PWGC Presentation

Measurement of system size dependence of directed flow of protons (anti-protons) at RHIC

Muhammad Farhan Taseer

mfarhan_taseer@impcas.ac.cn

On behalf of PAs

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

2025/04/22

中国科学院大学
University of Chinese Academy of Sciences

ANSO
Alliance of International Science Organizations

General Information

- **Paper title:** Measurement of system size dependence of directed flow of protons (anti-protons) at RHIC
- **PA List:** Jinhui Chen, Aditya Prasad Dash, Huan Huang, Hao Qiu, Diyu Shen, Subhash Singha, Aihong Tang, **Muhammad Farhan Taseer** and Gang Wang
- **Contact:** mfarhan_taseer@impcas.ac.cn
- **Targeted journal:** Phys. Rev. Lett.
- **Webpage:** https://drupal.star.bnl.gov/STAR/blog/mftaseer/Measurement-system-size-dependence-directed-flow-protons-anti-protons-RHIC-2
- **Analysis note:** https://drupal.star.bnl.gov/STAR/system/files/userfiles/6641/Analysis_Note_UU_Collisions_193_GeV.pdf
- **Paper draft:** in preparation

Previous Presentations

- **Talks in PWG meeting:**
  - ✓ https://drupal.star.bnl.gov/STAR/system/files/TASEER_UU_FCV%20%281-05-2024%29.pdf
  - ✓ https://drupal.star.bnl.gov/STAR/blog/mftaseer/Charge-dependent-directed-flow-UU-Collisions-193-GeV

- **Presentations in International meetings:**
  - ✓ https://drupal.star.bnl.gov/STAR/system/files/Version6_QM2025_poster_TASEER_STAR.pdf (QM-2025 Poster)
  - ✓ https://drupal.star.bnl.gov/STAR/system/files/Measurement%20of%20charge-dependent%20directed%20flow%20in%20STAR%20Beam%20Energy%20Scan%20%28BES-II%29%20Au%2BAu%20and%20U%2BU%20Collisions%20%282024-06-04%29_0.pdf (SQM-2024 Talk)

- **Preliminary figures:**
  - ✓ https://drupal.star.bnl.gov/STAR/system/files/TASEER_UU_Premilinary%20%2815-05-2024%29.pdf

- **SQM Proceedings:**
  - ✓ https://www.epj-conferences.org/articles/epjconf/pdf/2025/01/epjconf_sqm2024_06008.pdf (Published)

Directed flow

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

- For this analysis, v_1 is computed using **Event Plane Method** in which we estimate the reaction plane, called the event plane, from the observed event plane angle determined from the anisotropic flow itself.

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

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

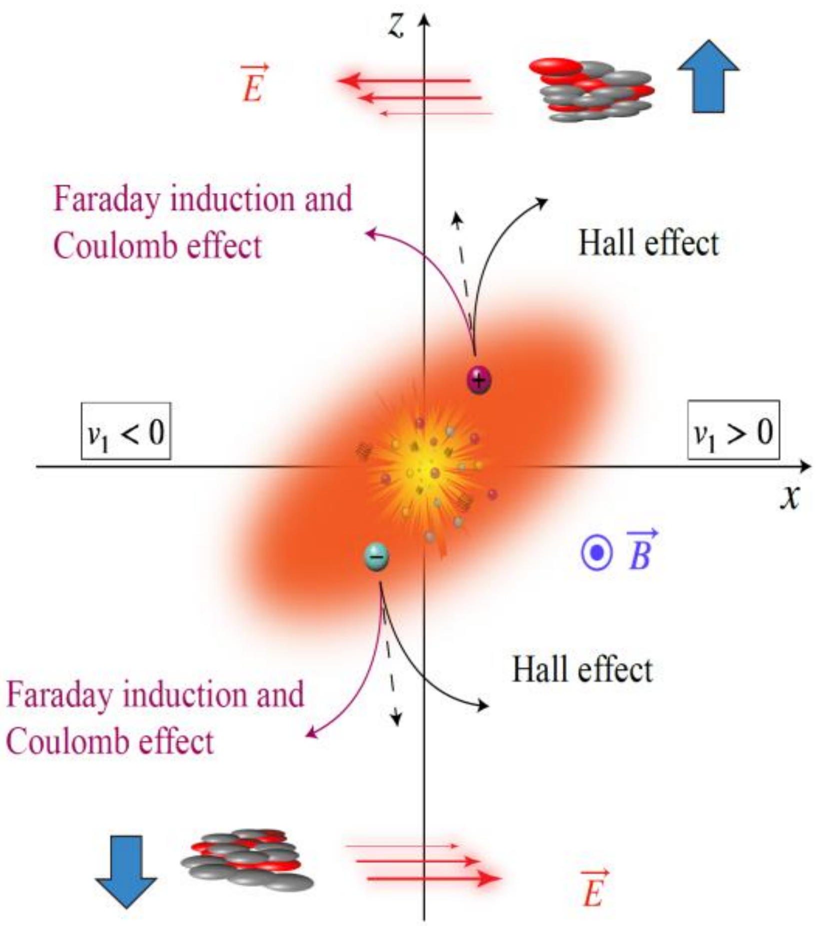
EM effects on directed flow

Charge dependent directed flow is used to probe the strong electromagnetic field effects in heavy ion collisions [1]:

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

Imprints of EM field effects

- **Hall Effect:** F = q (v x B) by Lorentz Force (positive Δv_1)
- **Coulomb Effect:** **E** generated by spectator nucleons (negative Δv_1)
- **Faraday Induction:** decreasing **B** as spectators fly away(negative Δv_1)



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

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

Directed Flow (v_1)

PRX 14, 011028 [STAR]

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

Transport effects on directed flow

- Transported quarks can also cause **positive/negative** $\Delta \mathbf{v_1}$.

Expectations from transported quark effects

$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$

$$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$$

$K^+ : u\bar{s}$ $K^- : \bar{u}s$

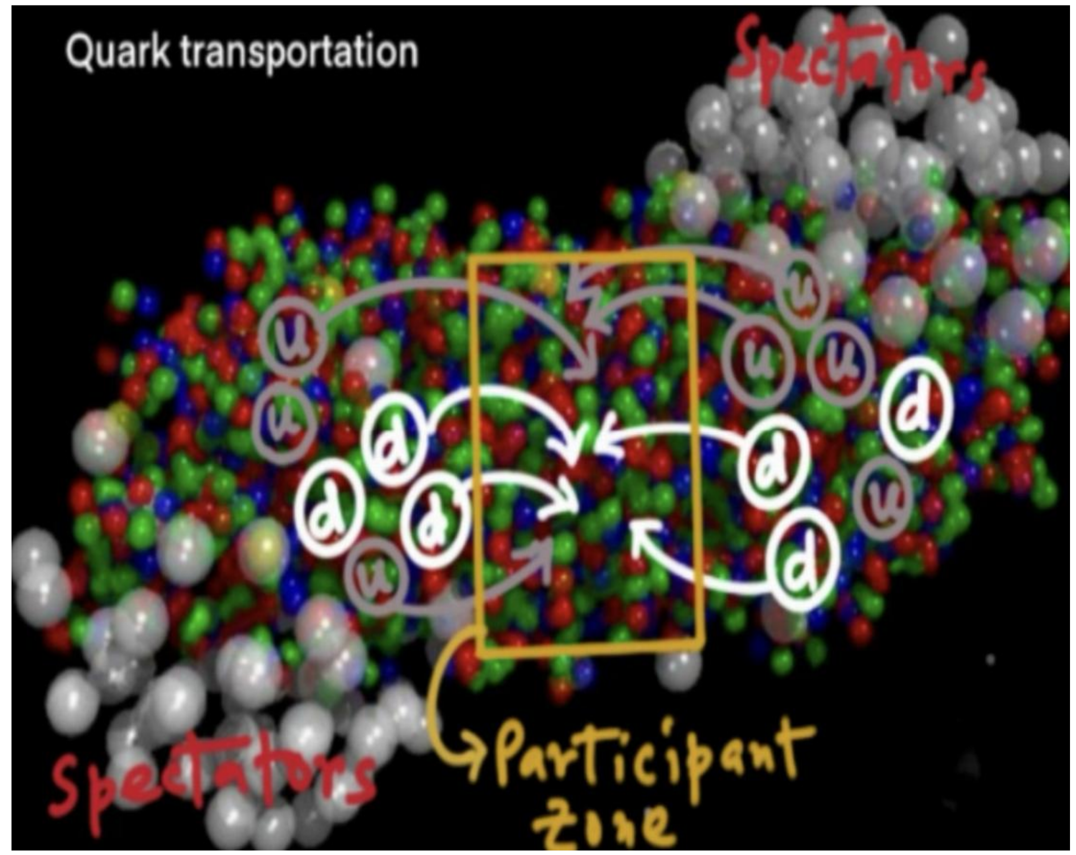
$$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$$

$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$

$$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} < 0$$

(#d>#u, Au neutron rich)

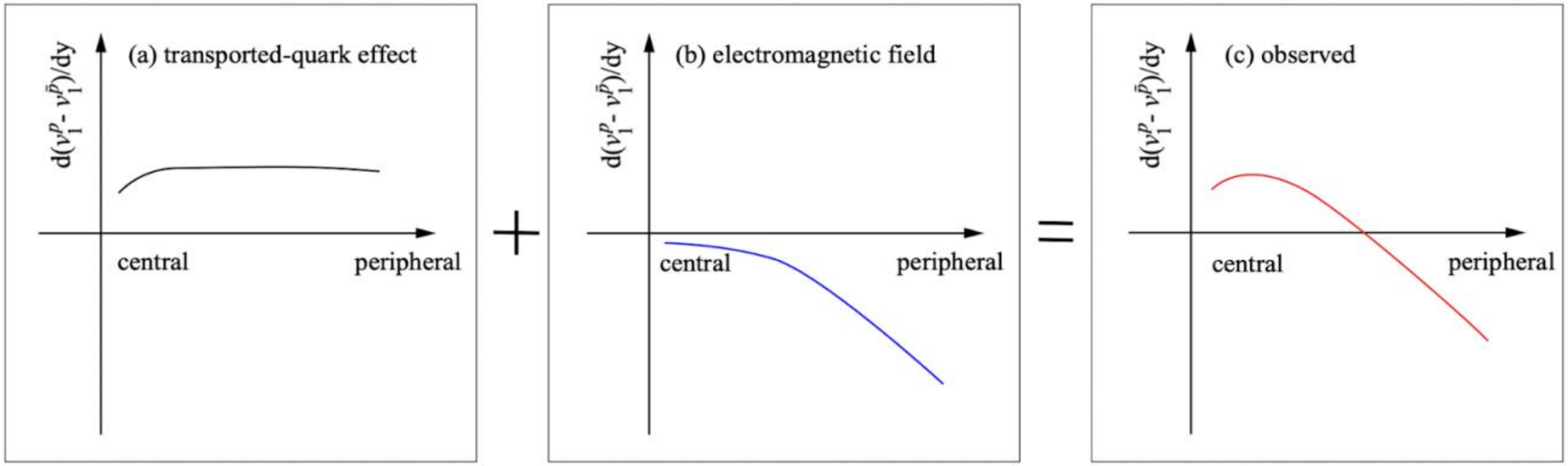
"u" and "d" quarks transported from incoming nuclei towards mid-rapidity



EM + Transport effects on directed flow

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

Expectation for protons



Transported Quark → Positive Δv_1
(Based on UrQMD)

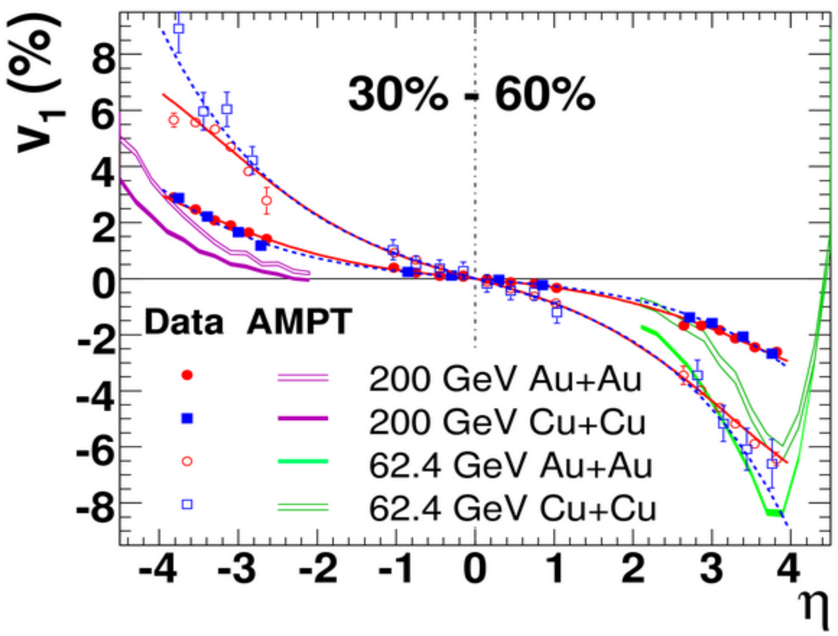
EM Field → Negative Δv_1

Combination
(Transported Quarks + EM)

