Measurement of charge-dependent directed flow in STAR Beam Energy Scan (BES-II) Au+Au and U+U Collisions

Muhammad Farhan Taseer

for the STAR collaboration

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

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Outline

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- STAR Experiment at RHIC
- Directed Flow Results
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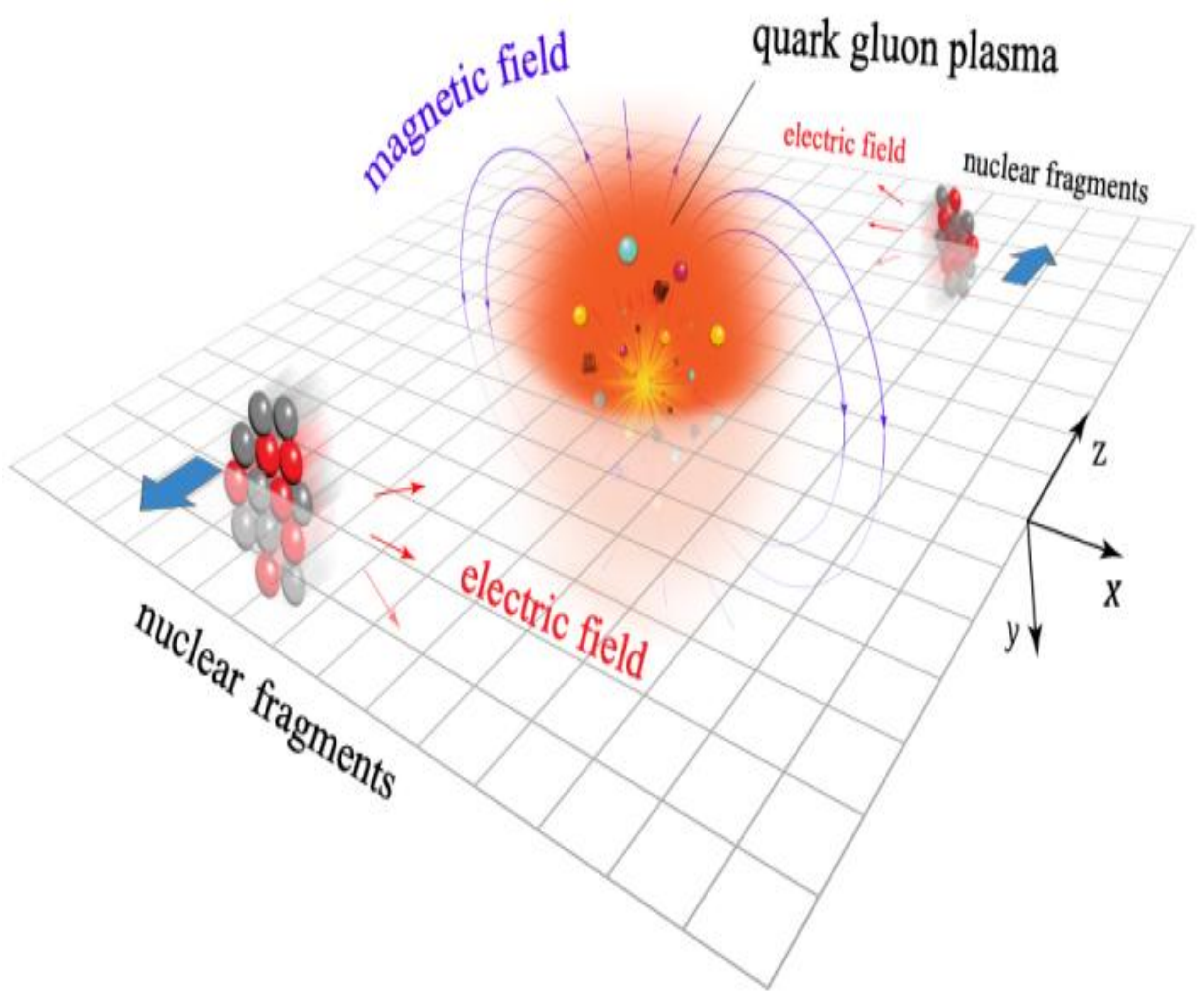
  - BES-II Au+Au Collisions @ 7.7 - 19.6 GeV
- Summary

Physics Motivation

- Ultra strong magnetic fields (**B~10^{18} Gauss**) are expected at very early stages in Heavy Ion Collisions
- B ~ Time dependent, decays rapidly as the medium (QGP) expands



PRX 14, 011028 [STAR]

- Important to understand QGP evolution in the presence of initial electromagnetic fields [1]

[1] U. Gürsoy et al. PRC 98,055201, PRC 89 054905

Electromagnetic Field Effects

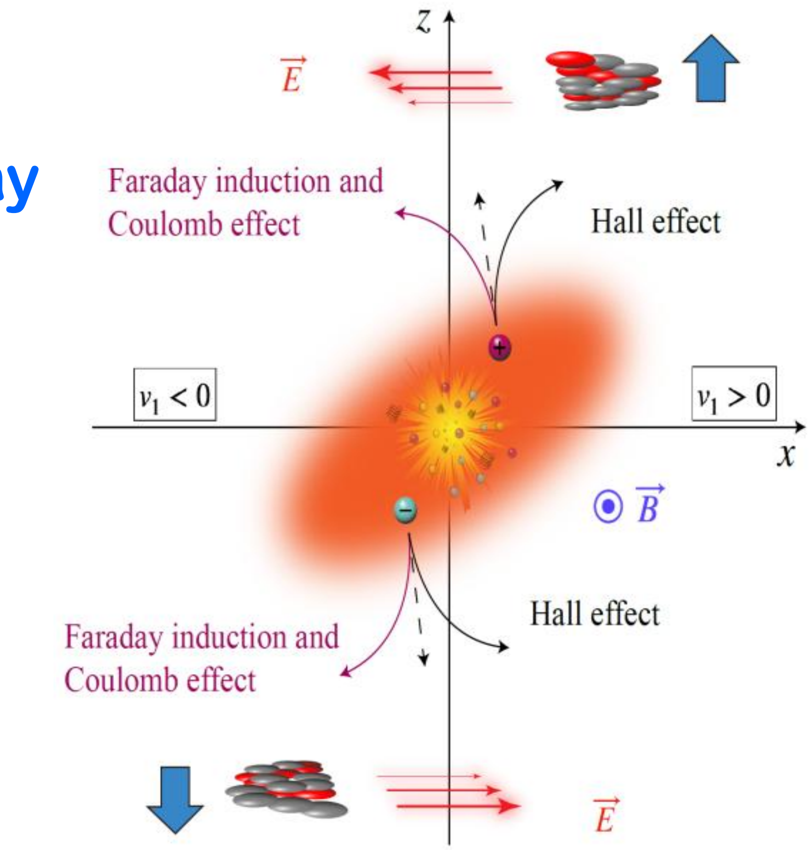
Directed Flow (v_1) describes the collective sideward motion of the produced particles and nuclear fragments → carries information from the early stages of collision

$$v_1 = \langle \cos(\phi - \Psi_{EP}) \rangle / R\{\Psi_{EP}\}$$

R Event Plane Resolution
Ψ Event Plane azimuthal Angle
ϕ Azimuthal angle of outgoing particles

In the expanding QGP, quarks experience following electromagnetic effects [1]

- **Hall Effect:** F = q (v x B) by Lorentz Force
- **Coulomb Effect:** **E** generated by spectator nucleons
- **Faraday Induction:** decreasing **B** as spectators fly away



These electromagnetic forces provide opposite contribution of v_1 to particles with opposite charges

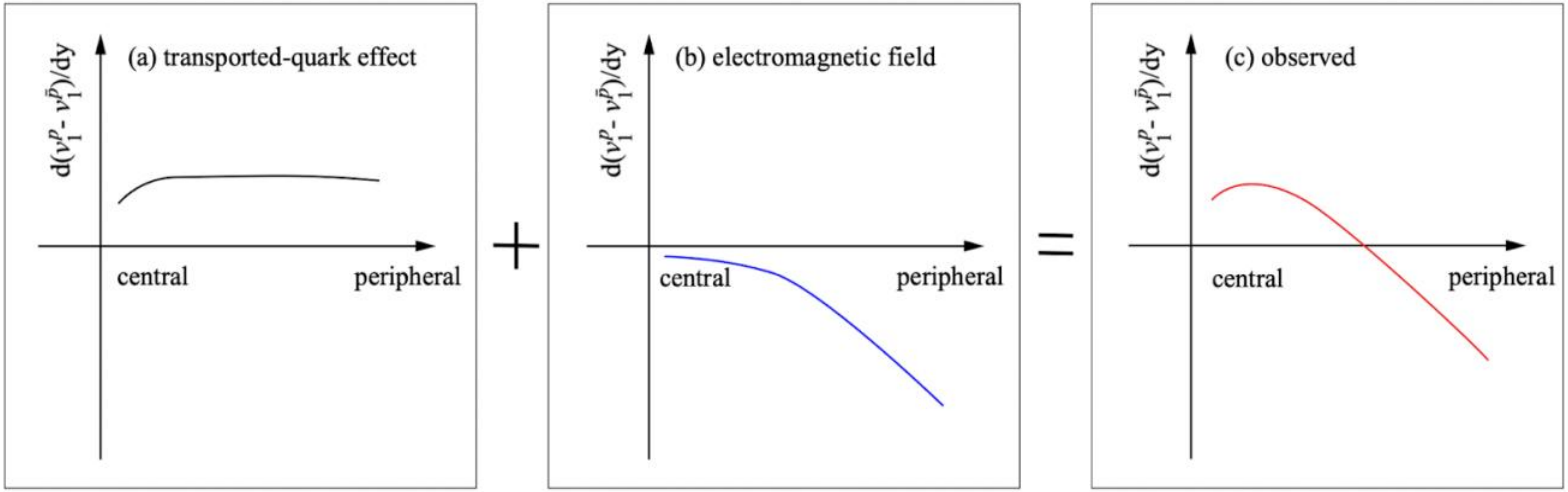
$$I_{(total)} = I_{(Hall)} + I_{(Faraday)}$$

