Paper proposal

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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- **Target journal:** Phys. Rev. Lett.
- **PA List:** Jinhui Chen, Aditya Prasad Dash, Huan Huang, Hao Qiu, Diyu Shen, Subhash Singha, Aihong Tang, Muhammad Farhan Taseer and Gang Wang

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:** in preparation
- **Analysis note:** in preparation
- **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

- **Talks in international meetings:**
  - ✓ 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)

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

- **SQM Proceedings:**
  - ✓ https://drupal.star.bnl.gov/STAR/presentations/SQM-2024/Measurement-charge-dependent-directed-flow-STAR-Beam-Energy-Scan-BES-II-AuA-2

Physics Motivation

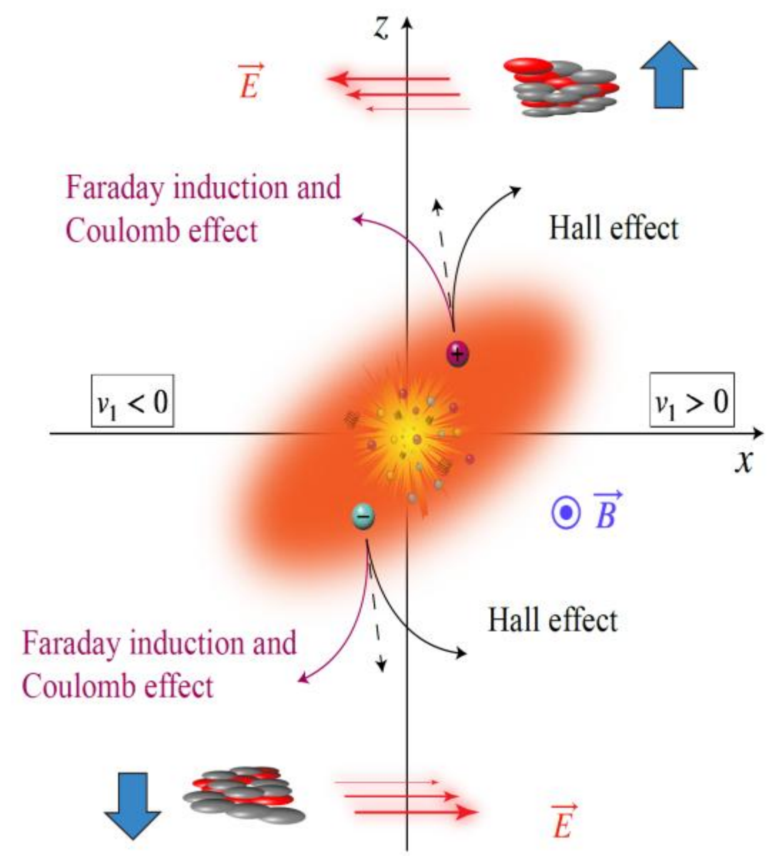
Directed Flow (v_1) describes the collective sideward motion of the produced particles and nuclear fragments → carries information from the early stages of collision

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

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



PRX 14, 011028 [STAR]

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

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

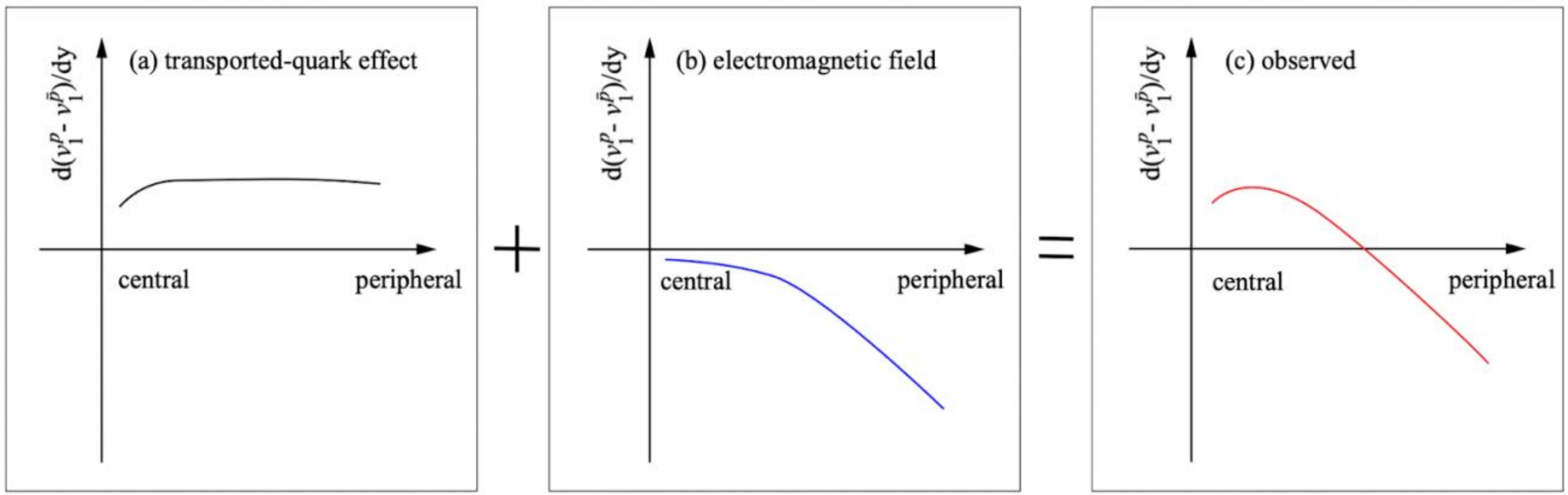
→ **Directed Flow (v_1)**

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

Electromagnetic Field Effects on v_1

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

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



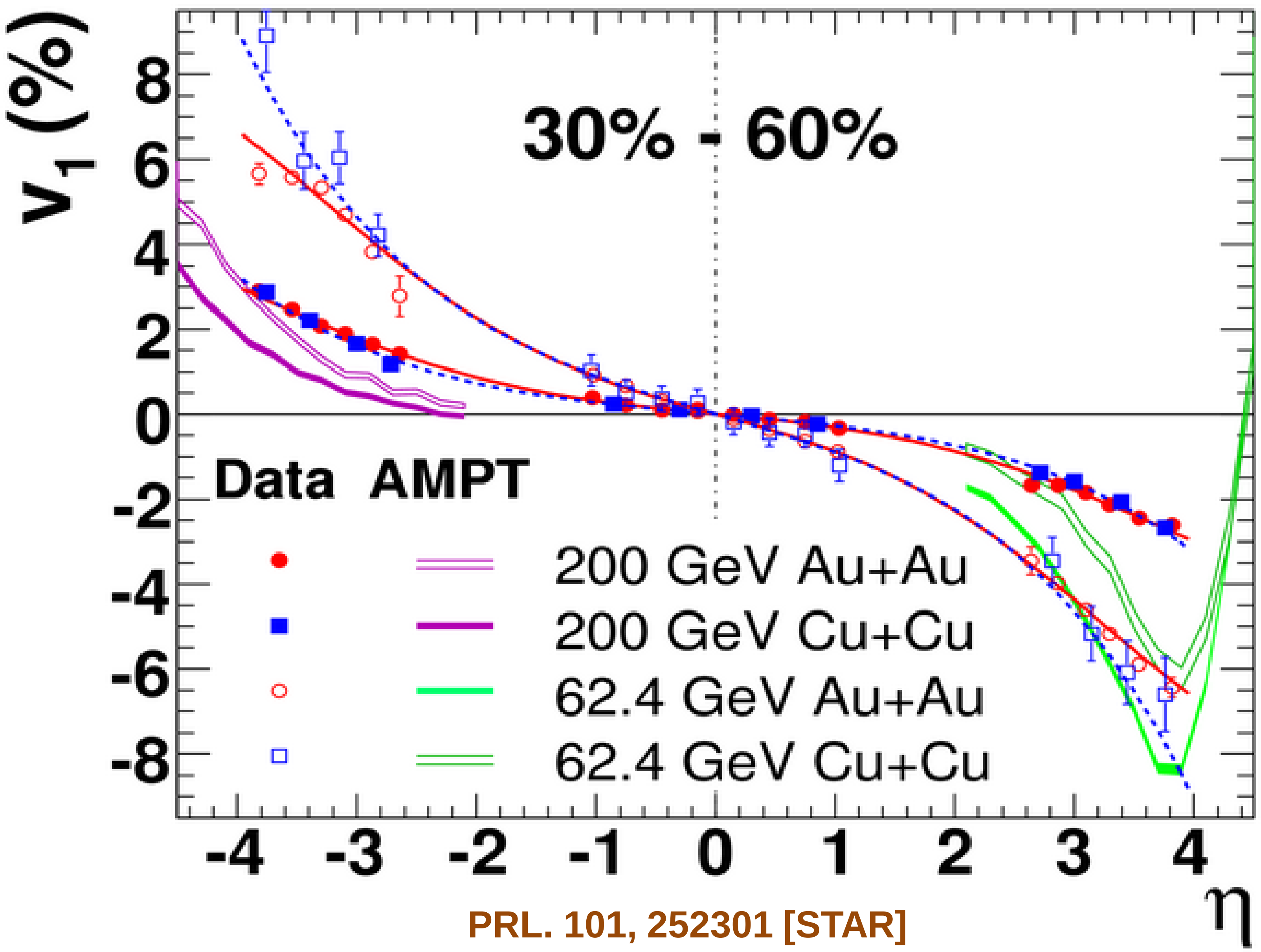
Transported Quark → Positive Δv_1
(Based on UrQMD)

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
- However, transport model (e.g. UrQMD) predicts a system size dependent v_1
- We shall present v_1 and Δv_1 in U+U, Au+Au and Isobar (RuRu + ZrZr)

Dataset and analysis details

Collision System: (U+U) New

Collision Energy	Production id	Run Numbers	Trigger id	No. of Events (After cut)
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

Analysis Procedure

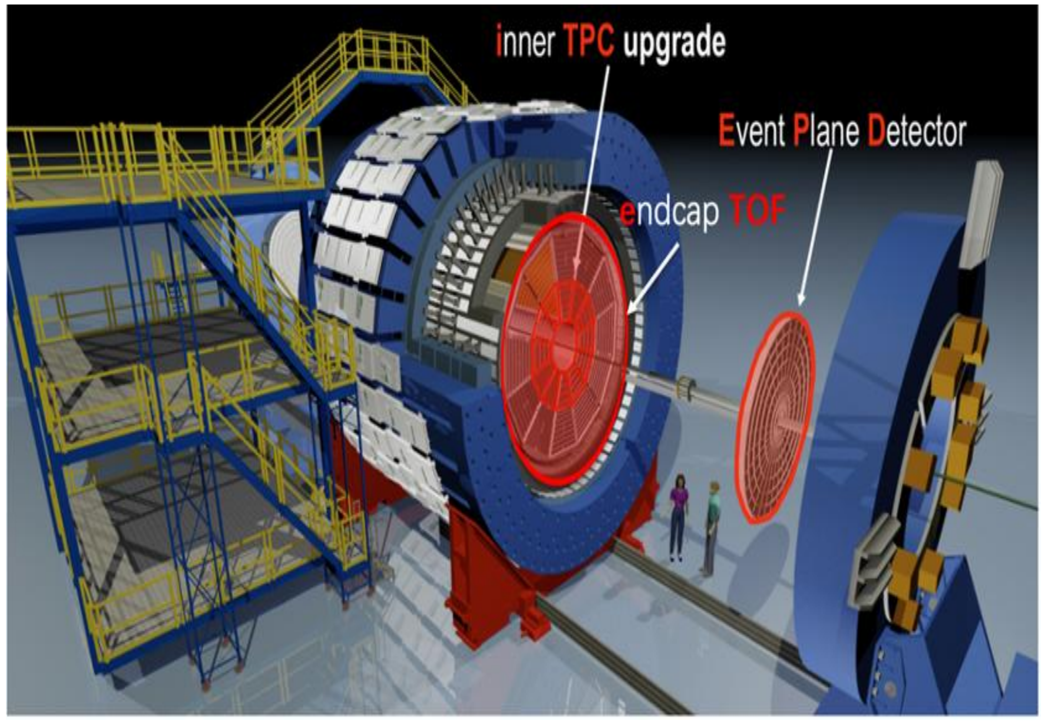
- For this analysis, v_1 is computed using **Event Plane Method** in which we estimate the reaction plane, called the event plane, from the observed event plane angle determined from the anisotropic flow itself.

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

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

STAR detector



- **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

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

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:**

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

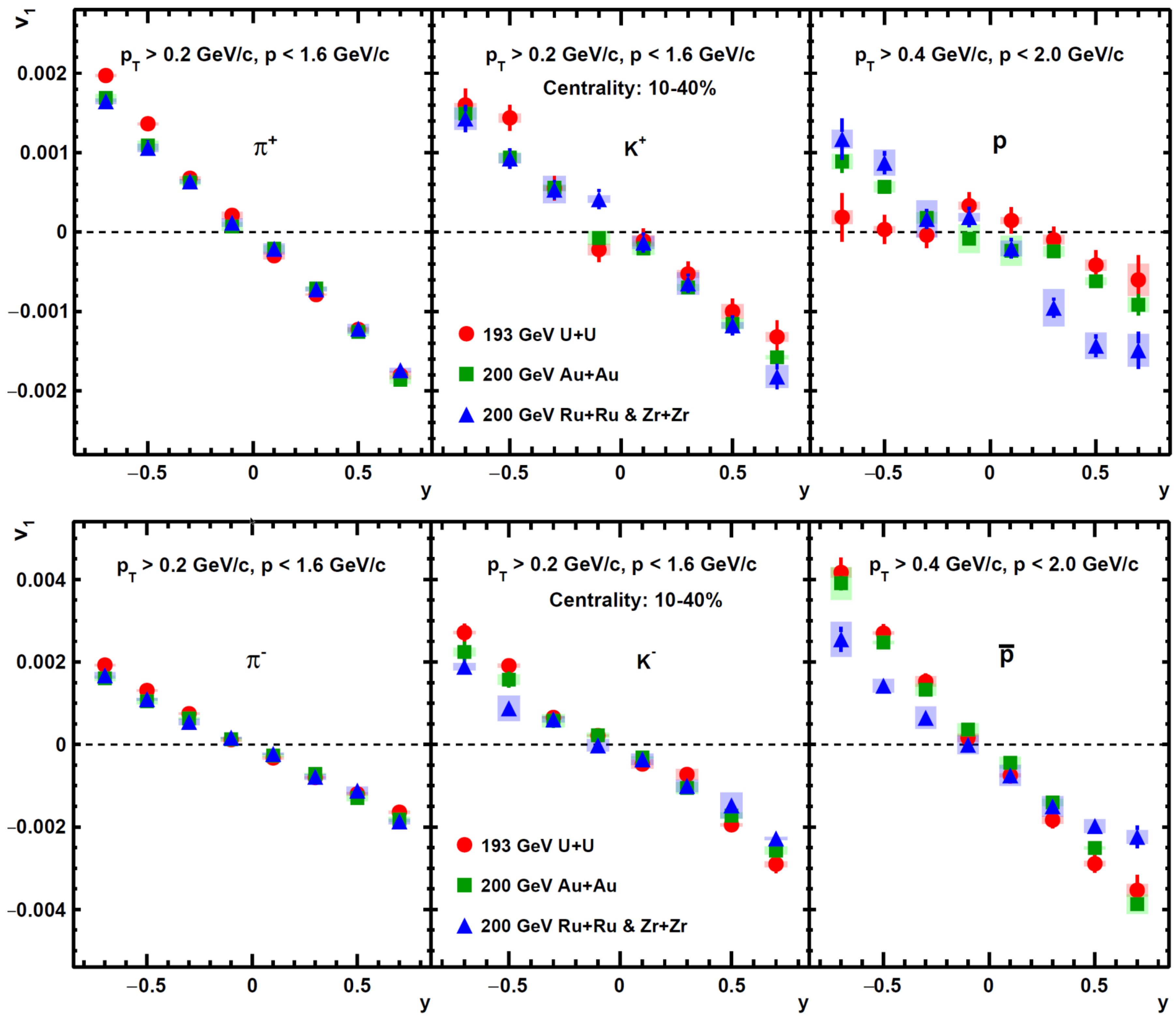
Where,
Y_i = variation result
Y_d = default result
σ = final systematic uncertainty

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 inclusive particles, particularly mesons ($\pi^{\pm}$ and $K^{\pm}$), show no dependence on system size, consistent with previous findings at RHIC [1]. The $\Delta(dv_1/dy)$ pattern for protons is primarily influenced by baryon transport and electromagnetic fields. In the most central collisions, where the electromagnetic field is minimal, baryon transport can be assessed more clearly. A hydrodynamic model with an inhomogeneous baryonic profile qualitatively captures the observed system size dependence, offering insights into baryon deposition and the transport properties of the QCD medium. Additionally, in mid-central and peripheral collisions, these data can provide insights into the strength of electromagnetic fields and the conductivities of the medium [2].

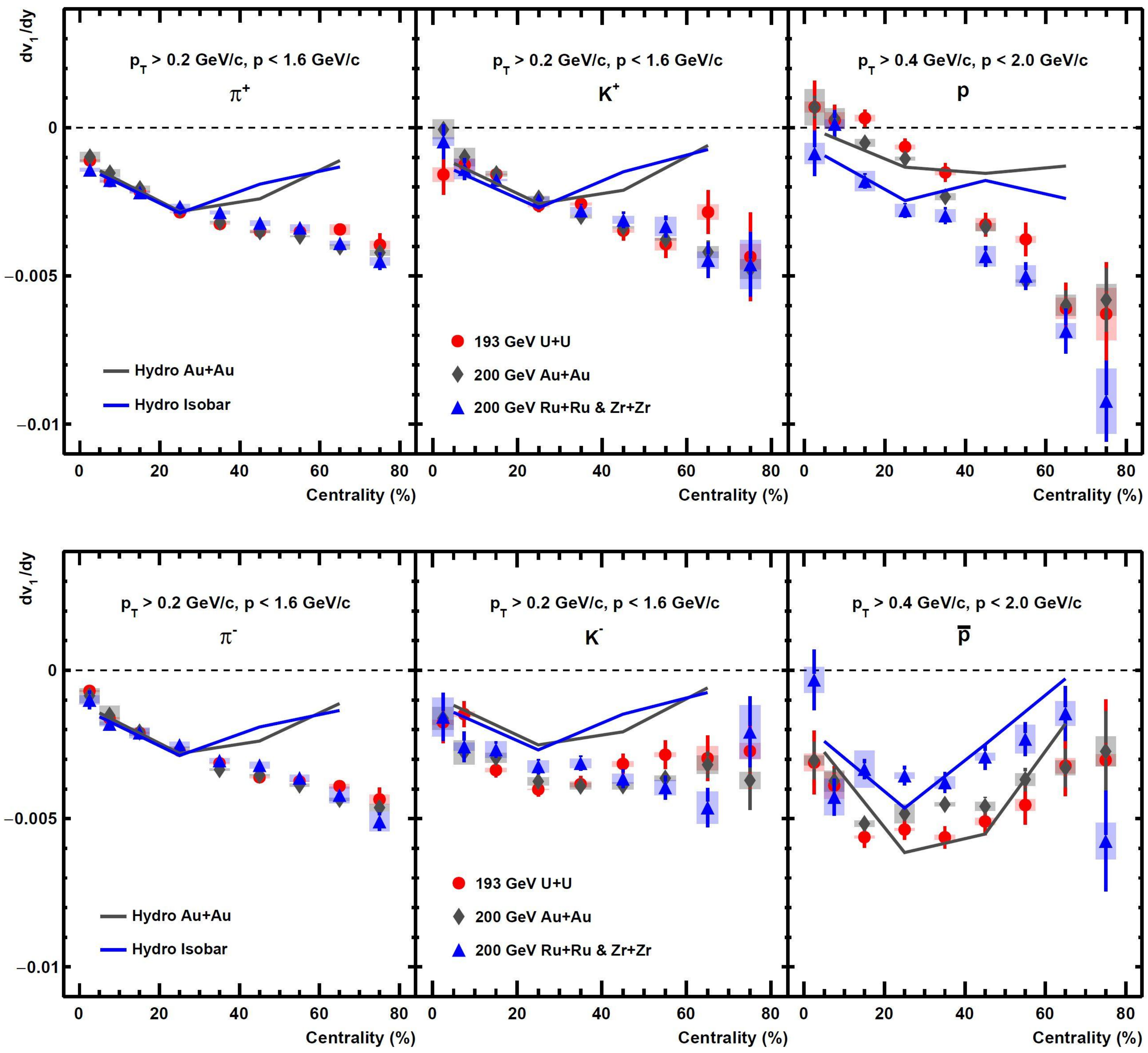
[1]. STAR Collaboration, Phys. Rev. Lett. 101, 252301
[2]. STAR Collaboration, Phys. Rev. X 14, 011028

Figure 1



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

Figure 2



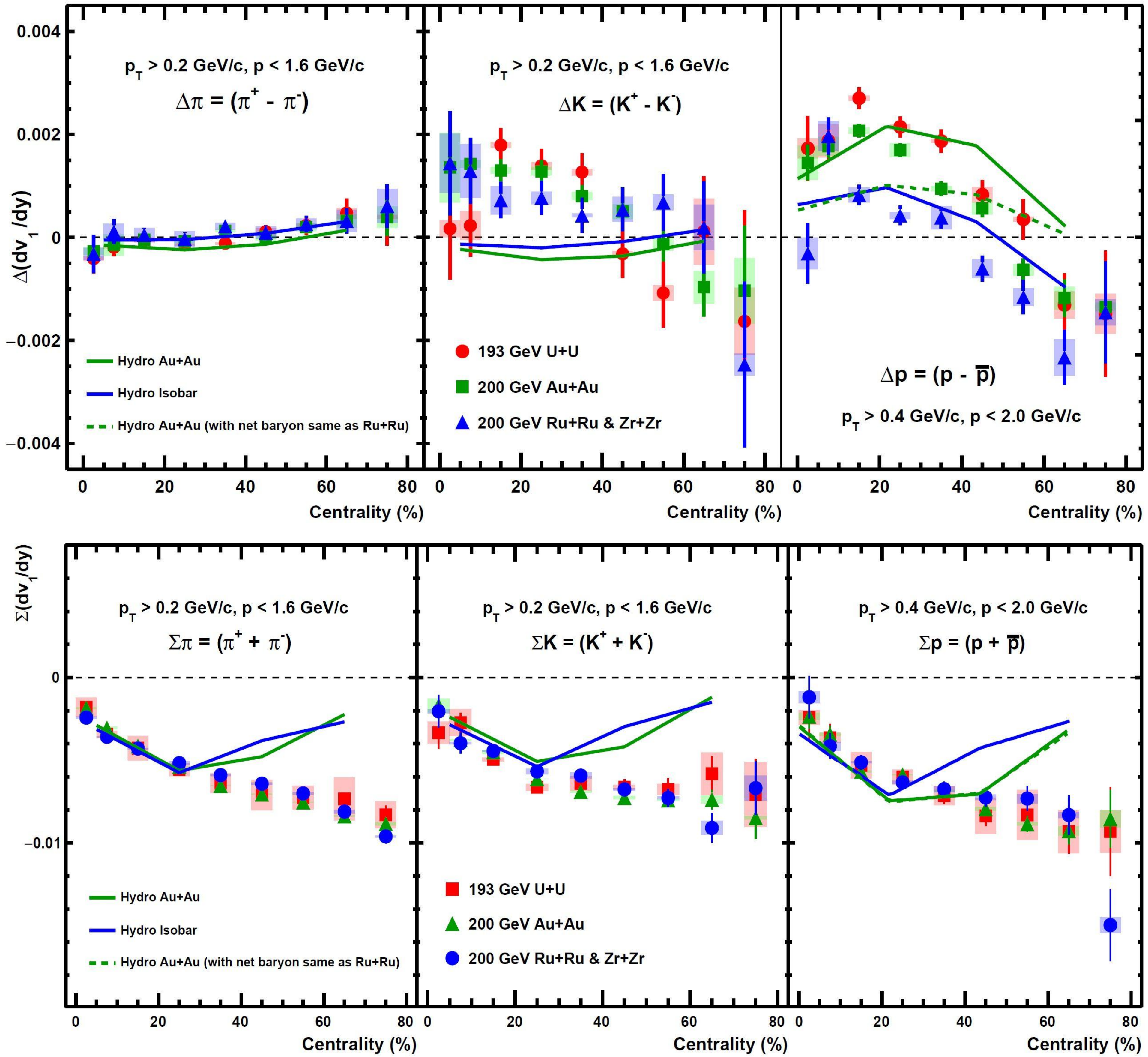
dv_1/dy:

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

- protons → Isobar > Au+Au > U+U
- anti-protons → U+U > Au+Au > Isobar

✓ **Hydro-model with inhomogeneous baryon deposition can qualitatively capture the system size dependence of proton and antiproton data**

Figure 3



❖ $\Delta dv_1/dy$:

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

❖ $\Sigma dv_1/dy$:

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

- **Hydro-model with inhomogeneous baryon distribution can qualitatively capture the system size dependence in $\Delta dv_1/dy$ of protons**

✓ **Hydro model special case (dashed green line): Hydro Au+Au (with net baryon same as Ru+Ru)**

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

Discussion

B. Hydrodynamics at finite baryon density

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

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

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

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

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

and

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

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

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

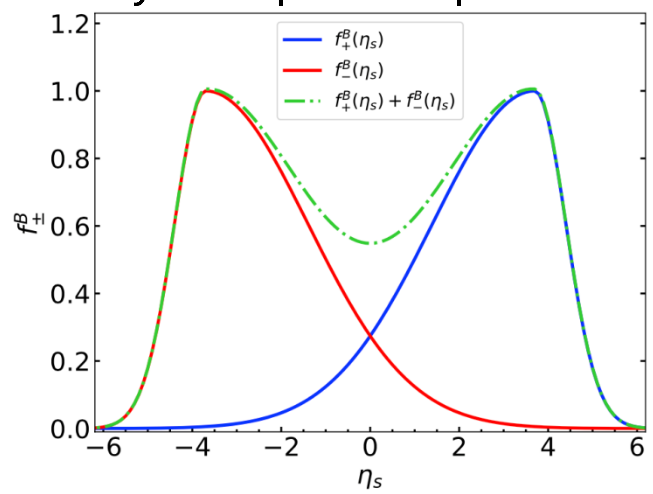
κ_B: Baryon diffusion coefficient constant;

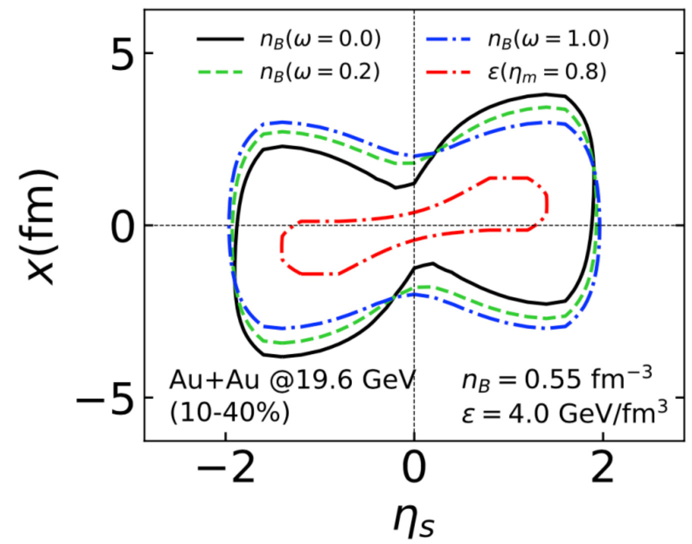
In hydro model amount of baryon diffusion is varied by tuning the prefactor C_B