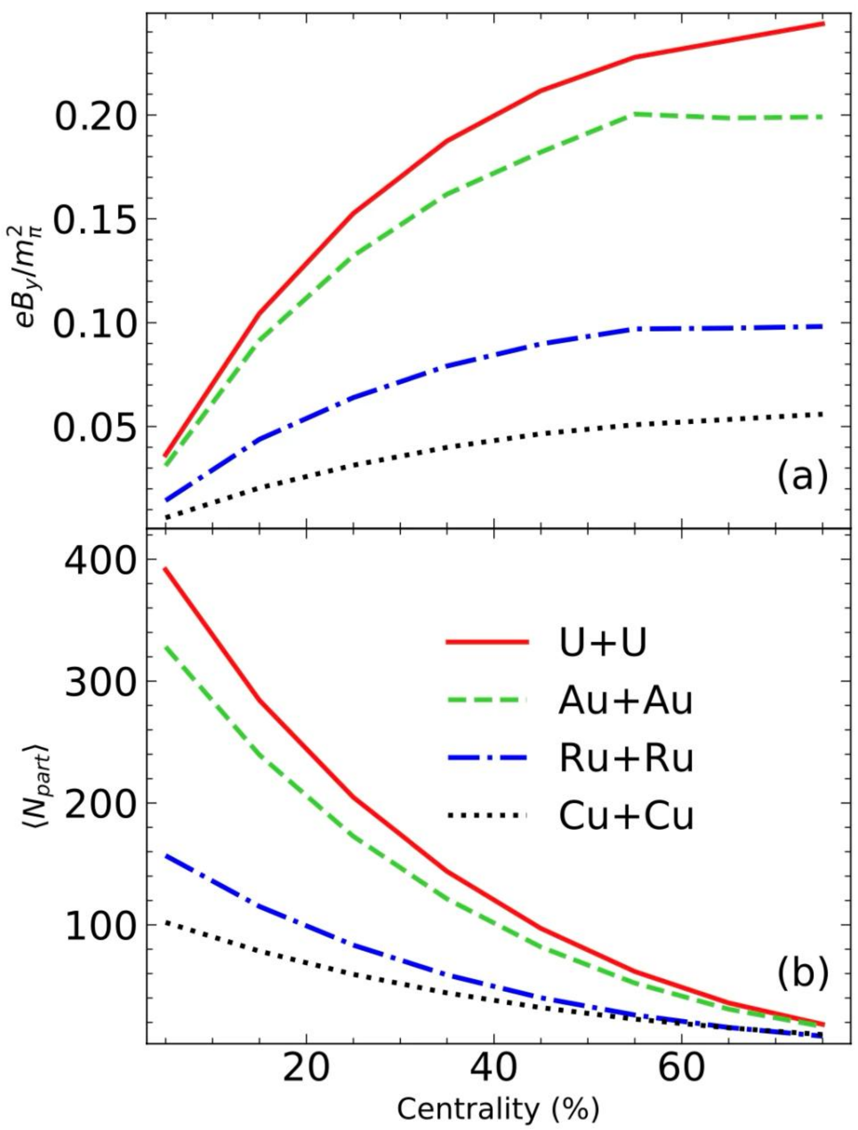
- We observed a sign change in $\Delta(dv_1/dy)$ for protons
- Observations are qualitatively consistent with above expectations

- STAR Collaboration, Phys. Rev. X 14, 011028

System size dependence in directed flow



- Previous observations by STAR (PRL. 101, 252301):
- For inclusive charged particles at a fixed centrality:
  - ✓ v_1 of Au+Au ≈ Cu+Cu



- However v_1 could be affected differently in different collision systems (Parida et al (2503.04660))

  1. EM-field: (B_y): U+U > Au+Au > Ru+Ru > Cu+Cu

  (expect stronger effect in peripheral collisions than in central collisions)

  2. Transport: (N_{part}): U+U > Au+Au > Ru+Ru > Cu+Cu

  (expect stronger effect in central collisions than in peripheral collisions)

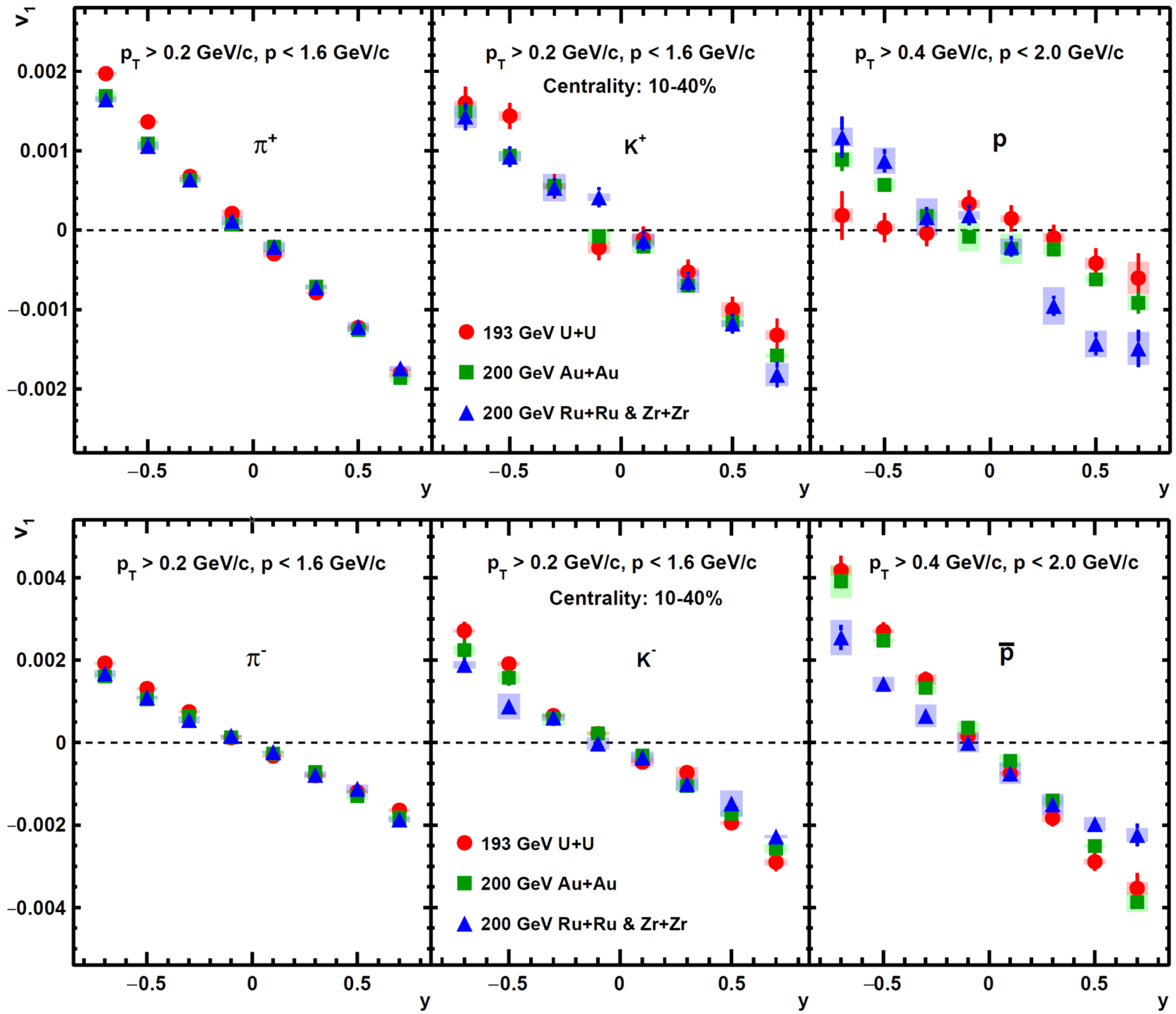
- **system size dependence of v_1 can help to probe above effects**

Abstract

We present the rapidity dependence of directed flow (v_1) and its slope (dv_1/dy) for $\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$ as a function of centrality in Au+Au and Isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV, and in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, as measured by the STAR experiment at RHIC. The slope dv_1/dy for $p(\bar{p})$ and the difference $\Delta(dv_1/dy)$ exhibit a clear system size dependence, with an ordering of U+U > Au+Au > Isobar (Ru+Ru and Zr+Zr), while total baryons ($p + \bar{p}$) remain independent of system size. This is the first observation of system size dependence of the v_1 and $\Delta(dv_1/dy)$ of baryons. In contrast, the mesons ($\pi^{\pm}$ and $K^{\pm}$), show no dependence on system size, consistent with previous findings at RHIC for inclusive particles [1]. A hydrodynamic model incorporating baryon transport with an inhomogeneous profile and electromagnetic field effects can explain the observed patterns in the data. The system-size dependence of $\Delta(dv_1/dy)$ for protons in central collisions is likely dominated by enhanced baryon stopping in larger systems, where electromagnetic fields play a negligible role. In contrast, $\Delta(dv_1/dy)$ in mid-central and peripheral collisions can arise from a combination of baryon transport and electromagnetic field effects. These measurements of v_1 across different centralities and system sizes offer valuable insights into the strength of electromagnetic fields, the medium's electrical conductivity, the baryon deposition and transport properties of the QCD medium [2, 3].

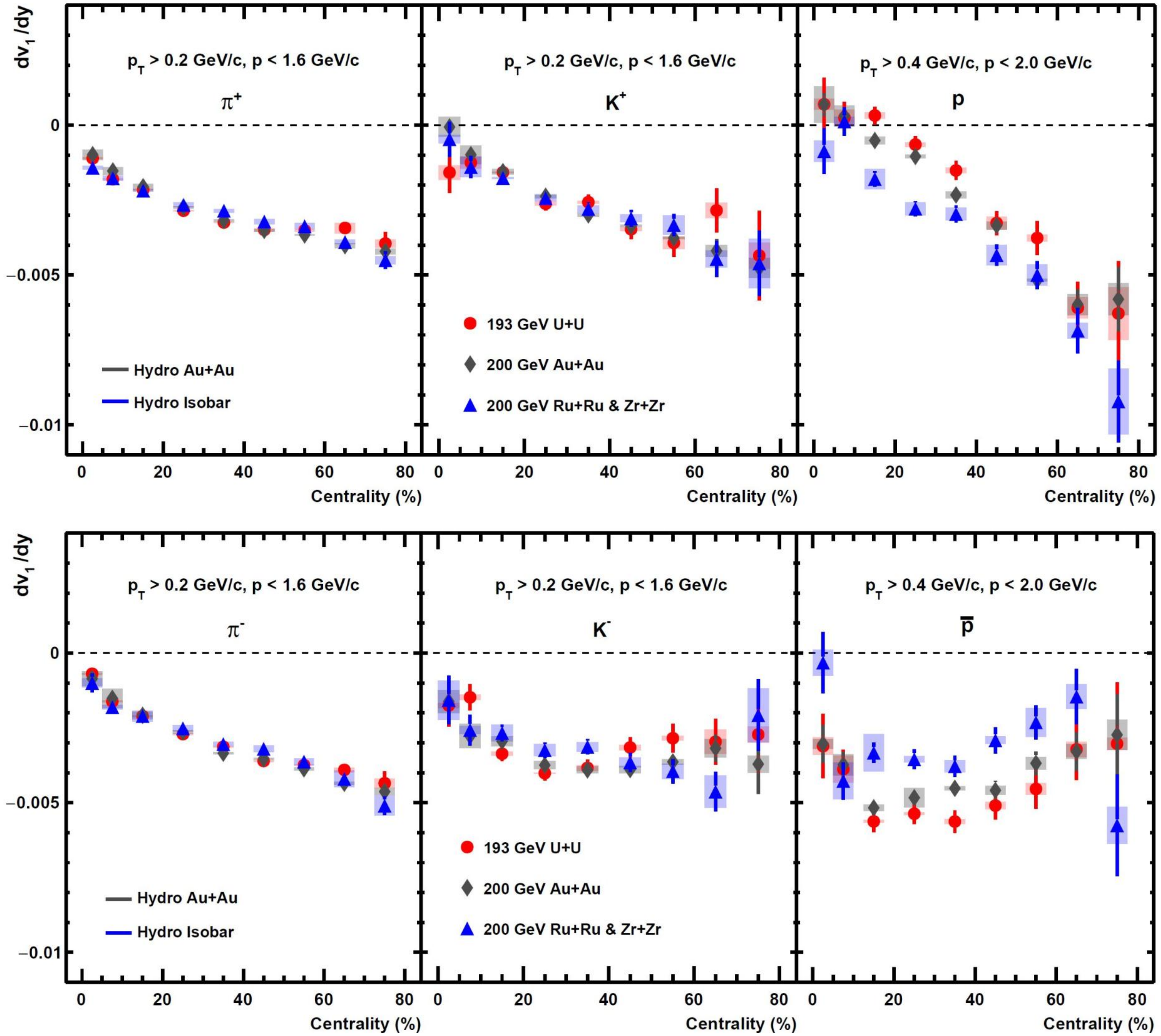
[1]. STAR Collaboration, Phys. Rev. Lett. 101, 252301
[2]. STAR Collaboration, Phys. Rev. X 14, 011028
[3]. T. Parida et al. arXiv: 2305.08806, 2503.04660

Figure 1



- v_1 vs y in U+U, Au+Au and Isobar collisions
- dv_1/dy is extracted by using a linear fit (|y| < 0.8)

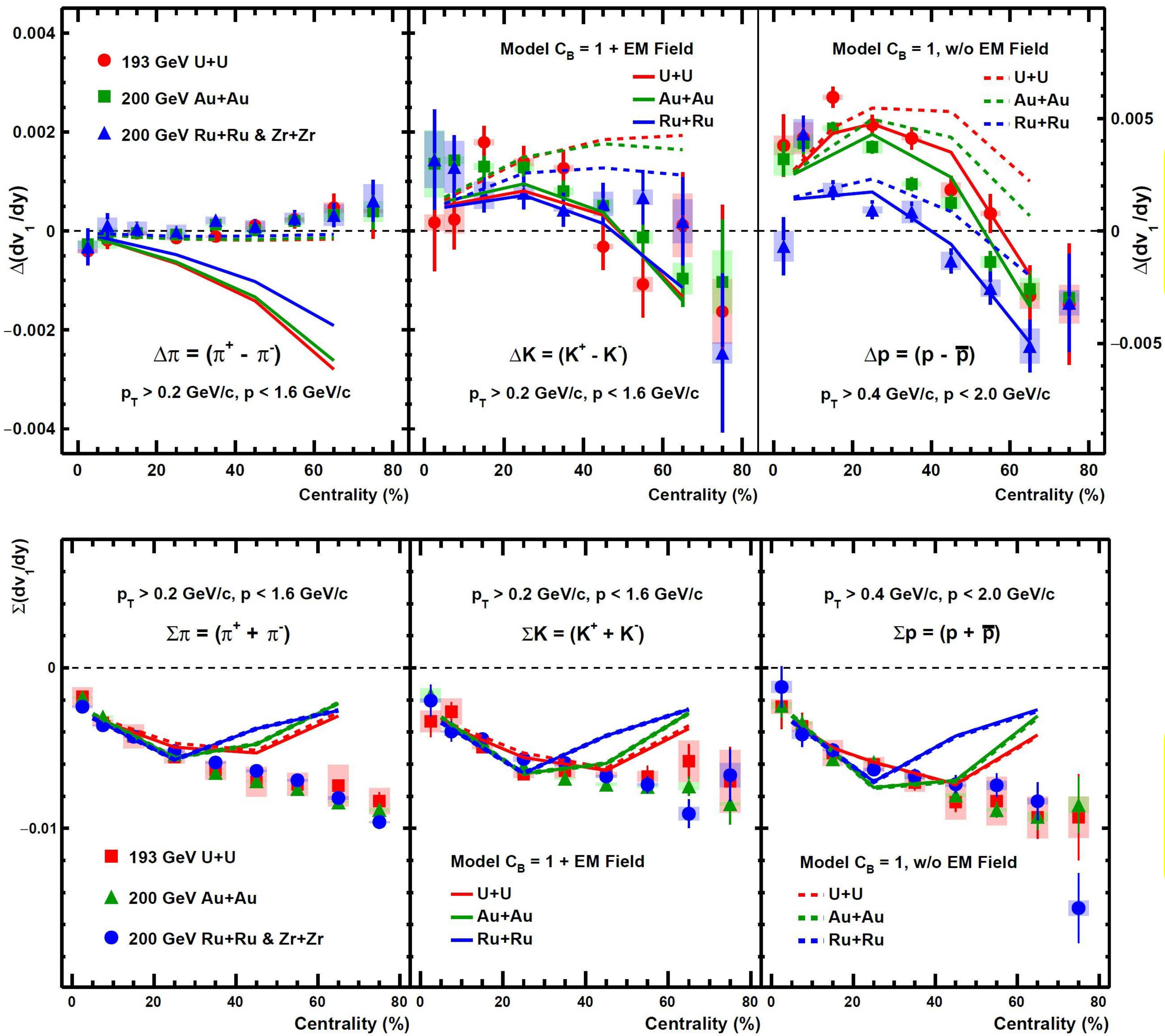
Figure 2



❖ **Slope (dv_1/dy):**

- **(a)** No system size dependence for mesons ($\pi^{\pm}$, $K^{\pm}$) among the three different collision systems
- **(b)** For protons the magnitude of the slope of the isobar > AuAu > UU and the ordering of the slopes is opposite for antiproton

