HP2024
NAGASAKI

PHENIX

Elliptic flow of light hadrons, HF muons, and J/ψ at forward rapidity in 200 GeV Au+Au collisions

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on behalf of the **PHENIX** collaboration

Based on arXiv:2409.12715 and arXiv: 2409.12756

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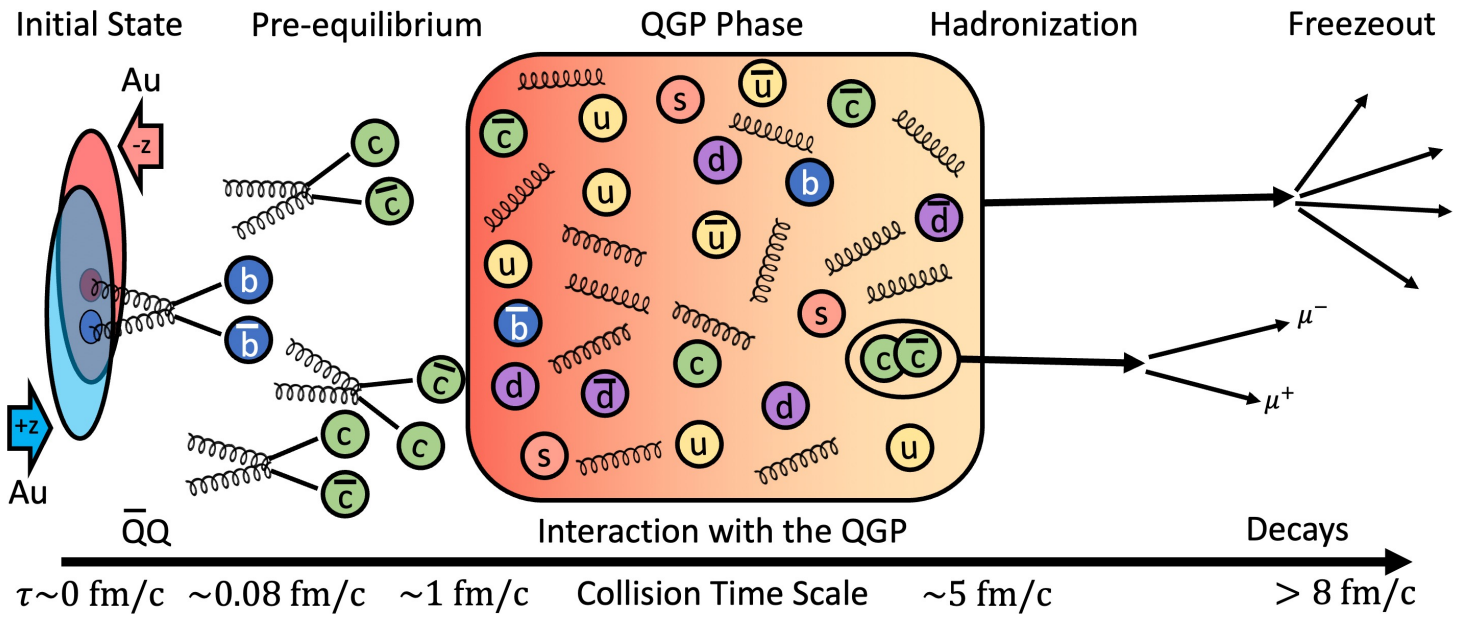
Probing QGP with HF and quarkonia

- Elliptic flow is a key observable: access to transport properties of QGP
- Heavy quarks are unique:
  - $m_Q \gg \Lambda_{QCD}$ → production cross-sections calculated in pQCD
  - $m_Q \gg T_{QGP}$ → no thermal production (charm and beauty are conserved)
  - Early production; incomplete thermalization; hadronization by coalescence



The PHENIX Experiment

CENTRAL ARM (Electrons)

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

FORWARD ARMS (Muons)

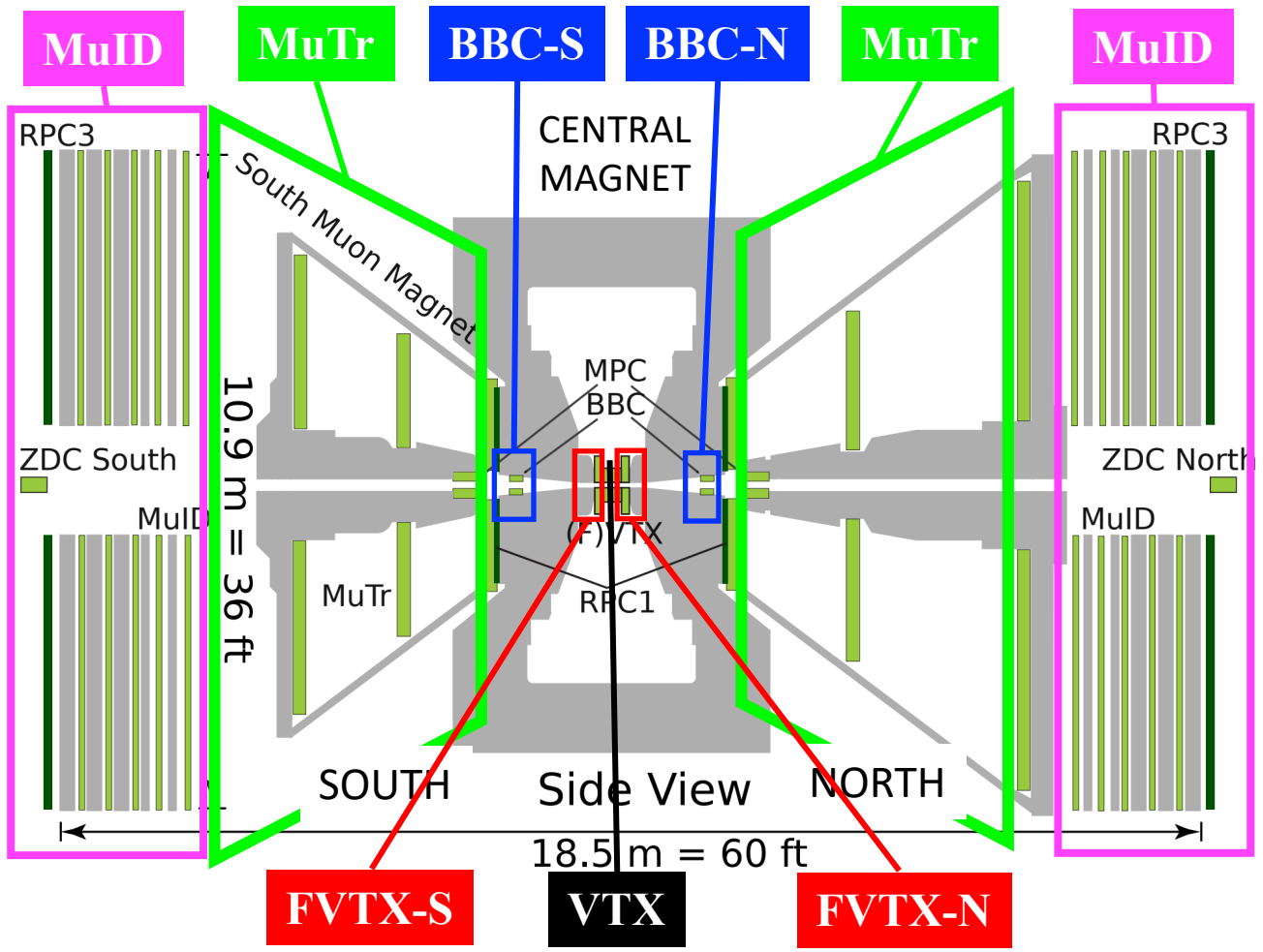
- $1.2 < |\eta| < 2.2$
- $\Delta\phi = 2\pi$
- Tracking: MuTr, FVTX
- MuID: Muon Identification detector

EVENT PLANE DETECTORS

FVTX $(1.2 < |\eta| < 2.2)$

BBC $(3.1 < |\eta| < 3.9)$

CNT $(|\eta| < 0.35)$

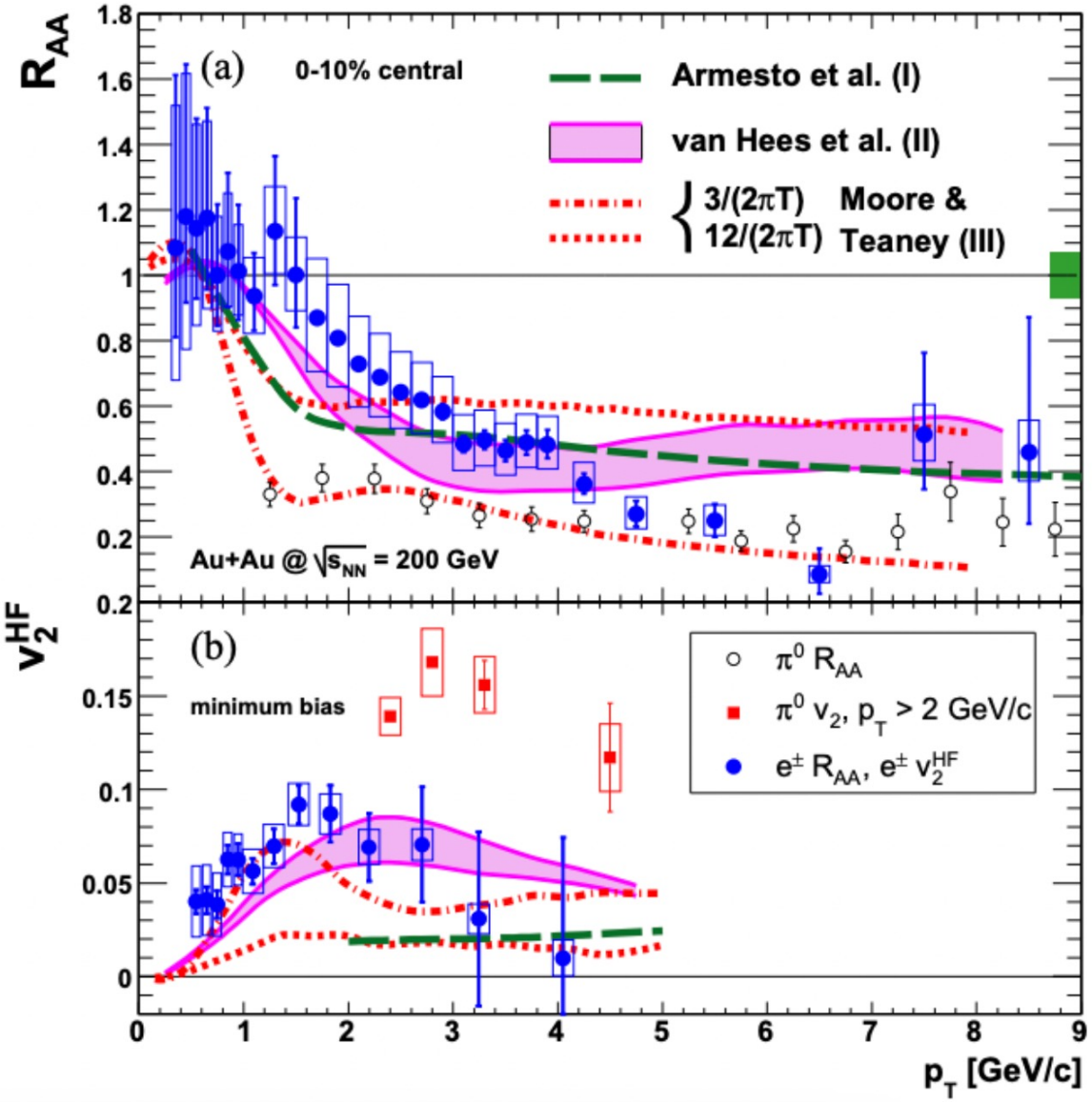


Run 14 Au+Au 200 GeV (19B MB events)

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

Mid-rapidity: inclusive HF R_{AA} and v_2

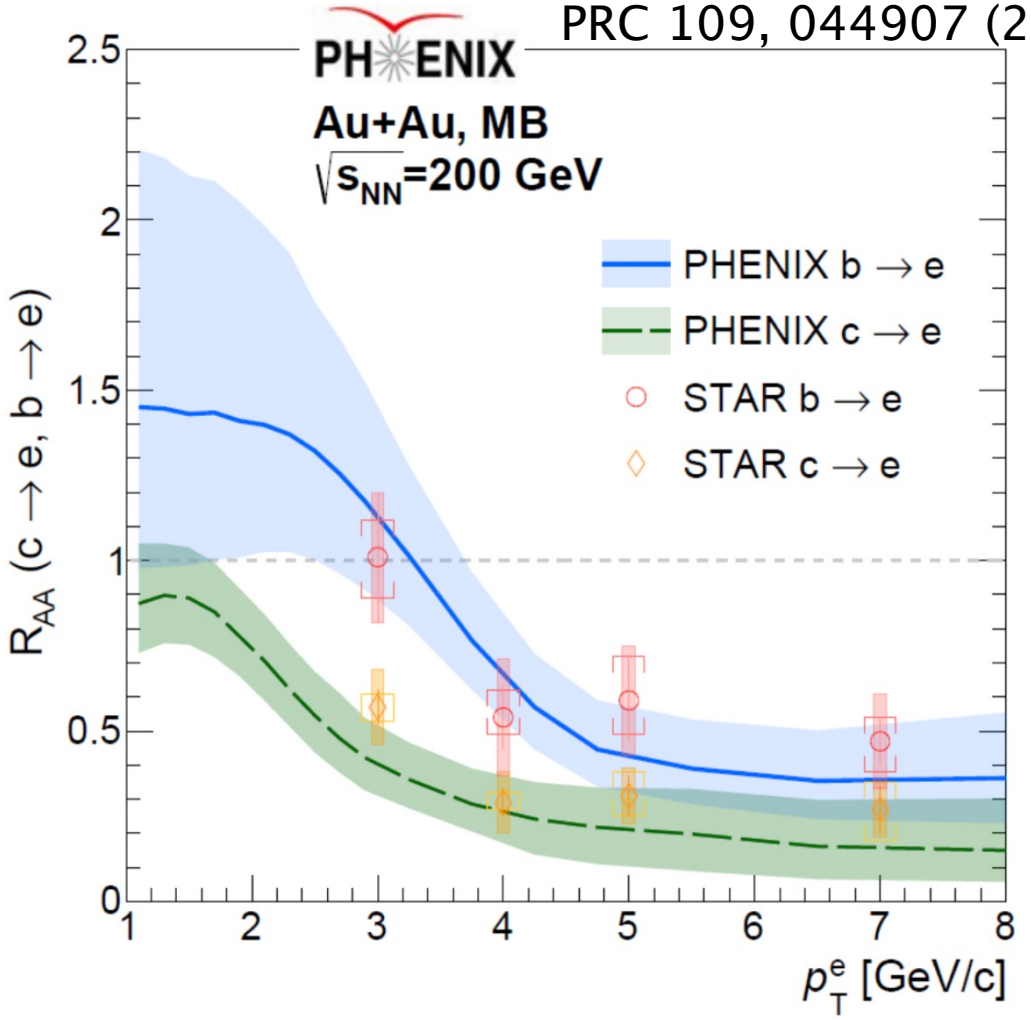
PRL 98, 172301 (2007)

