Role of stopping and diffusion of baryons in BES phenomenology

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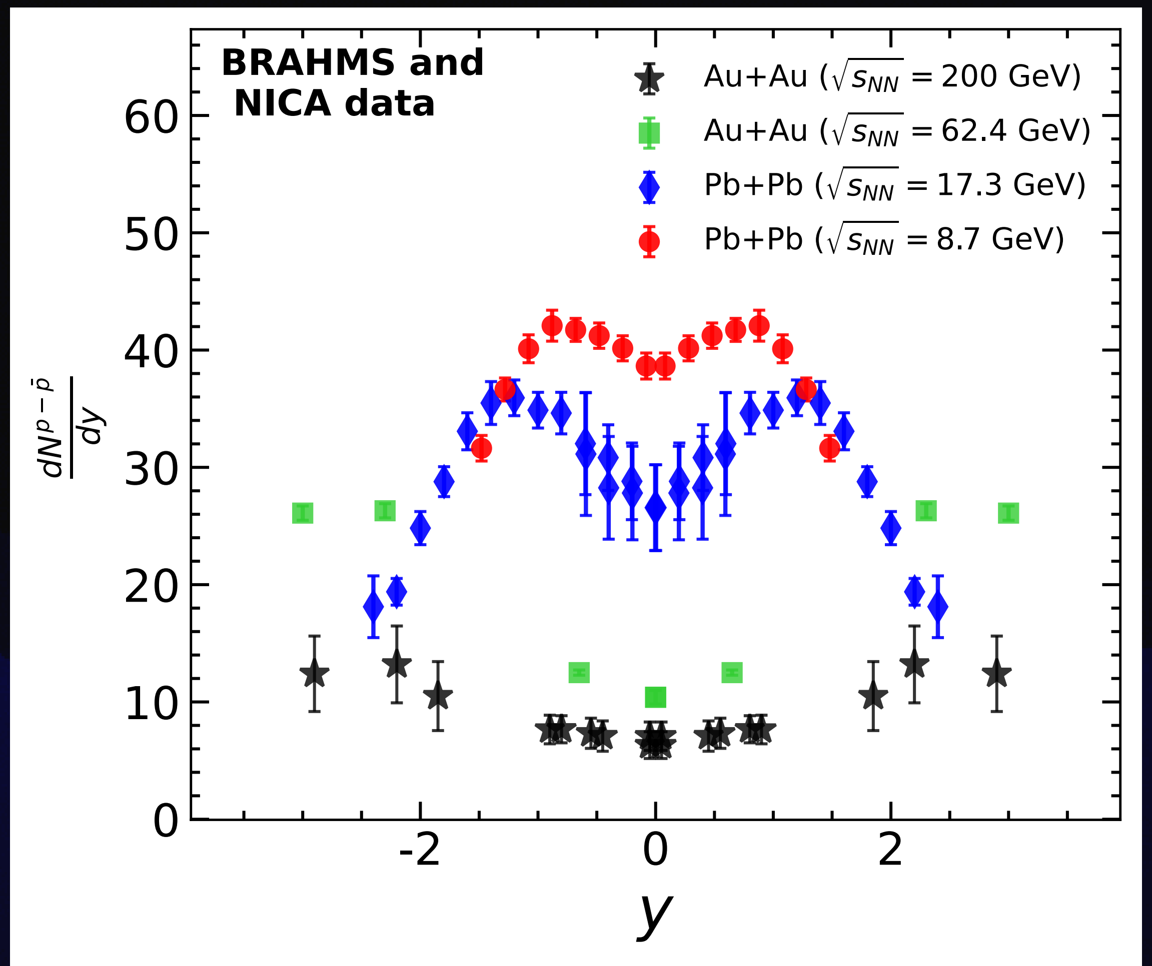
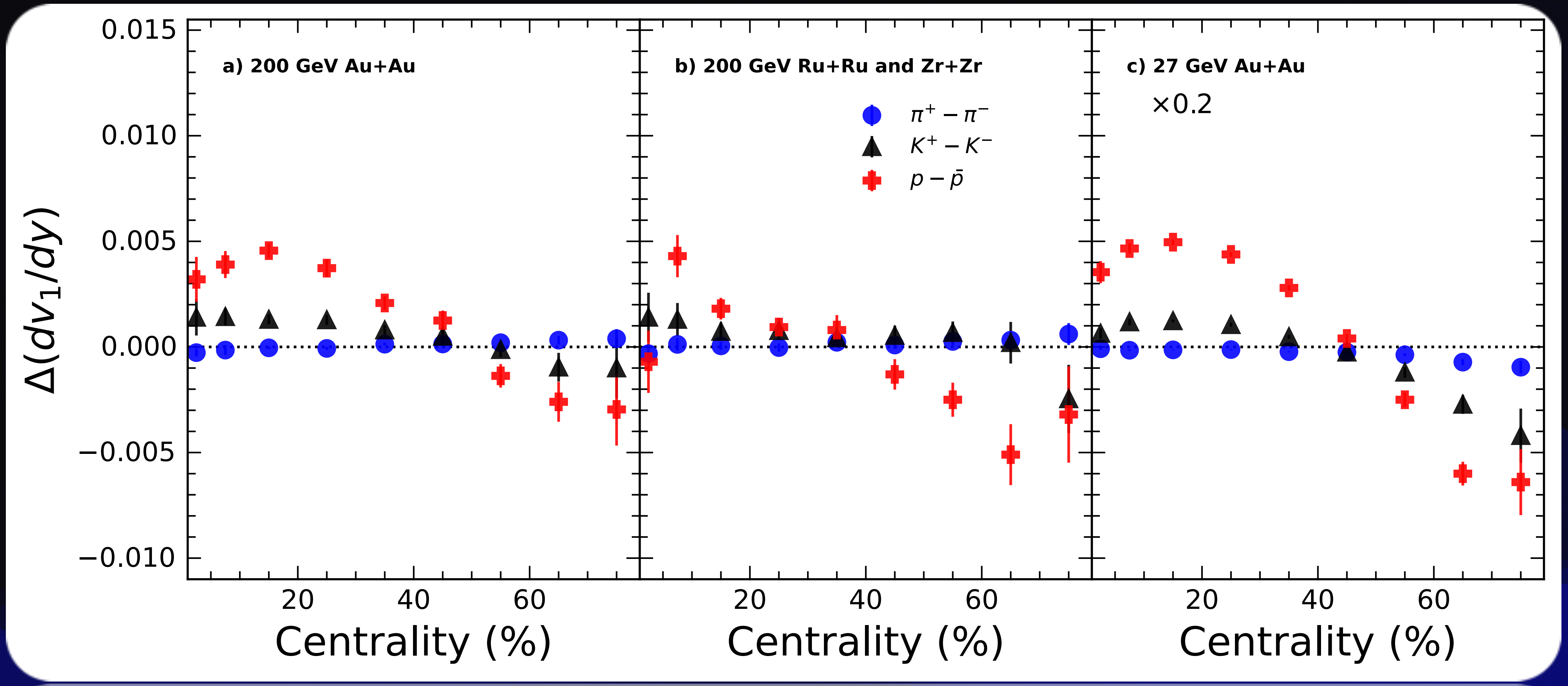
The 1st international workshop on physics at high baryon density at CCNU, Wuhan, China

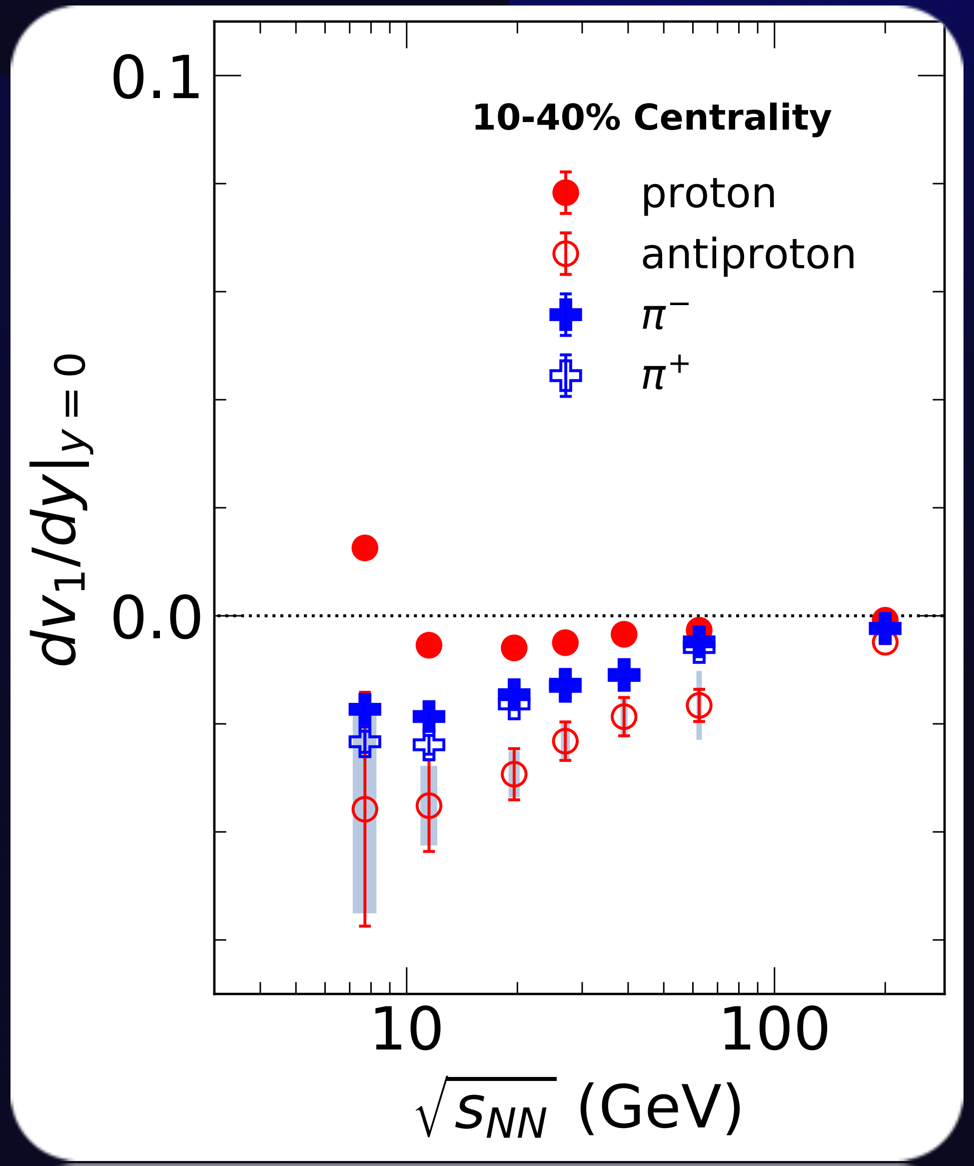
4th Nov. 2024

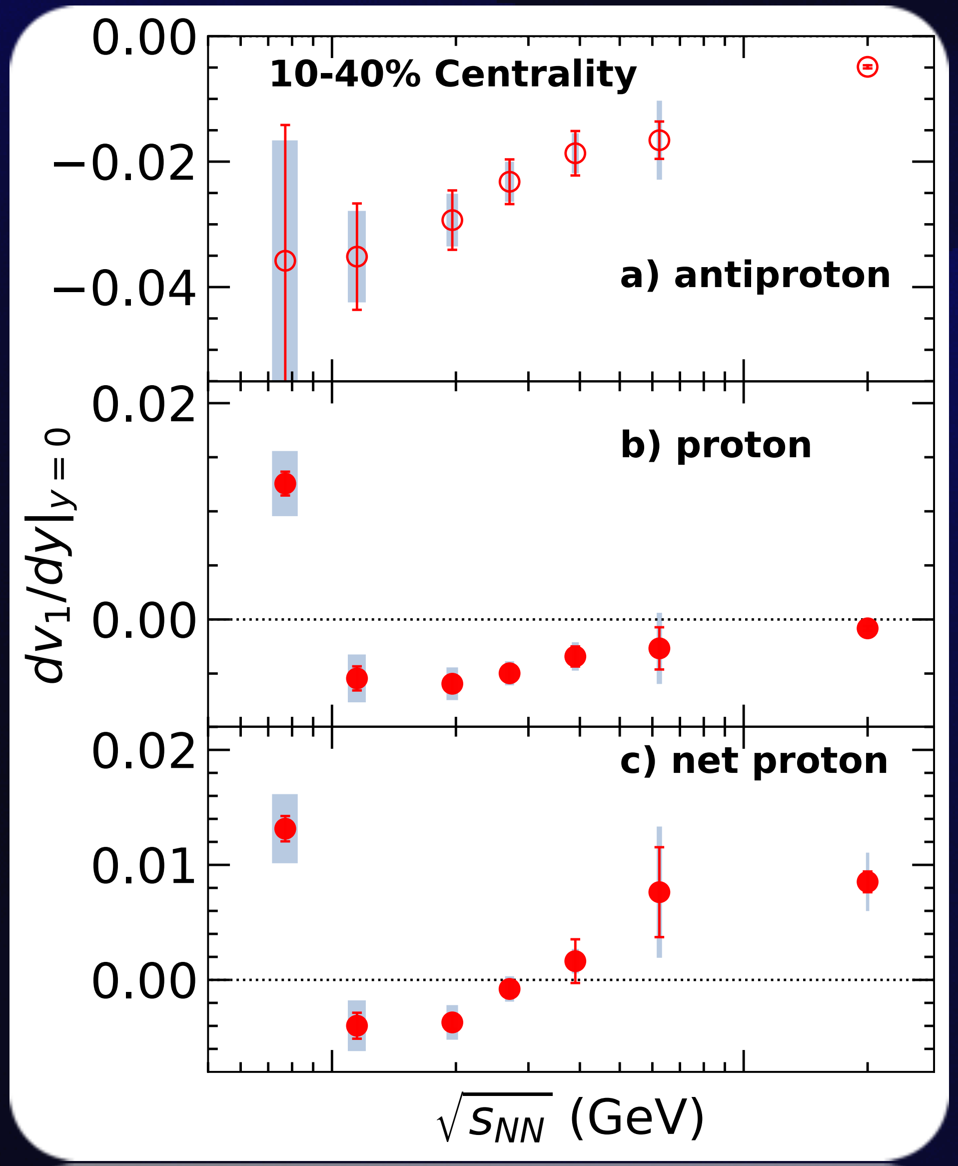
Baryon stopping related measurements at STAR and related physics interest



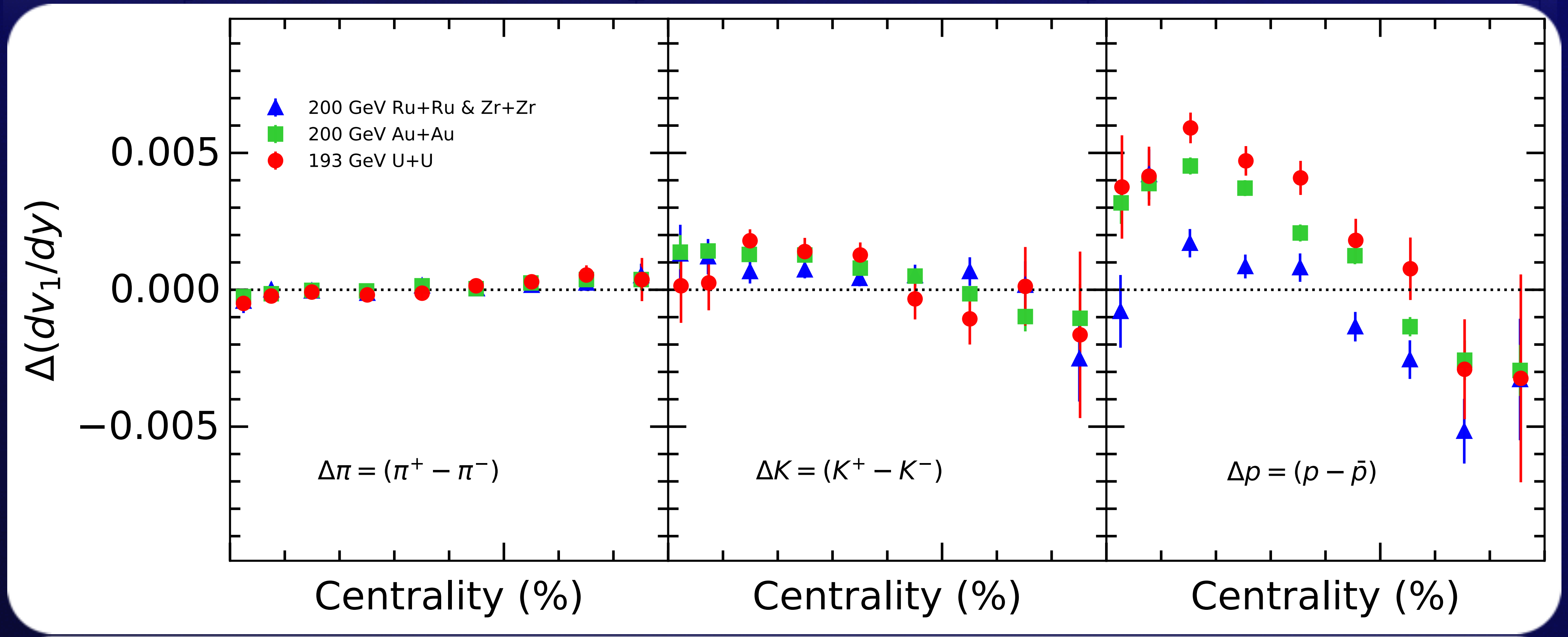
PRX (2024) 14, 011028 (STAR collaboration)







