PWGC Presentation

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

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On behalf of PAs

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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

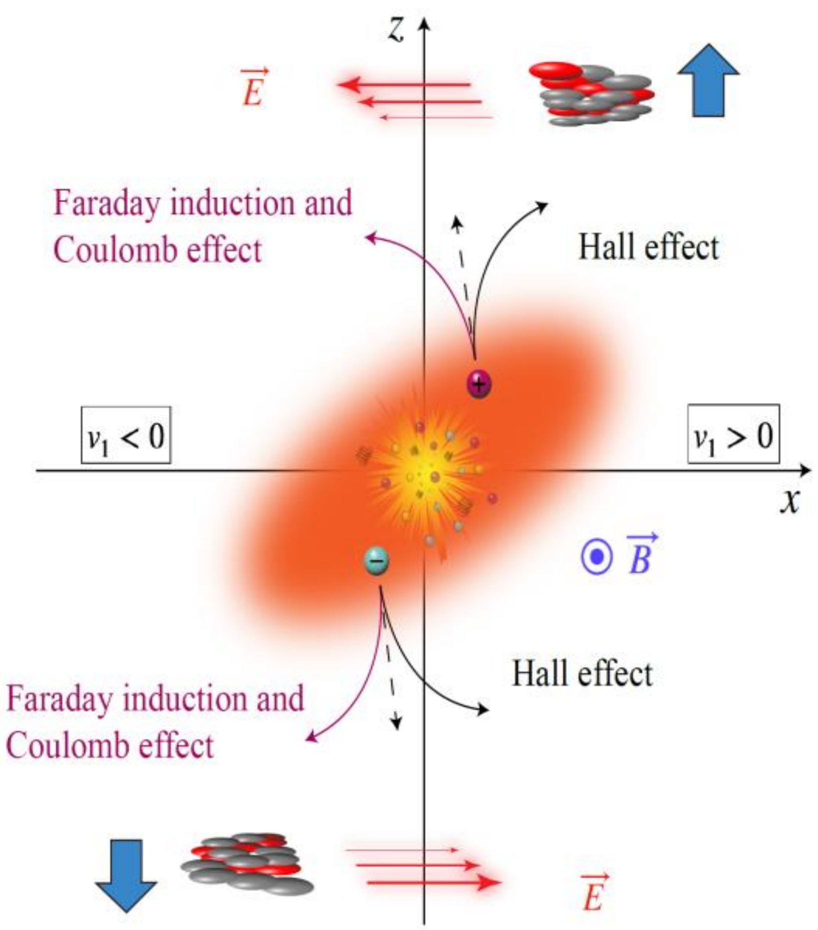
- **Hall Effect:** $F = q (v \times B)$ by Lorentz Force (positive Δv_1)
- **Coulomb Effect:** **E** generated by spectator nucleons (negative Δv_1)
- **Faraday Induction:** decreasing **B** as spectators fly away(negative Δv_1)

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

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

Directed Flow (v_1)

[1] U. Gürsoy, et al., PRC 98 055201,
[2] U. Gürsoy, et al., PRC 89 054905
[3] S.K. Das et al., PLB 768 260
[4] K. Nakamura et al., PRC 107 034912
[5] K. Nakamura et al., RPC 107 014901
[6] Y. Sun et al., PLB 843 138043



PRX 14, 011028 [STAR]

Transport effects on directed flow

- Transported quarks can also cause **positive/negative** Δv_1.

Expectations from transported quark effects

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

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

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

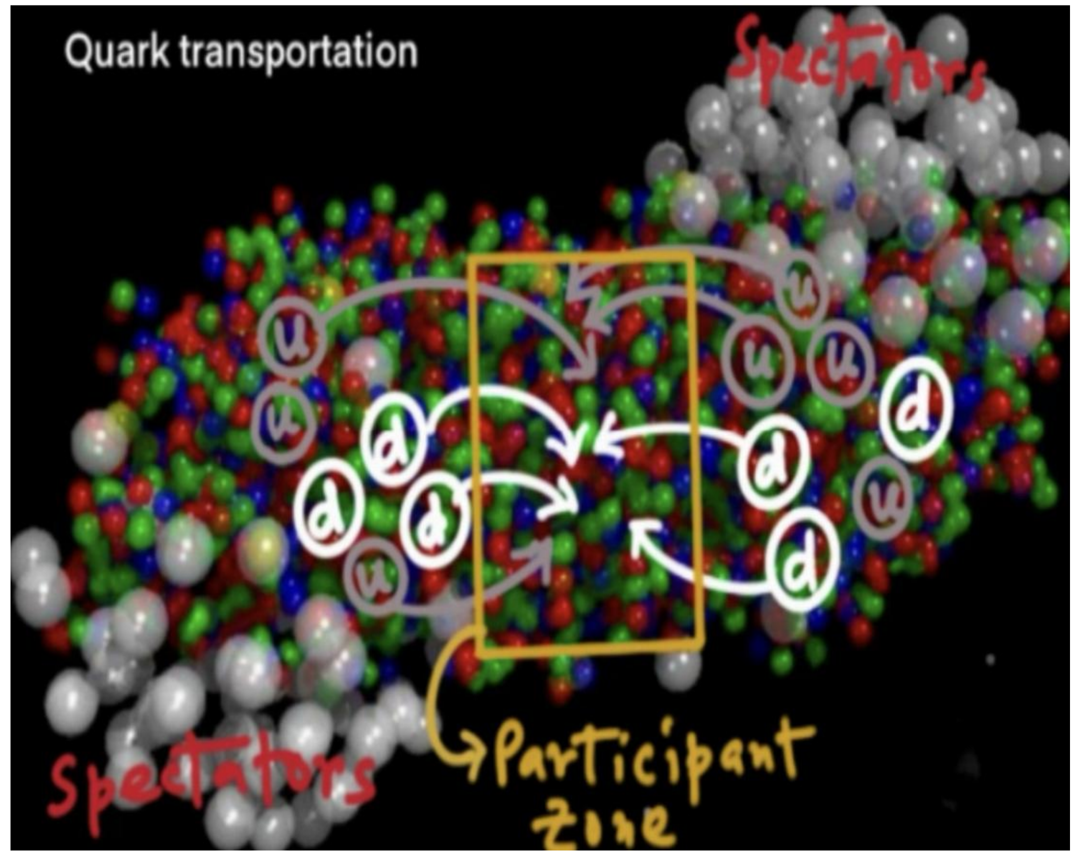
$$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$$

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

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

(#d>#u, Au neutron rich)

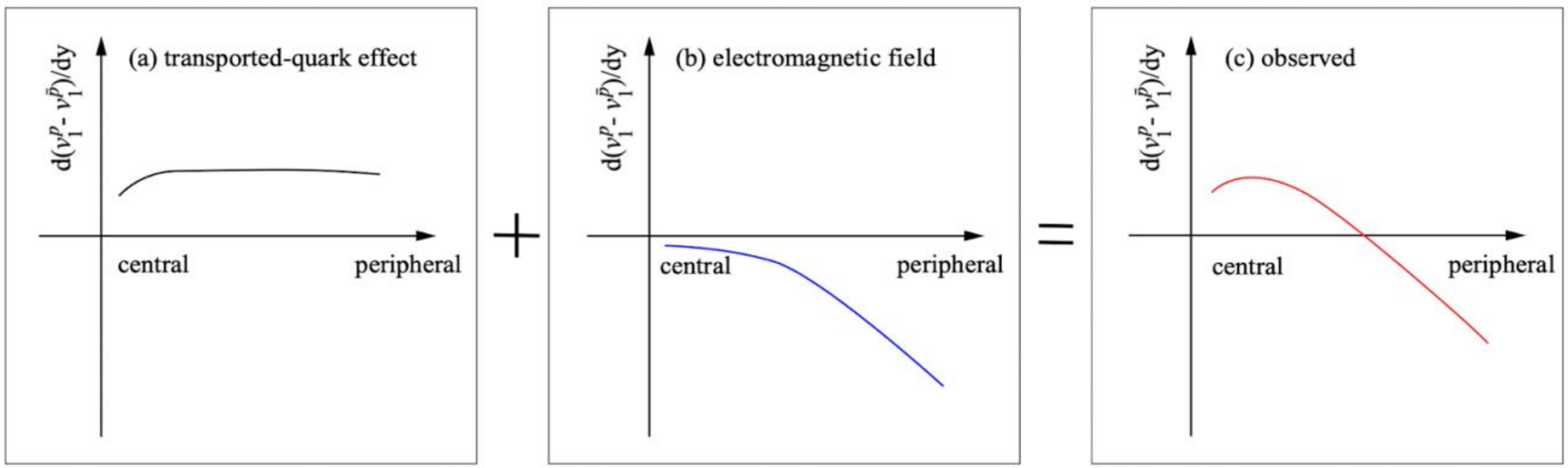
"u" and "d" quarks transported from incoming nuclei towards mid-rapidity



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

Hydro model: baryon transport

Hydro model at non-zero baryon density:
Follows conservation of energy-momentum ($T^{\mu\nu}$) and baryon (J_B^{μ}) conservation

$$T^{\mu\nu} = eu^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}, \qquad J_B^\mu = n_B u^\mu + q^\mu.$$

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

Parameters κ_B: Baryon diffusion coefficient constant
The amount of baryon diffusion is varied by tuning the prefactor $\mathbf{C_B}$

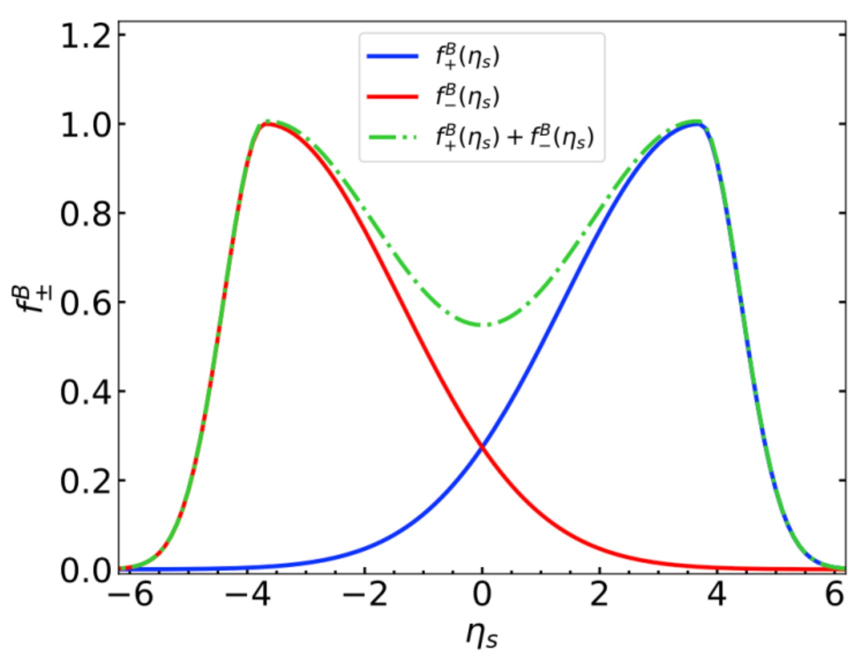
The **initial condition** for baryons is considered following two-component sources: (N_{part} + N_{coll})