PRX 14, 011028 [STAR]

Electromagnetic Field Effects on v_1

❖ The splitting of v_1 between particle and antiparticle is measured as:

$$\Delta v_1 = dv_1^{+}/dy - dv_1^{-}/dy$$



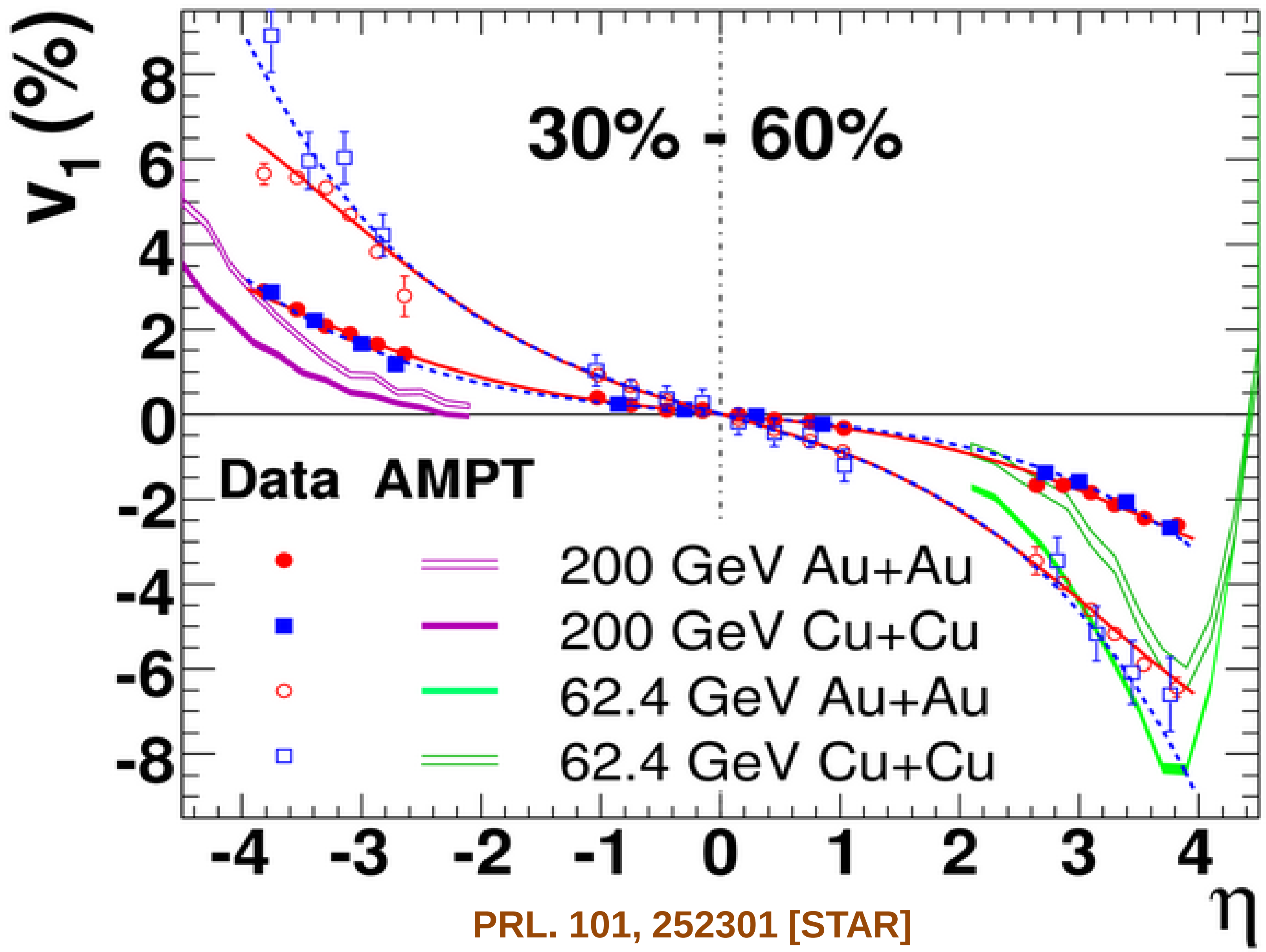
Transported Quark ⟶ Positive Δv_1

EM Field ⟶ Negative Δv_1

Combination (Transported Quarks + EM)

PRX 14, 011028 [STAR]

System Size Dependence on v_1

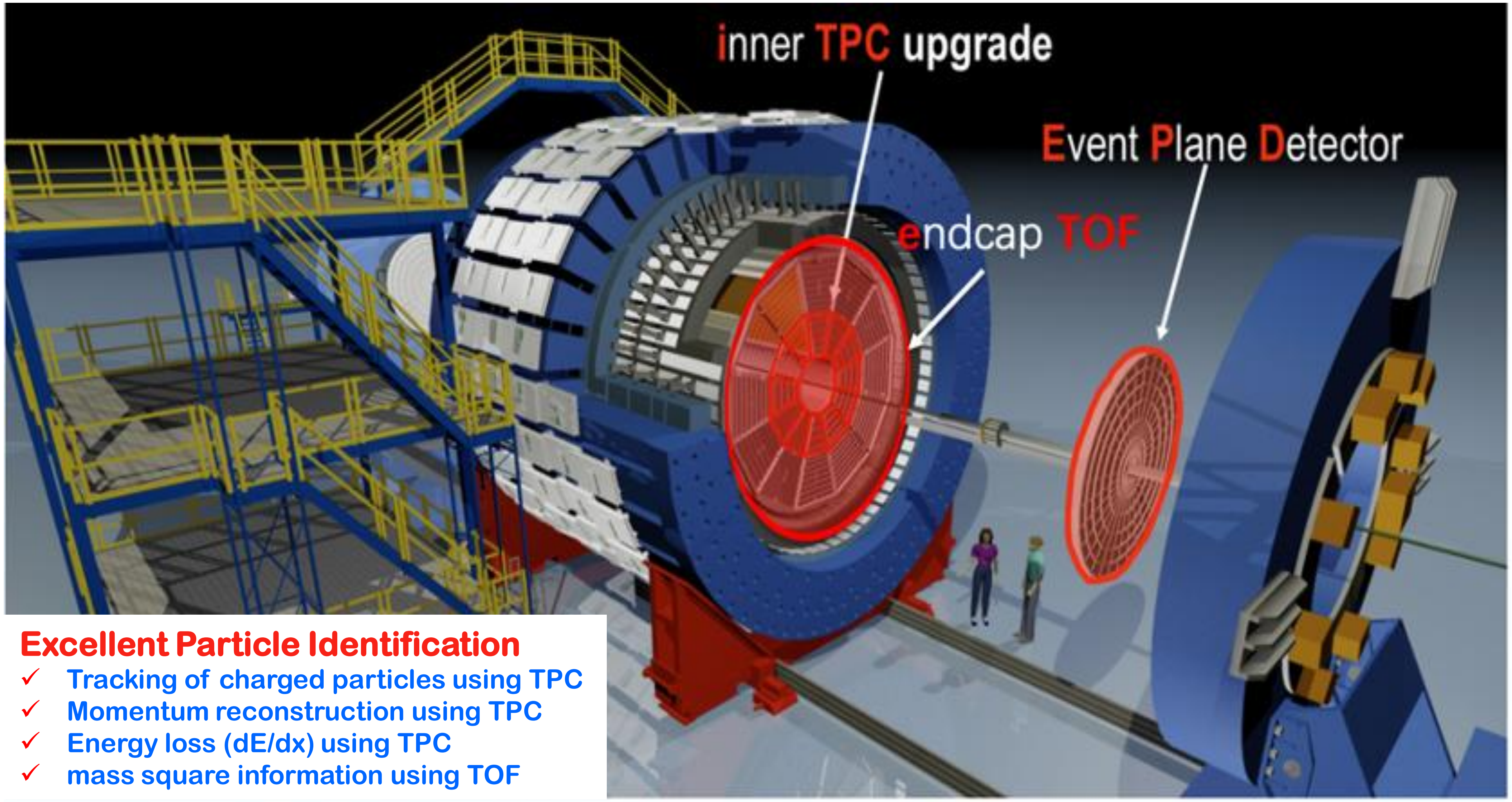


PRL. 101, 252301 [STAR]

- For inclusive charged particles, v_1 of Au+Au ≈ Cu+Cu at a fixed centrality
- We shall present v_1 and Δv_1 in U+U, Au+Au and Isobar (RuRu + ZrZr)