Figure 3



❖ $\Delta(dv_1/dy)$:

- pions → Isobar ~ Au+Au ~ U+U
- kaons → Isobar ~ Au+Au ~ U+U
- protons → U+U > Au+Au > Isobar

✓ Hydro-model with baryon transport and EM field can capture the system size dependence in $\Delta(dv_1/dy)$ of protons and kaons, however fails for pions

(T. Parida et al. arXiv: 2305.08806, 2503.04660)

❖ $\Sigma(dv_1/dy)$:

- pions → Isobar ~ Au+Au ~ U+U
- kaons → Isobar ~ Au+Au ~ U+U
- protons → Isobar ~ Au+Au ~ U+U

Summary

- **For inclusive charged particles (dominated by pions) STAR has observed:**
  - ✓ v_1 of Au+Au ≈ Cu+Cu [PRL 101, 252301] at a fixed centrality (called **system size independence of v_1**) → This observation lead to the concept of *tilted* fireball picture in hydrodynamic modelling

- **The main observation of this paper:**
  - ✓ v_1 of mesons (pions and kaons) and total baryons ($p + \bar{p}$, called $\sum v_1$) follow system-size independence
  - ✓ However, the baryons (protons and anti-protons) and their difference ($p - \bar{p}$, called Δv_1) show a clean system size ordering. This is a *first observation* of **system size dependence of v_1 of baryons and net-baryons**

- Hydrodynamic model with baryon transport combined with electromagnetic field and medium conductivity (σ = 0.023 fm^{-1}) can explain the system-size dependence of proton's $\Delta dv_1/dy$. **[T. Parida et al. arXiv: 2503.04660]**

- These results help understand baryon dynamics: initial baryon density profile, baryon stopping mechanism and constraint on baryon transport (baryon diffusion parameter)

- These results will provide constraint on the strength and lifetime of EM field as well as electrical conductivity of QGP

Thank you for your attention!

Backup Slides

Dataset and analysis details

Dataset and Analysis Details				
Collision Energy	Production id	Run Numbers	Trigger id	No. of Events (After cut)
U + U at 193 GeV (2012)	P12id	13114025-13136015 (783)	400005, 400015, 400025, 400035	≈ 250 M

Vertex Selection	
$\lvert Vz \rvert < 50$ cm	$\lvert Vr \rvert < 2$ cm

Track Selection		
$\lvert \eta \rvert < 1.0$	DCA < 3 cm	nHits Fits >= 15

Particle Identification			
Pion:	$\lvert N\sigma \rvert < 2.0$	$-0.01 < m^2 < 0.10$ $(GeV/c^2)^2$	$p < 1.6$ GeV/c && $p_t > 0.2$ GeV/c
Kaon:	$\lvert N\sigma \rvert < 2.0$	$0.20 < m^2 < 0.35$ $(GeV/c^2)^2$	$p < 1.6$ GeV/c && $p_t > 0.2$ GeV/c
Proton:	$\lvert N\sigma \rvert < 2.0$	$0.8 < m^2 < 1.0$ $(GeV/c^2)^2$	$p < 2.0$ GeV/c && $p_t > 0.4$ GeV/c

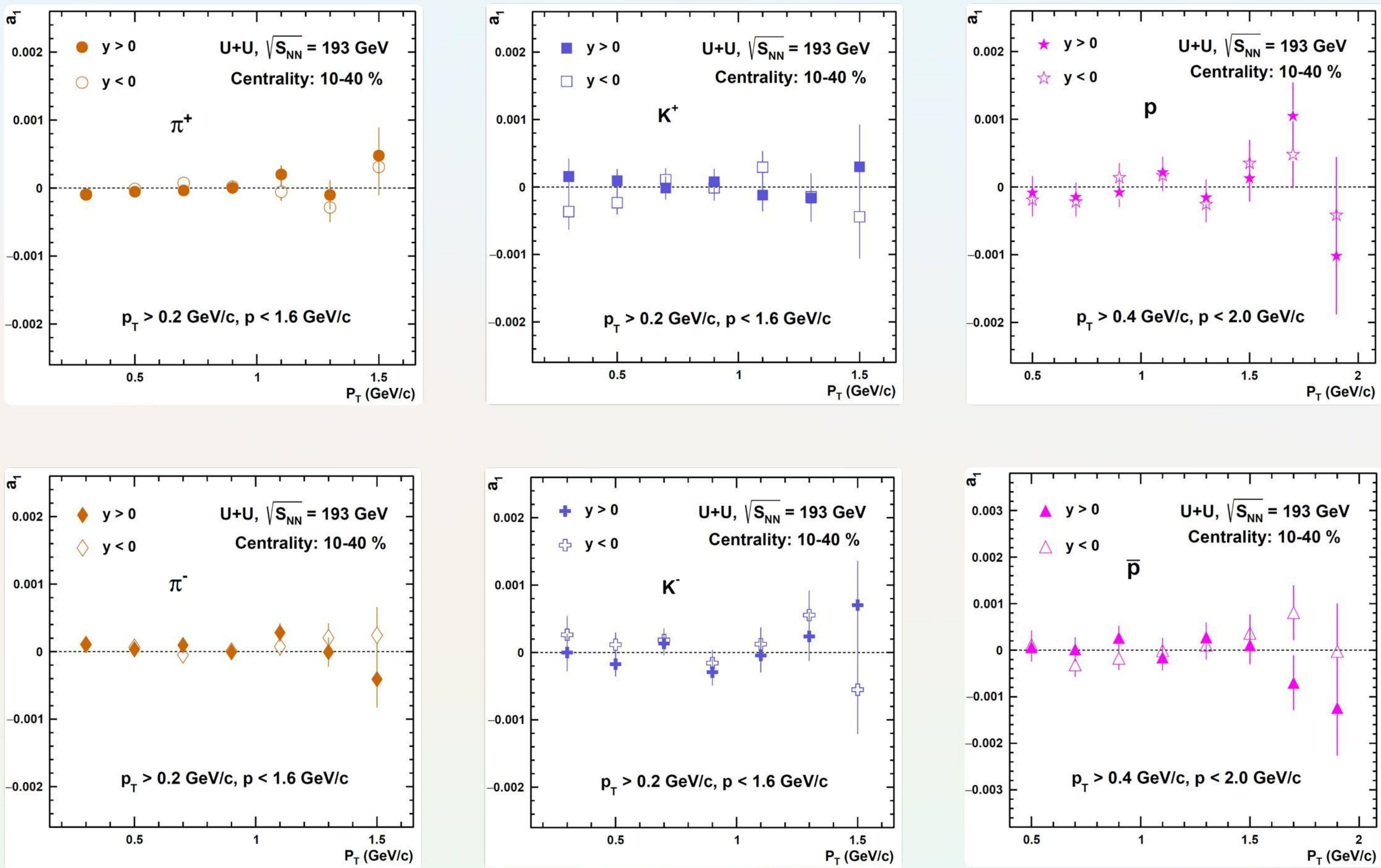
Bad Runs [19]

13117026, 13117027, 13117028, 3117029, 13117030, 13117031, 13117032, 13117033, 13117034, 13117035, 13117036, 13118009, 13118034, 13118035, 13119016, 13119017, 13129047, 13129048, 13132047

- Au+Au and Isobar (Ru+Ru & Zr+Zr) details can be found at: https://drupal.star.bnl.gov/STAR/system/files/Charge_v1_analysisNote_v7.pdf

$a_1(p_T)$ for U+U Collisions at 193 GeV

Mid Central
10-40 %



❖ a_1 = <sin(ϕ - Ψ)> versus p_T:

➢ For mid-central collisions → a_1 (p_T) ~ 0.0

Analysis Procedure

- For this analysis, v_1 is computed using **Event Plane Method** in which we estimate the reaction plane, called the event plane, from the observed event plane angle determined from the anisotropic flow itself.

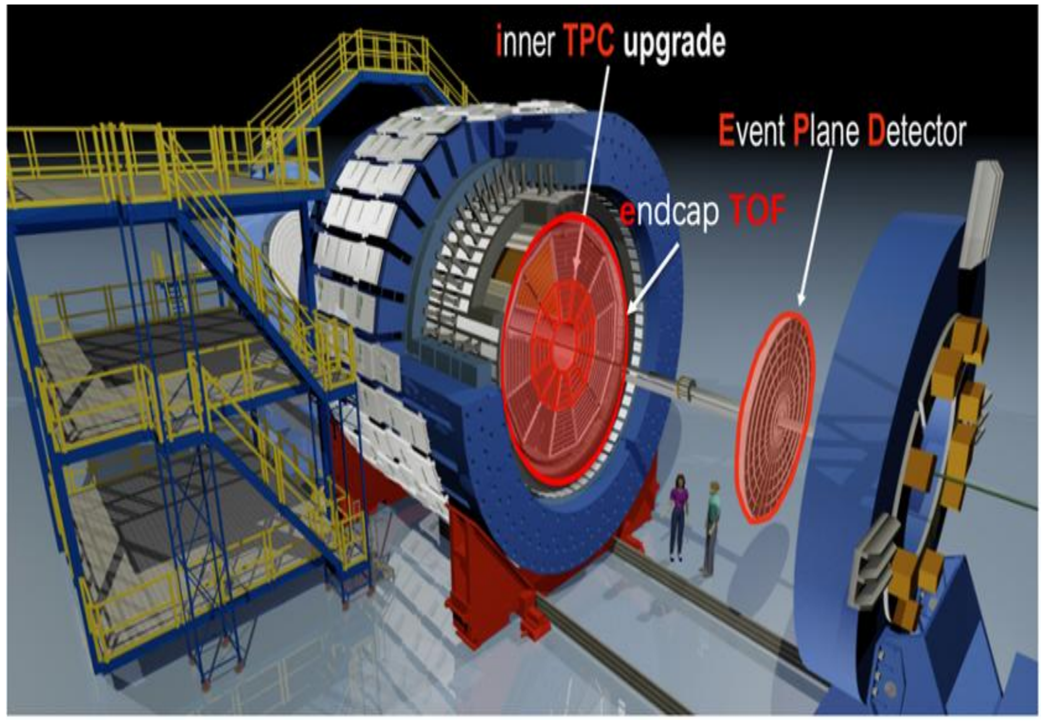
$$v_1 = \frac{\langle \cos(\phi - \Psi_1^{EP}) \rangle}{R_1}$$

R Event Plane Resolution
Ψ Event Plane Angle
φ Reaction Plane angle of outgoing particles
<> Average over all particles used in event plane calculations

Where, Ψ_1^{EP} is reconstructed using ZDC and the event plane is flatten by applying Shift correction

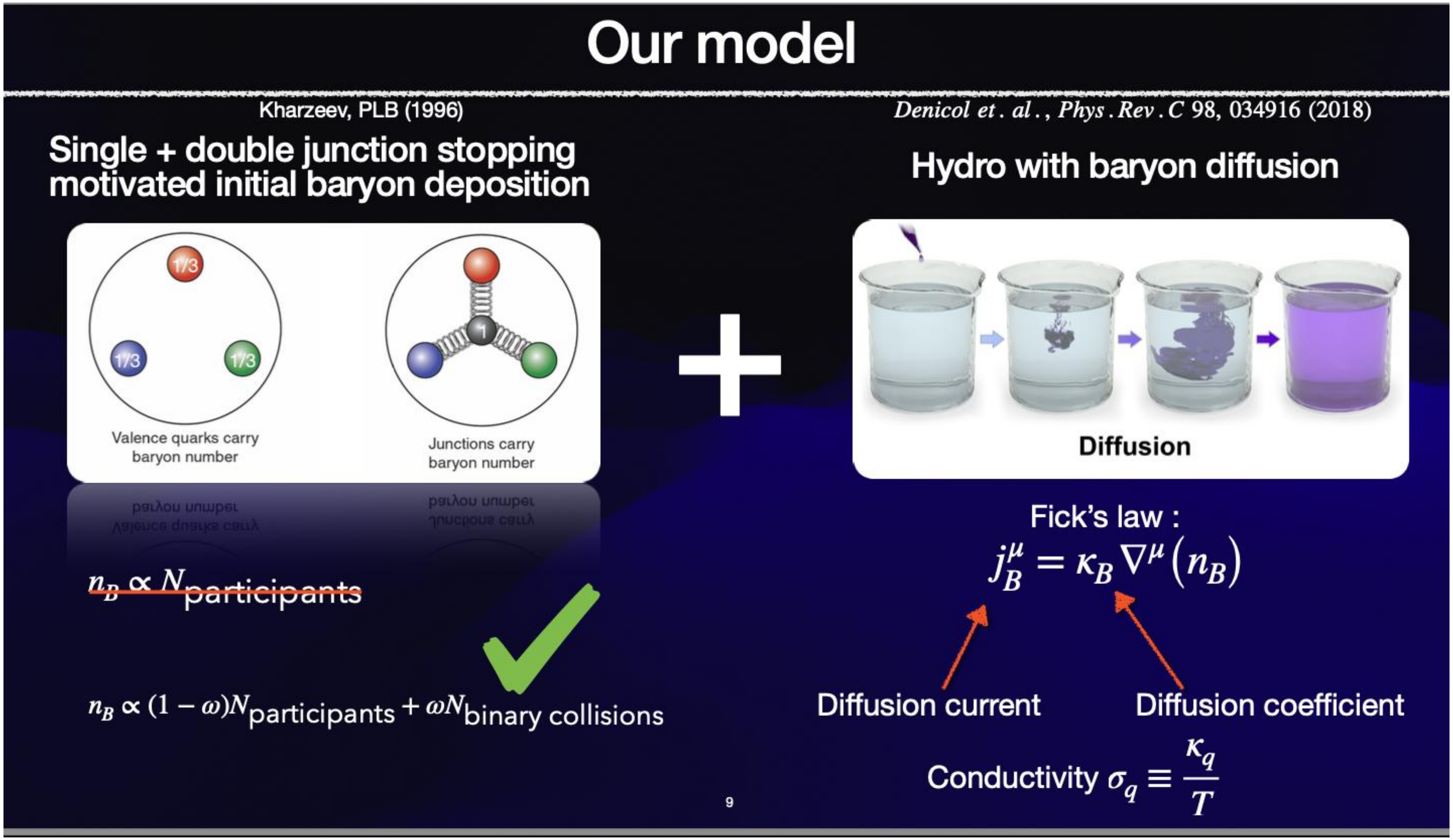
- **Analysis is carried out in four steps:**
  1- Datasets and Events Selection
  2- Event Plane reconstruction
  3- Particle Identification:
     π, k, p ---- TPC & TOF cuts
  4- Directed Flow (v_1) extraction using the above relation