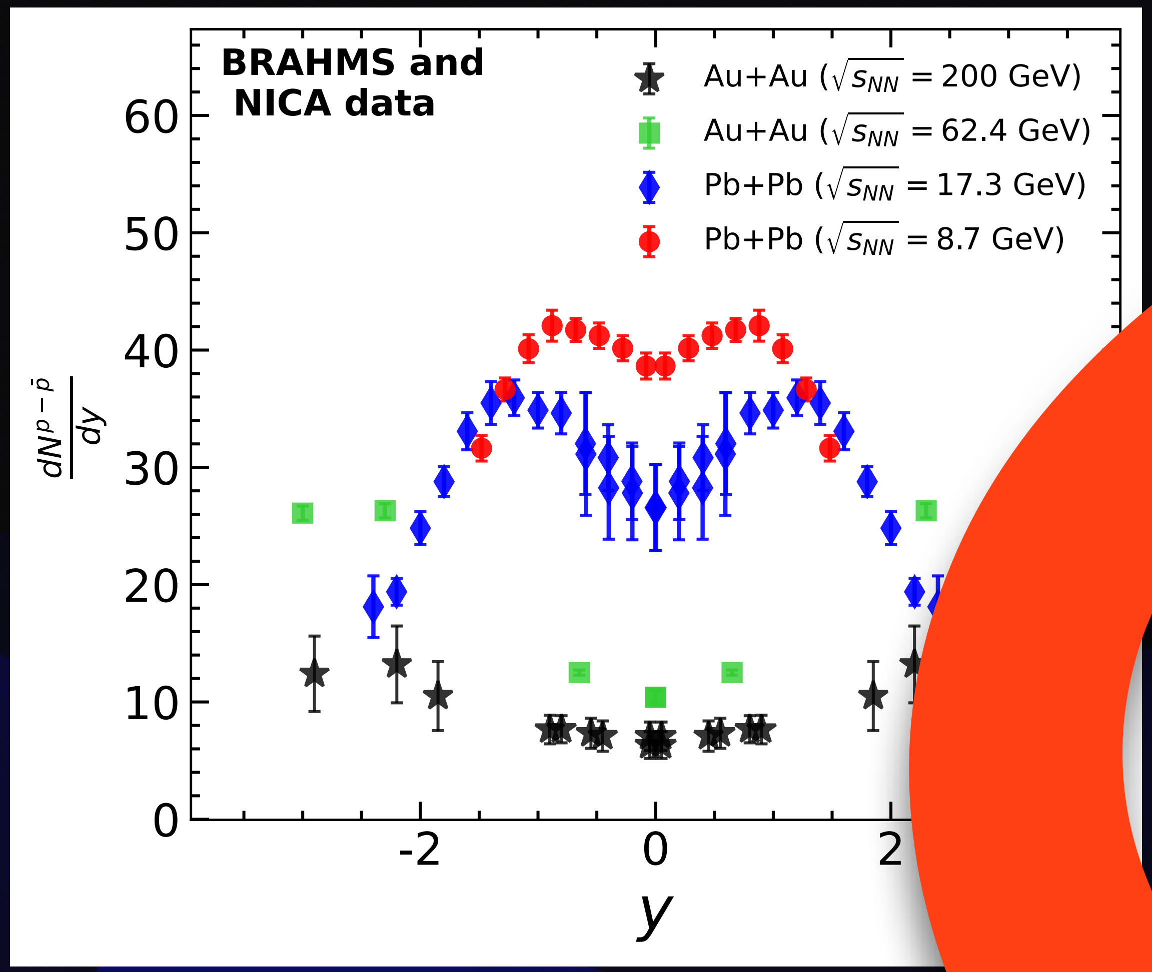
STAR collab. SQM, Strasbourg, 2024



STAR Collaboration PRL, 120, 62301 (2018)

STAR Collaboration PRL, 112, 163201 (2014)

Baryon stopping related measurements at STAR and related physics interest



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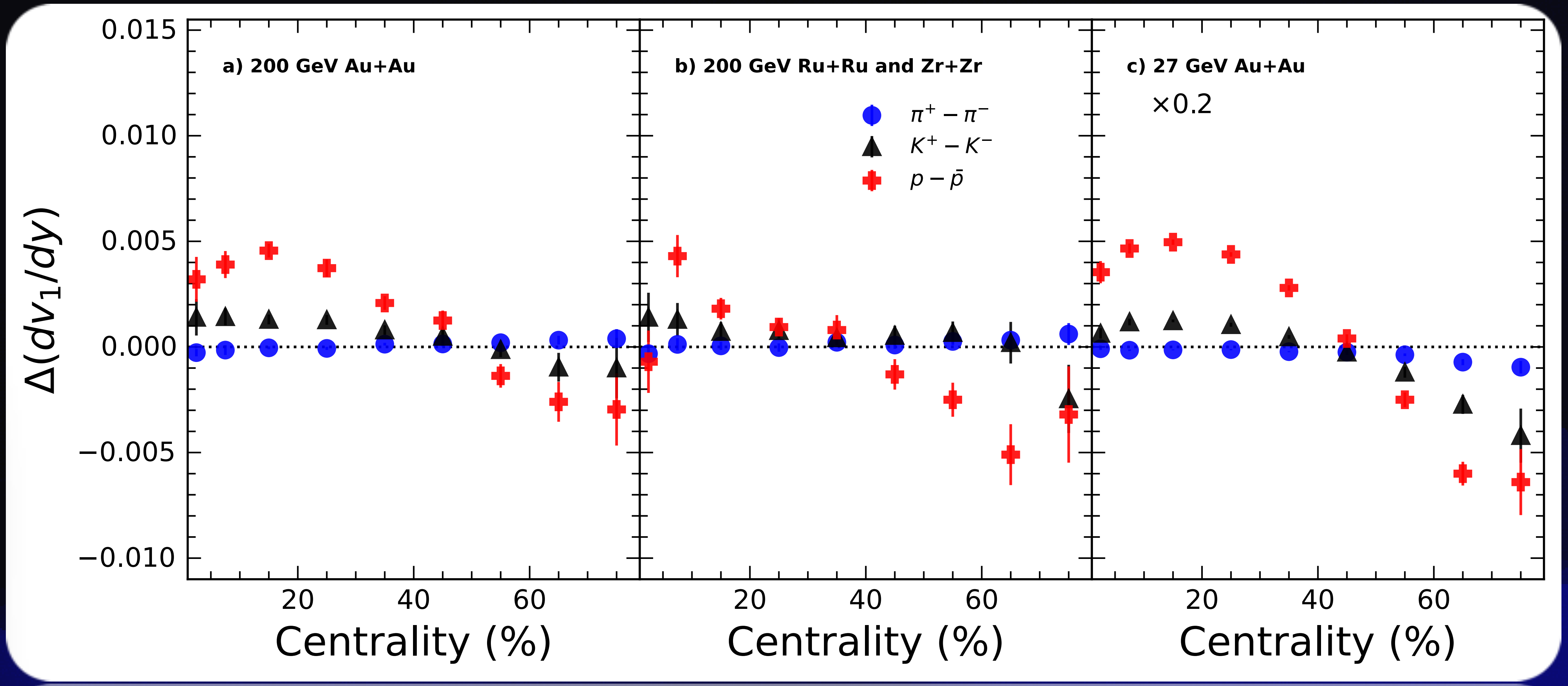
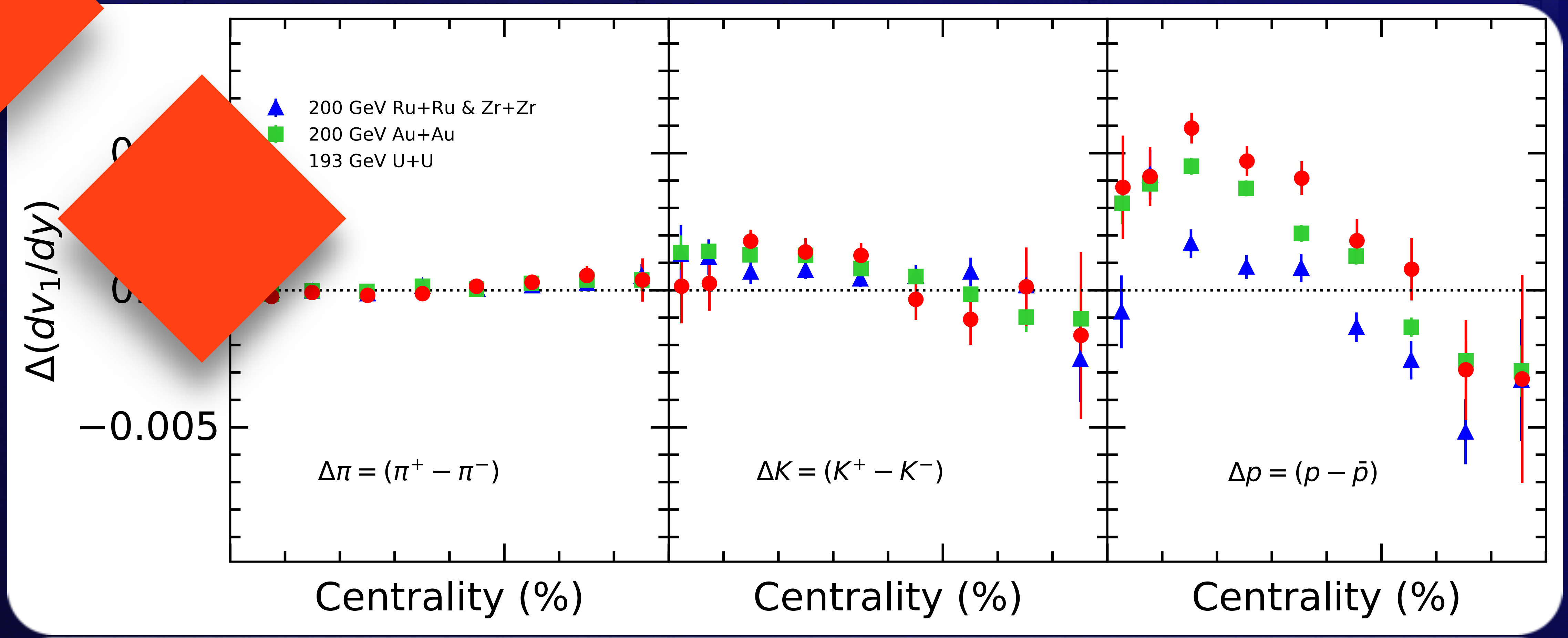
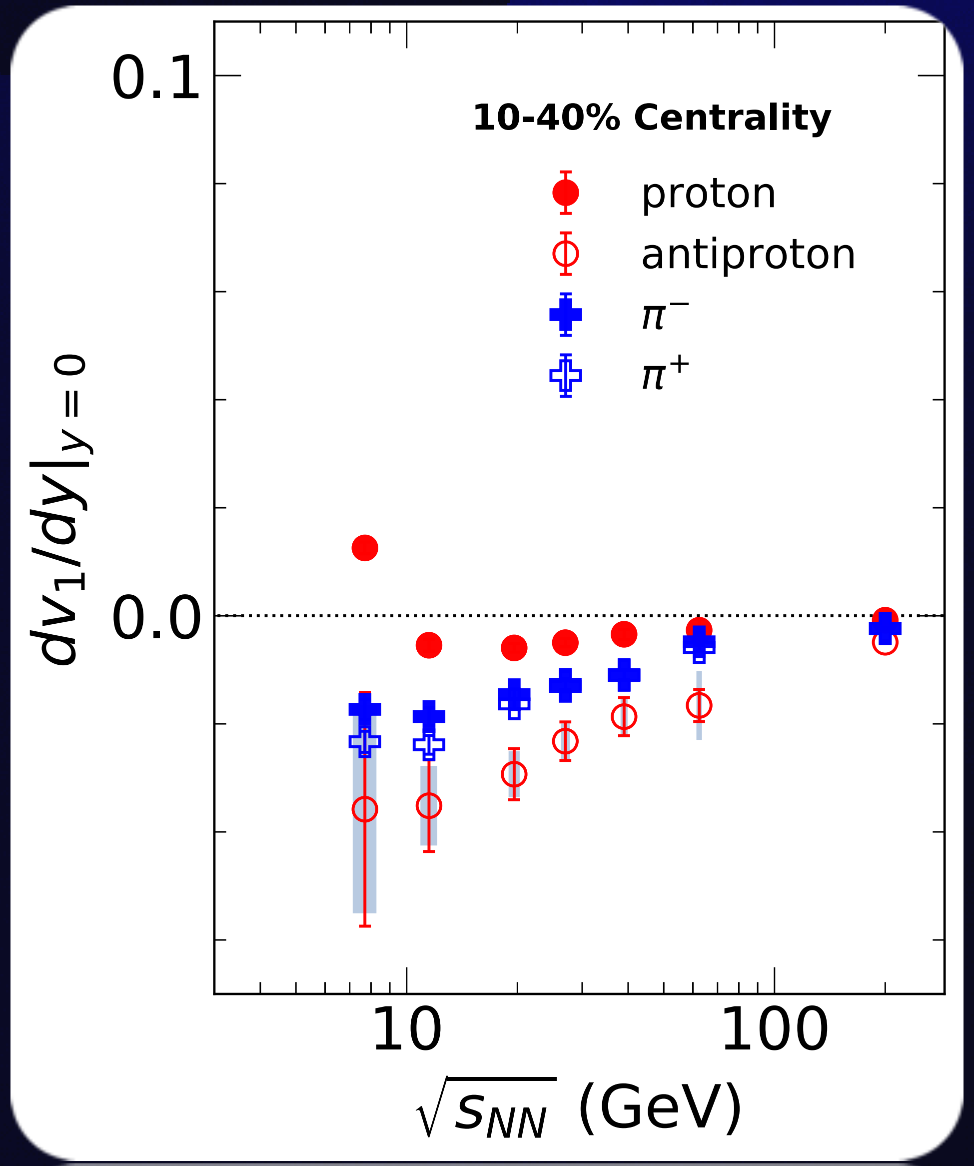
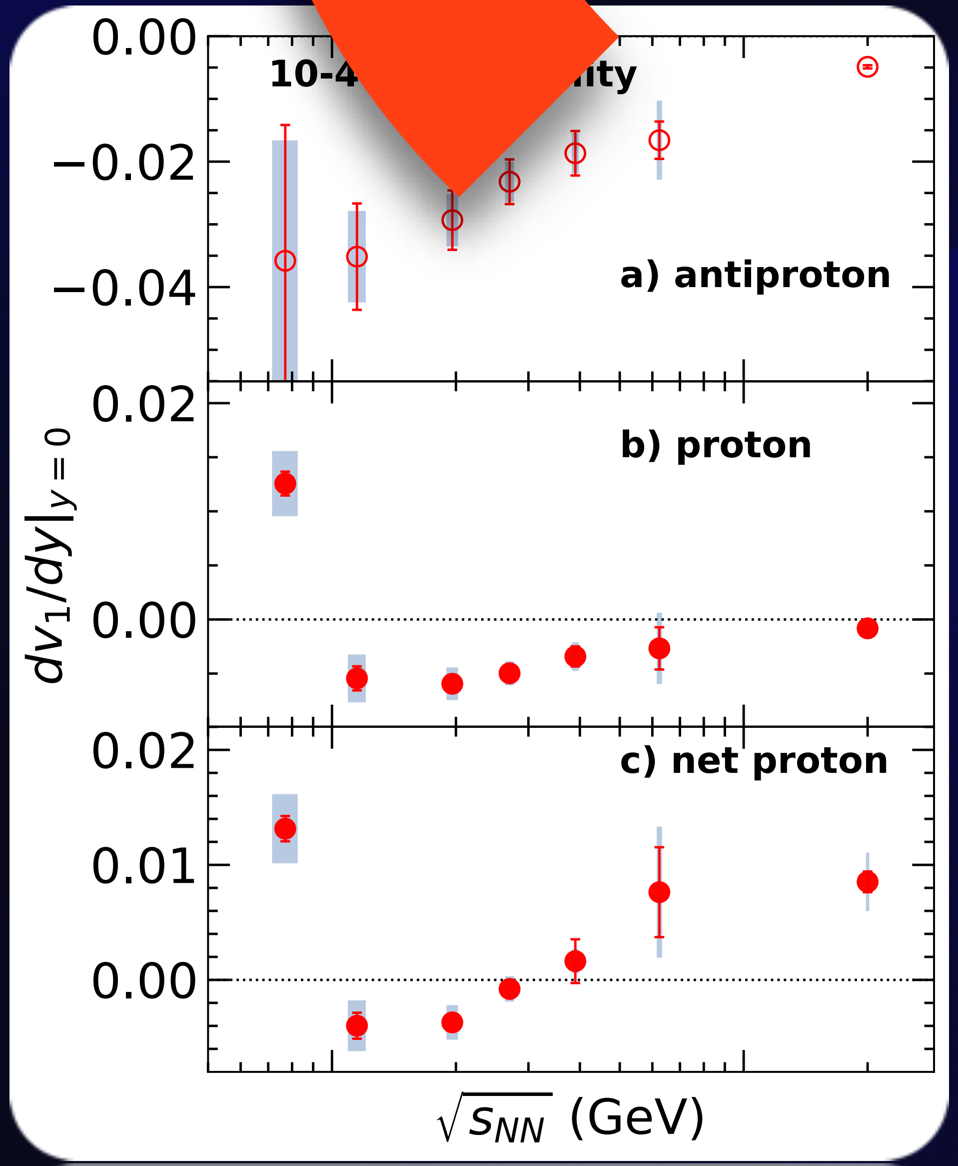


