Role of stopping and diffusion of baryons in BES phenomenology

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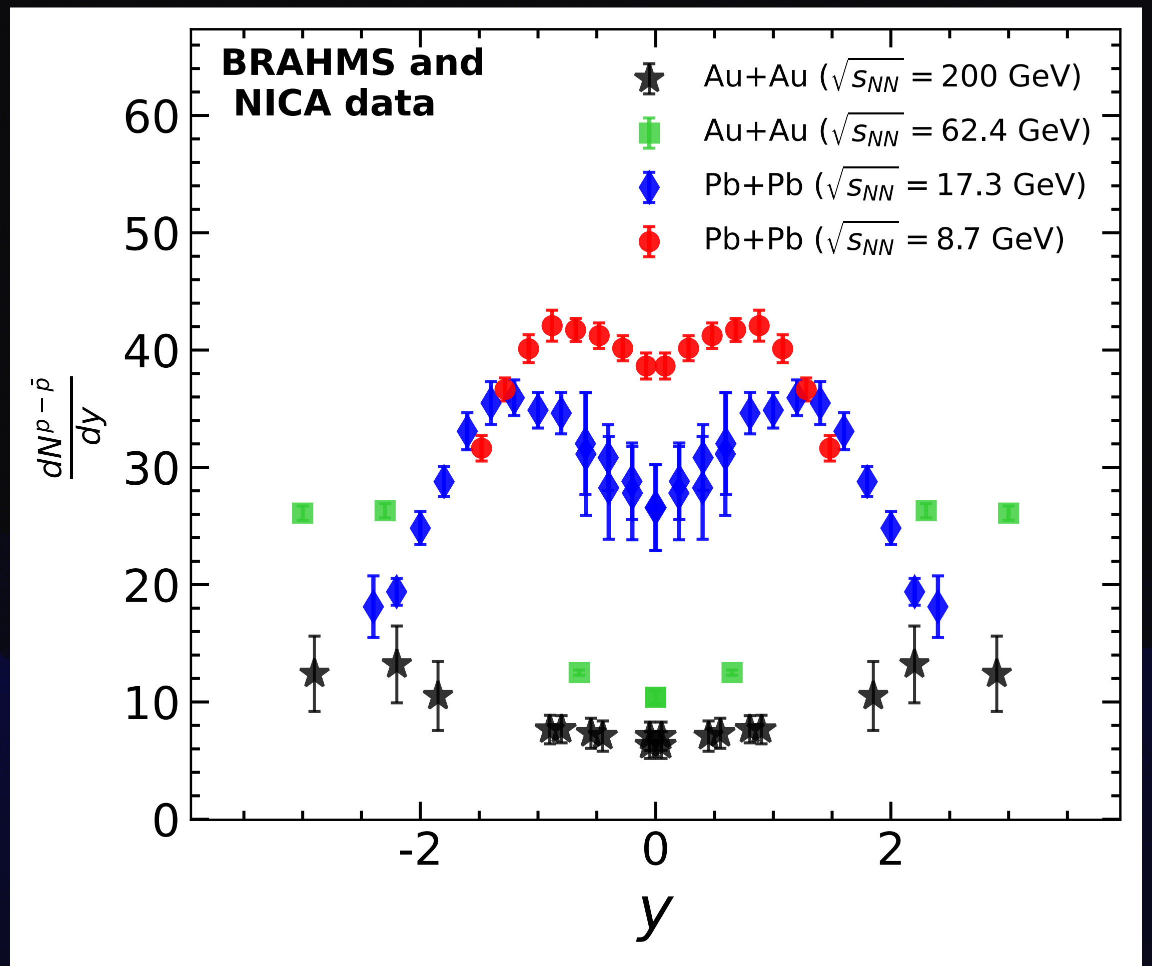
IISER Berhampur, India

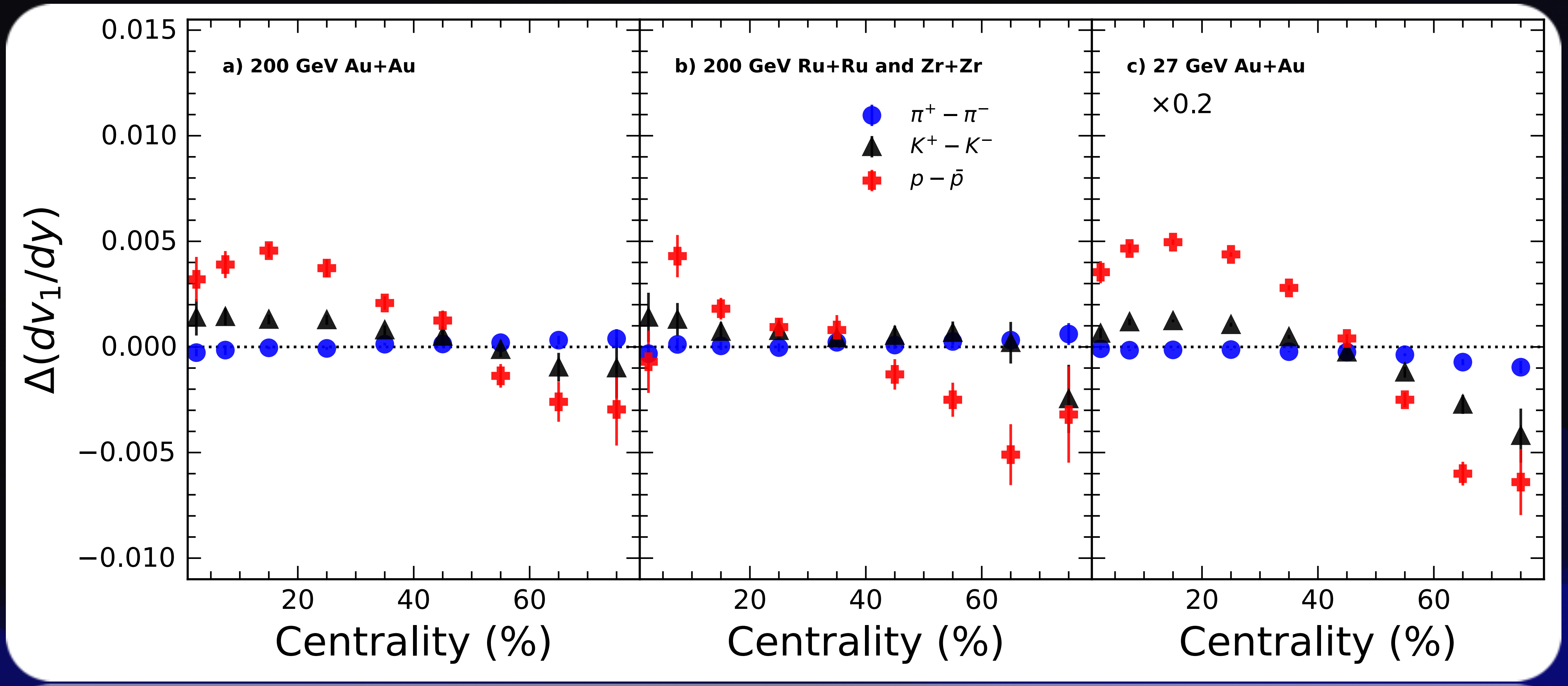
10th Asian triangle heavy-ion conference (ATHIC)-2025