STAR detector



- **Finally, Systematic study is done by varying Event, Track & PID selection**

Hydrodynamic modelling



Reference
Parida and Chatterjee:
https://indico.ihep.ac.cn/event/22462/contributions/170766/

Discussion

B. Hydrodynamics at finite baryon density

The hydrodynamical equation of motion at finite net-baryon density can be written as,

$$\partial_\mu T^{\mu\nu} = 0, \quad (9)$$

$$\partial_\mu J^\mu_B = 0, \quad (10)$$

where the system's energy momentum tensor can be decomposed as

$$T^{\mu\nu} = eu^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}, \quad (11)$$

and

$$J^\mu_B = n_B u^\mu + q^\mu. \quad (12)$$

The transport coefficients η and the baryon diffusion constant κ_B are chosen as

$$\frac{\eta T}{e + \mathcal{P}} = C_\eta \quad (15)$$

and

$$\kappa_B = \frac{C_B}{T} n_B \left(\frac{1}{3} \coth\left(\frac{\mu_B}{T}\right) - \frac{n_B T}{e + \mathcal{P}} \right). \quad (16)$$

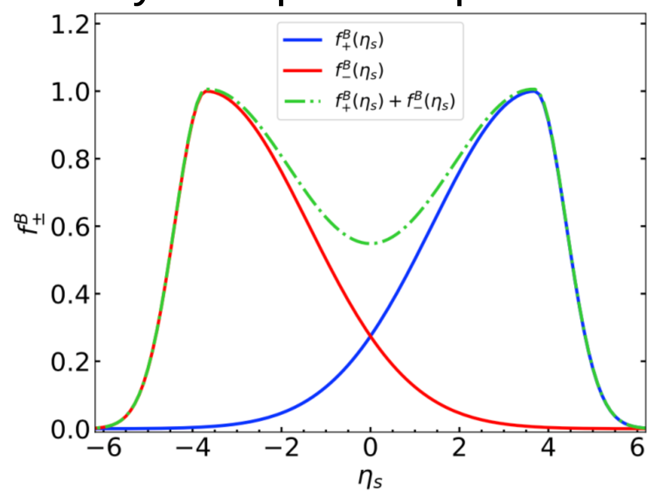
κ_B: Baryon diffusion coefficient constant;

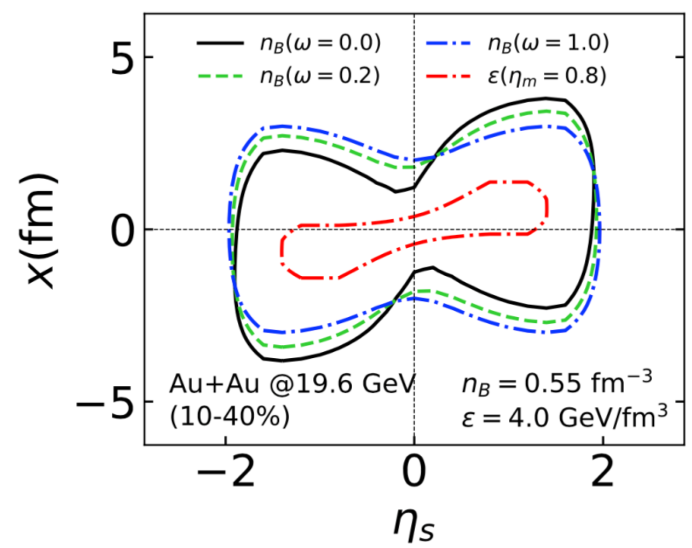
In hydro model amount of baryon diffusion is varied by tuning the prefactor C_B

Denicol et al, Phys. Rev. C. 98. 034916

Hydro model with inhomogeneous baryon deposition:

Baryon deposition profile:





Two component baryon deposition: ($N_{part} + N_{coll}$)

$$n_B(x, y, \eta_s) = N_B \left[(1-\omega)\left(N_+(x,y) f^B_+(\eta_s) + N_-(x,y) f^B_-(\eta_s)\right) + \omega N_{coll}(x,y)\left(f^B_+(\eta_s) + f^B_-(\eta_s)\right) \right]$$

Normalisation

$$\int \tau_0 \, d\eta \, dx \, dy \, n_B(x, y, \eta_s) = N_{part} = (N_+ + N_-)$$

Motivated by baryon junction mechanism
(Feature similar to single junction + double junction stopping)

- Parameters: η_m → tilt of bulk, ω → baryon tilt
- Pressure = P (ε,n_B)
- Evolve hydro with the above initial condition

- It can qualitatively capture system size dependence of proton (anti-proton) v_1 and Δv_1

Hydro: Parida and Chatterjee, arXiv: *2305.08806* (private communication)

Discussion

Hydro model with inhomogeneous baryon deposition:

$$n_B(x,y,\eta_s) = N_B\left[(1-\omega)\left(N_+(x,y)f_+^B(\eta_s)+N_-(x,y)f_-^B(\eta_s)\right)+\omega N_{coll}(x,y)\left(f_+^B(\eta_s)+f_-^B(\eta_s)\right)\right]$$

Normalisation

$$\int \tau_0\, d\eta\, dx\, dy\, n_B(x,y,\eta_s) = N_{part} = (N_+ + N_-)$$

- (p+$\overline{\text{p}}$): total charge zero, total baryon zero ~ effectively carry no quantum number
- (p-$\overline{\text{p}}$): non-zero net-charge and net-baryon

- Different system sizes → different net baryon and its gradient

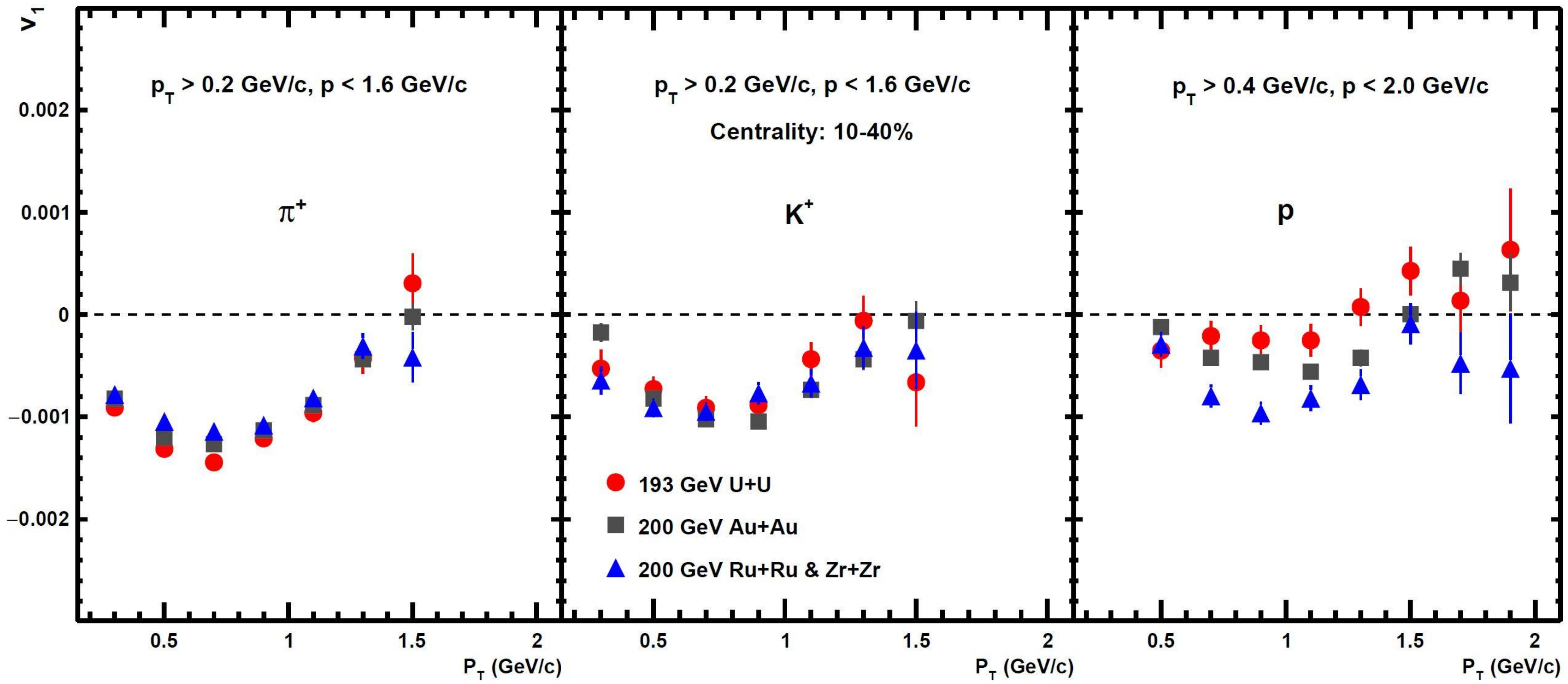
- ✓ **Simulated Au+Au hydro with net baryon same as Ru+Ru at a fixed <N_{part}> but all other parameters kept as default (e.g. entropy deposition is different)**
- ✓ **proton Δv_1 shows no system size dependence with enforced same net baryon, especially in central collisions**

- using data in central collisions (where EM-field contribution is expected to be small)
- proton Δv_1 in different collision systems → constrain baryon deposition in HIC
  → offer insights into baryon stopping mechanism

Hydro: Parida and Chatterjee, arXiv: *2305.08806* (private communication)