STAR collab. SQM, Strasbourg, 2024





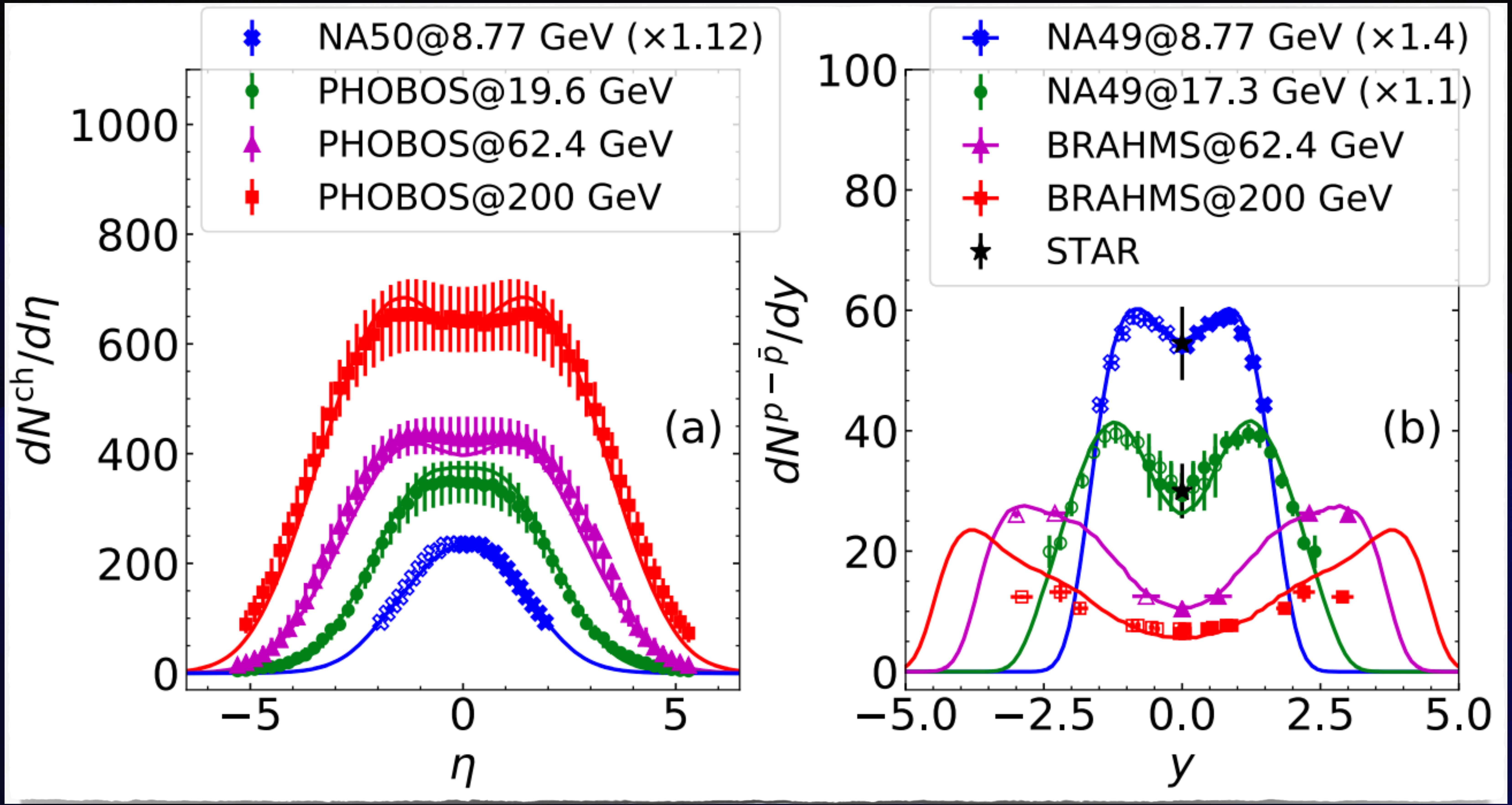


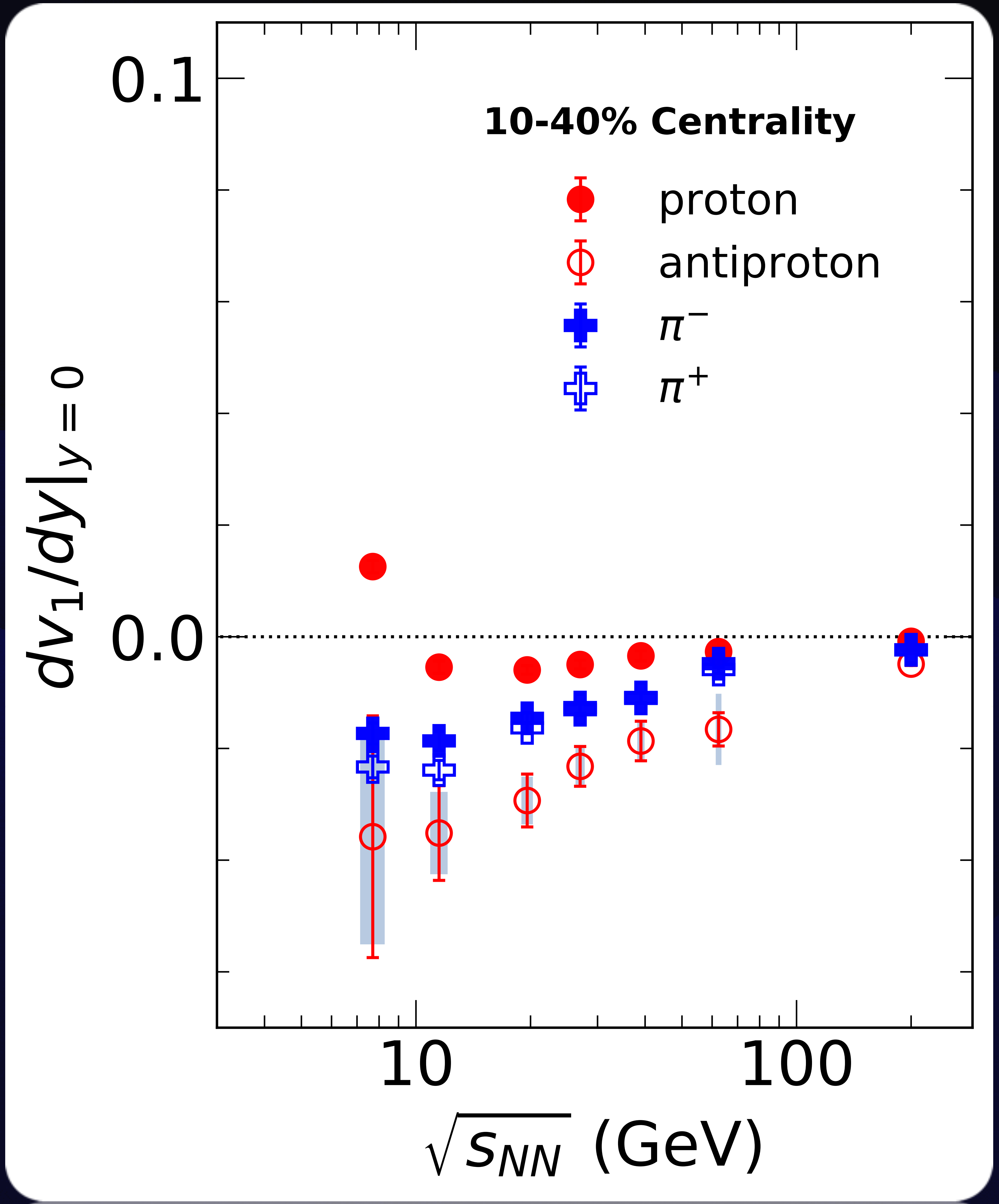
STAR Collaboration PRL, 120, 62301 (2018)

STAR Collaboration PRL, 112, 163201 (2014)

v_1 measurements at STAR and related physics interest

Lipei Du, Chun Shen, Charles Gale, Sangyong Jeon, PRC, 108, 4 (2023)

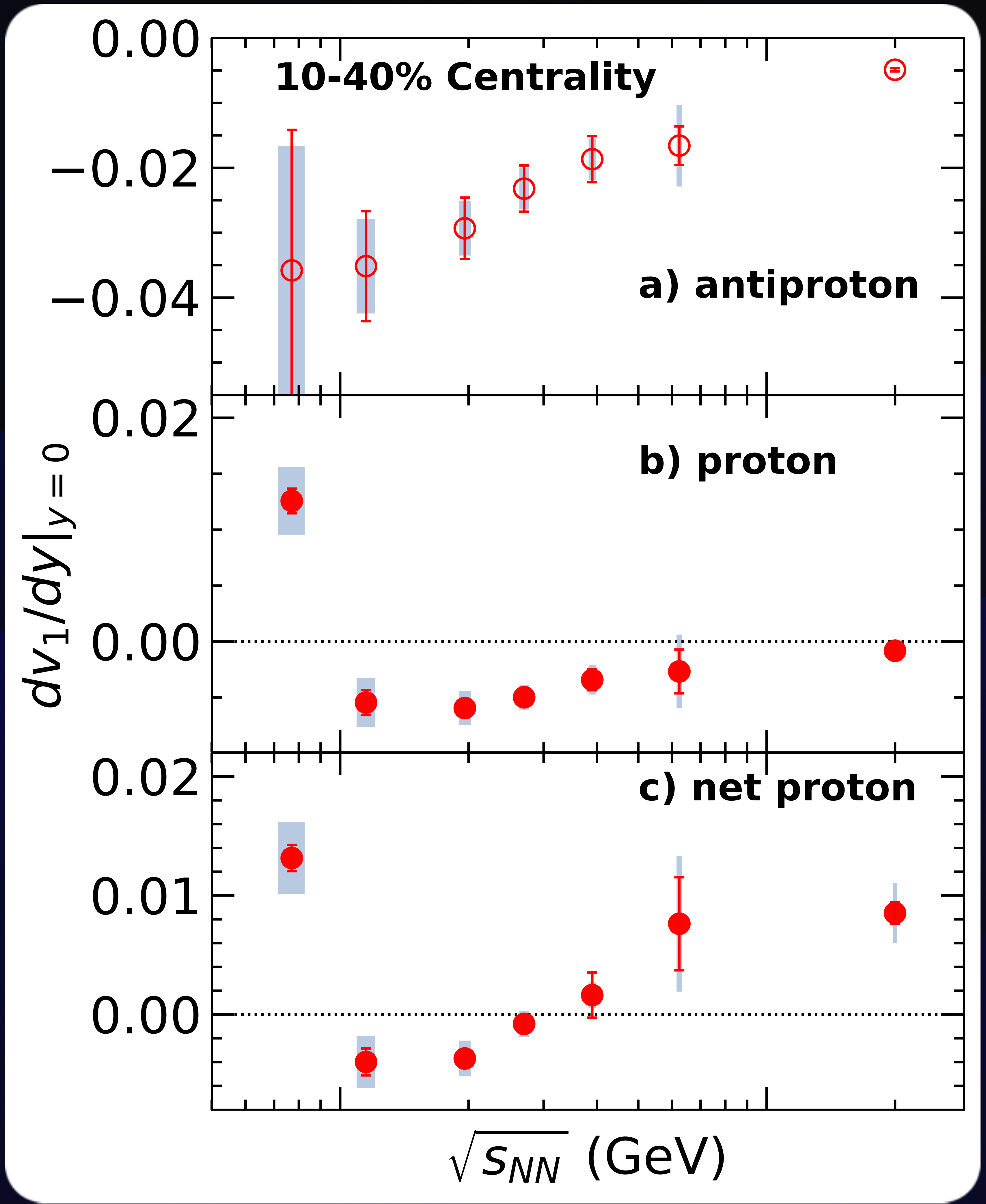




STAR Collaboration PRL, 112, 163201 (2014)

Lipei Du, Chun Shen, Charles Gale, Sangyong Jeon, PRC, 108, 4 (2023)

Feature	Physics	status
Splitting between proton and anti-proton increases with beam energy	Initial baryon stopping	Hydro model only explain proton Not Antiproton

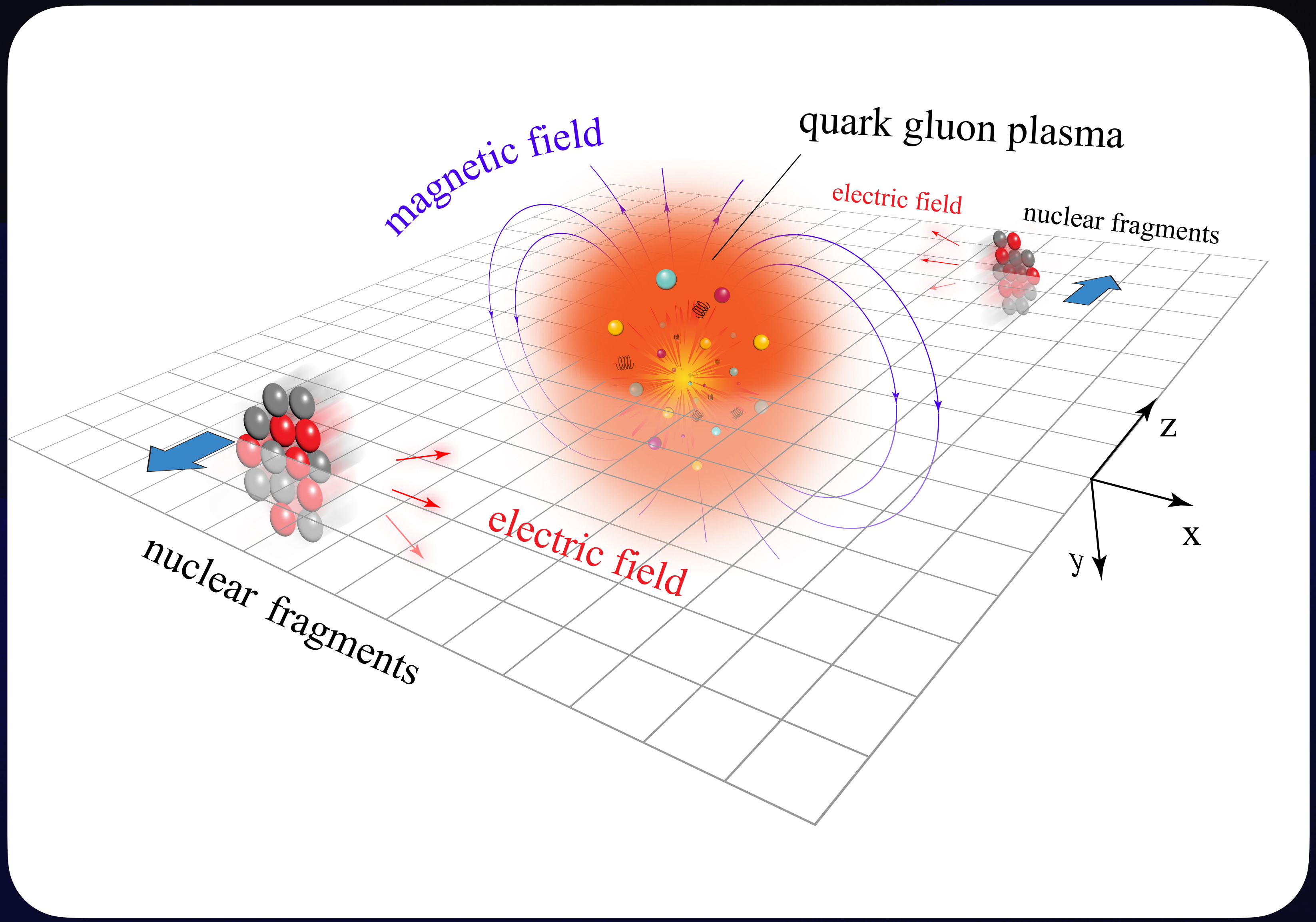


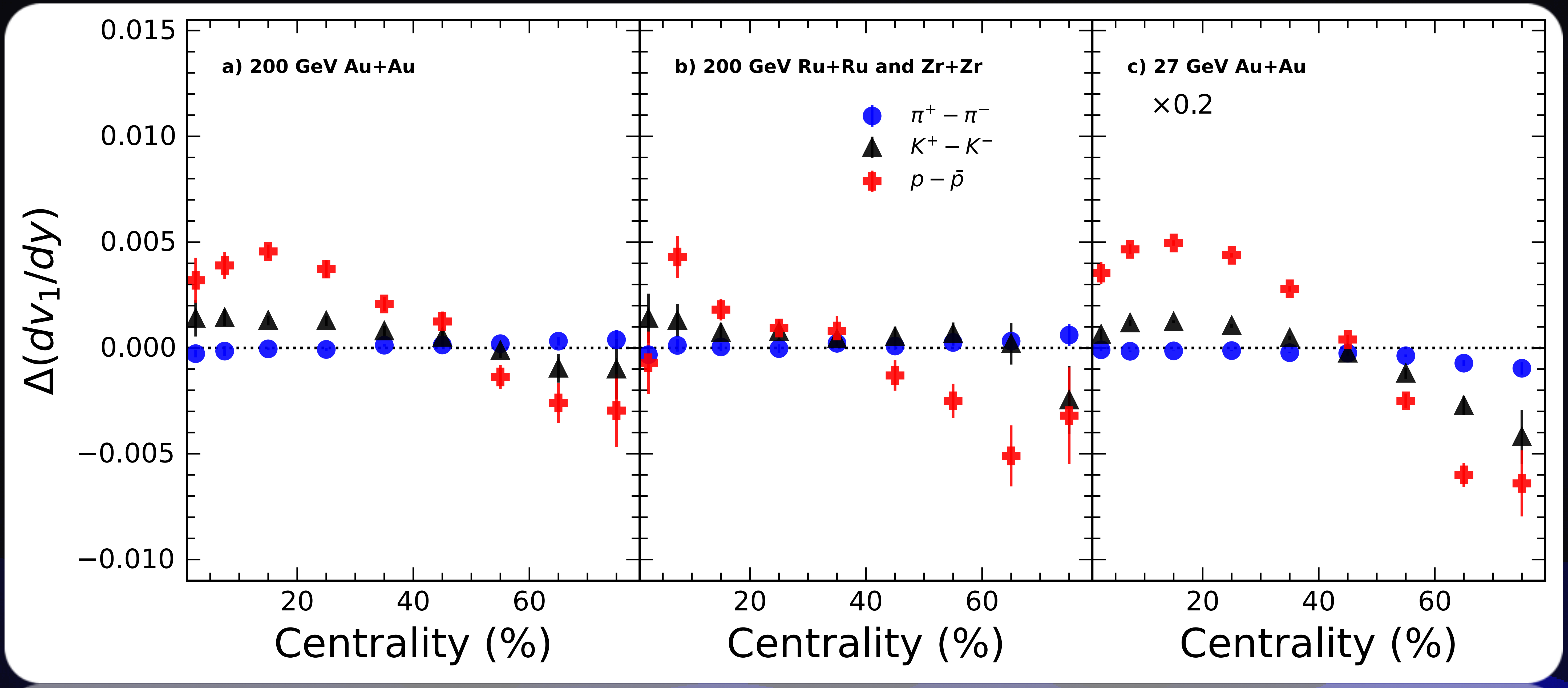
STAR Collaboration PRL, 112, 163201 (2014)

$$[v_1(y)]_{Net-p} = \frac{\frac{dN^p}{dy}[v_1(y)]_p - \frac{dN^{\bar{p}}}{dy}[v_1(y)]_{\bar{p}}}{\frac{dN^{p-\bar{p}}}{dy}}$$

