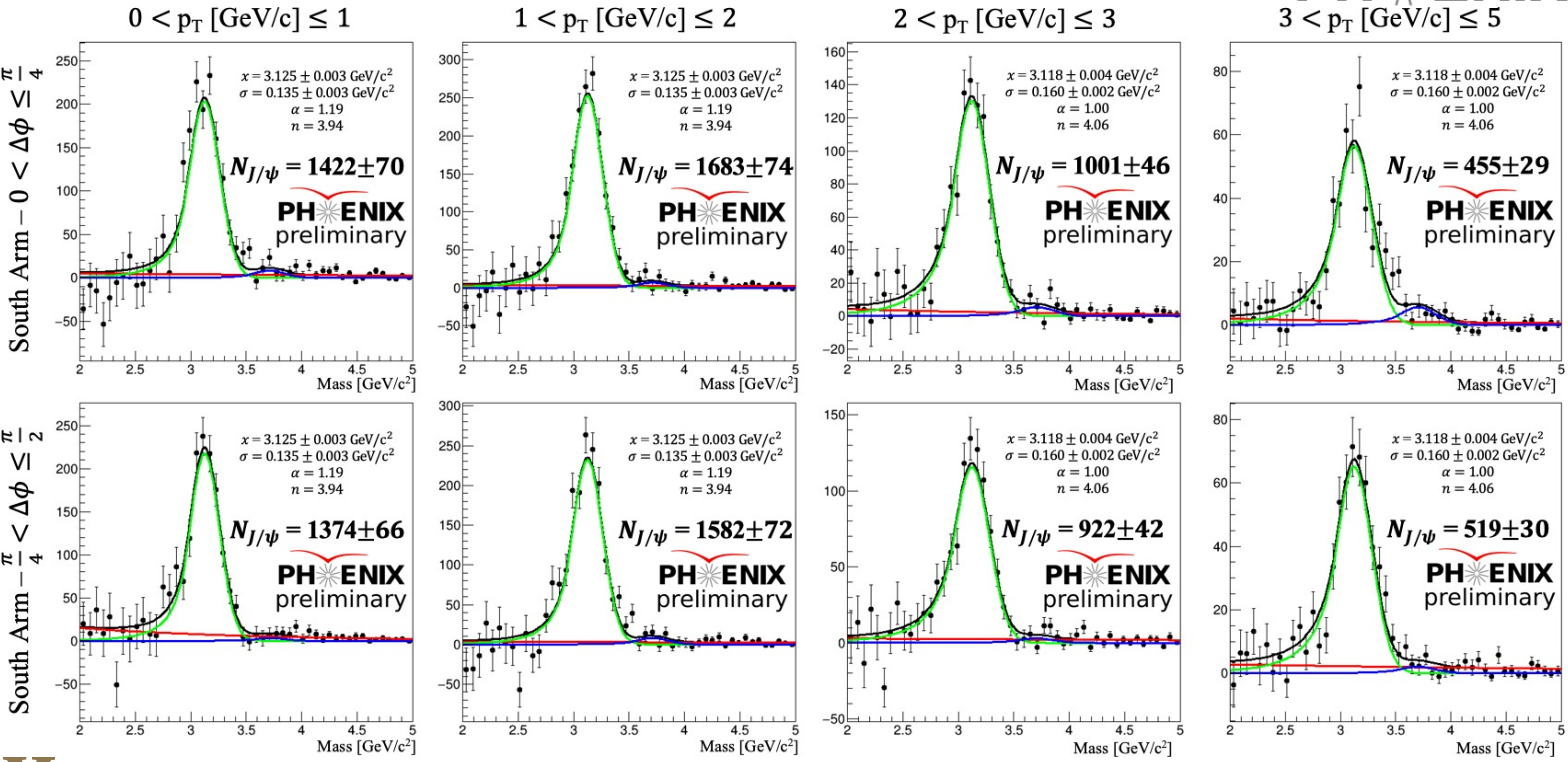
$$N_{in} = \Delta\phi \in [0, \pi/4]$$
$$N_{out} = \Delta\phi \in [\pi/4, \pi/2]$$

$$v_2^{obs} = \frac{\pi}{4}\frac{N_{in} - N_{out}}{N_{in} + N_{out}}$$

$$\sigma_{v_2^{obs}} = \frac{\pi}{2(N_{in} + N_{out})^2} \cdot \sqrt{(N_{out}\sigma_{in})^2 + (N_{in}\sigma_{out})^2}$$

$$v_2 = \frac{v_2^{obs}}{Res} \qquad \sigma_{v_2} = \frac{\sigma_{v_2^{obs}}}{Res}$$

J/ψ yield in plane and out of plane (South)



J/ψ yield in plane and out of plane (North)