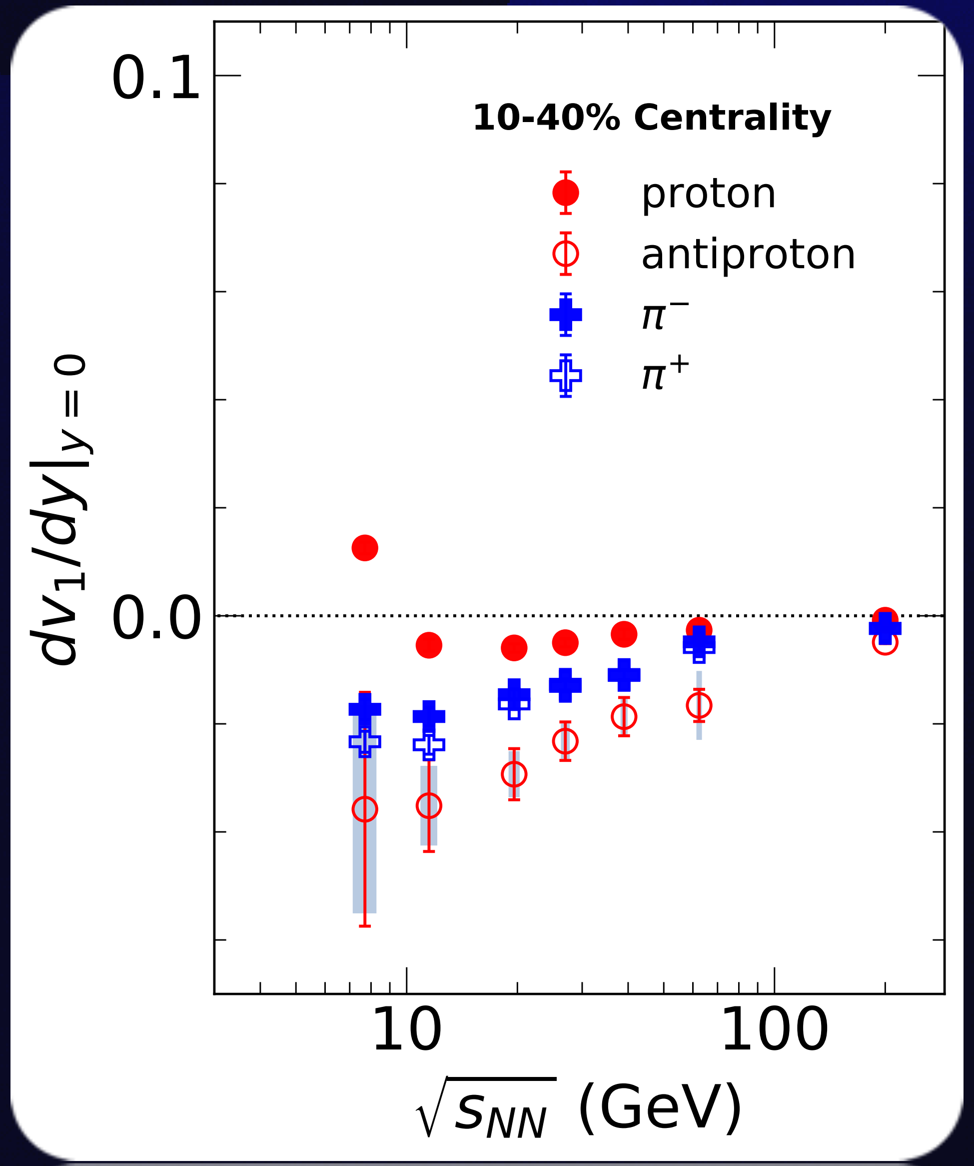
13-16 Jan. 2025

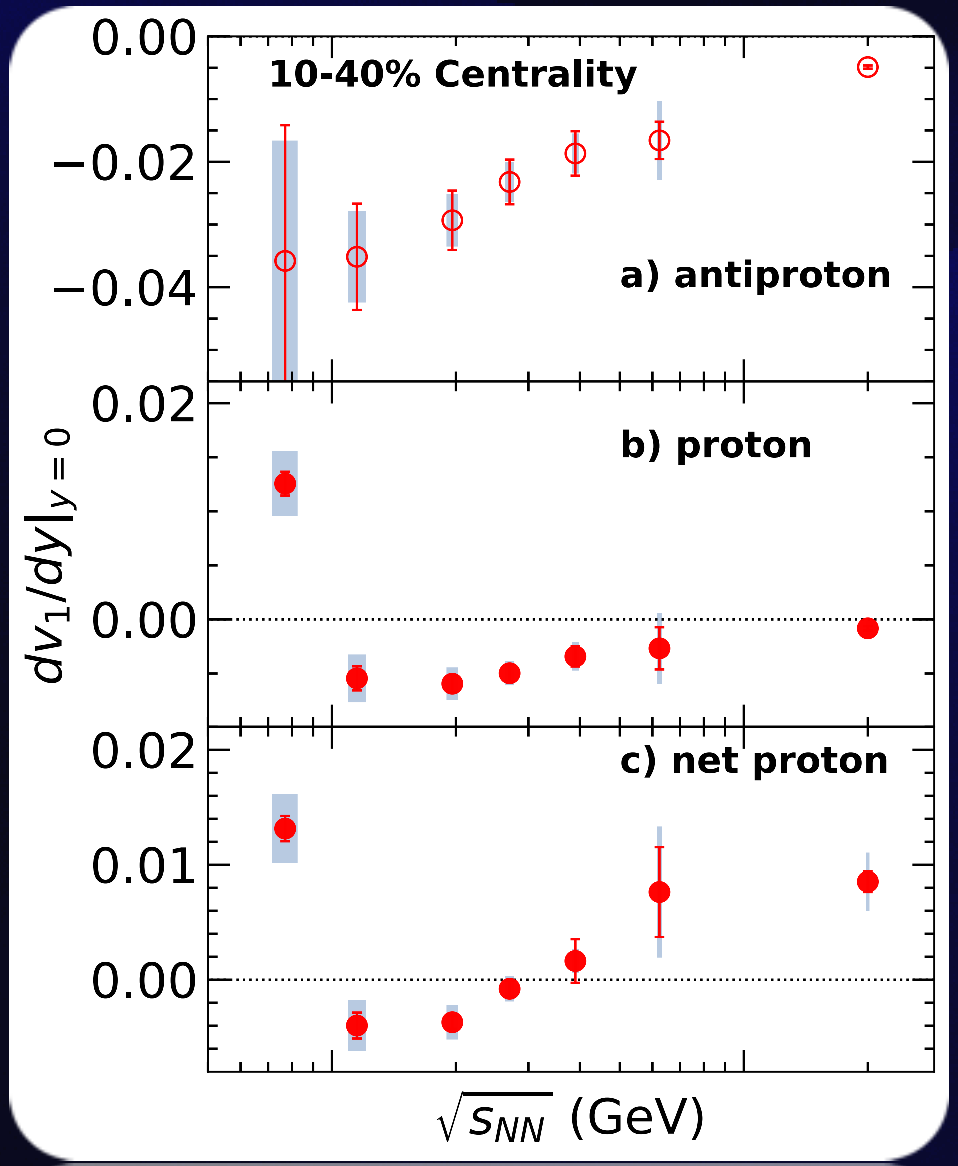
Baryon stopping related measurements at STAR and related physics interest



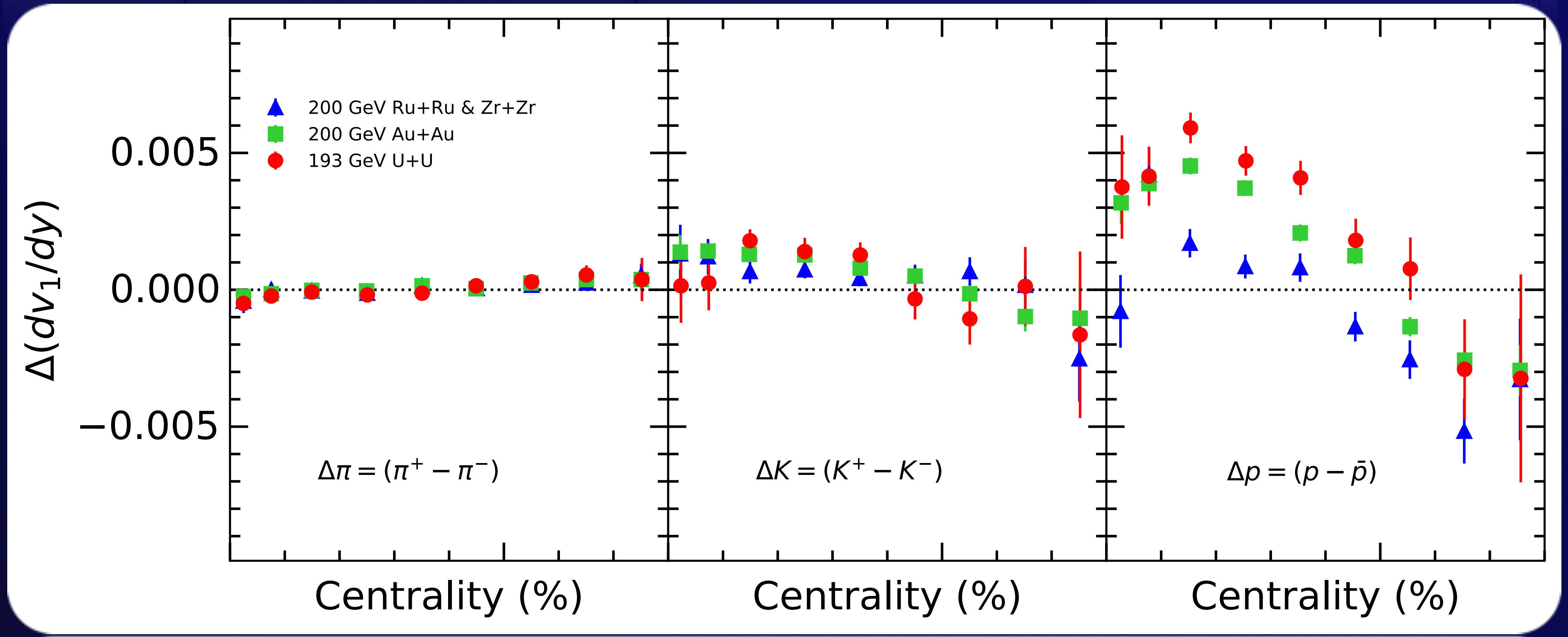
PRX (2024) 14, 011028 (STAR collaboration)