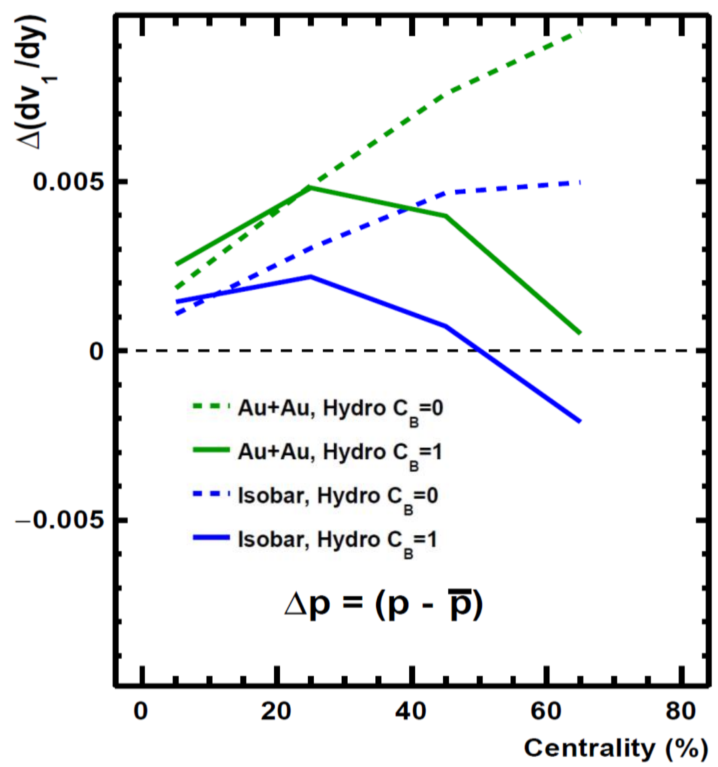
$$n_B(x,y,\eta_s) = N_B \left[(1-\omega)\left(N_+(x,y) f_+^B(\eta_s) + N_-(x,y) f_-^B(\eta_s)\right) + \omega N_{coll}(x,y)\left(f_+^B(\eta_s) + f_-^B(\eta_s)\right)\right]$$

Normalisation

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

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





It can introduce **system size dependence** in proton's Δv_1

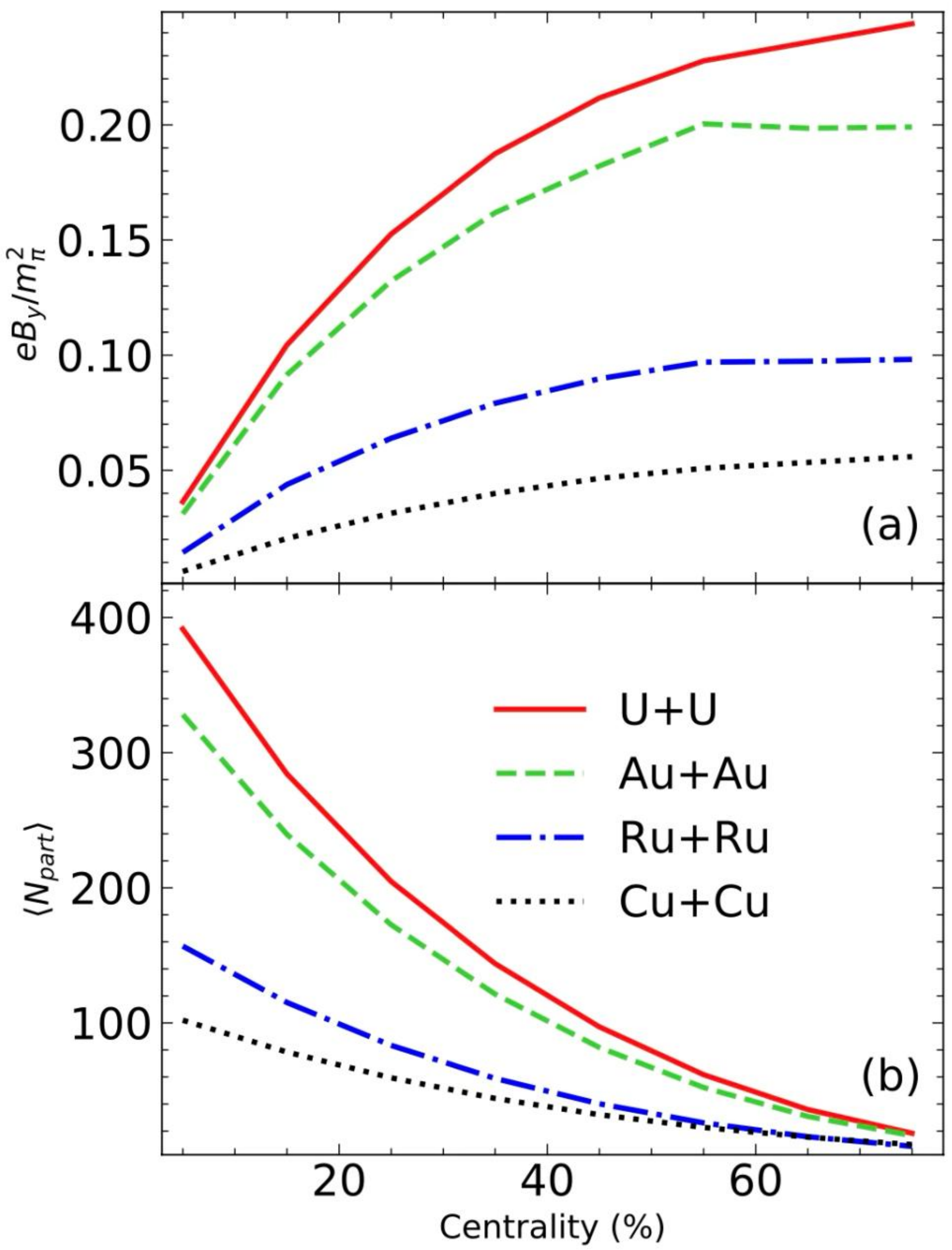
The Δv_1 is also sensitive to baryon diffusion parameter

Hydro: Parida et al, arXiv: *2305.08806, 2503.04660*

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

System size dependence of Δv_1

❖ Potentially two major sources of Δv_1 (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. Baryon Transport: (N_{part}): U+U > Au+Au > Ru+Ru > Cu+Cu

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

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
$-2.0 < n\sigma^{TPC} < 2.0$	$-1.0 < n\sigma^{TPC} < 1.0$ & $-1.5 < n\sigma^{TPC} < 1.5$
$Mass^2$ (pi) = -0.01 – 0.10 $(GeV/c^2)^2$ $Mass^2$ (k) = 0.20 – 0.35 $(GeV/c^2)^2$ $Mass^2$ (p) = 0.80 – 1.0 $(GeV/c^2)^2$	$Mass^2$ (pi) = -0.009 – 0.09 $(GeV/c^2)^2$ $Mass^2$ (k) = 0.21 – 0.34 $(GeV/c^2)^2$ $Mass^2$ (p) = 0.82 – 0.98 $(GeV/c^2)^2$ & $Mass^2$ (p) = 0.84 – 0.96 $(GeV/c^2)^2$

- **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

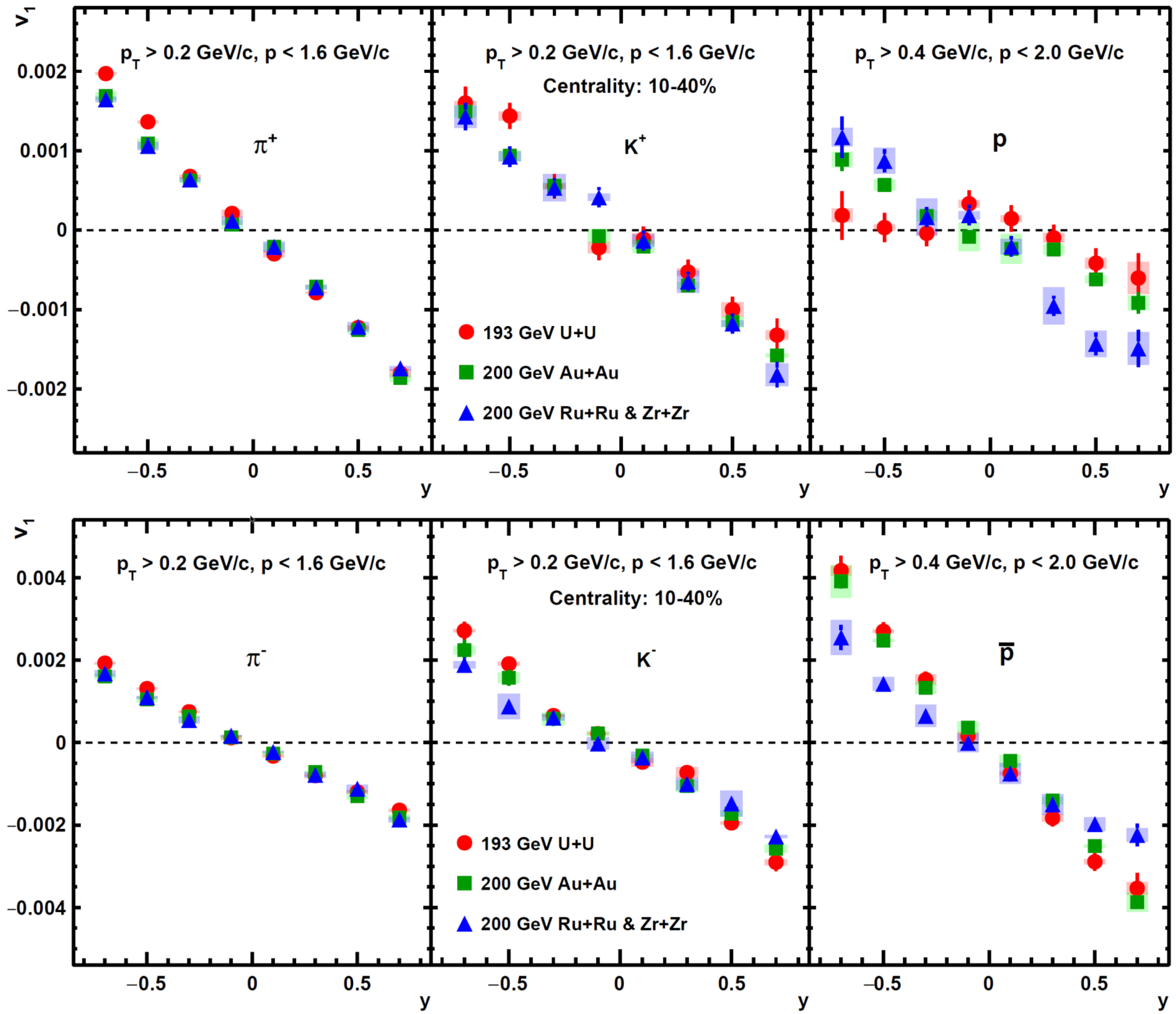
- **Note:** These are the preliminary estimation. The systematic error method will be revisted within the FCV working group and subsequently in GPC.