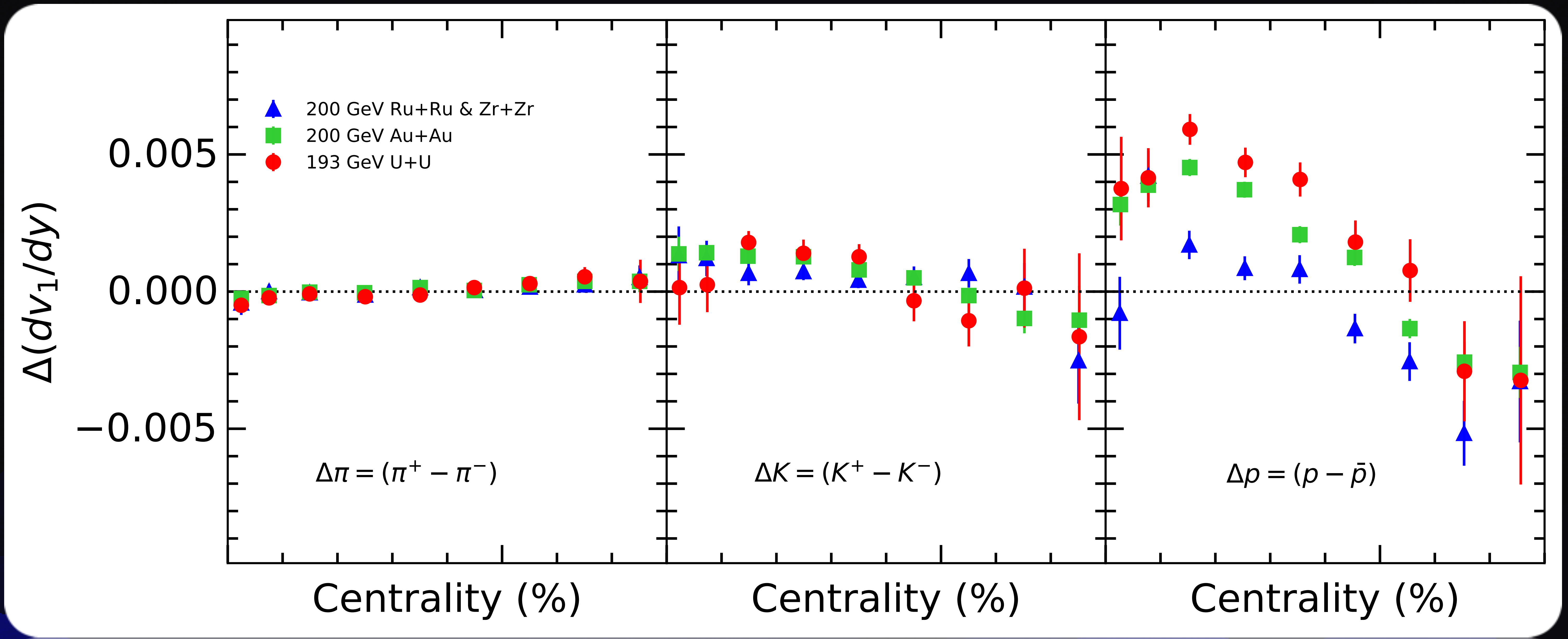
Feature	Physics	status
Sign change of proton and double sign change of net proton	Initial baryon stopping and Signature of 1st order phase transition	No model captures

PRX (2024) 14, 011028 (STAR collaboration)





Feature	Physics	status
Sign change at larger centrality	Signature of EM field ?	No model captures



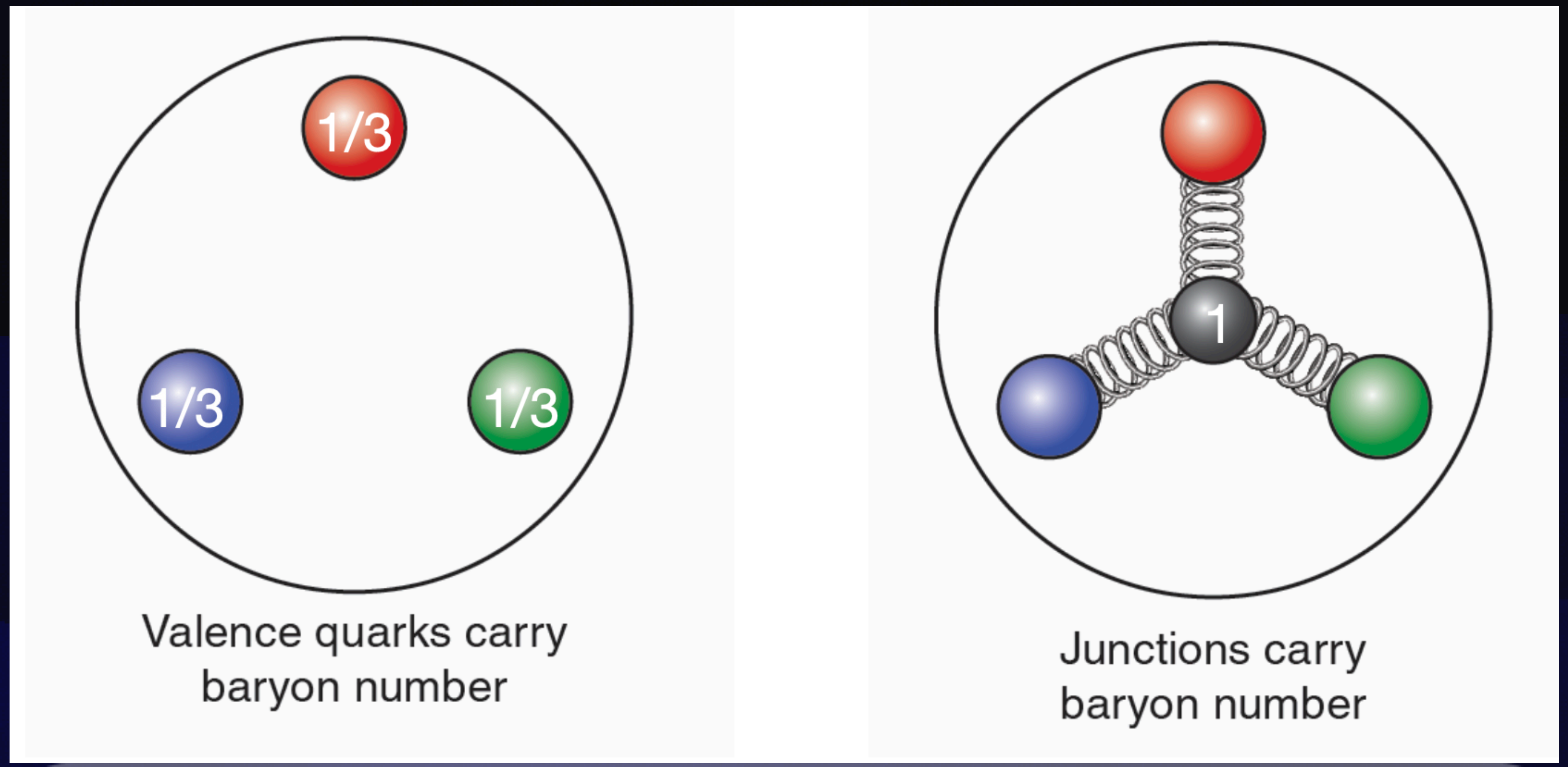
STAR collab. SQM, Strasbourg, 2024

Feature	Physics	status
System size dependence	Signature of EM field ?	No model captures

Our model

Kharzeev, PLB (1996)

Single + double junction stopping motivated initial baryon deposition



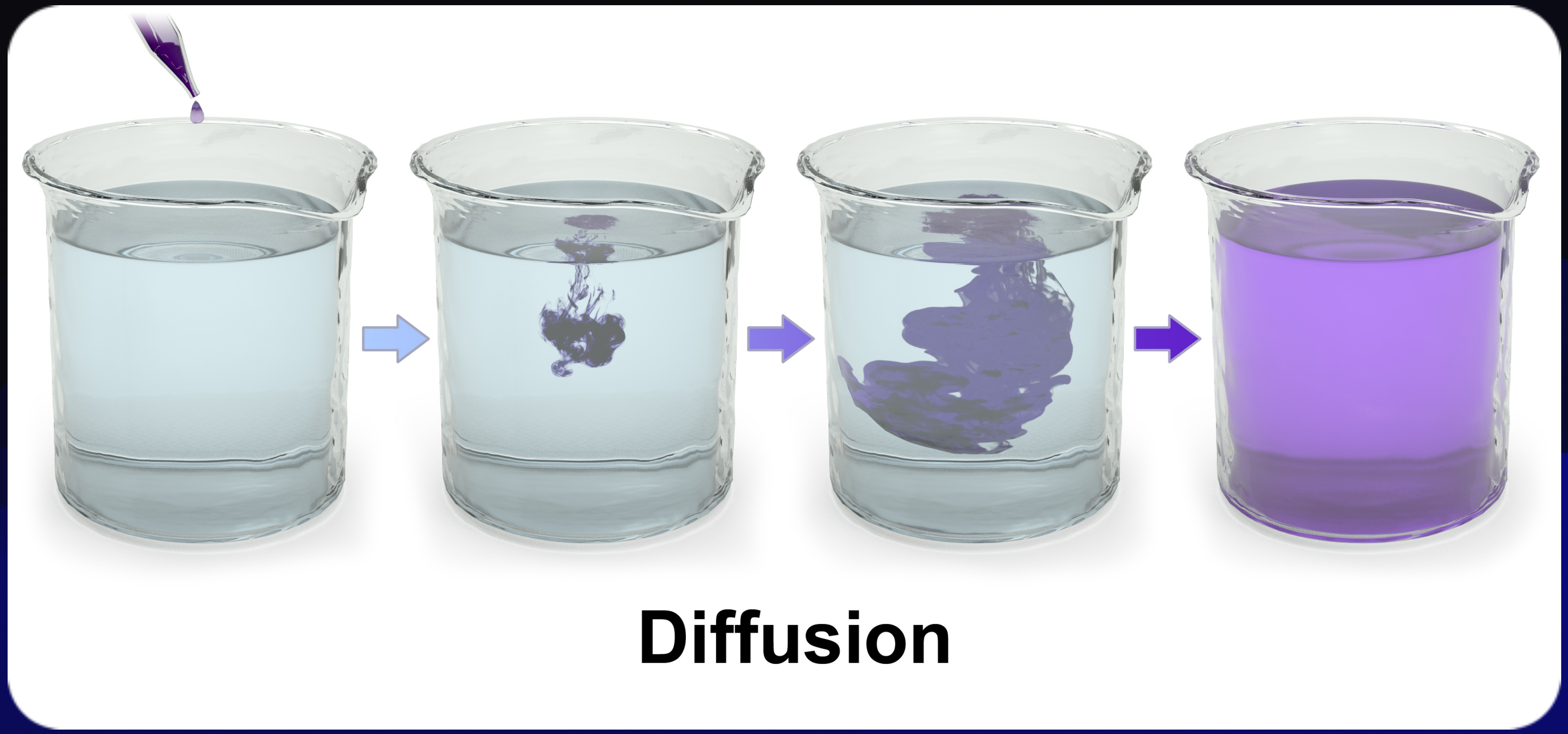
~~$n_B \propto N_{\text{participants}}$~~

$n_B \propto (1-\omega)N_{\text{participants}} + \omega N_{\text{binary collisions}}$

+

Denicol et. al., Phys. Rev. C 98, 034916 (2018)

Hydro with baryon diffusion



Fick's law :

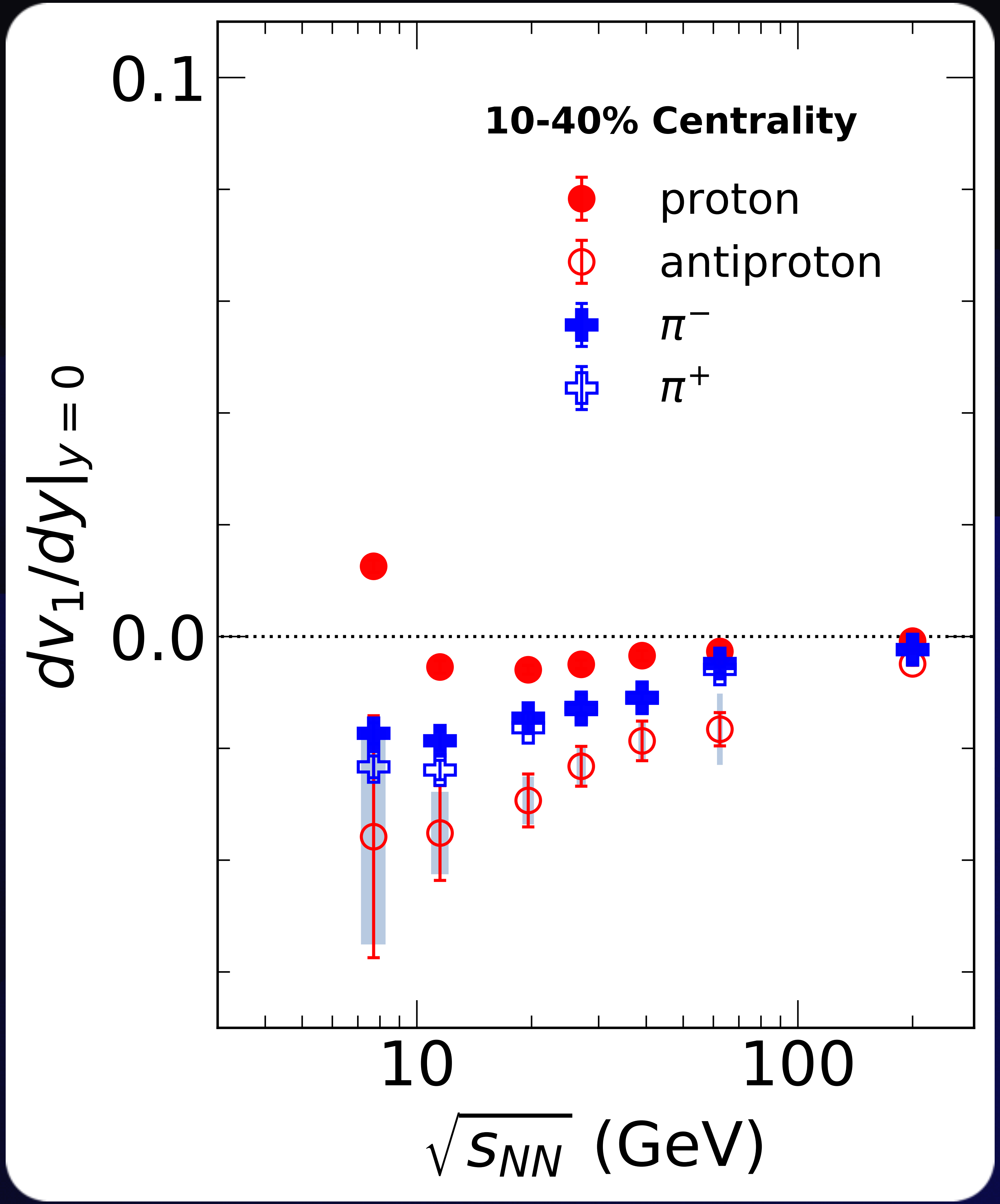
$$j_B^\mu = \kappa_B \nabla^\mu (n_B)$$

Diffusion current

Diffusion coefficient

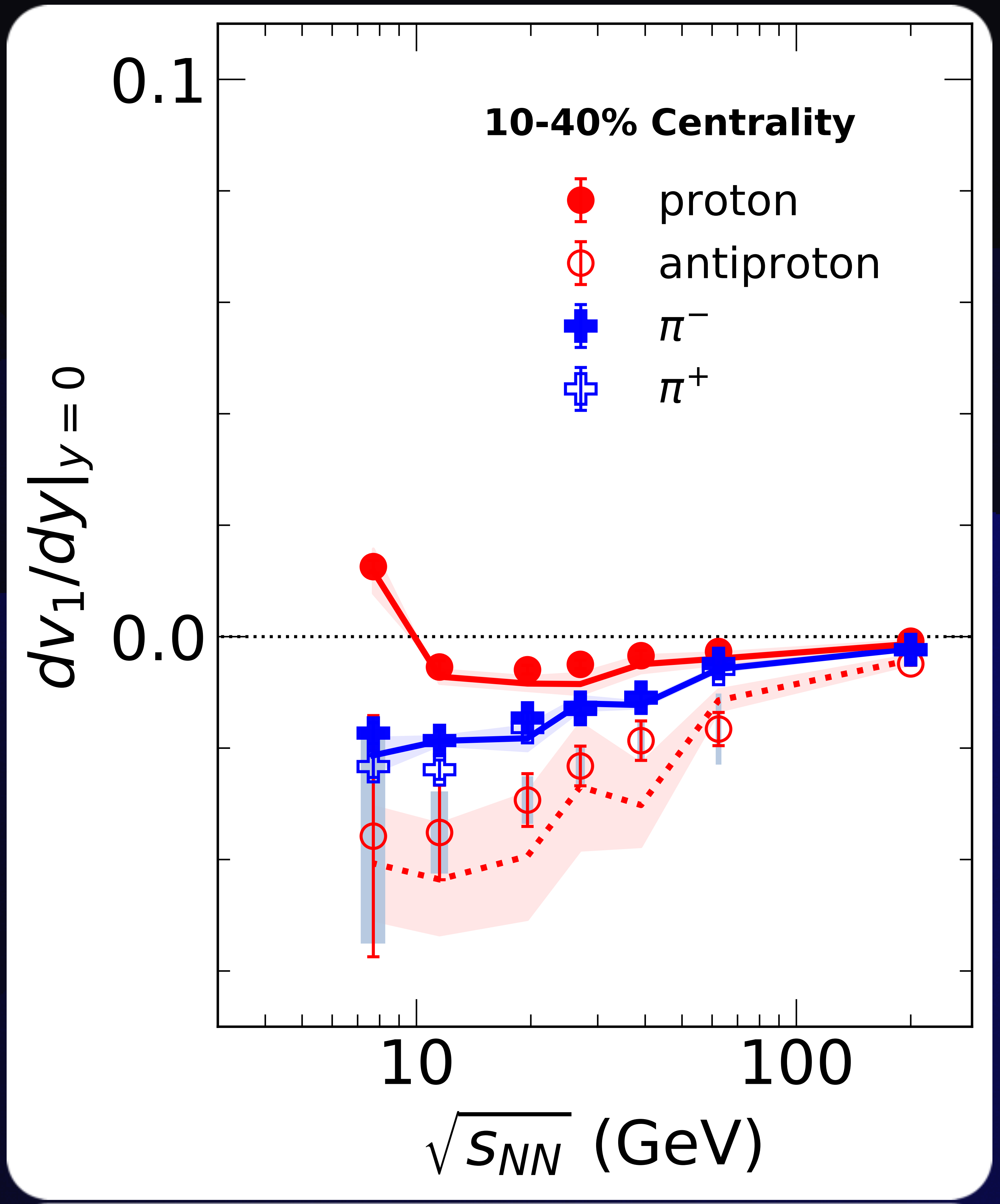
Conductivity $\sigma_q \equiv \frac{\kappa_q}{T}$