STAR Experiment

- Solenoidal Tracker at RHIC is a multipurpose detector with full azimuthal coverage
- Upgrade of inner-TPC (Better Track Quality, Wide acceptance ($|\eta| < 1.5$)
- Event Plane Detector and Zero Degree Calorimeter used for event plane reconstruction, EPD ($2.1<|\eta|<5.1$), ZDC-SMD($|\eta|>6.3$)



Excellent Particle Identification
- ✓ Tracking of charged particles using TPC
- ✓ Momentum reconstruction using TPC
- ✓ Energy loss (dE/dx) using TPC
- ✓ mass square information using TOF

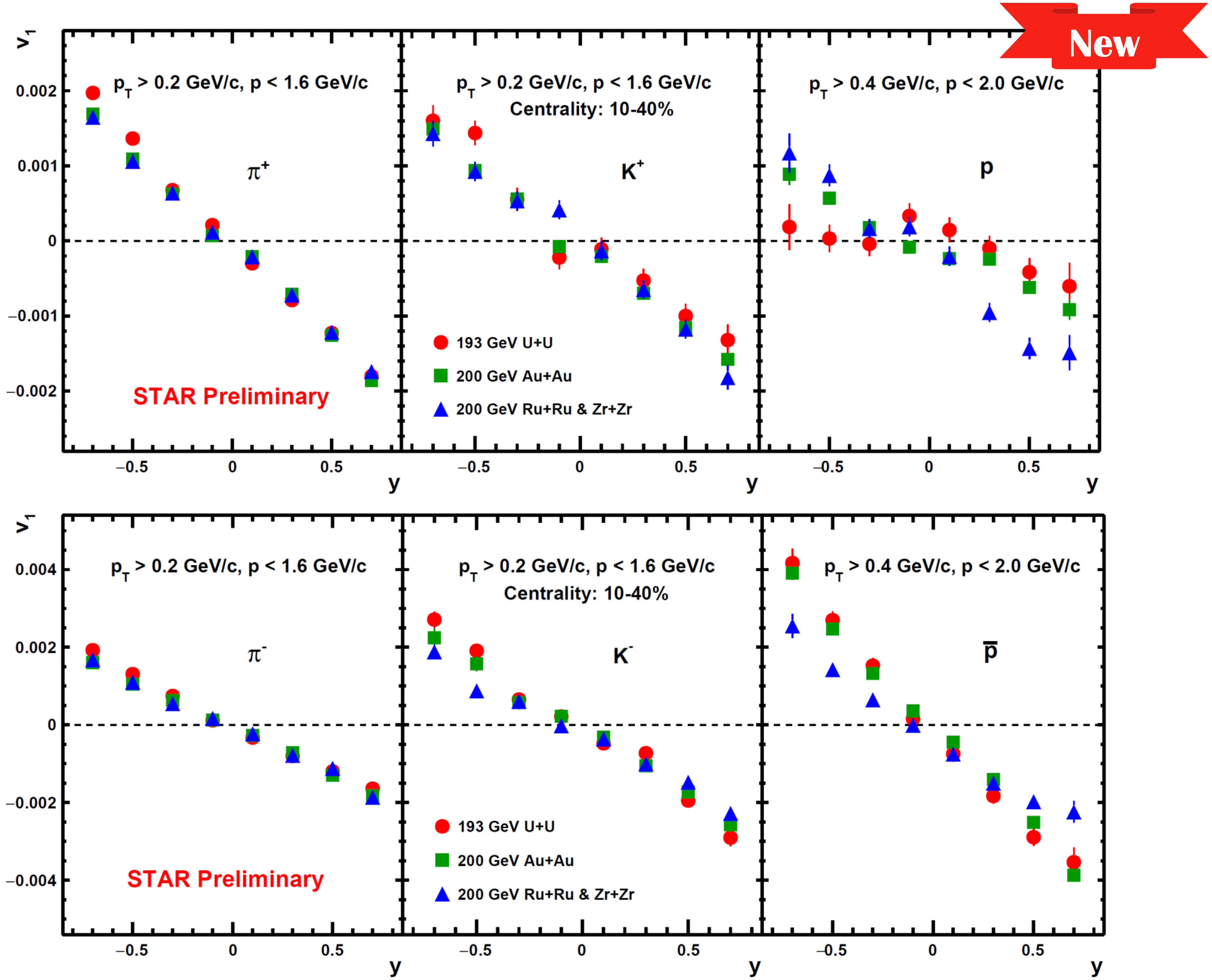
The STAR detector

Results

$v_1(y)$ for Mid-Central U+U, Au+Au & Isobar

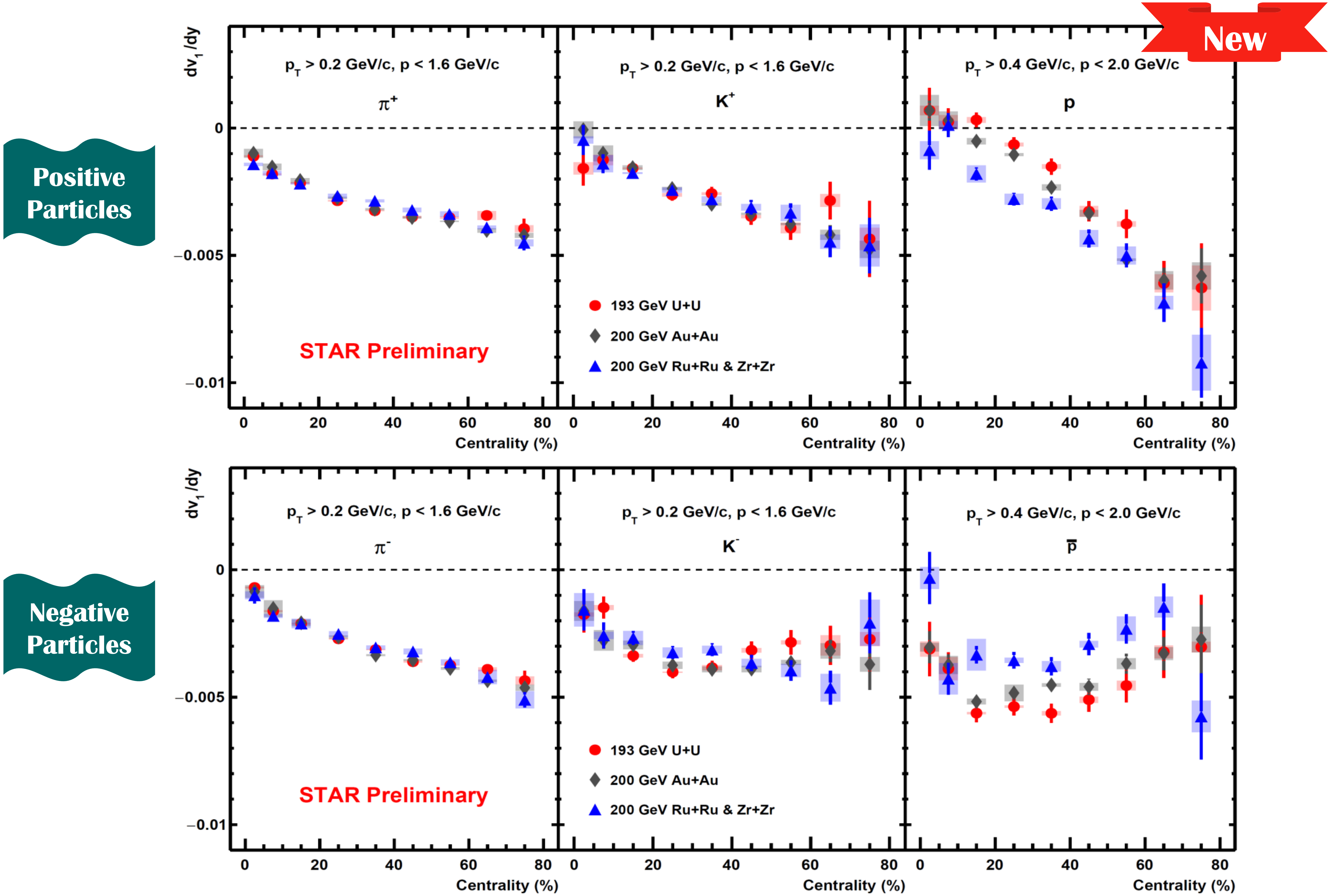
Positive Particles

Negative Particles



- v_1 vs y in U+U, Au+Au and Isobar collisions
- Extracted v_1 slope using linear fit (|y| < 0.8)