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

Hydro model with inhomogeneous baryon deposition:

Baryon deposition profile:





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

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

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

Normalisation

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

- However, in pure EM field expectation:
- Faraday + Coulomb → negative Δv_1
- Hall → positive Δv_1

- The hydro-model do not rule out EM-field scenario
- Need further model prediction (baryon transport + EM) to better understand underlying physics mechanisms

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

Summary

- We observed a system size dependent v_1 and $\Delta(dv_1/dy)$ for protons (antiprotons) among three different collision systems at similar collision energy

- However, mesons (pions and kaons) as well as total baryons ($p + \bar{p}$) are found to be independent of system size (consistent with previous findings at RHIC)

$(p - \bar{p})\ v_1$: U+U > Au+Au > Isobar
$(p + \bar{p})\ v_1$: U+U ~ Au+Au ~ Isobar

- These results will help understand baryon deposition (such as baryon stopping mechanism) in heavy-ion collisions and provide strong constraint on baryon transport (such as baryon diffusion)
- These results will provide constraint on the strength and lifetime of the electromagnetic field as well as the medium electrical conductivity of the QGP in different collision system sizes

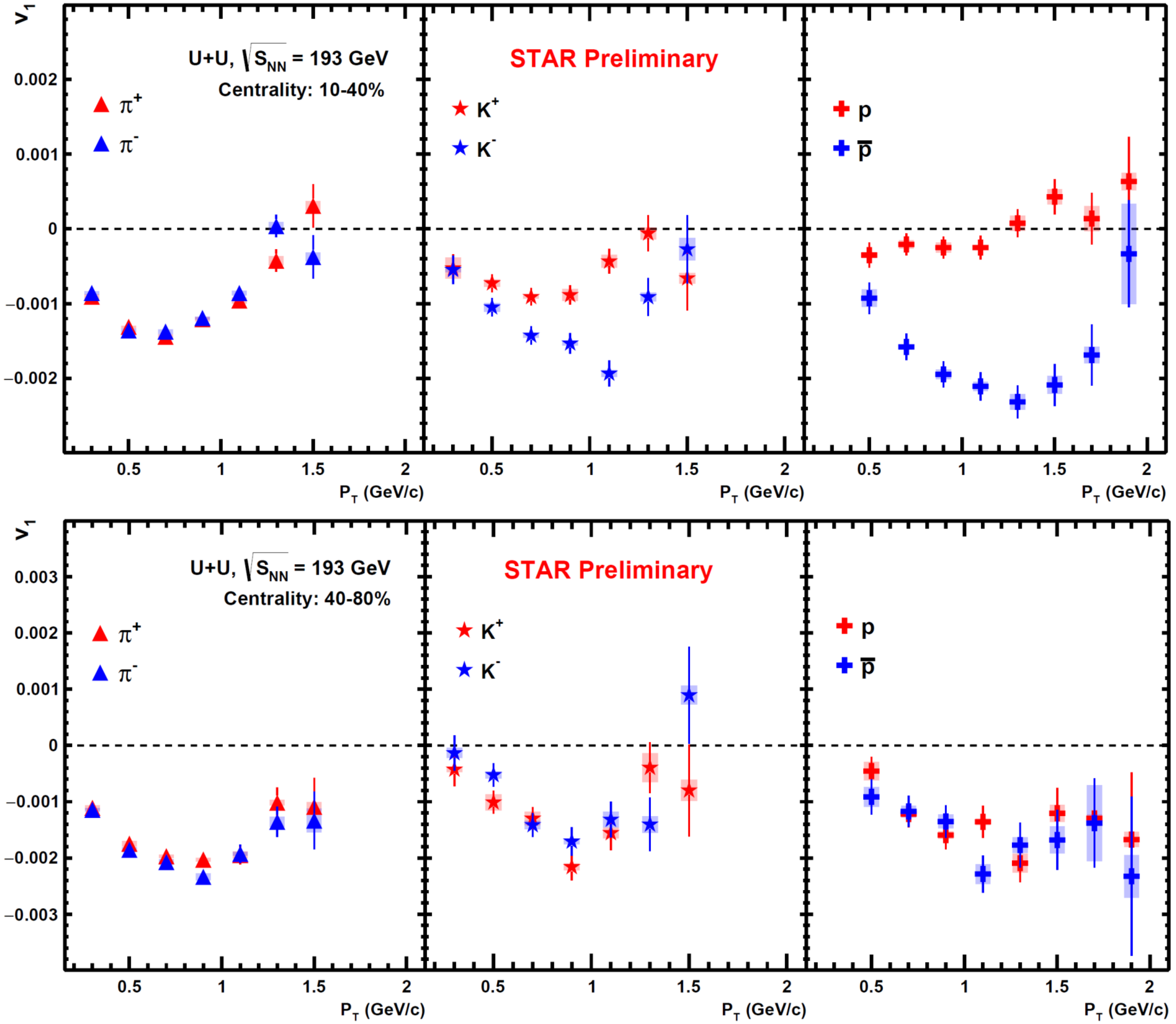
Thank you for your attention!

Backup Slides

$v_1(p_T)$ for U+U Collisions

Mid Central 10-40 %

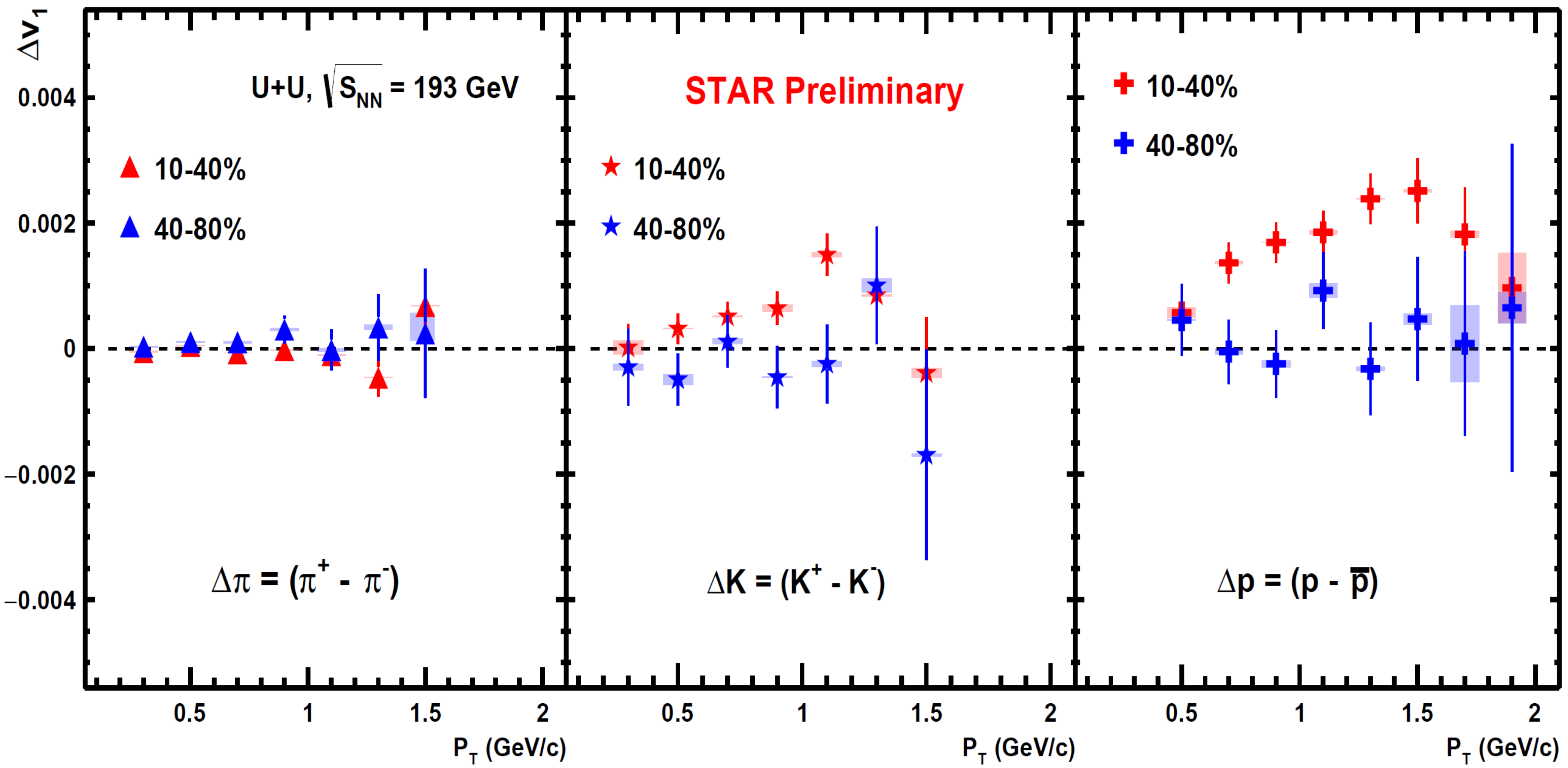
Peripheral 40-80 %



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

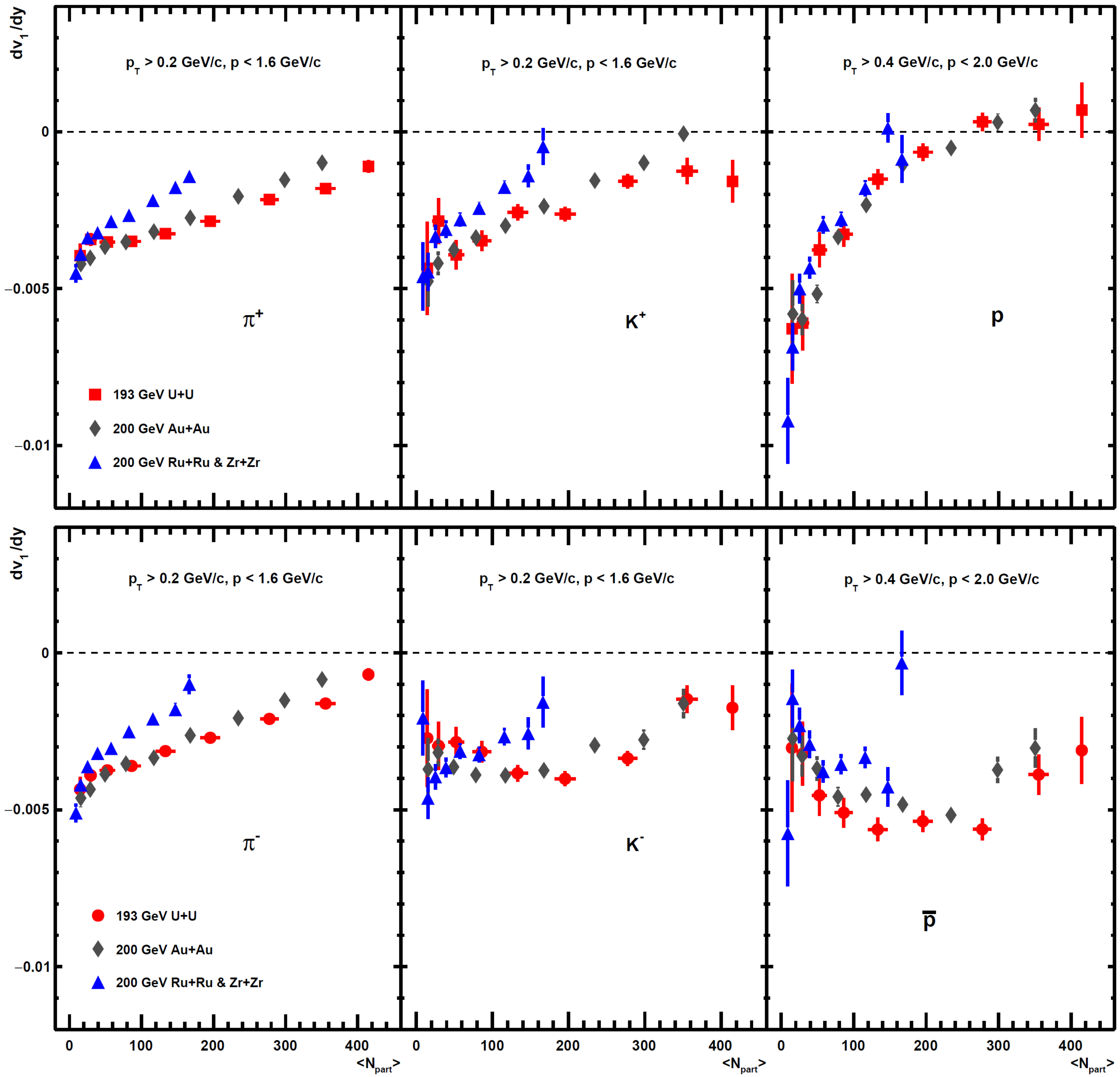
$\Delta v_1(p_T)$ for U+U Collisions

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

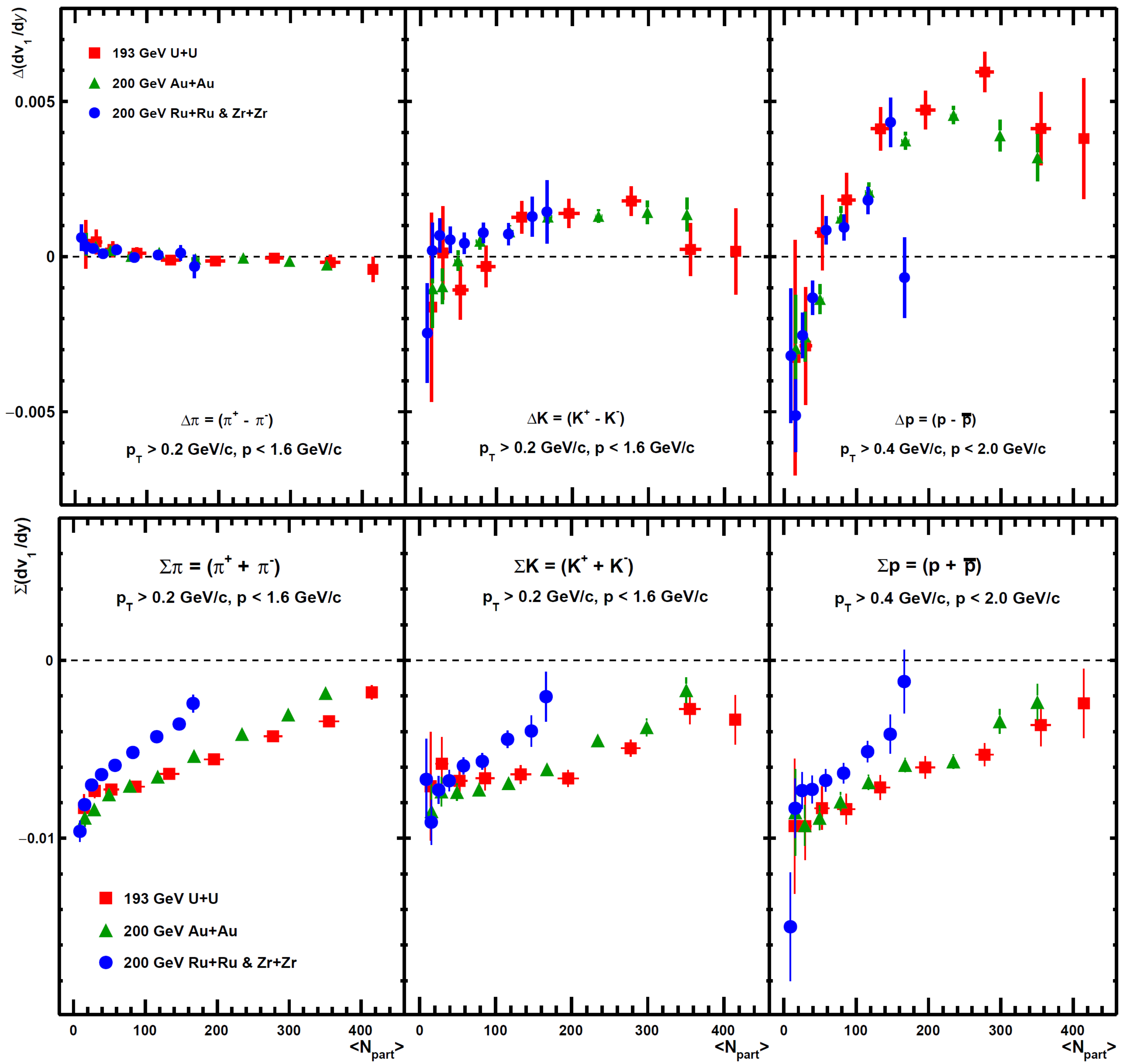


- **Pions (Kaons)** → consistent with zero within uncertainties
- **Protons** → mid-central collisions → Δv_1 keep increasing with p_T
  peripheral collisions → no oblivious p_T dependence

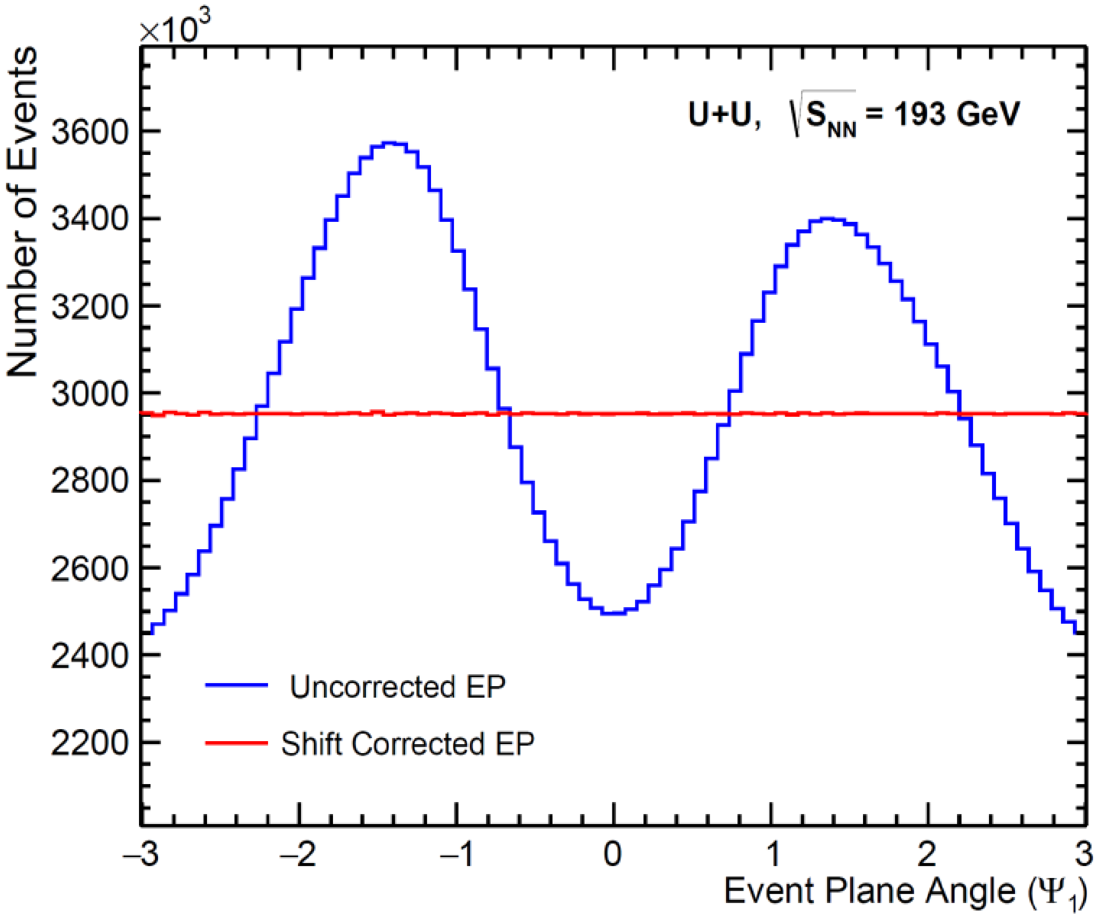
dv_1/dy as a function of < Npart >



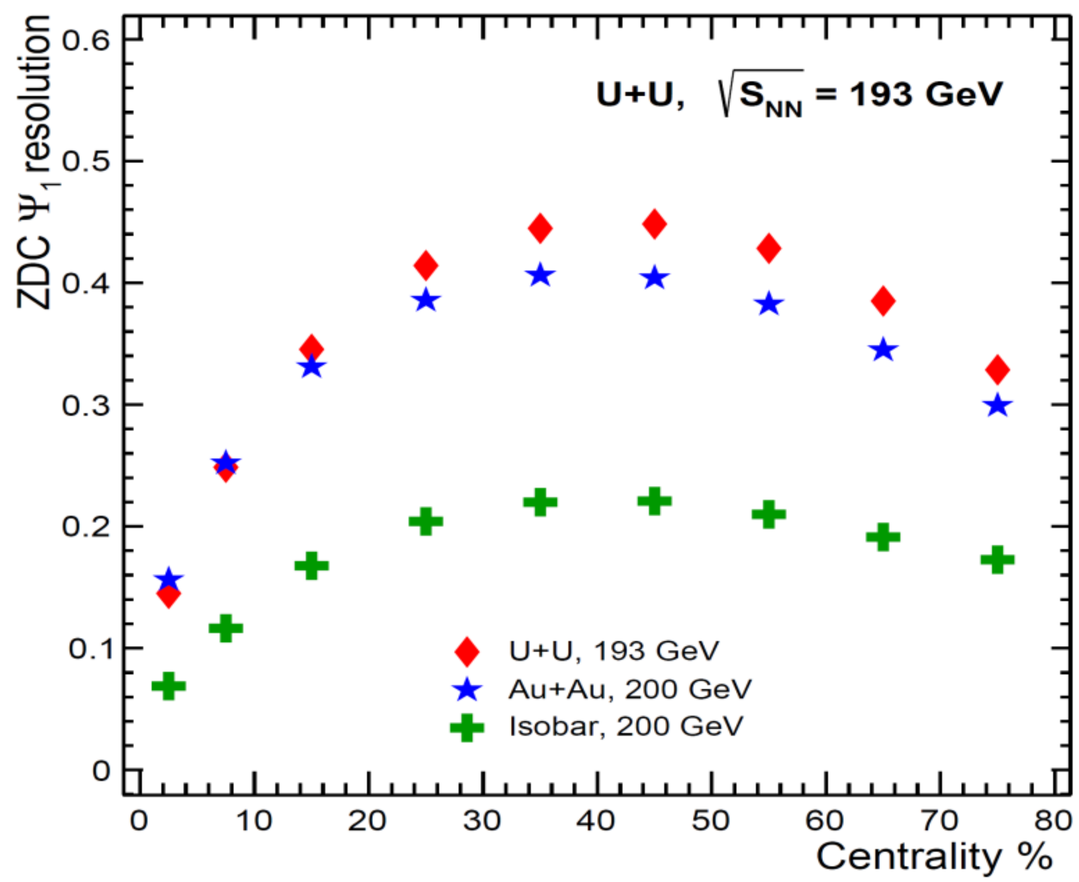
Δ(dv$_1$/dy) as a function of < Npart >



Event Plane & Resolution Plots



Ψ_1 is reconstructed using ZDC



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

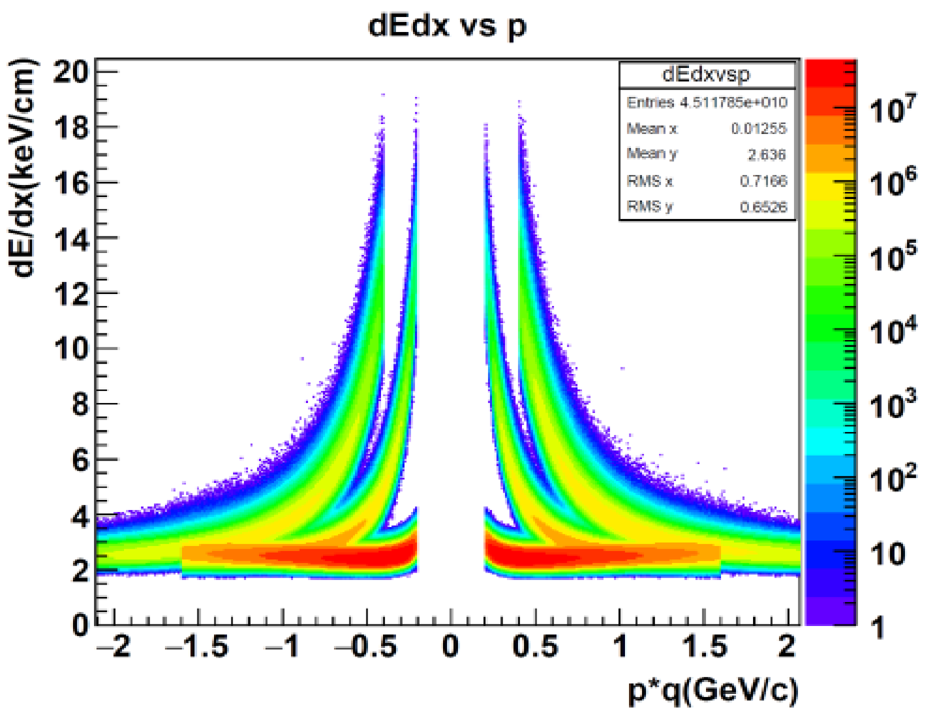
Resolution Values: -

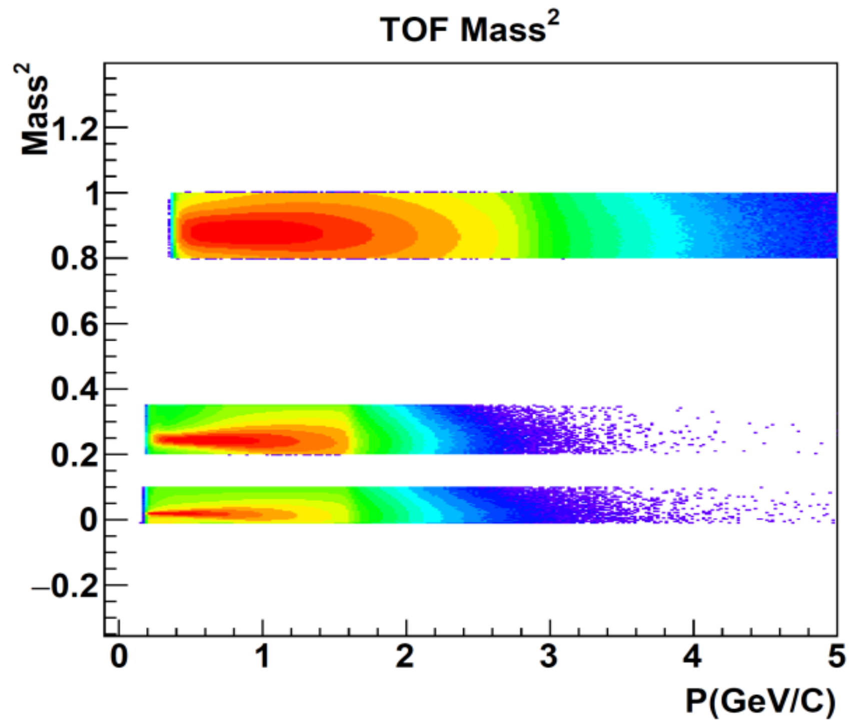
U+U[9] = {0.145016, 0.248548, 0.345383, 0.414196, 0.444727, 0.448302, 0.428285, 0.385058, 0.328569}

