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

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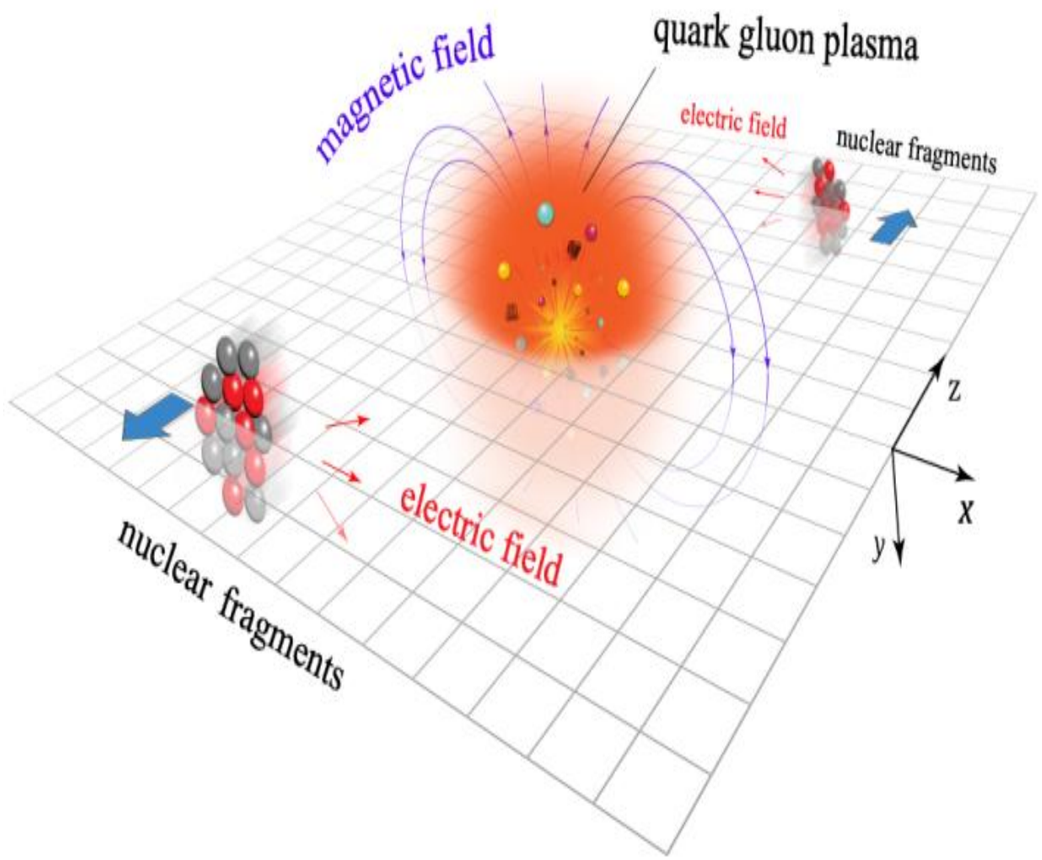
Outline

- Physics Motivation
- STAR Experiment at RHIC
- Directed Flow Results
  - U+U Collisions @ 193 GeV
  - 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

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

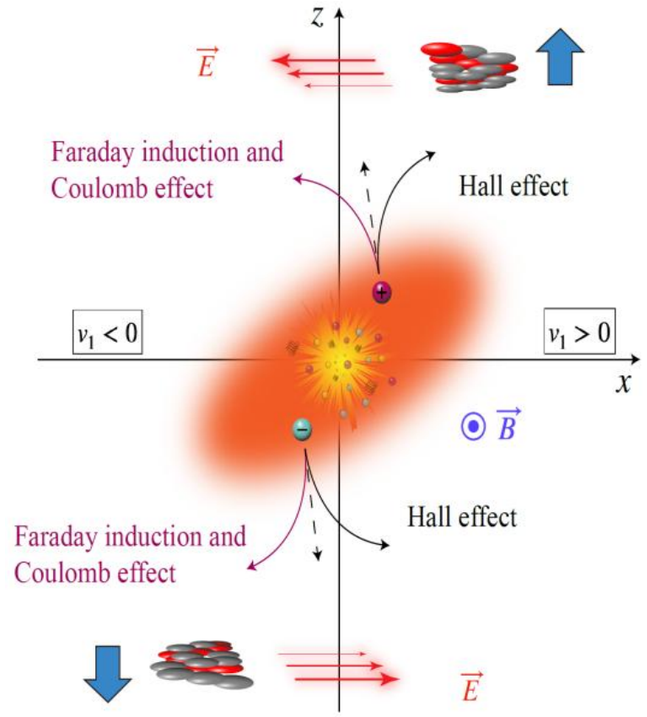
- **R** Event Plane Resolution
- **Ψ** Event Plane azimuthal Angle
- **ϕ** Azimuthal angle of outgoing particles

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

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

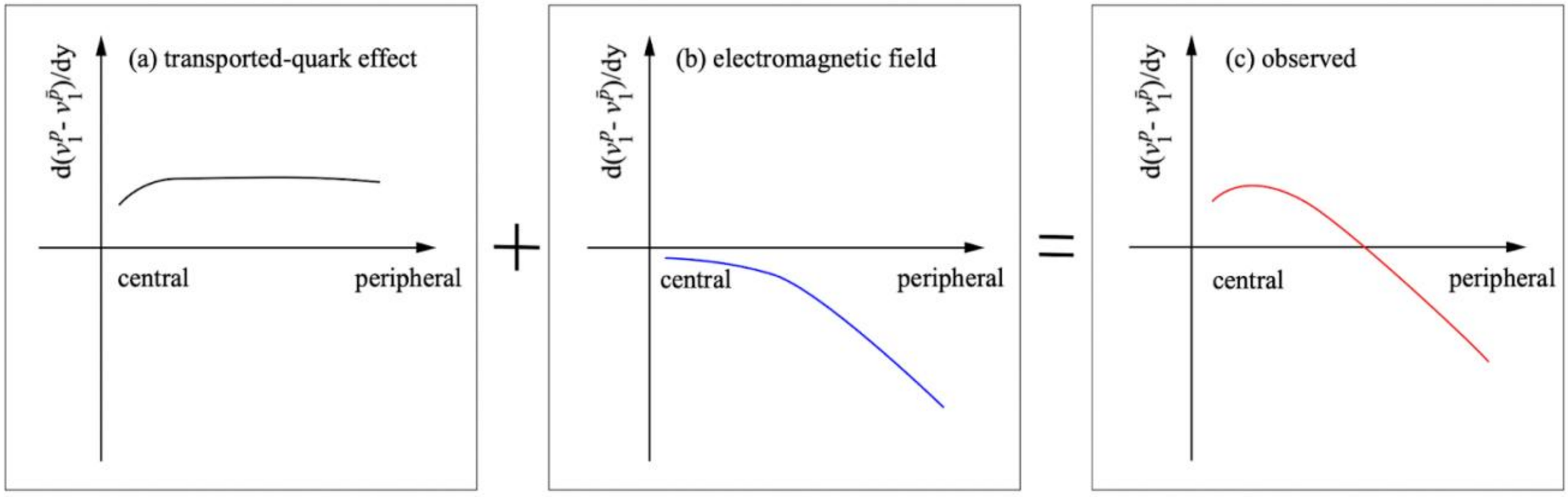


PRX 14, 011028 [STAR]