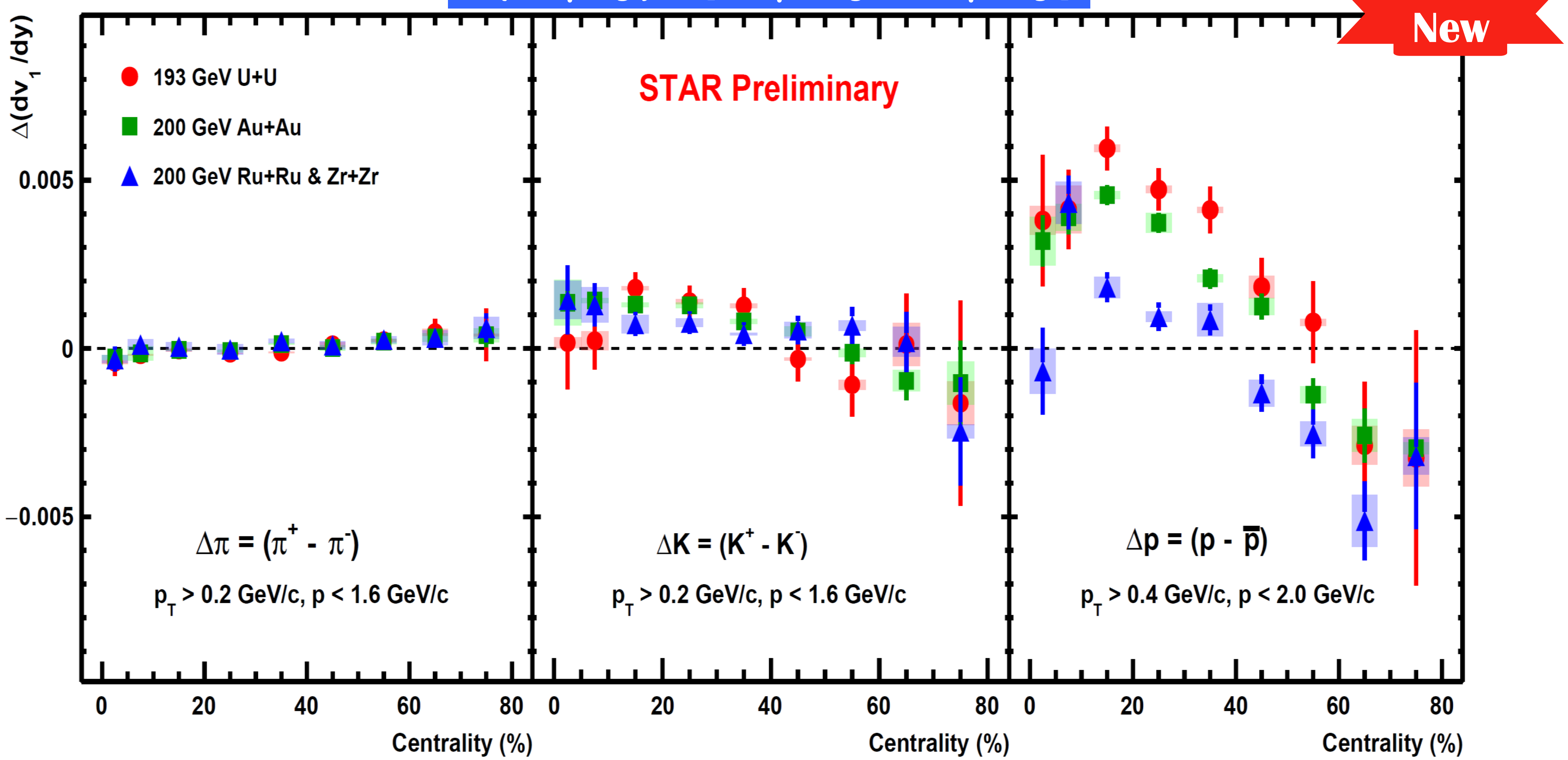
Slope (dv_1/dy vs centrality) for U+U, Au+Au & Isobar



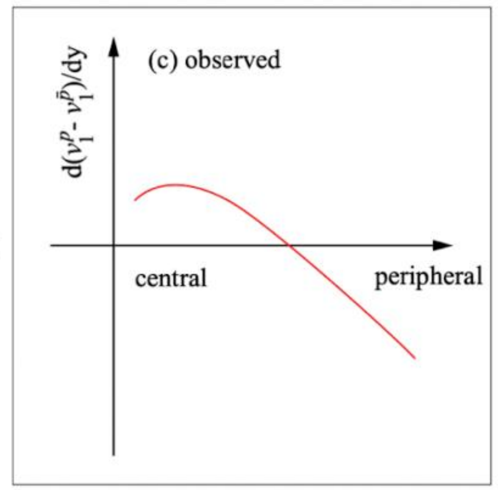
- **Positive and Negative Pions (Kaons)** → consistent within uncertainties
- **Protons and antiprotons** → observe system size dependence in mid-central collisions

$\Delta(dv_1/dy)$ for U+U, Au+Au & Isobar

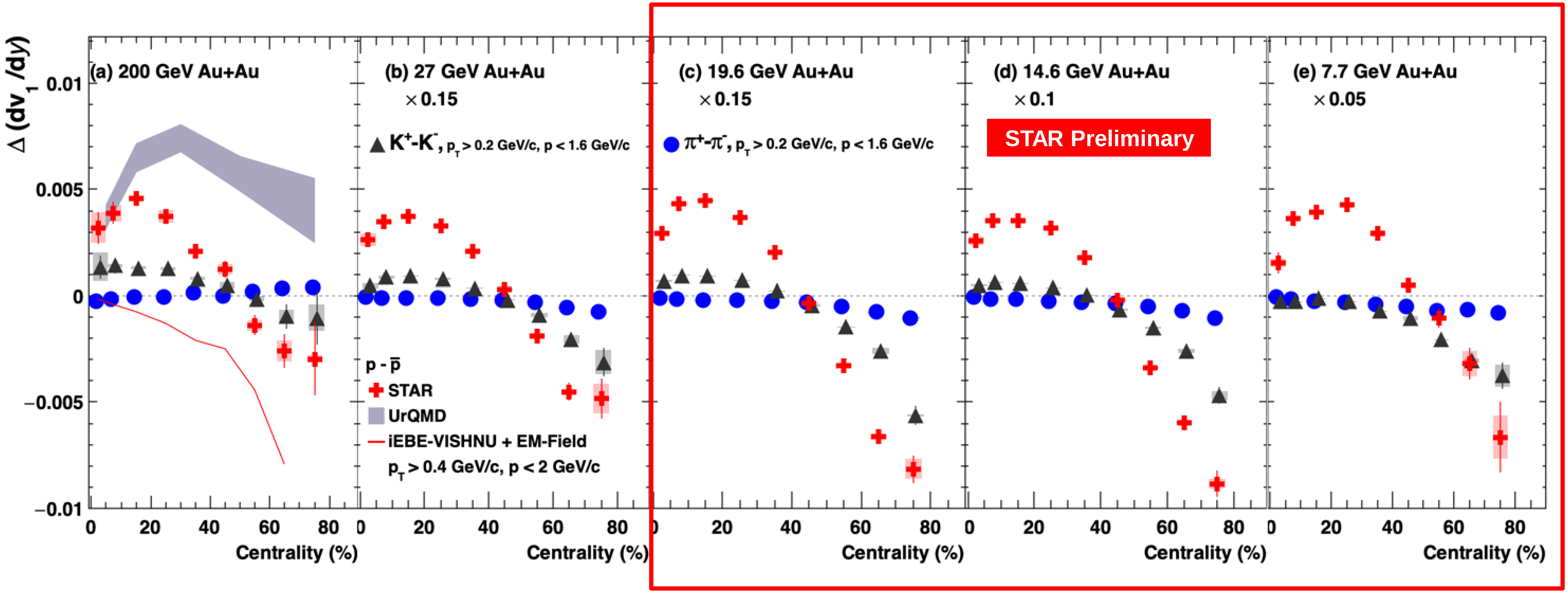
$\Delta(dv_1/dy) = [dv_1^+/dy - dv_1^-/dy]$



- **Pions (Kaons)** → consistent within uncertainties
- **Protons** → clean ordering in the mid-central collisions 10-40%
  → sign change in the peripheral collisions 50-80%
- **Δv_1 sign change** → consistent with naive expectations of transport + EM effects



$\Delta(dv_1/dy)$ for Beam energy dependence



- Negative $\Delta(dv_1/dy)$ in peripheral collisions meet naive expectation from transport + EM effects
- Δv_1 increases with decrease in beam energy
- Consistent with the dominance of (Faraday + Coulomb) effect in peripheral collisions (other mechanisms such as baryon inhomogeneities are under investigation)