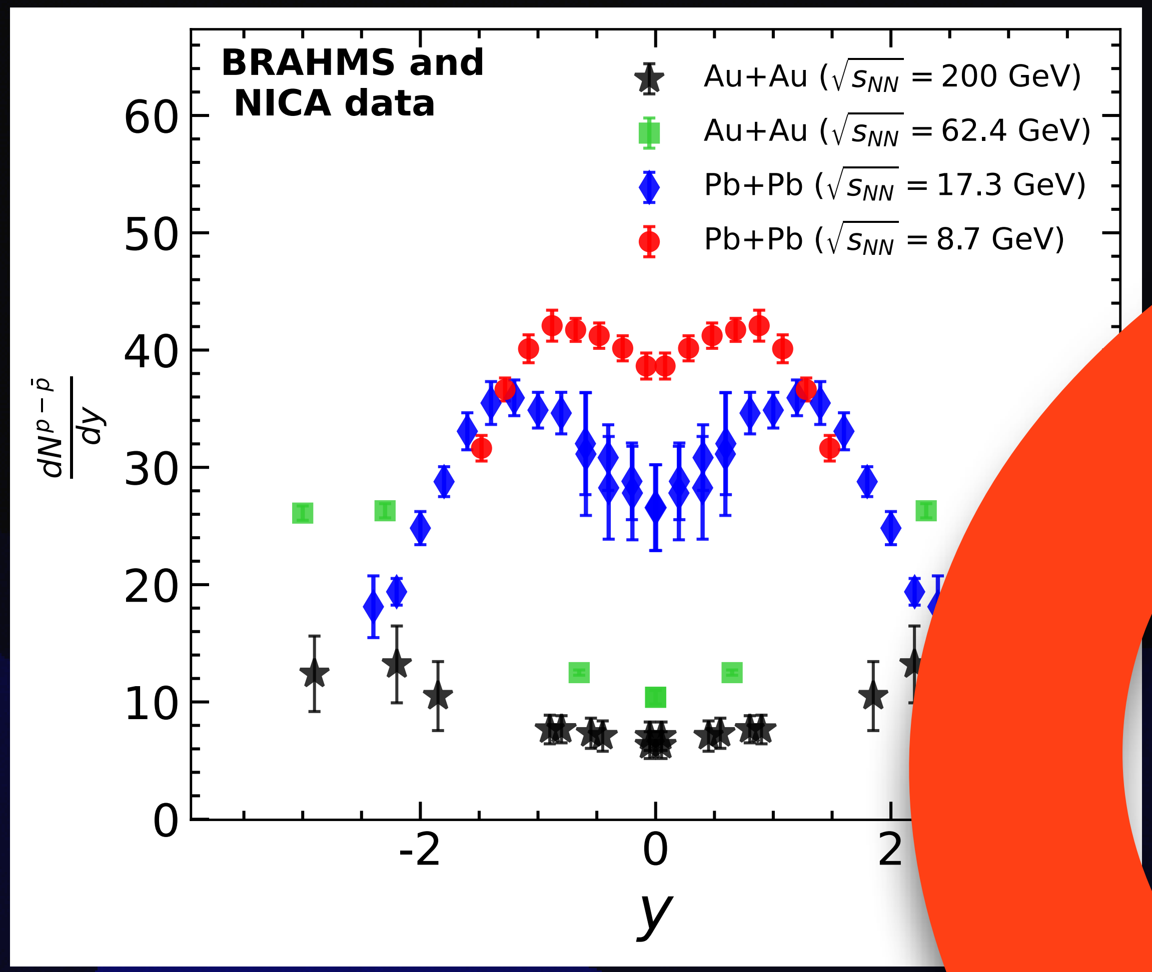
STAR collab. SQM, Strasbourg, 2024



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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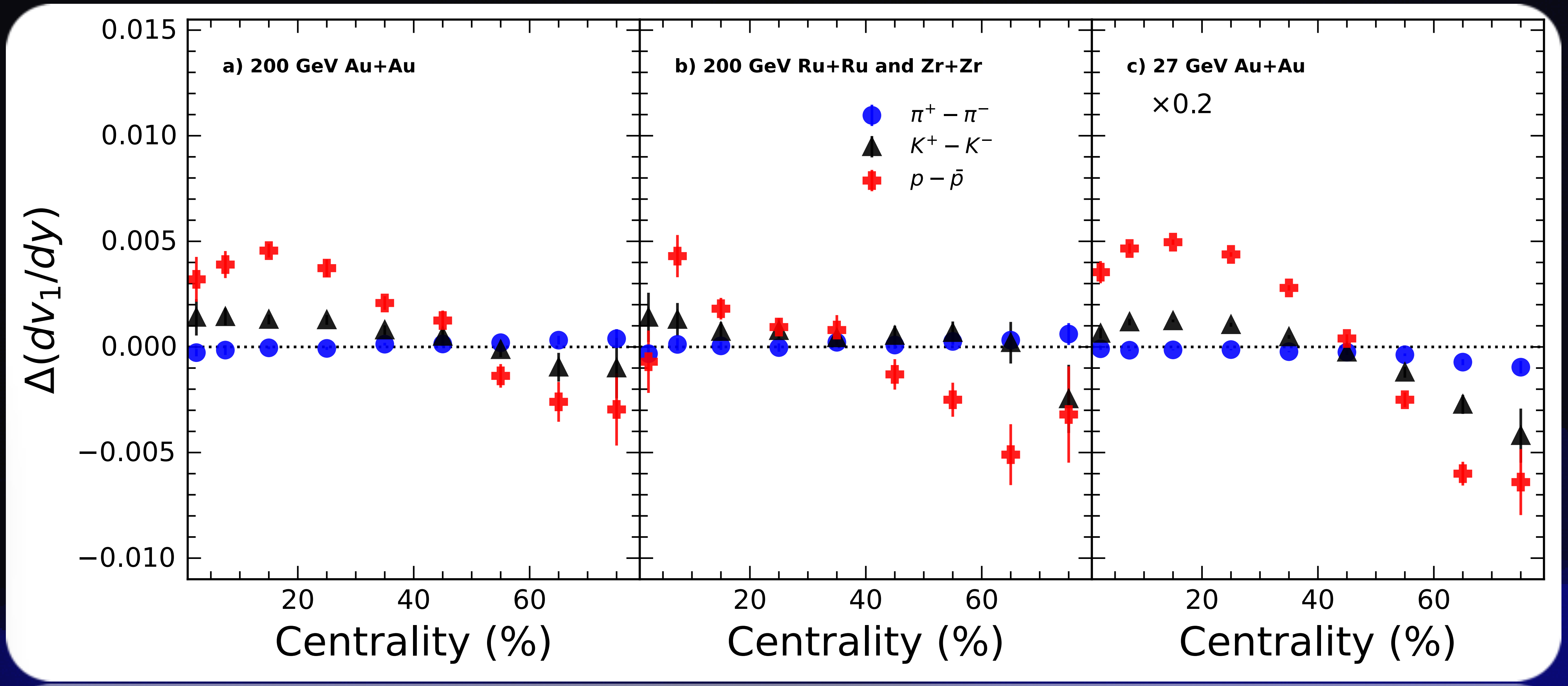
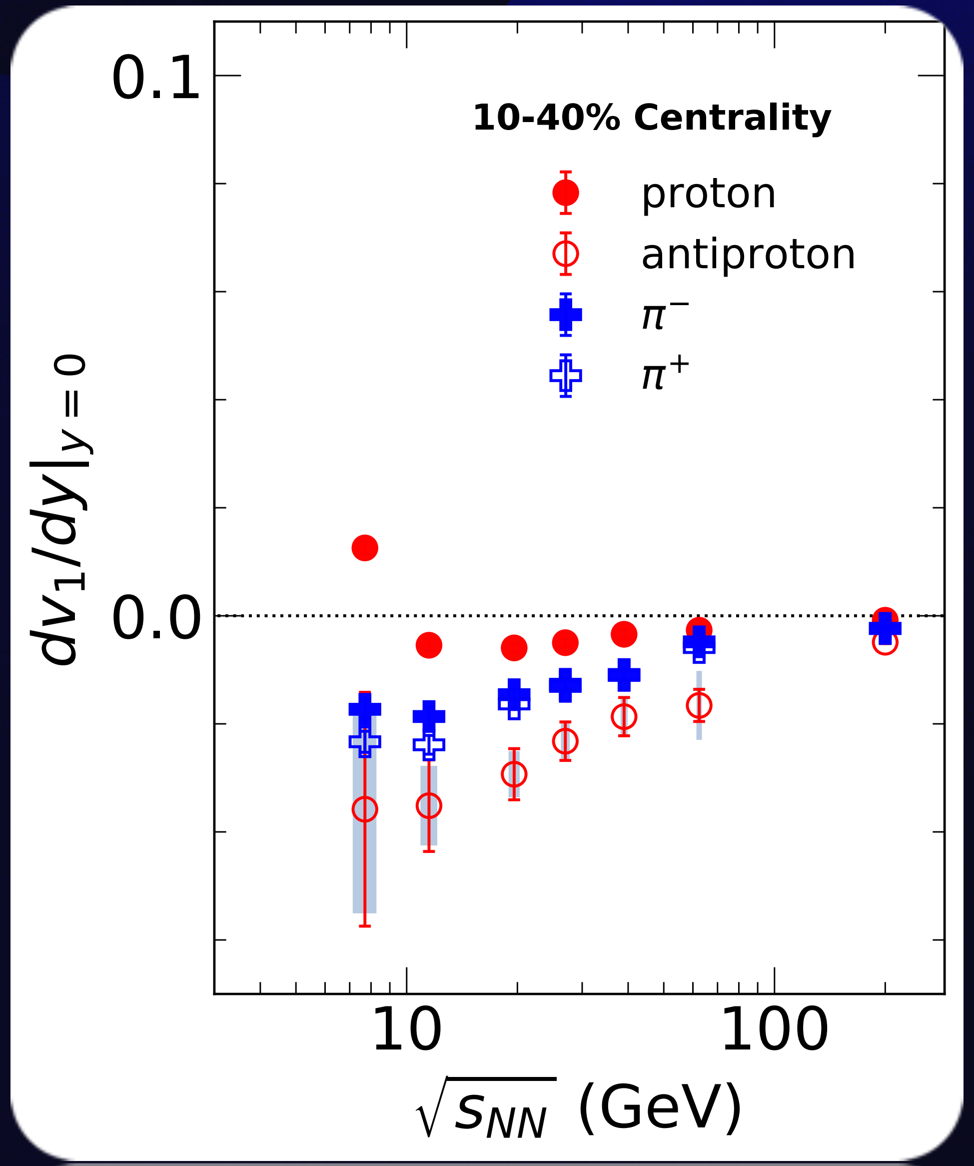
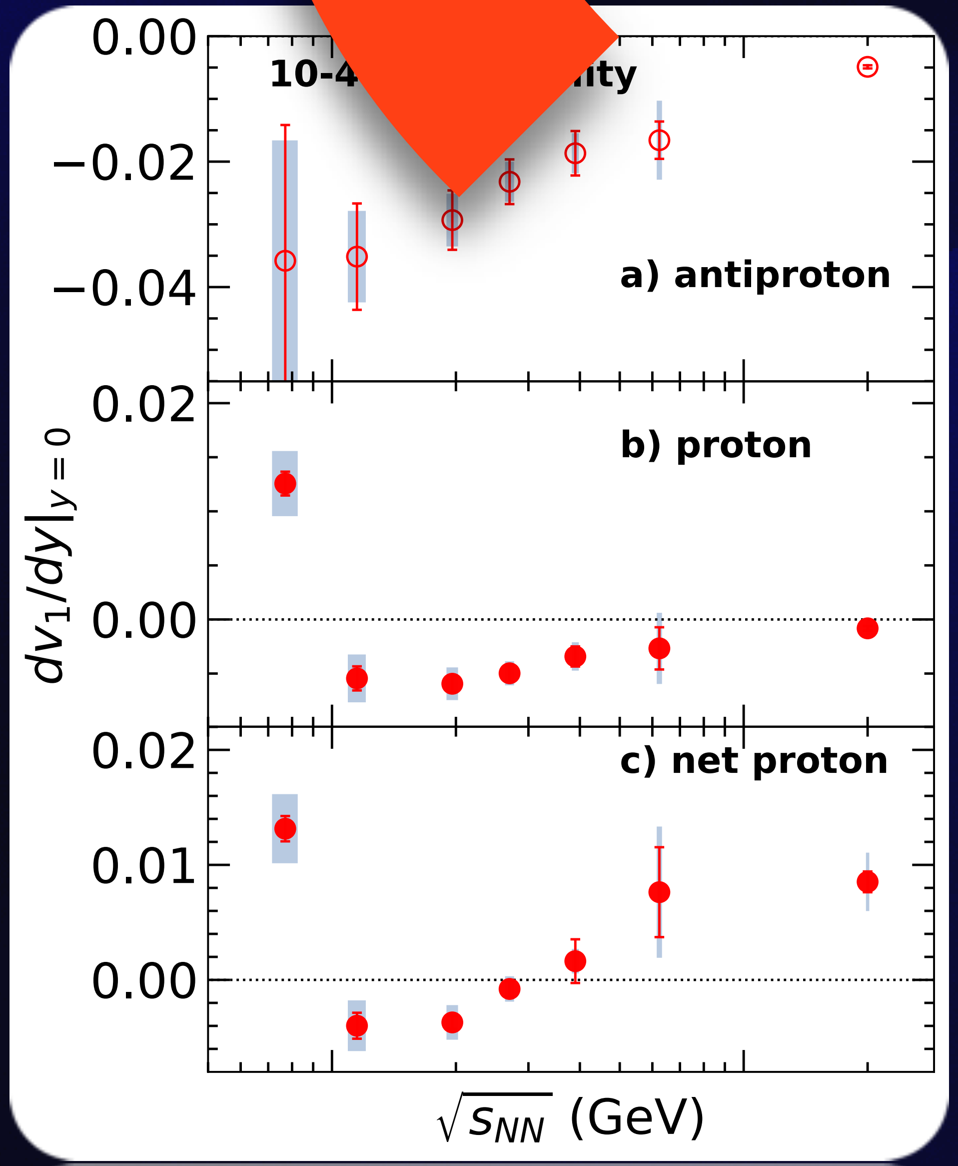
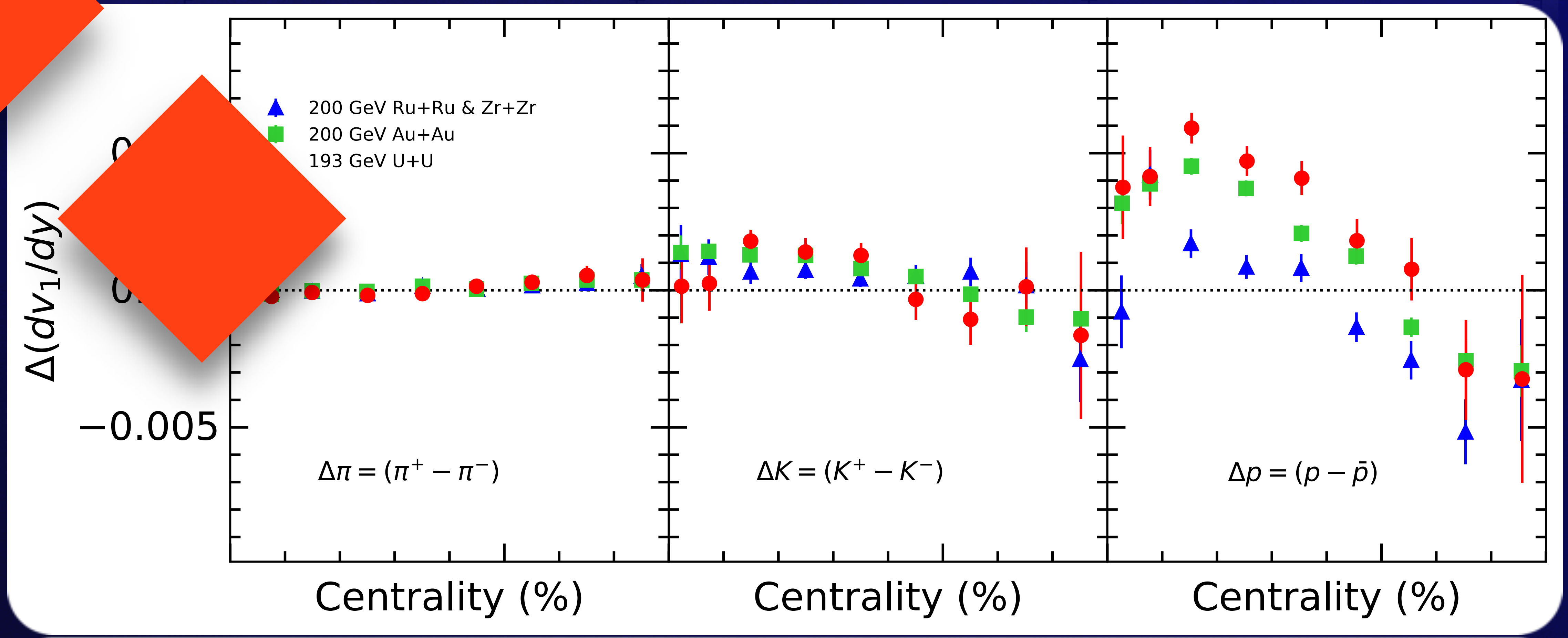