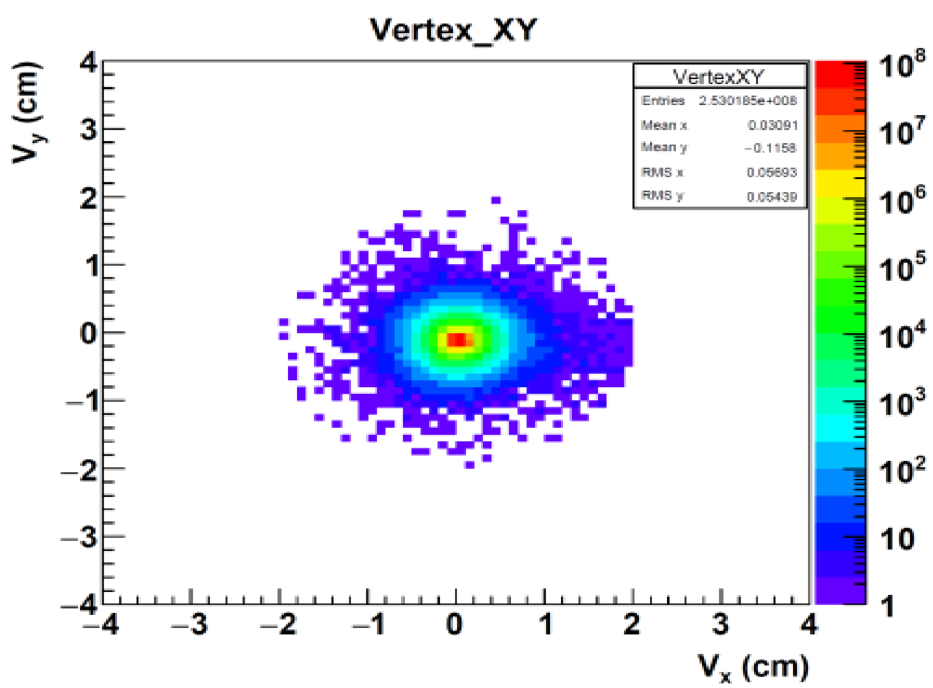
Au+Au[9] = {0.1563, 0.252126, 0.331136, 0.385756, 0.406247, 0.404069, 0.382588, 0.344916, 0.299311}

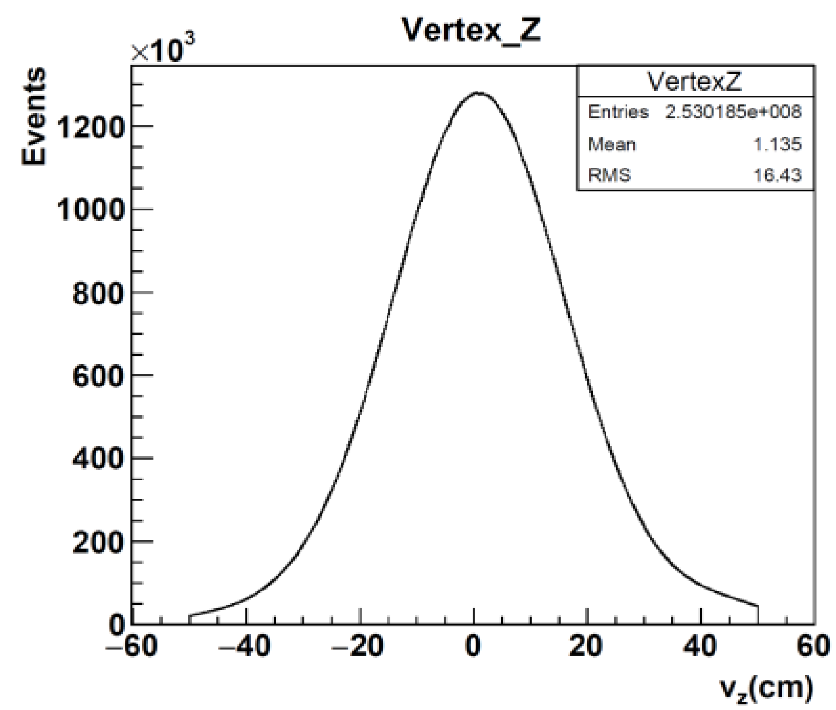
Isobar[9] = {0.0688674, 0.11634, 0.167703, 0.204098, 0.21988, 0.220753, 0.20985, 0.191277, 0.1727}

QA Plots


dEdx vs p
dEdxvsp
Entries 4.511785e+010
Mean x 0.01255
Mean y 2.636
RMS x 0.7166
RMS y 0.6526
dE/dx(keV/cm)
p*q(GeV/c)


TOF Mass^2
Mass^2
P(GeV/C)

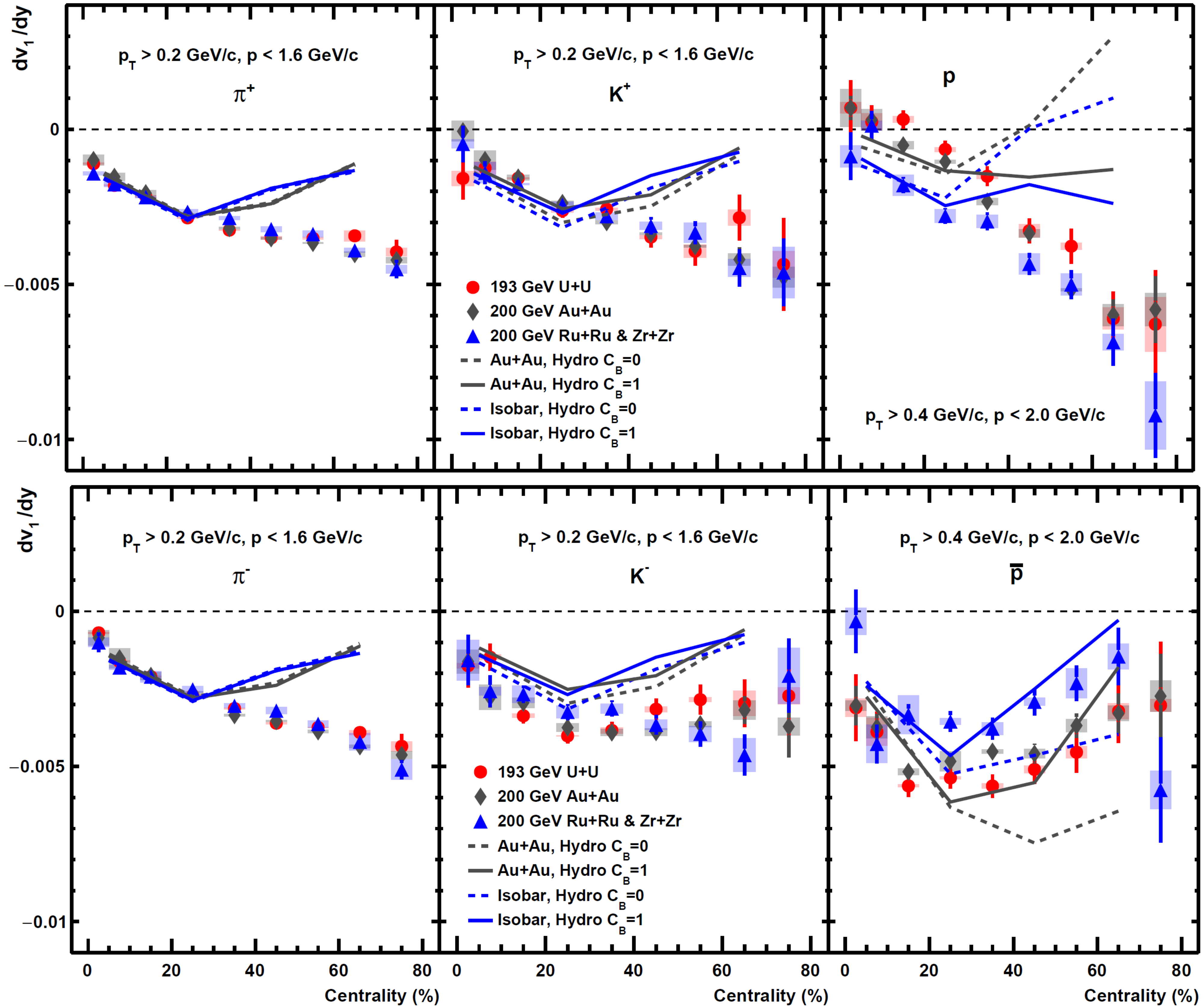

Vertex_XY
VertexXY
Entries 2.530185e+008
Mean x 0.03091
Mean y −0.1158
RMS x 0.05693
RMS y 0.05439
V_y (cm)
V_x (cm)


Vertex_Z
VertexZ
Entries 2.530185e+008
Mean 1.135
RMS 16.43
Events
$\times 10^3$
v_z(cm)

Slope (dv_1/dy) for Different Collision Systems

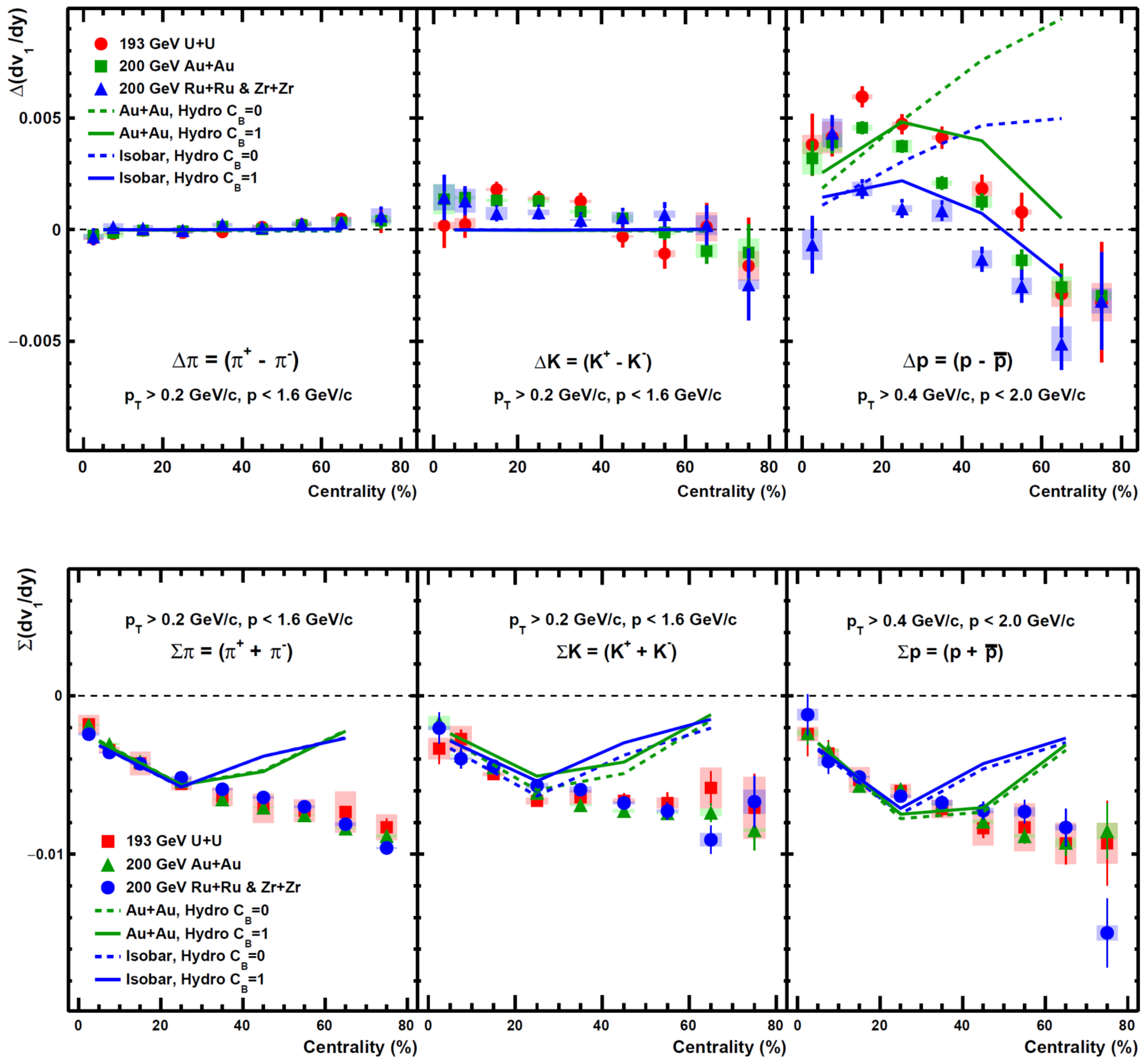
Positive Particle

Negative Particle

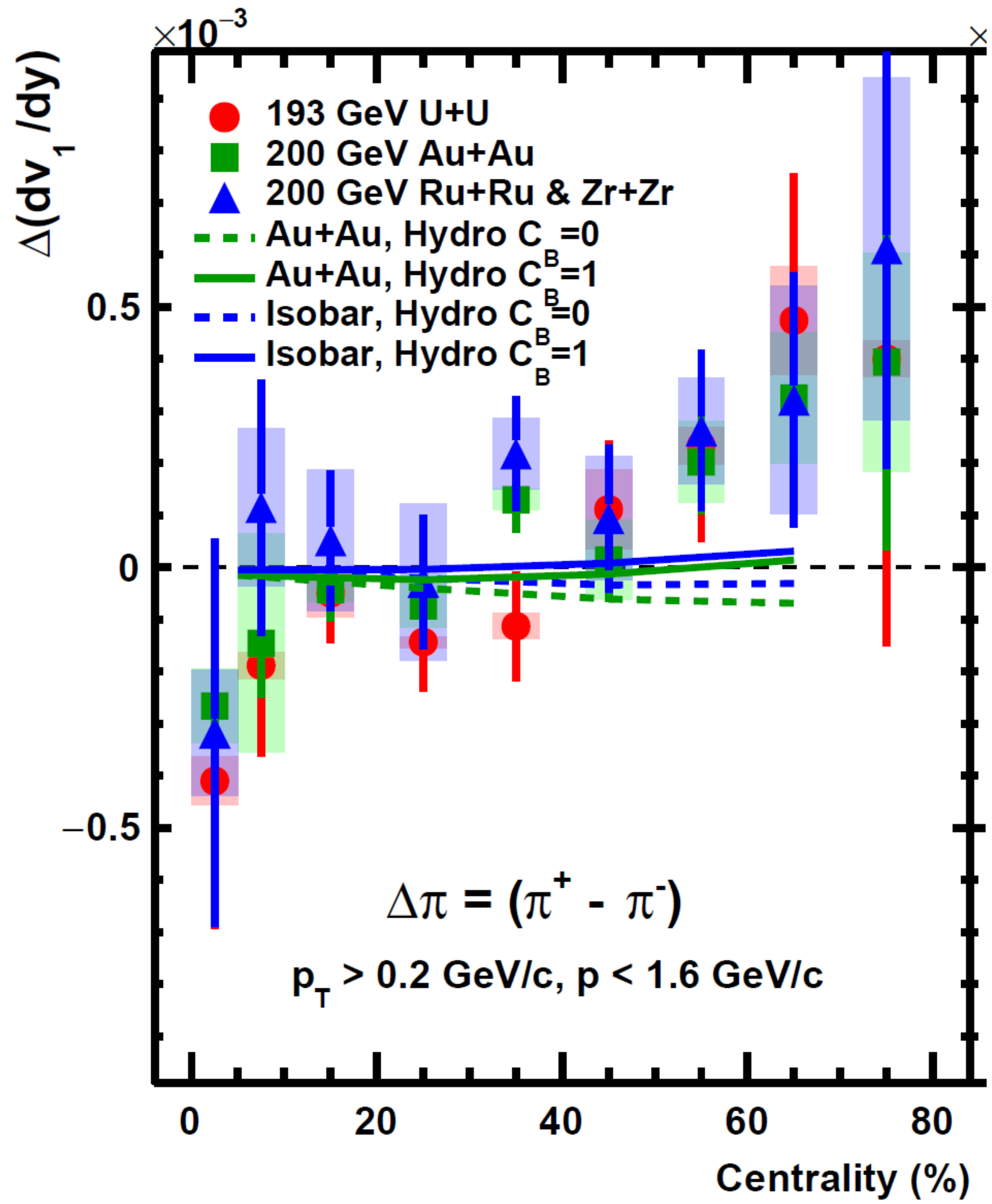


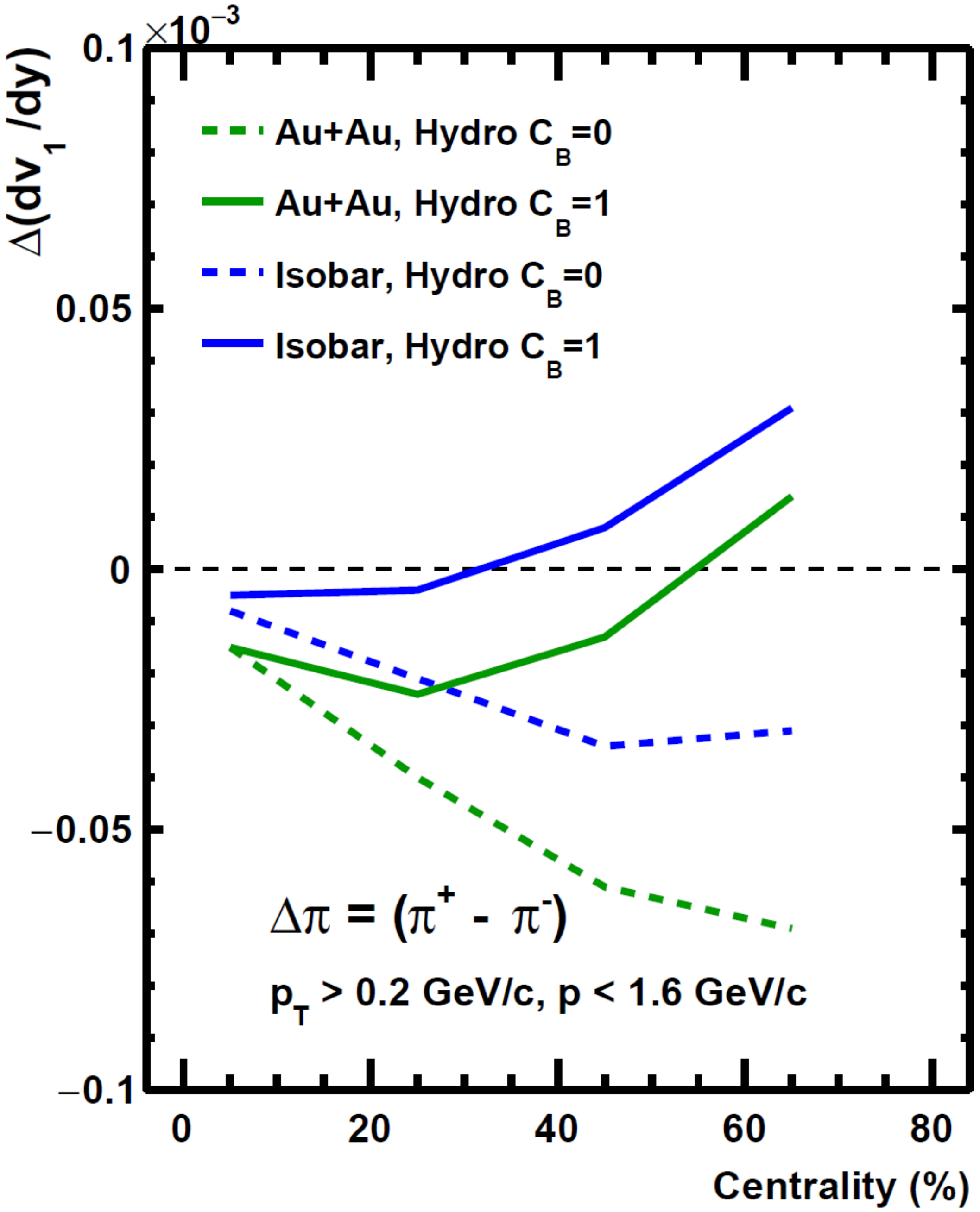
- Slopes are fitted using a linear function "y = mx" within rapidity range (-0.8, 0.8)
- Significant negative slopes (from linear fit) are observed for proton in all the three collision systems
- For proton and antiproton, splitting in slopes are prominent in mid central (10-40)% collisions