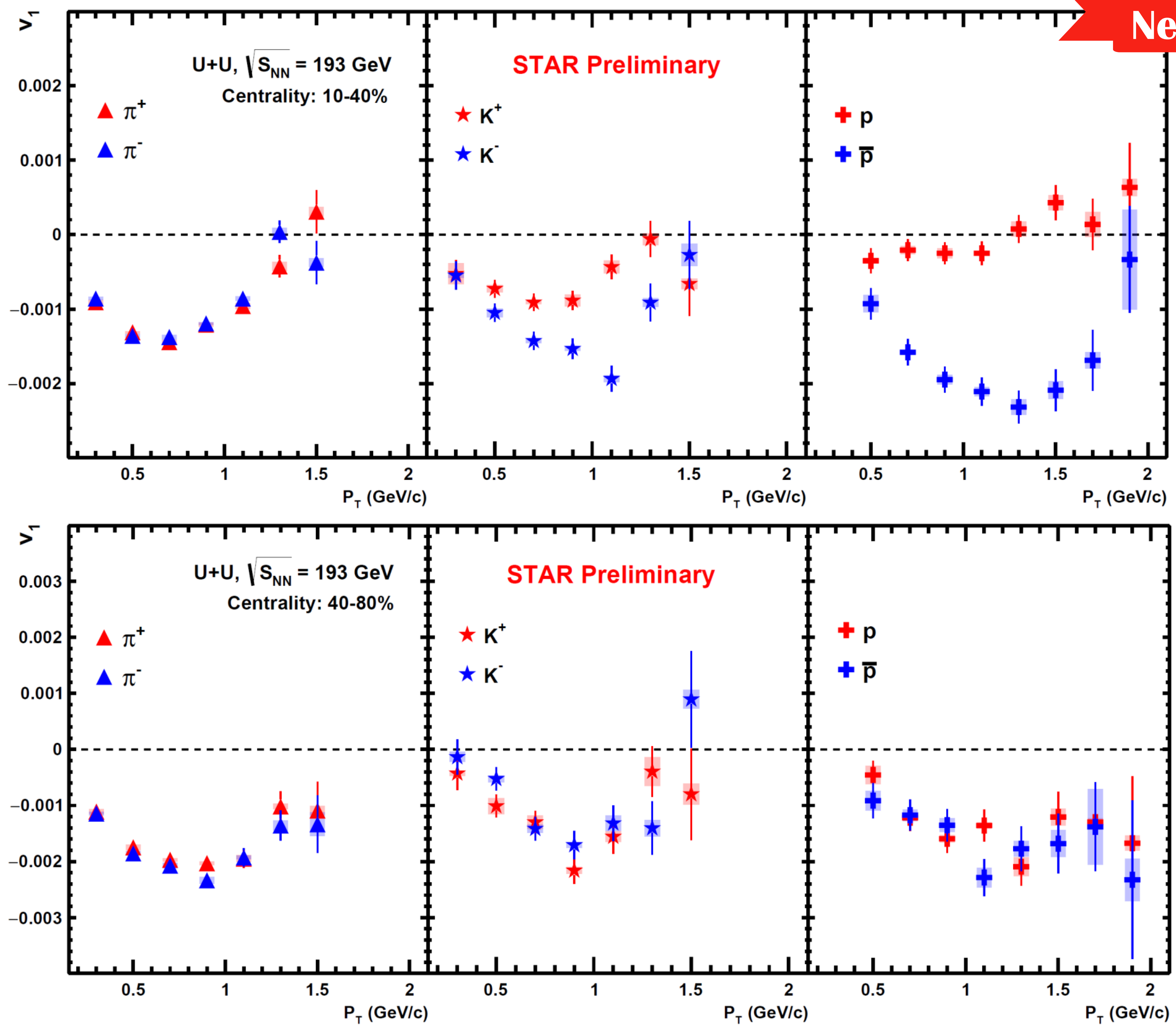
[T. Parida et al. arXiv:2305.8806]

$v_1(p_T)$ for U+U Collisions

New

Mid Central 10-40 %

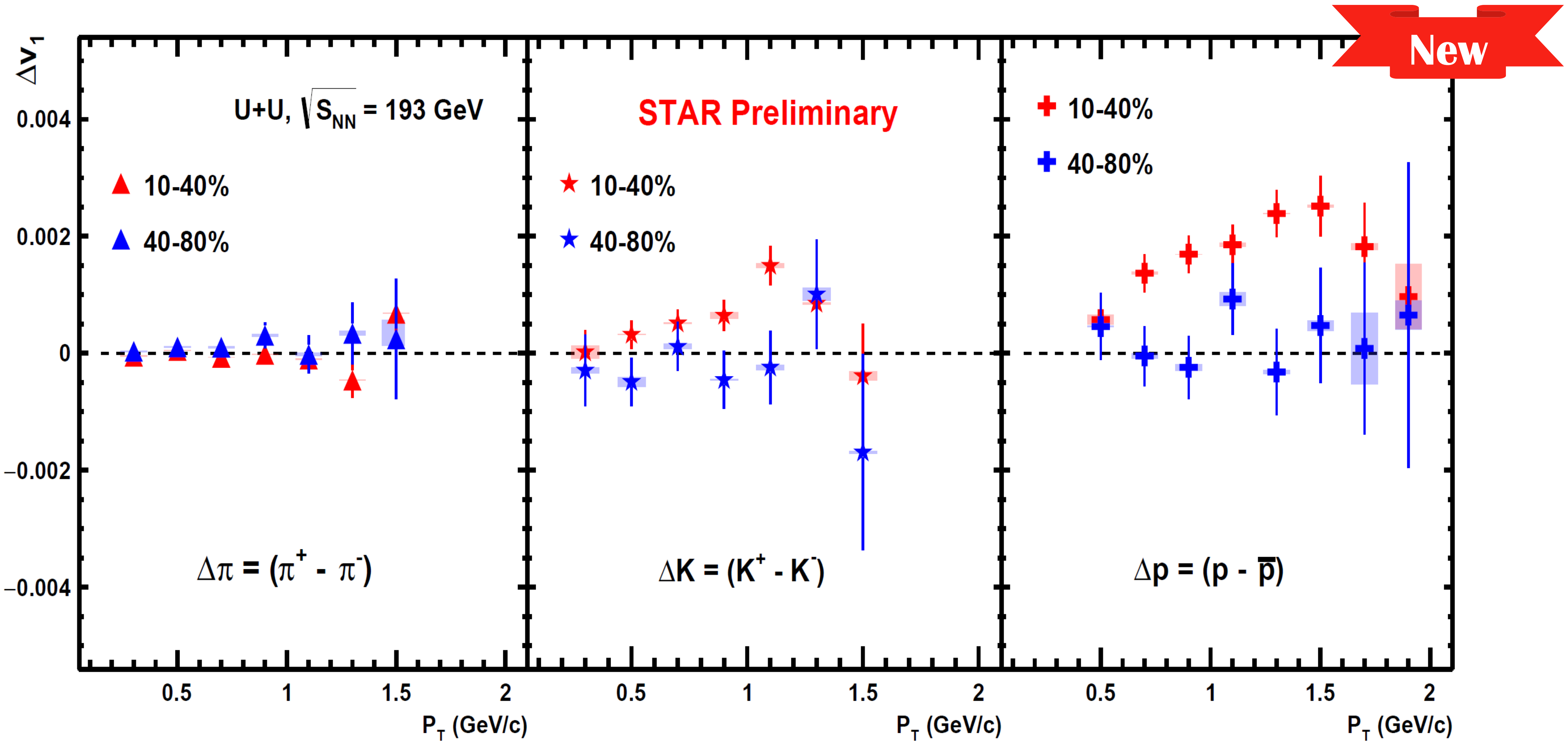
Peripheral 40-80 %



- For Proton (antiproton) → Significant splitting in mid-central collisions (10-40)%

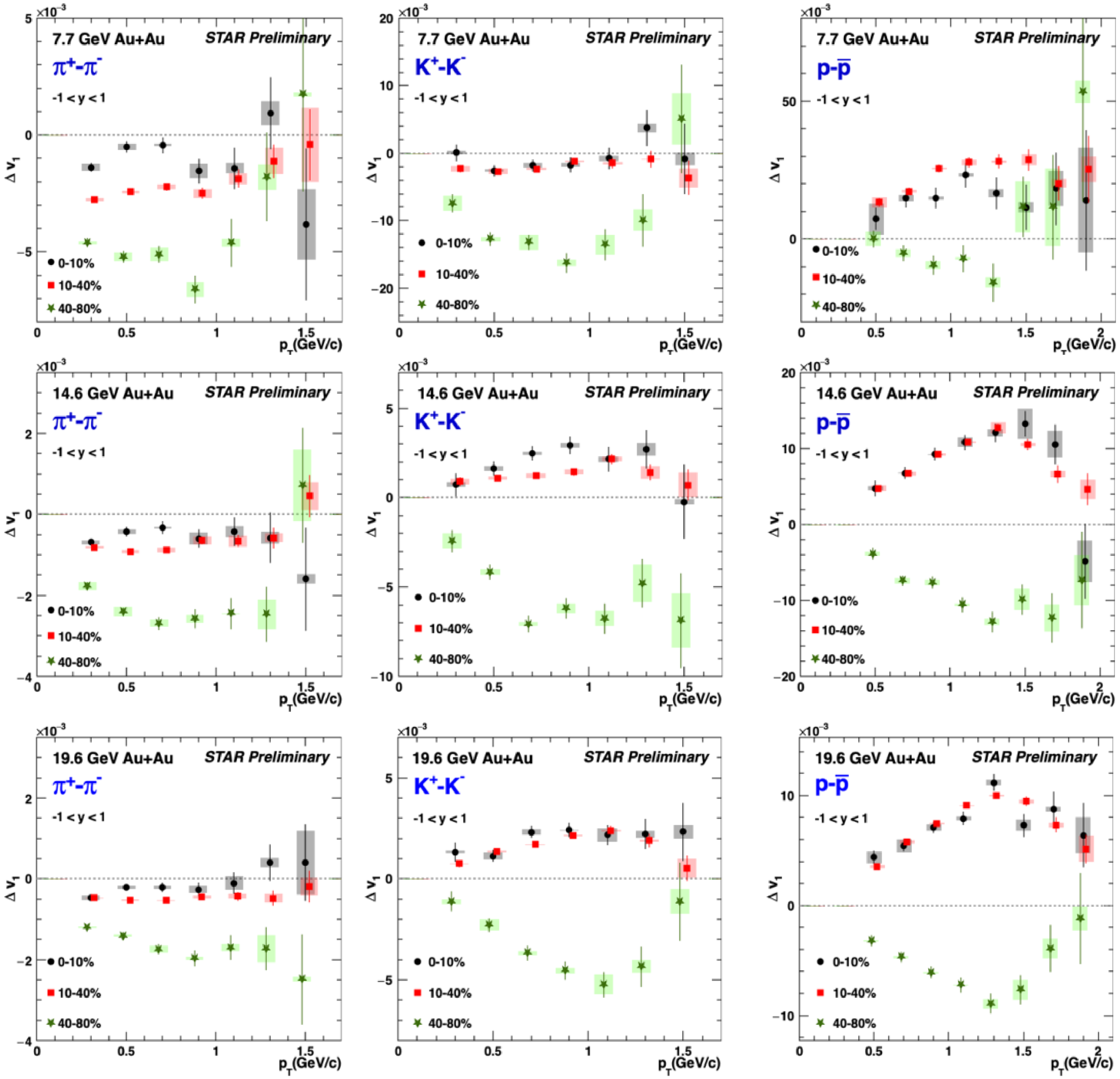
$\Delta v_1(p_T)$ for U+U Collisions

$\Delta v_1 = v_1^+ - v_1^-$



- **Pions (Kaons)** → consistent with zero within uncertainties
- **Protons** → mid-central collisions → Δv_1 keep increasing with p_T
  peripheral collisions → no oblivious p_T dependence