STAR collab. SQM, Strasbourg, 2024

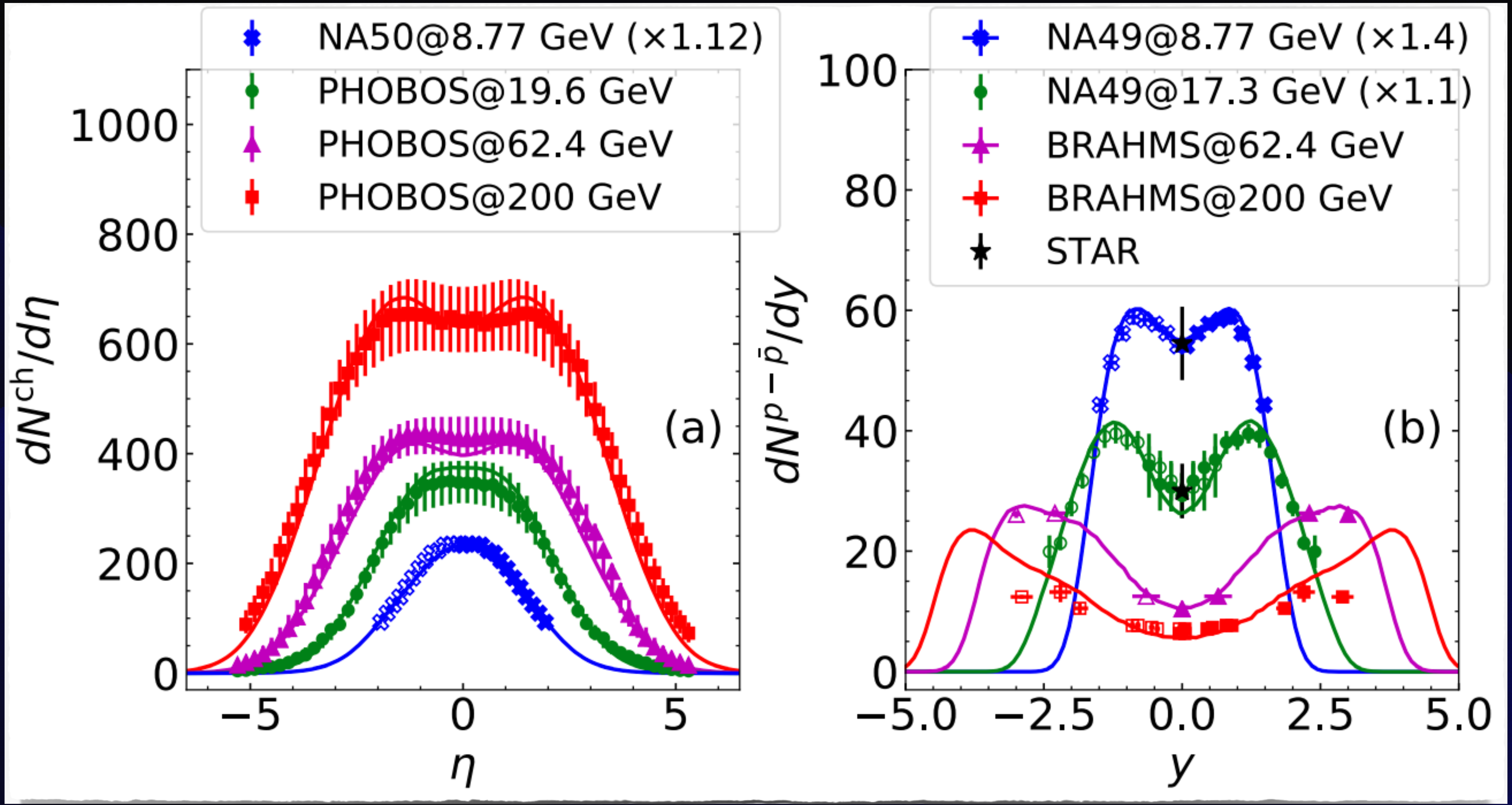


STAR Collaboration PRL, 120, 62301 (2018)