Electromagnetic Field Effects on v_1

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

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



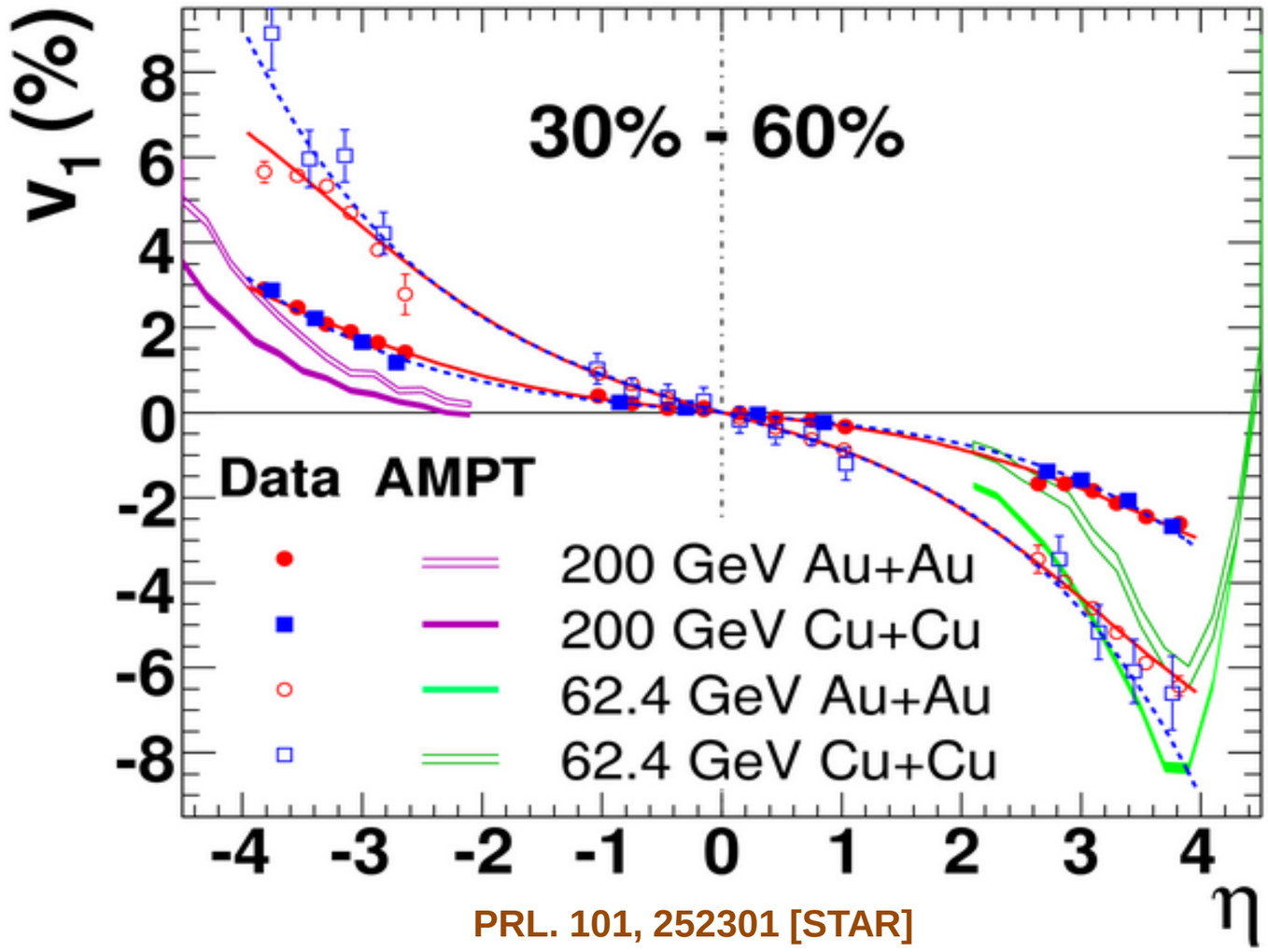
Transported Quark → Positive Δv_1

EM Field → Negative Δv_1

Combination
(Transported Quarks + EM)

PRX 14, 011028 [STAR]

System Size Dependence on v_1

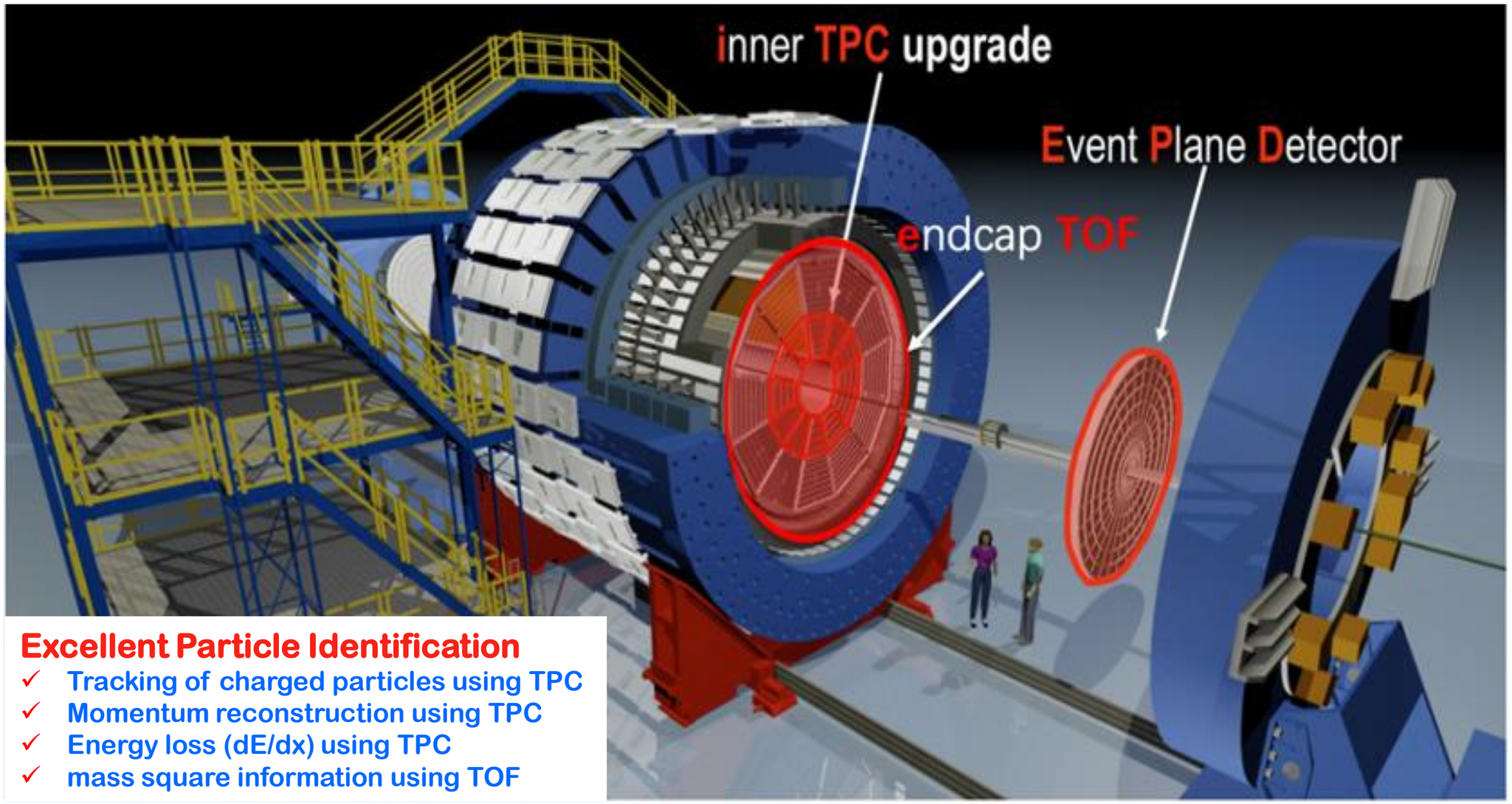


PRL. 101, 252301 [STAR]