$\Delta v_1(p_T)$ for BES-II at 7.7 - 19.6 GeV



- For peripheral collisions, Δv_1 is negative
- Indication of larger splitting with increasing p_T as expected from theory

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905]

Summary

➡ Δv_1 from U+U Collision (Top RHIC Energy)

- We observe a significant difference for proton Δv_1 in mid-central collisions (10-40)% among three different collision systems

Proton Δv_1 : U+U > Au+Au > Isobar

- For Proton, Δv_1 changes sign in peripheral collisions as observed in the previous Au+Au and isobar data
- For pion and kaon all data points are consistent among three different collision systems at the same collision energy

➡ Δv_1 from Au+Au Collision in BES-II

- Splitting in Δv_1 increases with decreasing beam energies
- More negative Δv_1 for lower collision energies → consistent with longer lifetime of the electromagnetic field → shorter lifetime of the fireball

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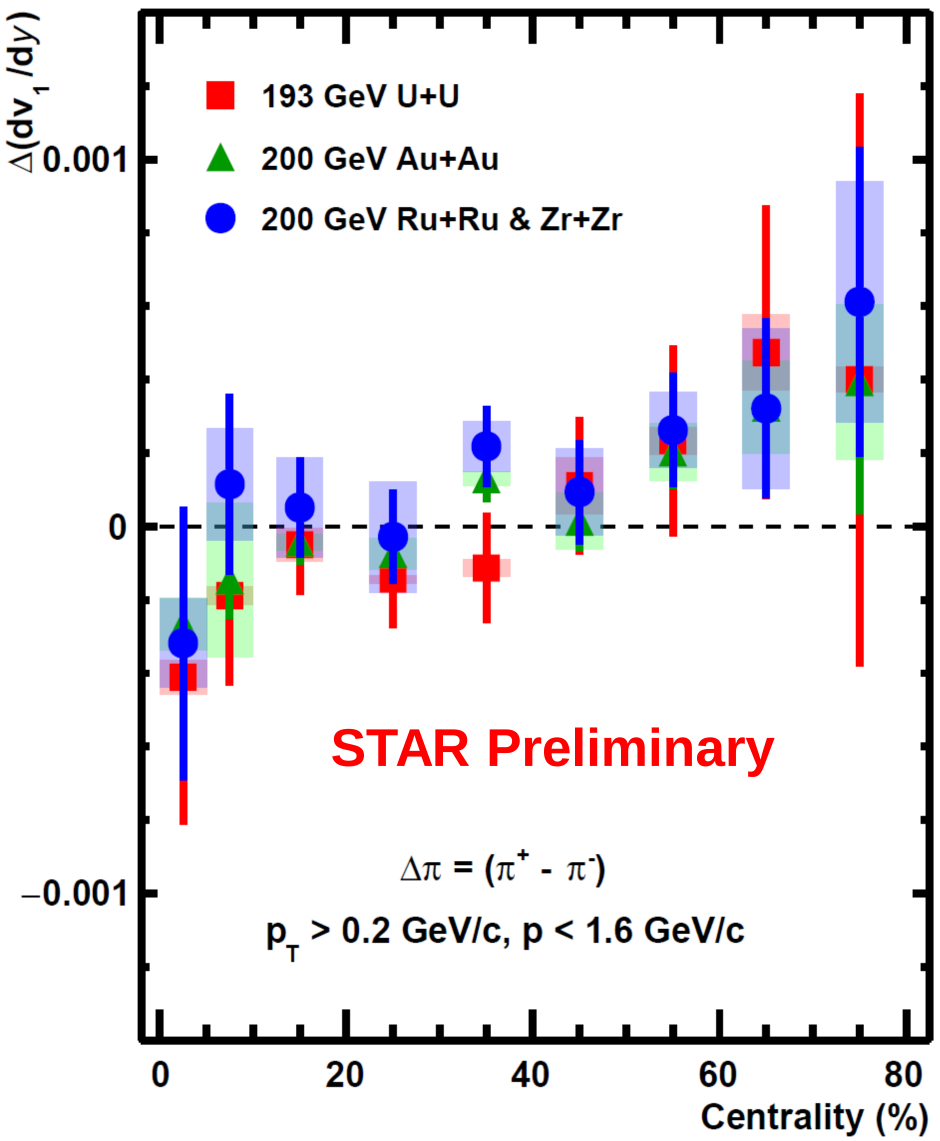
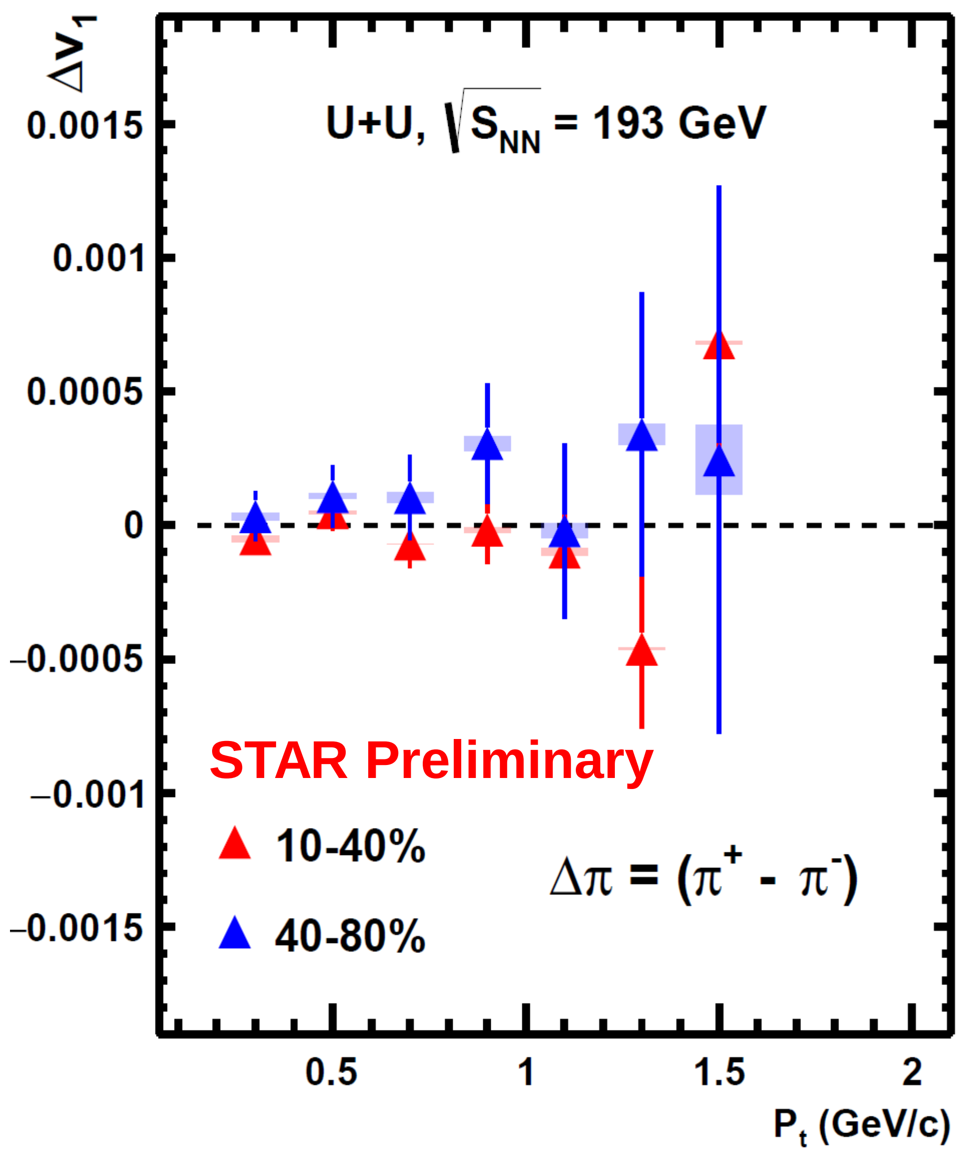
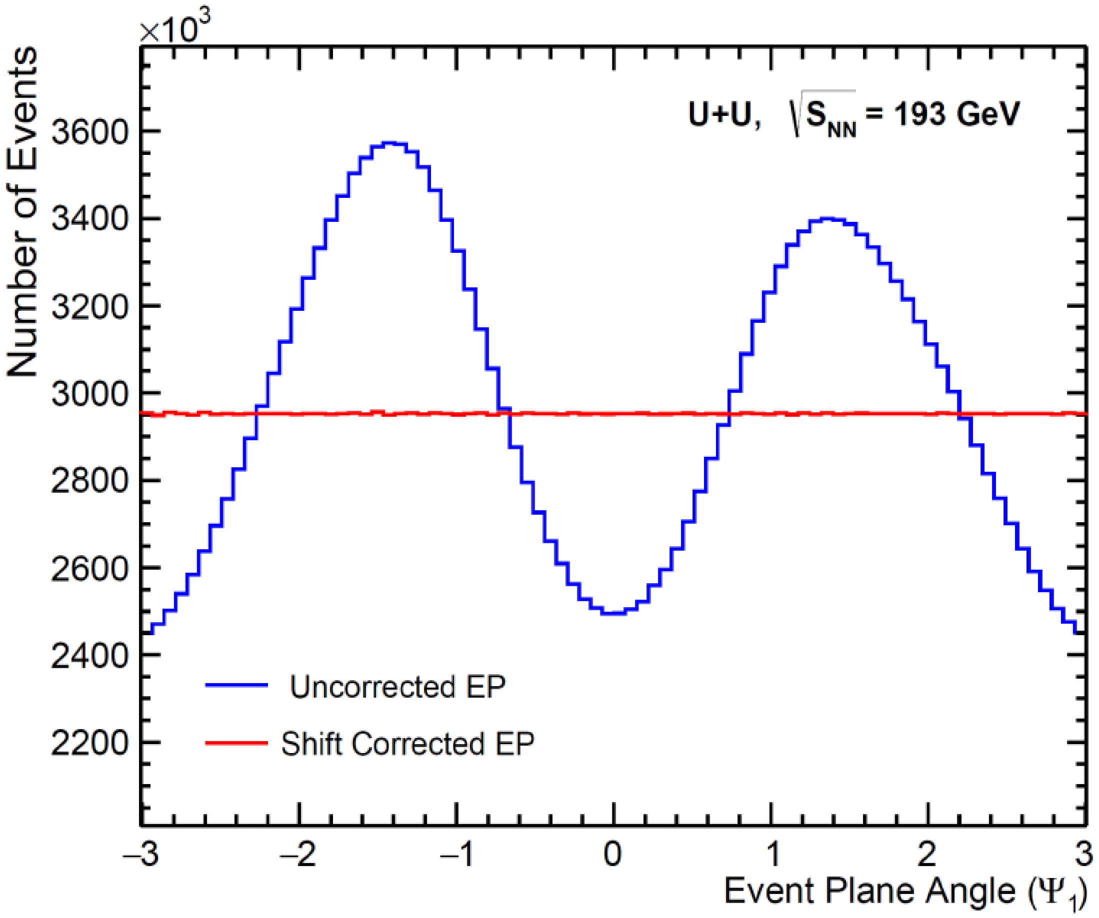
Backup Slides