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)



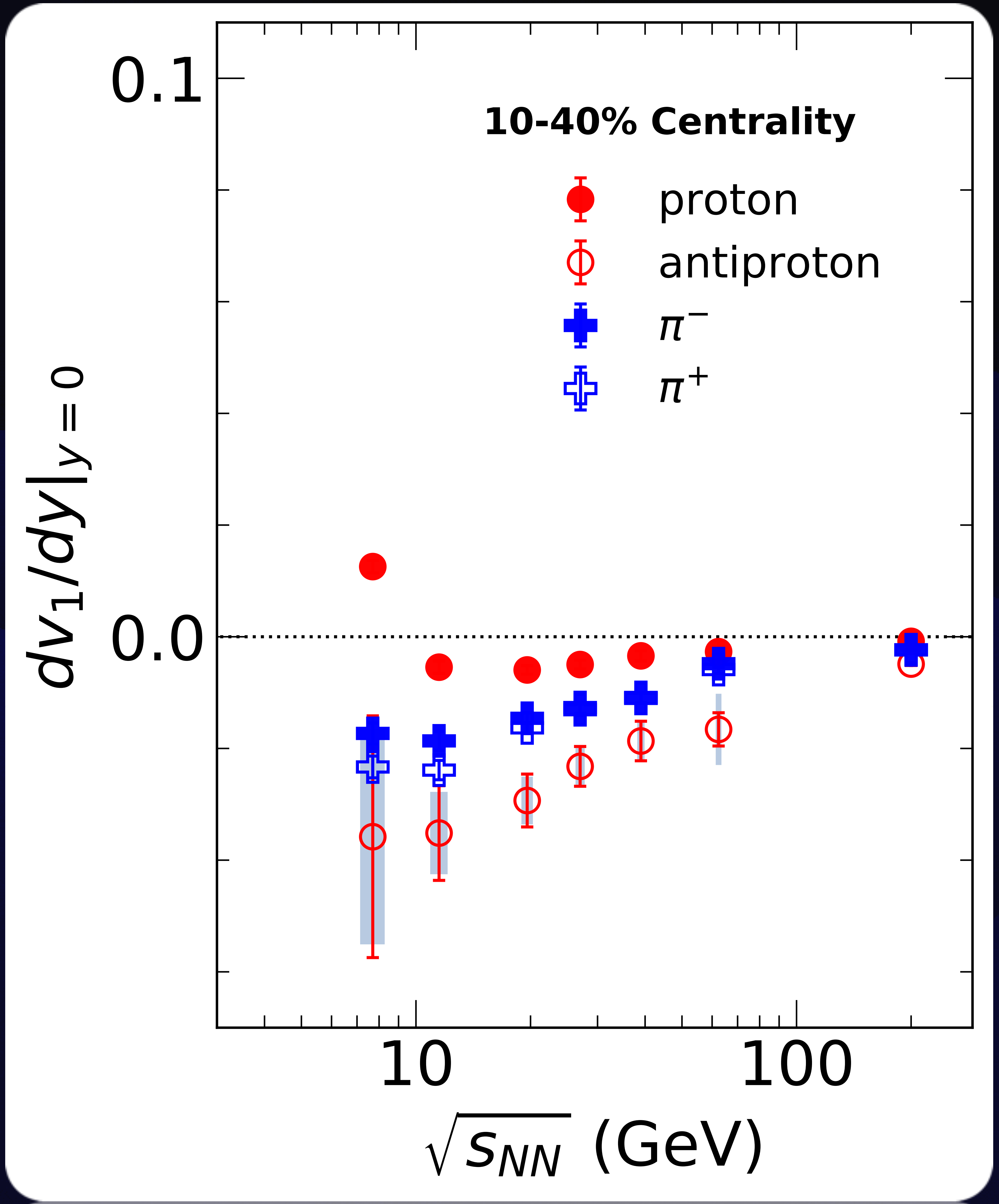
STAR collab., Phys. Rev. C 96, 044904 (2017)

STAR collab., Phys. Rev. C 79, 034909 (2009)

BRAHMS collab., Phys. Lett. B 677, 267 – 271 (2009)

BRAHMS collab., Phys. Rev. Lett. 93, 102301 (2004)

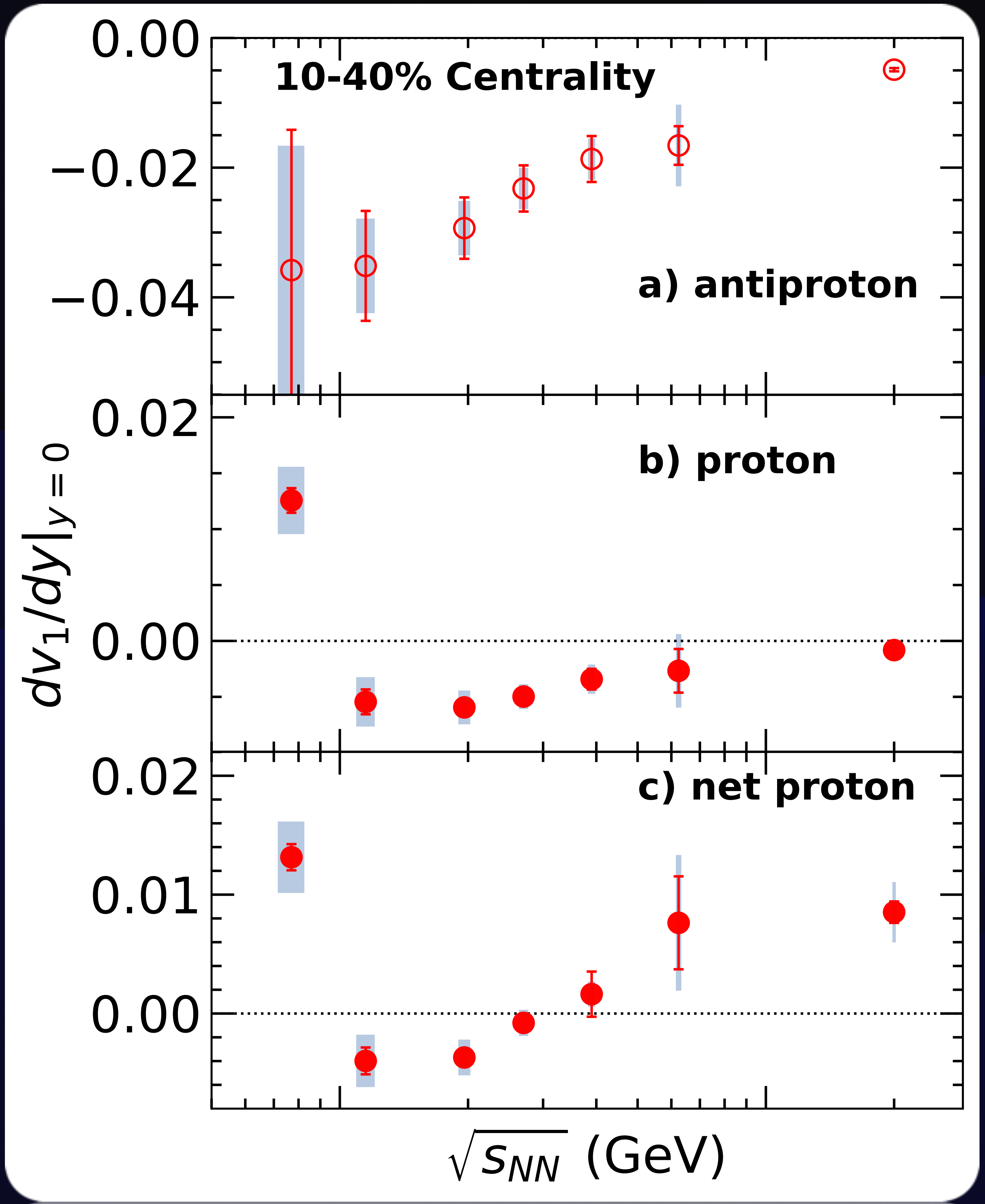
Phys. Rev. Lett. 82, 2471 – 2475 (1999)