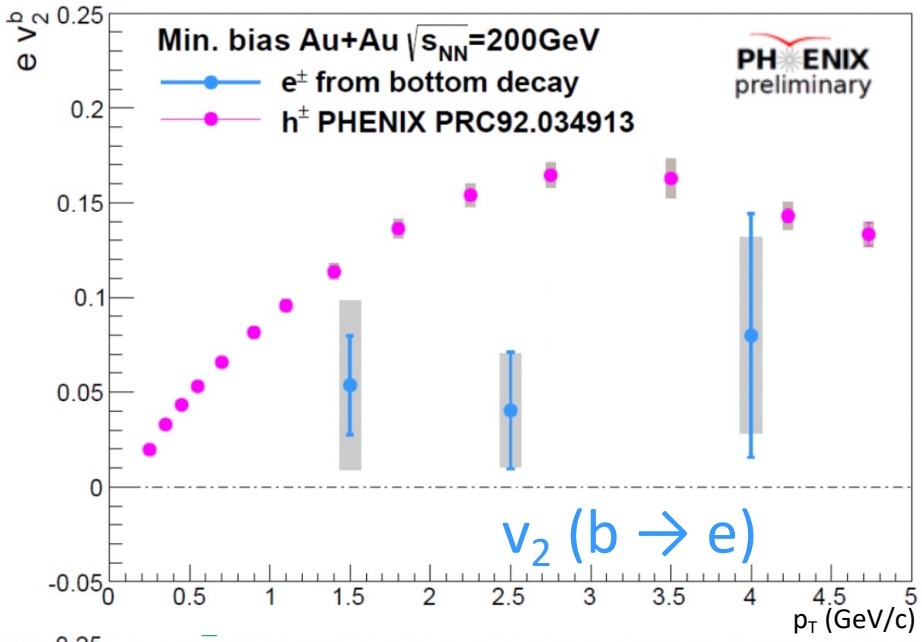


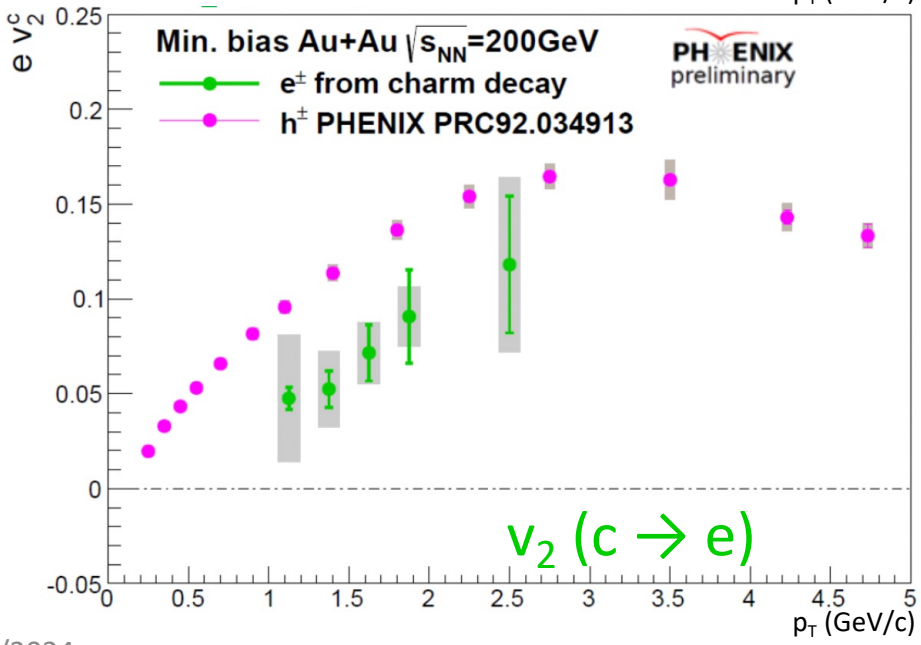
- $e^{\pm}$ from inclusive HF show significant suppression and non-zero v_2
- HF $e^{\pm}$ R_{AA} and v_2 different from neutral pions
  - Indicates mass ordering
- Do *c* and *b* exhibit the same mass ordering behavior?

Separated Charm and Beauty R_{AA} and v_2

PRC 109, 044907 (2024)

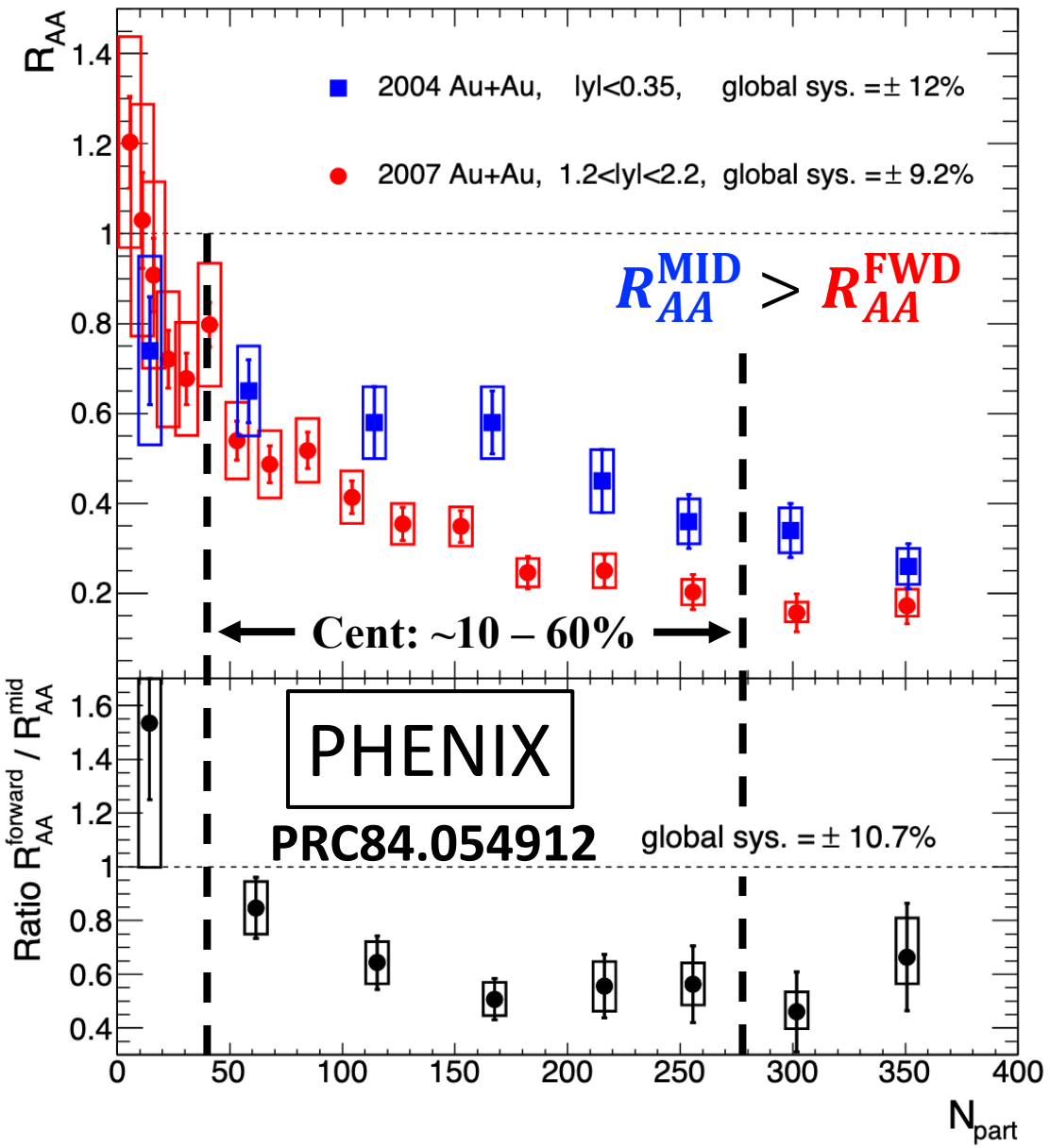


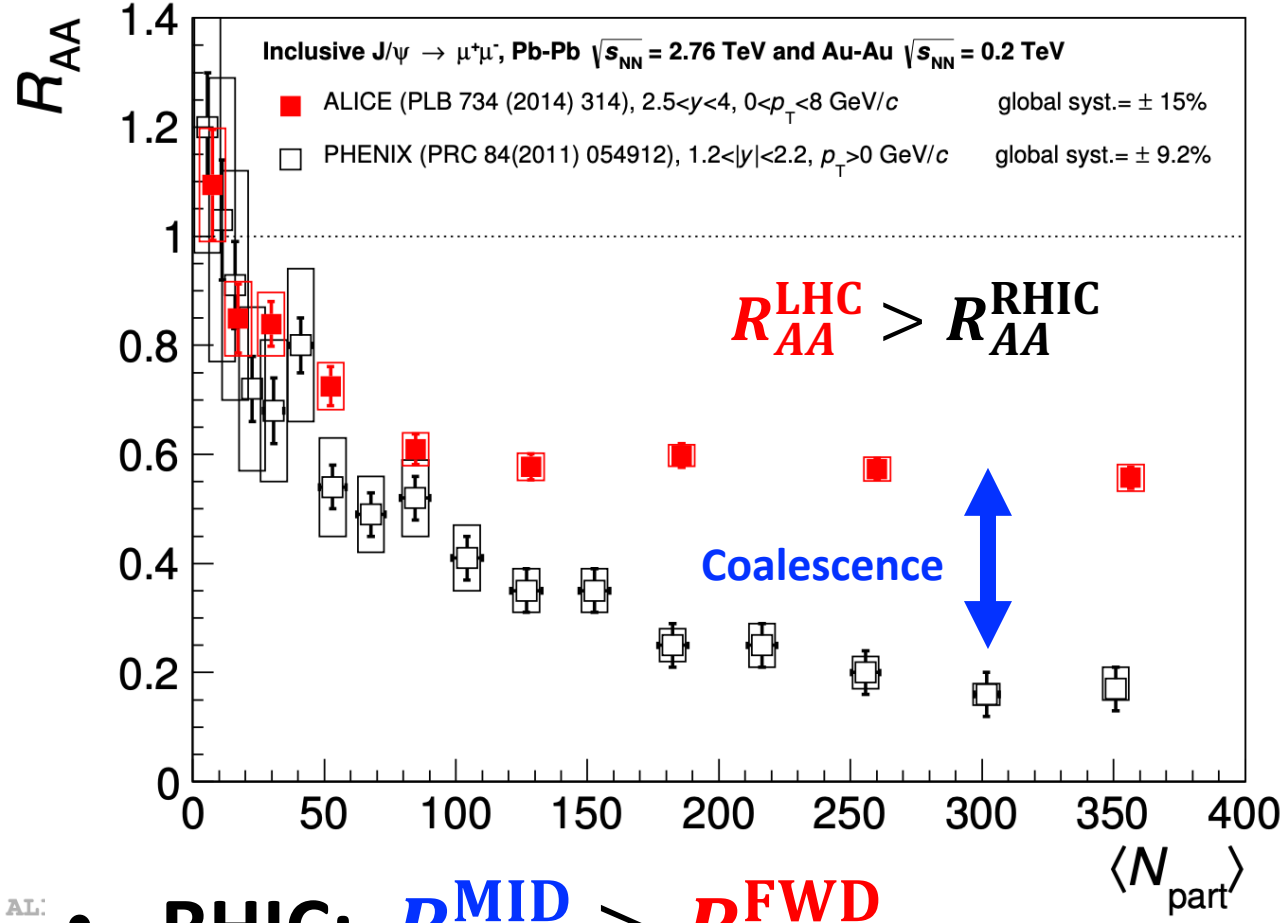




R_{AA} and v_2 at low $p_T < 4$ GeV/c:
mass ordering for $\boldsymbol{b \rightarrow e}$ and $\boldsymbol{c \rightarrow e}$

J/ψ Nuclear Modification (R_{AA})