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

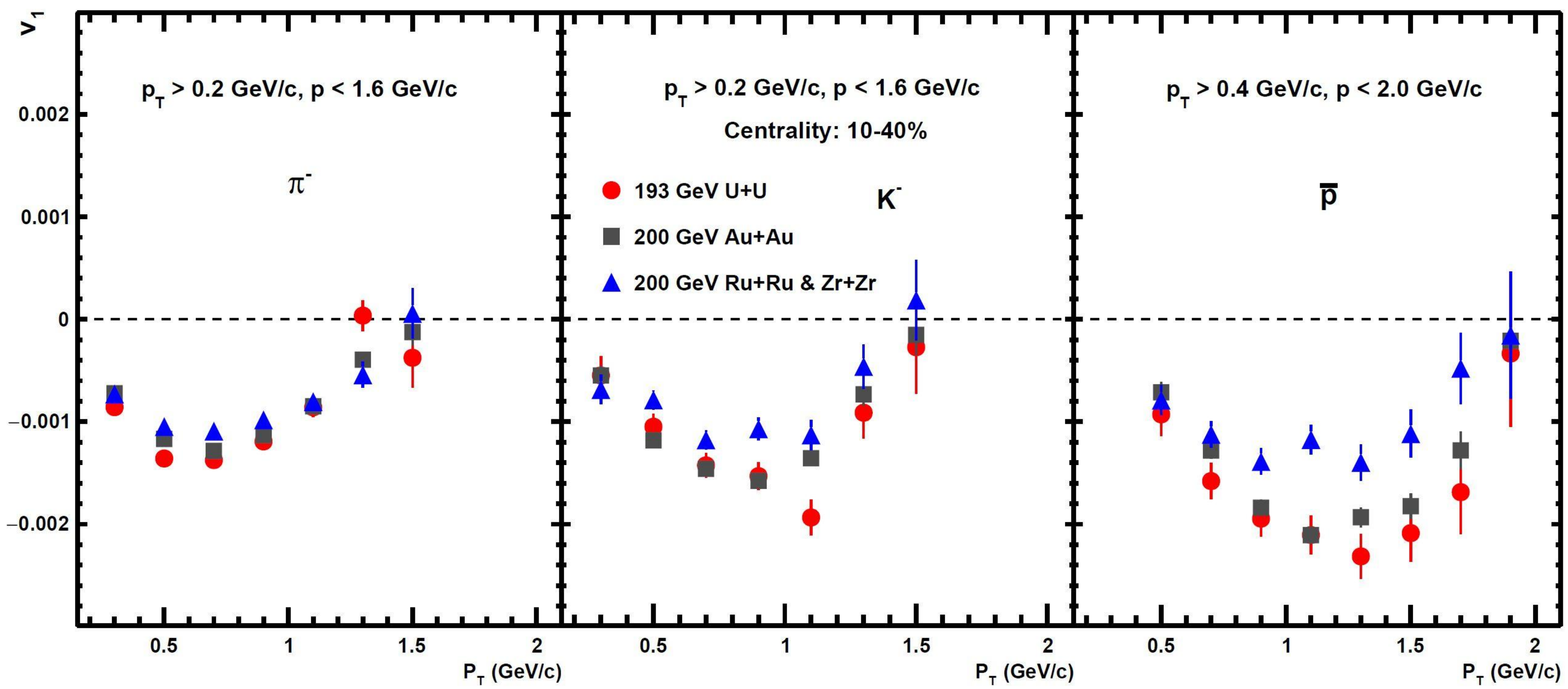
Mid Central
10-40 %



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

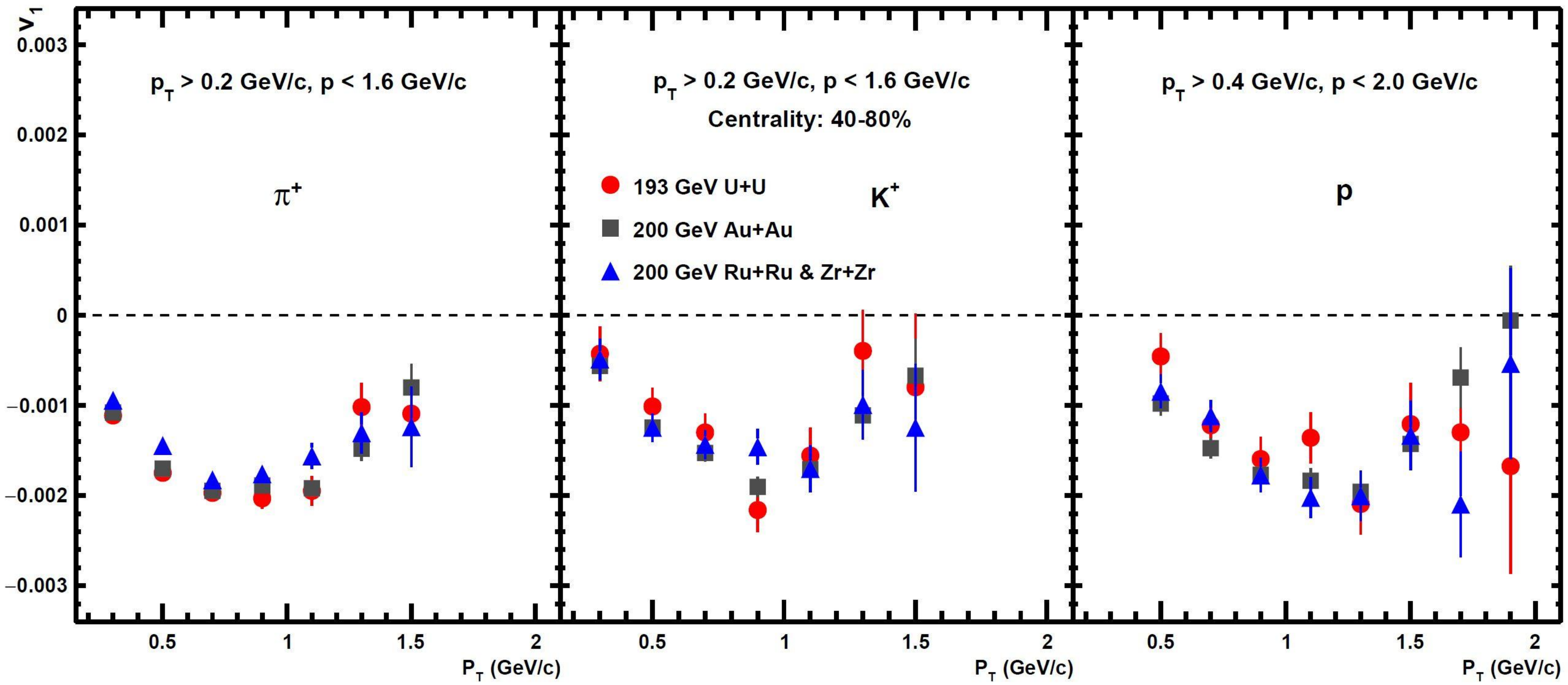
❖ dv_1/dy:

- pions → Isobar ~ Au+Au ~ U+U
- kaons → Isobar ~ Au+Au ~ U+U
- antiprotons → U+U > Au+Au > Isobar

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

Peripheral 40-80 %

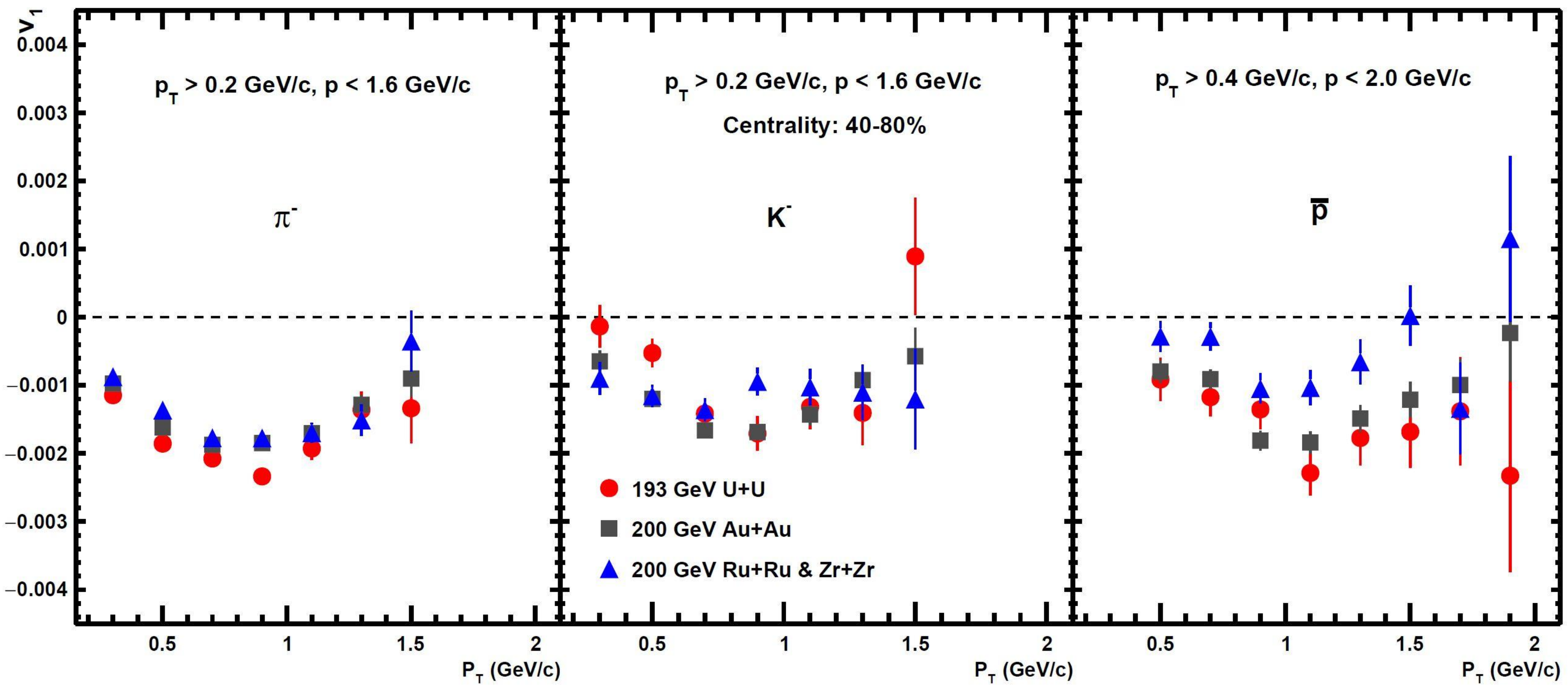
Positive Particles



❖ dv_1/dy:

- pions → Isobar ~ Au+Au ~ U+U
- kaons → Isobar ~ Au+Au ~ U+U
- protons → U+U ~ Au+Au ~ Isobar

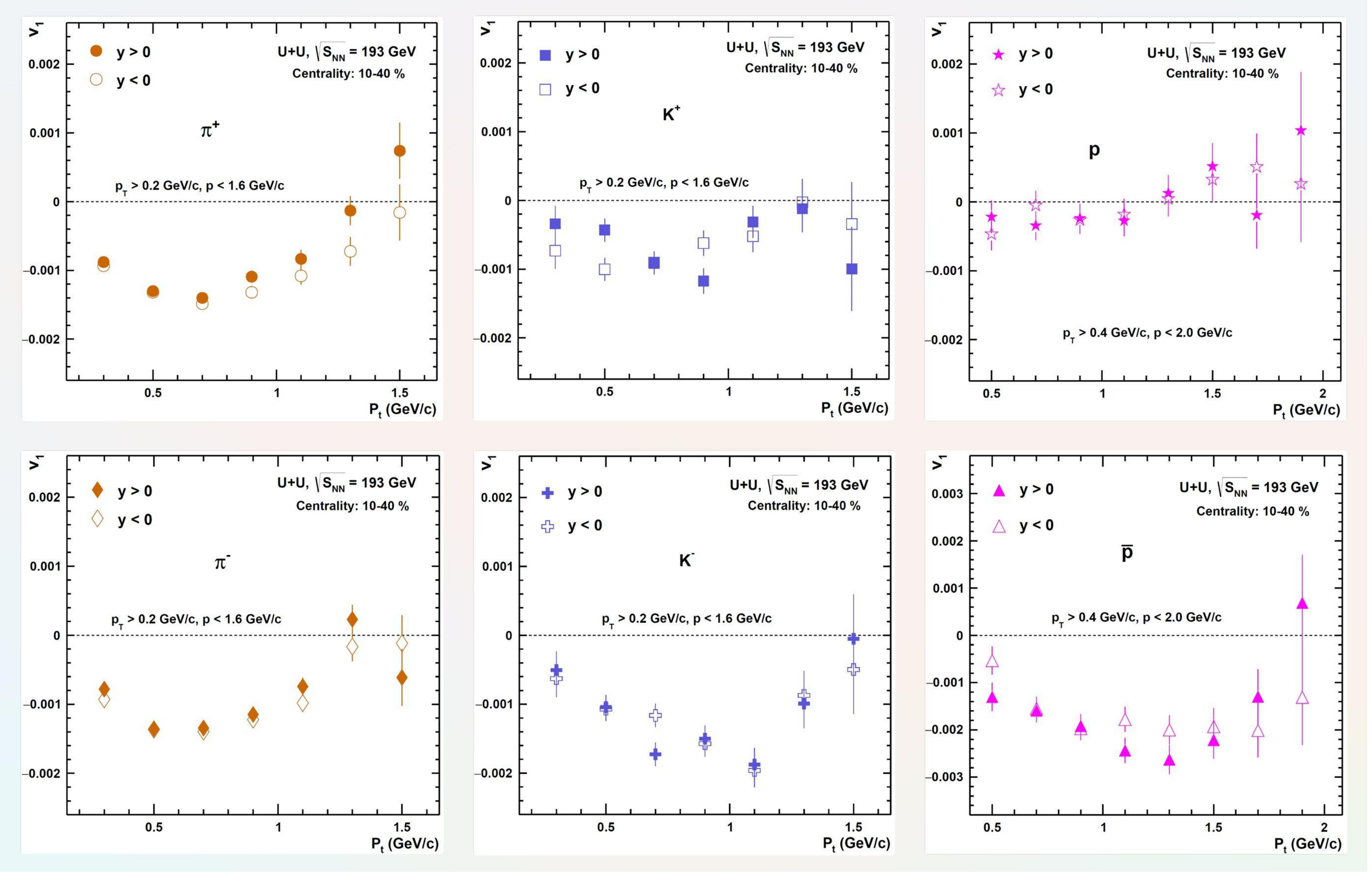
Negative Particles



❖ dv_1/dy:

- pions → Isobar ~ Au+Au <~ U+U
- kaons → Isobar ~ Au+Au ~ U+U
- protons → U+U > Au+Au > Isobar

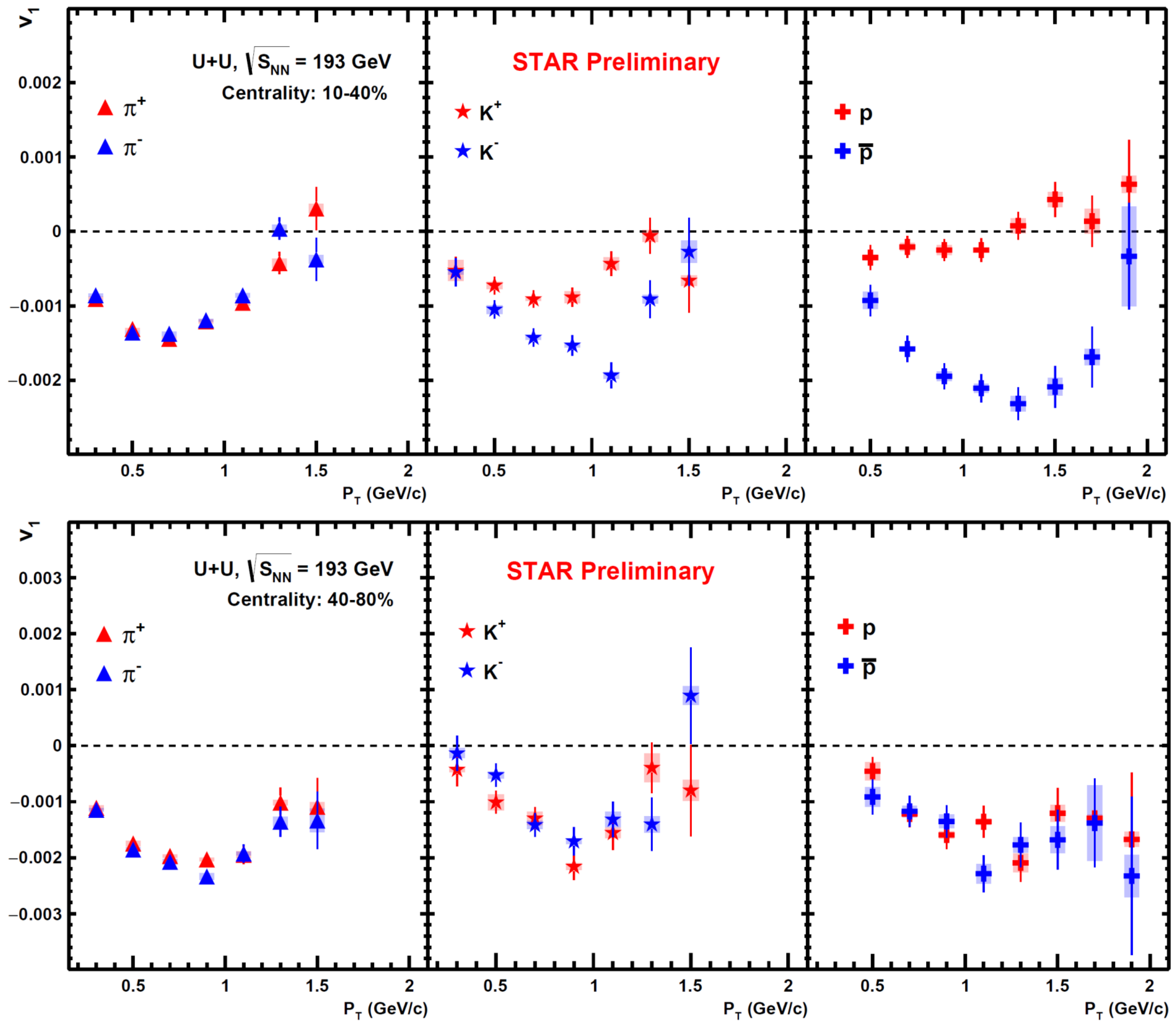
$v_1(p_T)$ for Positive and Negative Rapidity in U+U Collisions