Results



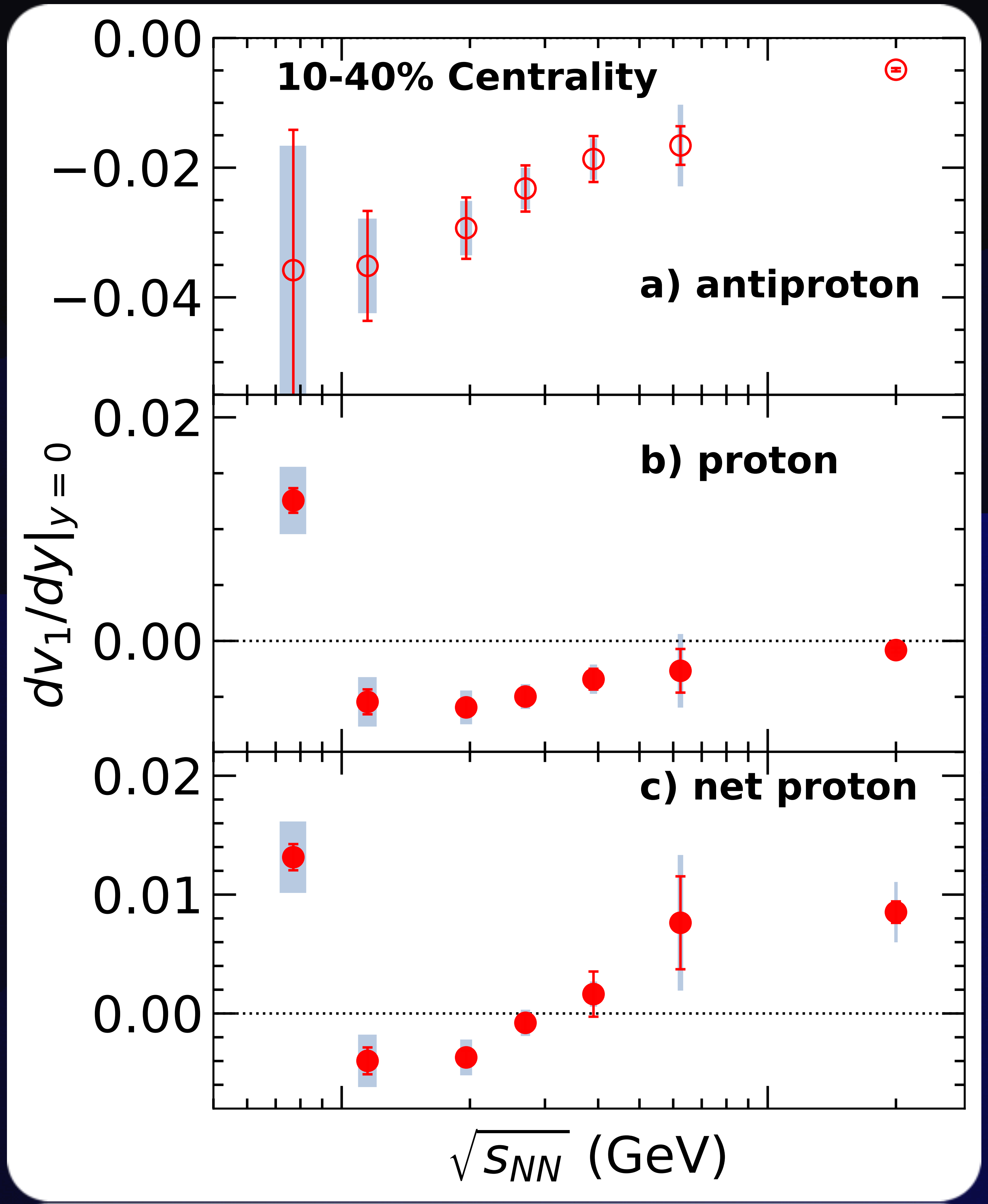
10-40% Centrality
proton
antiproton
π^-
π^+
0.1
0.0
$dv_1/dy|_{y=0}$
10
100
$\sqrt{s_{NN}}$ (GeV)

Results



10-40% Centrality
proton
antiproton
π^-
π^+
0.1
0.0
$dv_1/dy|_{y=0}$
10
100
$\sqrt{s_{NN}}$ (GeV)

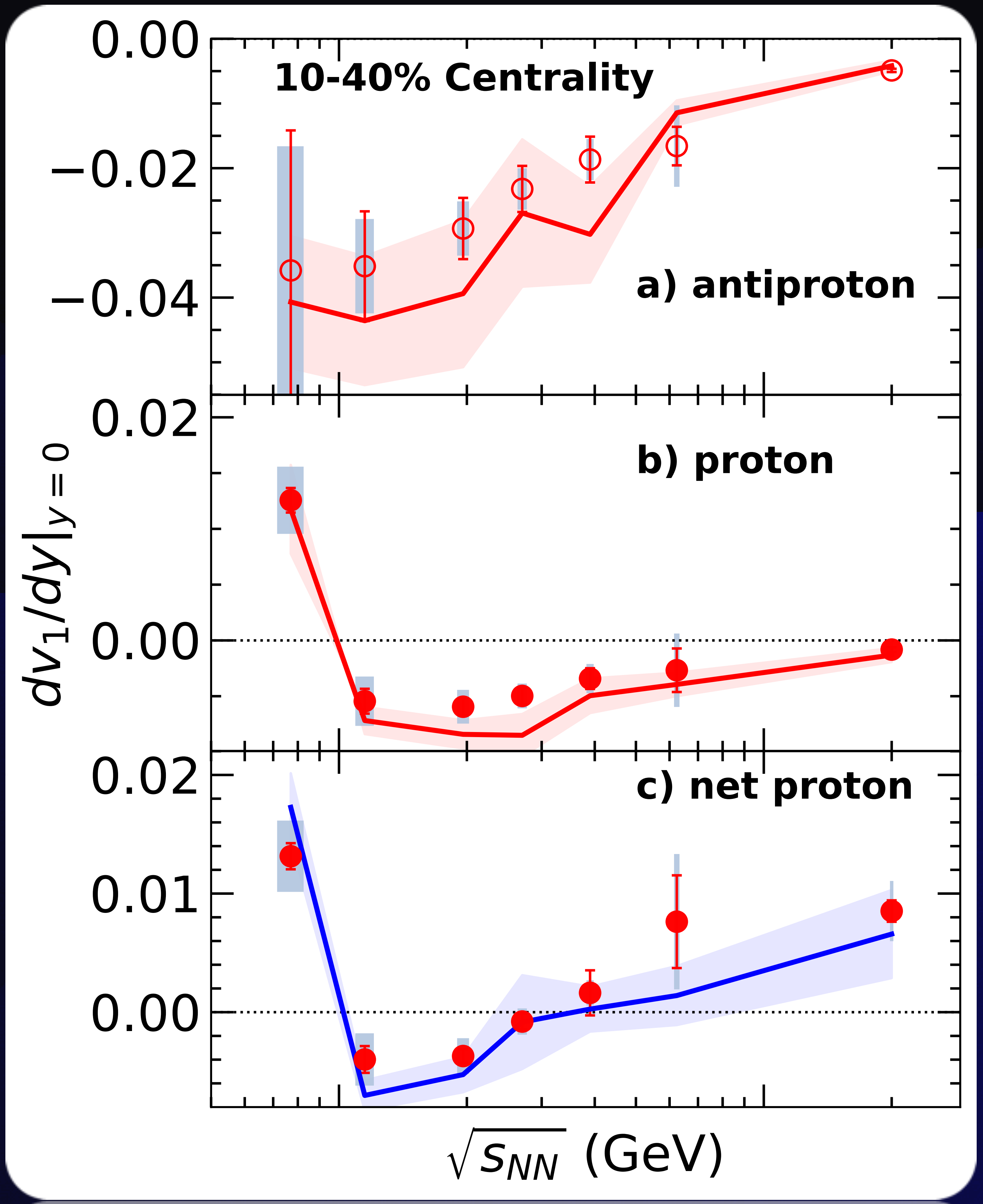
Results



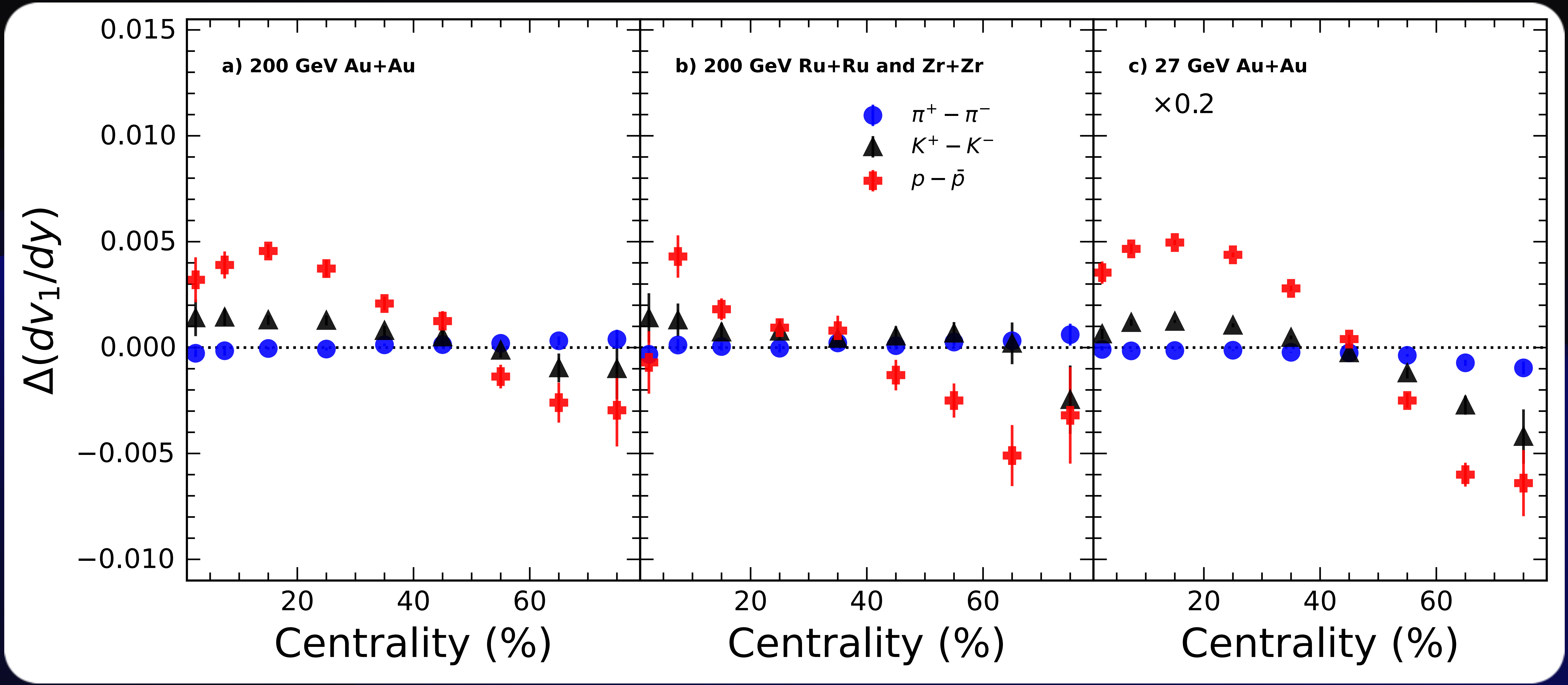
10-40% Centrality
a) antiproton
b) proton
c) net proton
0.00
−0.02
−0.04
0.02
0.00
0.02
0.01
0.00
$dv_1/dy|_{y=0}$
$\sqrt{s_{NN}}$ (GeV)

Results

$$[v_1(y)]_{Net-p} = \frac{\frac{dN^p}{dy}[v_1(y)]_p - \frac{dN^{\bar{p}}}{dy}[v_1(y)]_{\bar{p}}}{\frac{dN^{p-\bar{p}}}{dy}}$$



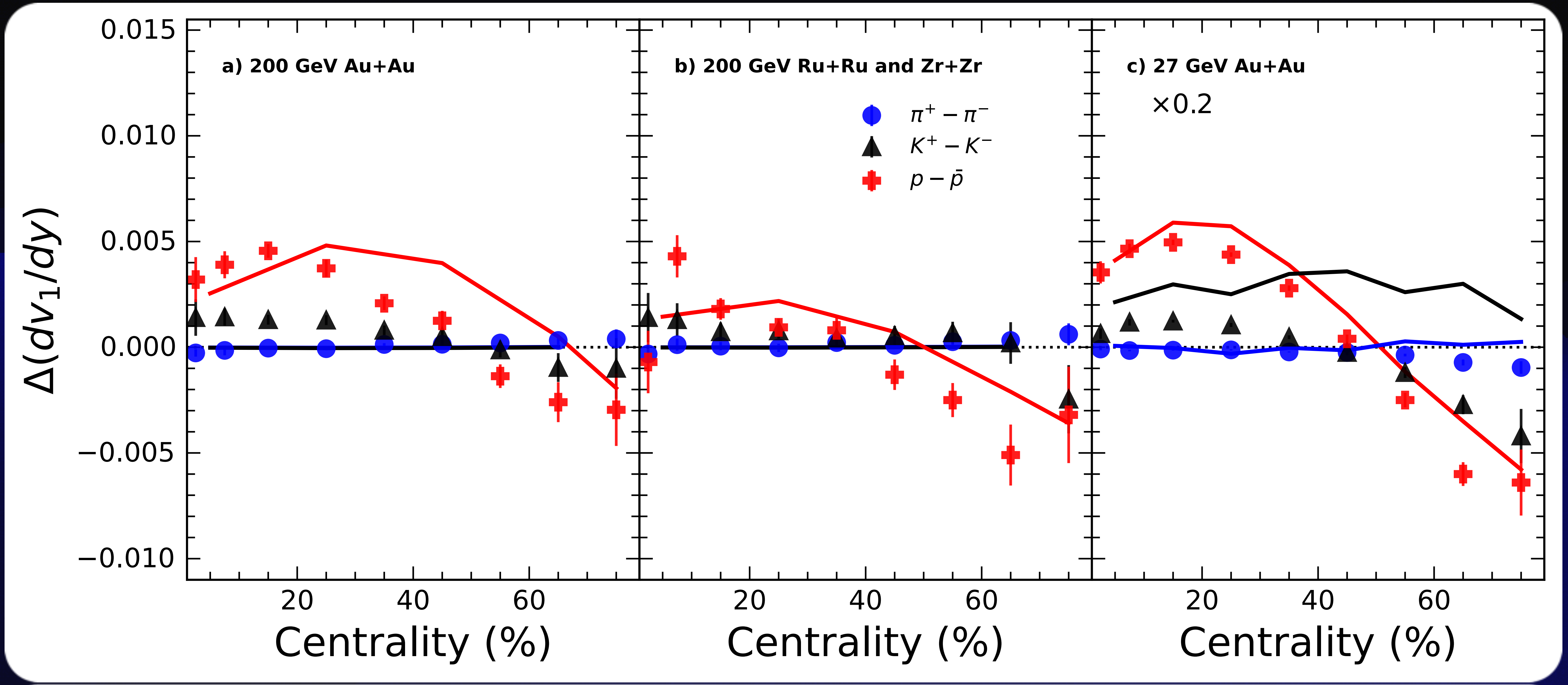
Results



0.015
0.010
0.005
0.000
−0.005
−0.010
Δ(dv1/dy)
a) 200 GeV Au+Au
b) 200 GeV Ru+Ru and Zr+Zr
c) 27 GeV Au+Au
×0.2
π+ − π−
K+ − K−
p − p̄
20
40
60
Centrality (%)