- 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 (|η| < 1.5)**
- Event Plane Detector and Zero Degree Calorimeter used for event plane reconstruction, EPD (2.1<|η|<5.1), ZDC-SMD(|η|>6.3)



Excellent Particle Identification

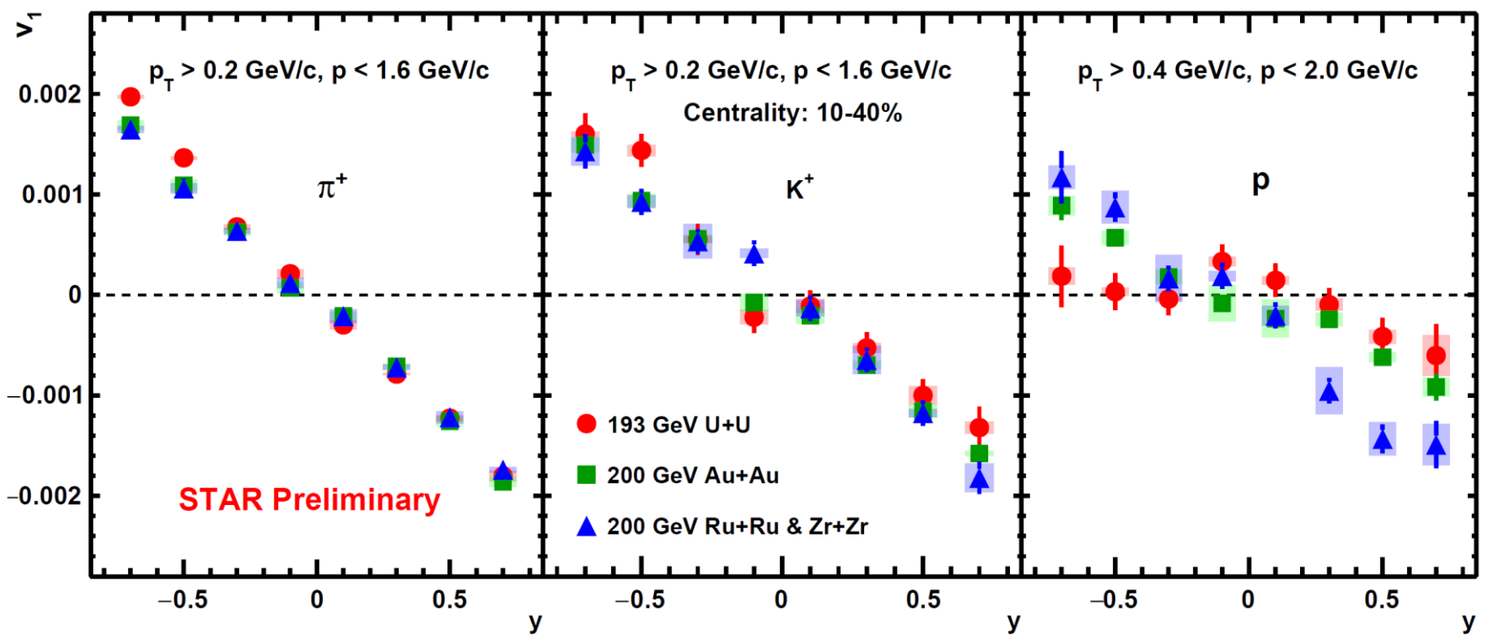
- ✓ Tracking of charged particles using TPC
- ✓ Momentum reconstruction using TPC
- ✓ Energy loss (dE/dx) using TPC
- ✓ mass square information using TOF