$v_1(p_T)$ for U+U Collisions

Mid Central 10-40 %

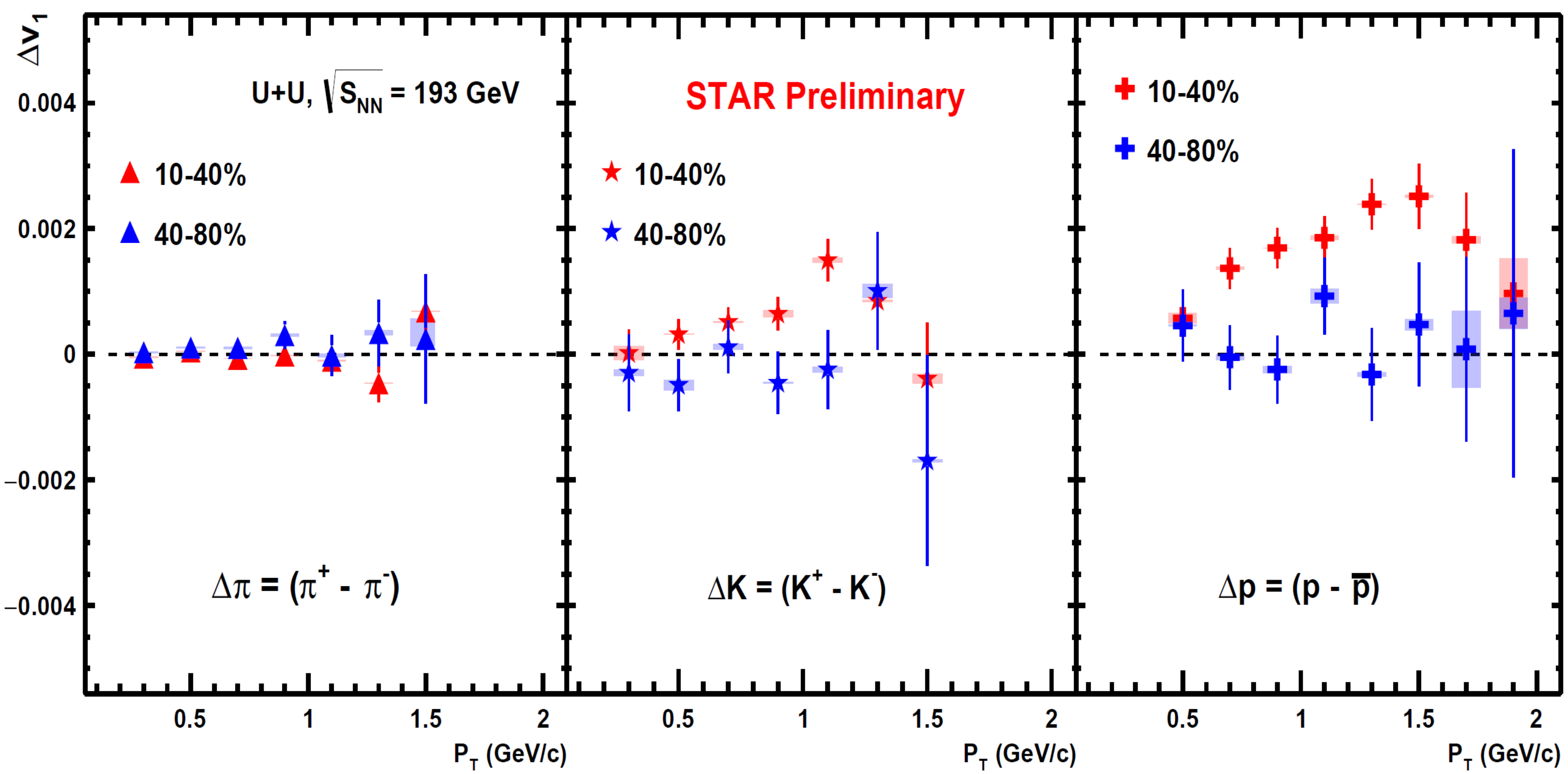
Peripheral 40-80 %



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

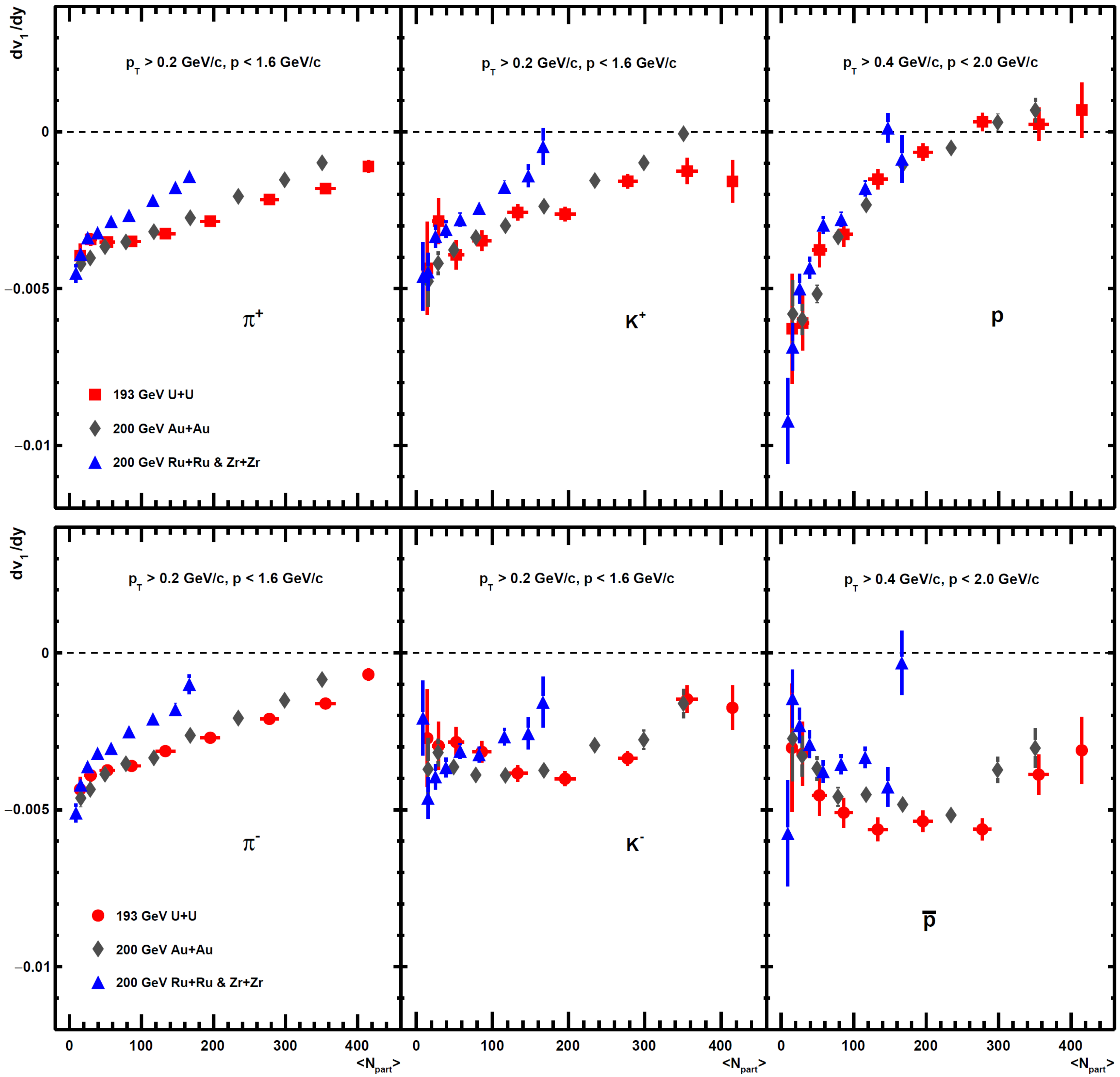
$\Delta v_1(p_T)$ for U+U Collisions

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

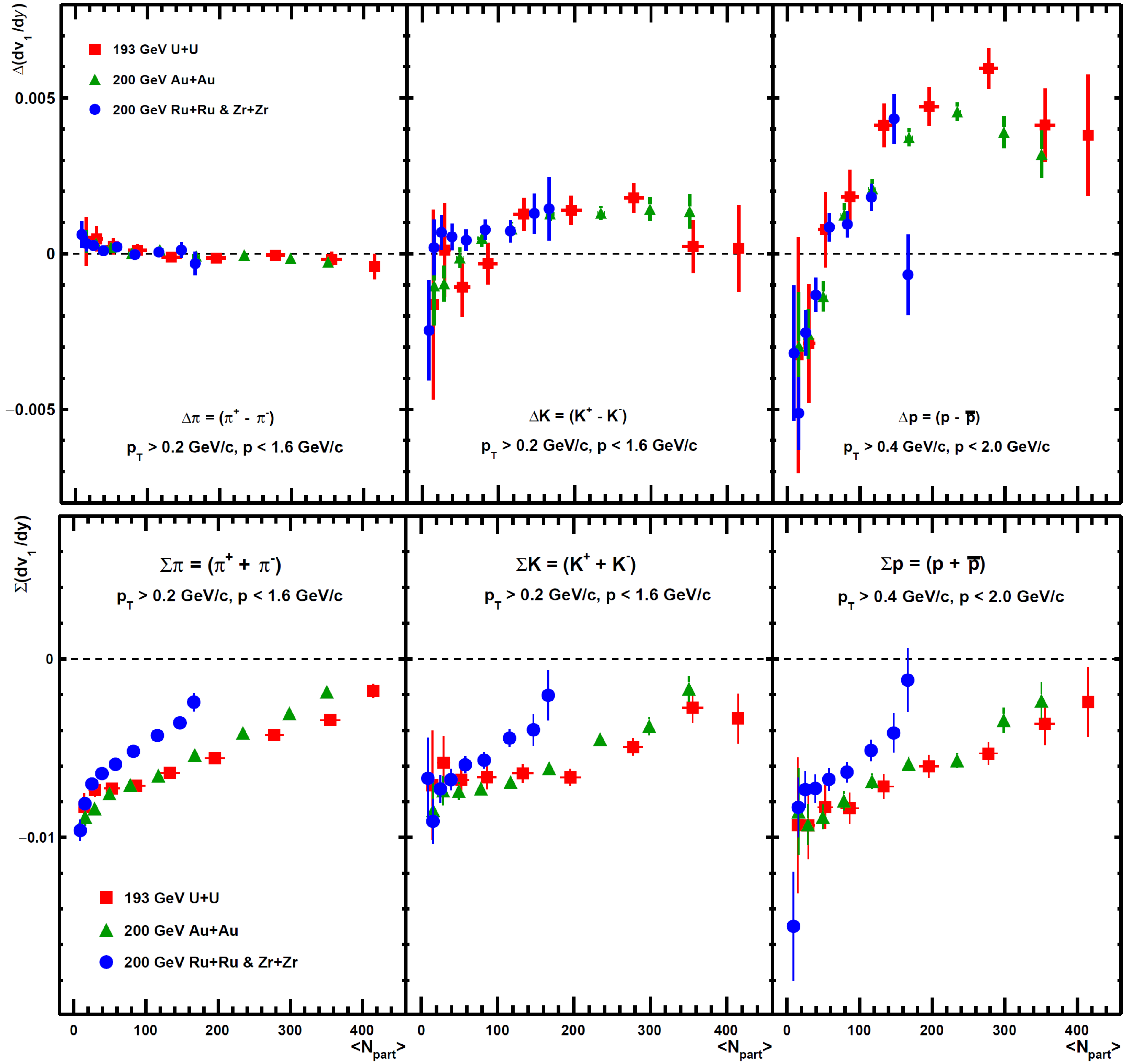


- **Pions (Kaons)** → consistent with zero within uncertainties
- **Protons** → mid-central collisions → Δv_1 keep increasing with p_T
  peripheral collisions → no oblivious p_T dependence