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 v_1 of total baryons ($p + \bar{p}$) show very weak dependence. In contrast, the dv_1/dy of mesons is consistent among all the three systems [1]. A hydrodynamic model incorporating baryon transport with an inhomogeneous baryon deposition profile and electromagnetic (EM) effects quantitatively describes the observed $\Delta(dv_1/dy)$ patterns. 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].

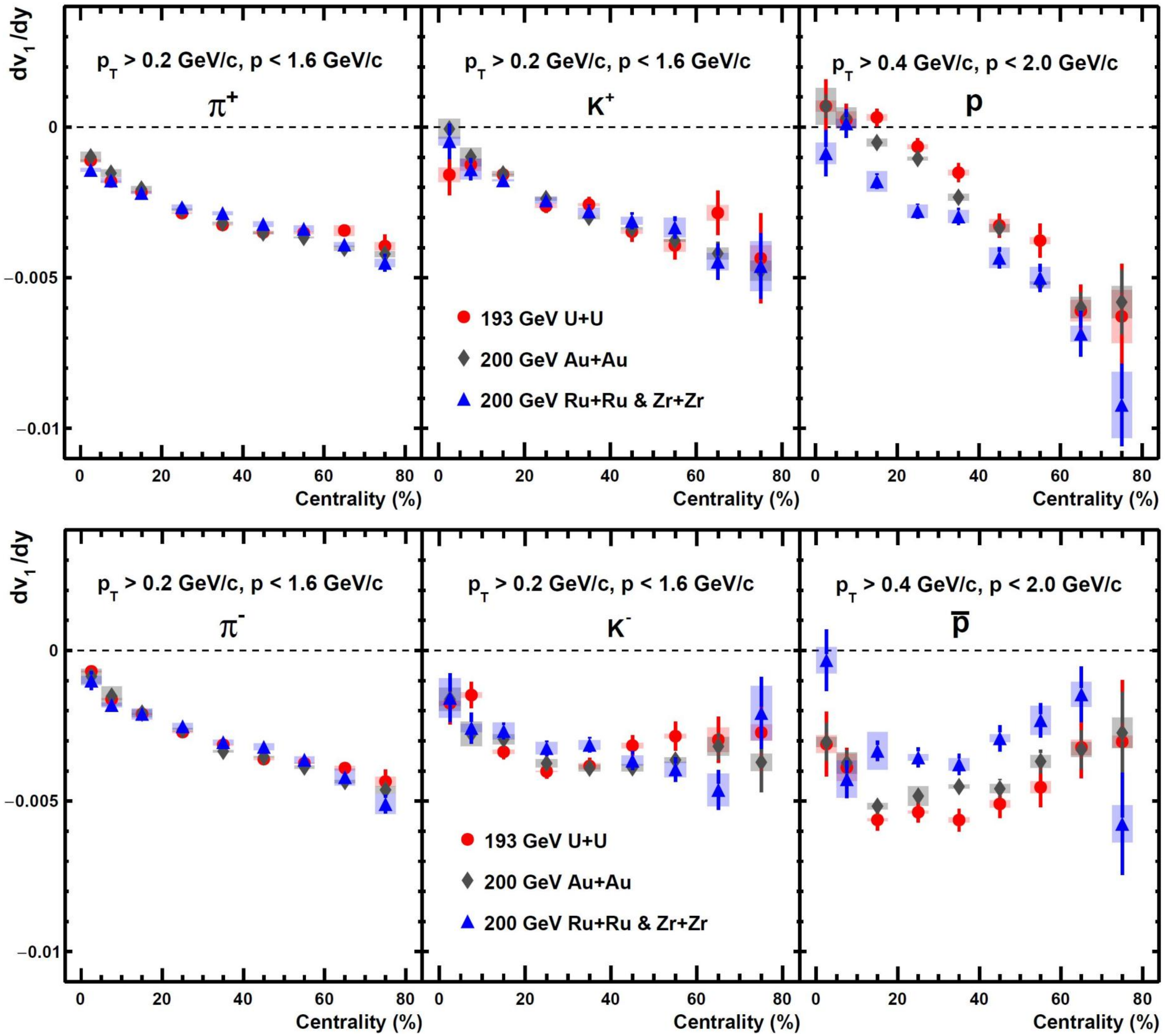
[1]. STAR Collaboration, Phys. Rev. Lett. 101, 252301
[2]. STAR Collaboration, Phys. Rev. X 14, 011028
[3]. T. Parida et al. arXiv: 2305.08806, 2503.04660

Figure 1



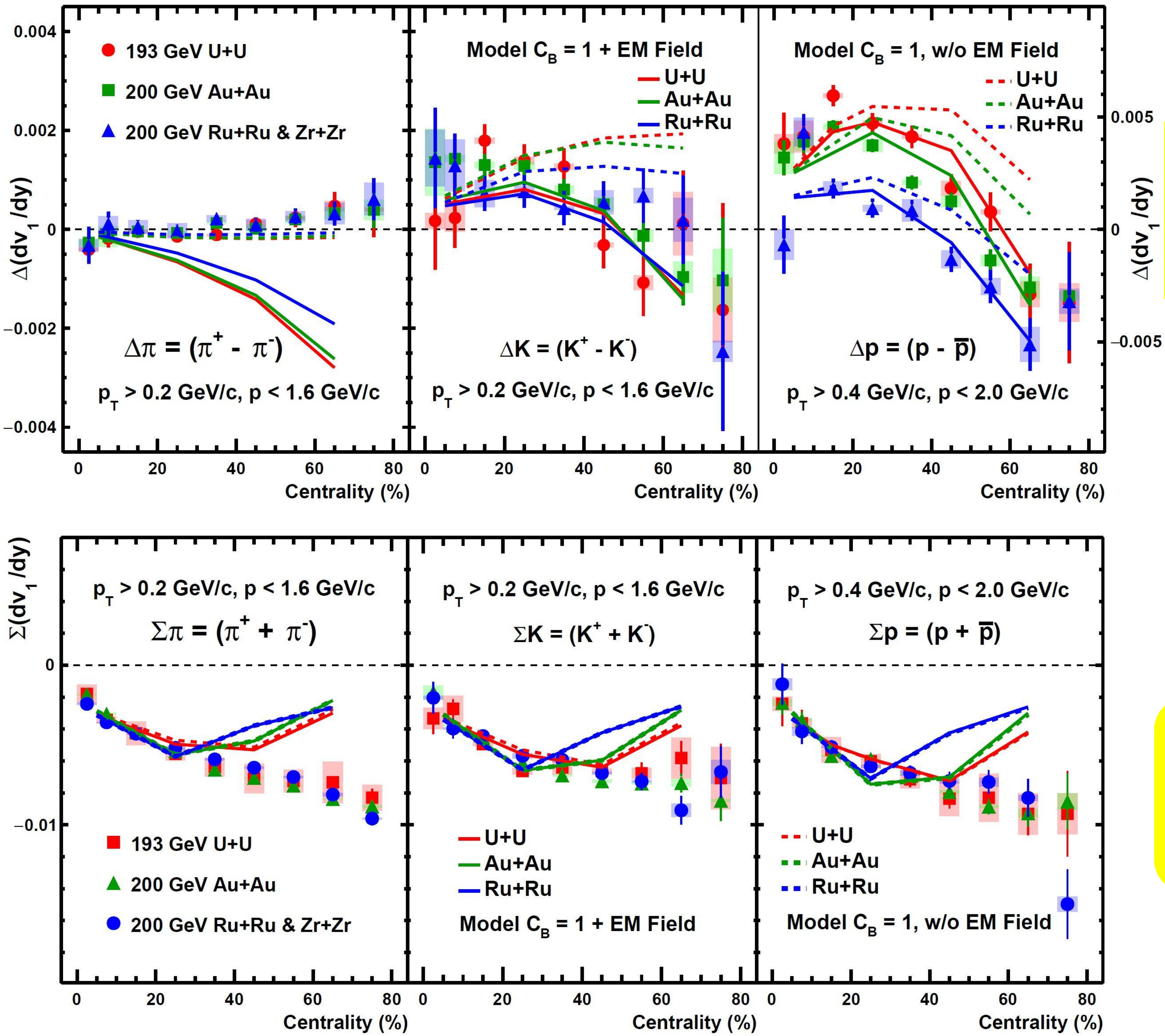
- v_1 vs y in U+U, Au+Au and Isobar collisions
- dv_1/dy is extracted by using a linear fit ($|y| < 0.8$)

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, antibaryons and their difference Δv_1**

- Hydrodynamic model with baryon transport combined with electromagnetic field and medium conductivity (σ = 0.023 fm^{-1}) can **quantatively capture** 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	
$\|V_z\| < 50$ cm	$\|V_r\| < 2$ cm