The STAR detector

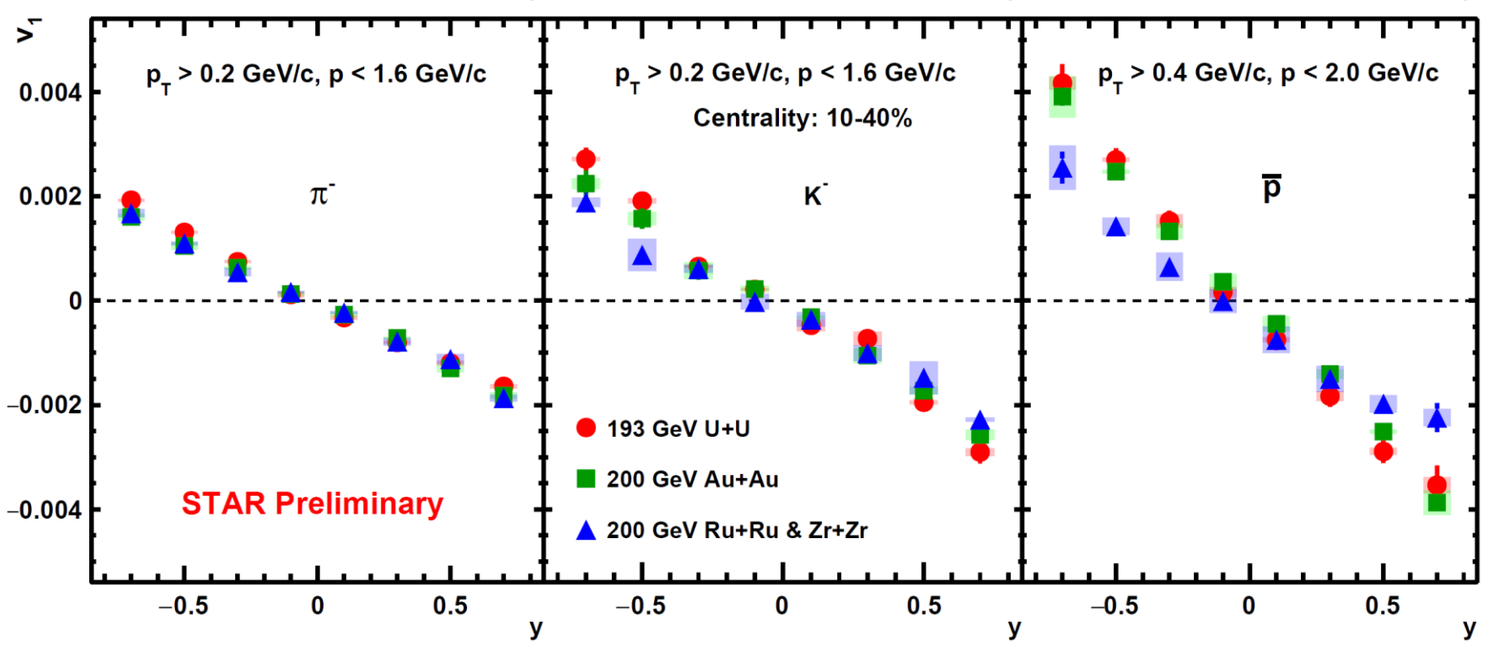
Results

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

Positive Particles



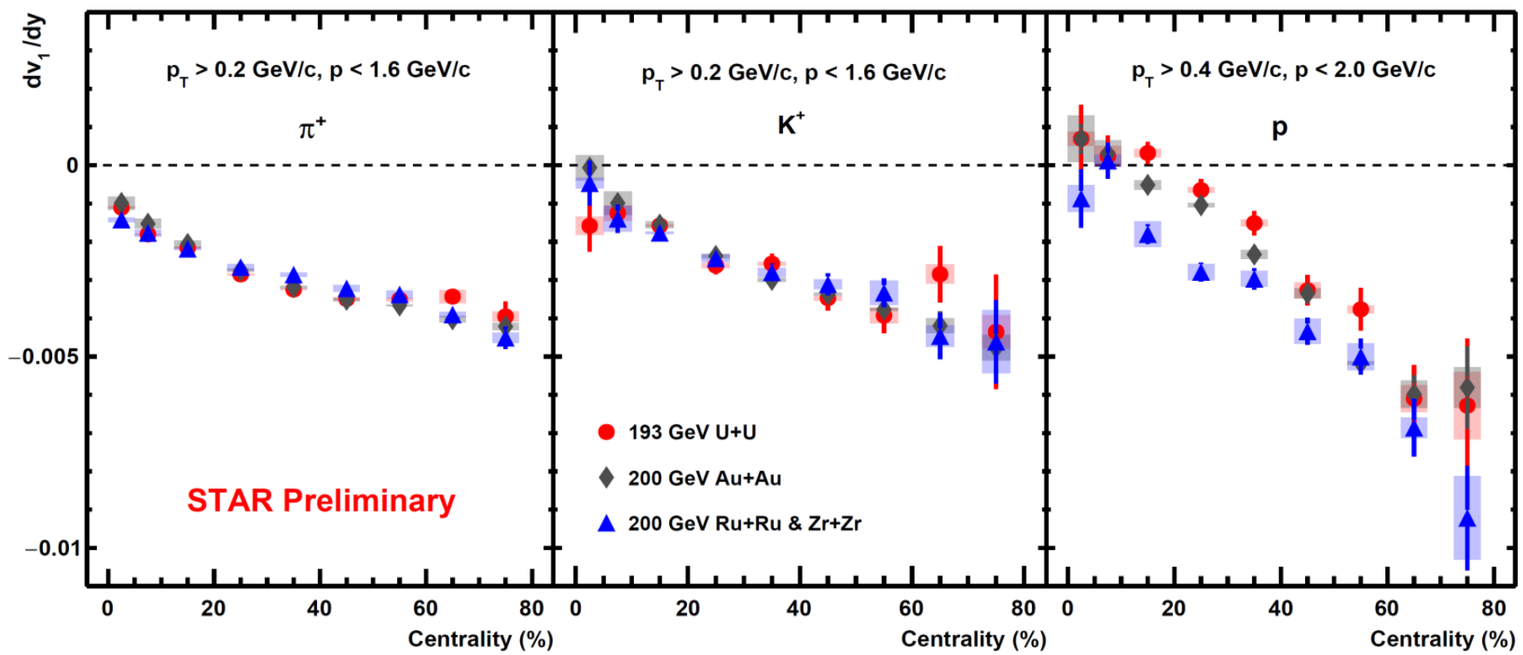
Negative Particles



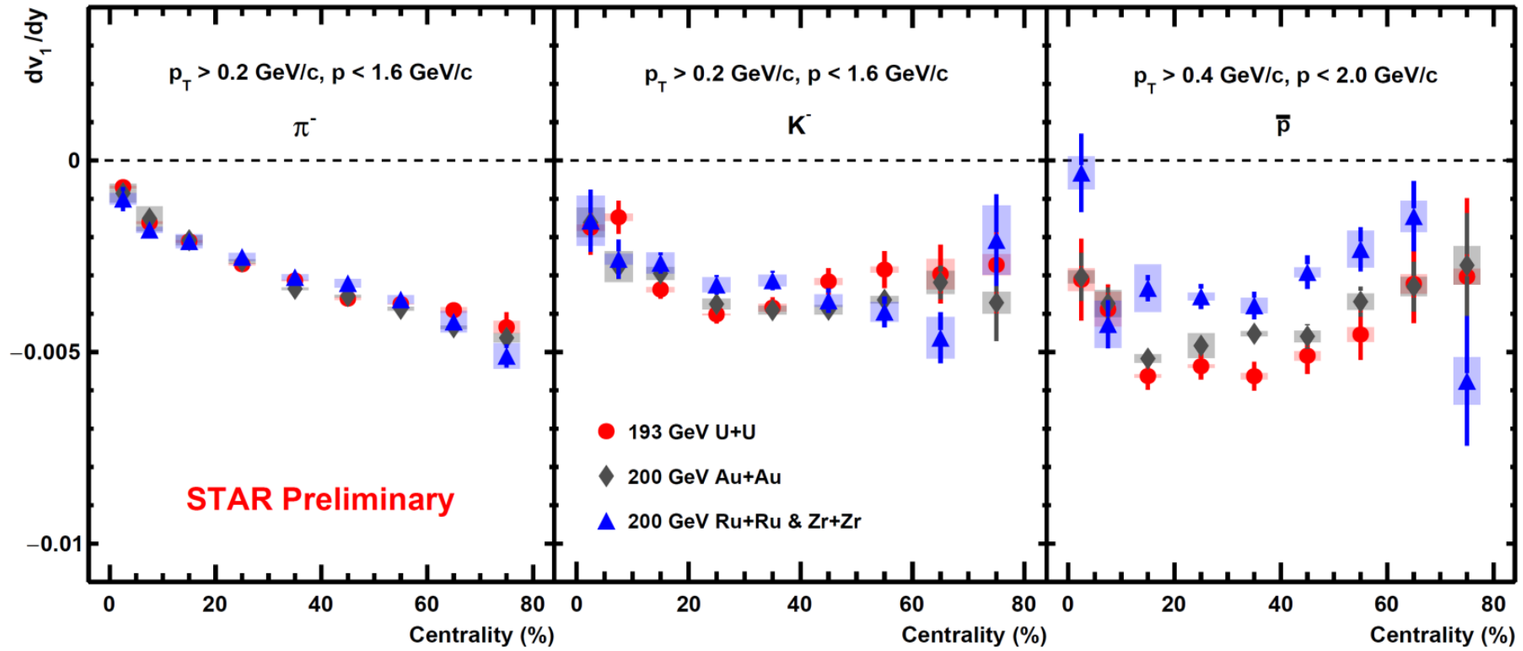
- v_1 vs y in U+U, Au+Au and Isobar collisions
- Extracted v_1 slope using linear fit ($|y| < 0.8$)