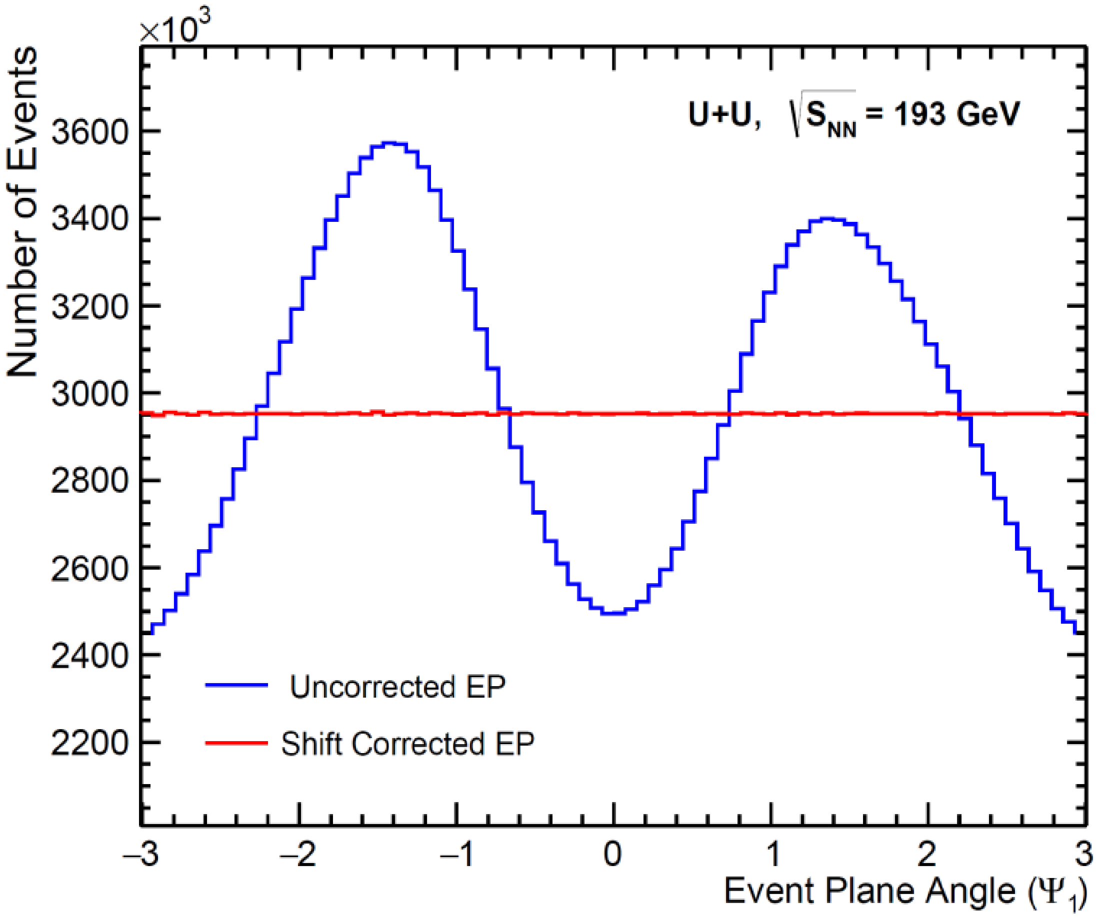
dv_1/dy as a function of < Npart >



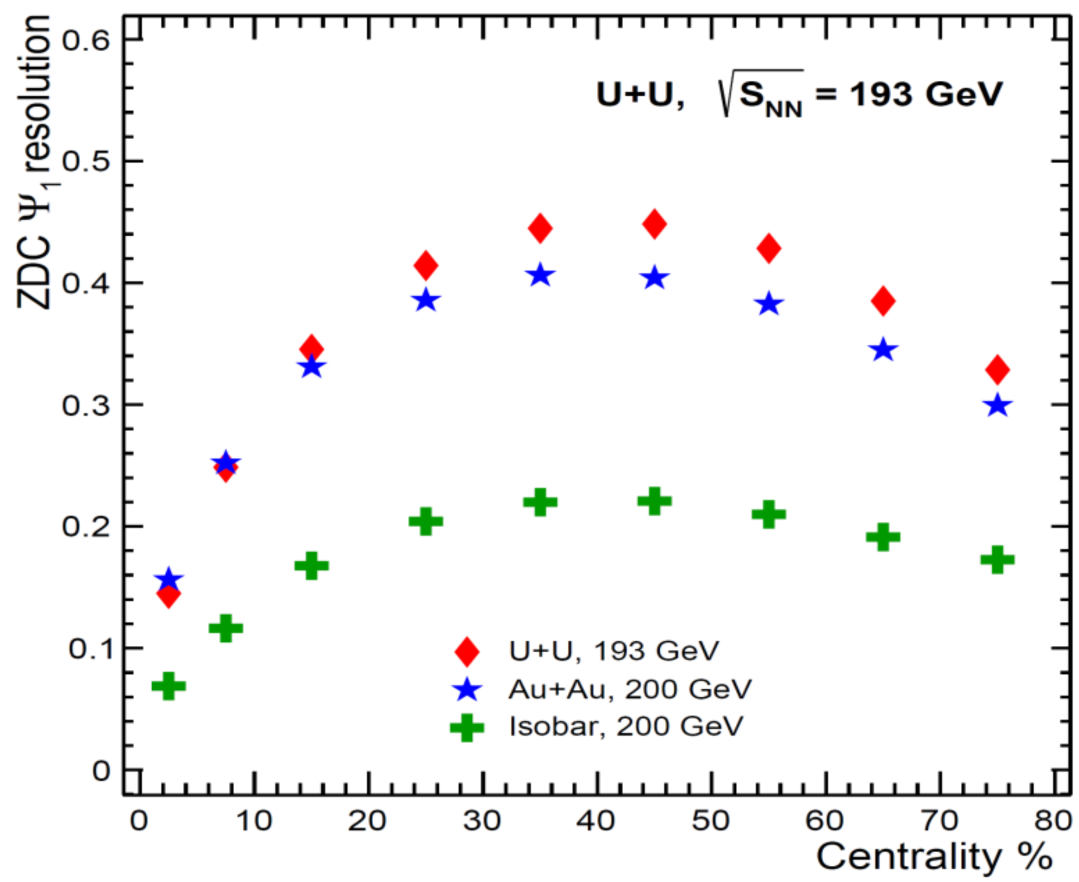
$\Delta(dv_1/dy)$ as a function of < Npart >



Event Plane & Resolution Plots



Ψ_1 is reconstructed using ZDC



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

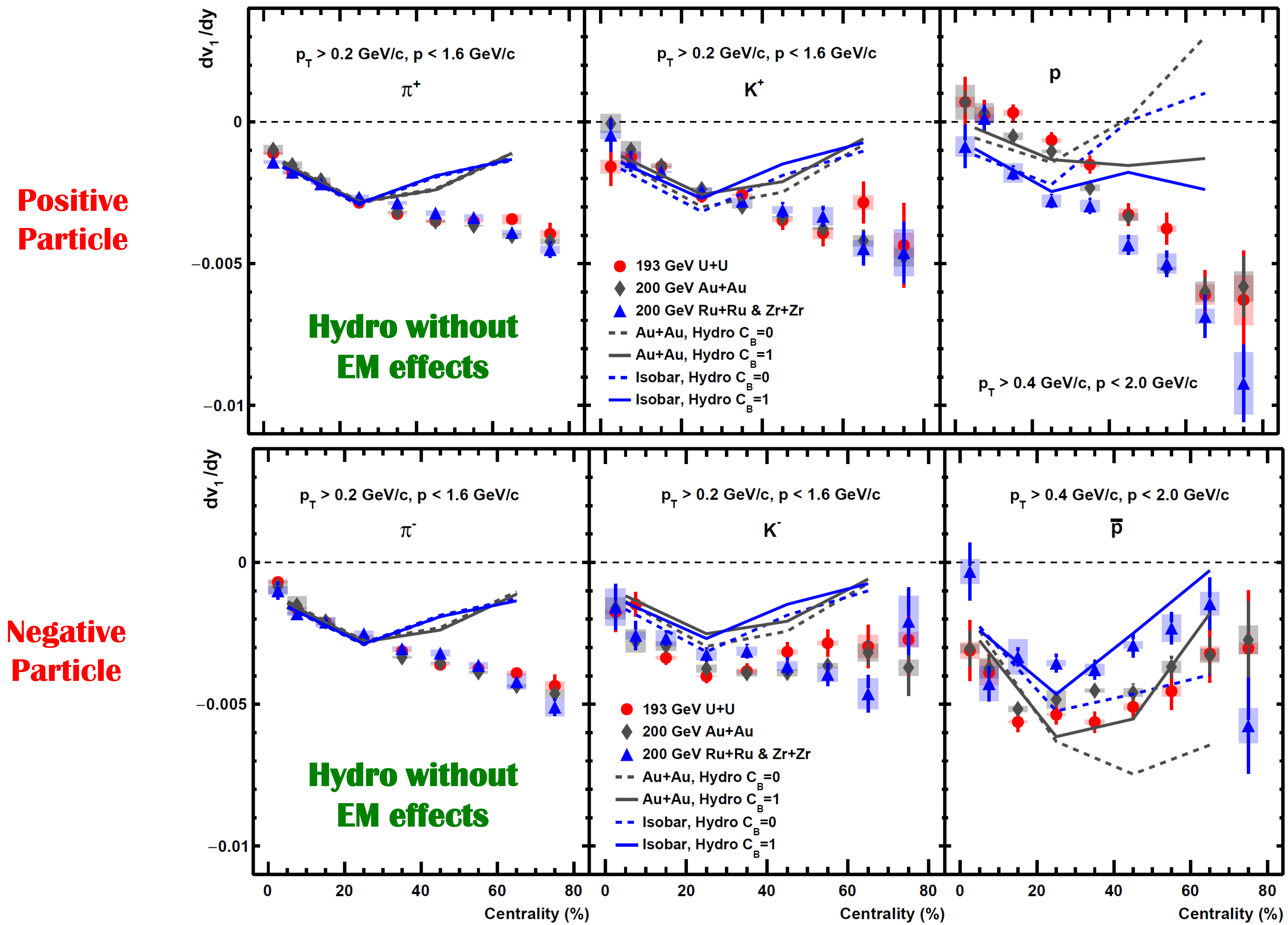
Resolution Values: -

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}

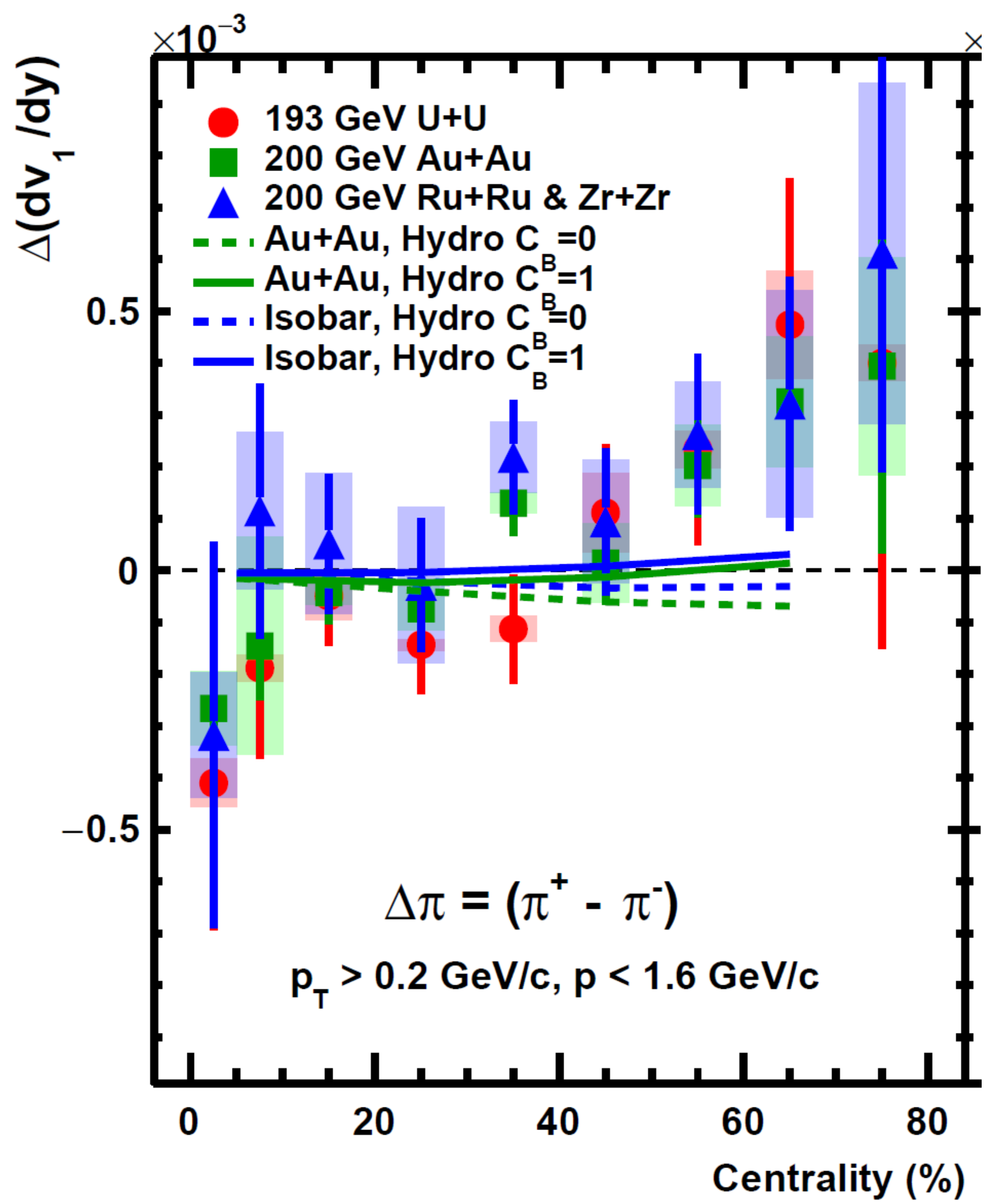
Isobar[9] = {0.0688674, 0.11634, 0.167703, 0.204098, 0.21988, 0.220753, 0.20985, 0.191277, 0.1727}

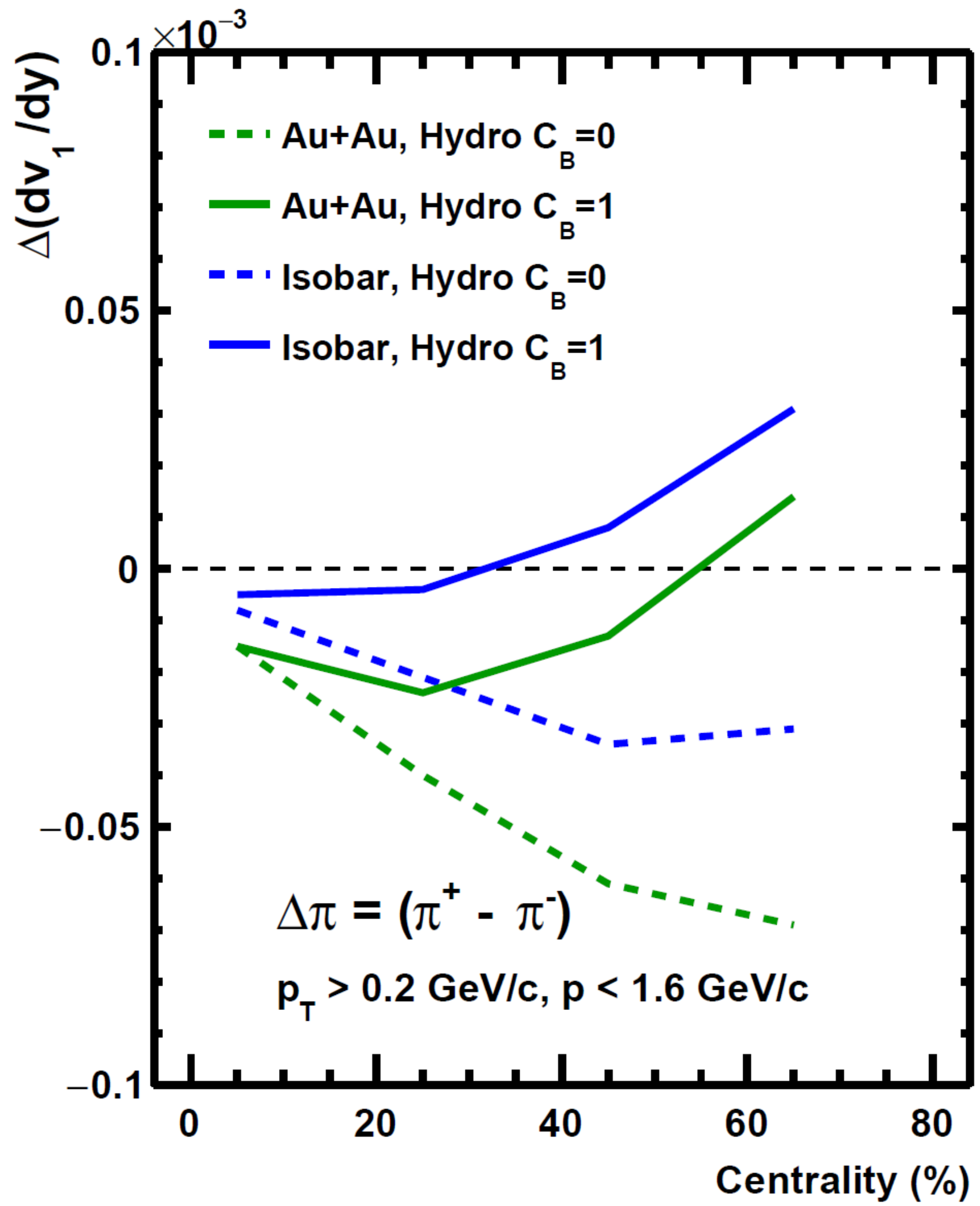
Slope (dv_1/dy) for Different Collision Systems