$\Delta(dv_1/dy)$ and $\sum(dv_1/dy)$ for Different Collision Systems

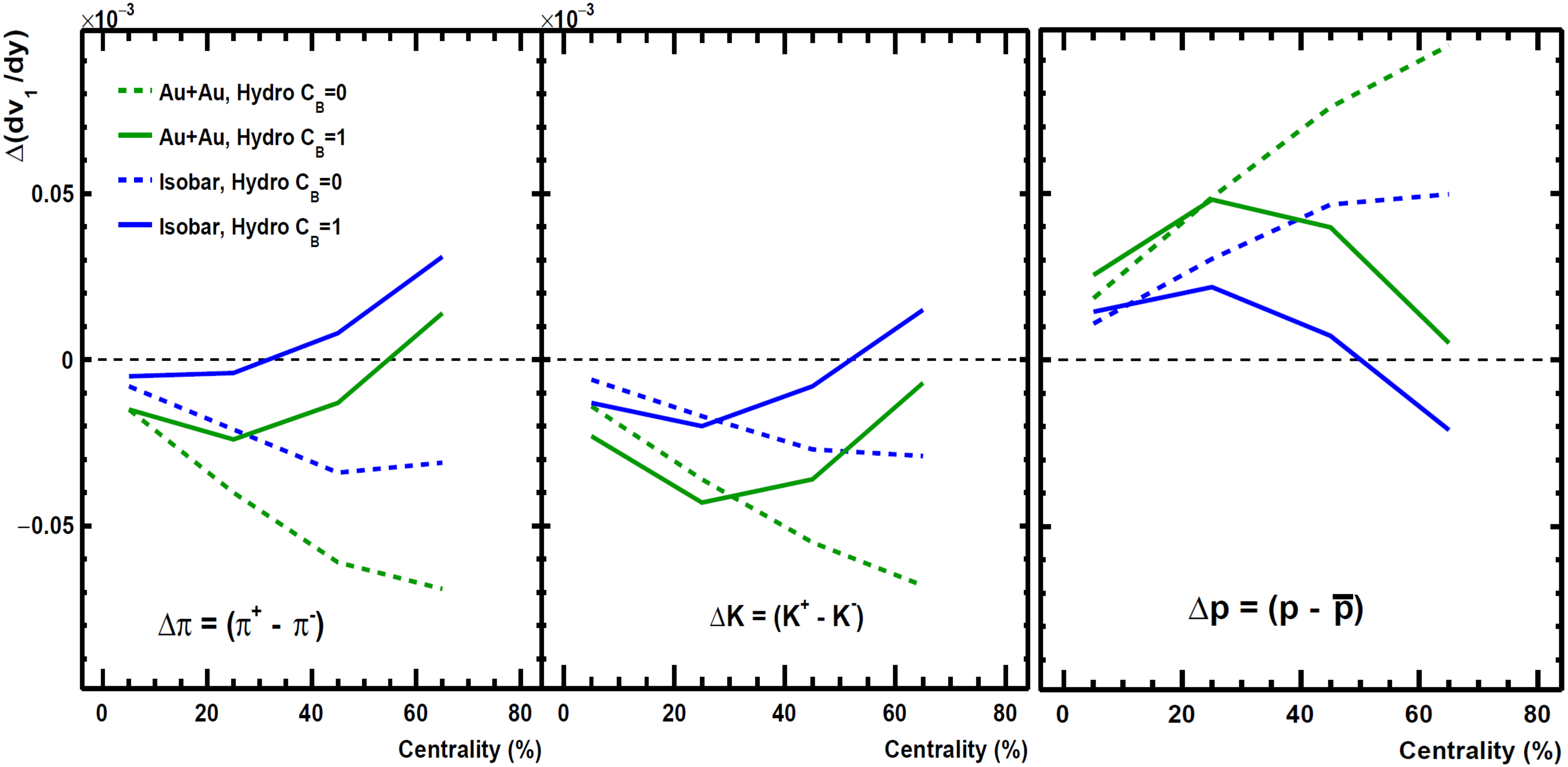


$\Delta(dv_1/dy)$ for Pion

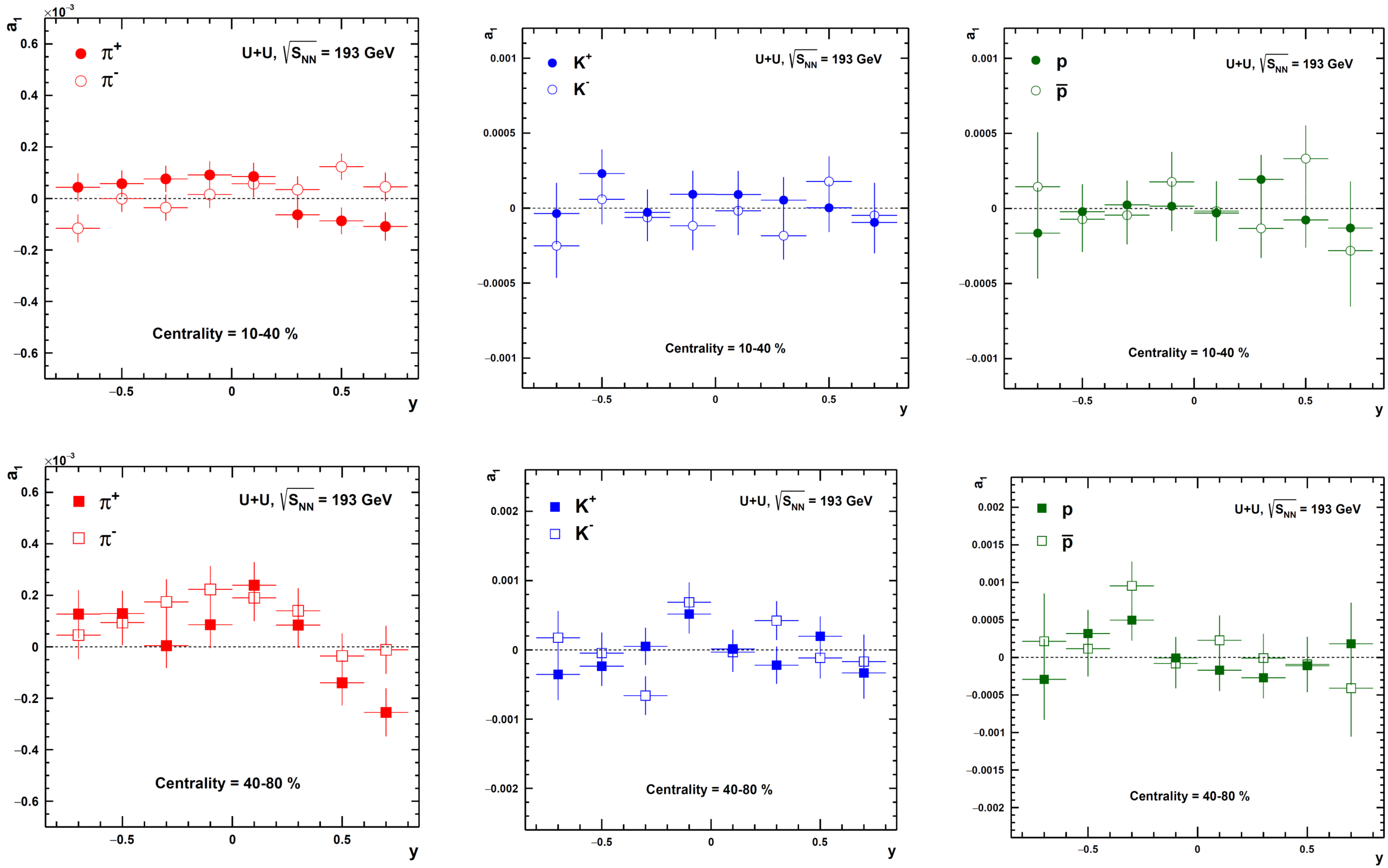




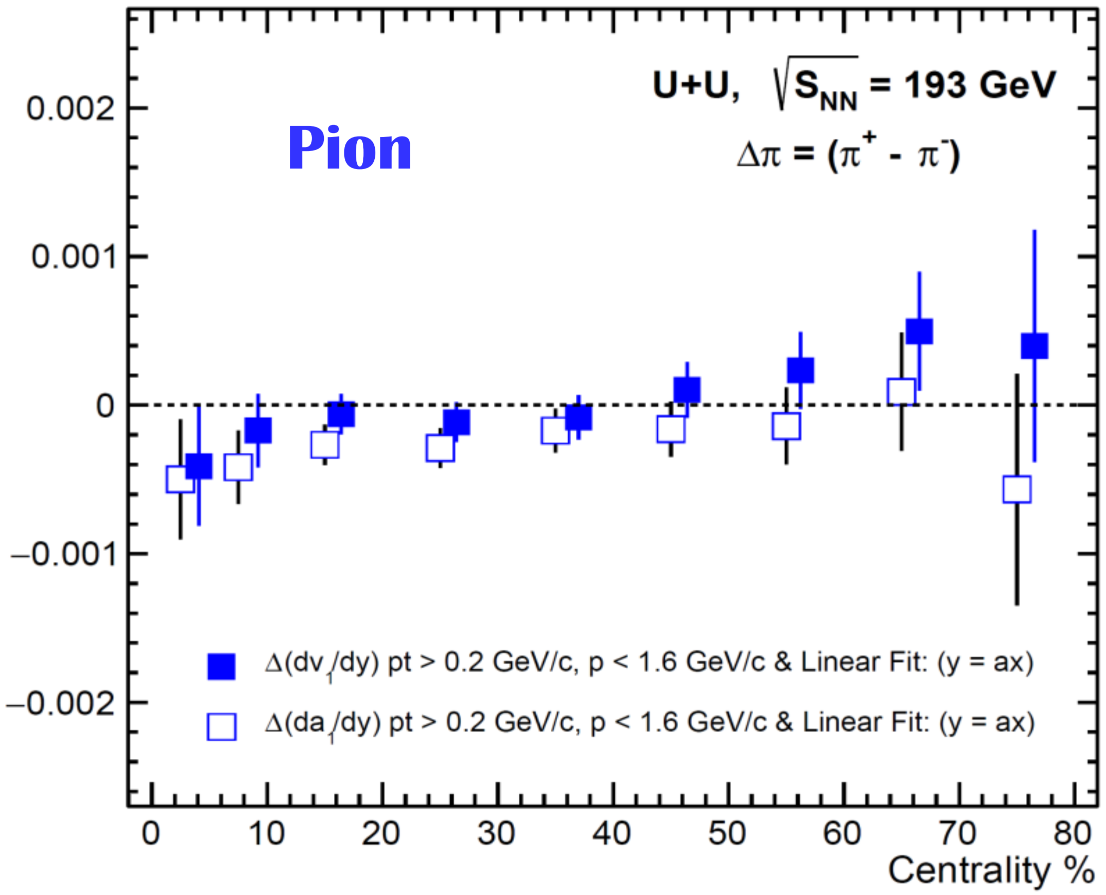
$\Delta(dv_1/dy)$ for Pion

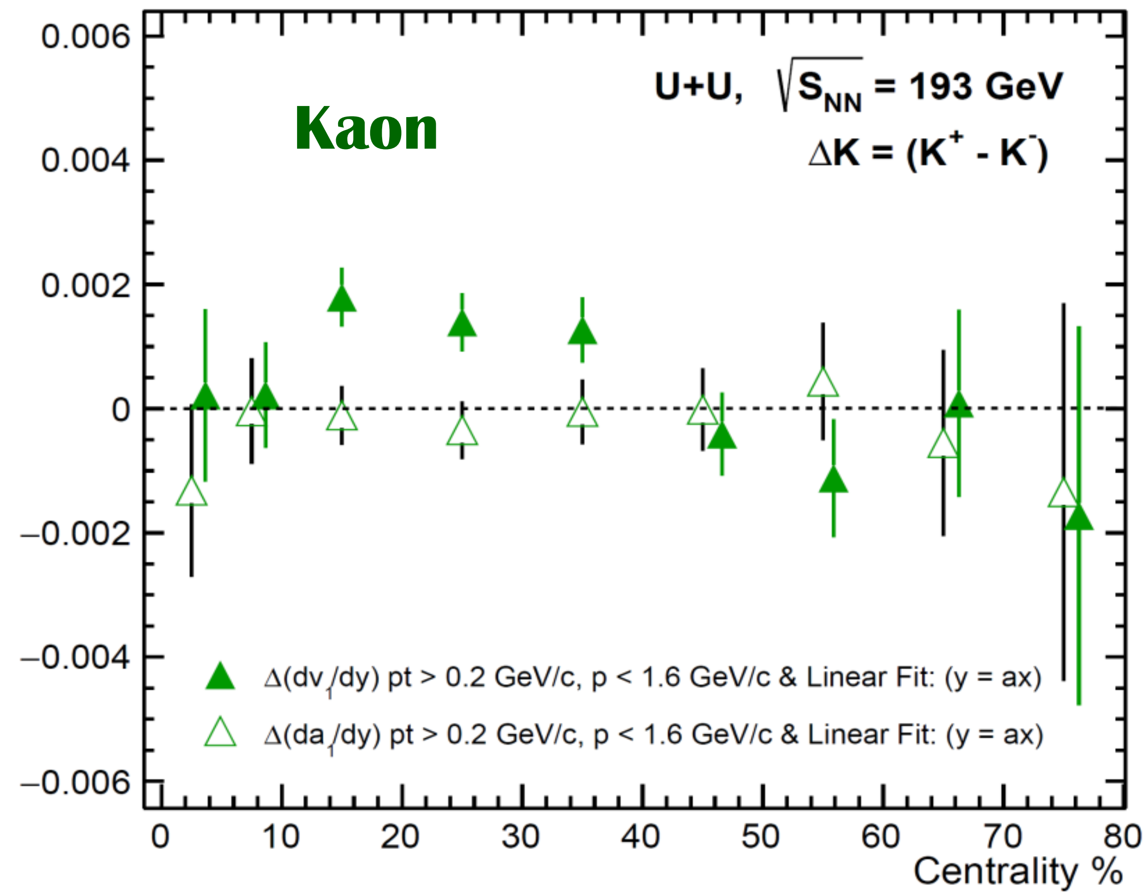


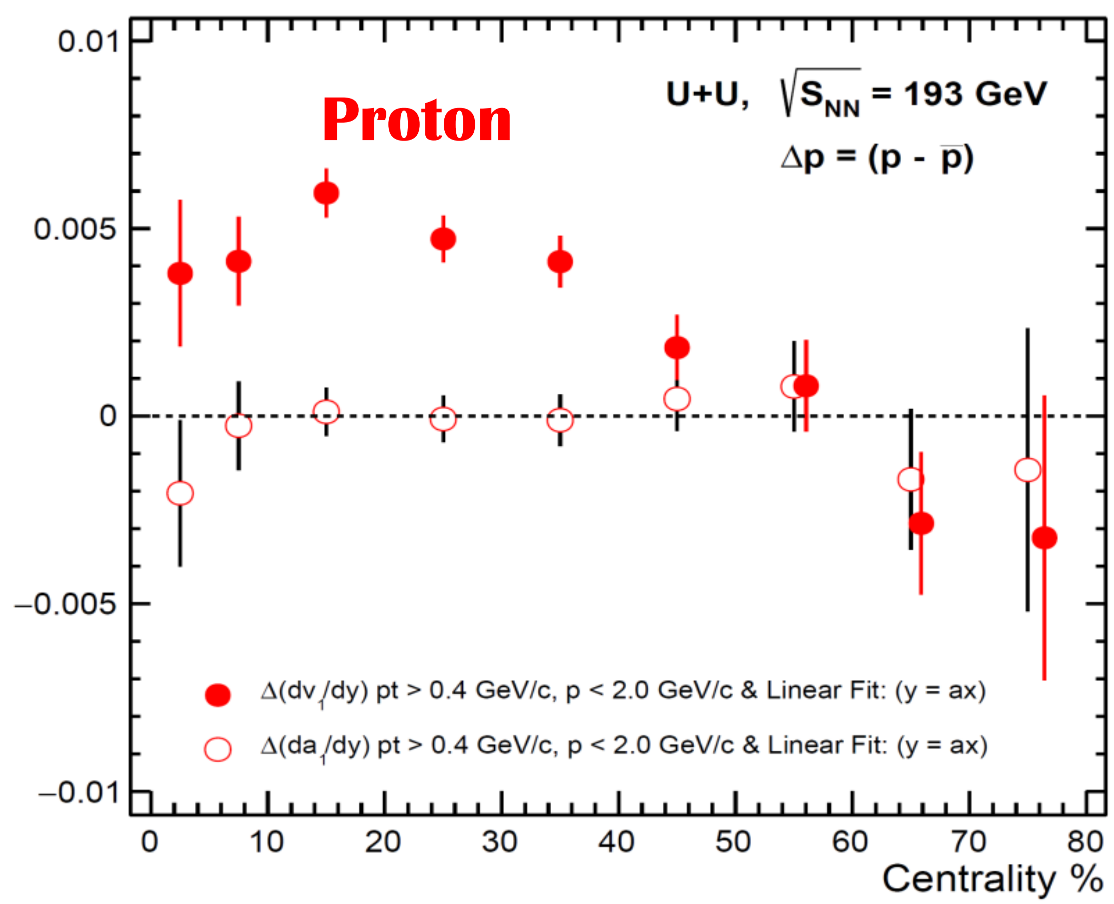
$a_1(y)$ for U+U Collisions



Δ(da_1/dy) for Proton

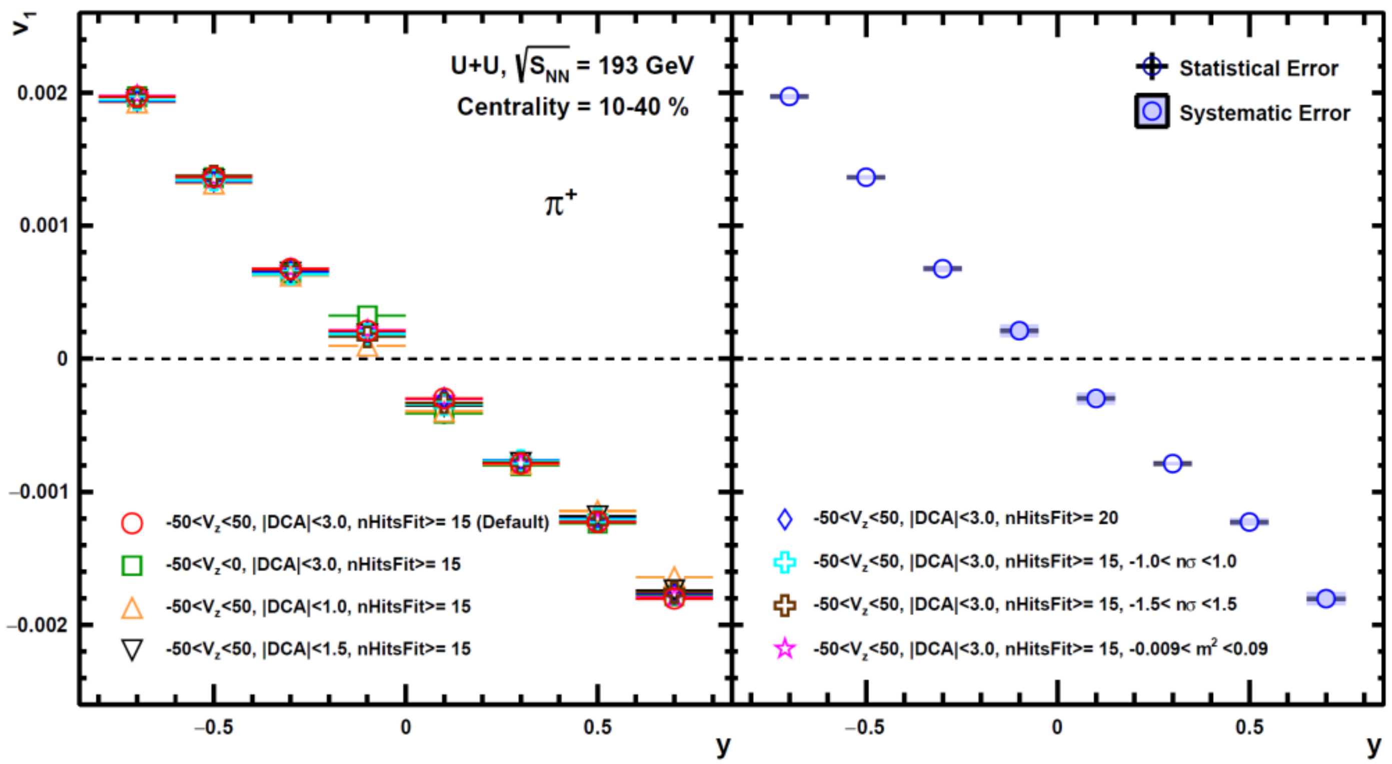


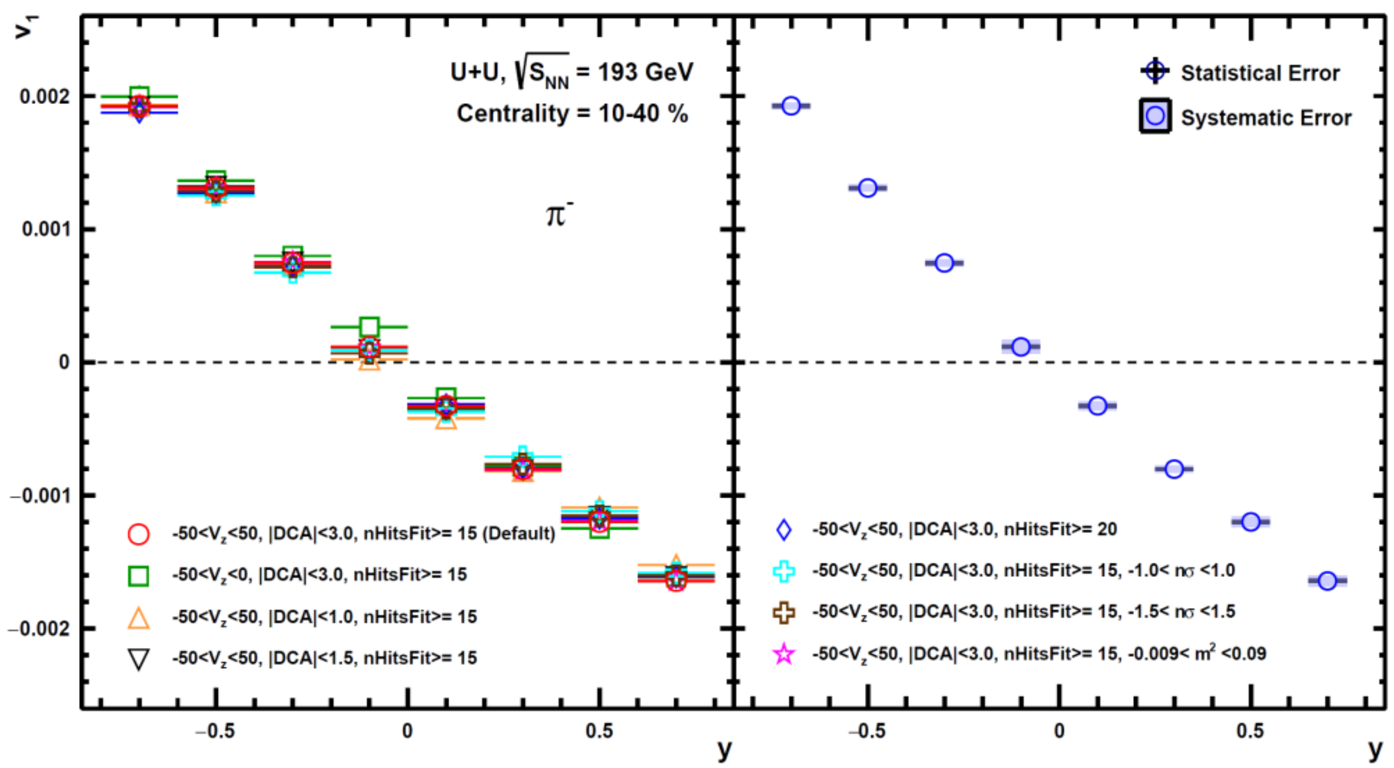




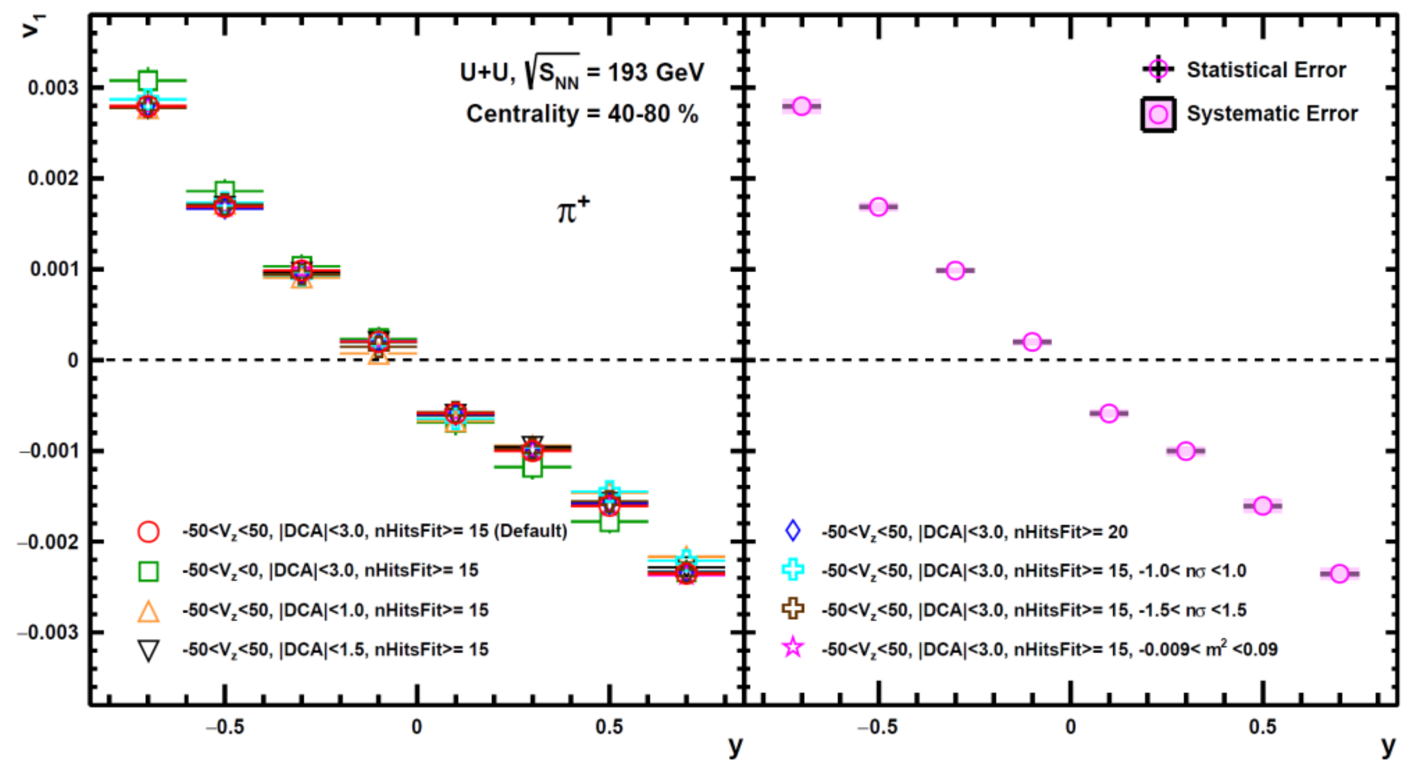
Rapidity dependent v_1 (Pion)