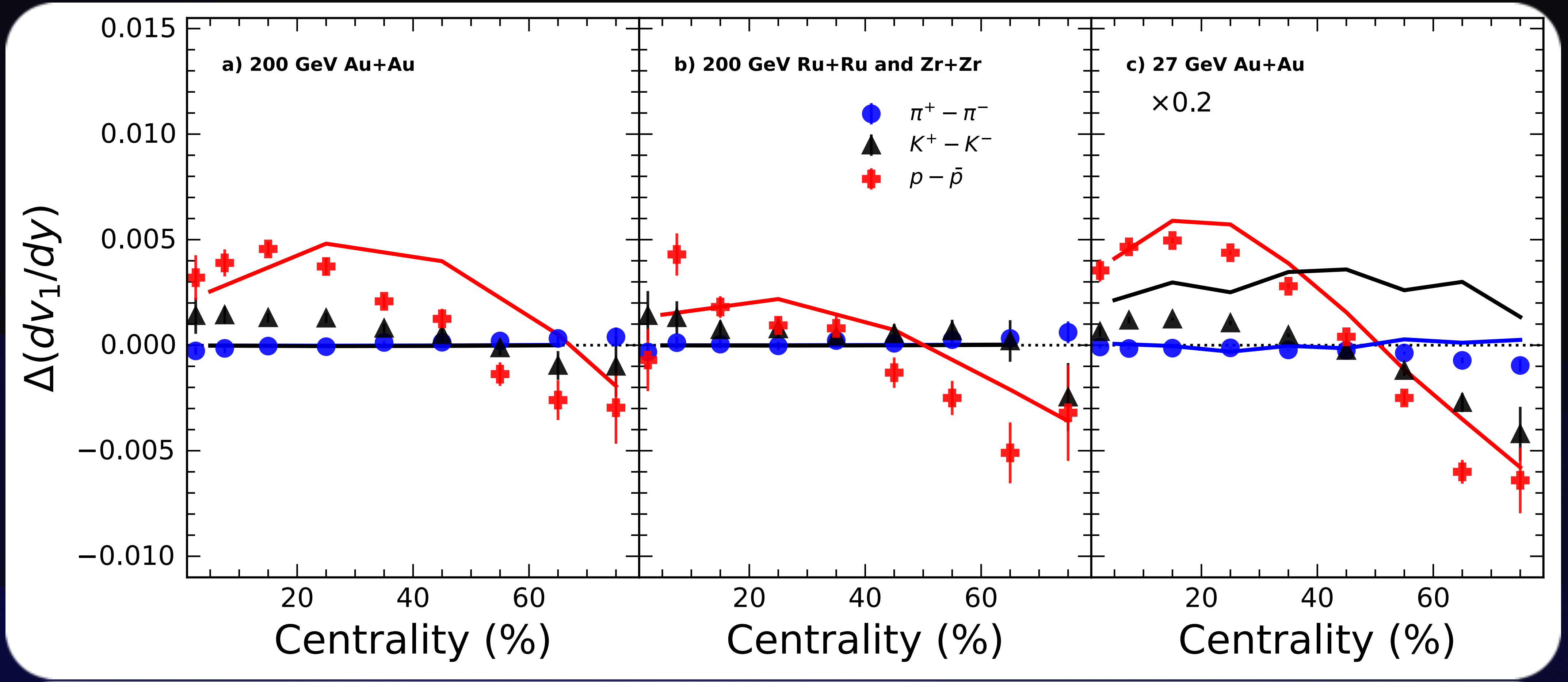
Results

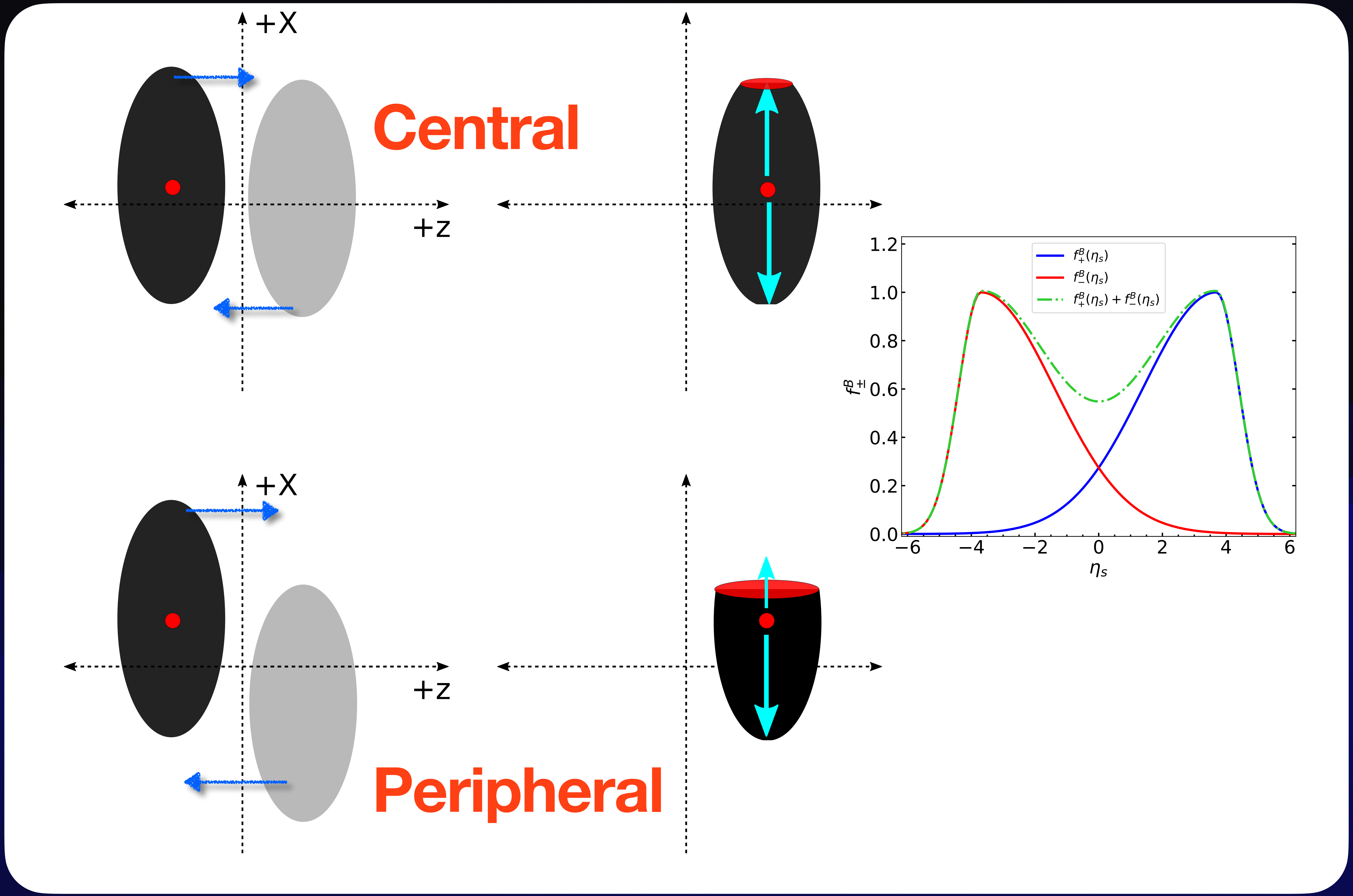
No EM field effect in our model



Background of conserved charge physics to the signals of EM field

What's in our model to capture this feature of the data

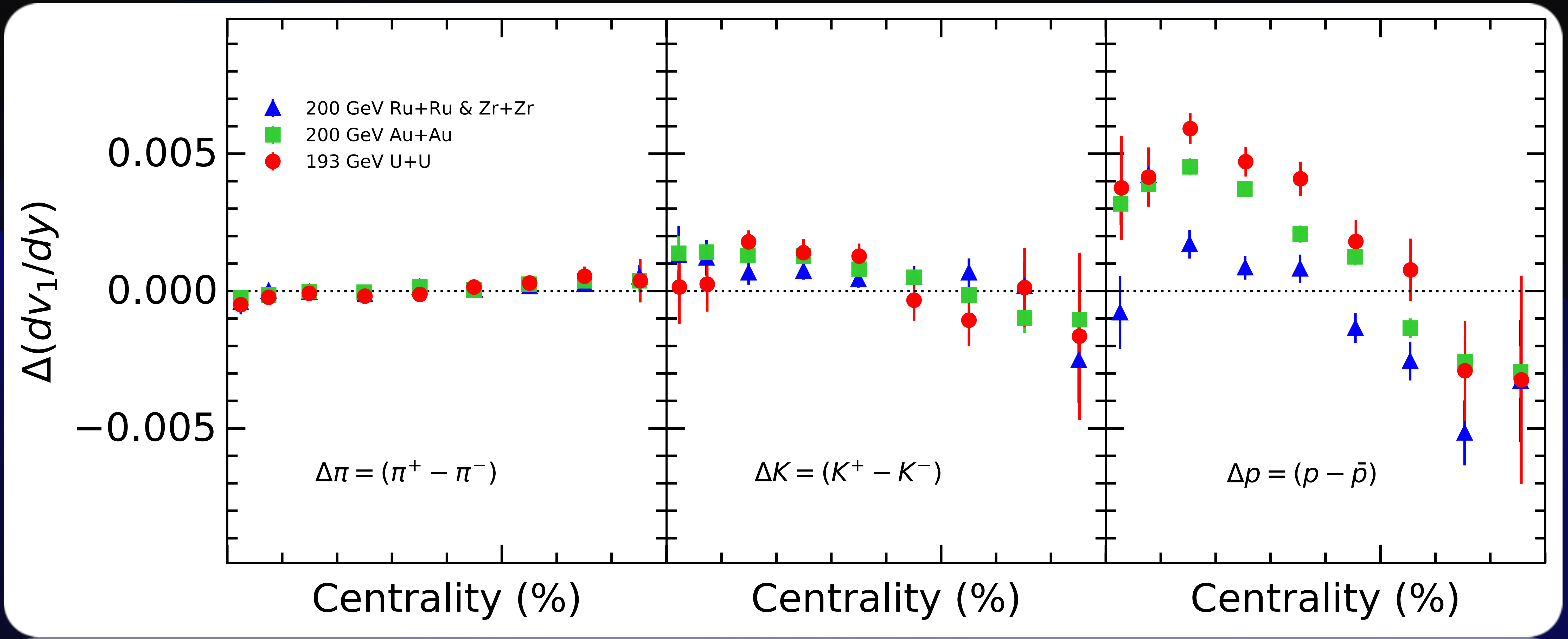




Asymmetric baryon gradient along +x to -x

$$j_B^\mu = \kappa_B \nabla^\mu (n_B)$$

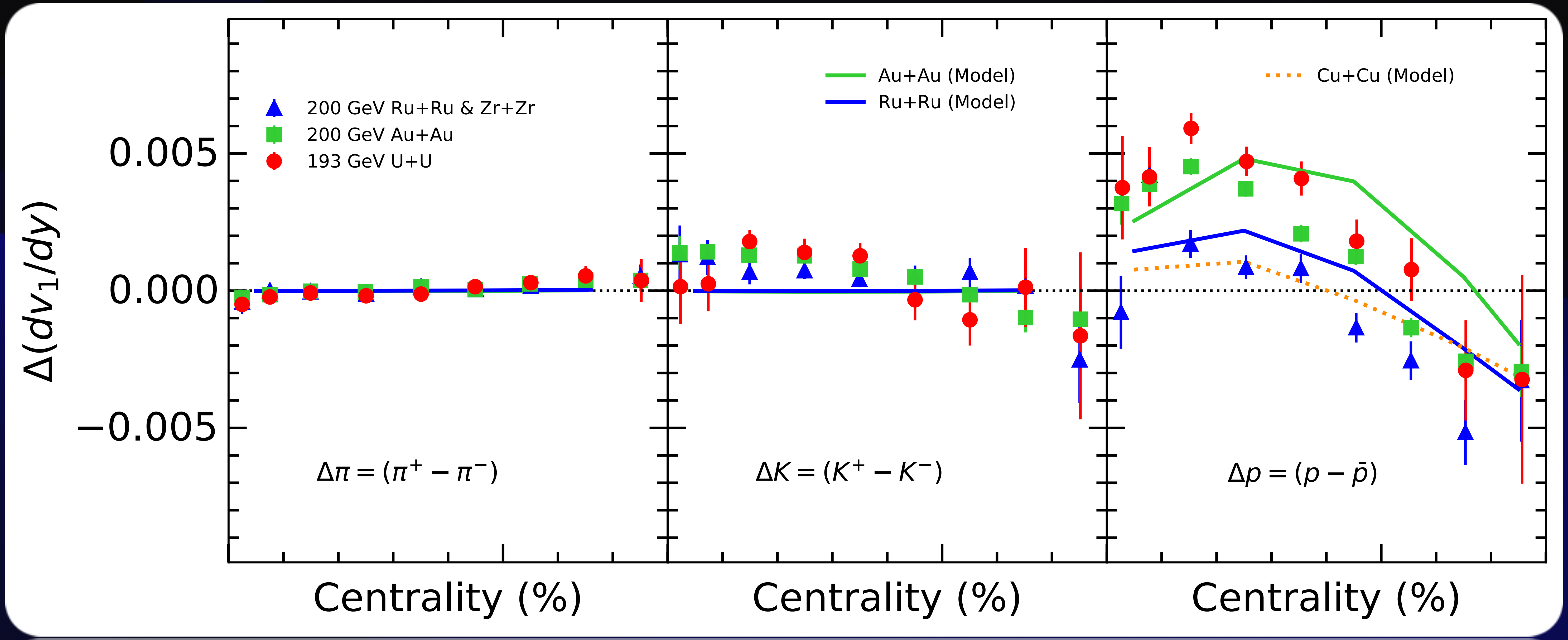
Results



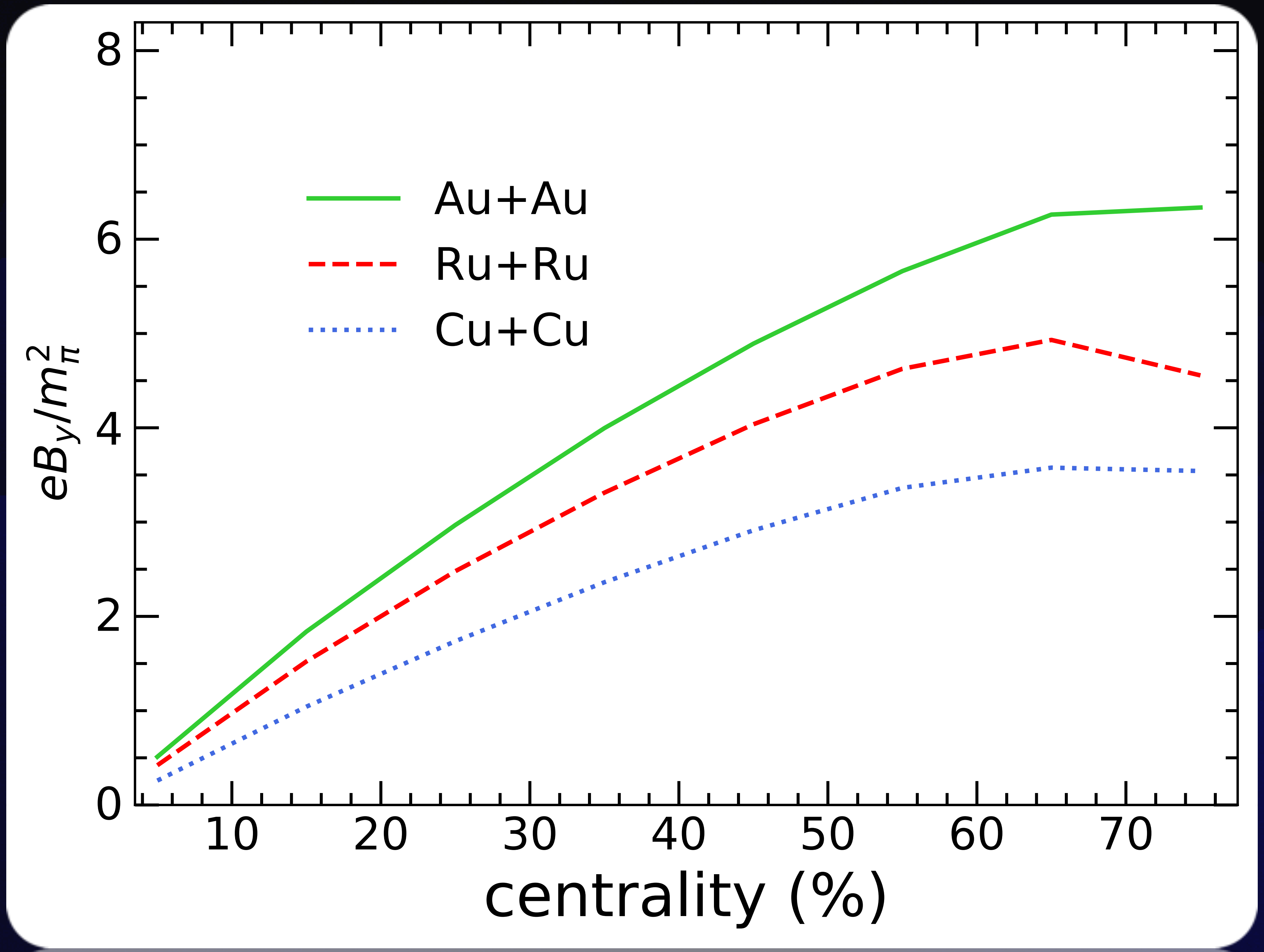
200 GeV Ru+Ru & Zr+Zr
200 GeV Au+Au
193 GeV U+U
0.005
0.000
−0.005
$\Delta(dv_1/dy)$
$\Delta\pi = (\pi^+ - \pi^-)$
$\Delta K = (K^+ - K^-)$
$\Delta p = (p - \bar{p})$
Centrality (%)
Centrality (%)
Centrality (%)

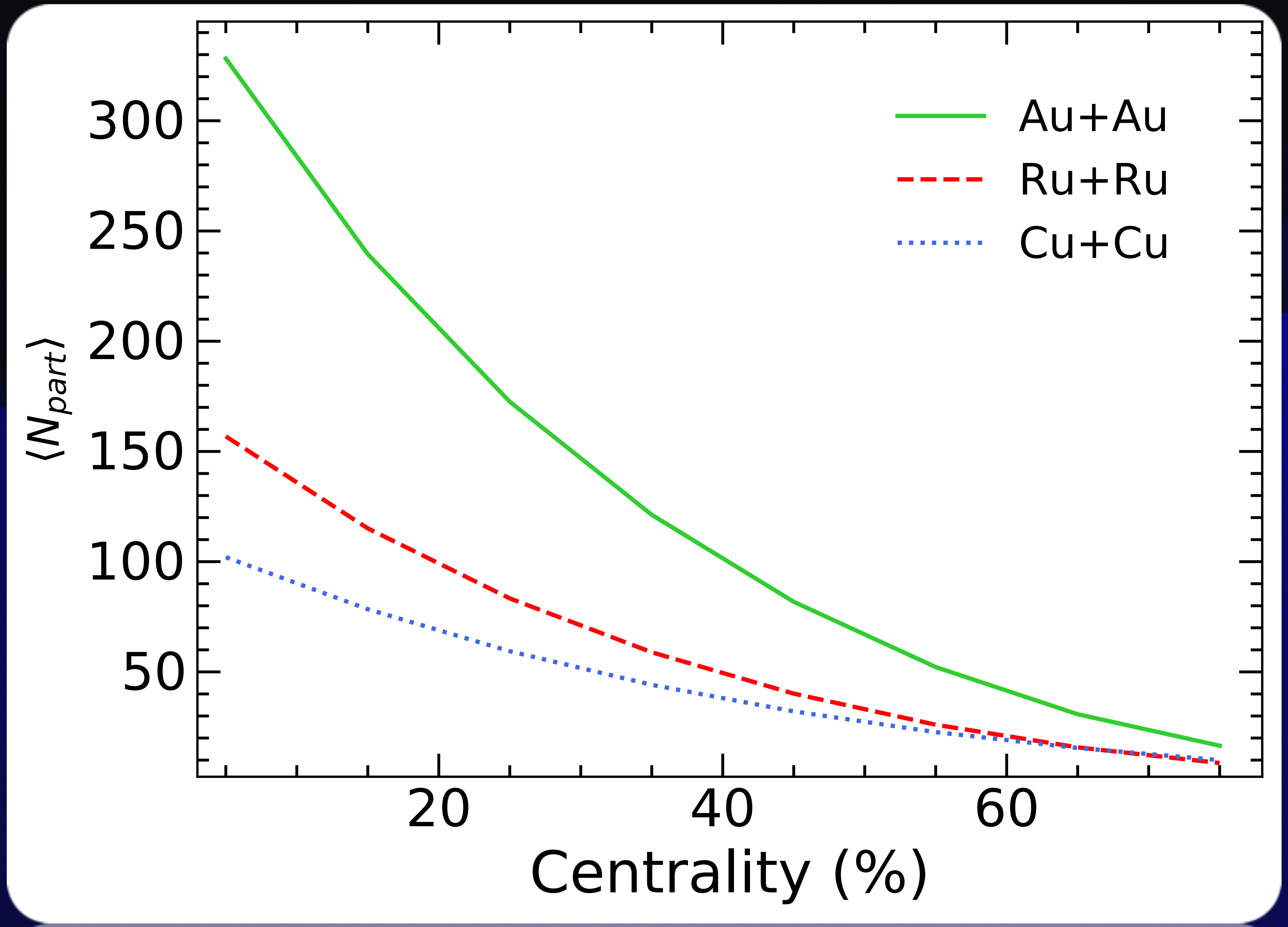
Results

TP, Sandeep Chatterjee and Subhash Singha



What’s in our model to capture this feature of the data





Successful baryon phenomenology framework.