Δv_1 as a function of Centrality and p_T (Pion)

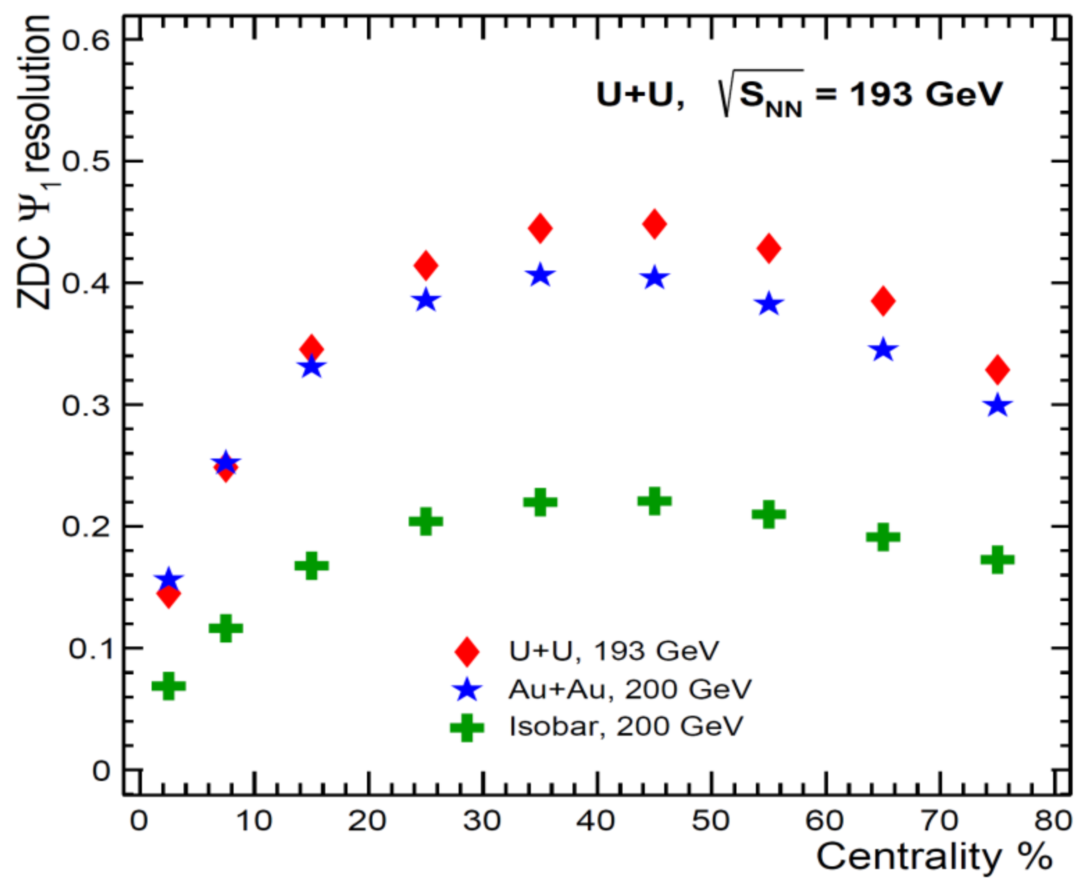




Event Plane & Resolution Plots



Ψ_1 is reconstructed using ZDC



First order Full ZDC calculated from the correlation between East and West ZDC

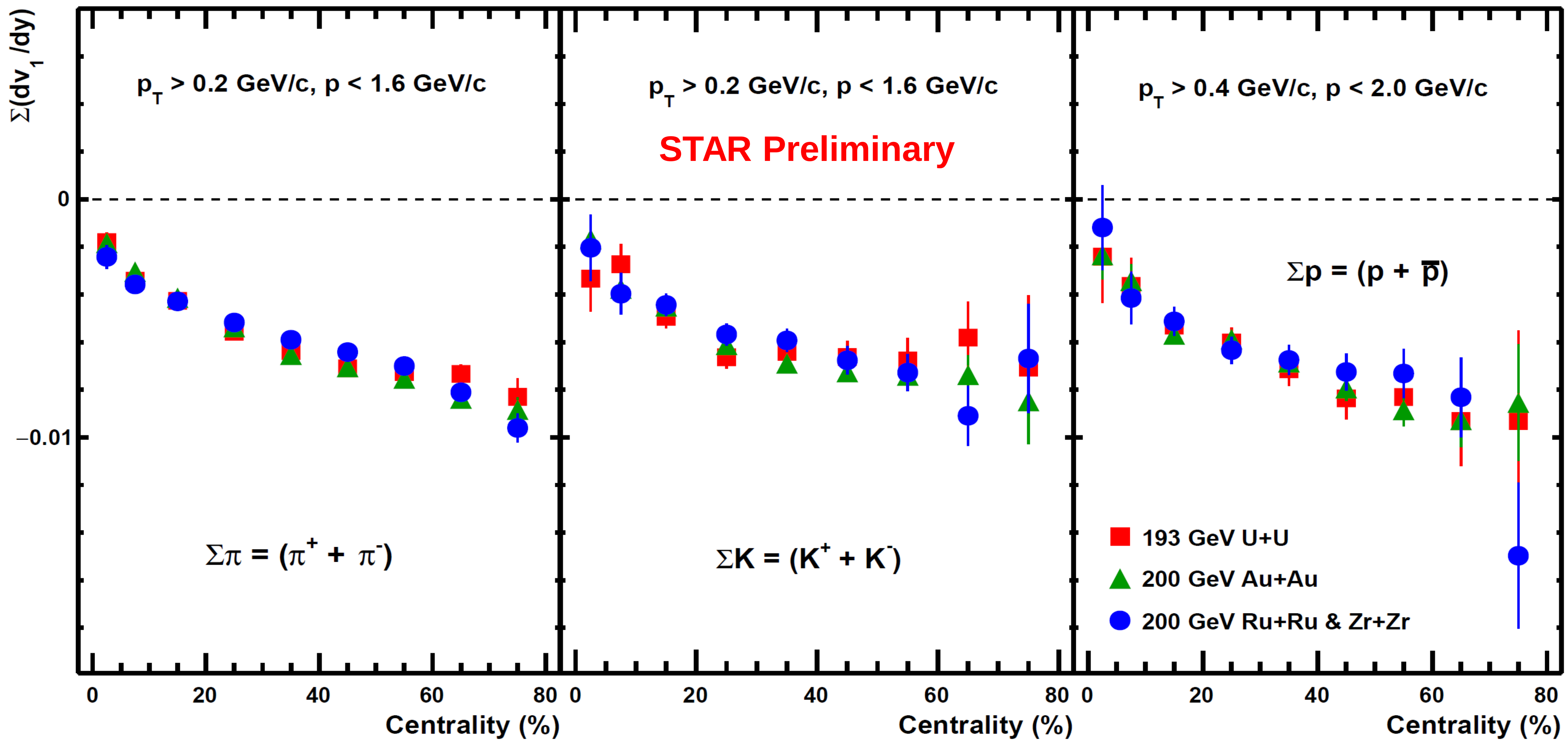
Resolution Values: -

U+U[9] = {0.145016, 0.248548, 0.345383, 0.414196, 0.444727, 0.448302, 0.428285, 0.385058, 0.328569}

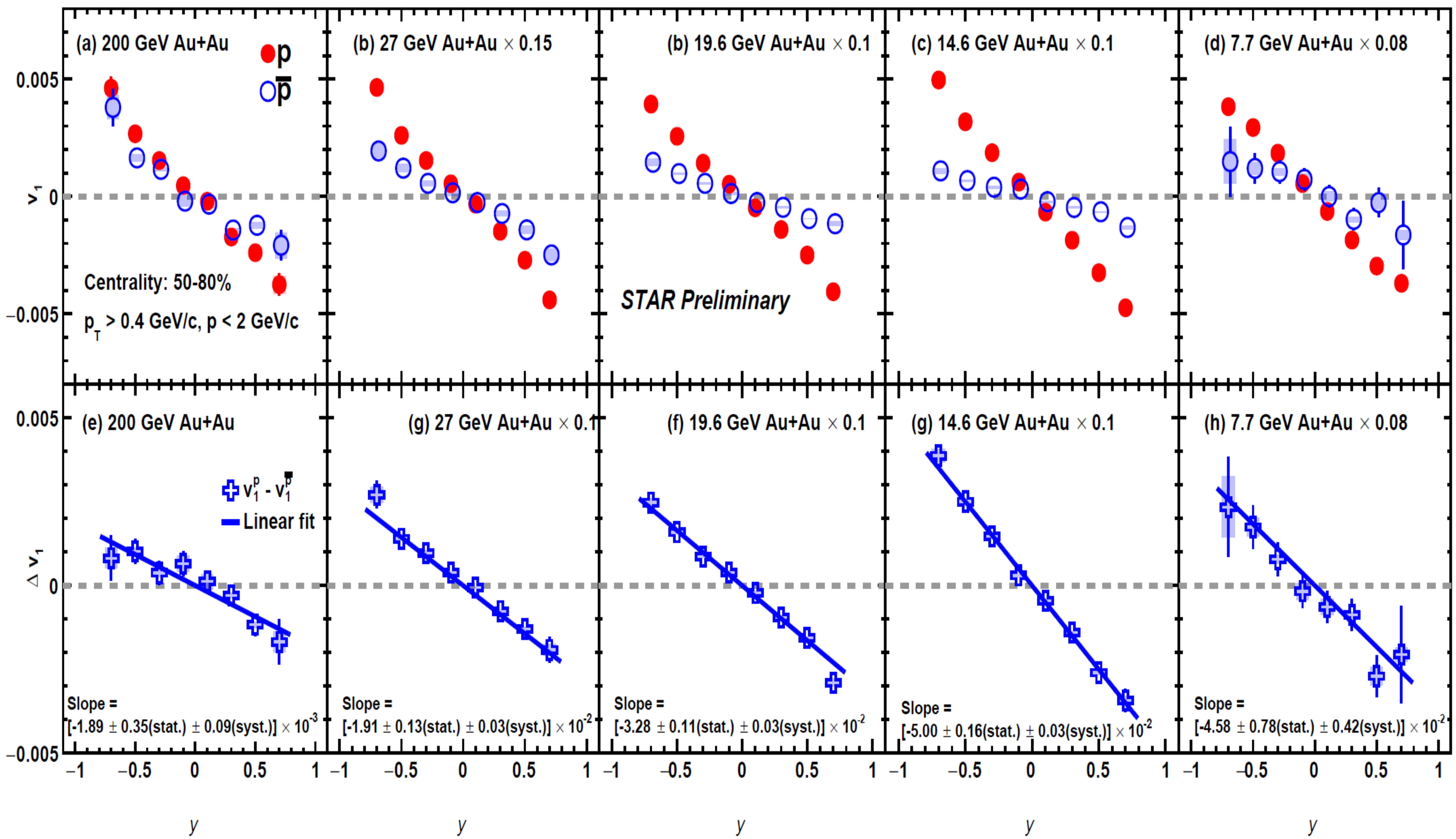
Au+Au[9] = {0.1563, 0.252126, 0.331136, 0.385756, 0.406247, 0.404069, 0.382588, 0.344916, 0.299311}

Isobar[9] = {0.0688674, 0.11634, 0.167703, 0.204098, 0.21988, 0.220753, 0.20985, 0.191277, 0.1727}