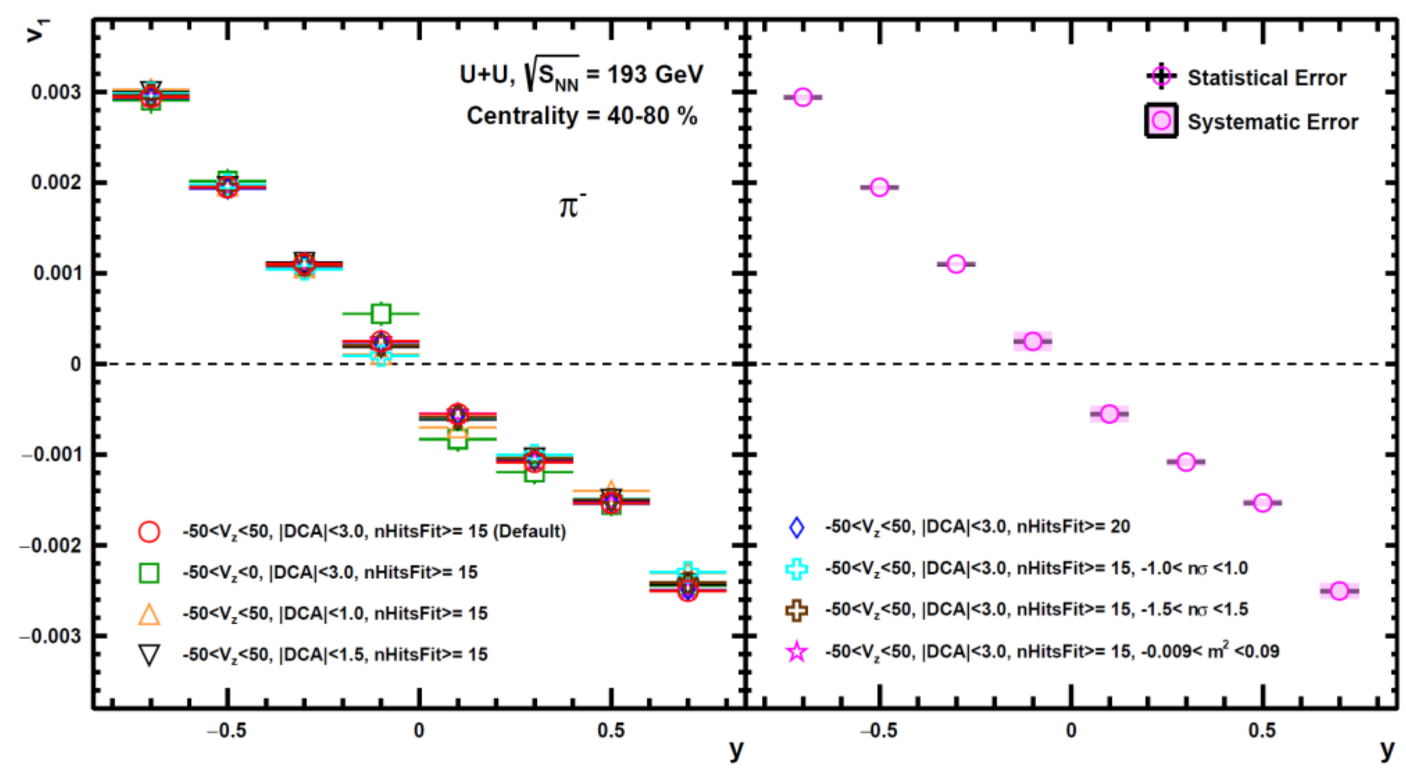
Mid Central (10 - 40)%





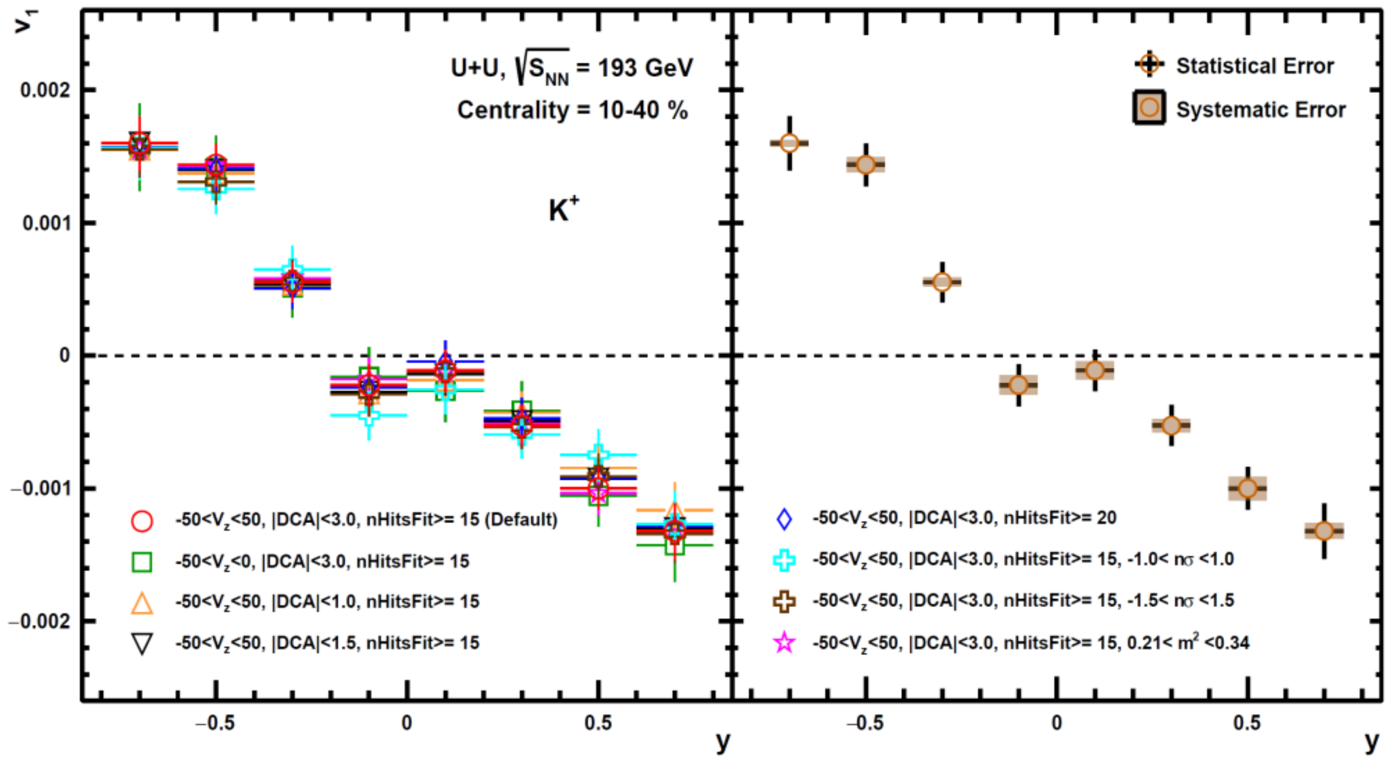
Peripheral (40 - 80)%

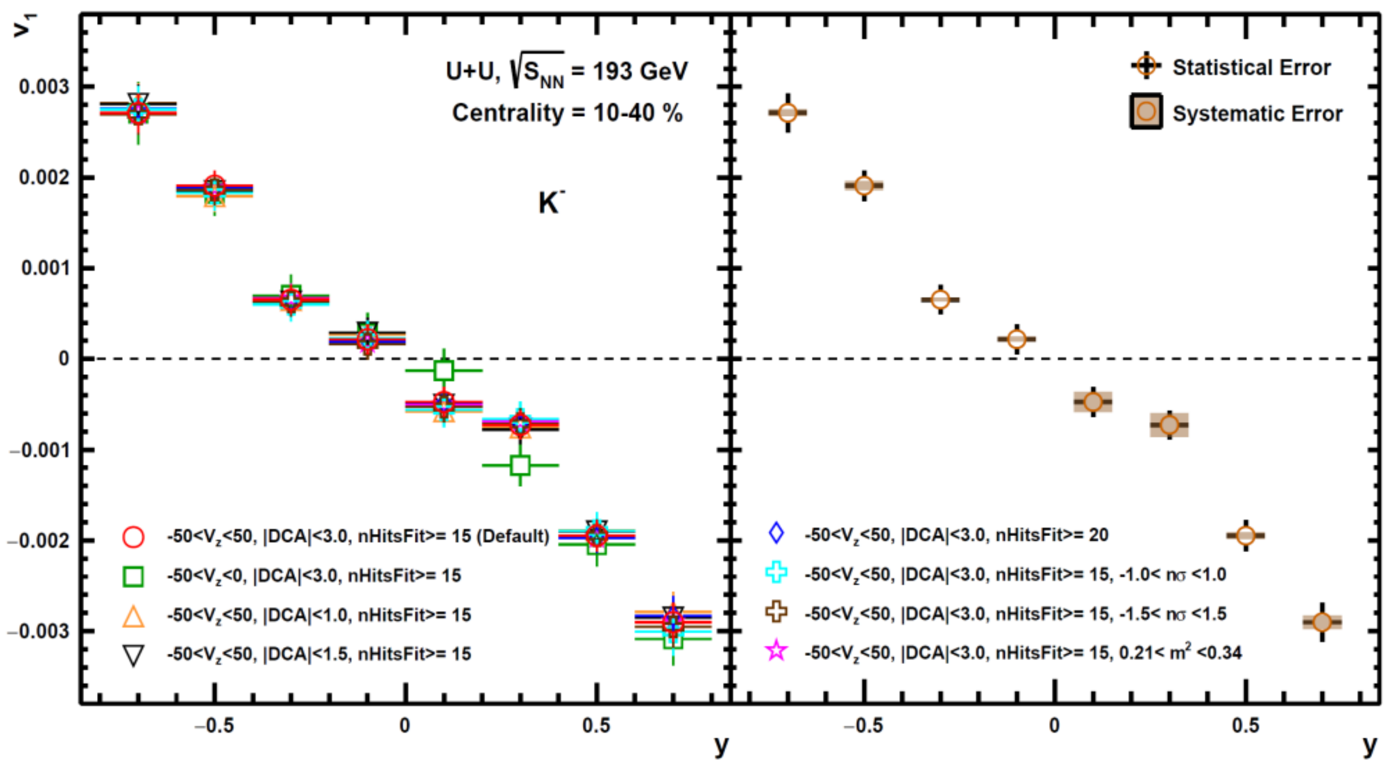




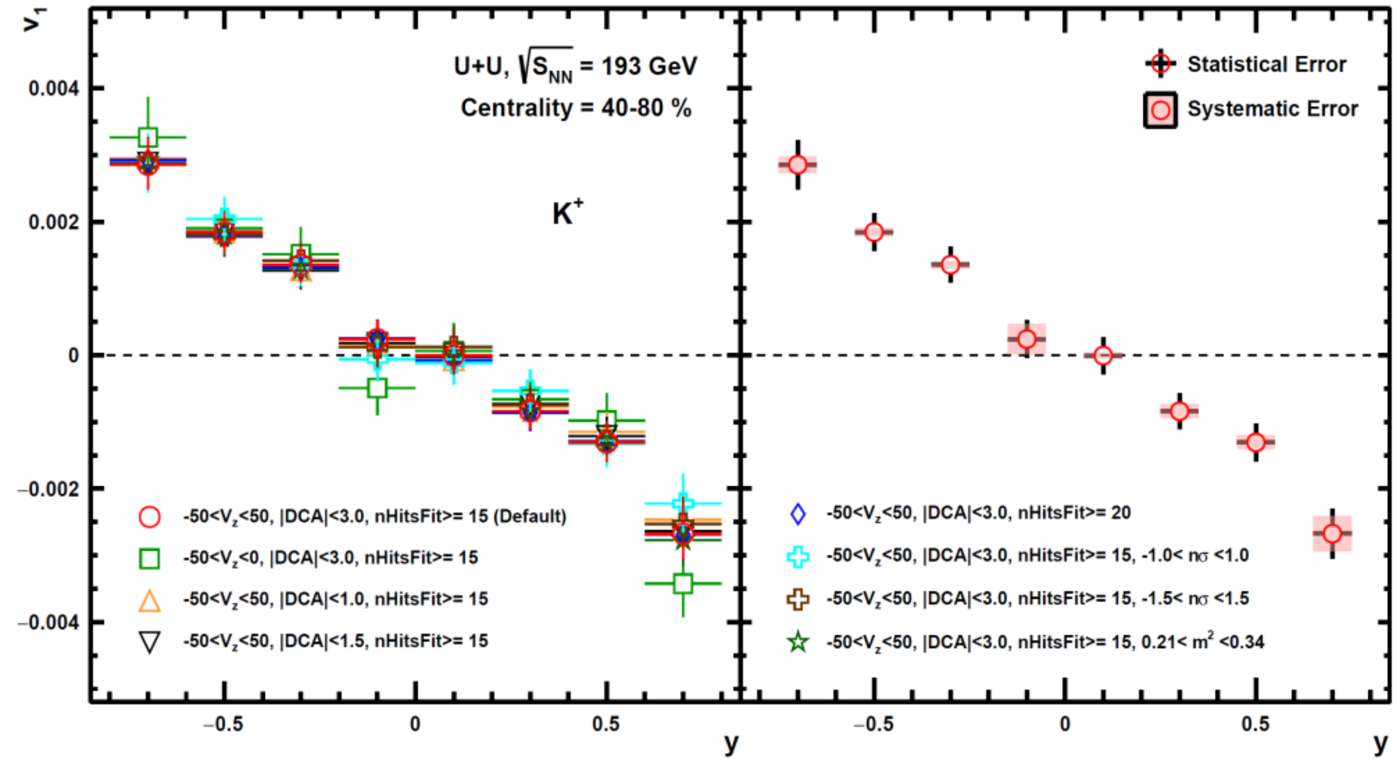
Rapidity dependent v_1 (Kaon)

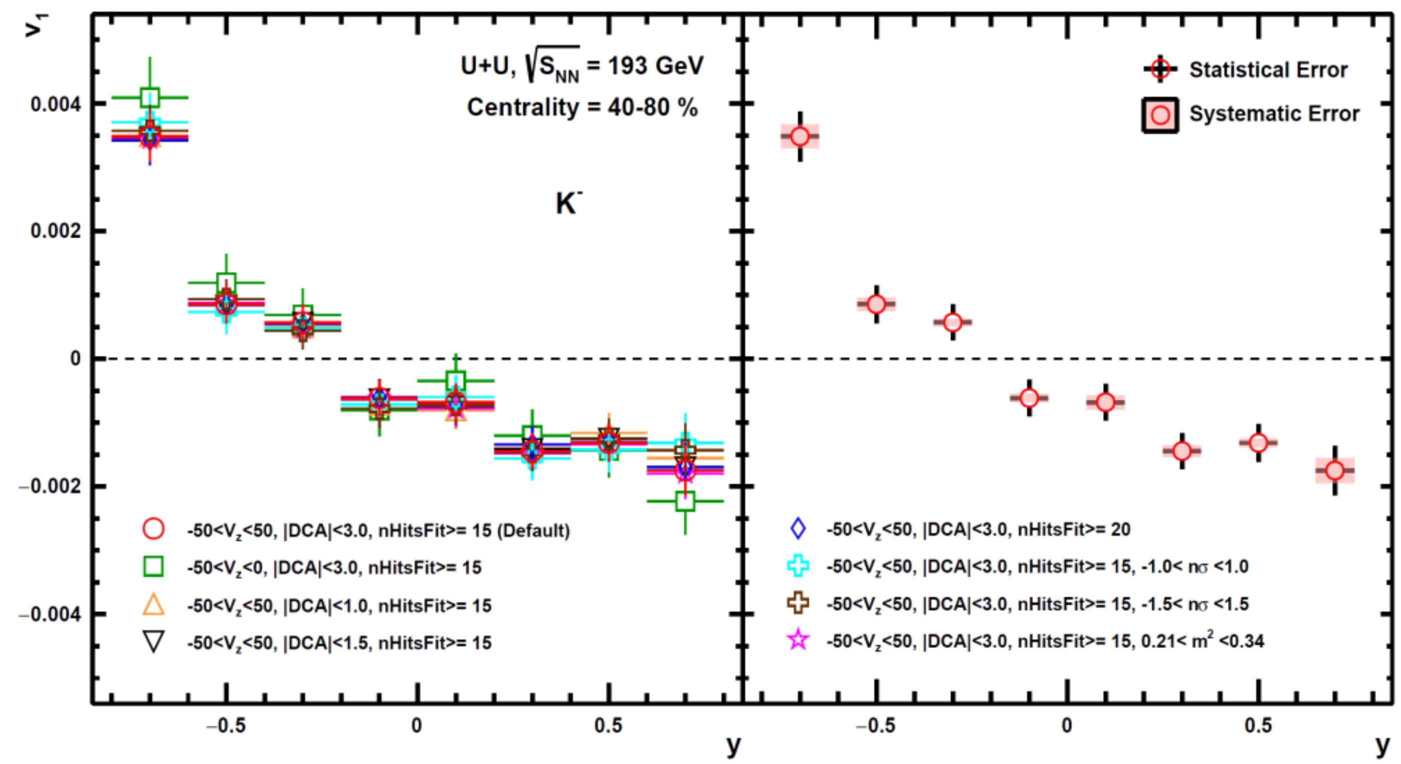
Mid Central (10 -40)%





Peripheral (40 - 80)%

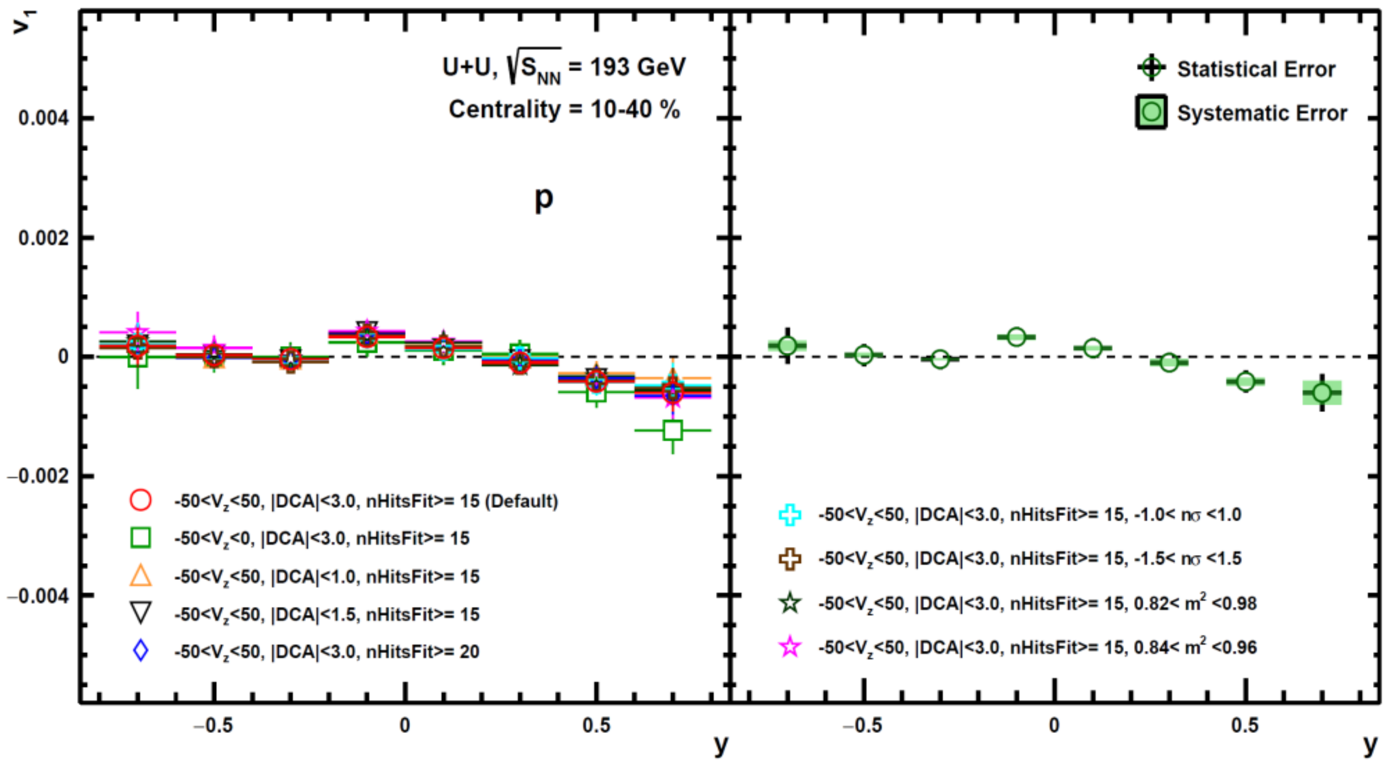


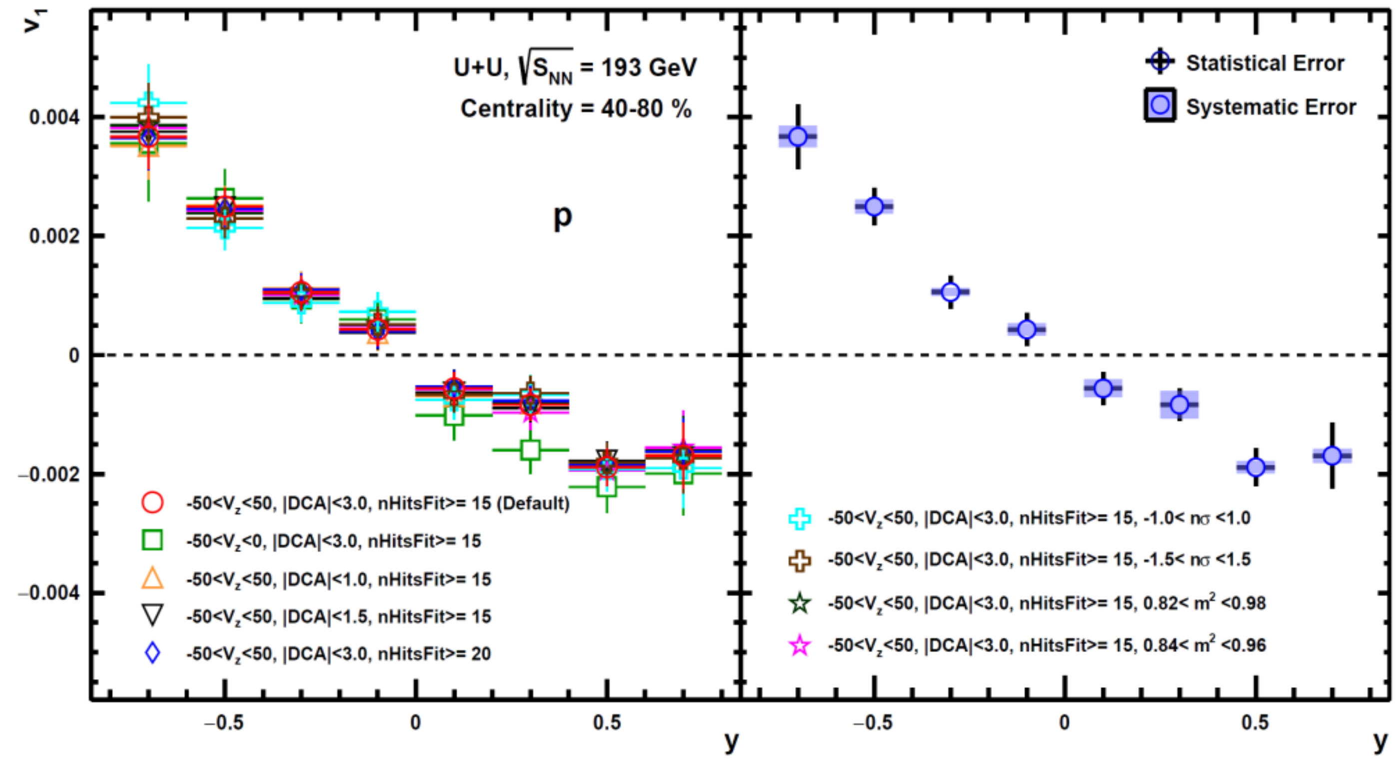


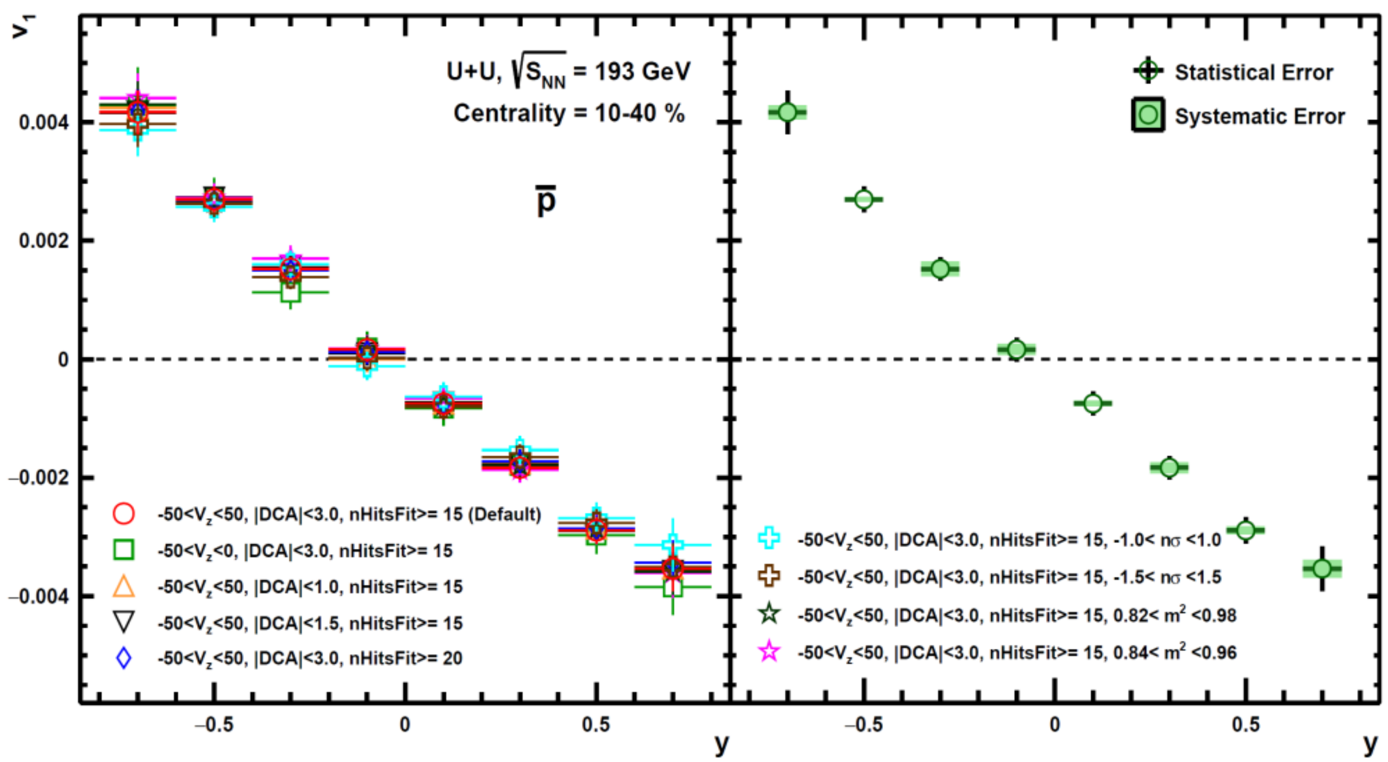
Rapidity dependent v_1 (Proton)

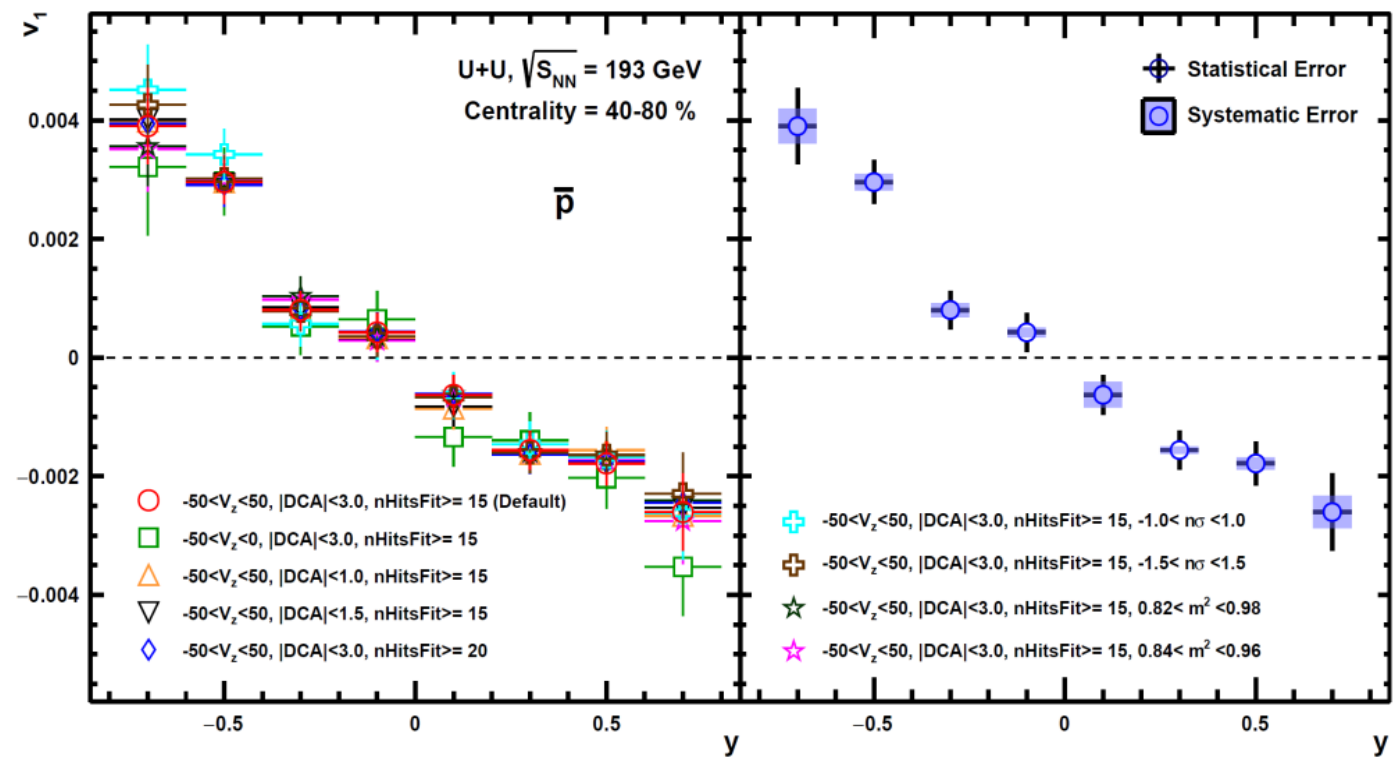
Mid Central (10 -40)%

Peripheral (40 - 80)%





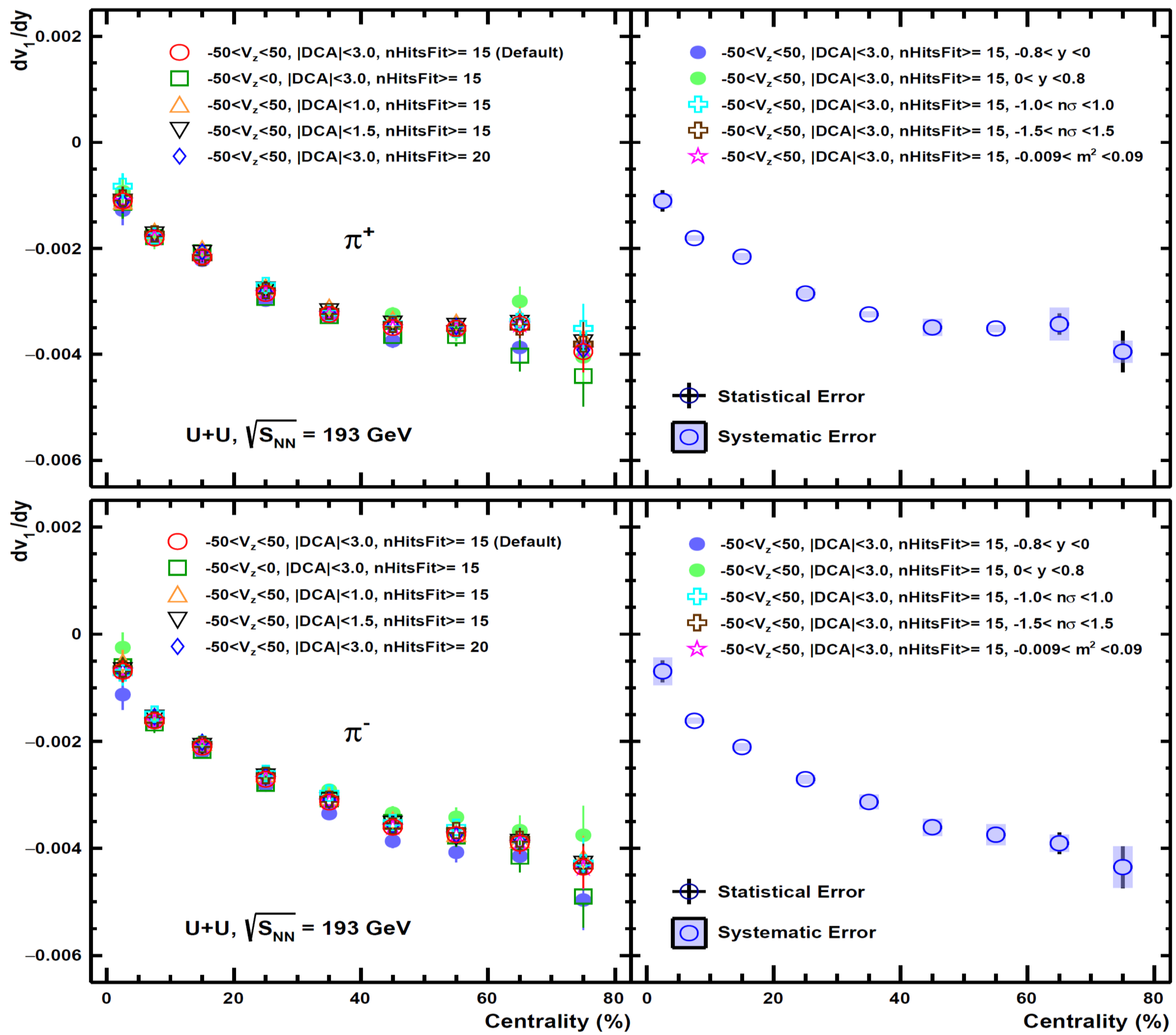




Centrality dependent dv_1/dy of Pion

Positive Particle

Negative Particle

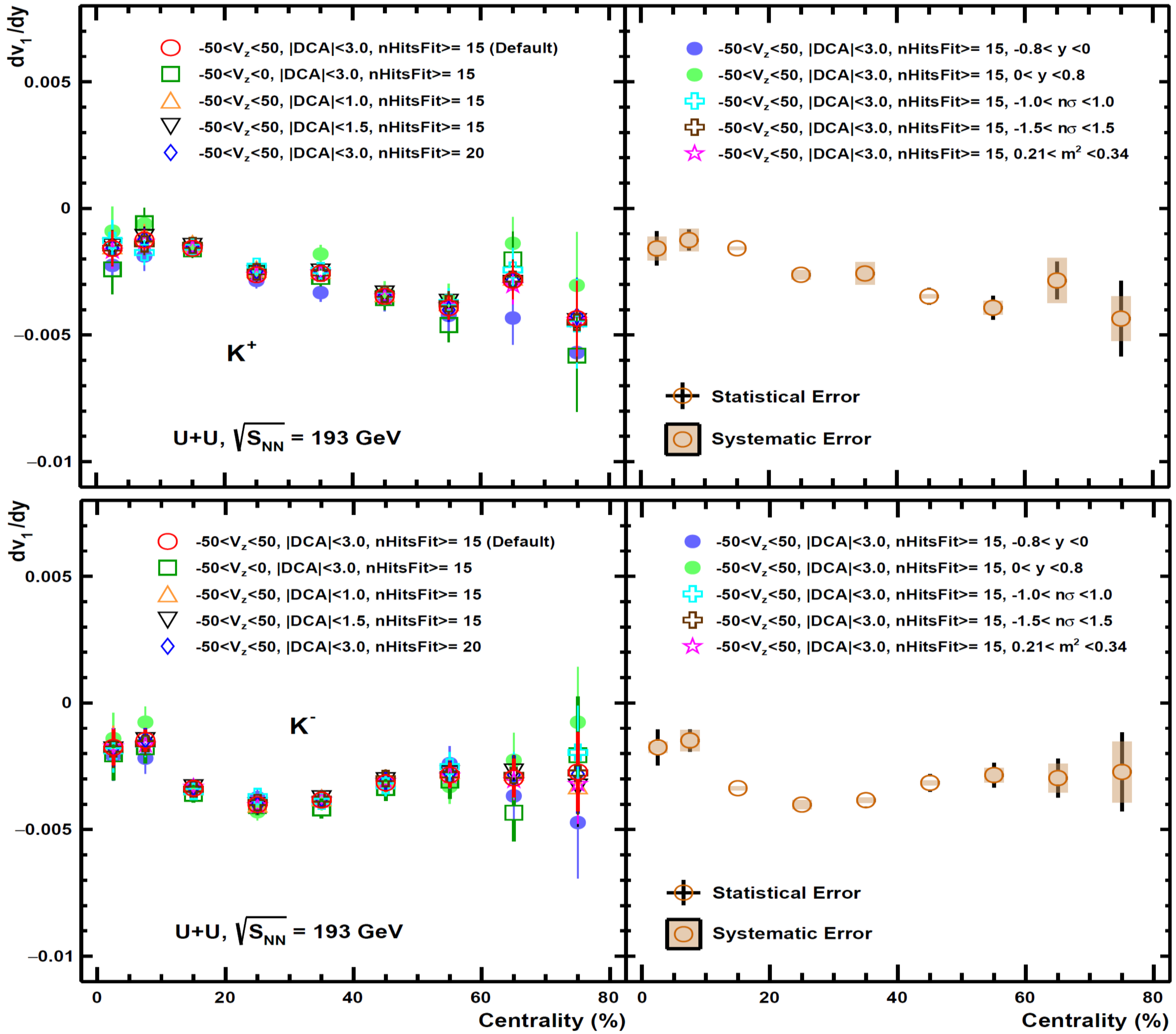


❑ **A linear function "y = mx" is used to get slope (dv_1/dy) within rapidity range (-0.8, 0.8)**