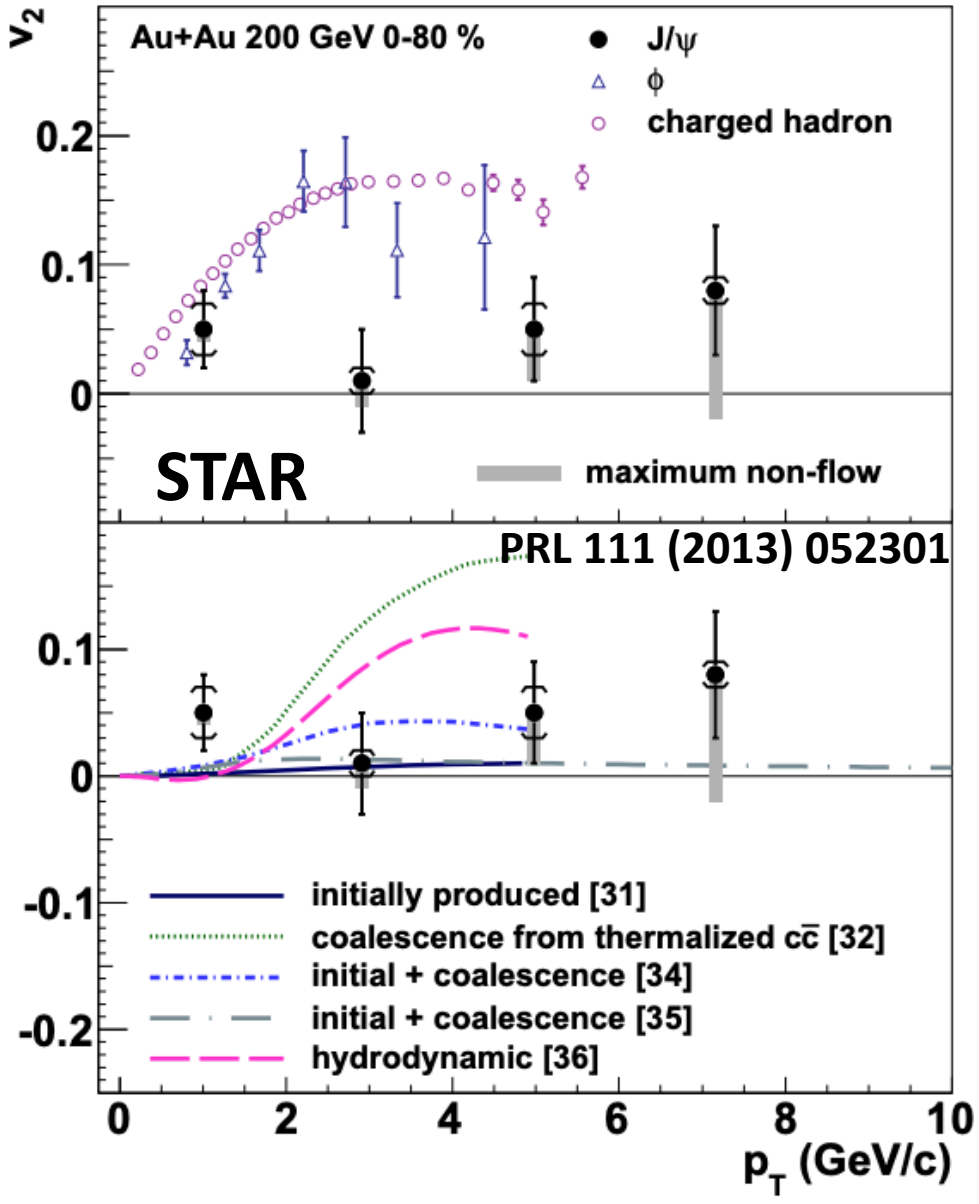


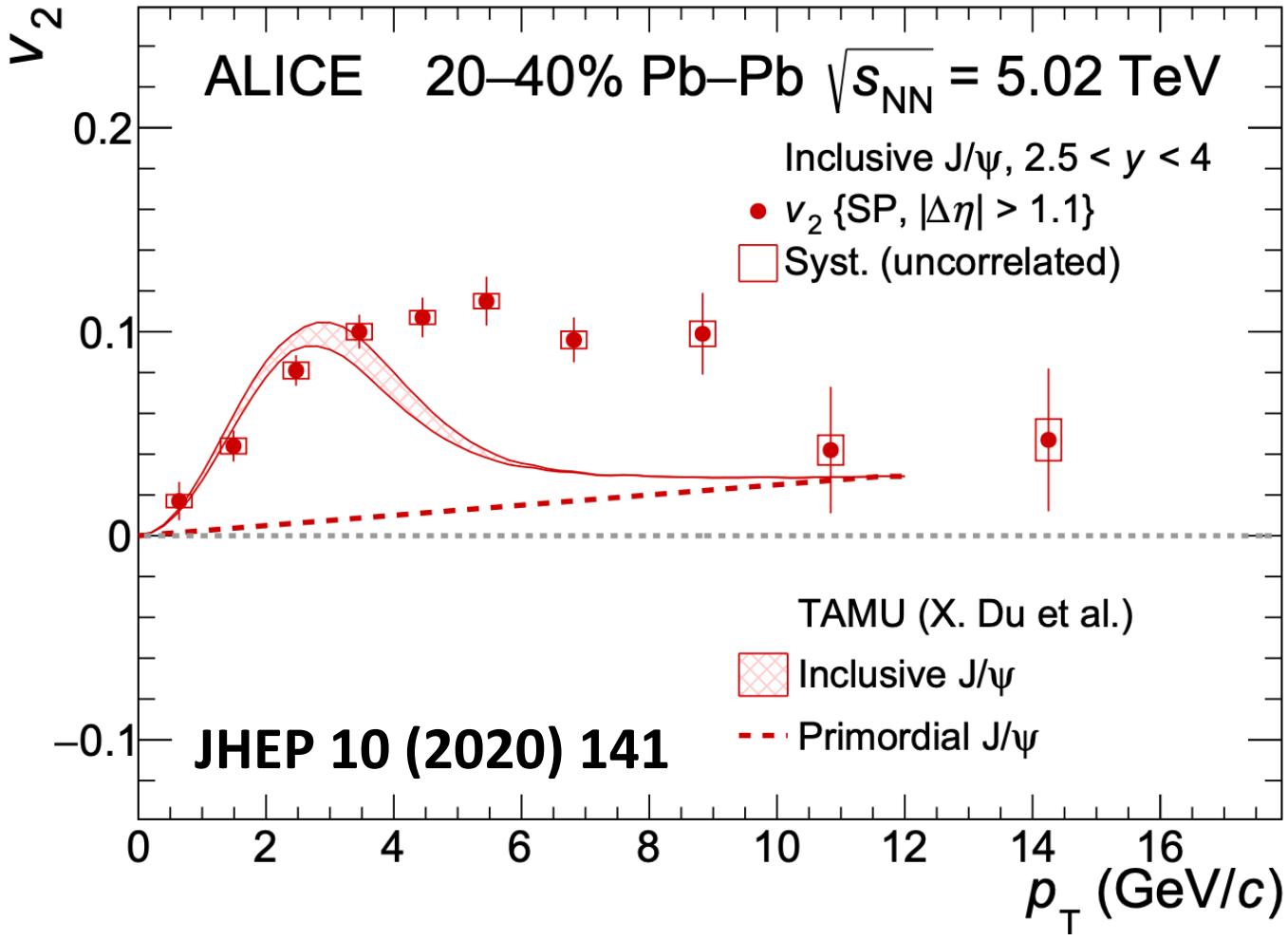


- **RHIC:** $R_{AA}^{MID} > R_{AA}^{FWD}$
- **Forward:** $R_{AA}^{LHC} > R_{AA}^{RHIC}$

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

J/ψ Elliptic Flow at RHIC and LHC

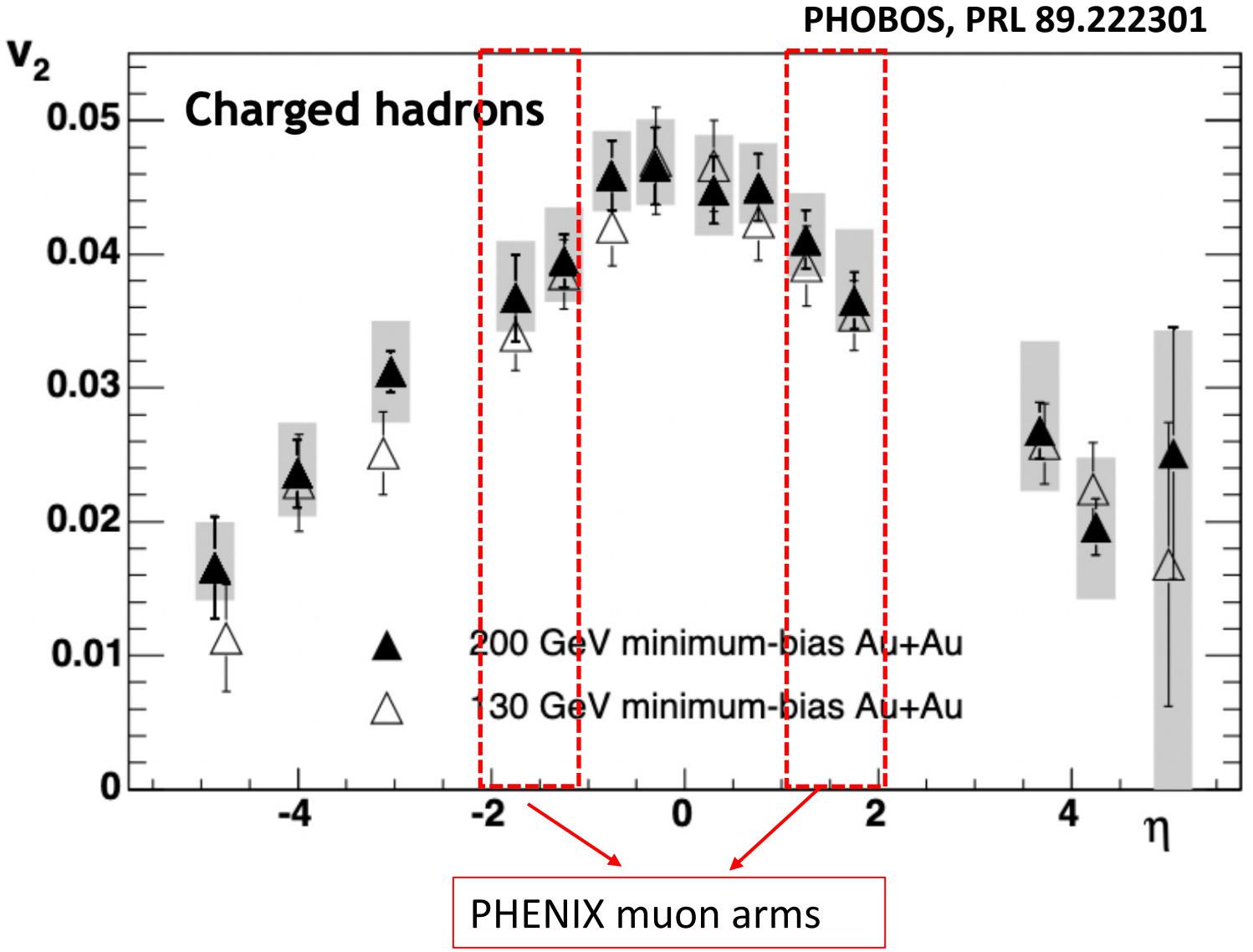




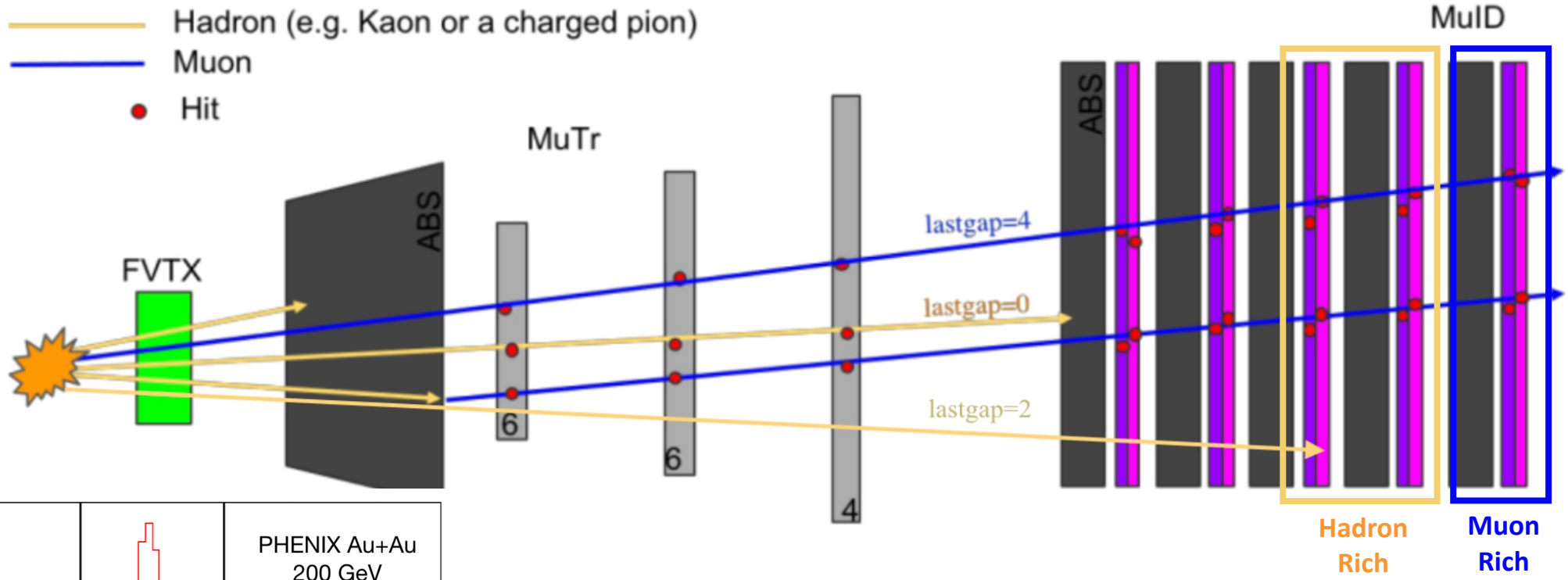
J/ψ v_2 at mid-rapidity at RHIC inconclusive
significant non-zero v_2 is observed at LHC

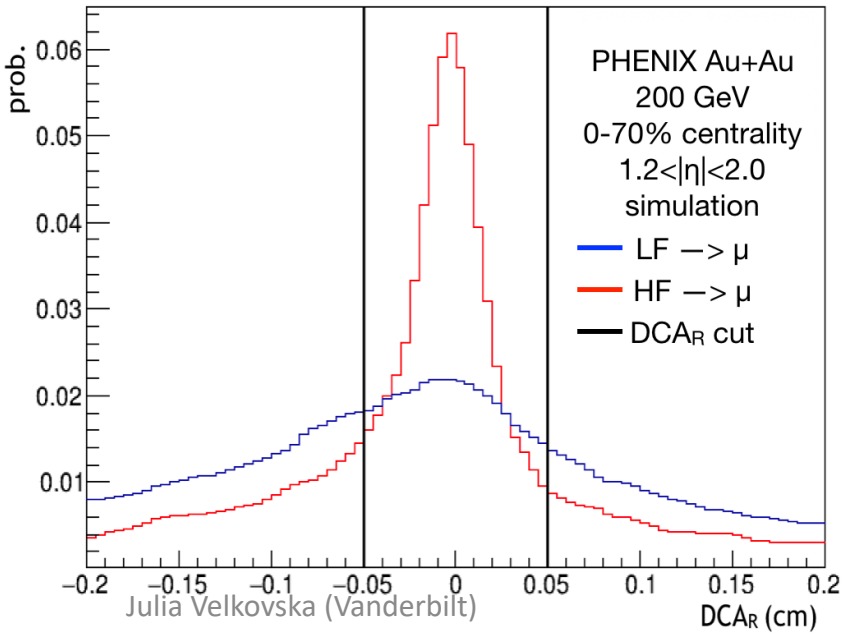
Rapidity dependence of QGP interactions

- Rapidity dependence of flow gives access to the longitudinal dynamics of the QGP
- Heavy flavor and quarkonia have rapidity-dependent initial state effects
- Pressure gradients and T are different at forward rapidity
- How is HF dynamics affected ?