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

Positive Particles



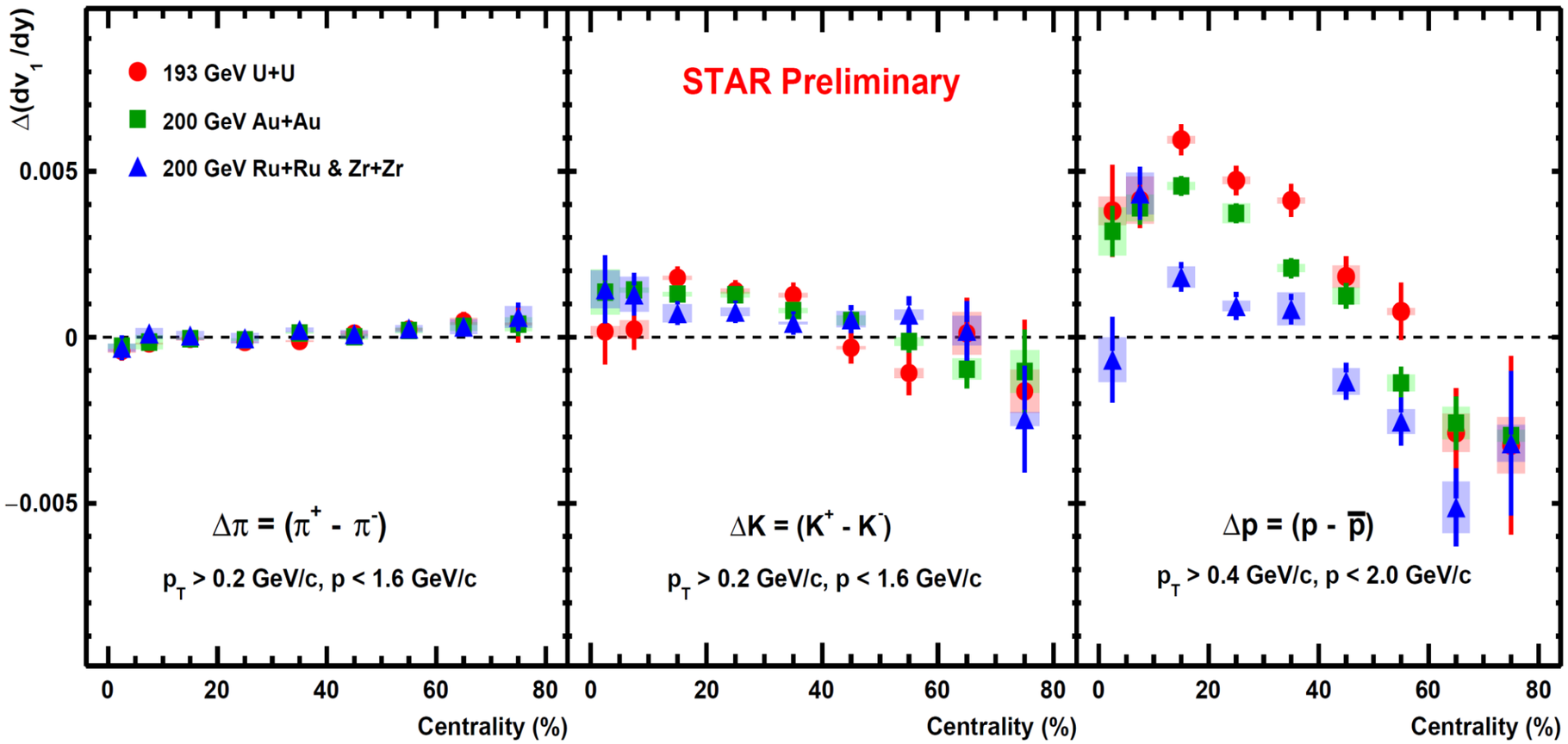
Negative Particles



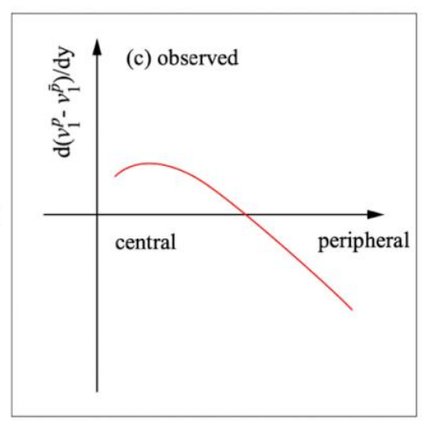
- **Positive and Negative Pions (Kaons)** → consistent within uncertainties
- **Protons and antiprotons** → observe system size dependence in mid-central collisions

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

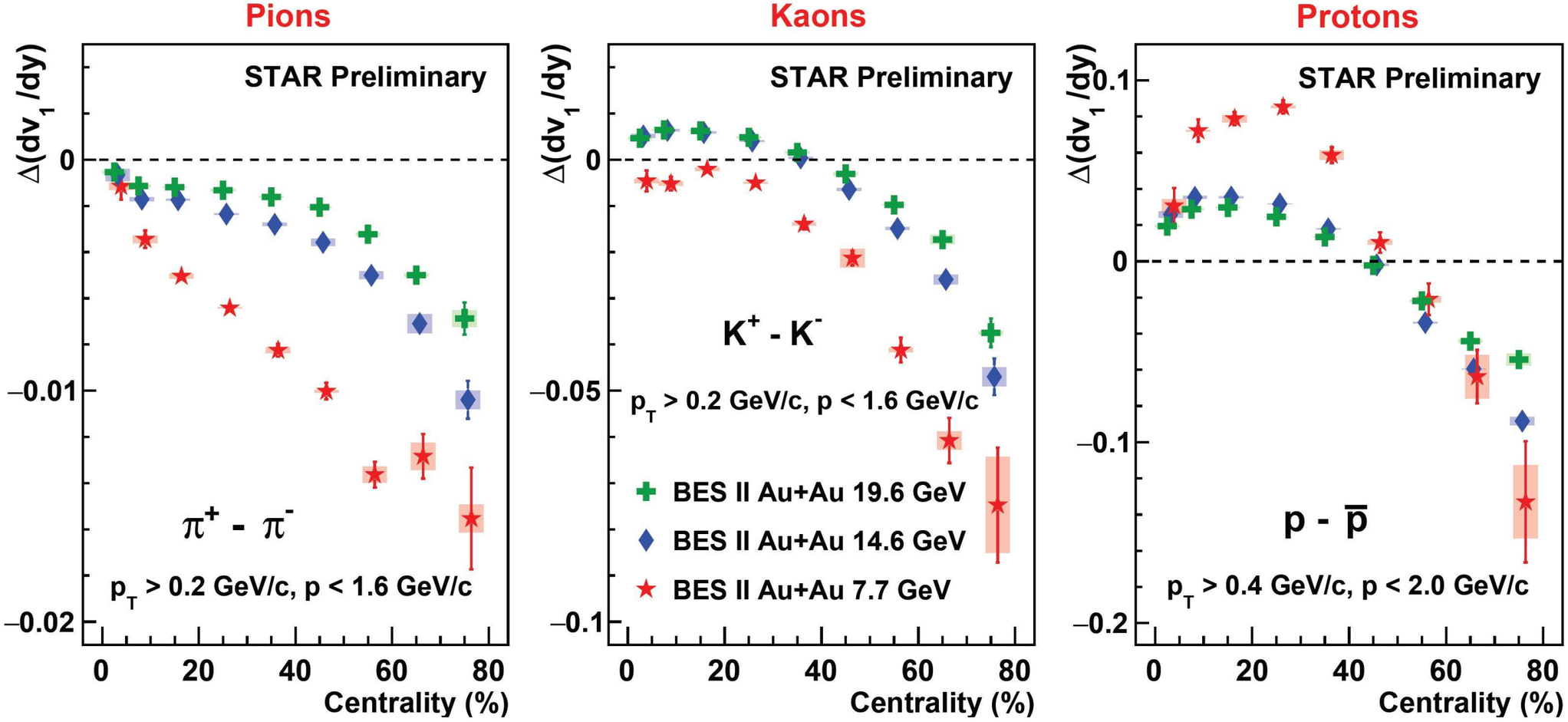
$$\Delta(dv_1/dy) = [dv_1^+/dy - dv_1^-/dy]$$



- **Pions (Kaons)** → consistent within uncertainties
- **Protons** → clean ordering and a system size dependence 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 in Au+Au