Centrality dependent $\sum(dv_1/dy)$ for Different Collision Systems

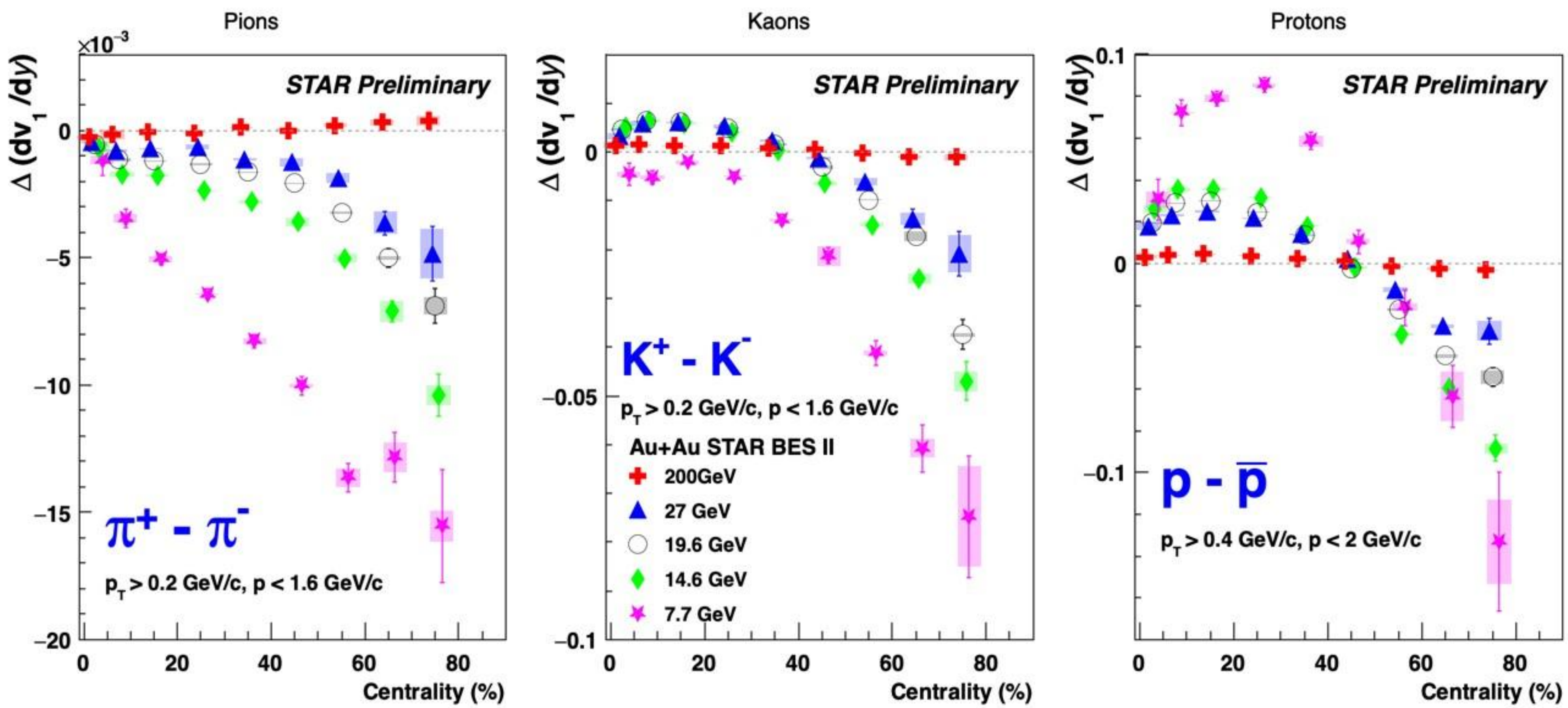


$v_1(y)$ for peripheral Collisions (50-80%)



- In peripheral collisions (50-80%), proton Δv_1 slope turns negative
- Significantly negative slopes (from linear fit) in all considered energies

$\Delta(dv_1/dy)$ for BES-II Energies



- ❖ $\Delta(dv_1/dy)$ in peripheral collisions is more negative at lower collision energies for each species
- ❖ The lifetime of the fireball seems shorter at lower energies which predict the longer life of magnetic field