Our initial baryon stopping model, and the baryon diffusion coefficient which is consistent with experimental data can provide a non-critical baryonic baseline that is crucial in the ongoing searches for the

- **QCD critical point and**
- **signatures of EM field.**

Thanks

Backups

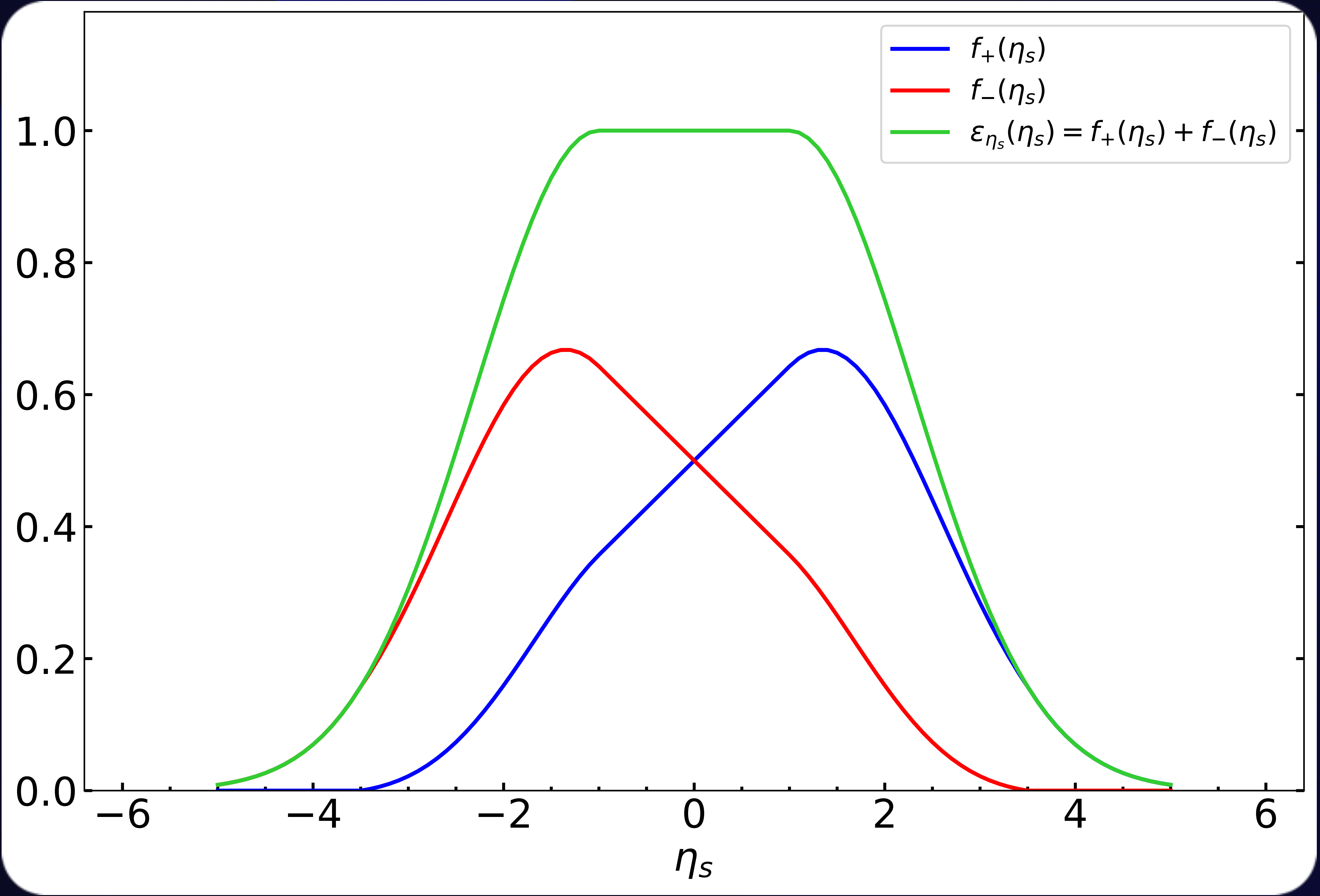
Tilted fireball

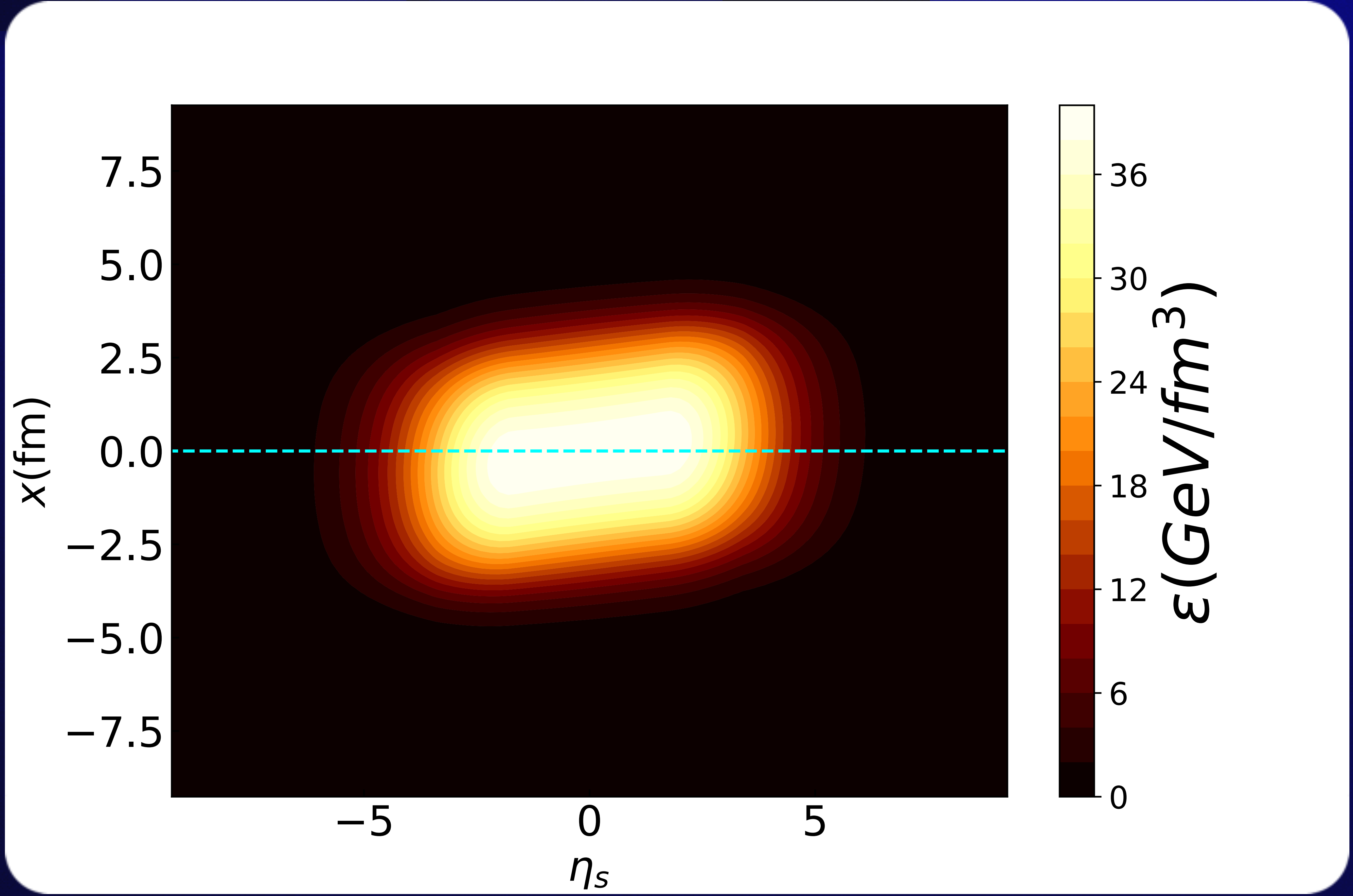
P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)

A participant nucleon deposits more energy along it's direction of motion.

$$\epsilon(x,y,\eta_s) = \epsilon_0 \left[\left(N_+(x,y) f_+(\eta_s) + N_-(x,y) f_-(\eta_s) \right)(1-\alpha) + N_{coll}(x,y)\epsilon_{\eta_s}(\eta_s)\alpha \right]$$

$$f_+(\eta_s) = \frac{\eta_s + \eta_m}{2\eta_m}\epsilon_{\eta_s}(\eta_s) \quad (-\eta_m < \eta_s < \eta_m)$$





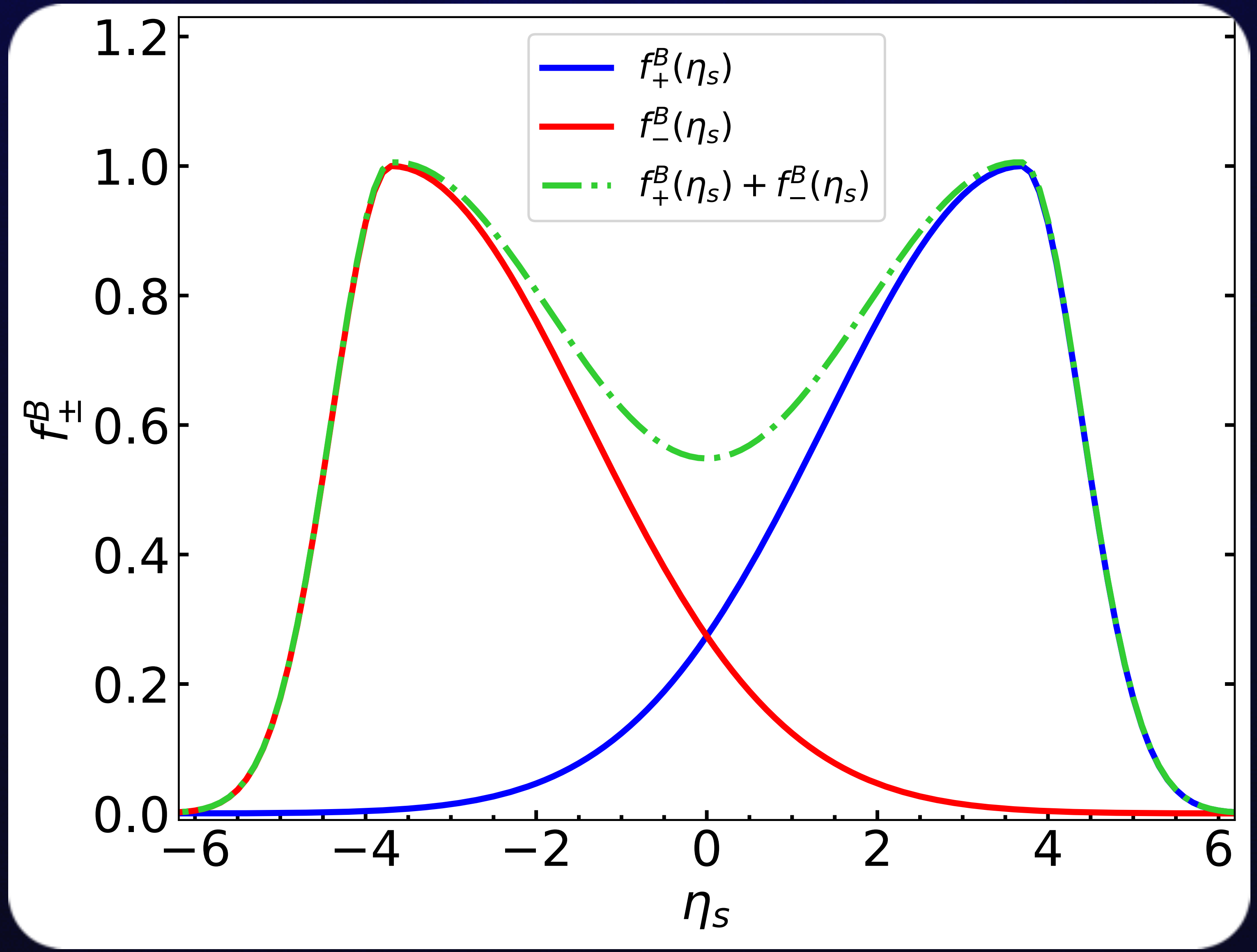
Model of the initial baryon profile

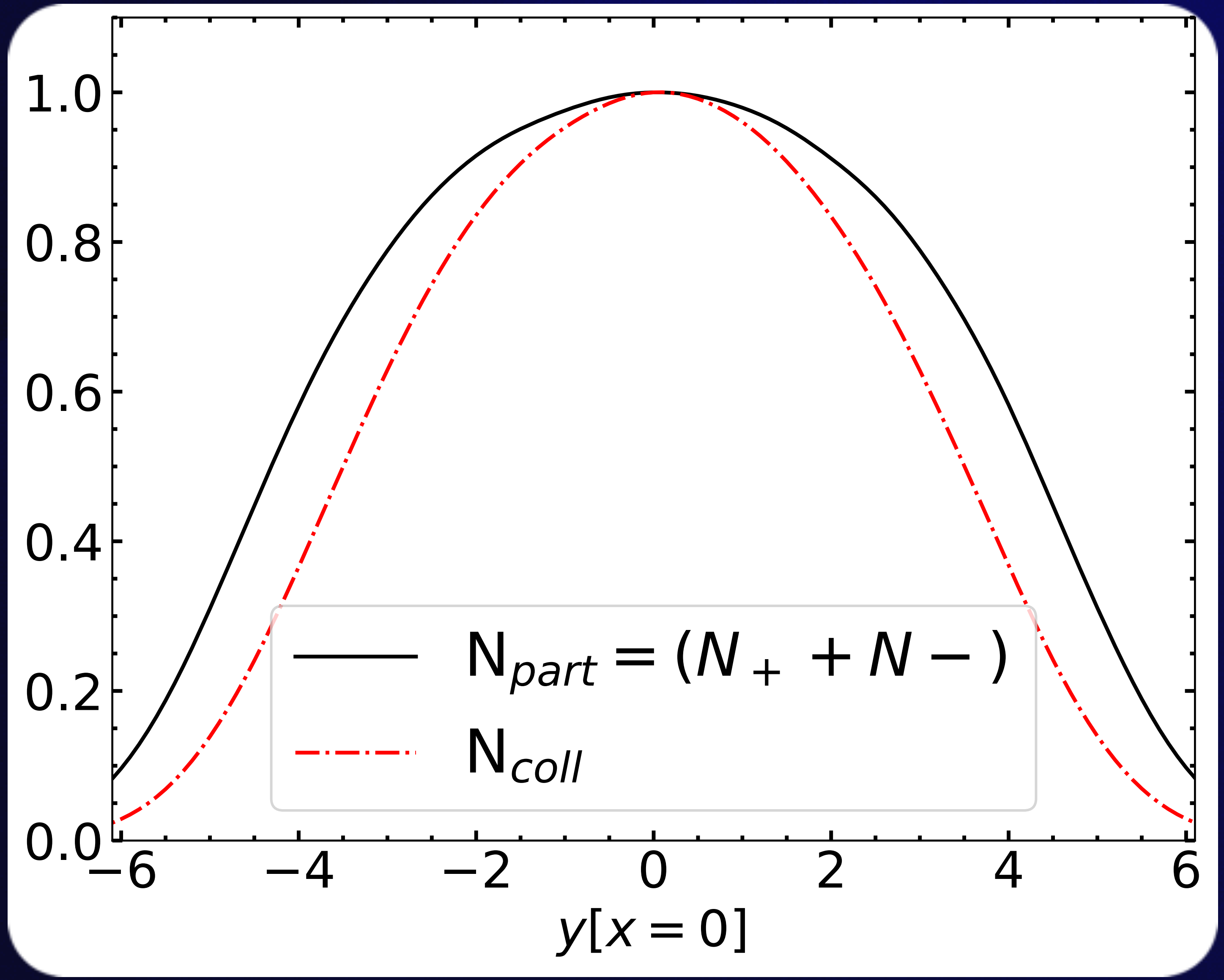
$$n_B(x,y,\eta_s) = N_B\left[(1-\omega)\Big(N_+(x,y)f_+^B(\eta_s)+N_-(x,y)f_-^B(\eta_s)\Big) + \omega N_{coll}(x,y)\Big(f_+^B(\eta_s)+f_-^B(\eta_s)\Big)\right]$$

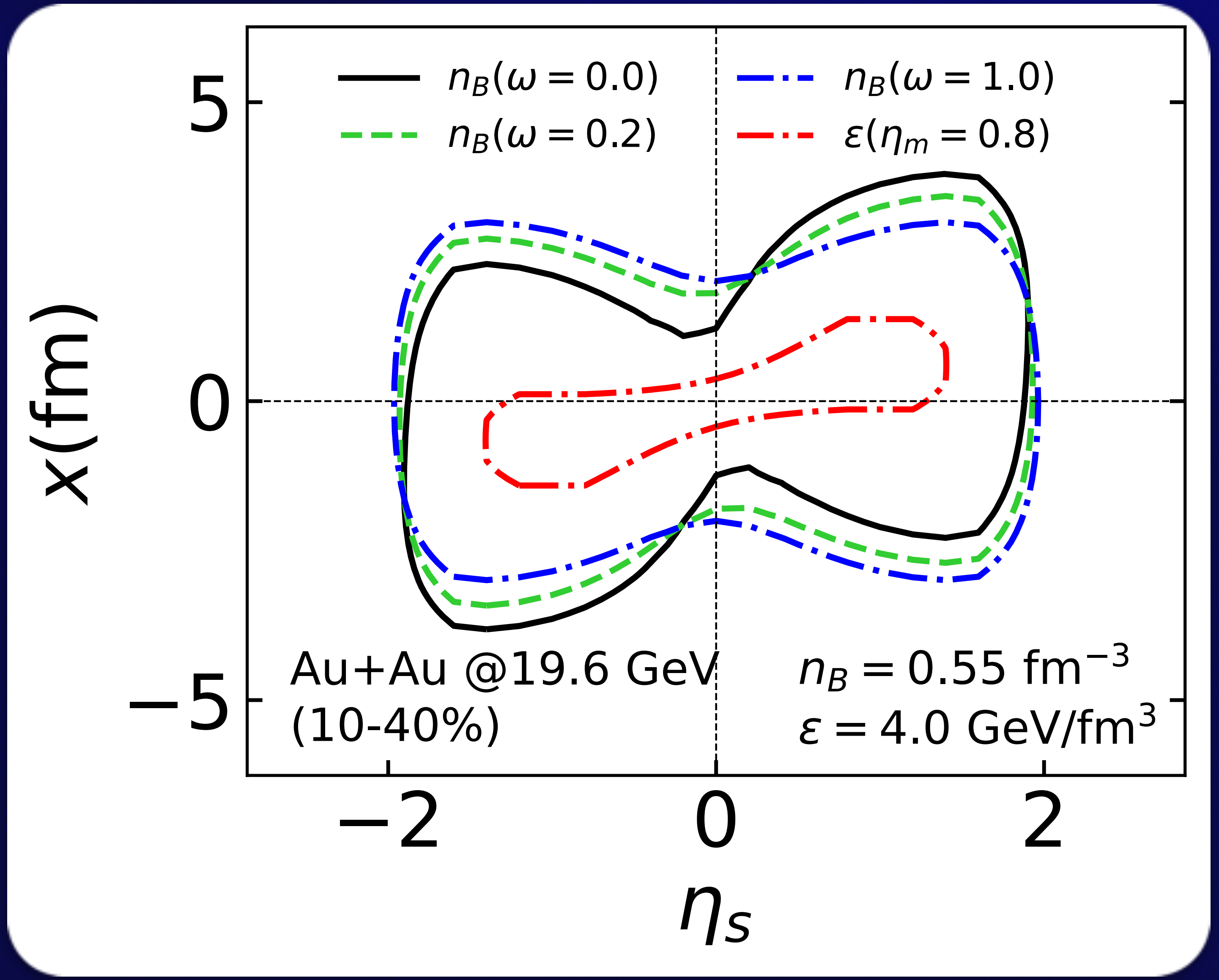
$$\int \tau_0\, d\eta\, dx\, dy\; n_B(x,y,\eta_s) = N_{part} = (N_+ + N_-)$$

- Unlike participant sources, the binary collision sources carry no rapidity bias
- In microscopic models rapidity loss depends on number of binary collisions.