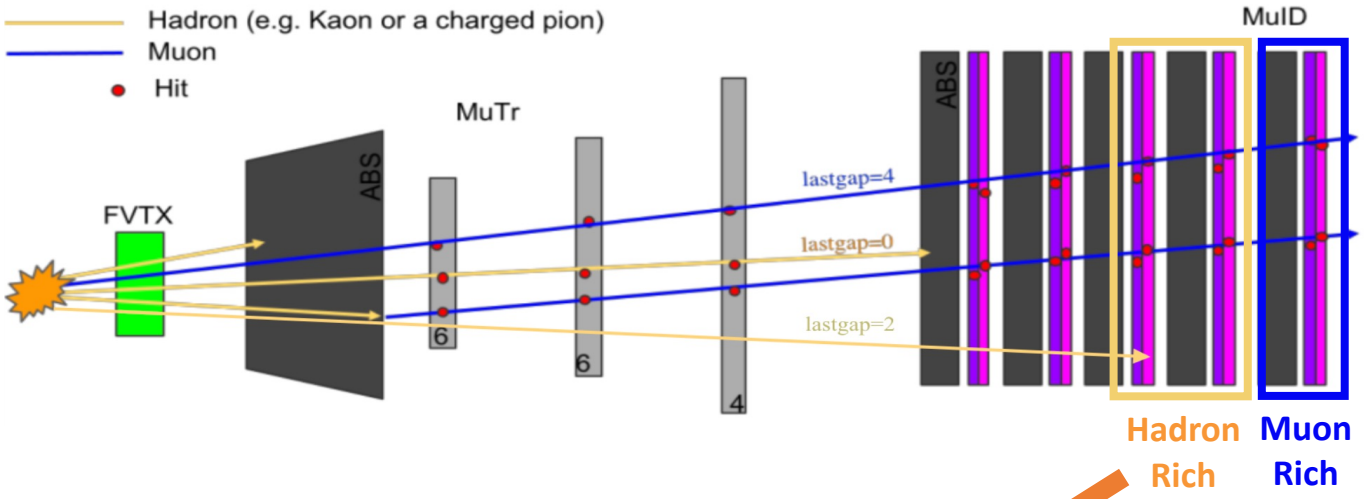
Single Muon Analysis: arXiv:2409.12715

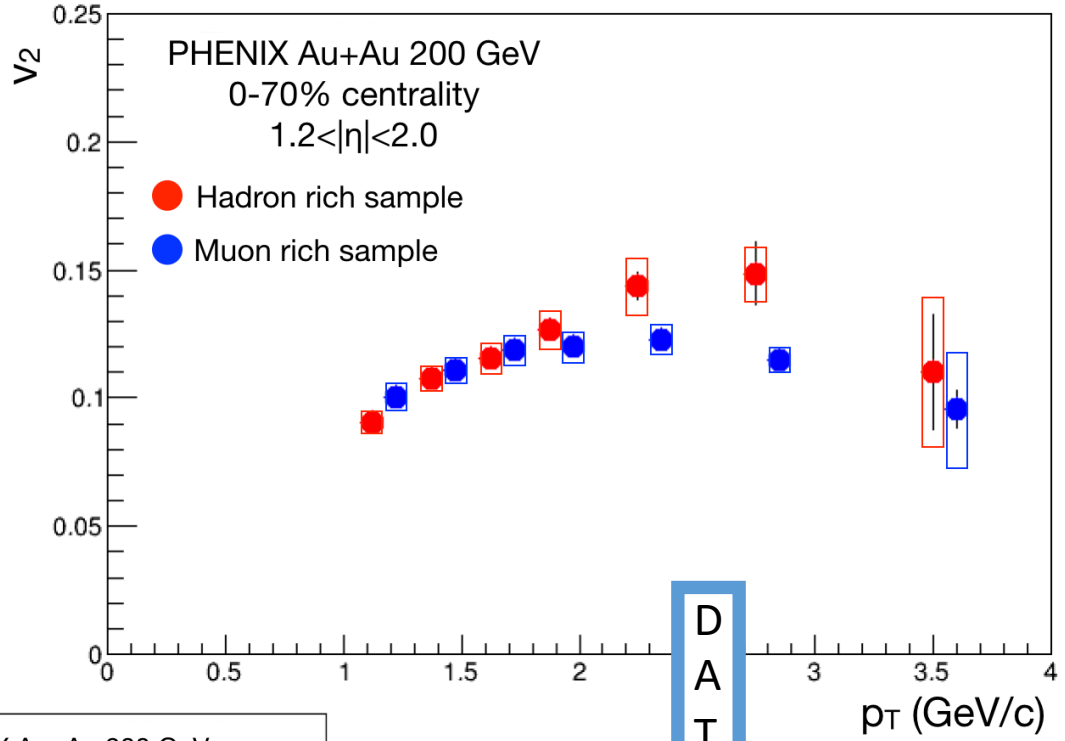




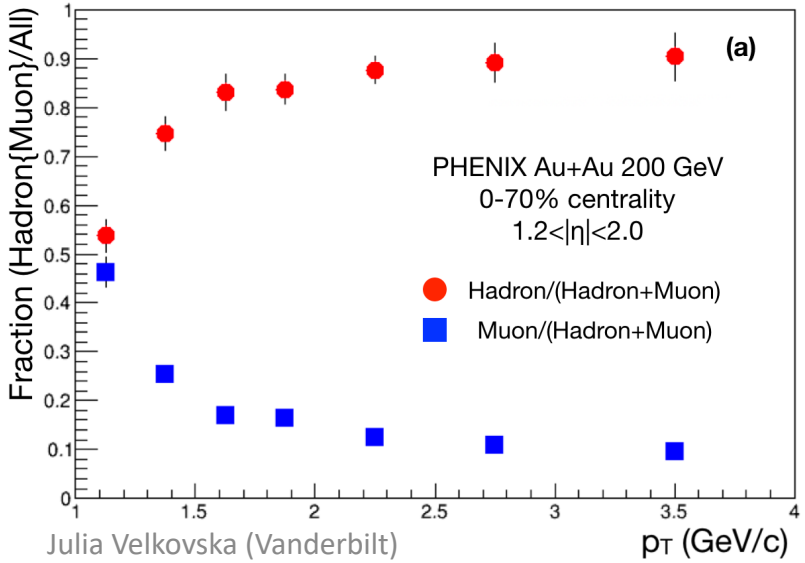
- Track quality cuts to enhance heavy flavor
- Measure v_2 in hadron-rich and muon-rich samples
- Tuned MC with precise light hadron composition
  - use PHENIX mid-rapidity data and BRAHMS
- separate muons from light and heavy flavor decays

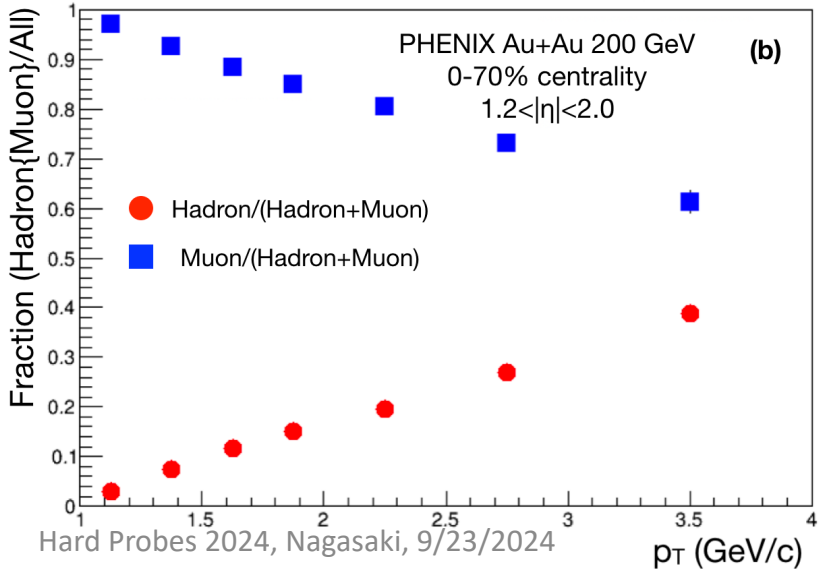
Separating $h^{+/-}$ from inclusive muons