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

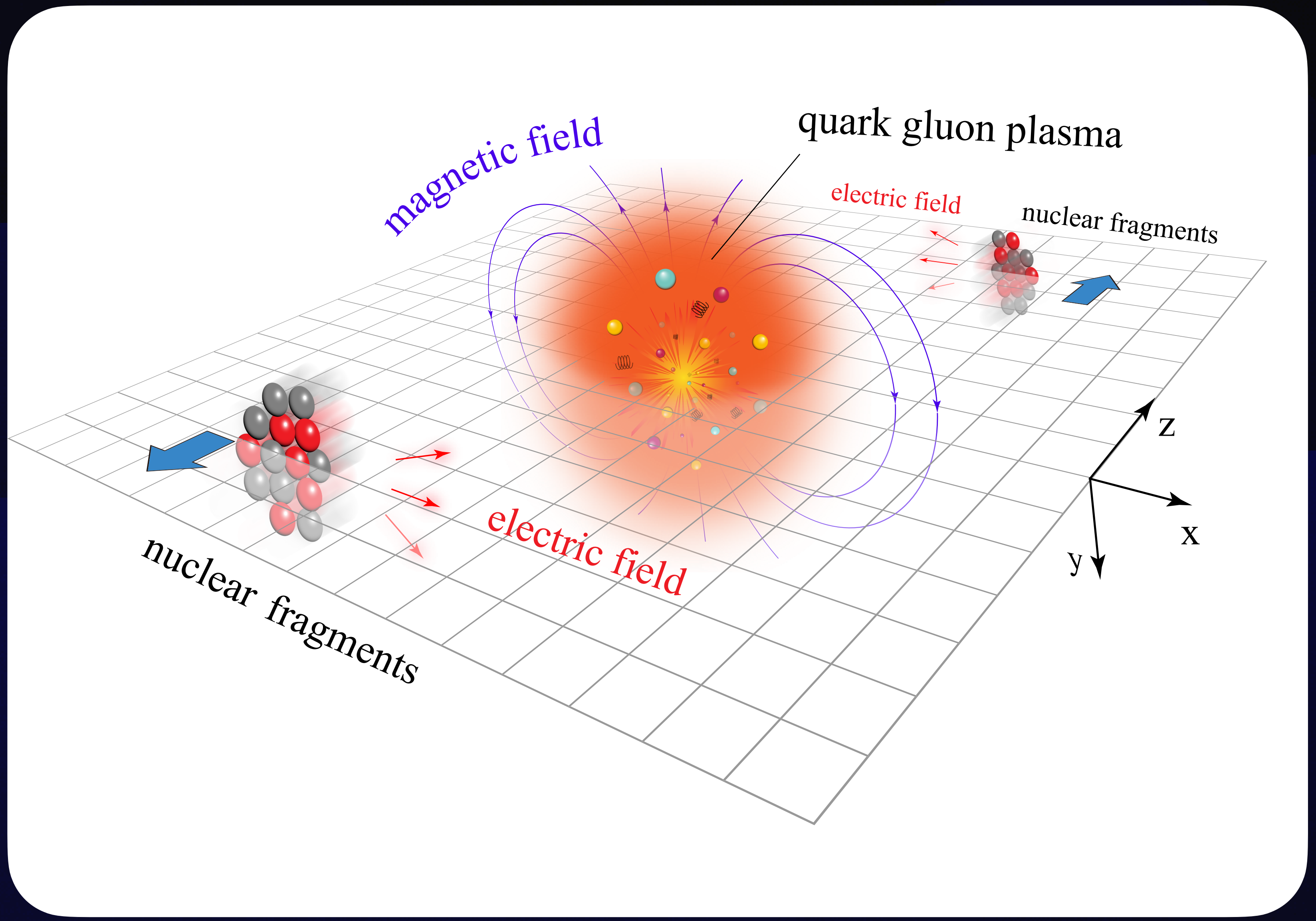


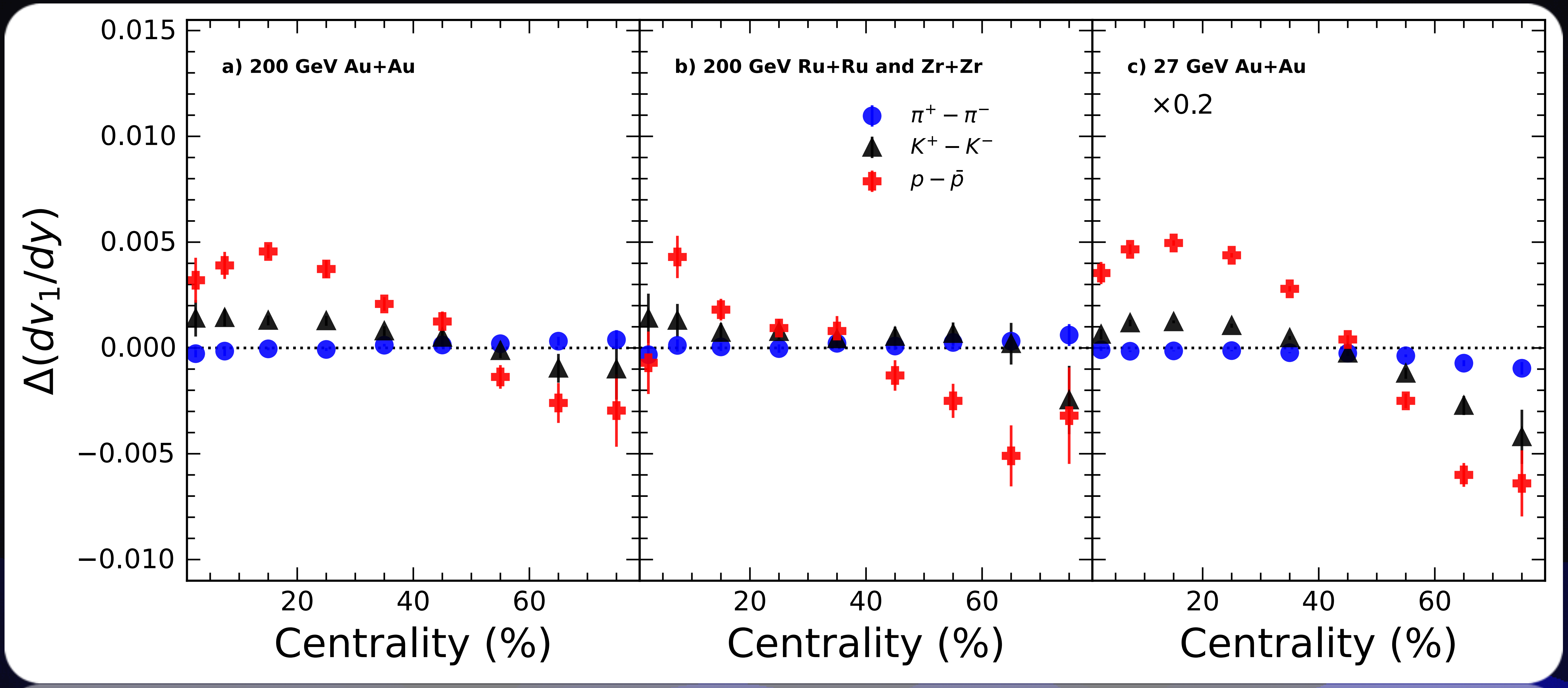
STAR Collaboration PRL, 112, 163201 (2014)

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

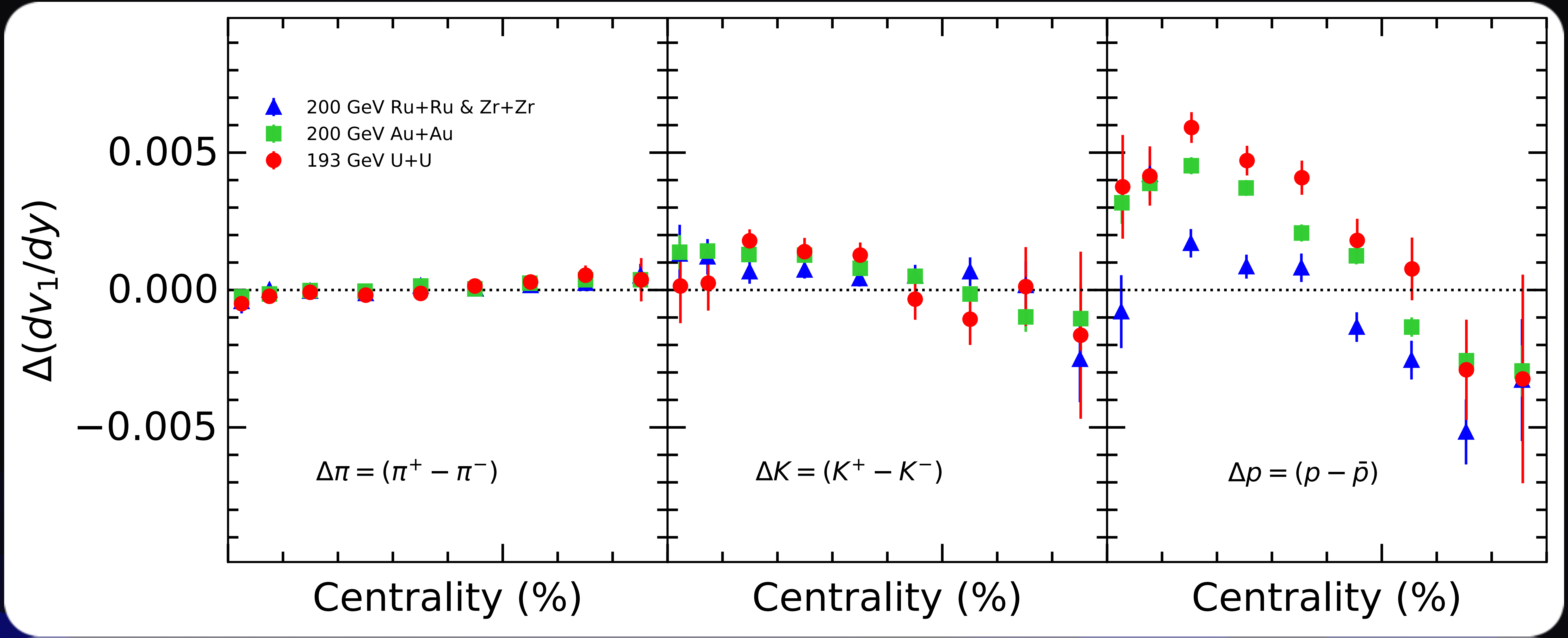
Feature	Physics	status
Sign change of proton and double sign change of net proton	Initial baryon stopping and Signature of 1st order phase transition	No model captures

PRX (2024) 14, 011028 (STAR collaboration)