- Baryon junction picture : single junction stopping with forward-backward asymmetric profile (similar to participant deposition in our model), double junction stopping has no rapidity bias (similar to Ncoll deposition)







Simulation framework

Glauber model for initial energy and baryon deposition → MUSIC (Hydrodynamic evolution) → iSS (Particlization/ Cooper-Frye Sampling) → UrQMD (Late stage hadronic transport)

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu J^\mu_B = 0$$

$$J^\mu_B = n_B u^\mu + q^\mu$$

$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right)$$

Baryon diffusion coefficient

$$\kappa_B = \frac{C_B}{T} n_B \left[\frac{1}{3}\coth\left(\frac{\mu_B}{T}\right) - \frac{n_B T}{\epsilon + p}\right]$$

Denicol et. al., Phys. Rev. C 98, 034916 (2018)

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Simulation framework

NEoS-BQS

Constraints

$n_S = 0, \quad n_Q = 0.4 n_B$

$\mu_S \neq 0$

$\mu_Q \neq 0$

$A.\ Monnai,\ C.\ Shen\ and\ B.\ Schenke,\ Phys.\ Rev.\ C$ 100, 024907 (2019)

Starting hydro at a constant τ_0

$$u^\mu(\tau_0) = \tau_0(\cosh \eta_s, 0, 0, \sinh \eta_s)$$

$$C_\eta = \frac{\eta T}{\epsilon + P} = 0.08$$

$$\zeta = 0$$

$$C_B = 1$$

(Baryon diffusion coefficient)

$$\epsilon_f = 0.26 \text{ GeV/fm}^3$$

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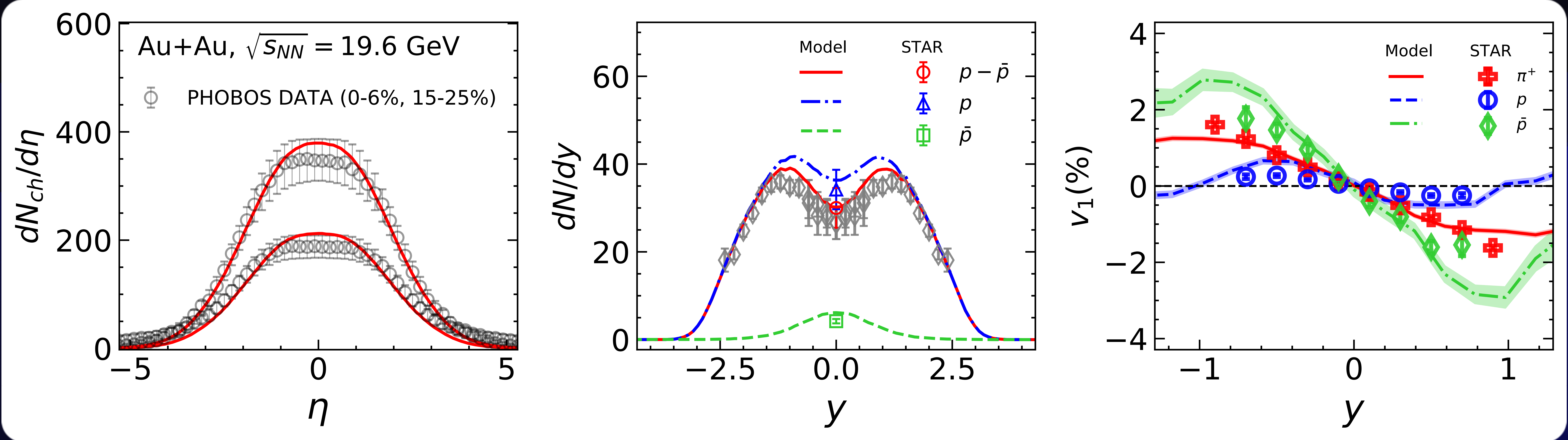
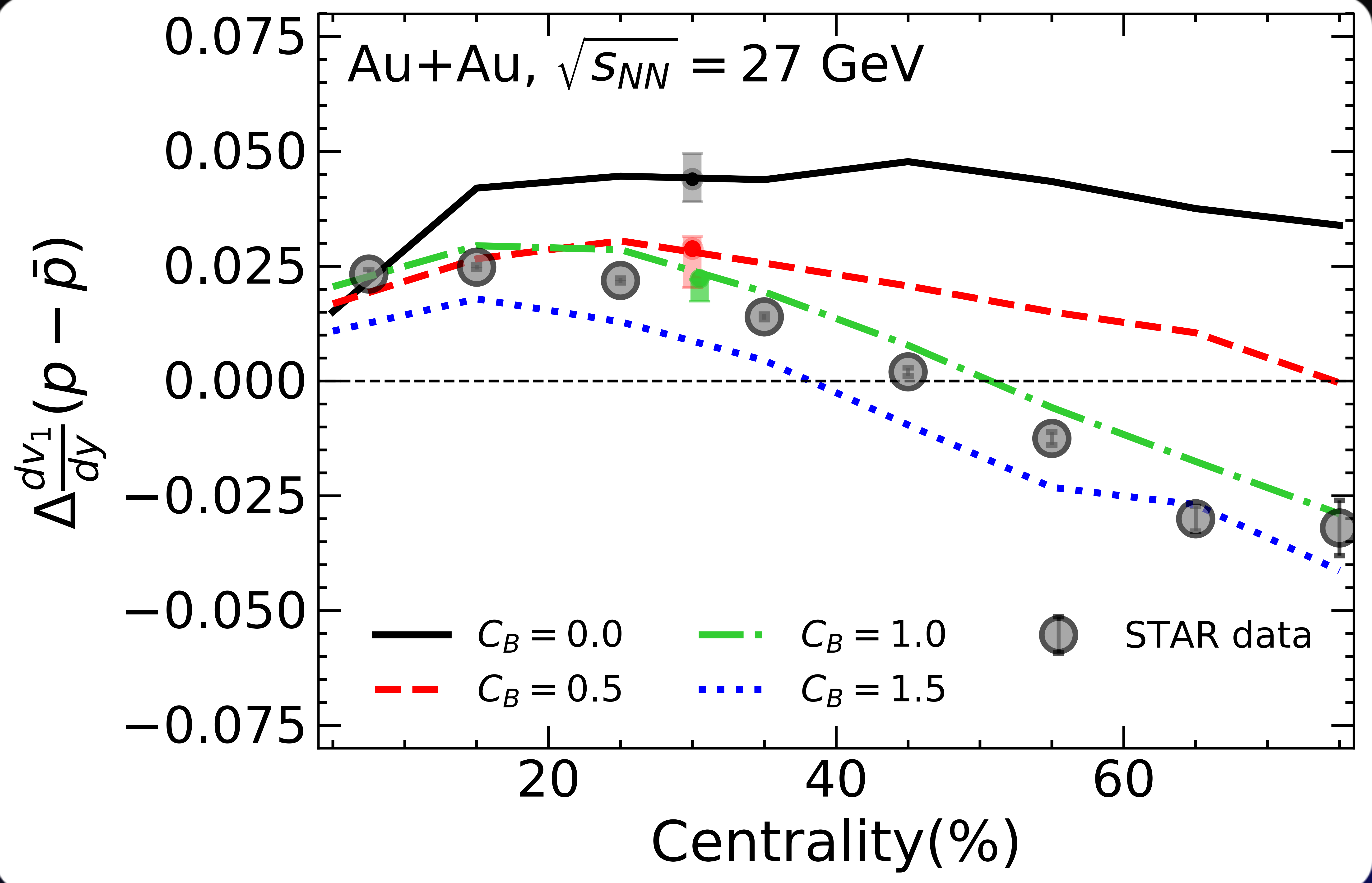
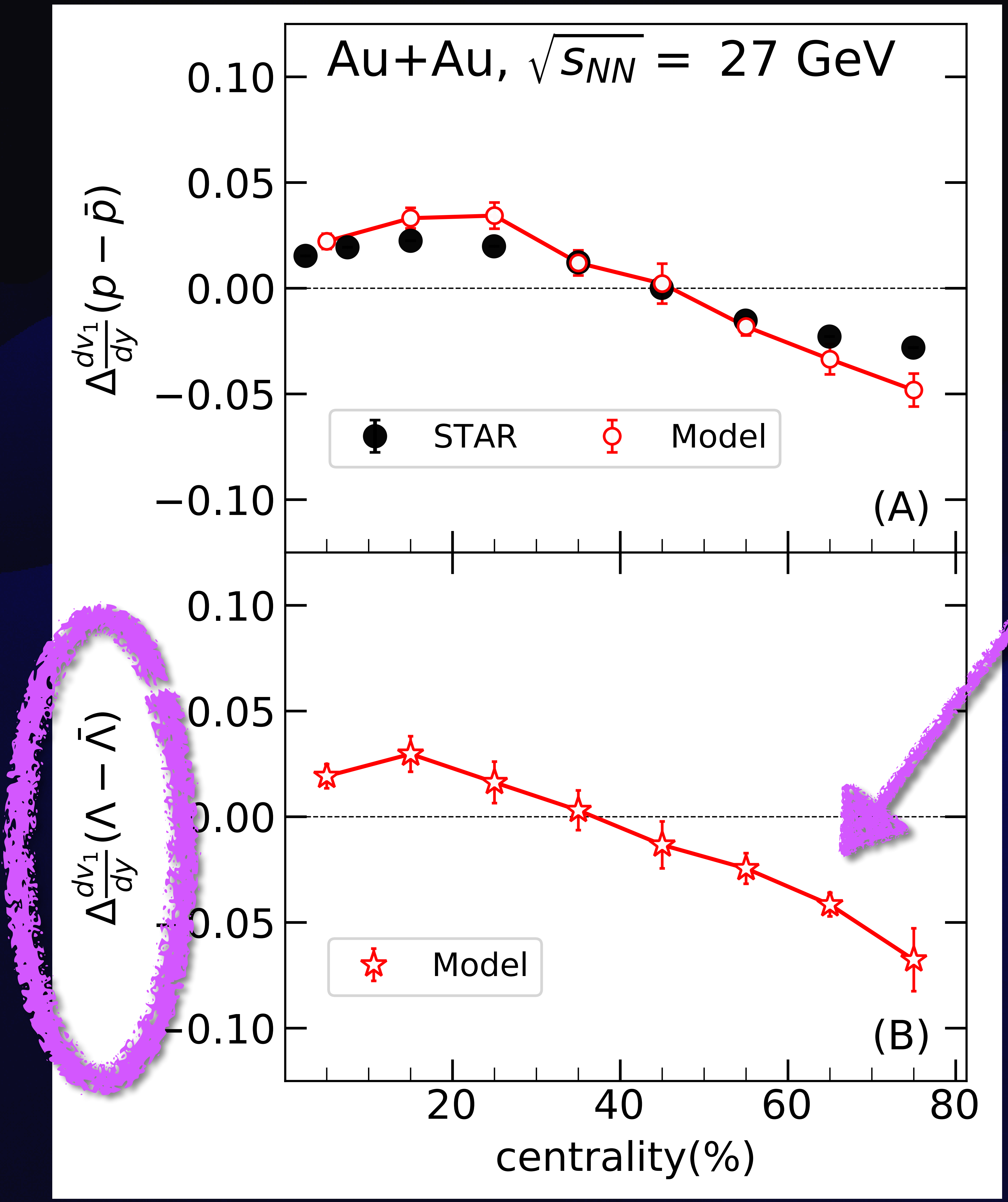
Simulation results

$$\eta_m = 0.8,\ \omega = 0.15$$

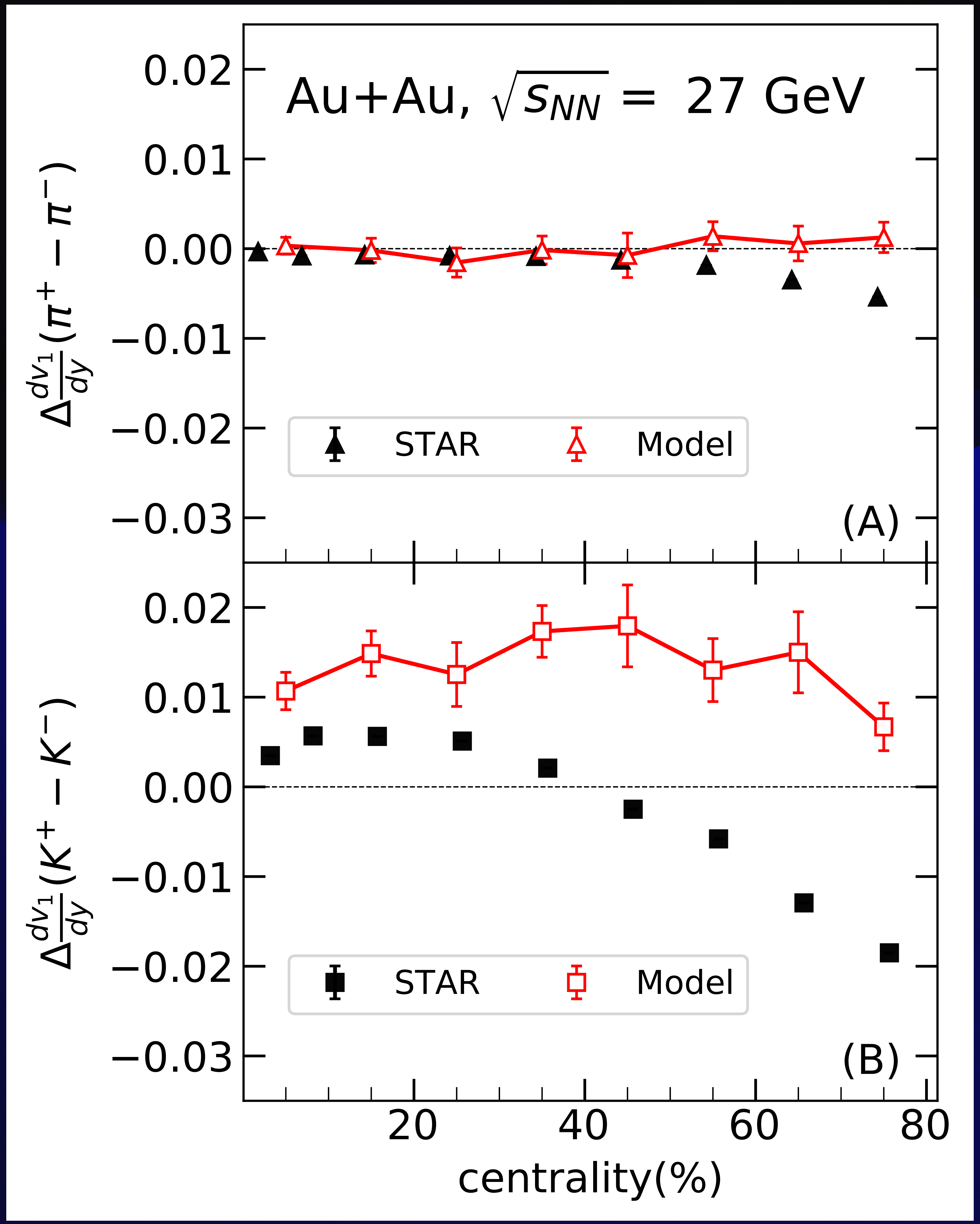


our model parameters are tuned to capture the above observables simultaneously


Au+Au, $\sqrt{s_{NN}}$ = 27 GeV
$\Delta\frac{dv_1}{dy}(p-\bar{p})$
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
20
40
60
Centrality(%)
$C_B = 0.0$
$C_B = 0.5$
$C_B = 1.0$
$C_B = 1.5$
STAR data



Au+Au, $\sqrt{s_{NN}}$ = 27 GeV
$\Delta\frac{dv_1}{dy}(p-\bar{p})$
STAR
Model
(A)
$\Delta\frac{dv_1}{dy}(\Lambda-\bar{\Lambda})$
Model
(B)
centrality(%)



Au+Au, $\sqrt{s_{NN}}$ = 27 GeV
$\Delta\frac{dv_1}{dy}(\pi^+-\pi^-)$
STAR
Model
(A)
$\Delta\frac{dv_1}{dy}(K^+-K^-)$
STAR
Model
(B)
centrality(%)