Centrality dependent dv_1/dy of Kaon

Positive Particle

Negative Particle

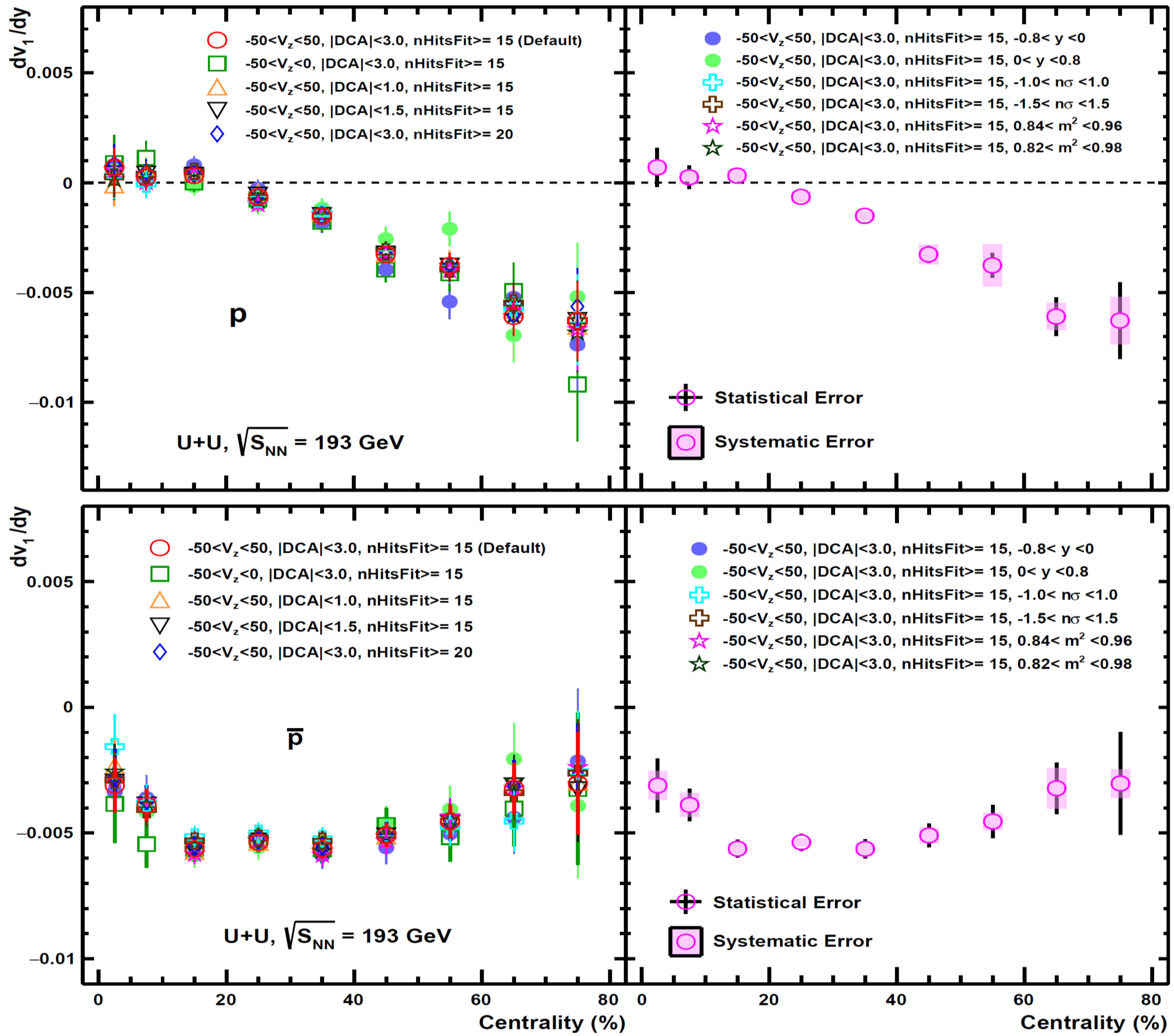


- A linear function "y = mx" is used to get slope (dv_1/dy) within rapidity range (-0.8, 0.8)

Centrality dependent dv_1/dy of Proton

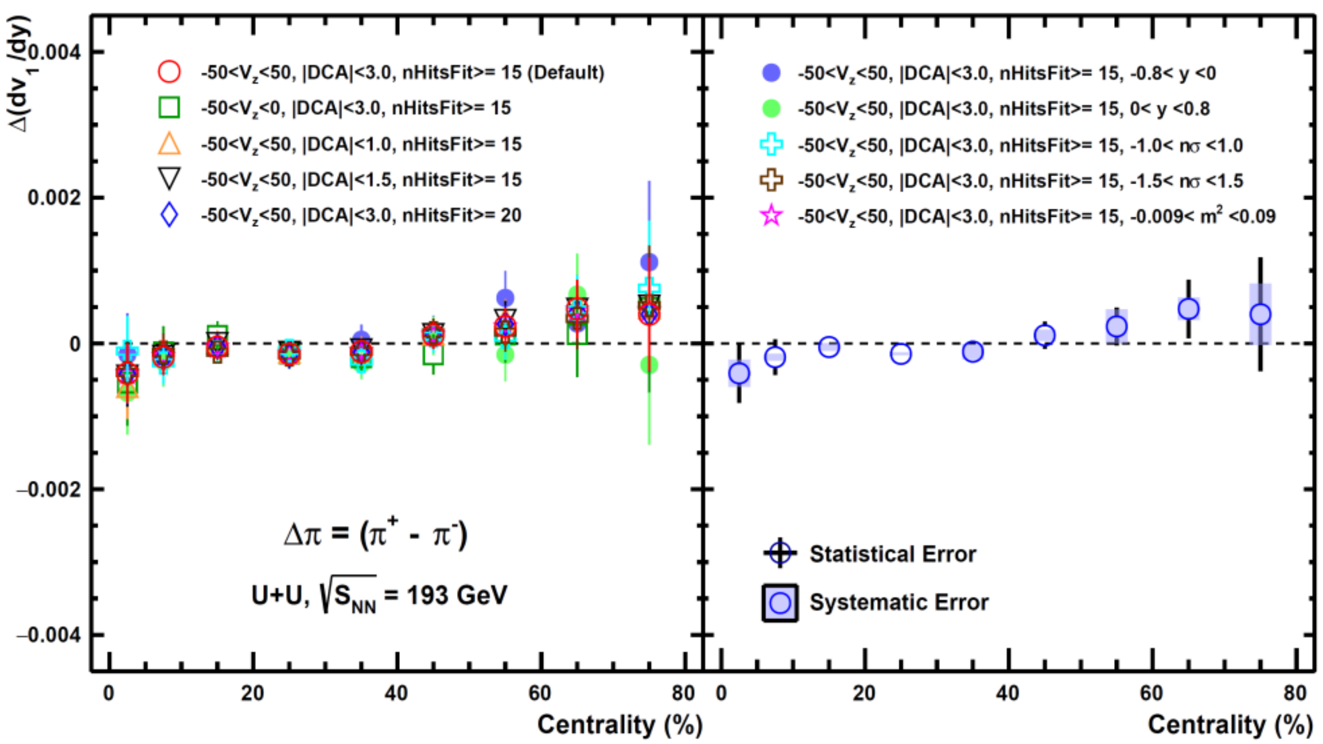
Positive Particle

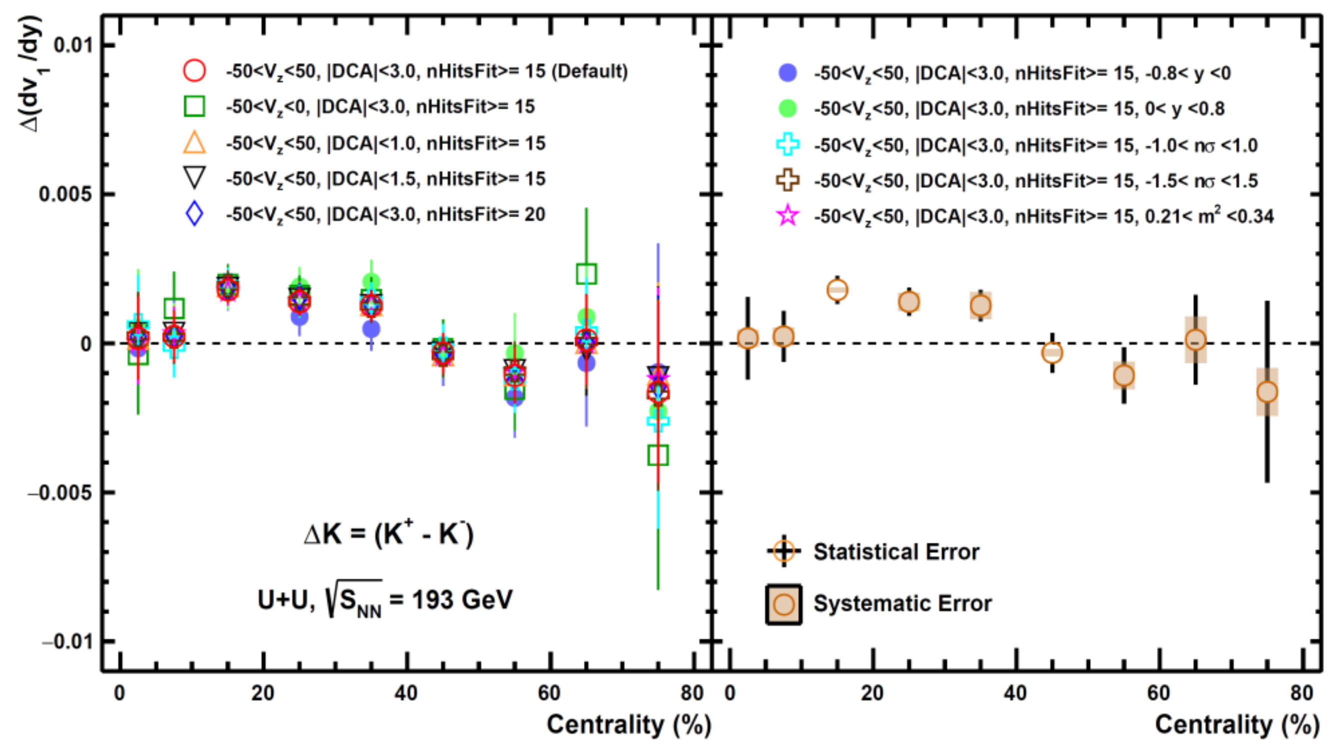
Negative Particle

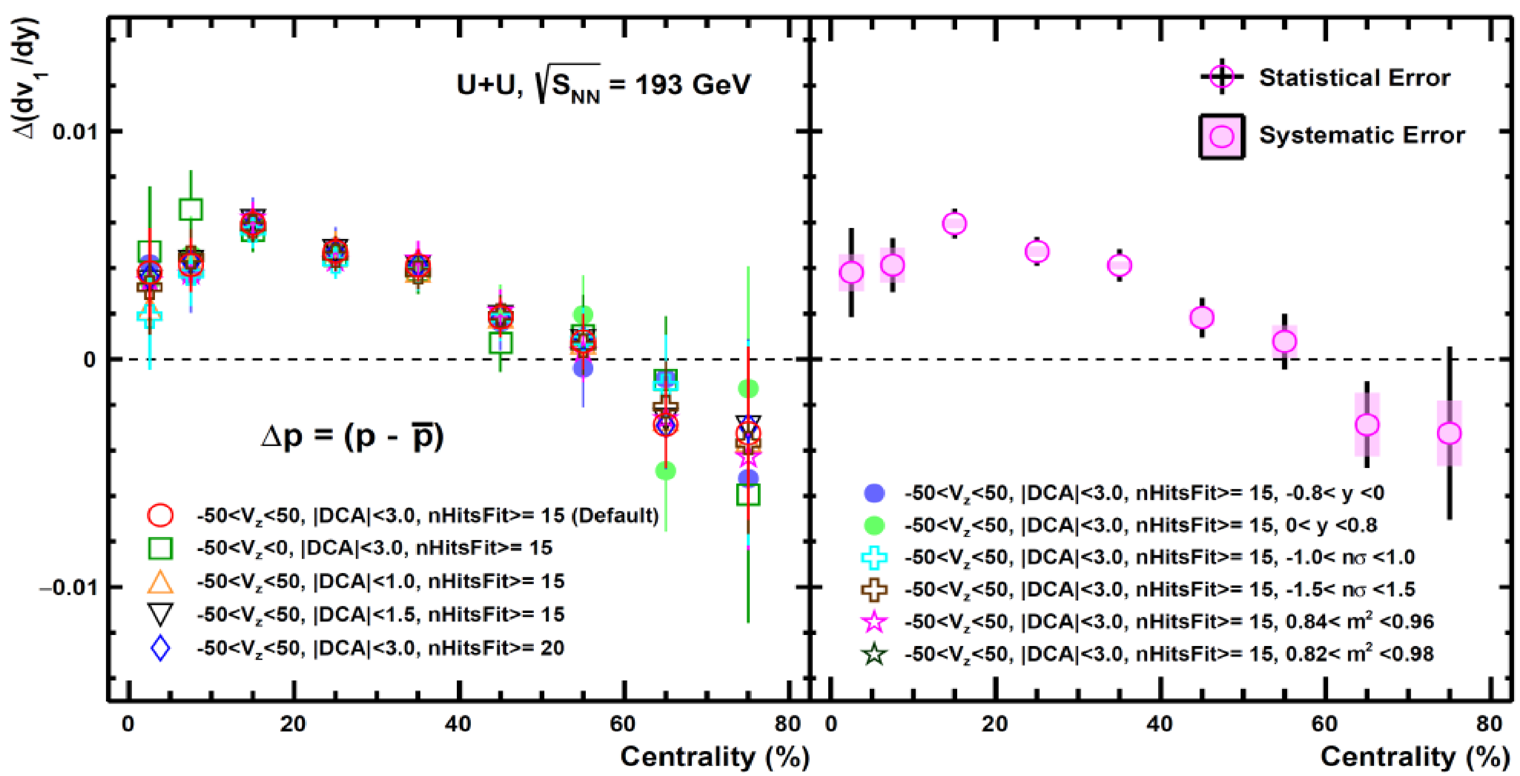


- A linear function "y = mx" is used to get slope (dv_1/dy) within rapidity range (-0.8, 0.8)
- For Proton, a sign change in dv_1/dy is observed in the mid central region

Centrality dependent $\Delta(dv_1/dy)$ of pi, k, p

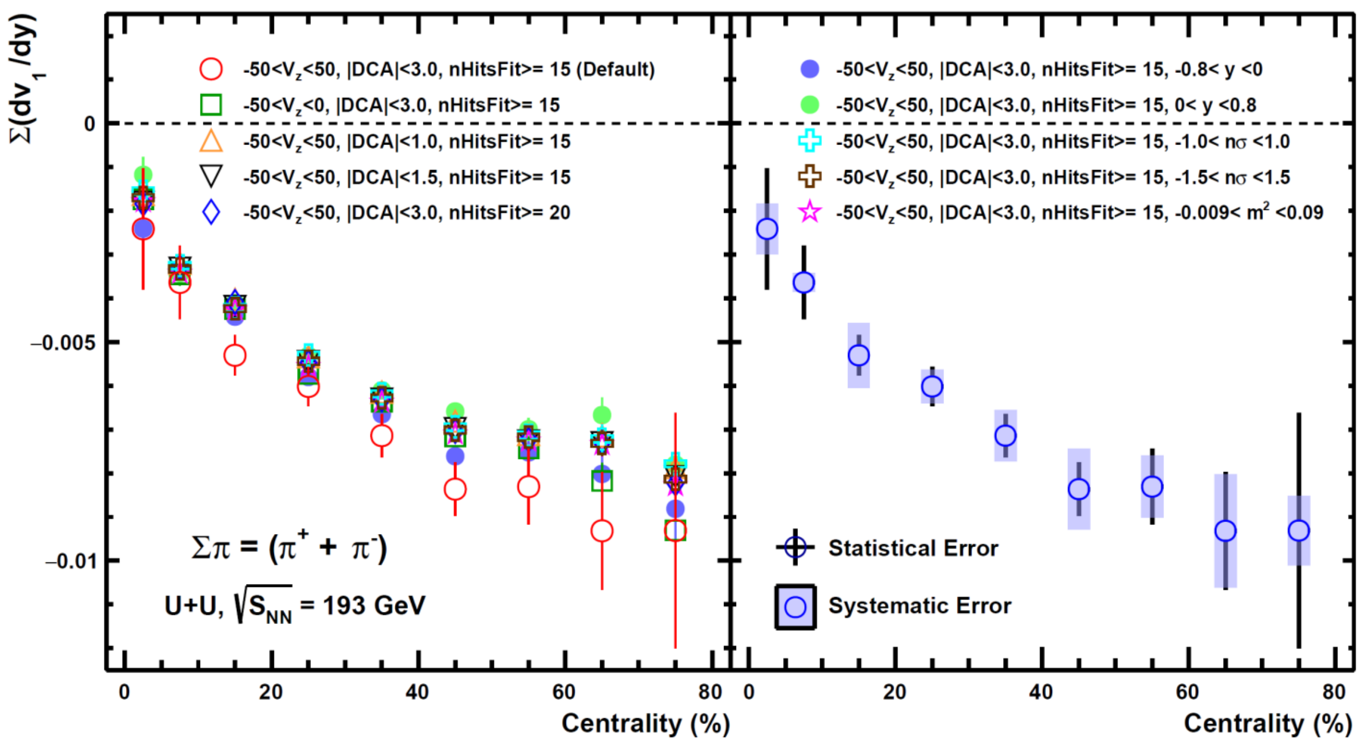


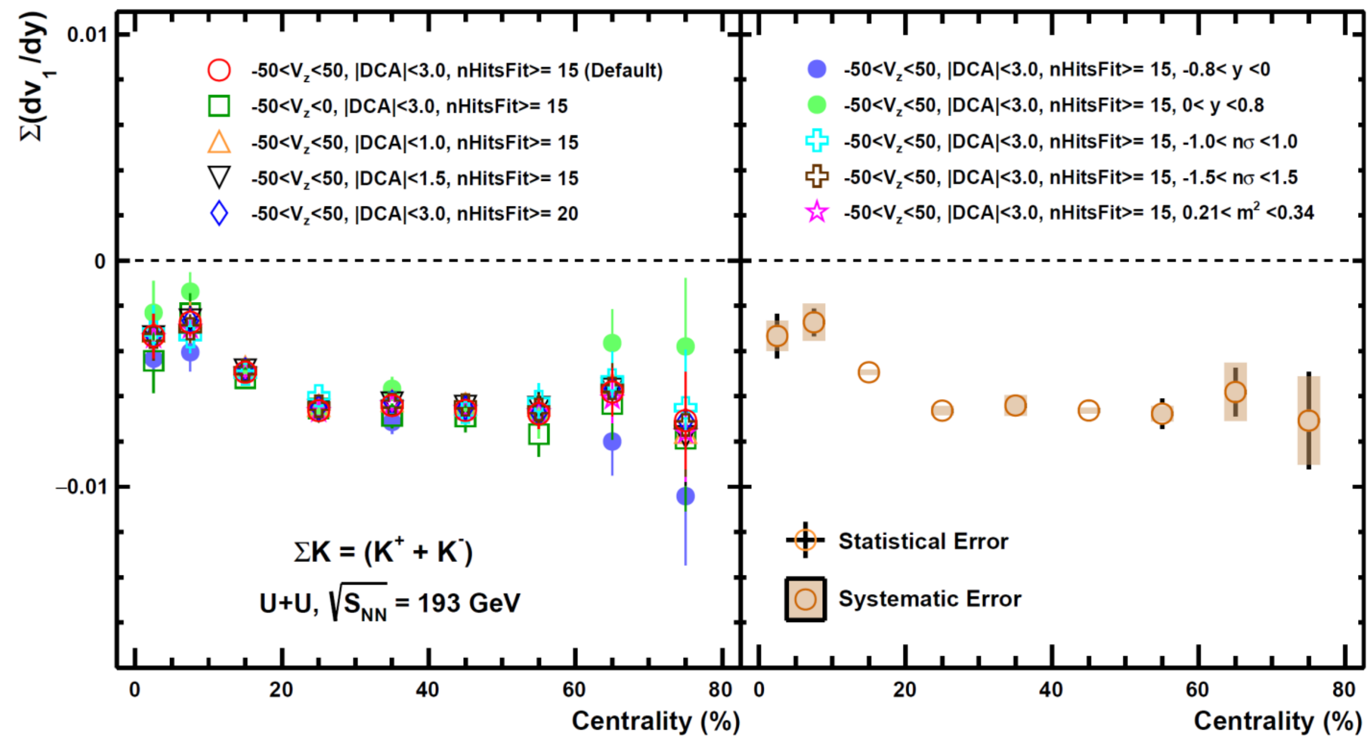


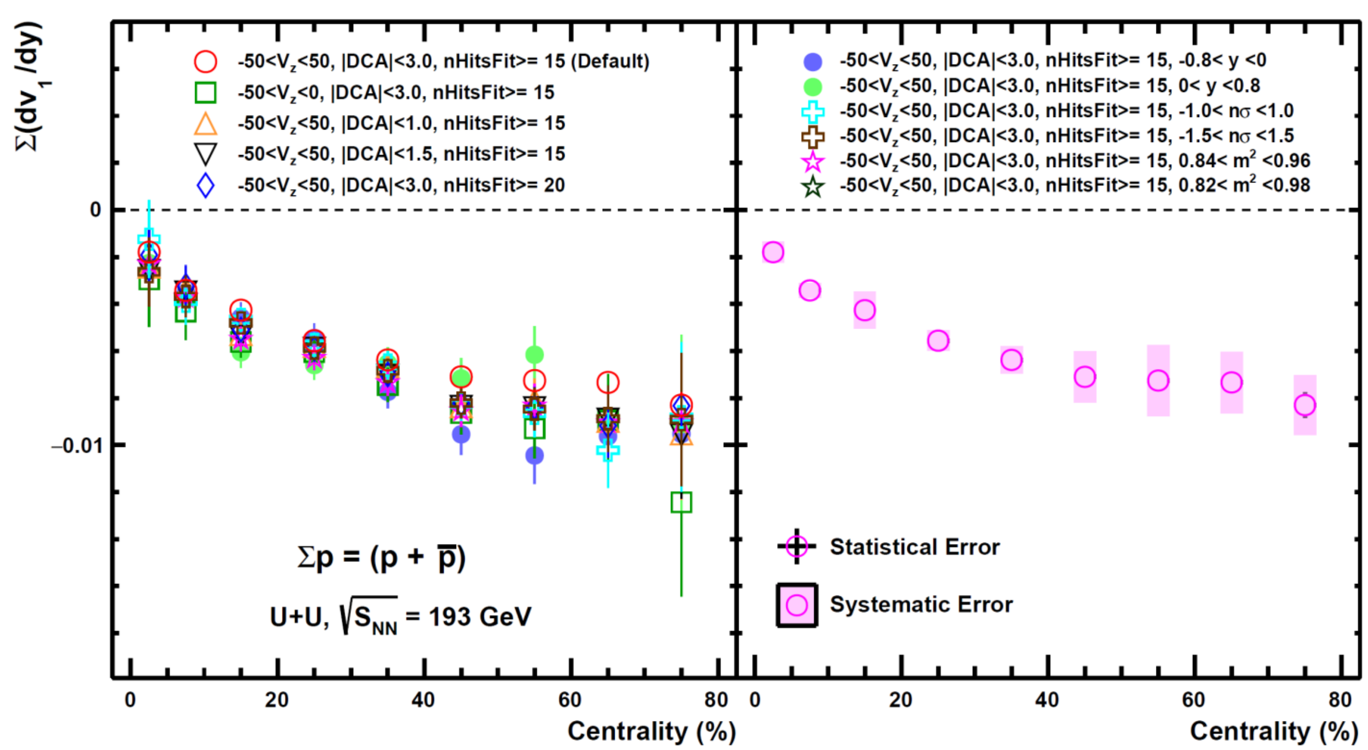


- $\Delta(dv_1/dy)$ is obtained using: $\Delta(dv_1/dy) = [dv_1^+/dy - dv_1^-/dy]$