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



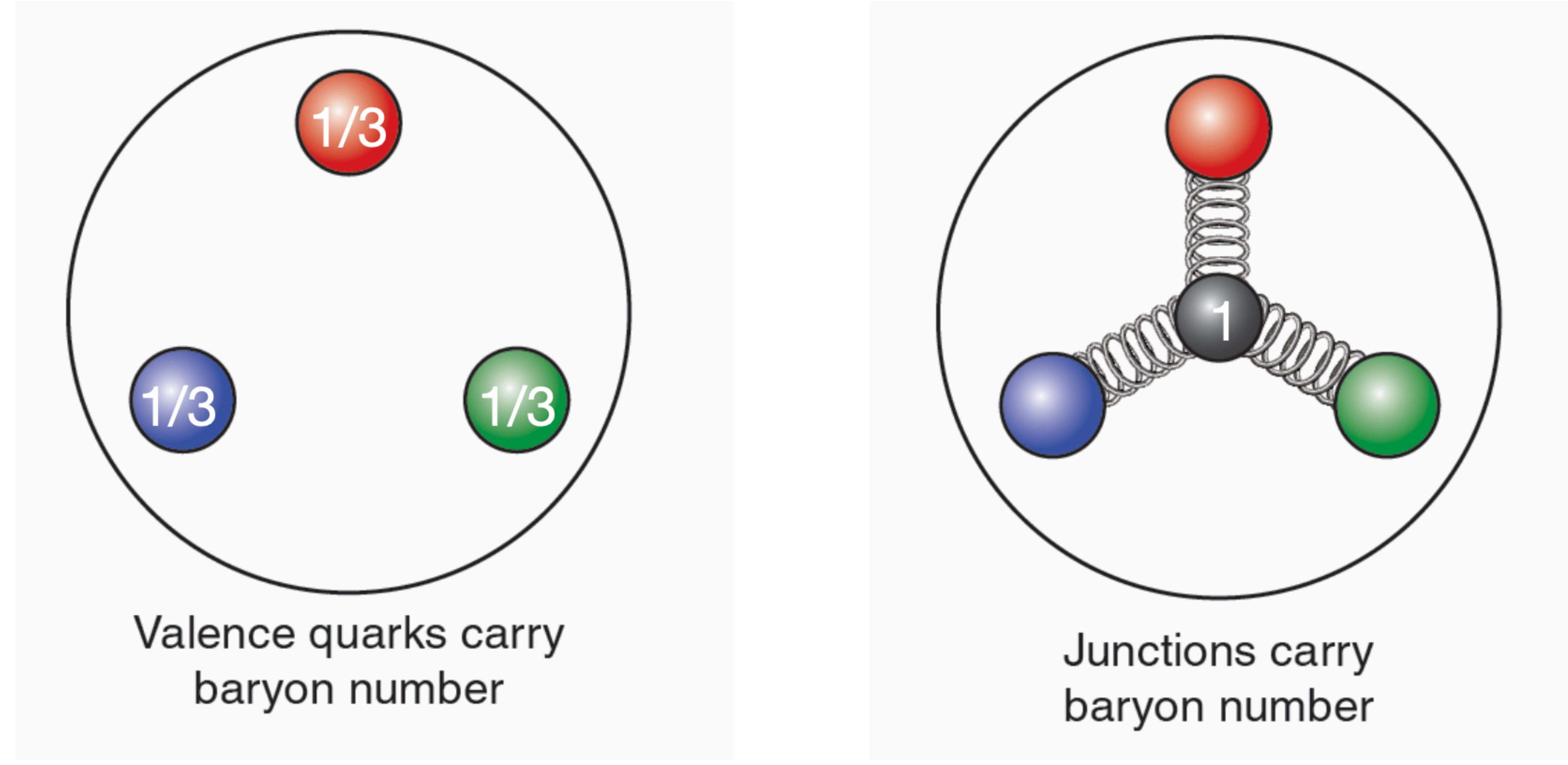
STAR collab. SQM, Strasbourg, 2024

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



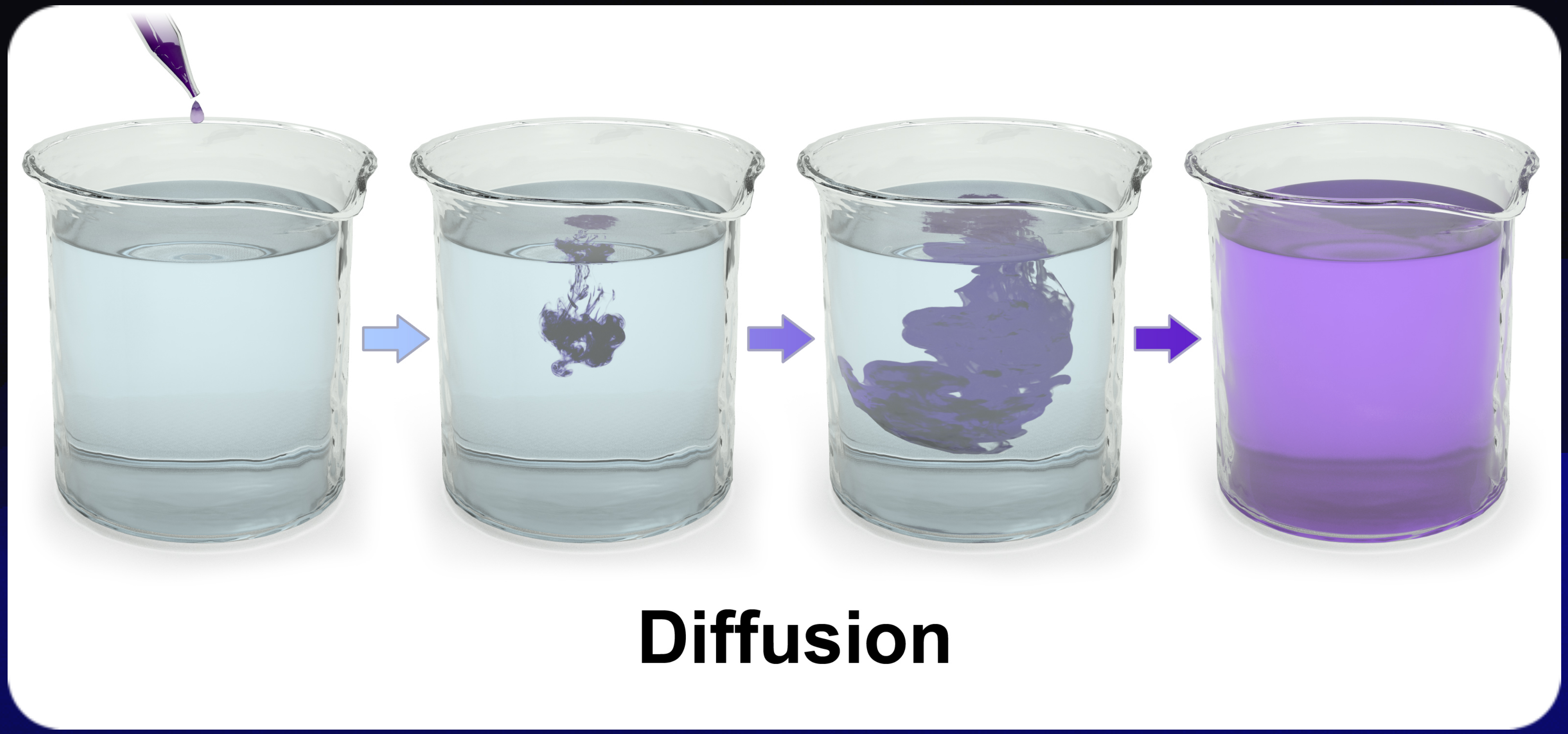
~~$n_B \propto N_{\text{participants}}$~~

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

+

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

Hydro with baryon diffusion



Fick's law :