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

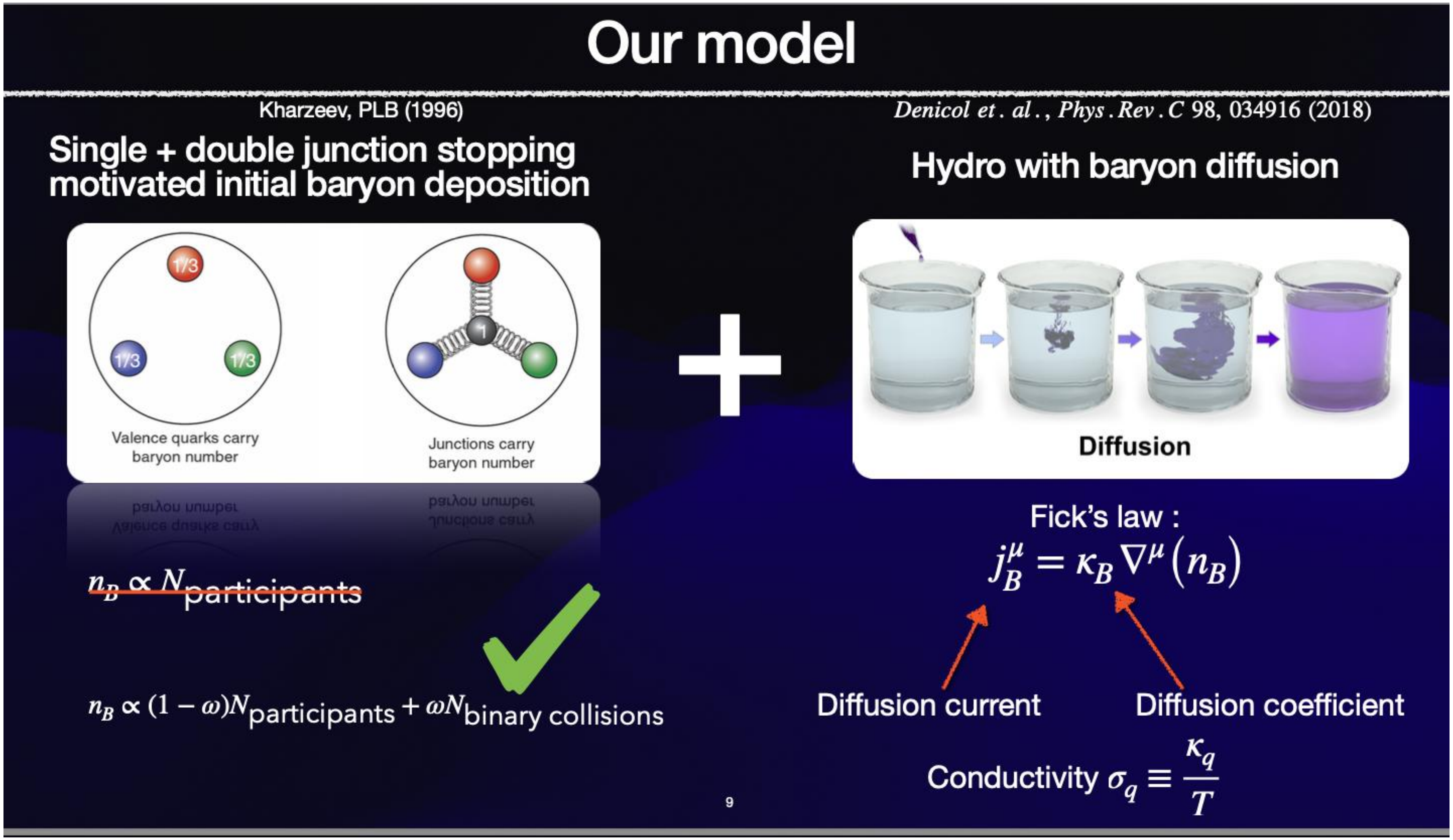
Particle Identification			
Pion:	$\|N\sigma\| < 2.0$	$-0.01 < m^2 < 0.10\ (GeV/c^2)^2$	$p < 1.6$ GeV/c && $p_t > 0.2$ GeV/c
Kaon:	$\|N\sigma\| < 2.0$	$0.20 < m^2 < 0.35\ (GeV/c^2)^2$	$p < 1.6$ GeV/c && $p_t > 0.2$ GeV/c
Proton:	$\|N\sigma\| < 2.0$	$0.8 < m^2 < 1.0\ (GeV/c^2)^2$	$p < 2.0$ GeV/c && $p_t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

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,

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

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

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

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

and

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

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

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

and

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

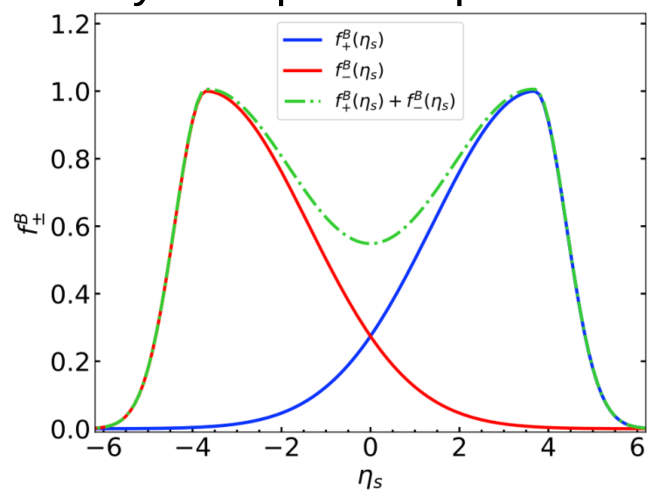
κ_B: Baryon diffusion coefficient constant;

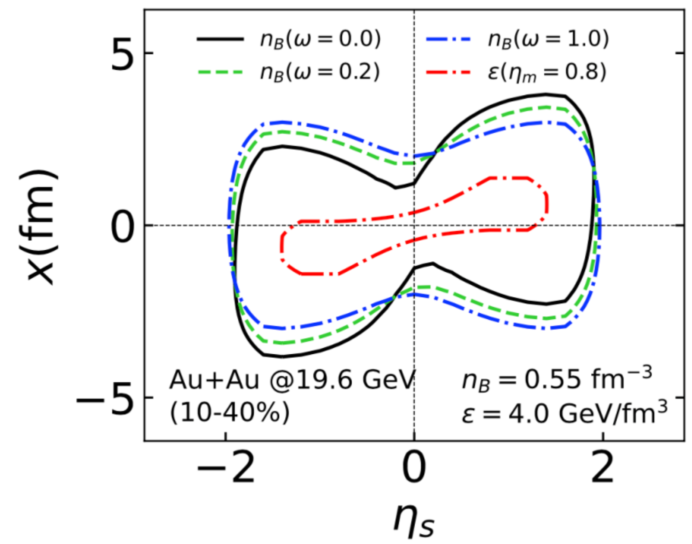
In hydro model amount of baryon diffusion is varied by tuning the prefactor C_B

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

- Different system sizes → different net baryon and its gradient

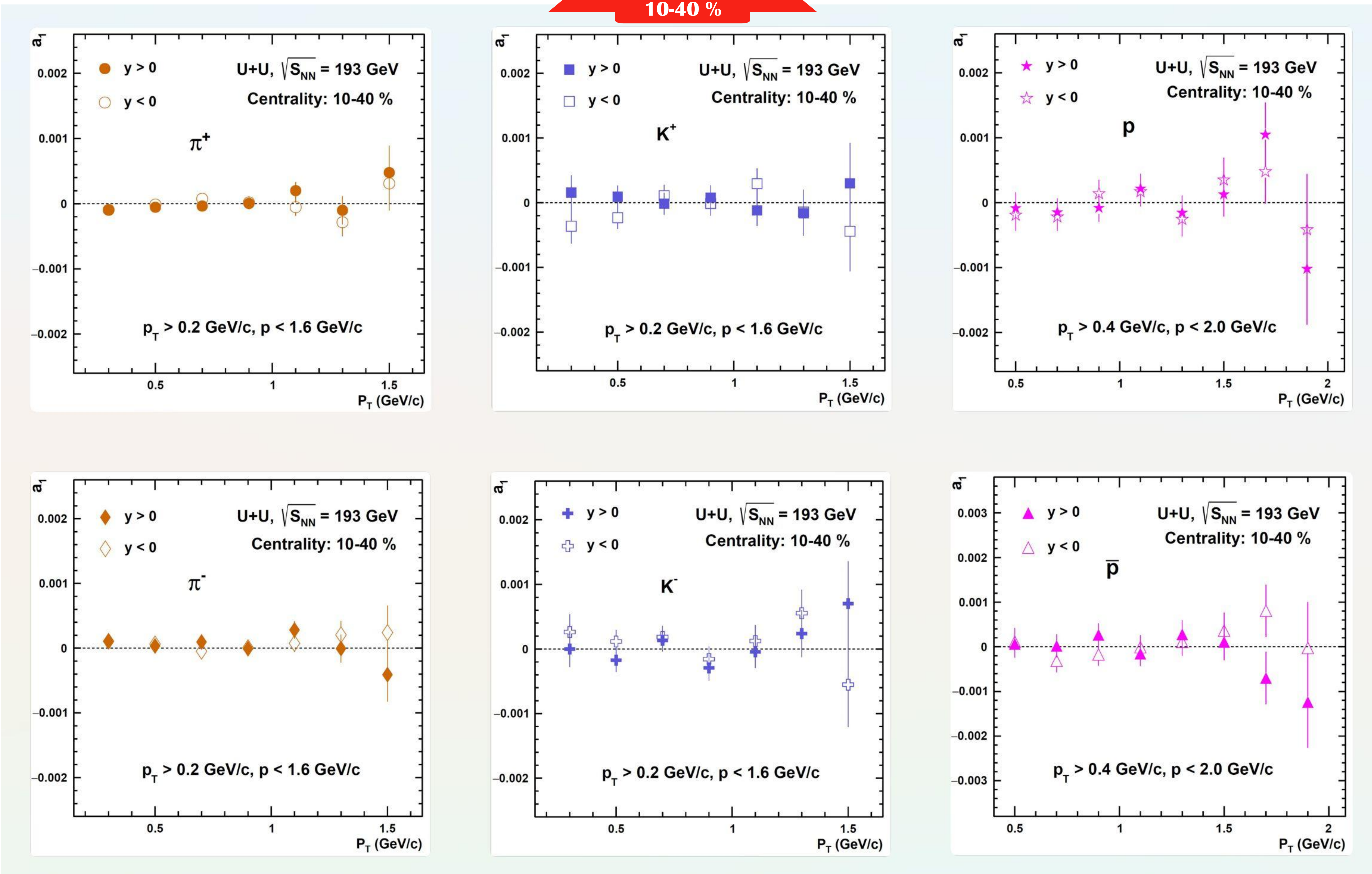
- ✓ **Simulated Au+Au hydro with net baryon same as Ru+Ru at a fixed <N_{part}> but all other parameters kept as default (e.g. entropy deposition is different)**
- ✓ **proton Δv_1 shows no system size dependence with enforced same net baryon, especially in central collisions**

- 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)

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

Mid Central 10-40 %



❖ $a_1 = \langle\sin(\phi - \Psi)\rangle$ versus p_T:

➢ For mid-central collisions → $a_1 (p_T) \sim 0.0$

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.