Centrality dependent $\sum(dv_1/dy)$ of pi, k, p



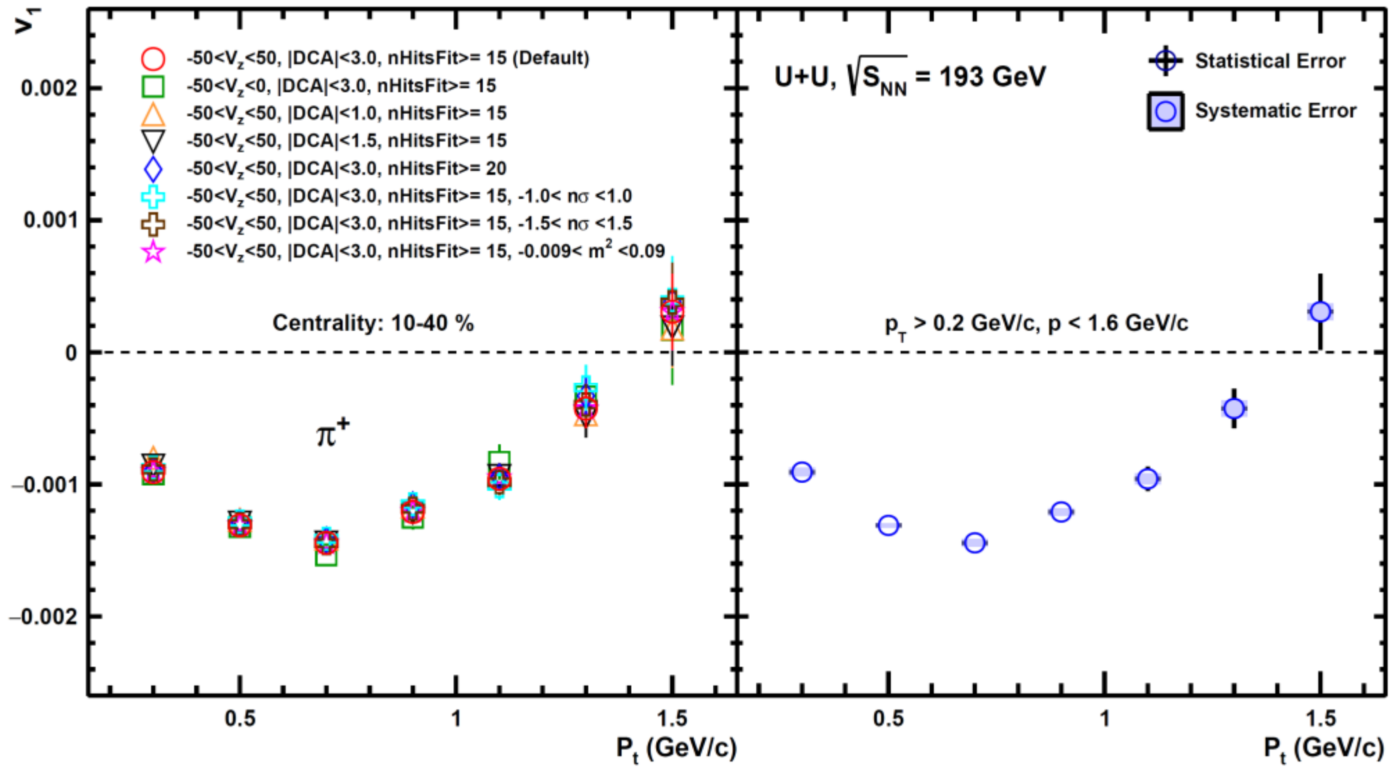




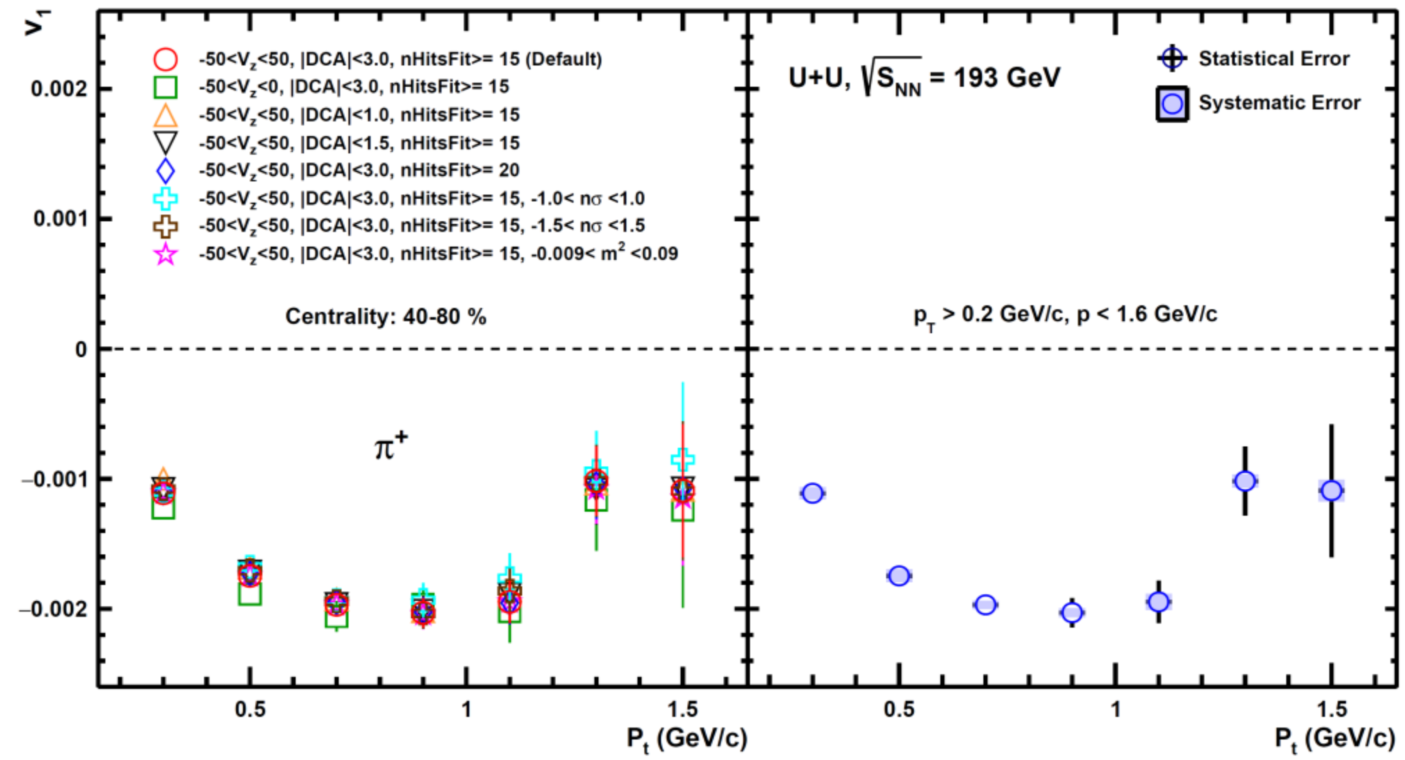
- $\sum(dv_1/dy)$ is obtained using: $\sum(dv_1/dy) = [dv_1^+/dy + dv_1^-/dy]$

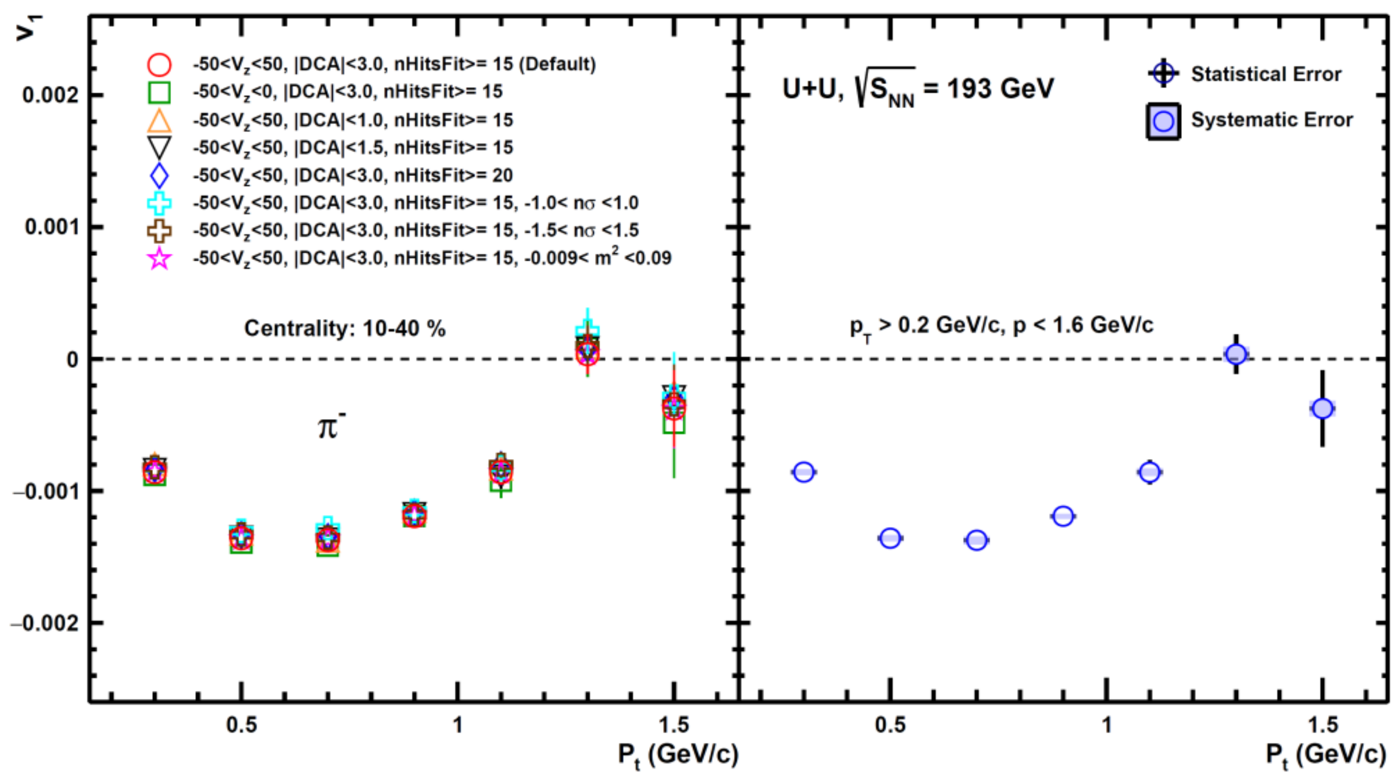
p_t dependent v_1 (Pion)

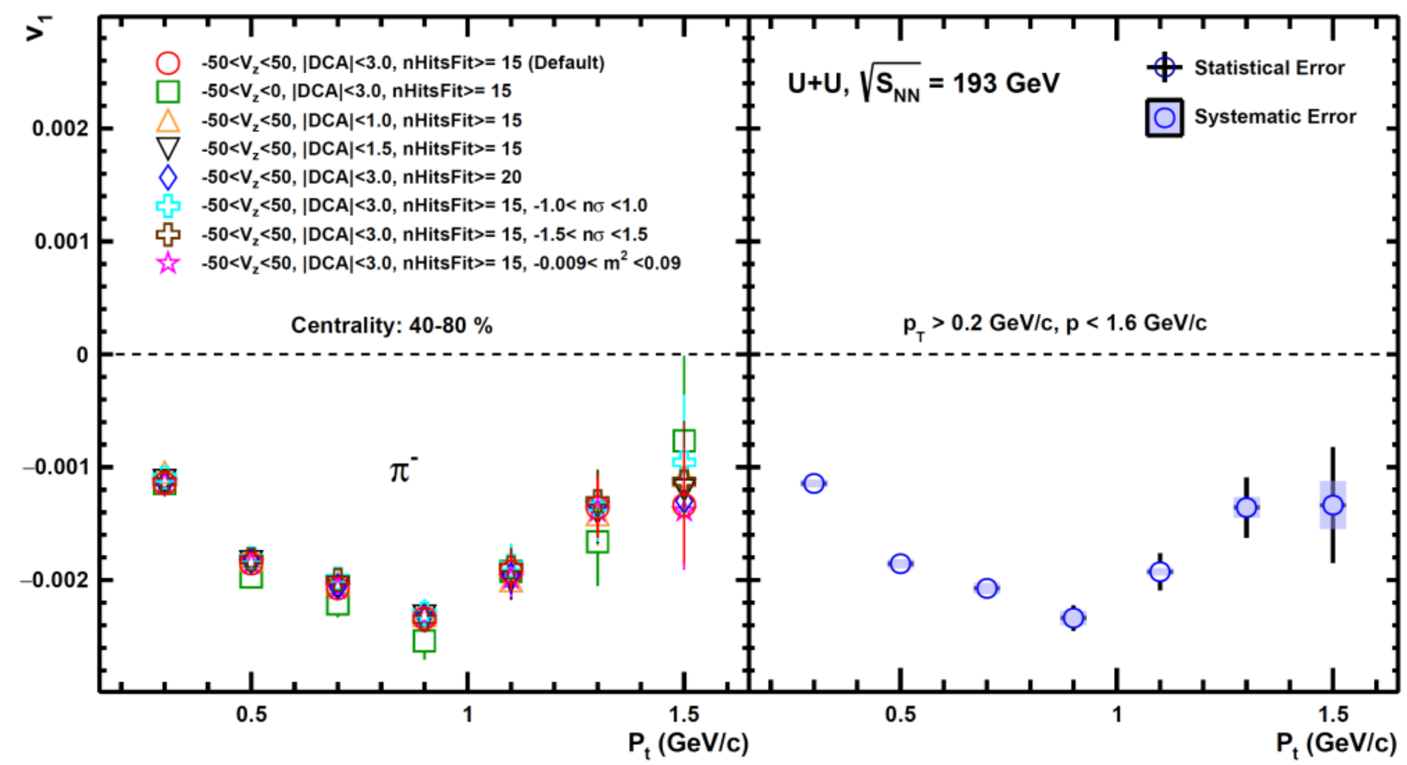
Mid Central (10 - 40)%



Peripheral (40 - 80)%

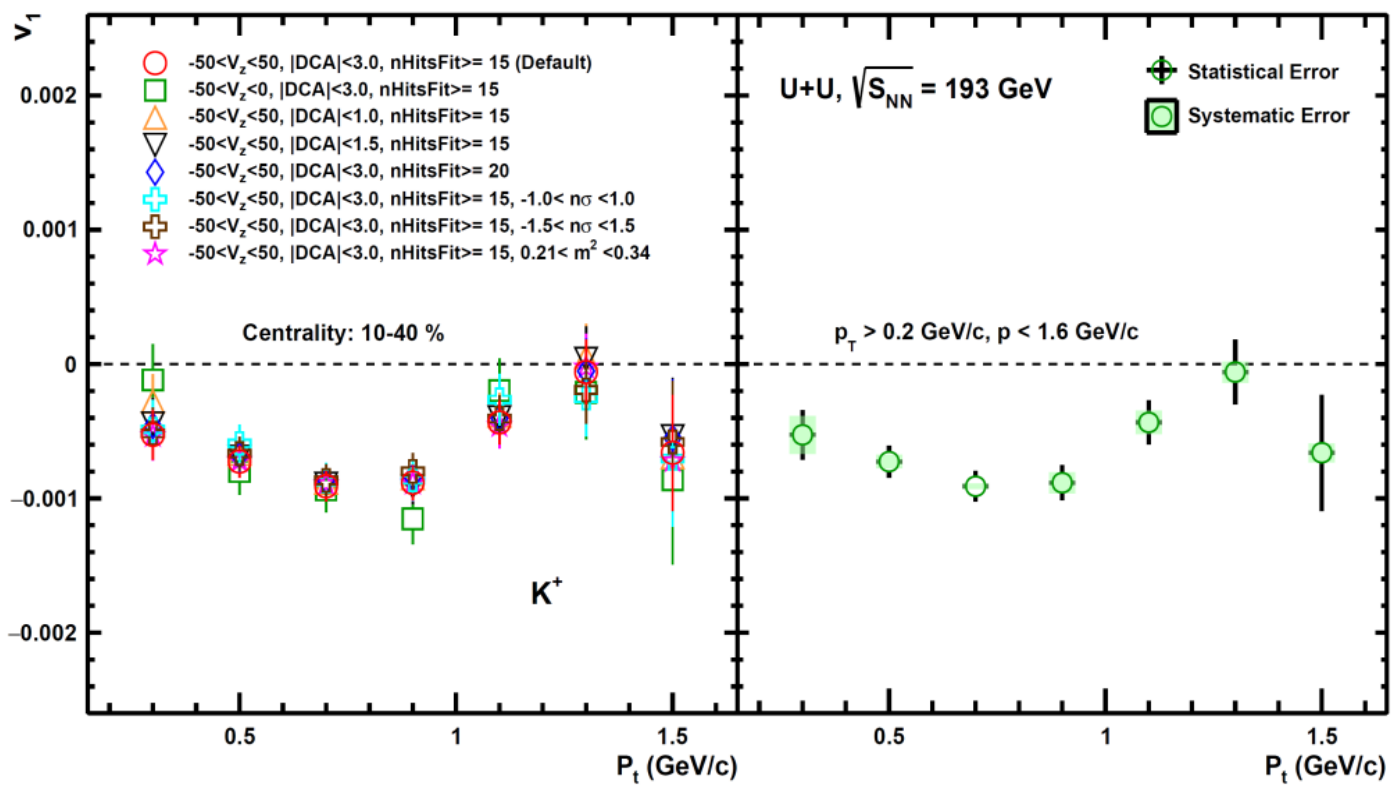


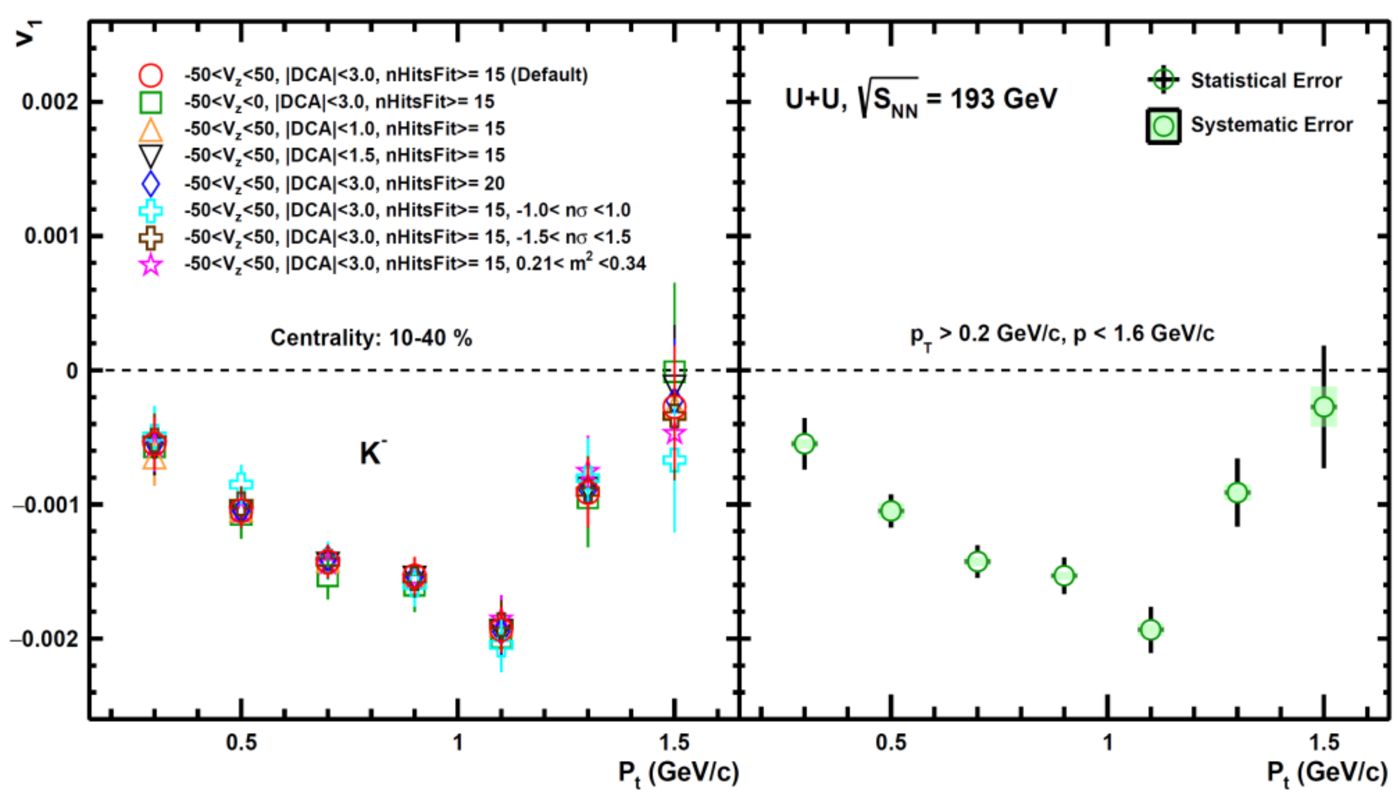




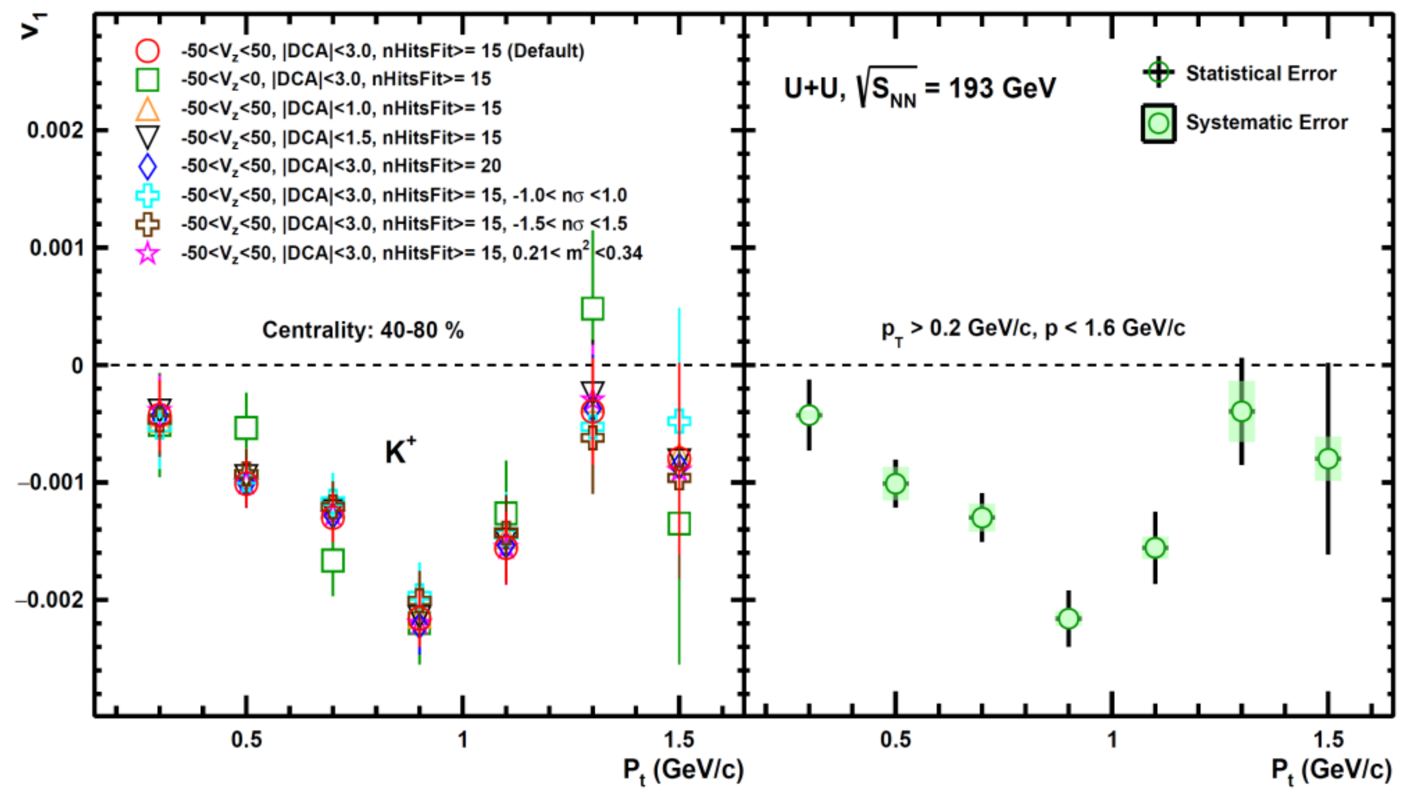
p_t dependent v_1 (Kaon)