DATA

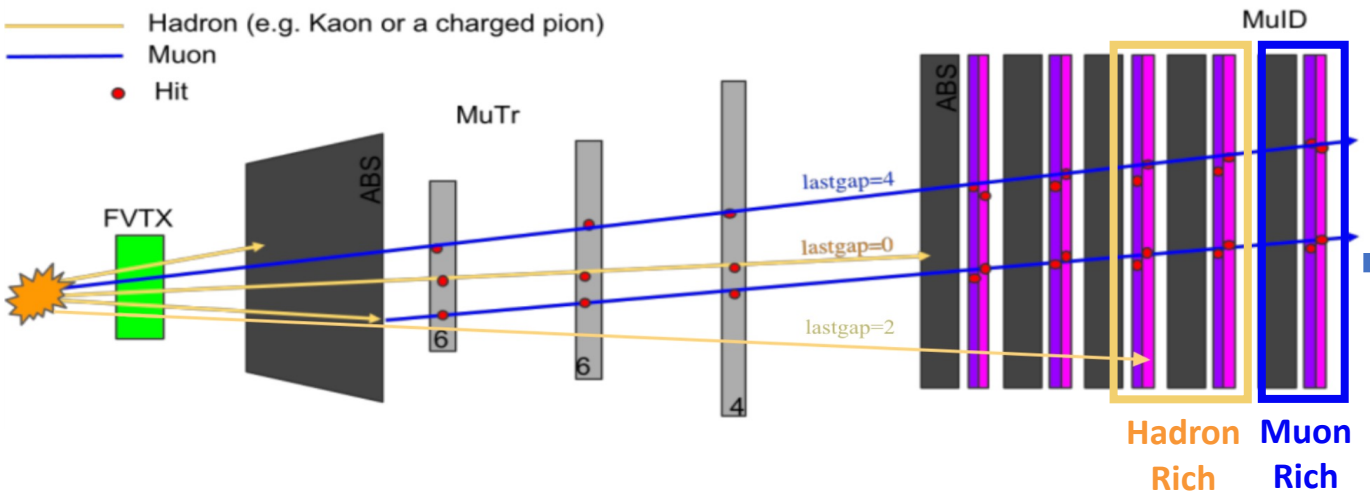


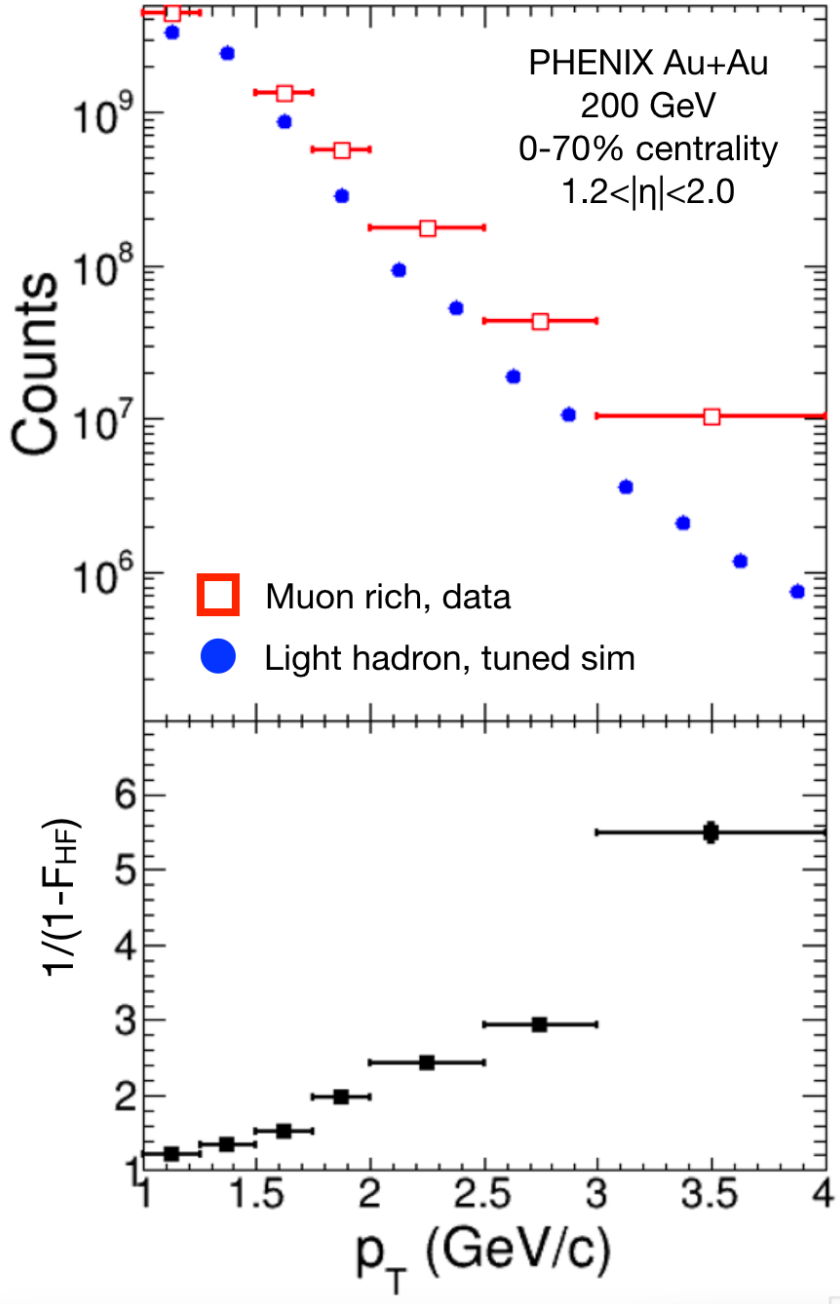


SIM

Extract v_2 for charged hadrons and inclusive muons

Single Muon Analysis: HF flow

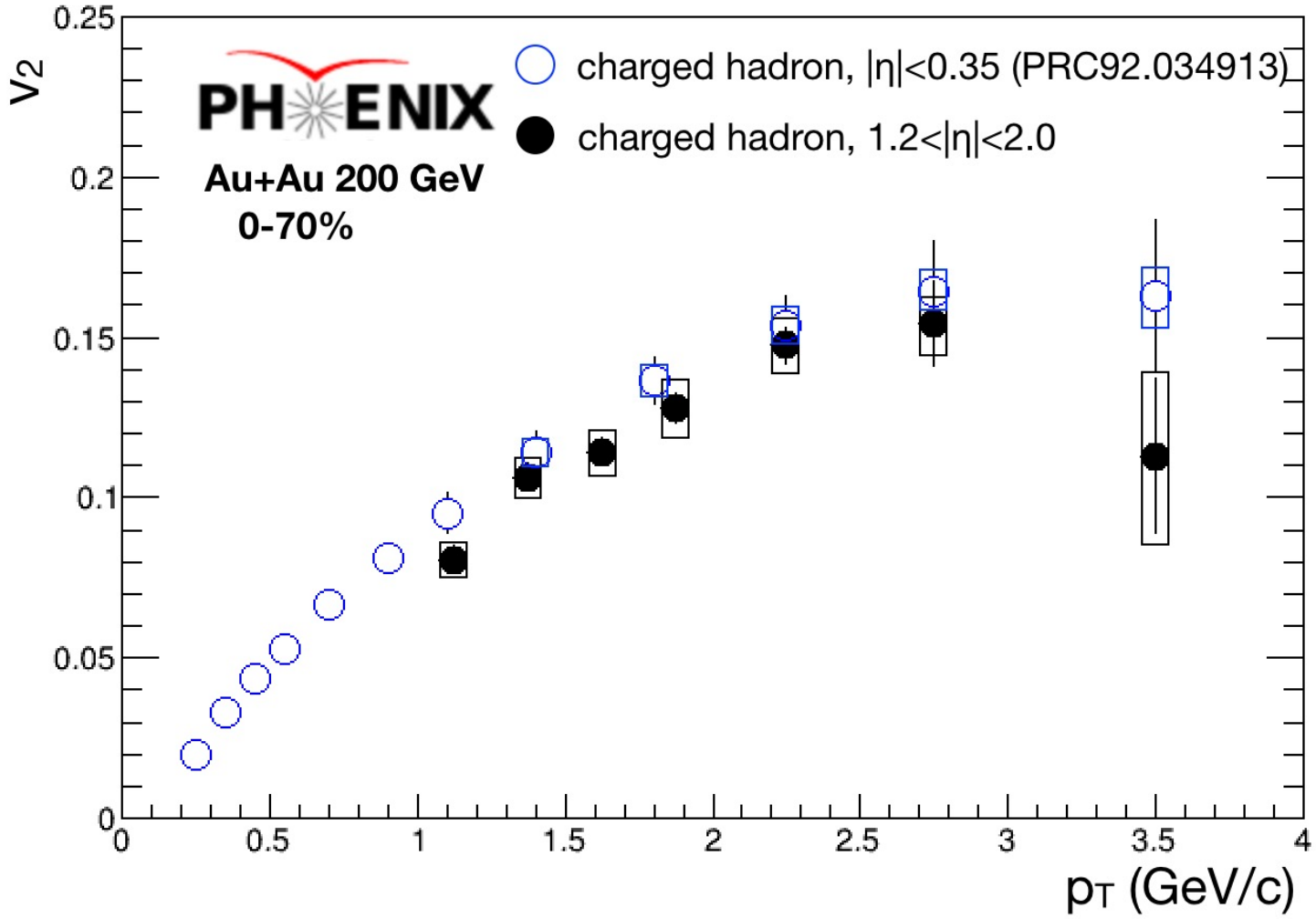




- PYTHIA+GEANT4 embedded in real Au+Au events tuned to reproduce measured particle spectra in hadron-rich region
- Extract the HF muon fraction by comparing data to tuned simulation with HF contribution excluded → determine F^{HF}
- Used the measured hadron v_2 and tuned simulation to get v_2^{LF}
- Determine heavy flavor muon v_2 in the inclusive muon sample:

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

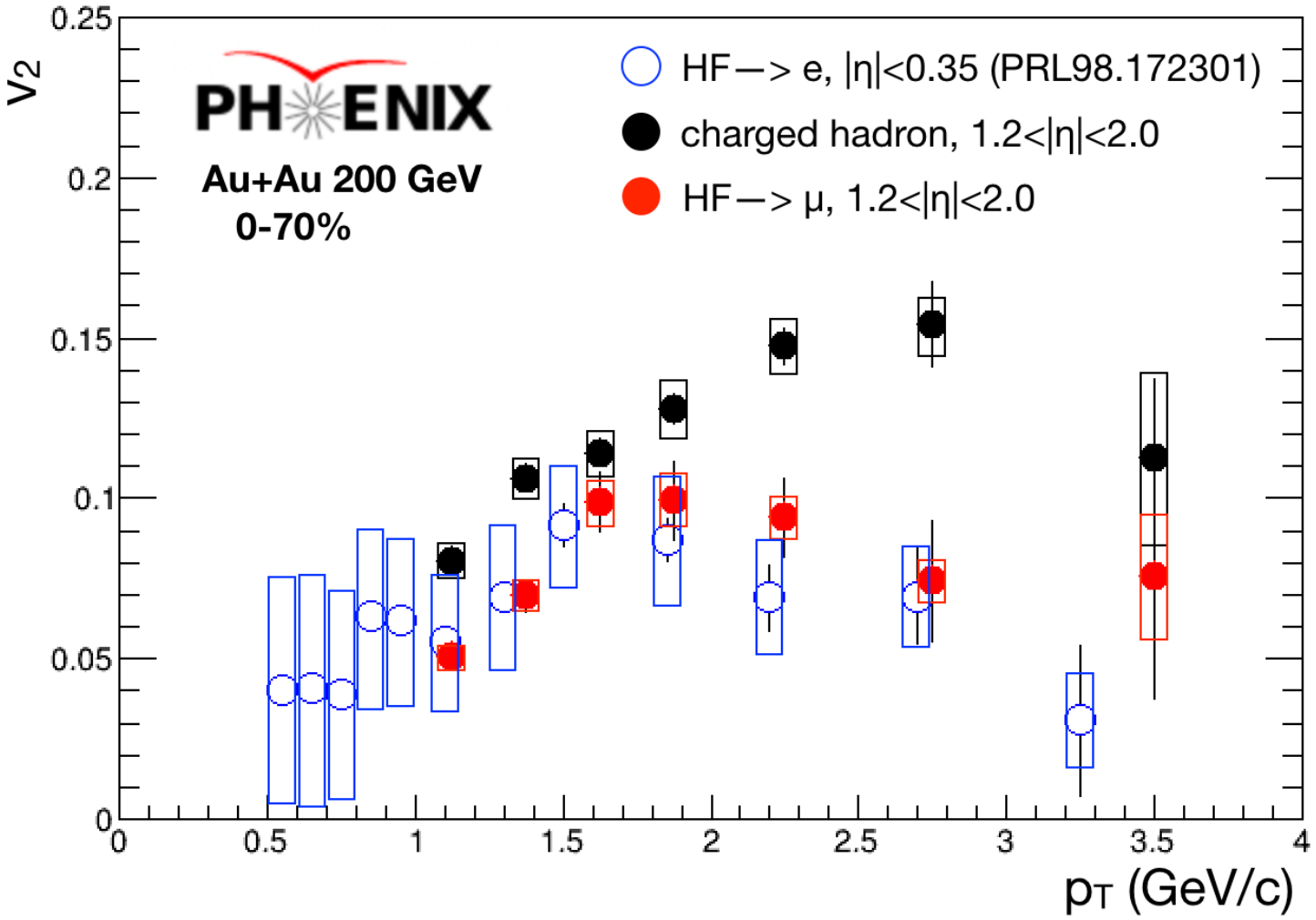
PHENIX Charged Hadron v_2 Measurements



- Charged hadron v_2:

Hint of rapidity dependence, consistent with PHOBOS

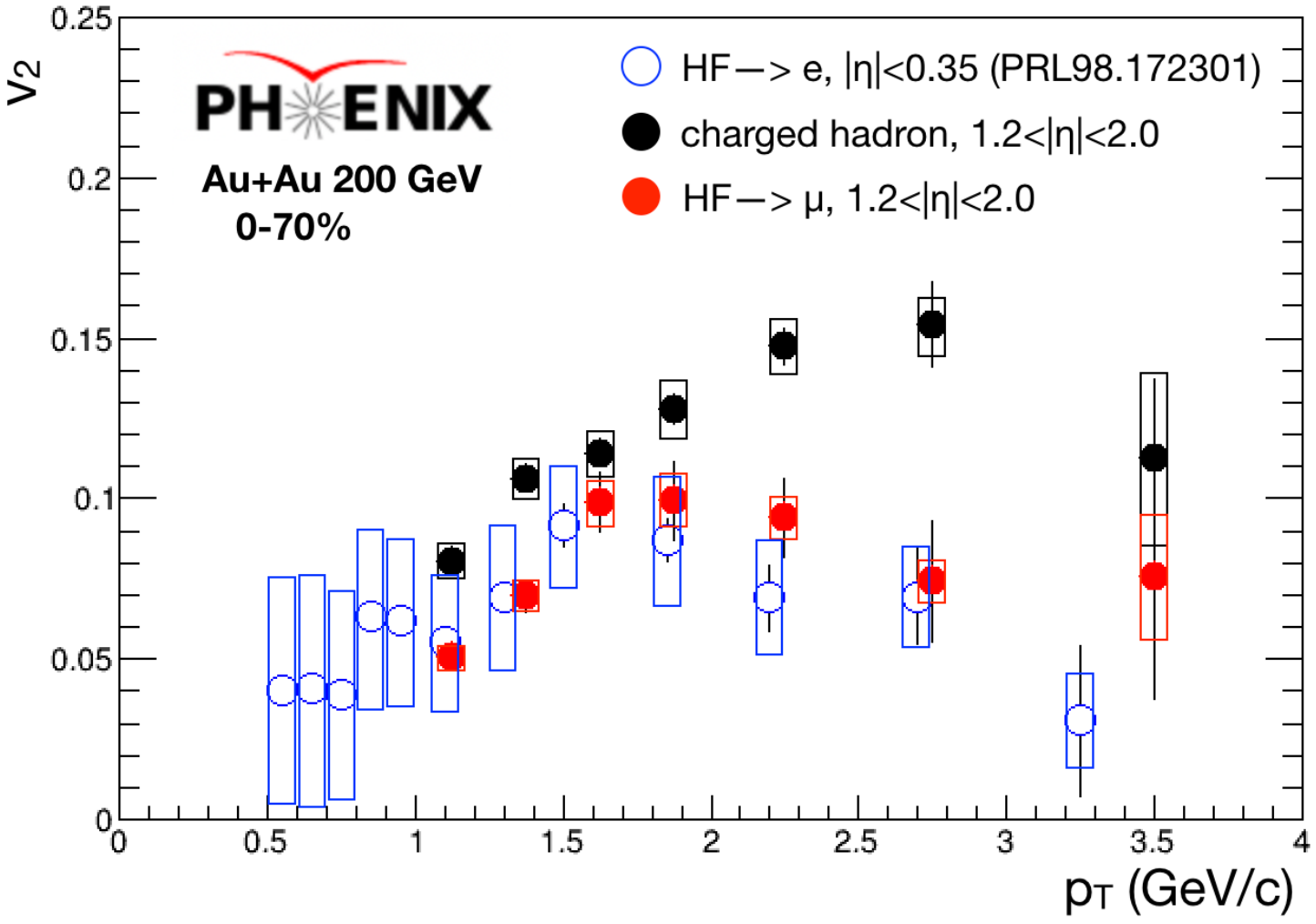
PHENIX Heavy Flavor v_2 Measurement



- Charged hadron v_2: Hint of rapidity dependence, consistent with PHOBOS

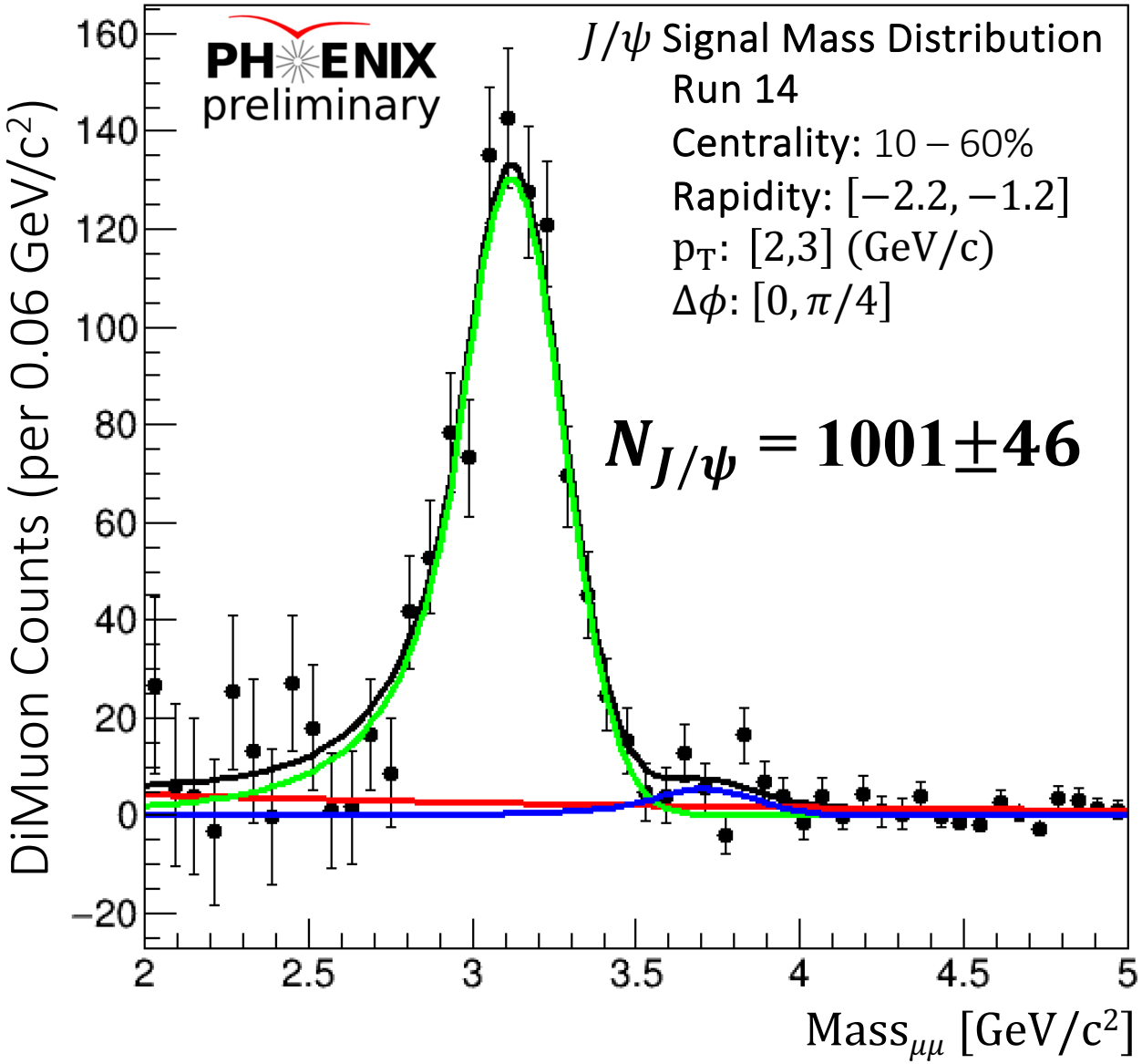
- Open HF v_2 is consistent with previous PHENIX results at mid-rapidity

PHENIX Heavy Flavor v_2 Measurement



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

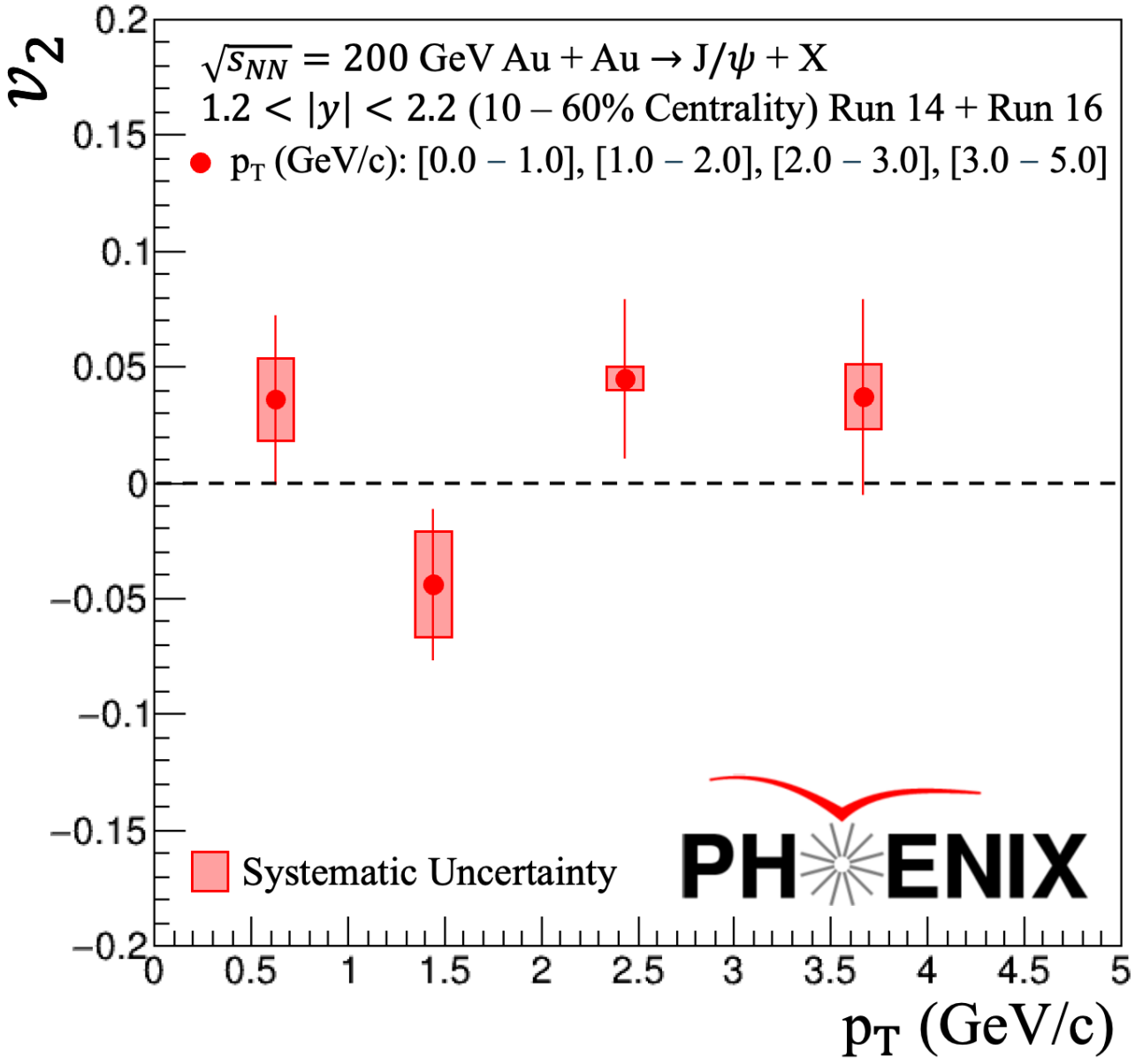
J/ψ Signal Reconstruction (J/$\psi \rightarrow \mu^+ + \mu^-$)



arXiv: 2409.12756

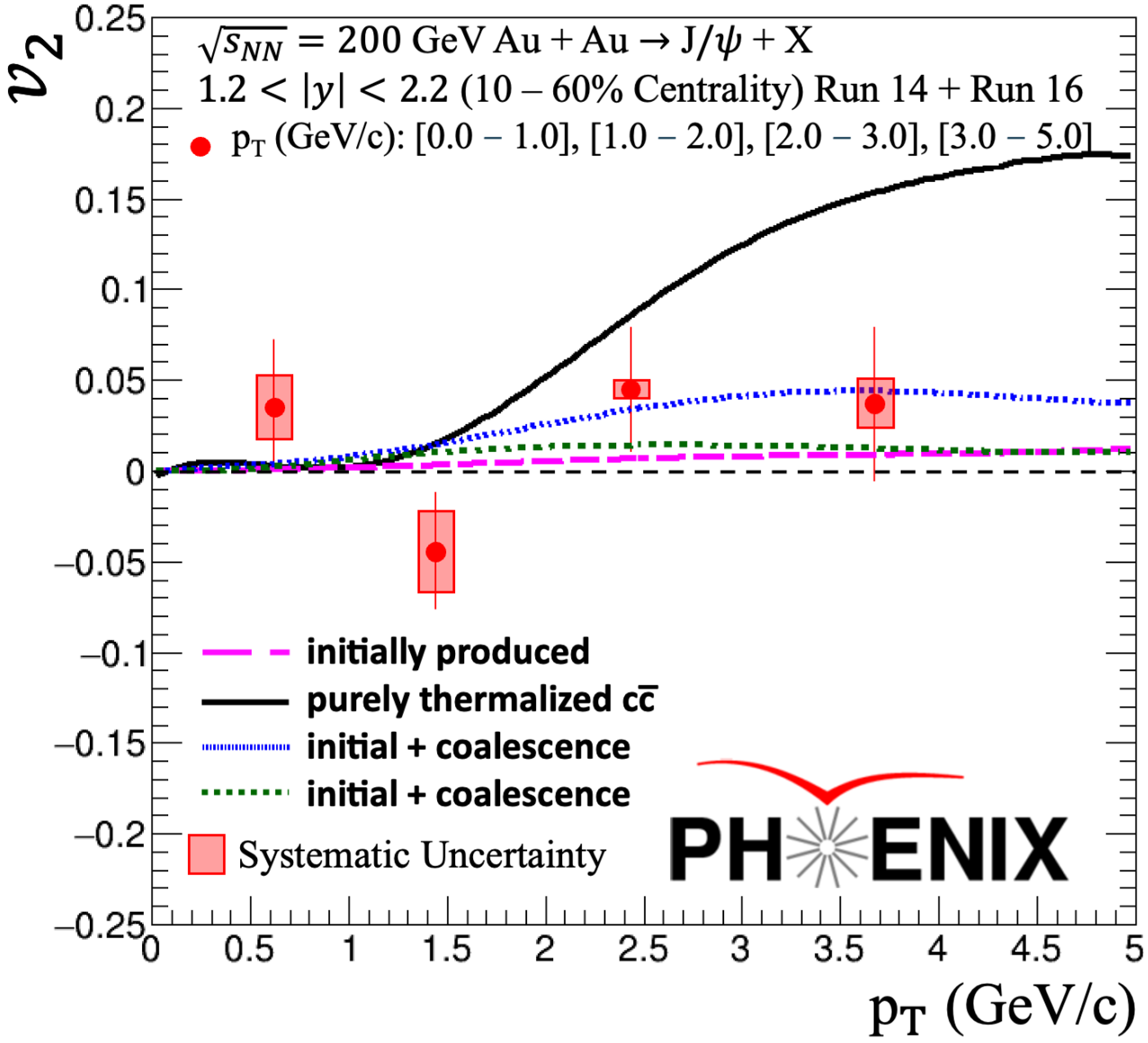
- Candidate J/ψ are reconstructed using dimuon decay channel
- 10-60% centrality will maximize potential v_2 signal
- Measure the J/ψ yield in-plane and out-of-plane to determine v_2

PHENIX J/ψ v_2 Measurement



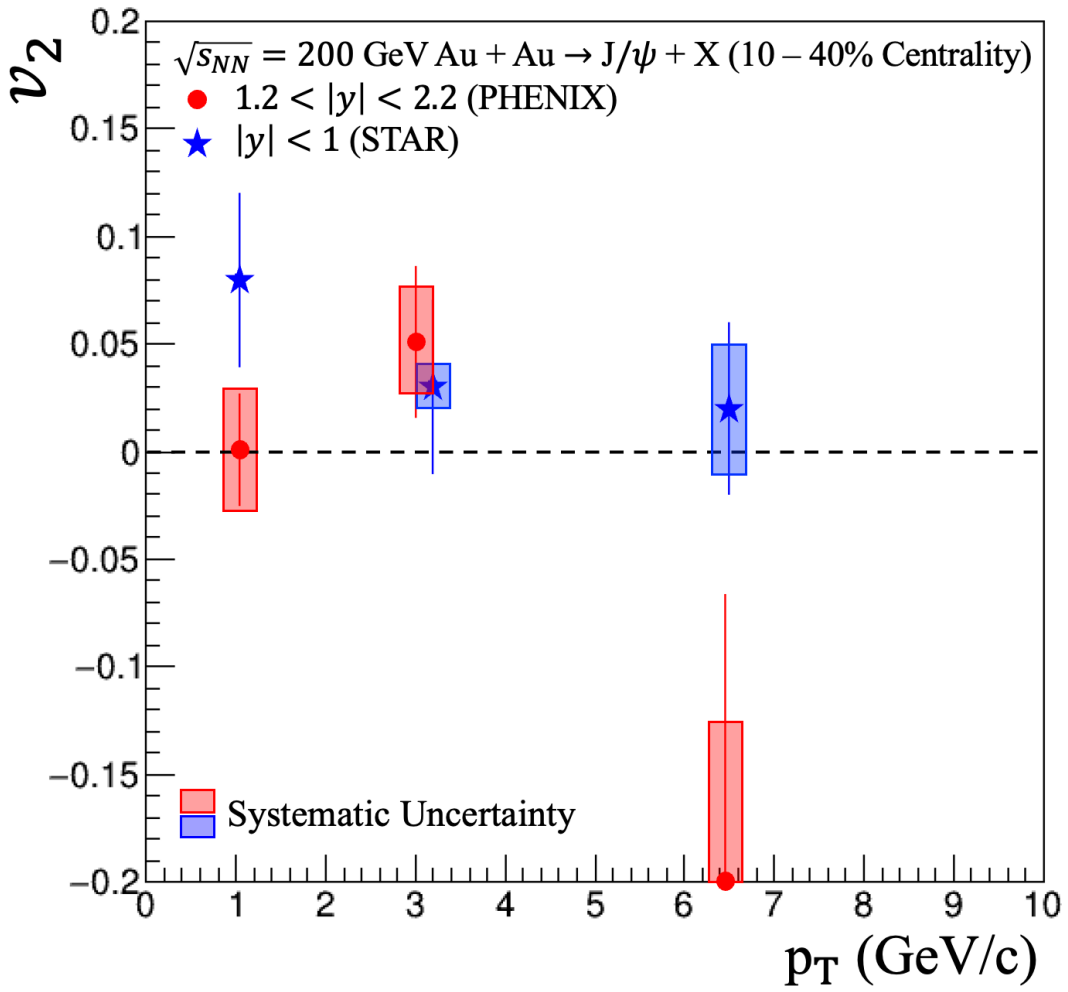
- v_2 of J/ψ at forward rapidity is consistent with 0