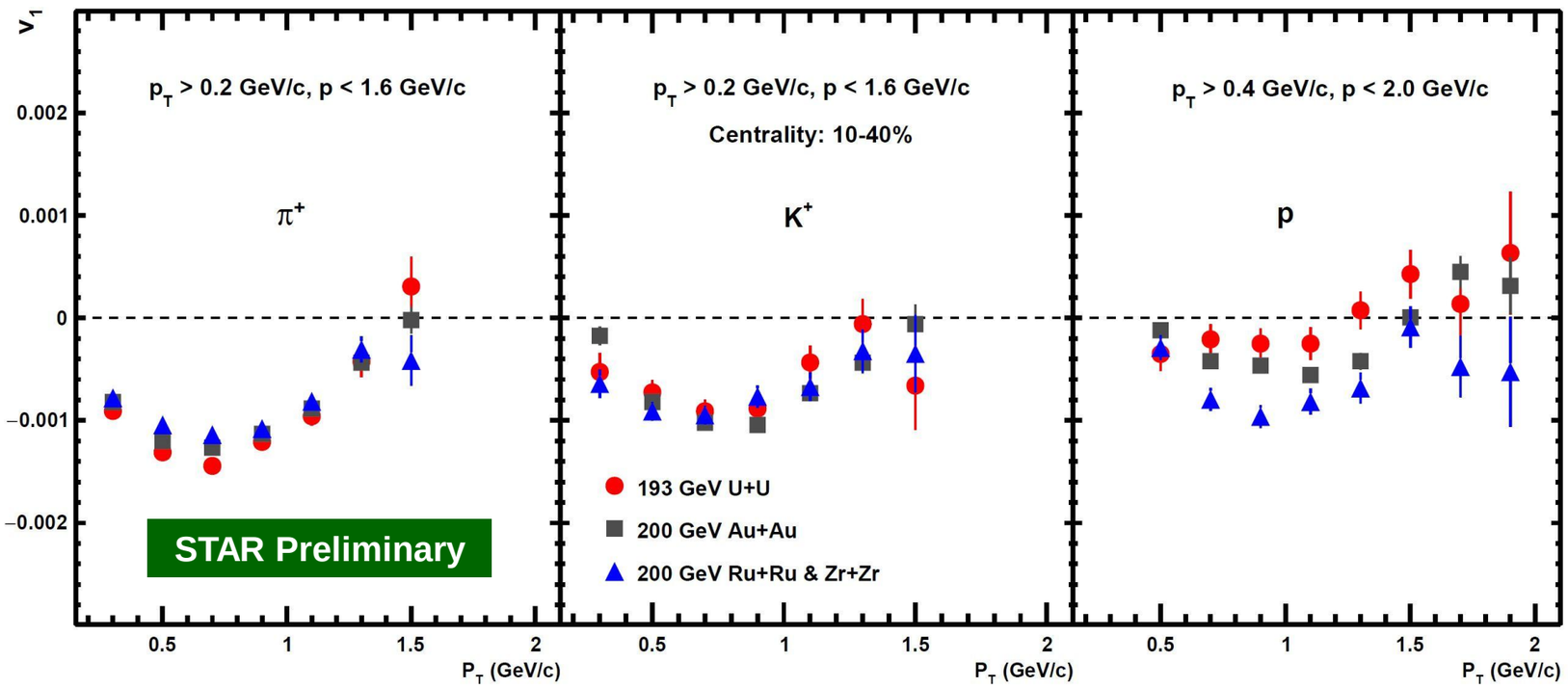


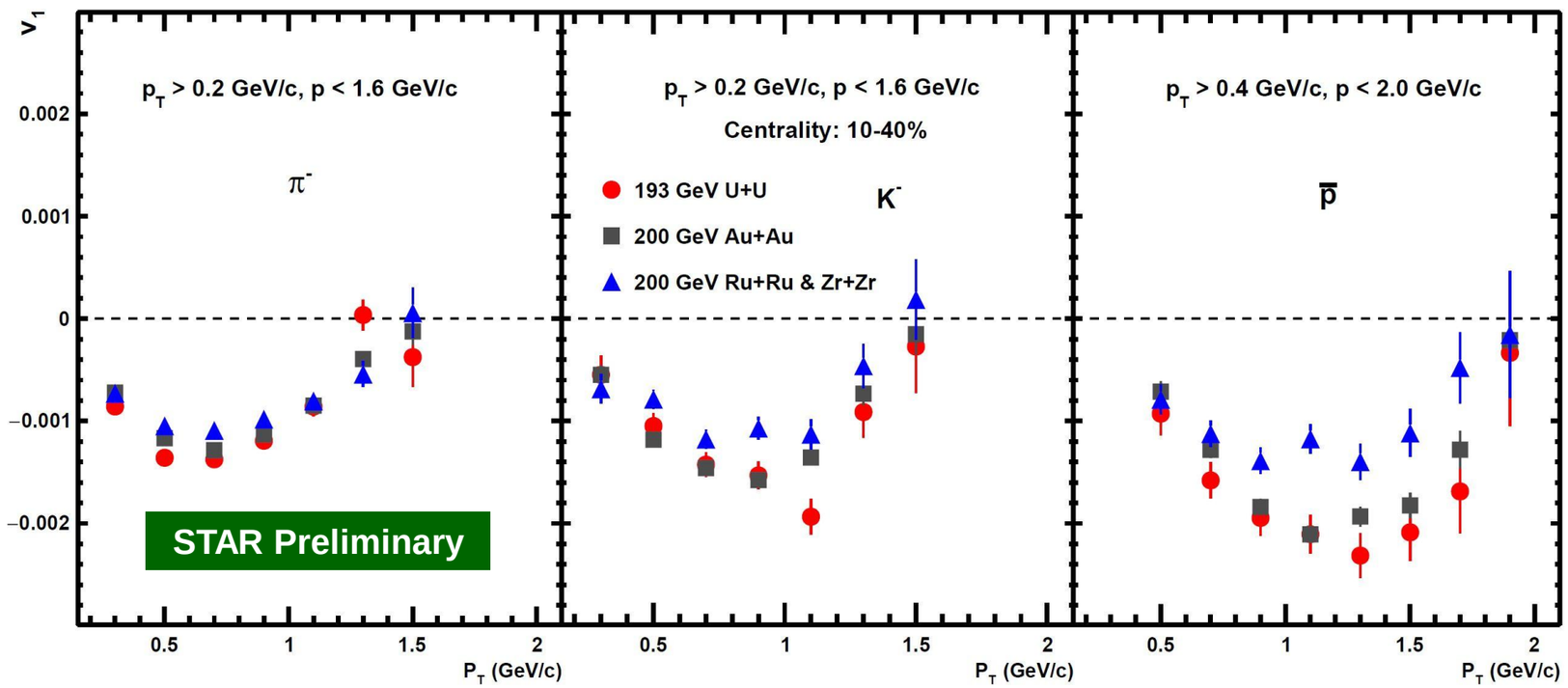
- Negative $\Delta(dv_1/dy)$ in peripheral collisions meet naive expectation from transport + EM effects
- Δv_1 increases with decrease in beam energy
- Consistent with the dominance of (Faraday + Coulomb) effect in peripheral collisions (other mechanisms such as baryon inhomogeneities are under investigation)

[T. Parida et al. arXiv:2305.8806]