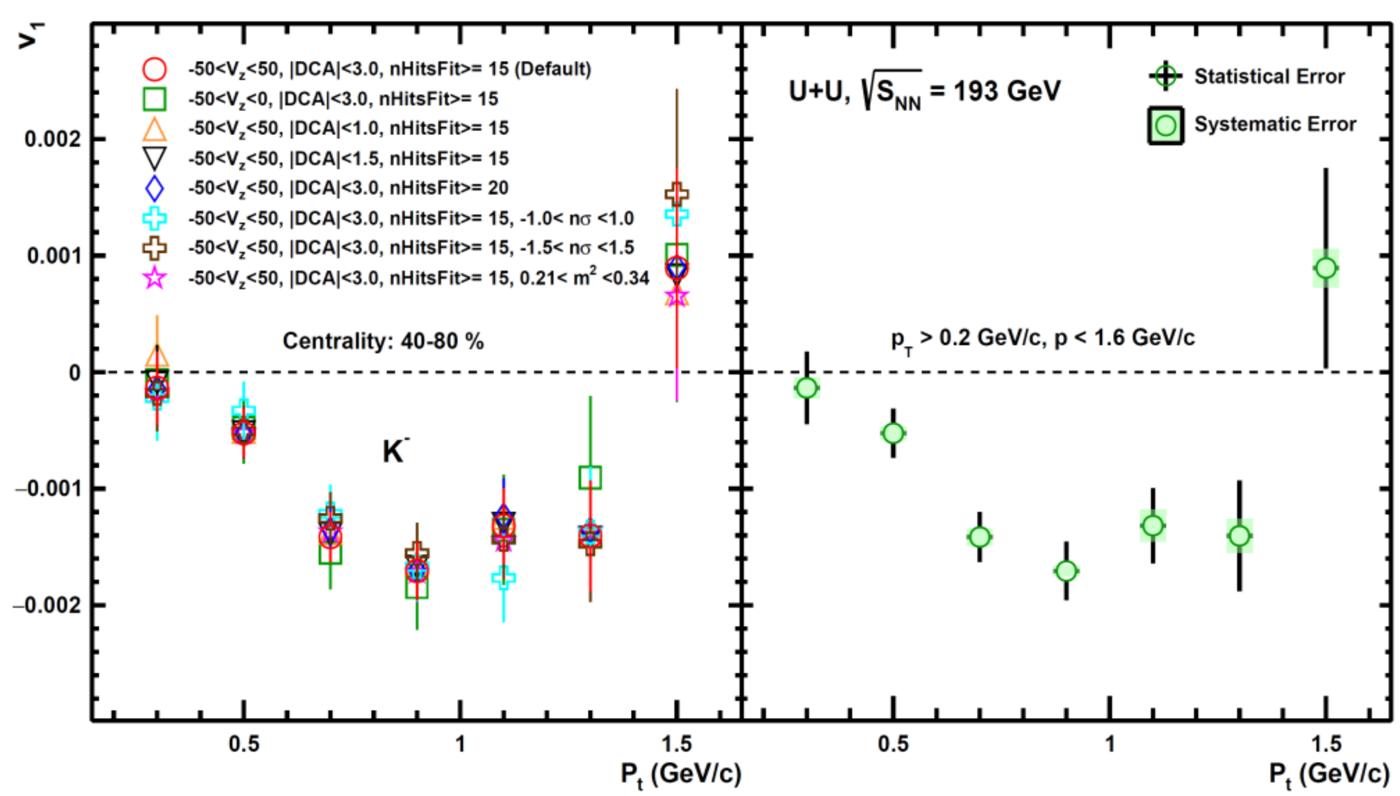
Mid Central (10 -40)%





Peripheral (40 - 80)%

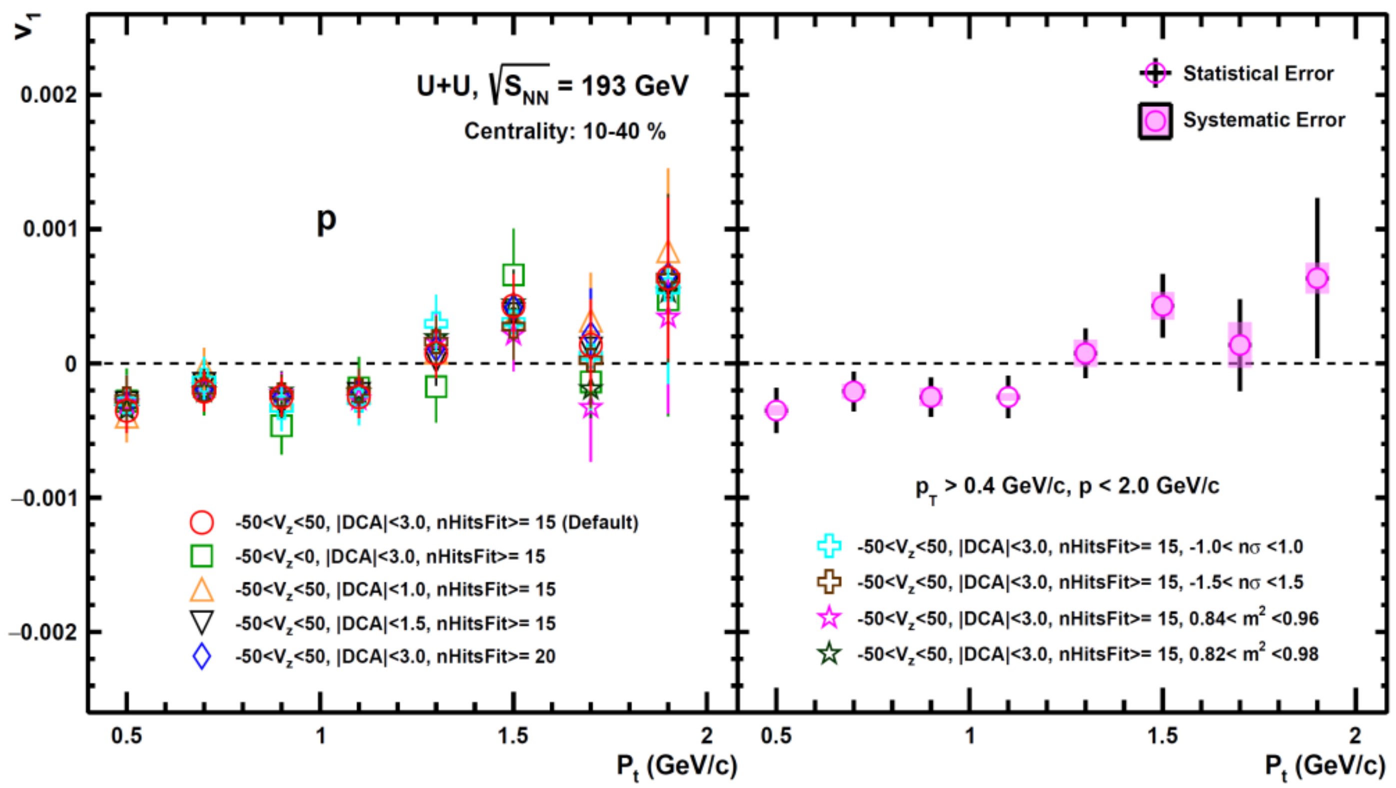


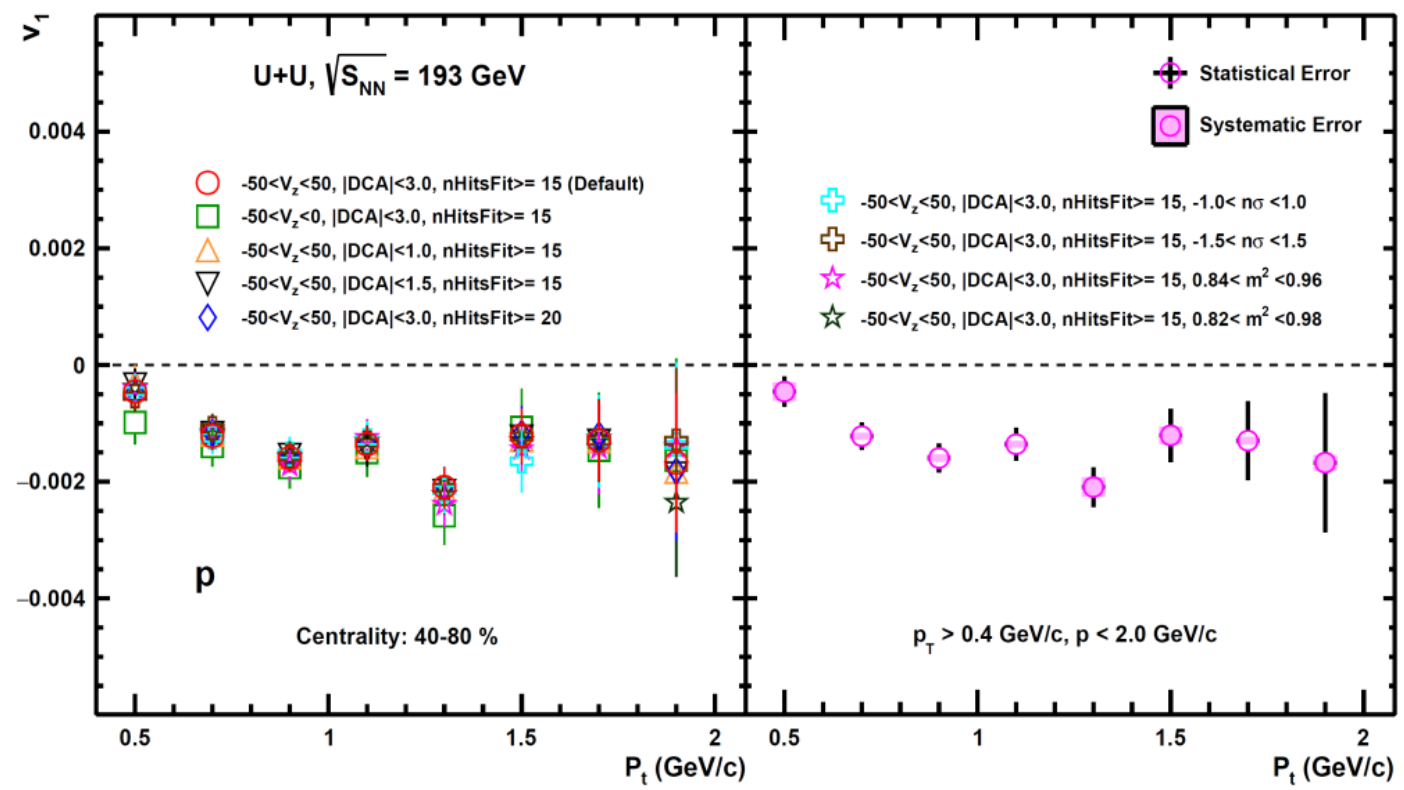


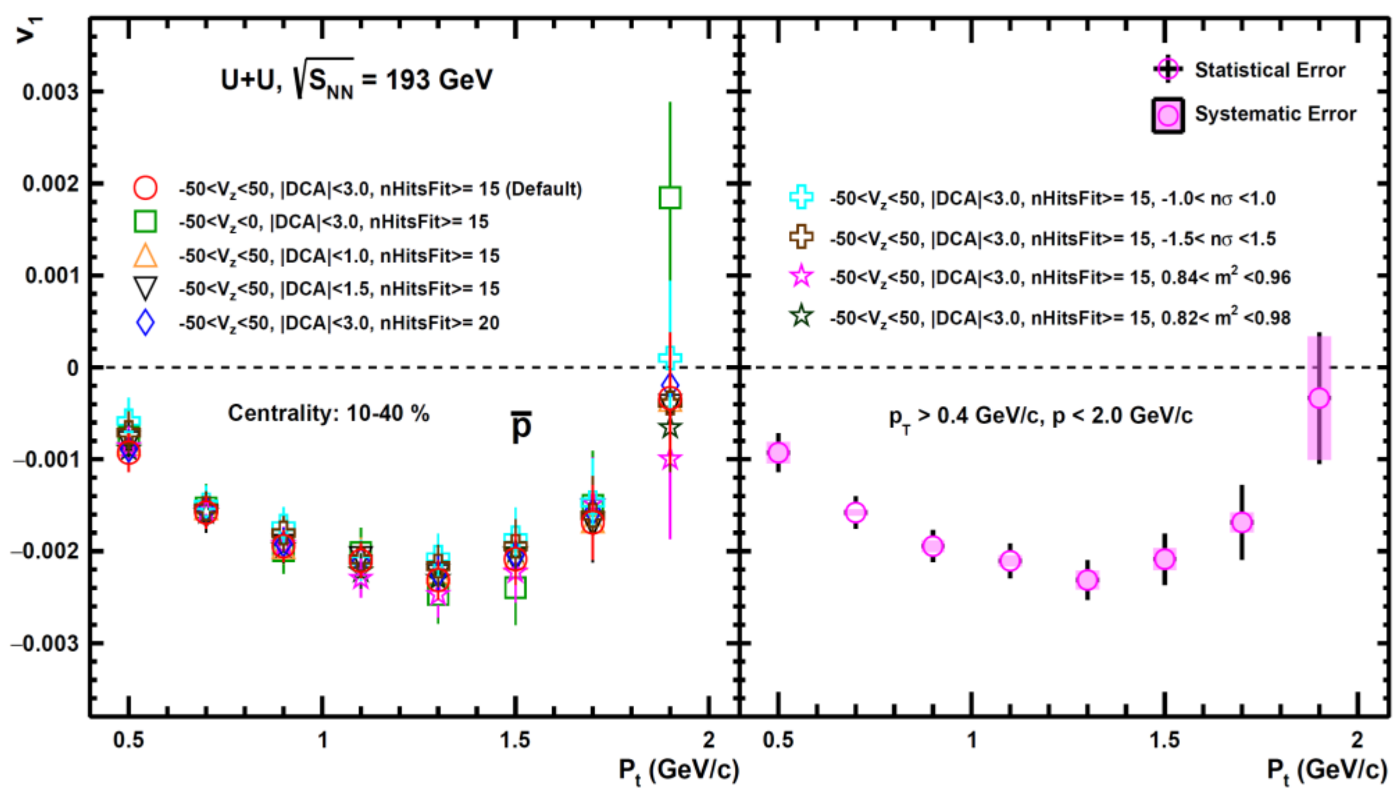
p_t dependent v_1 (Proton)

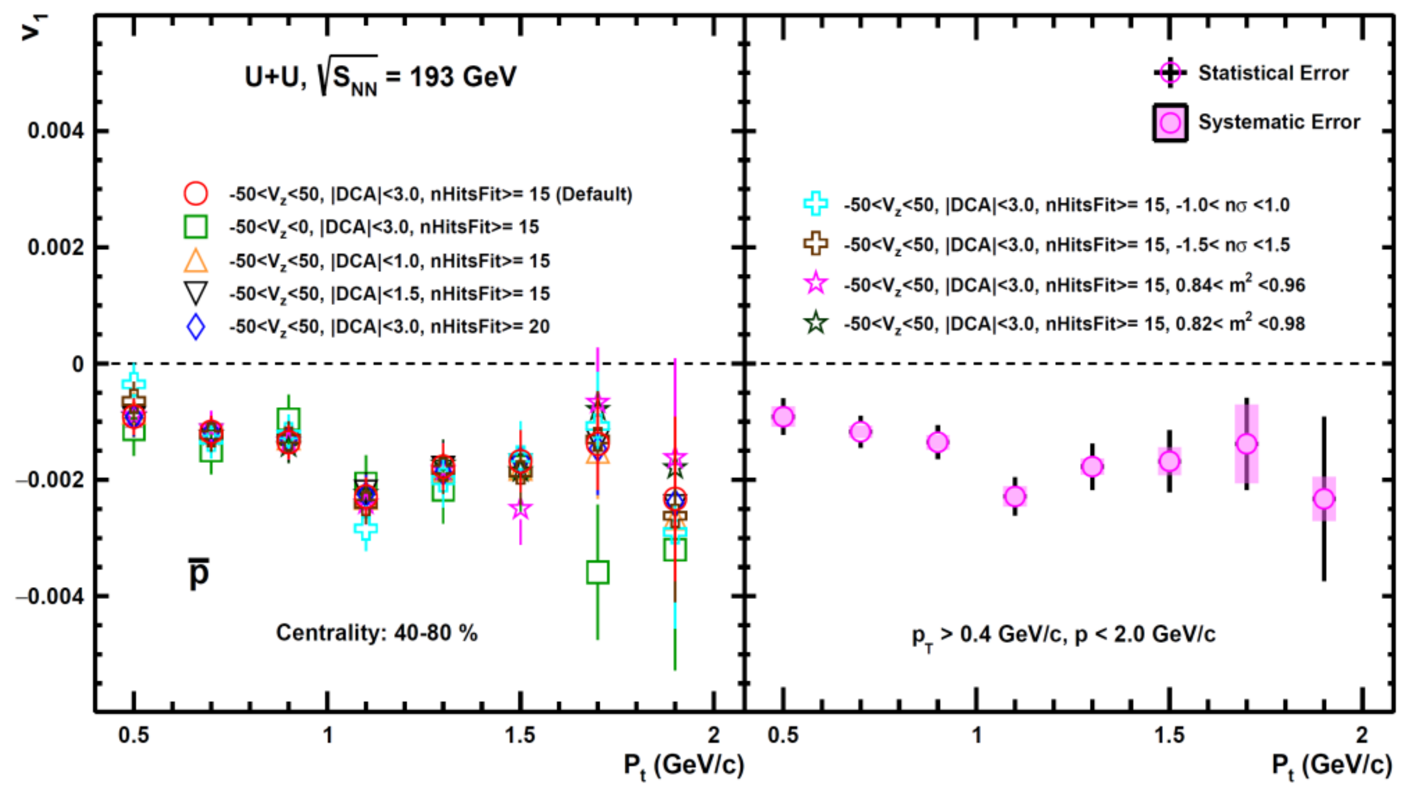
Mid Central (10 -40)%

Peripheral (40 - 80)%



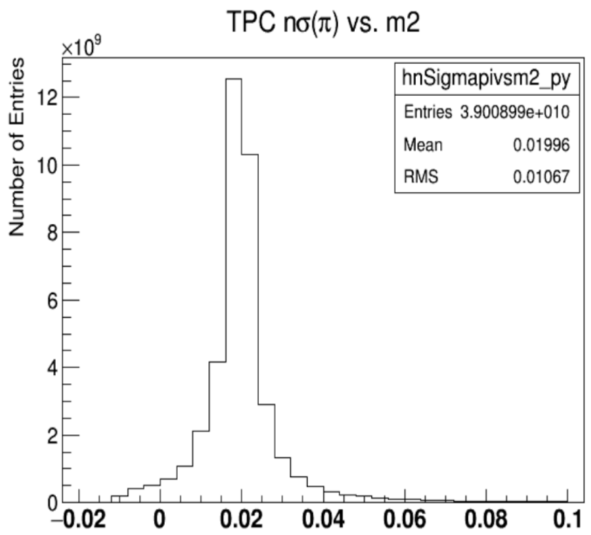




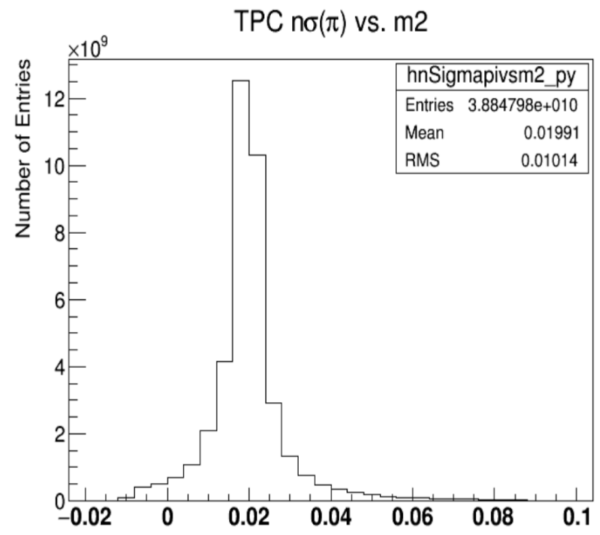


TOF Mass Square Distribution

Pion

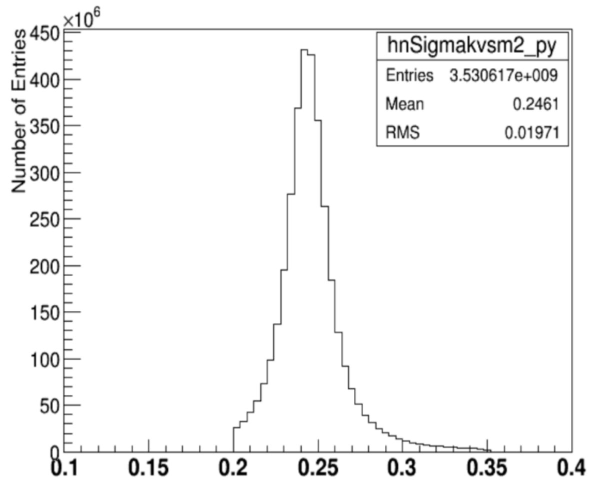


Default: -0.01 – 0.10

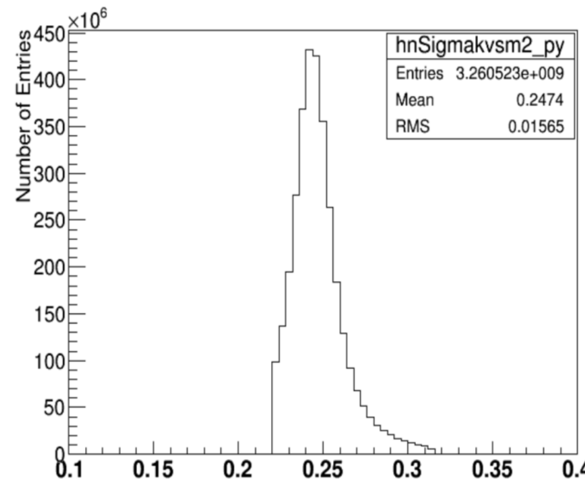


Systematics: -0.009 – 0.09

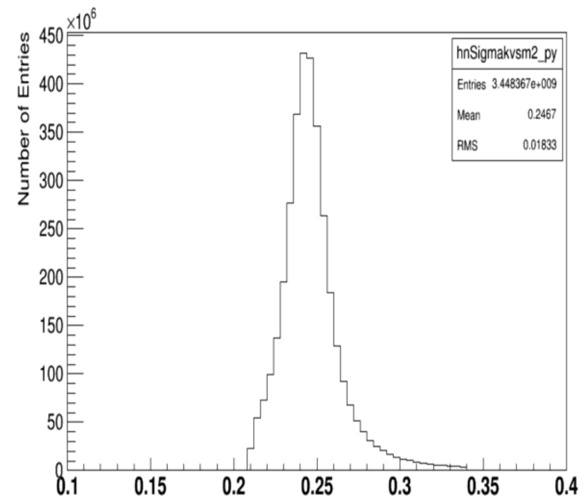
Kaon



Default: 0.20 – 0.35

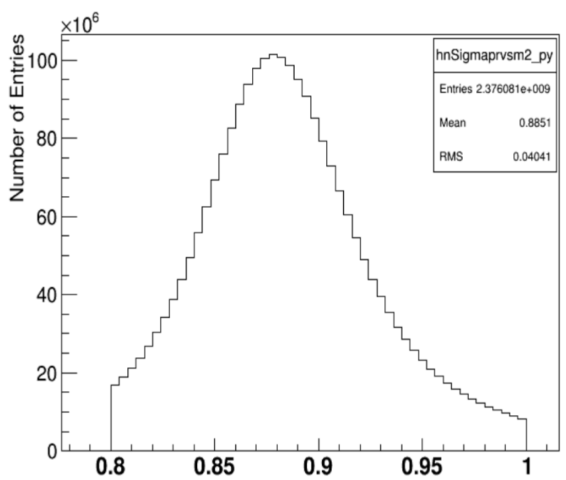


Systematics: 0.22 – 0.315

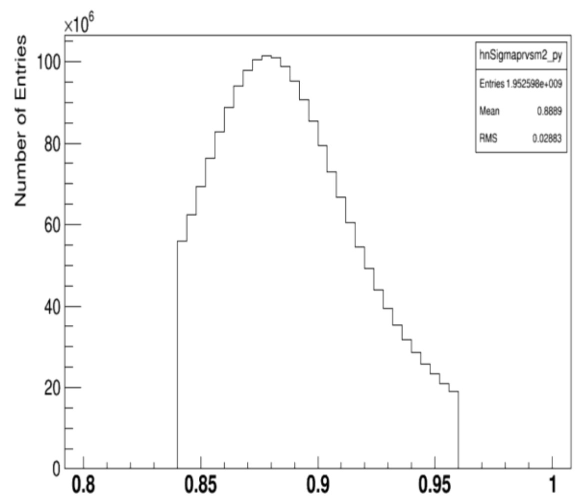


Systematics: 0.21 – 0.34

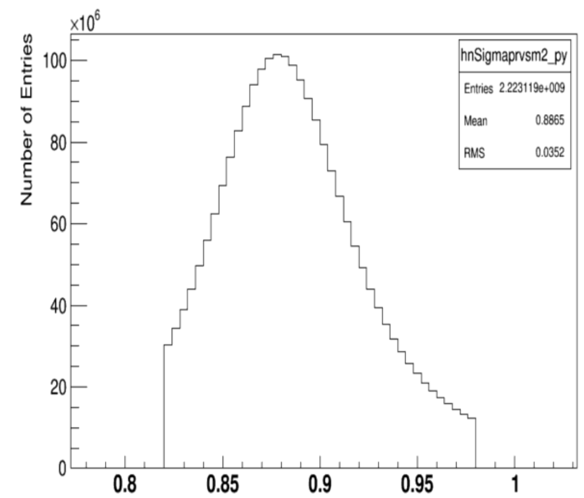
Proton



Default: 0.80 – 1.00

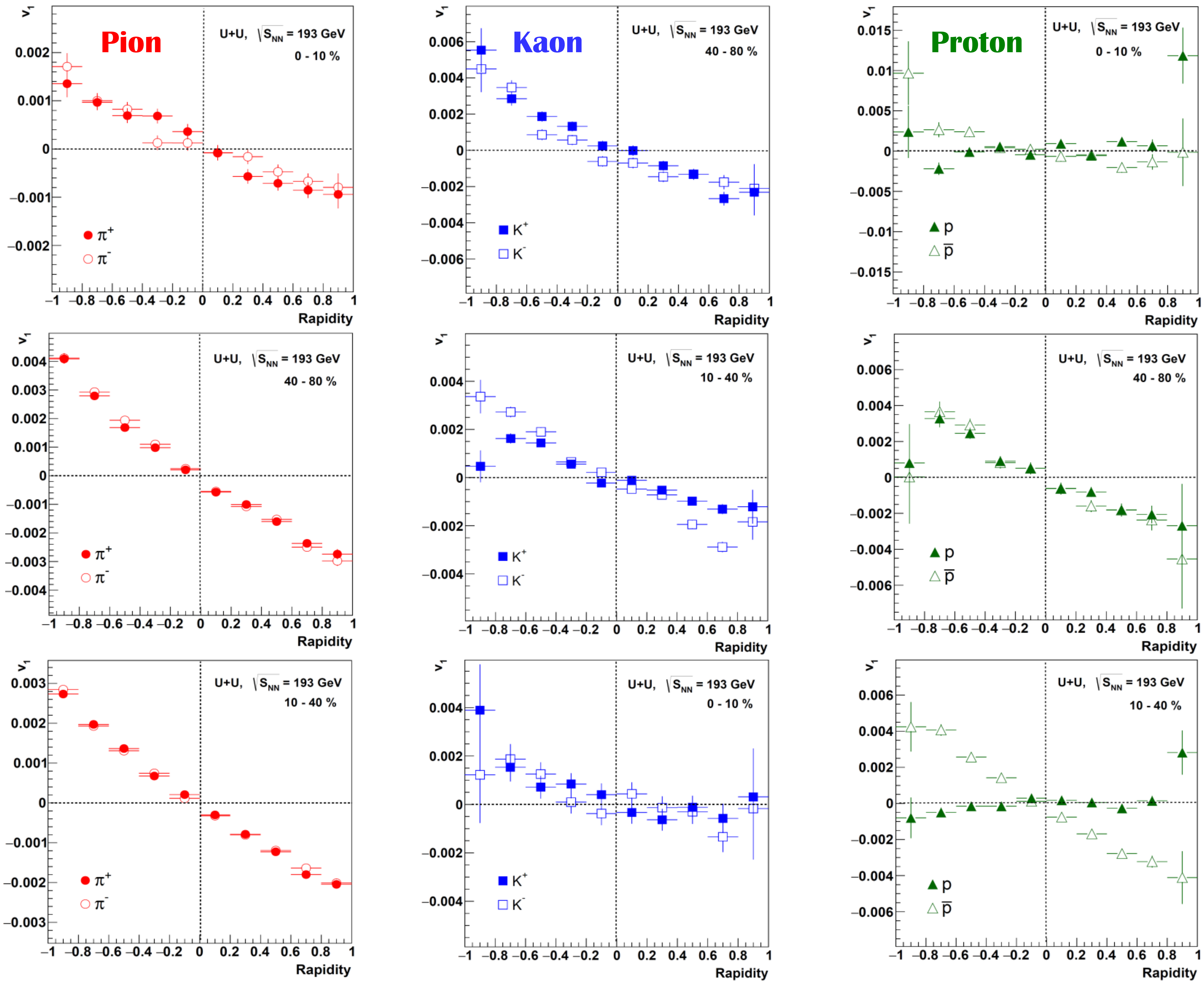


Systematics: 0.84 – 0.96



Systematics: 0.82 – 0.98

Asymmetry in (v_1 vs y) Results



- The U+U collision shows Asymmetry in (v_1 vs y) results