PHENIX J/ψ v_2 Measurement

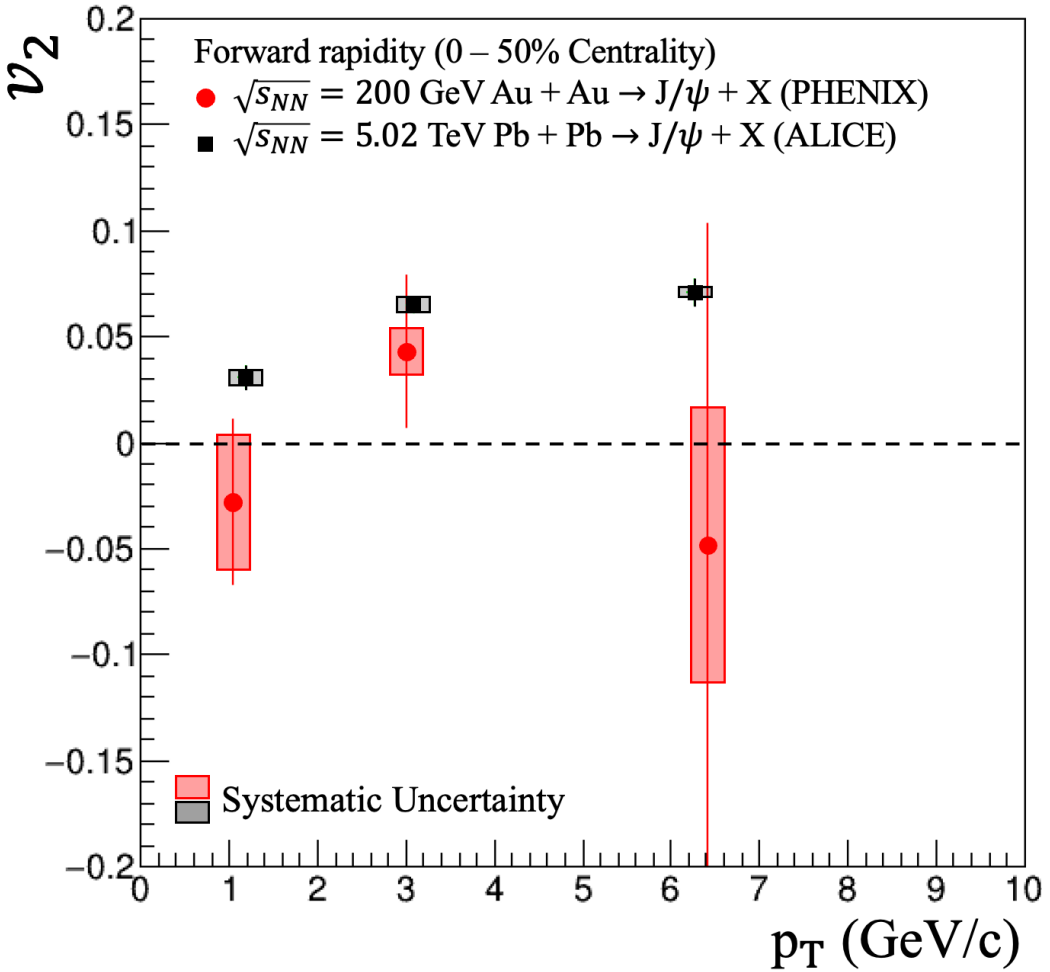


- v_2 of J/ψ at forward rapidity is consistent with 0
- Theoretical calculations that include coalescence of partially thermalized ccbar are also consistent with the data

PHENIX J/ψ v_2 compared to STAR and ALICE

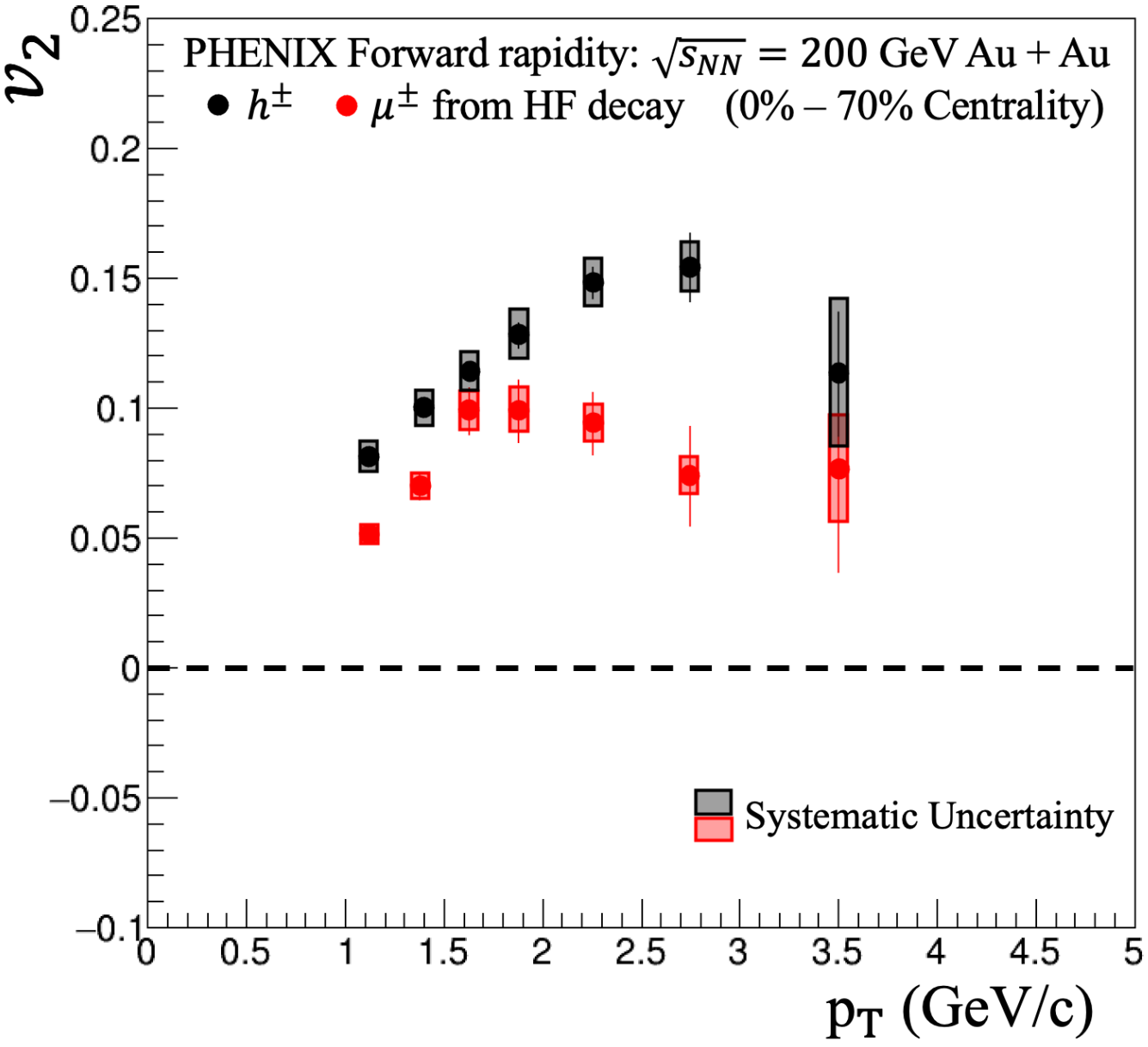


PHENIX and STAR J/ψ v_2 forward and mid-rapidity are consistent



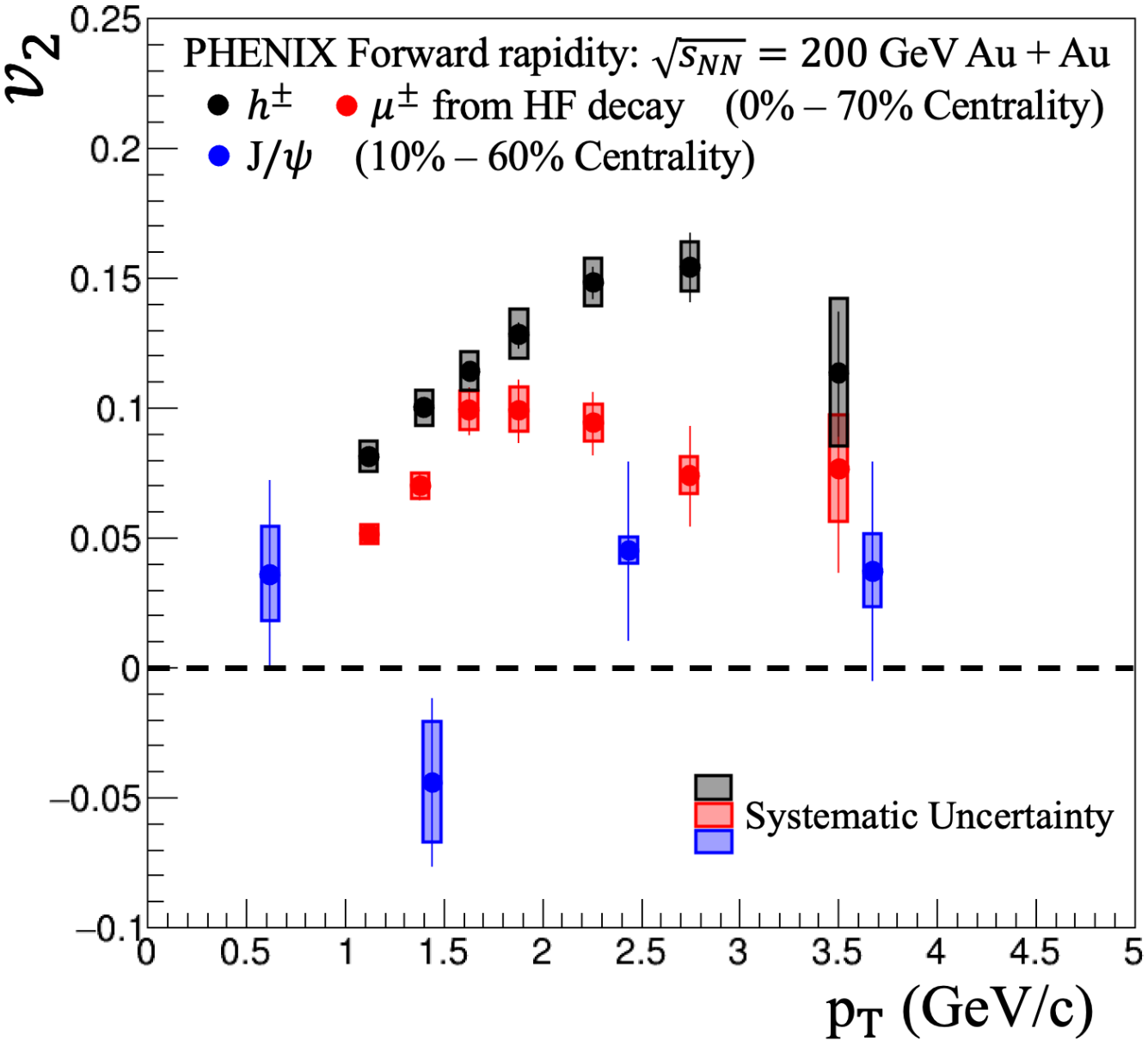
PHENIX J/ψ v_2 measurement distinctly different from the ALICE non-zero result

Summary



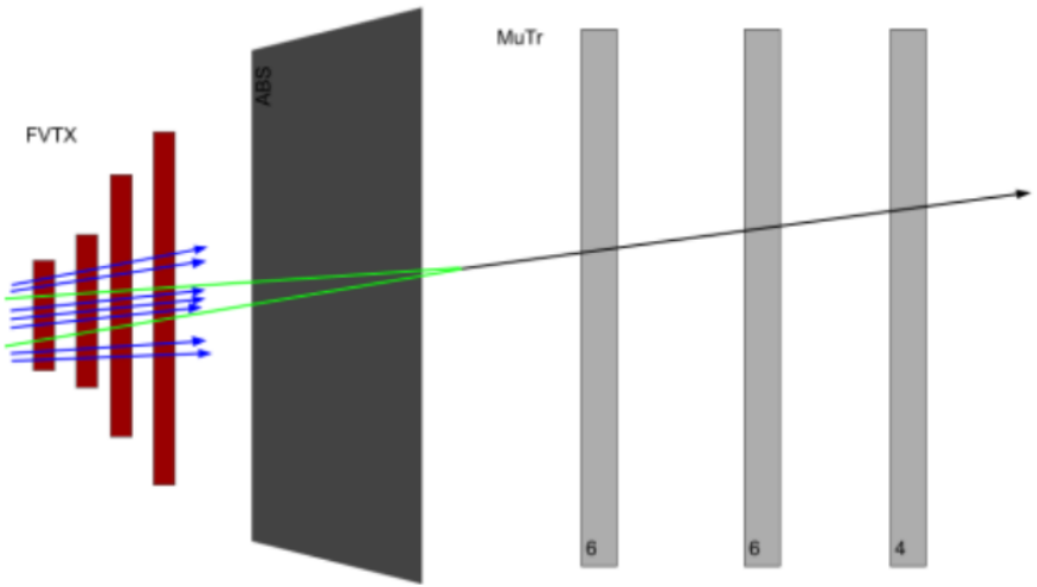
- PHENIX has measured the v_2 of charged hadrons, HF muons, J/ψ at forward rapidity
- Significant flow in HF muons!
- $v_2^h > v_2^{HF}$