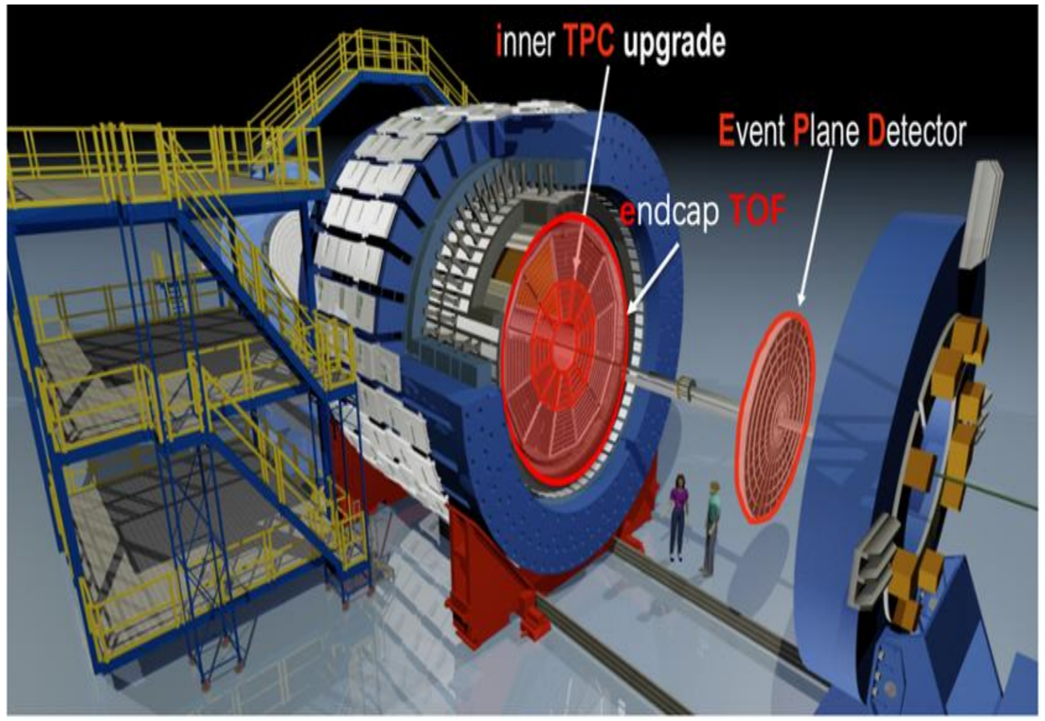
$$v_1 = \frac{\langle \cos(\phi - \Psi_1^{EP}) \rangle}{R_1}$$

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

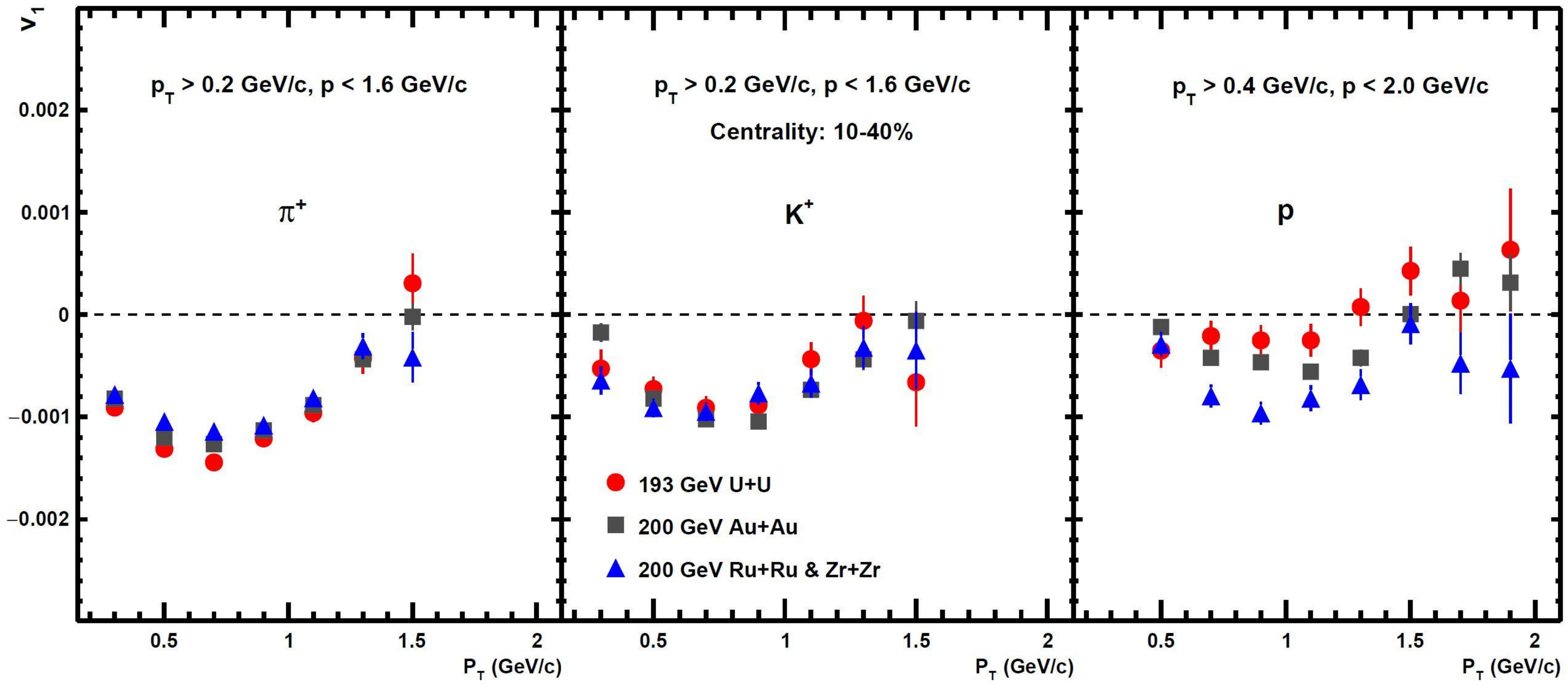
STAR detector



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

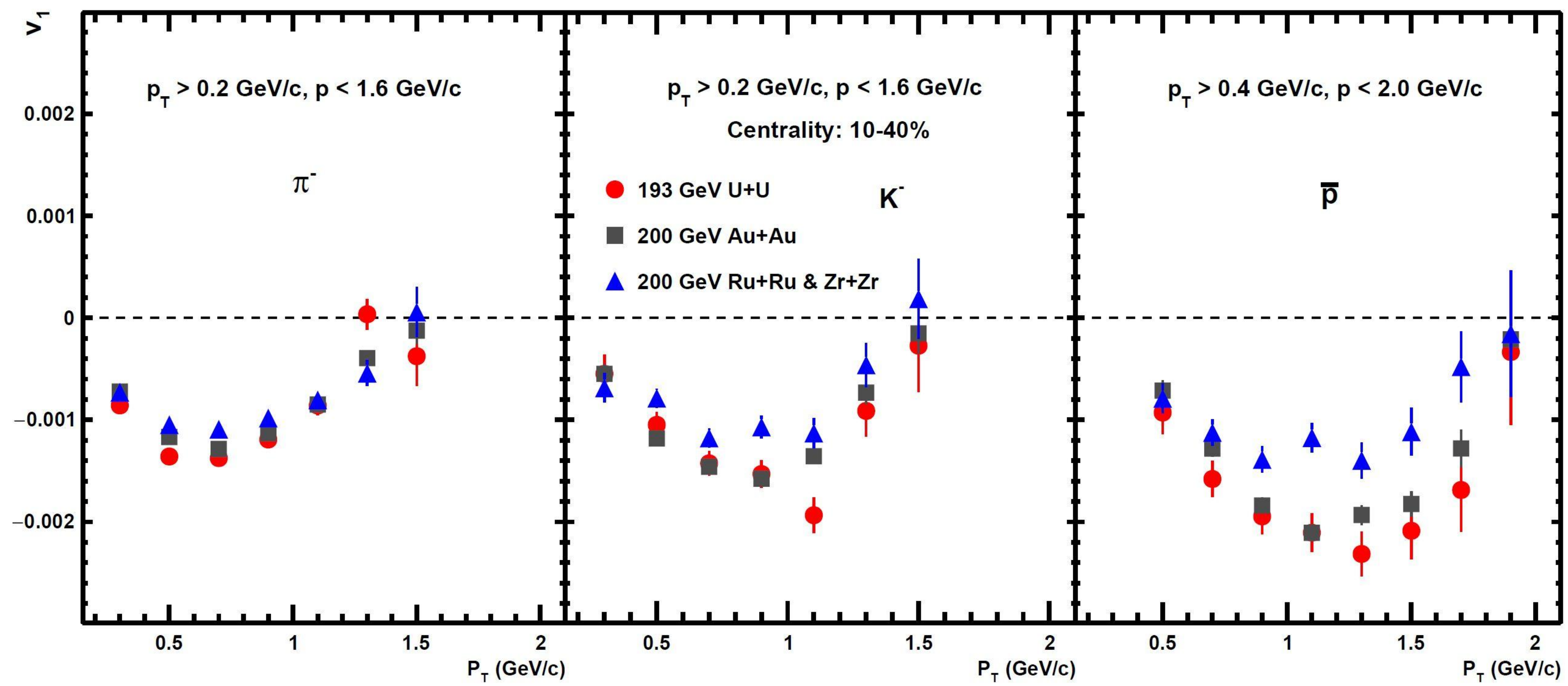
$v_1(p_T)$ for U+U, Au+Au and Isobar Collisions