$v_1(p_T)$ for U+U, Au+Au and Isobar Collisions

Mid Central 10-40 %





Positive Particles

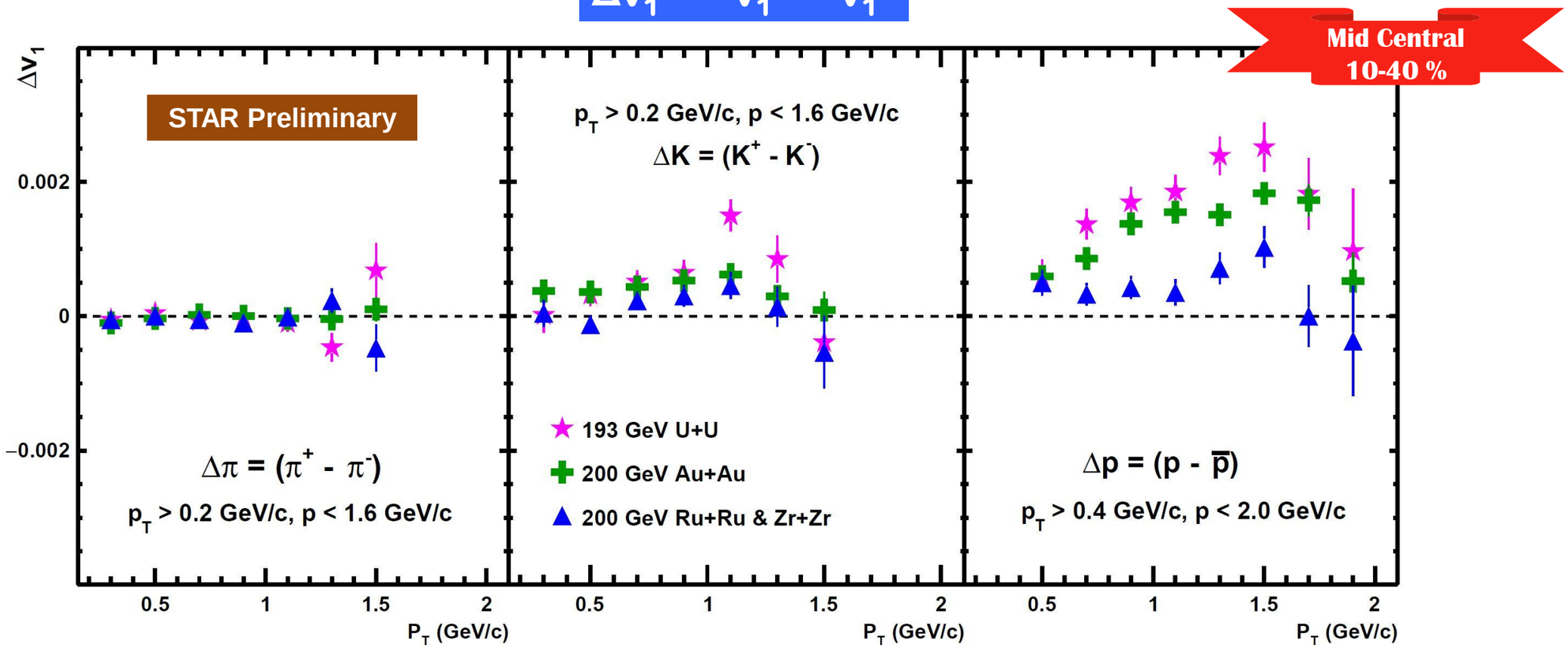
- dv_1/dy:
  - pions → Isobar ~ Au+Au ~ U+U
  - kaons → Isobar ~ Au+Au ~ U+U
  - protons → Isobar > Au+Au > U+U

Negative Particles

- dv_1/dy:
  - pions → Isobar ~ Au+Au ~ U+U
  - kaons → Isobar ~ Au+Au ~ U+U
  - protons → U+U > Au+Au > Isobar

$\Delta v_1(p_T)$ for U+U, Au+Au & Isobar

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



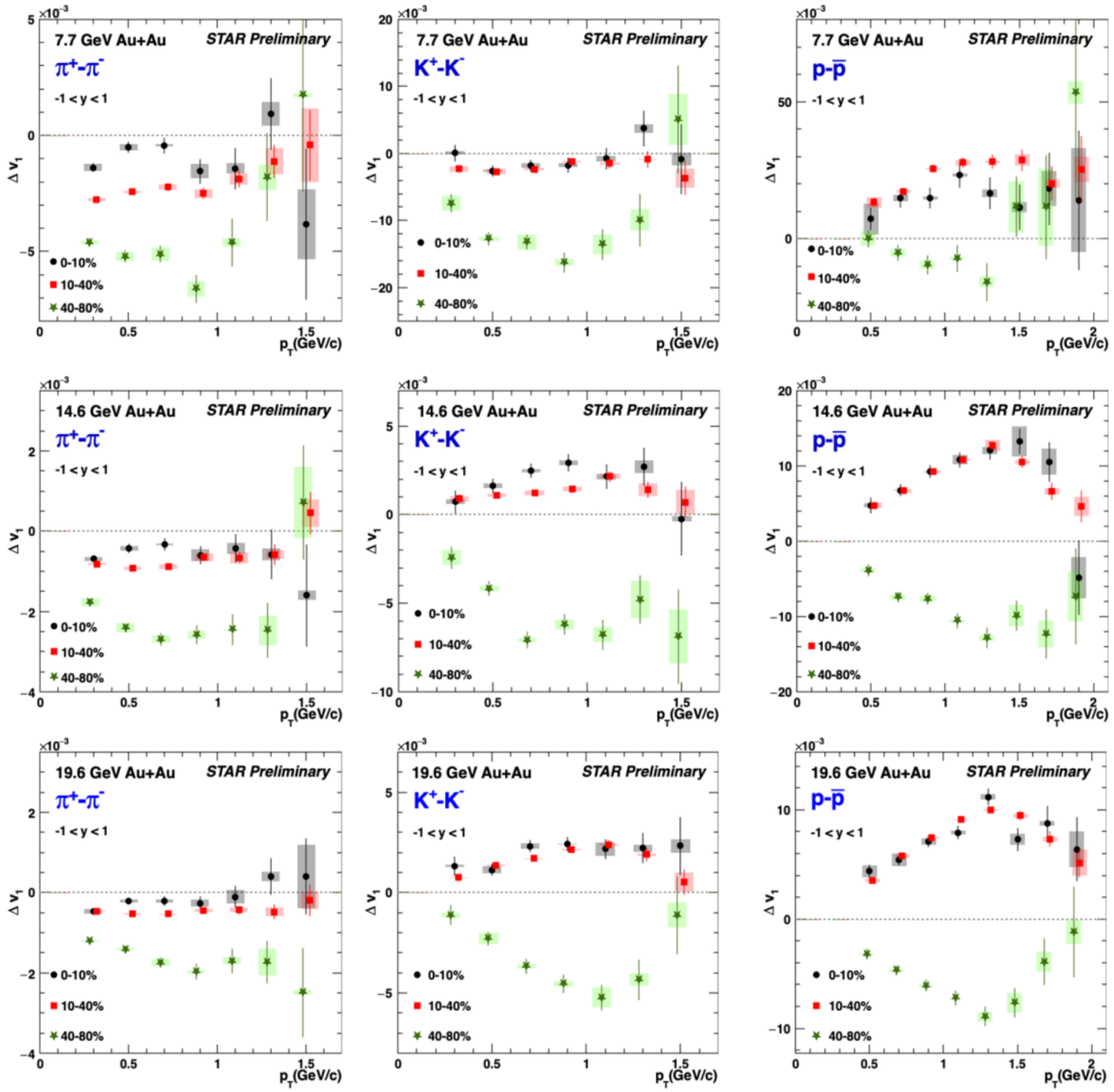
- **Pions (Kaons)** → consistent within uncertainties
- **Protons** → Δv_1 keep increasing with p_T upto 1.5 GeV
  → clean ordering and a system size dependence