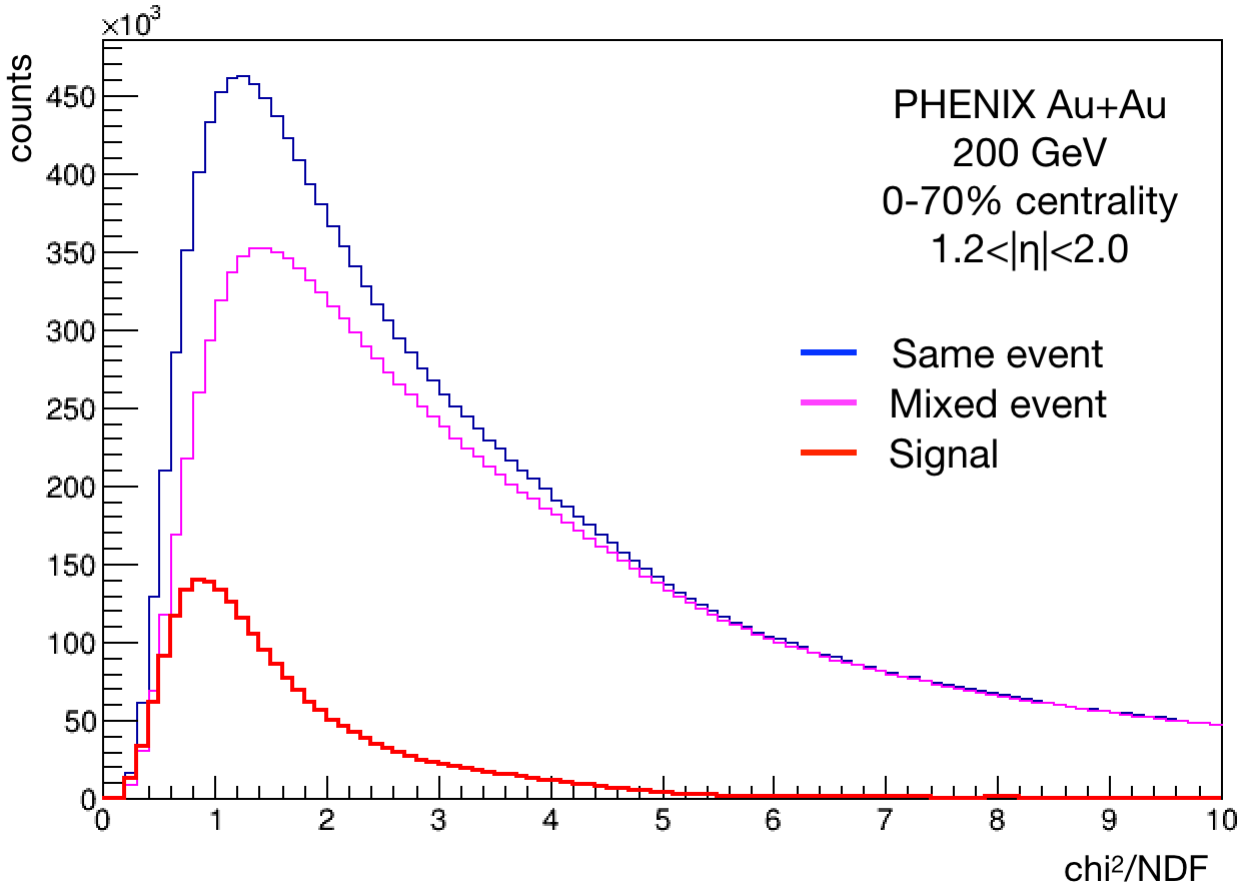
Summary



- PHENIX has measured the v_2 of charged hadrons, HF muons, J/ψ at forward rapidity
- Significant flow in HF muons!
- $v_2^h > v_2^{HF} > v_2^{J/\psi}$
- $v_2^{J/\psi}$ is consistent with 0, but does not rule out coalescence from partially thermalized ccbar
- No significant longitudinal dependence in HF dynamics
- Hint of rapidity dependence in v_2^h

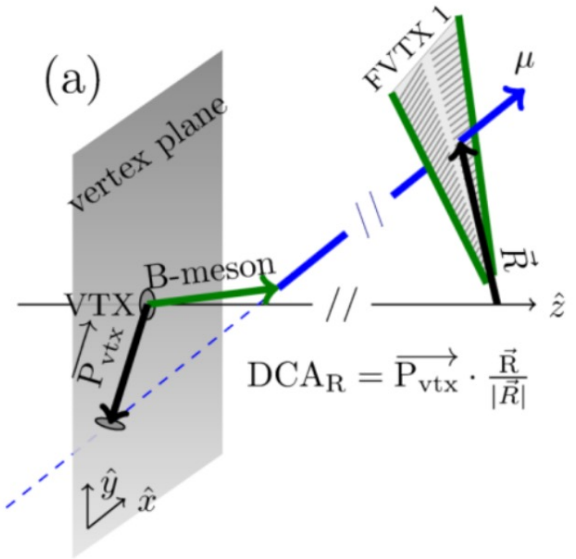
Backup Slides


FVTX
ABS
MuTr
6
6
4

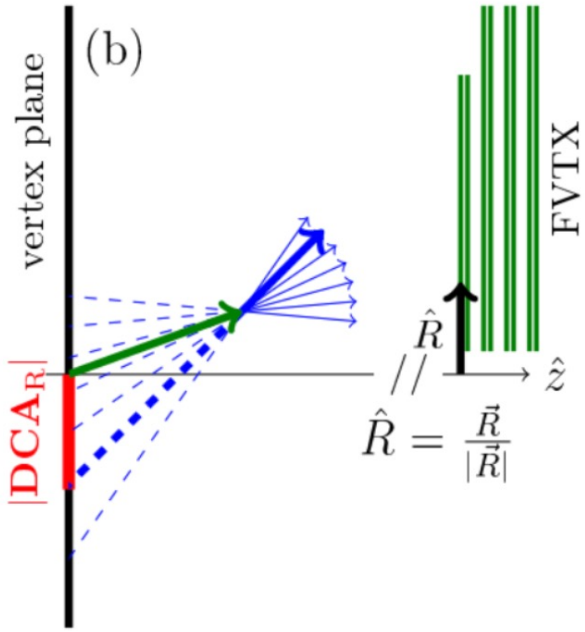

×10^3
counts
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
chi²/NDF
PHENIX Au+Au
200 GeV
0-70% centrality
1.2<|η|<2.0
Same event
Mixed event
Signal

Radial Distance of Closest Approach

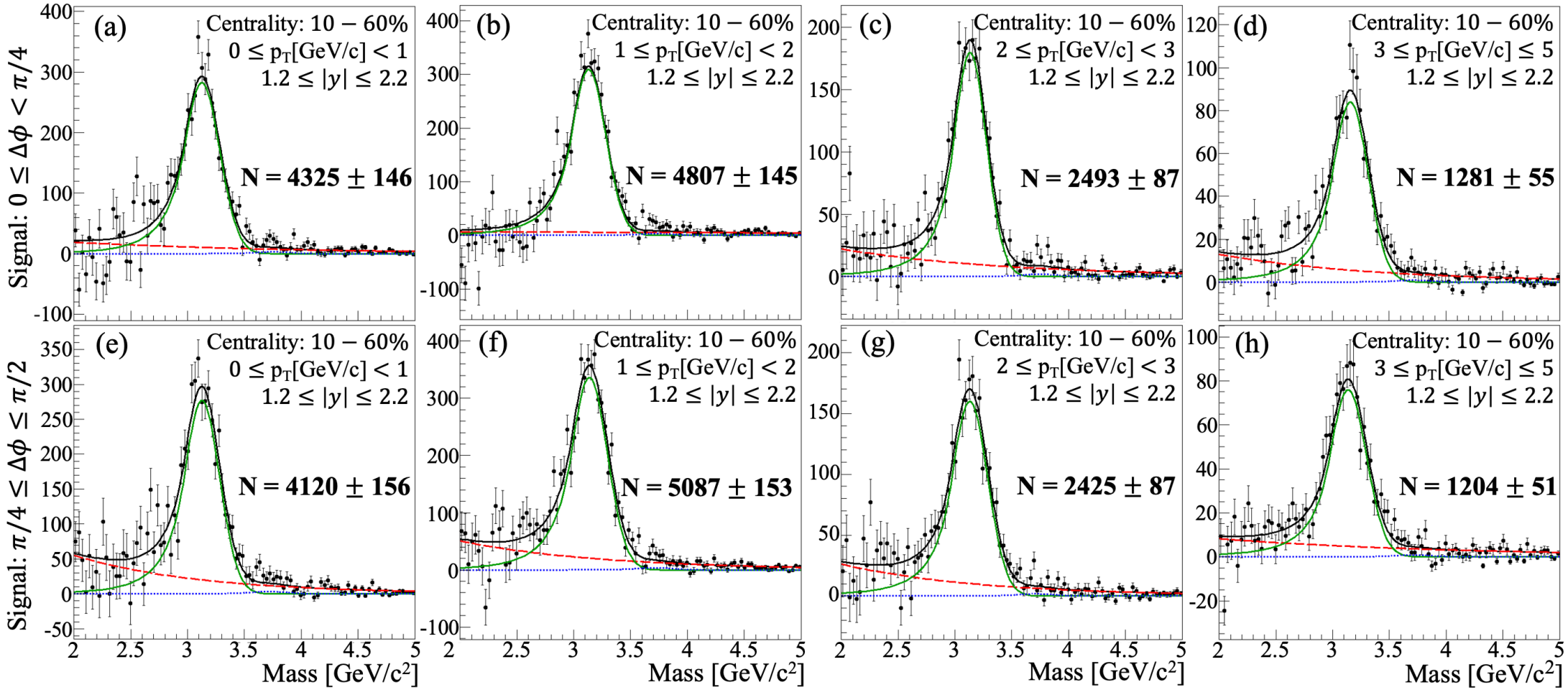
- DCA_r is determined by projecting the particle track determined by the FVTX onto a plane in the *z*-axis located at the initial collision point
- Essentially this is a measurement of the distance from the primary vertex at which a particle was produced, i.e. for a prompt particle $DCA_r = 0$
- With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



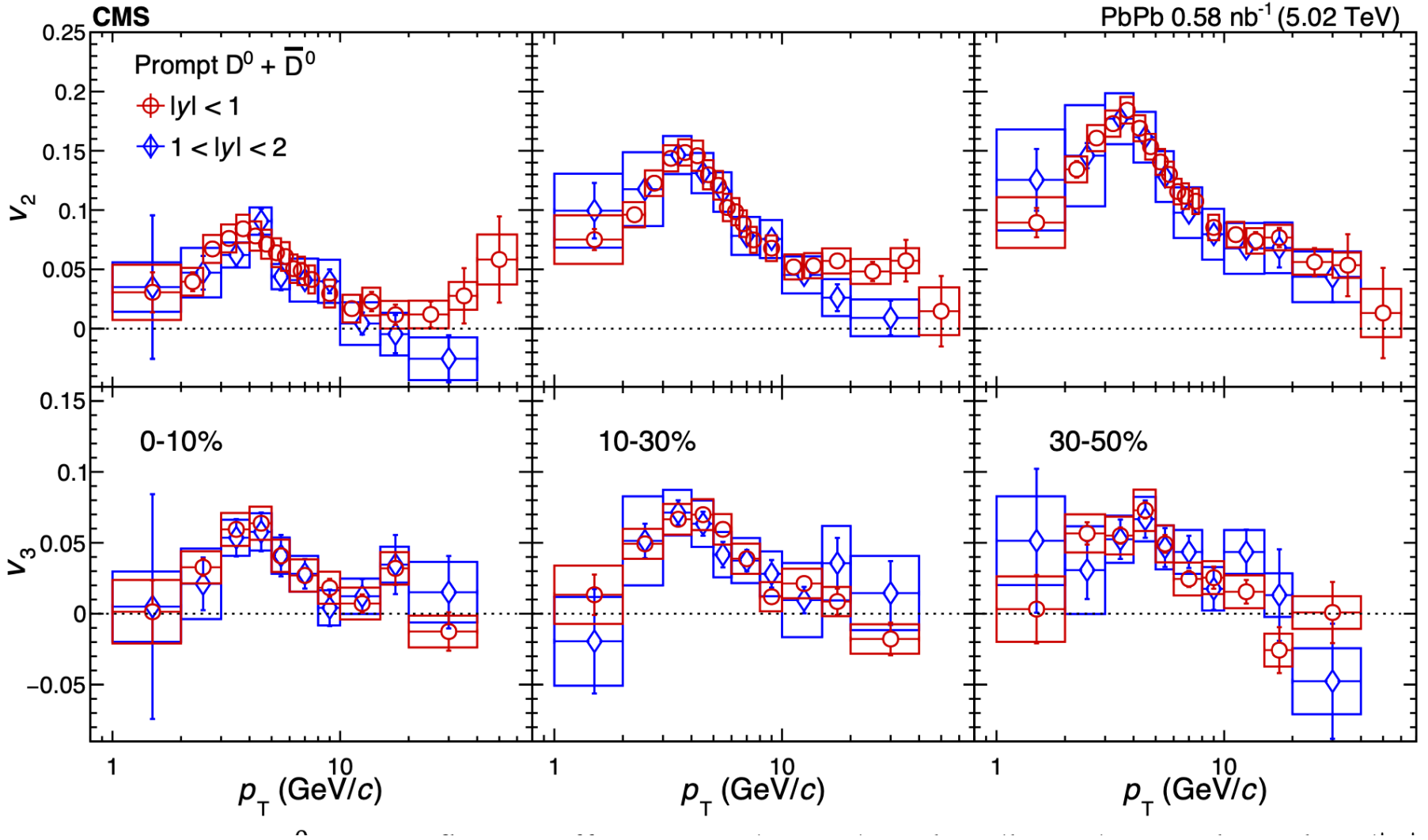
3D visualization of DCA_r



r-z plane visualization of DCA_r


(a)
Centrality: 10 − 60%
0 ≤ p_T[GeV/c] < 1
1.2 ≤ |y| ≤ 2.2
N = 4325 ± 146
(b)
Centrality: 10 − 60%
1 ≤ p_T[GeV/c] < 2
1.2 ≤ |y| ≤ 2.2
N = 4807 ± 145
(c)
Centrality: 10 − 60%
2 ≤ p_T[GeV/c] < 3
1.2 ≤ |y| ≤ 2.2
N = 2493 ± 87
(d)
Centrality: 10 − 60%
3 ≤ p_T[GeV/c] ≤ 5
1.2 ≤ |y| ≤ 2.2
N = 1281 ± 55
(e)
Centrality: 10 − 60%
0 ≤ p_T[GeV/c] < 1
1.2 ≤ |y| ≤ 2.2
N = 4120 ± 156
(f)
Centrality: 10 − 60%
1 ≤ p_T[GeV/c] < 2
1.2 ≤ |y| ≤ 2.2
N = 5087 ± 153
(g)
Centrality: 10 − 60%
2 ≤ p_T[GeV/c] < 3
1.2 ≤ |y| ≤ 2.2
N = 2425 ± 87
(h)
Centrality: 10 − 60%
3 ≤ p_T[GeV/c] ≤ 5
1.2 ≤ |y| ≤ 2.2
N = 1204 ± 51
Signal: 0 ≤ Δφ < π/4
Signal: π/4 ≤ Δφ ≤ π/2
Mass [GeV/c²]

No rapidity dependence for flow of D0 at LHC



LHC J/ψ R_{AA} and v_2: mid- and forward rapidity