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



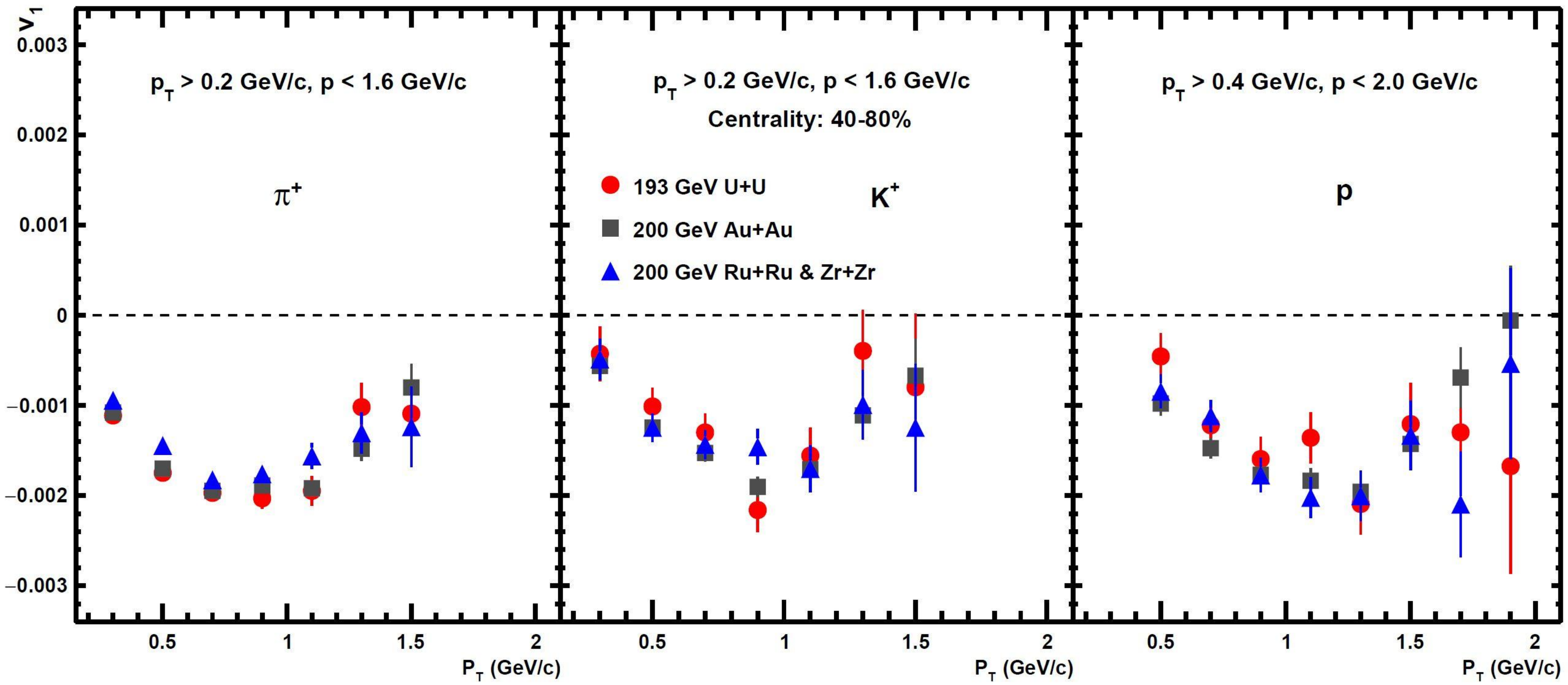
Negative Particles

- ❖ 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 %

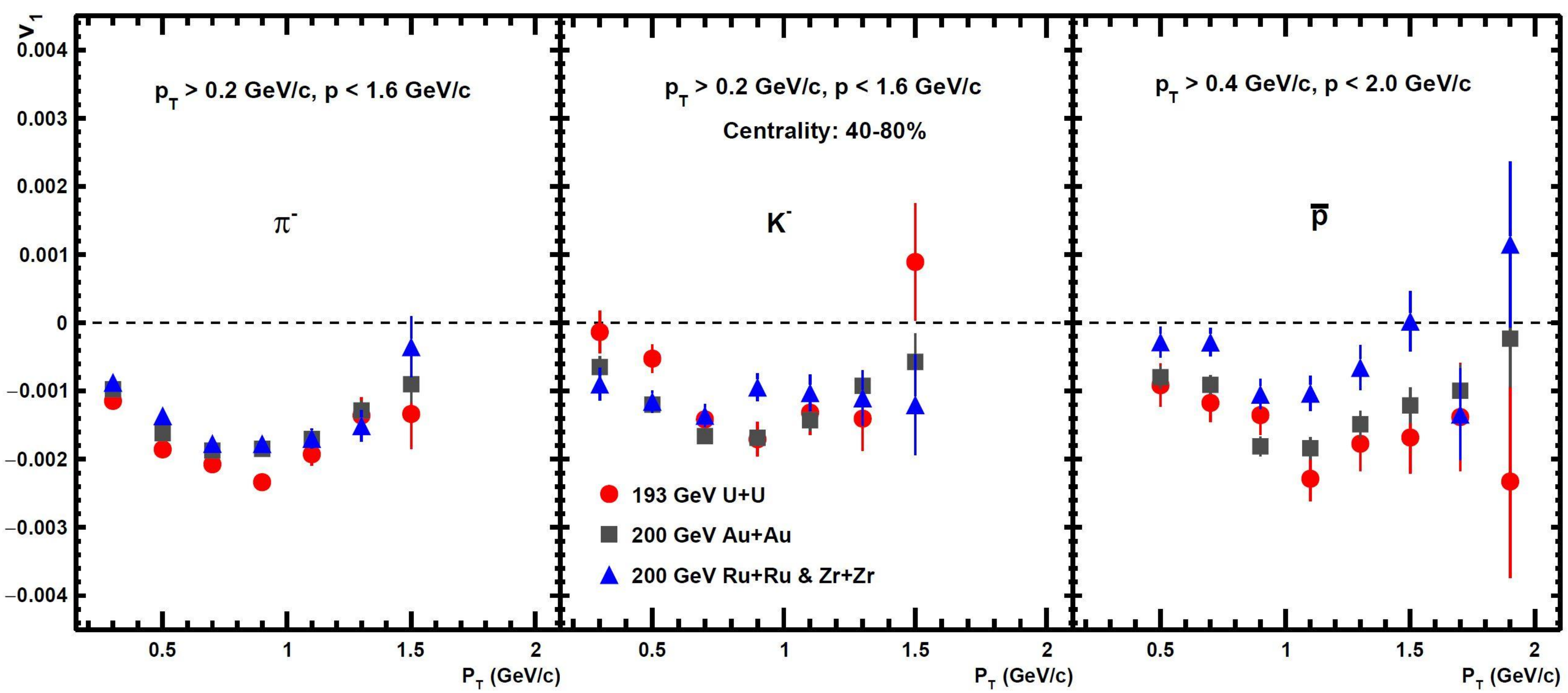
Positive Particles



❖ dv_1/dy:

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

Negative Particles

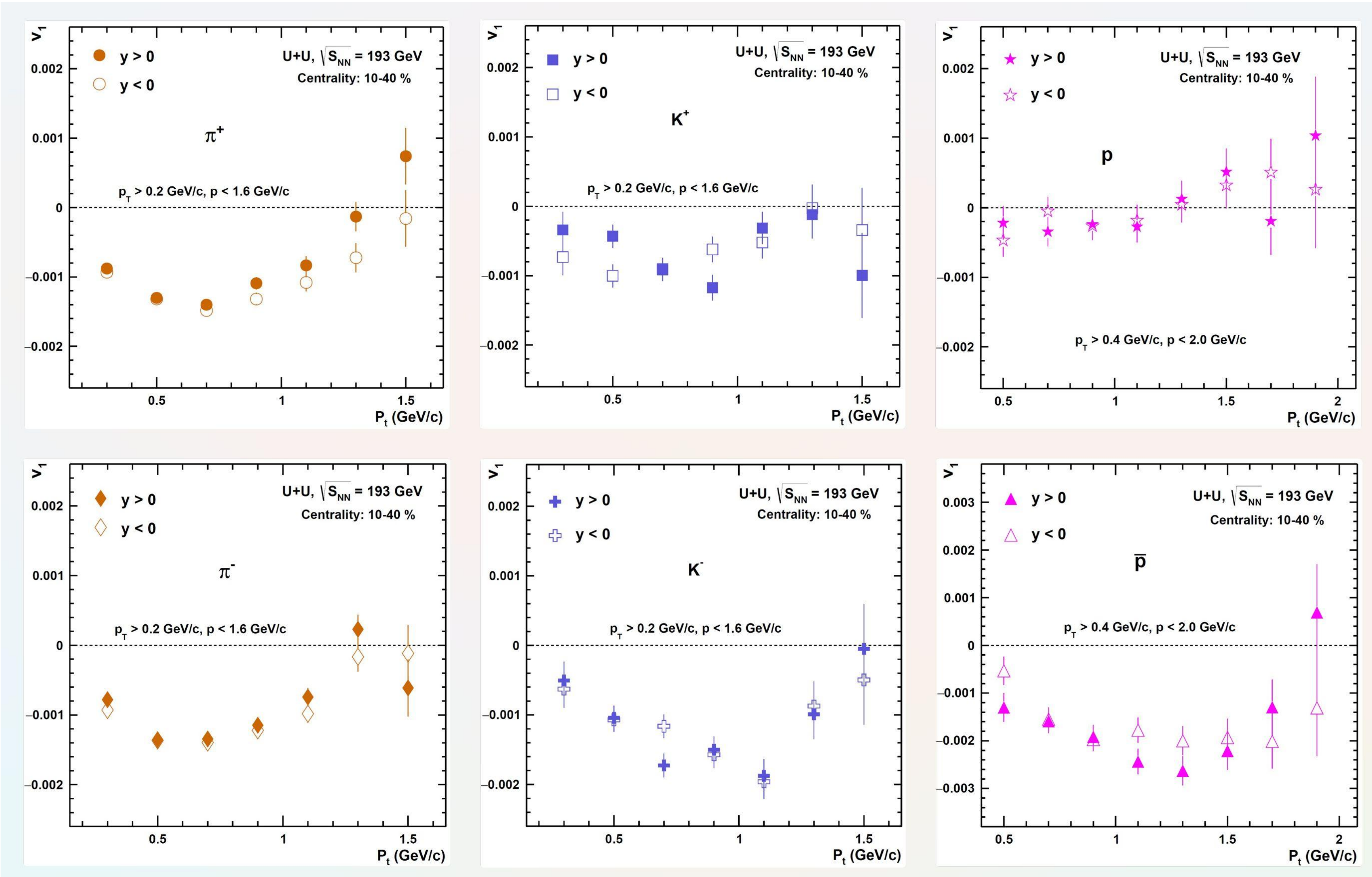


❖ dv_1/dy:

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

- protons → U+U > Au+Au > Isobar

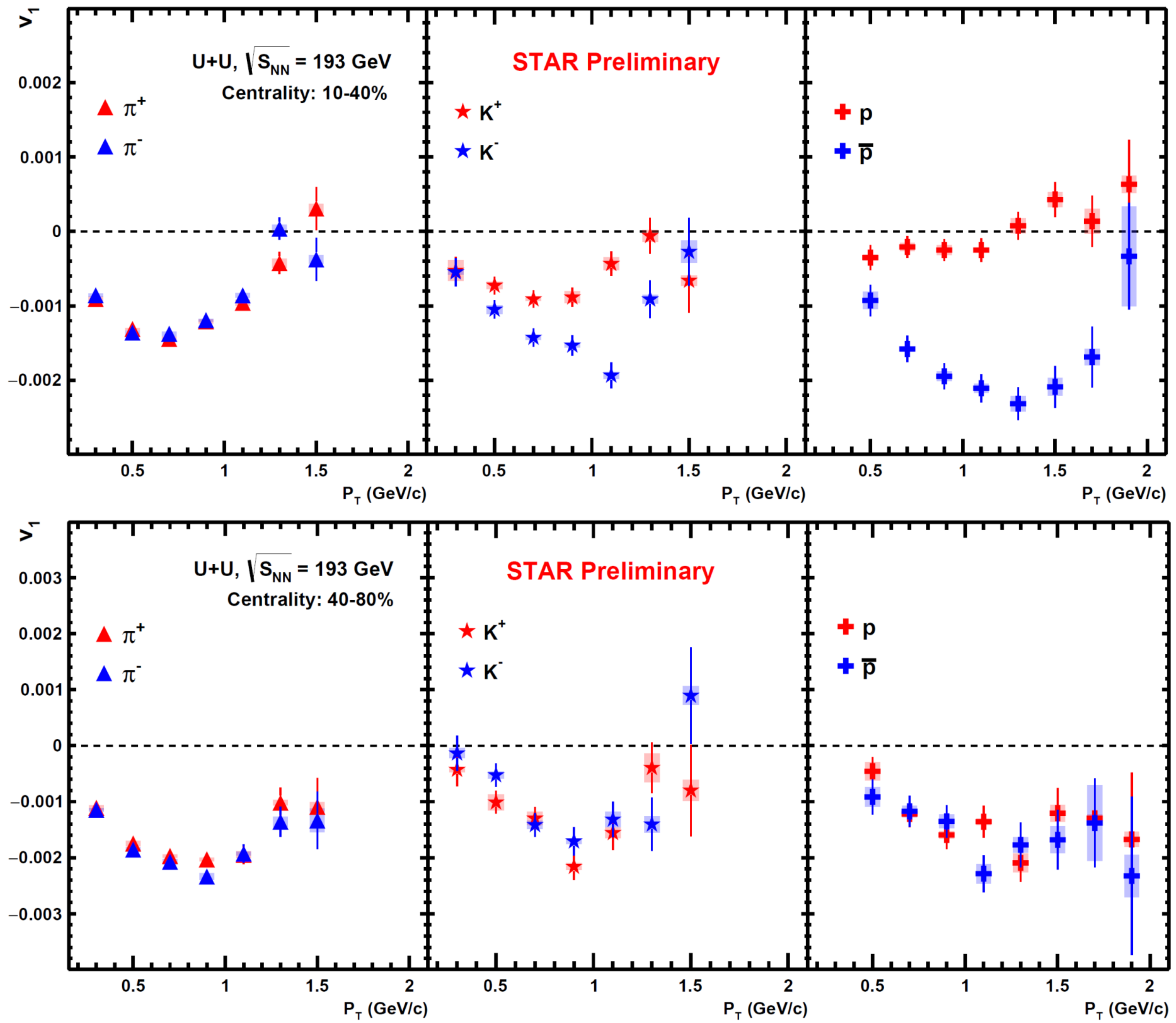
$v_1(p_T)$ for Positive and Negative Rapidity in U+U Collisions