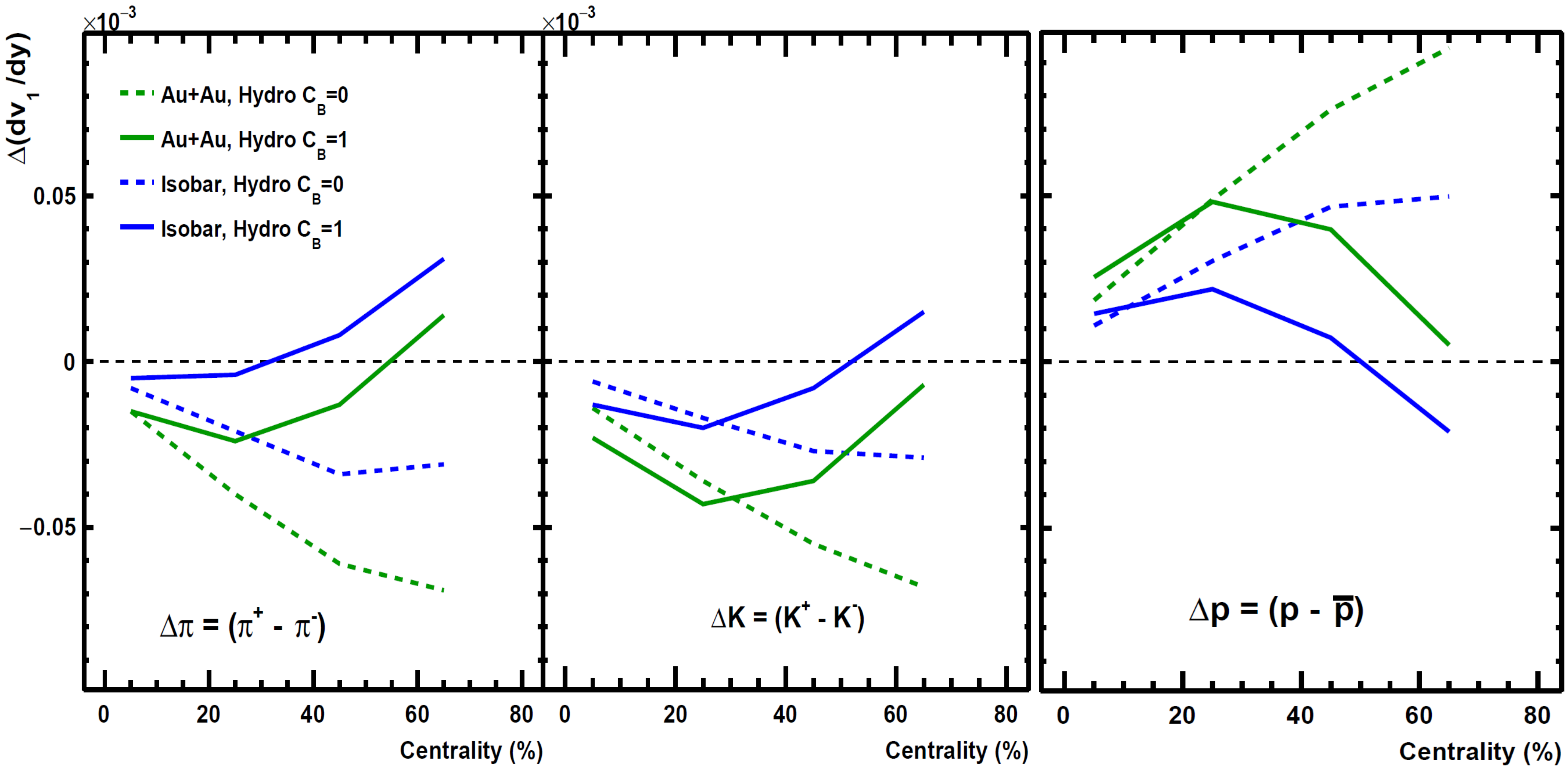
- Slopes are fitted using a linear function "y = mx" within rapidity range (-0.8, 0.8)
- Significant negative slopes (from linear fit) are observed for proton in all the three collision systems
- For proton and antiproton, splitting in slopes are prominent in mid central (10-40)% collisions

$\Delta(dv_1/dy)$ for Pion without EM effects

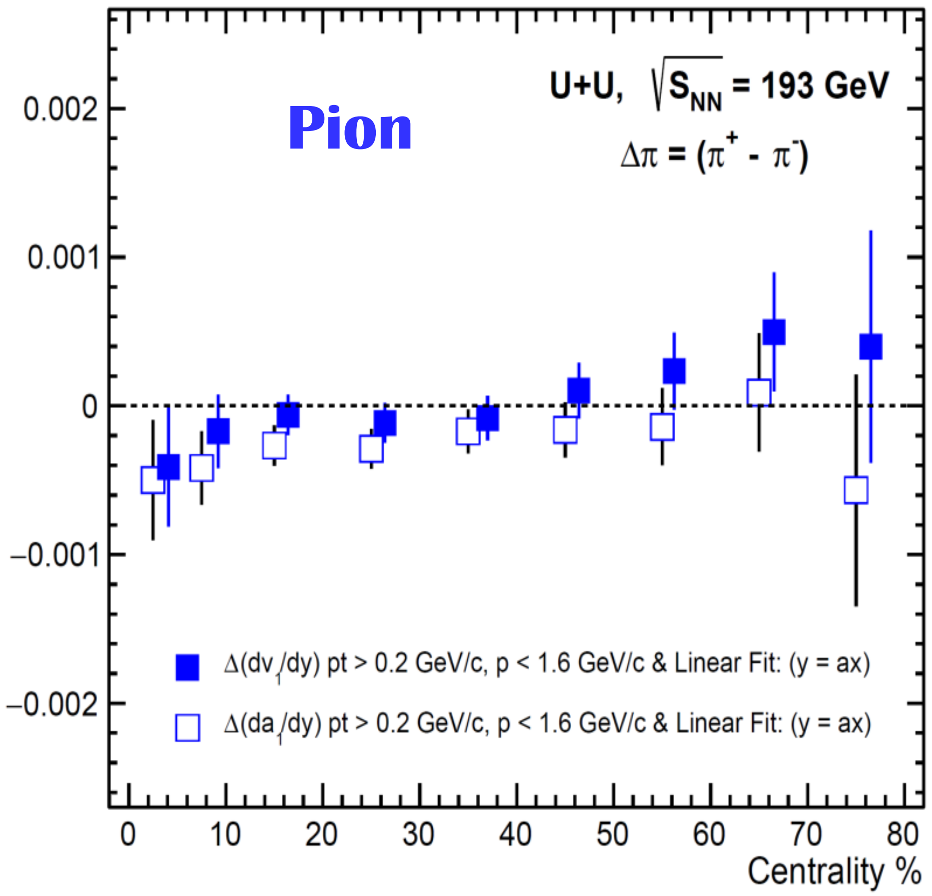


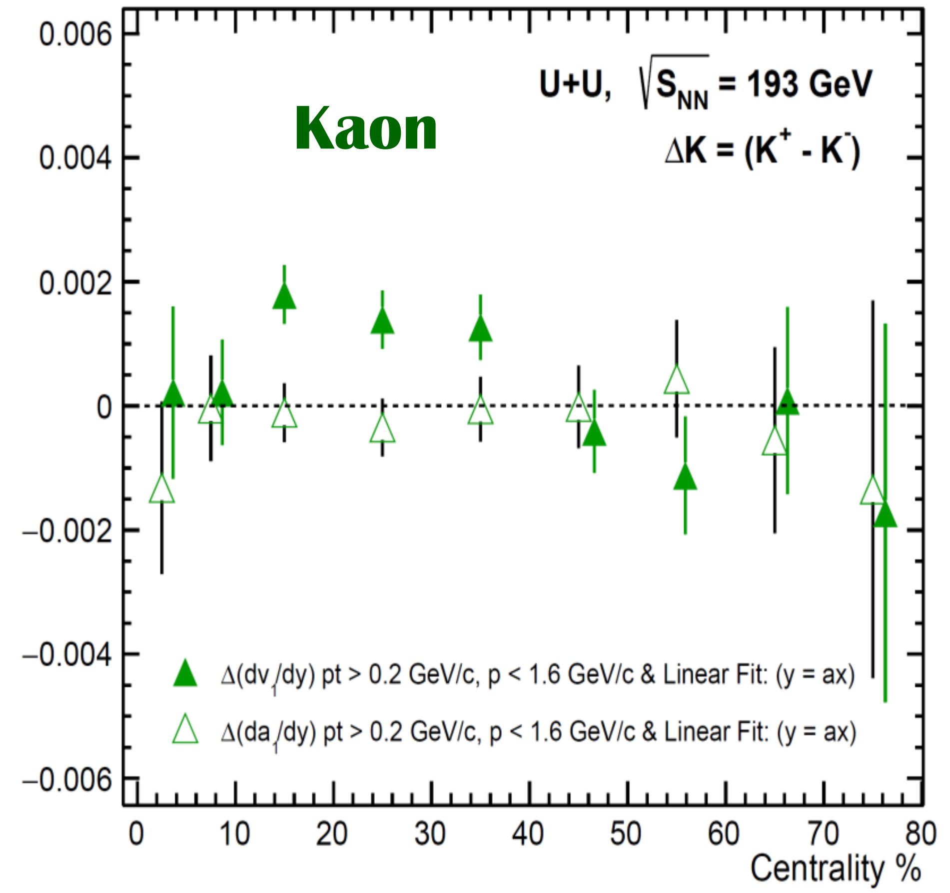


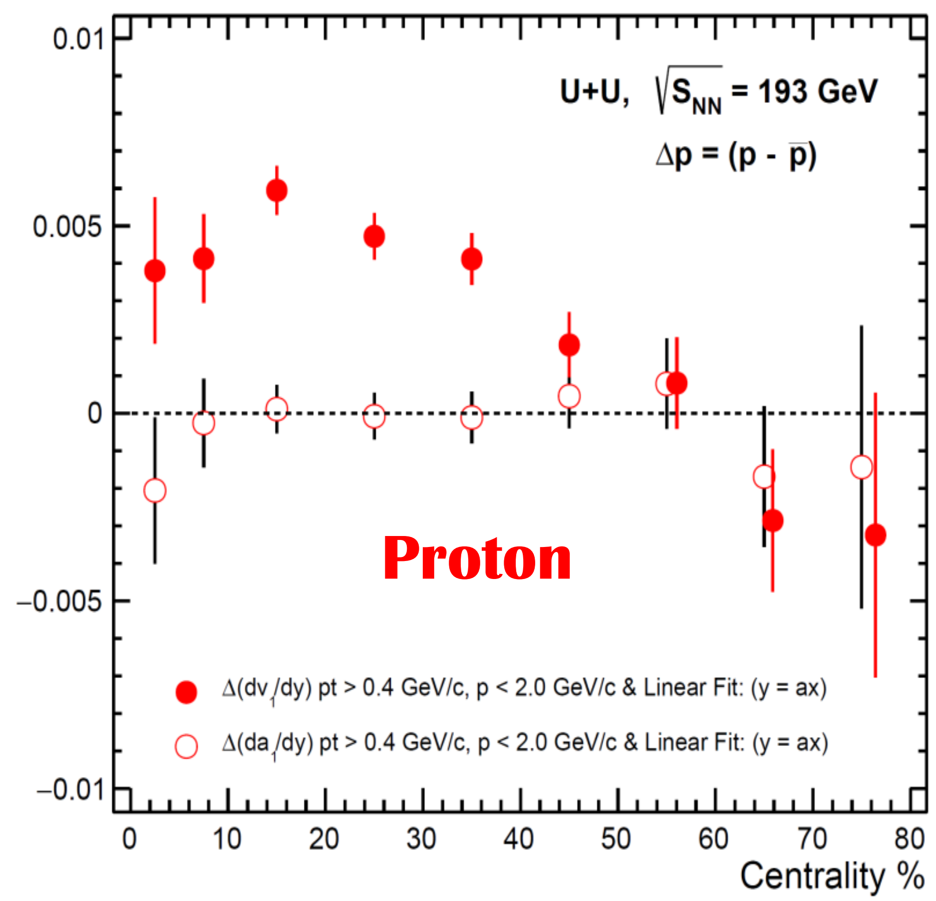
$\Delta(dv_1/dy)$ prediction without EM effects



$\Delta(da_1/dy)$ for Proton







Systematic Uncertainties of v_1

Default	Systematic
$-50 < V_z^{TPC} < 50$ cm	$-50 < V_z^{TPC} < 0$ cm
$N_{fits} > 15$	$N_{fits} > 20$
$-0.8 < y < 0.8$	$-0.8 < y < 0.0$ & $0.0 < y < 0.8$
DCA < 3 cm	DCA < 1.0 cm & DCA < 1.5 cm
$-2.0 < n\sigma^{TPC} < 2.0$	$-1.0 < n\sigma^{TPC} < 1.0$ & $-1.5 < n\sigma^{TPC} < 1.5$
Mass² (pi) = -0.01 – 0.10 (GeV/c²)² Mass² (k) = 0.20 – 0.35 (GeV/c²)² Mass² (p) = 0.80 – 1.0 (GeV/c²)²	Mass² (pi) = -0.009 – 0.09 (GeV/c²)² Mass² (k) = 0.21 – 0.34 (GeV/c²)² Mass² (p) = 0.82 – 0.98 (GeV/c²)² & Mass² (p) = 0.84 – 0.96 (GeV/c²)²

- **The formula used for calculation is:**

$$\sigma_i = |Y_i - Y_d|/\sqrt{12},$$
$$\sigma = \sqrt{\sum \sigma_i^2},$$

Where,
Y_i = variation result
Y_d = default result
σ = final systematic uncertainty