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

Au+Au 7.7 GeV

Au+Au 14.6 GeV

Au+Au 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

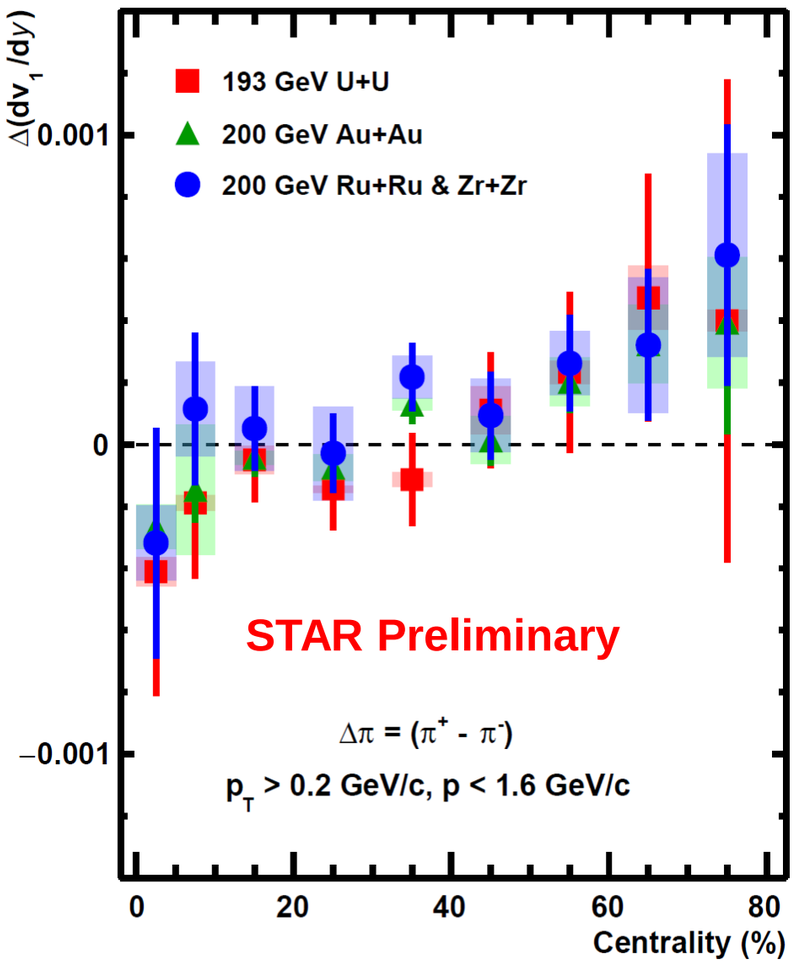
- Splitting in Δv_1 increases with decreasing beam energies
- More negative Δv_1 for lower collision energies → consistent with longer lifetime of the electromagnetic field → shorter lifetime of the fireball

These results will help to understand baryon deposition/transport mechanism and also provide constraint on the strength and lifetime of the electromagnetic field as well as the medium electrical conductivity in Heavy-Ion collisions

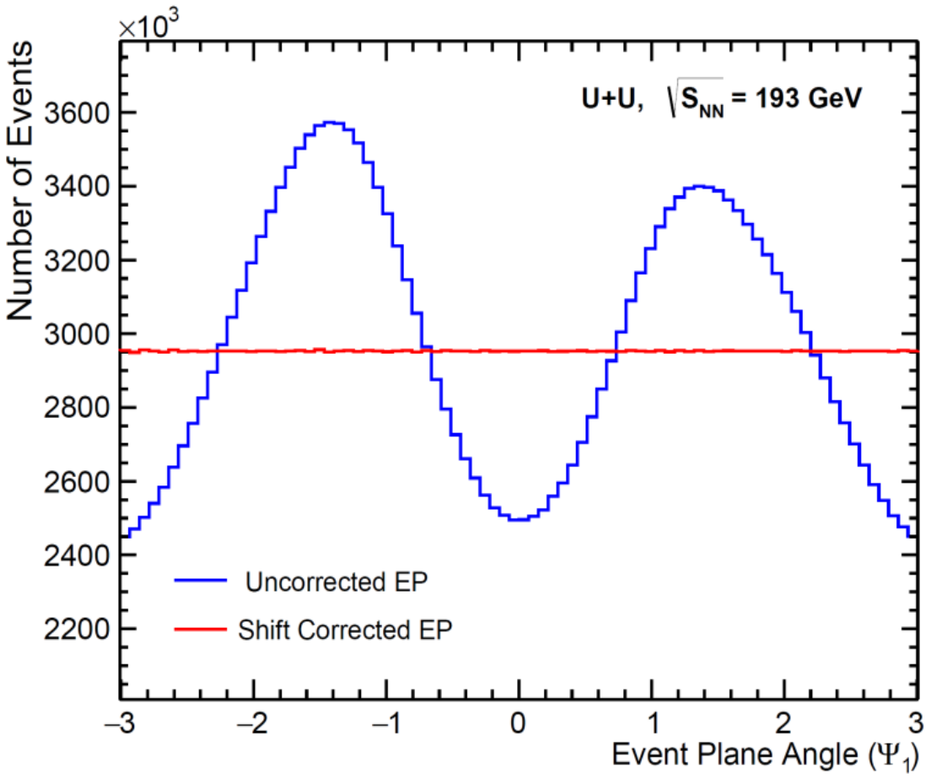

THANK YOU
FOR YOUR
ATTENTION

Backup Slides

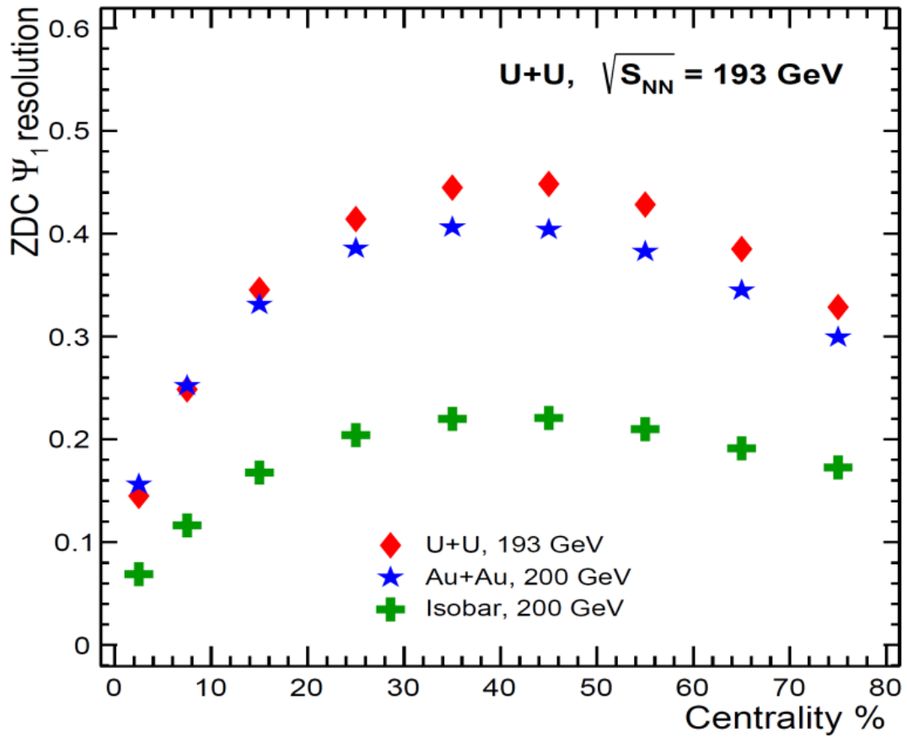
Δv_1 as a function of Centrality (Pion)



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