$v_1(p_T)$ for U+U Collisions

Mid Central 10-40 %

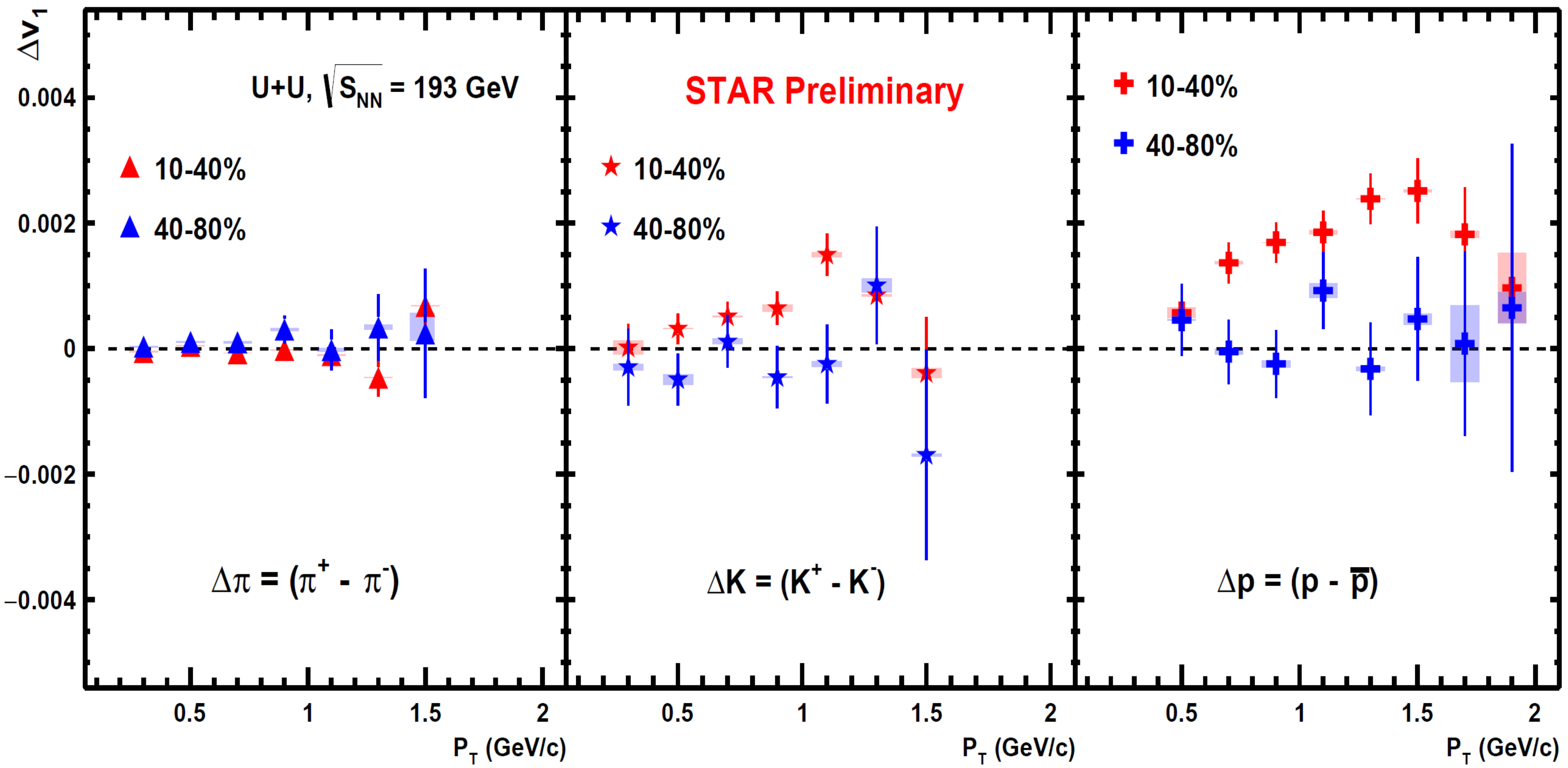
Peripheral 40-80 %



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

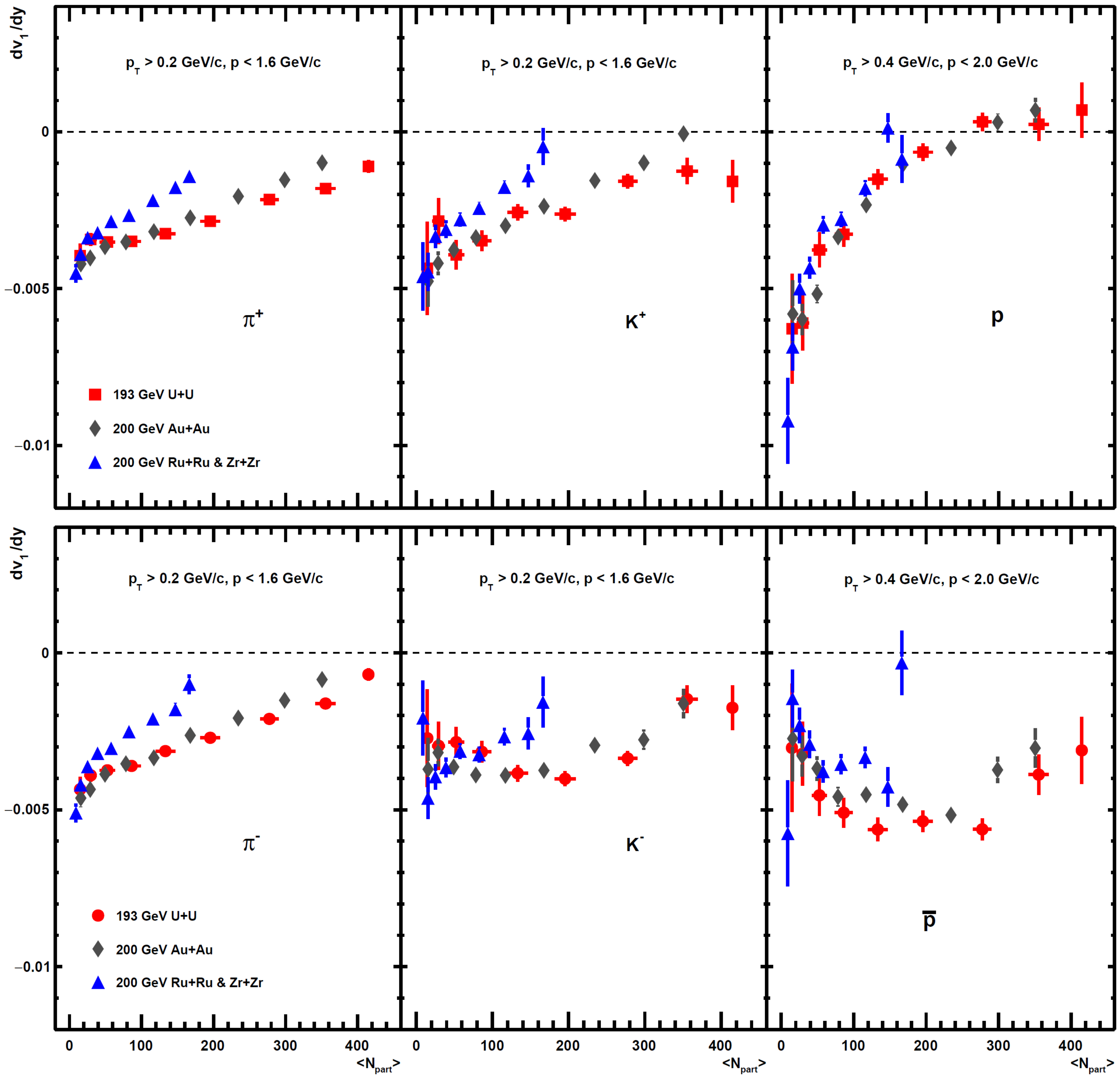
$\Delta v_1(p_T)$ for U+U Collisions

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

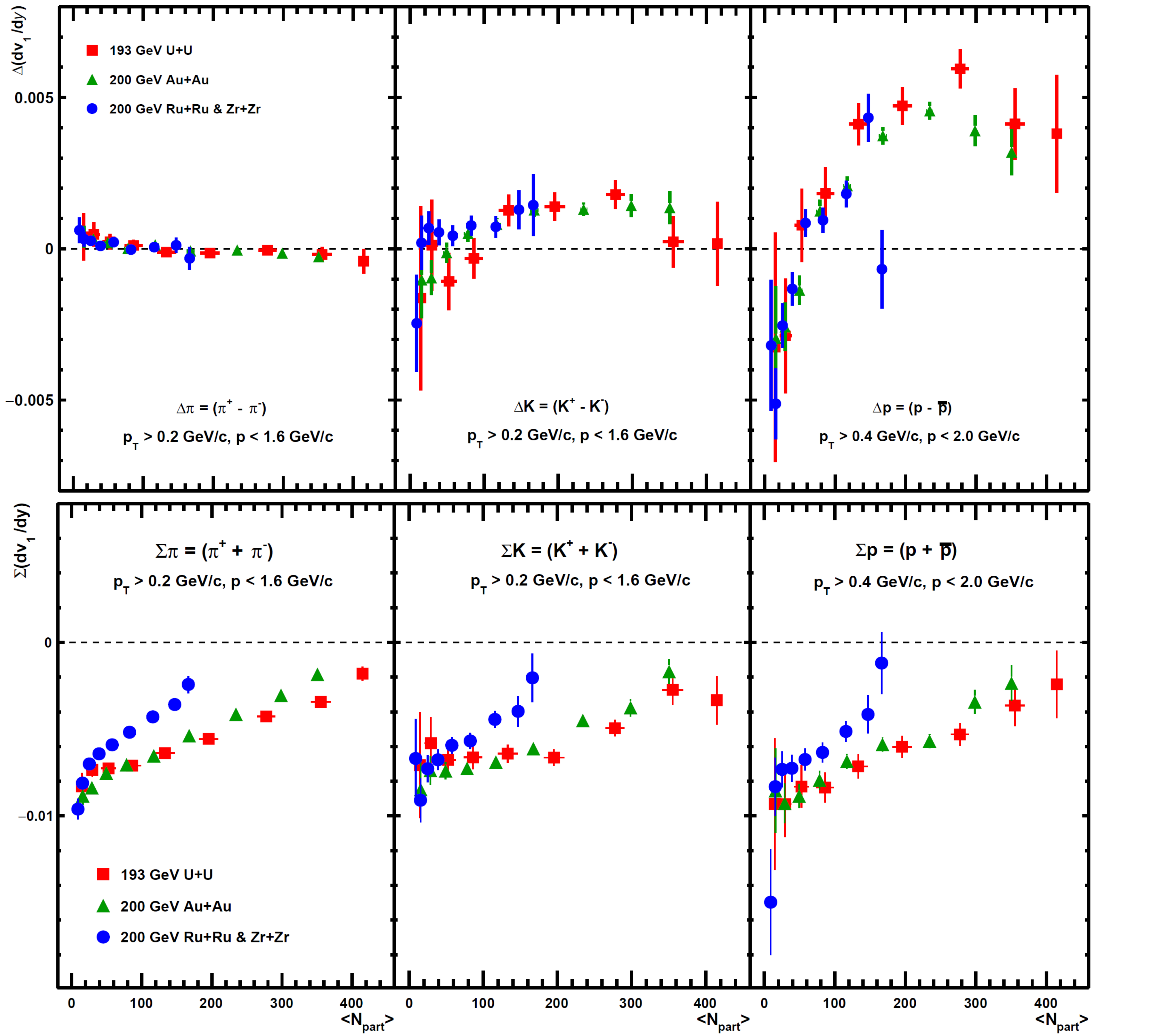


- **Pions (Kaons)** → consistent with zero within uncertainties
- **Protons** → mid-central collisions → Δv_1 keep increasing with p_T
  peripheral collisions → no oblivious p_T dependence

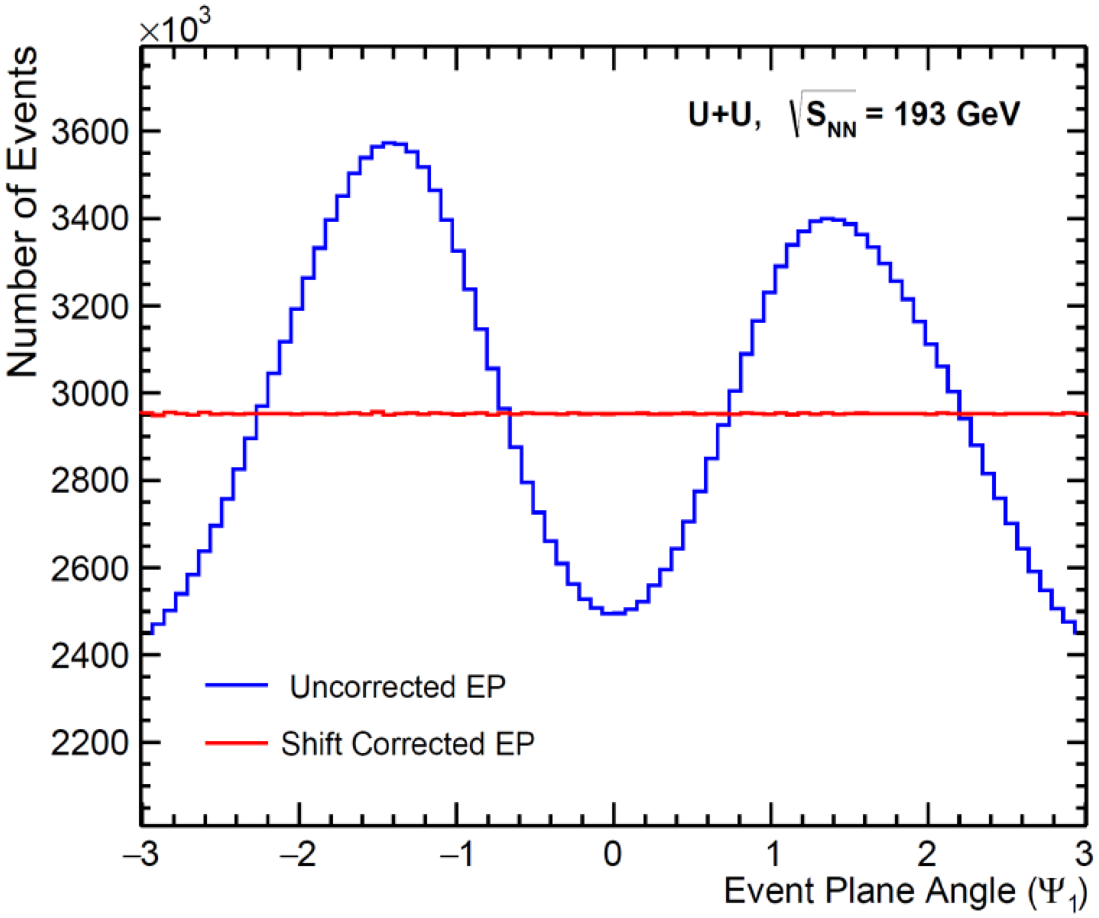
dv_1/dy as a function of < Npart >



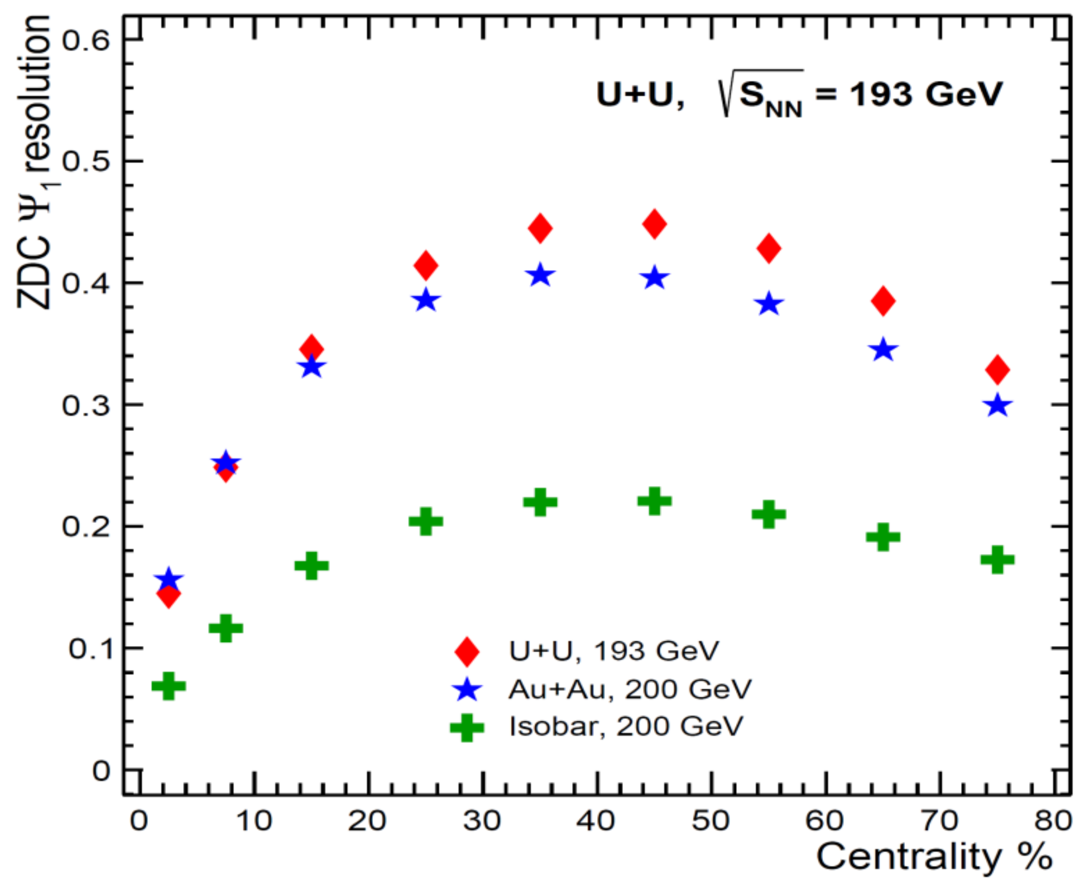
$\Delta(dv_1/dy)$ as a function of < Npart >



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}

Δ(da_1/dy) for Proton