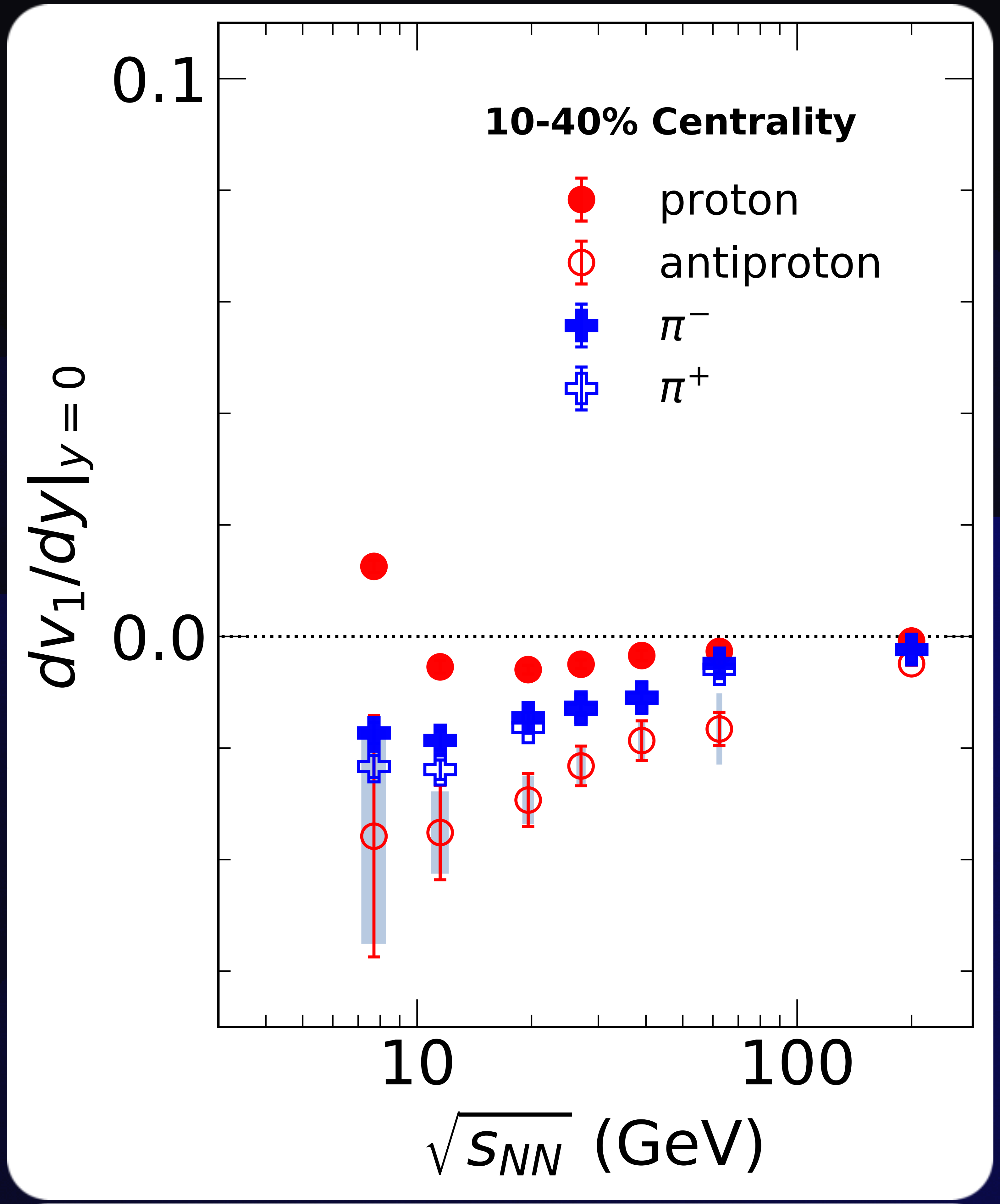
$$j_B^\mu = \kappa_B \nabla^\mu (n_B)$$

Diffusion current

Diffusion coefficient

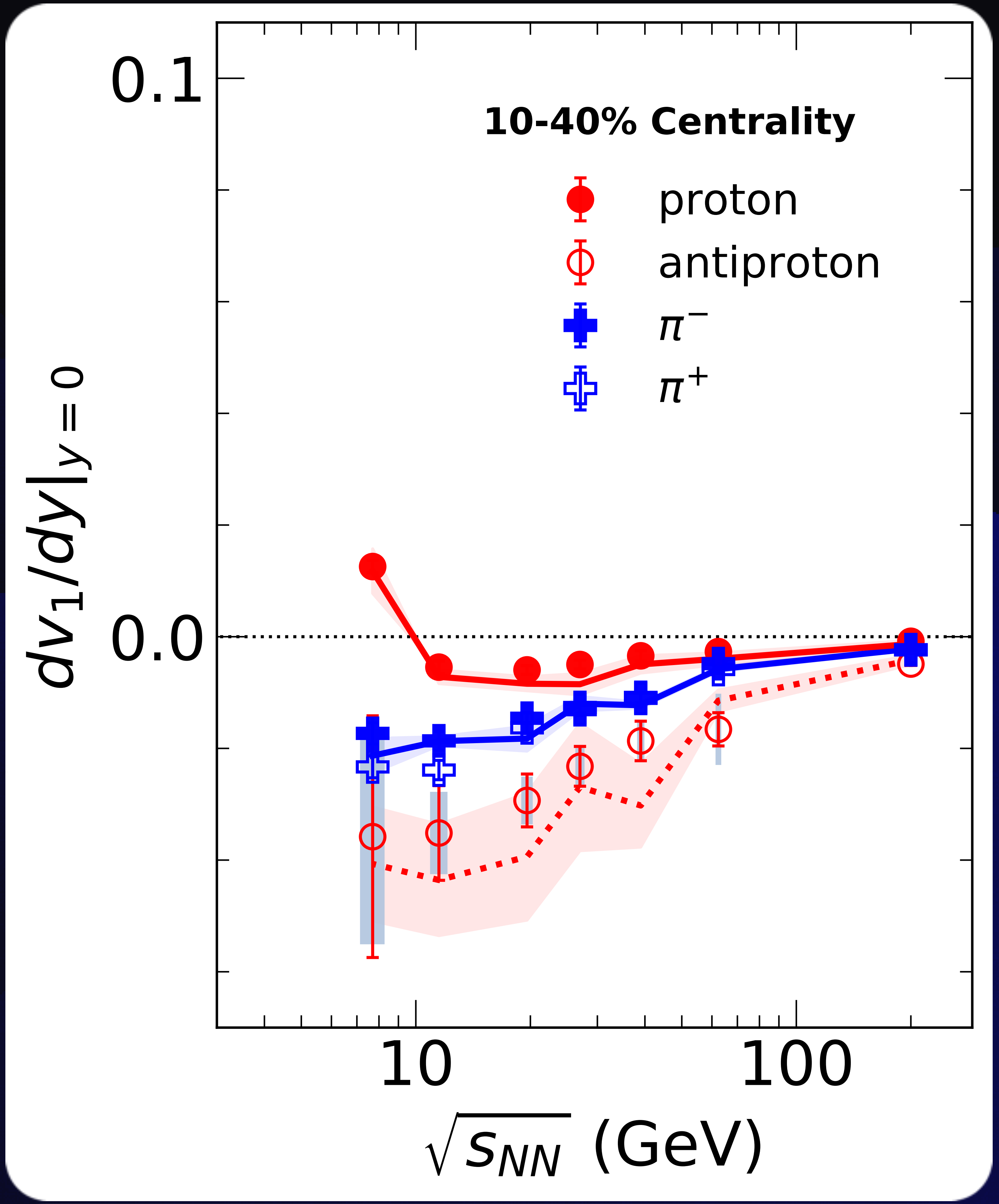
$$\kappa_B = \frac{C_B}{T} n_B \left[\frac{1}{3} \coth\left(\frac{\mu_B}{T}\right) - \frac{n_B T}{\epsilon + p} \right]$$

Results



STAR Collaboration PRL, 112, 163201 (2014)

Results

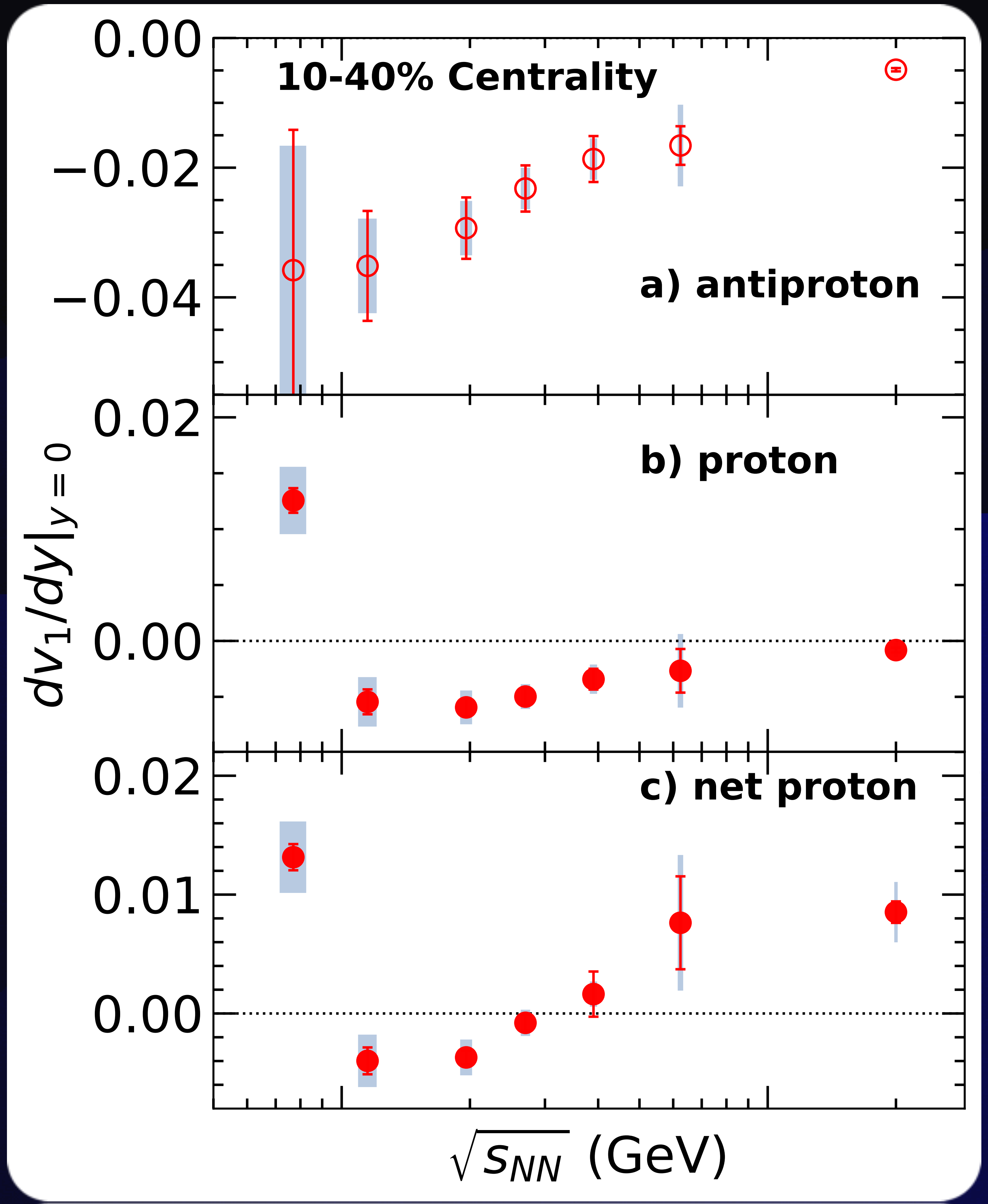


TP and Sandeep Chatterjee arxiv: 2211.15729

TP and Sandeep Chatterjee arxiv: 2211.15659

STAR Collaboration PRL, 112, 163201 (2014)

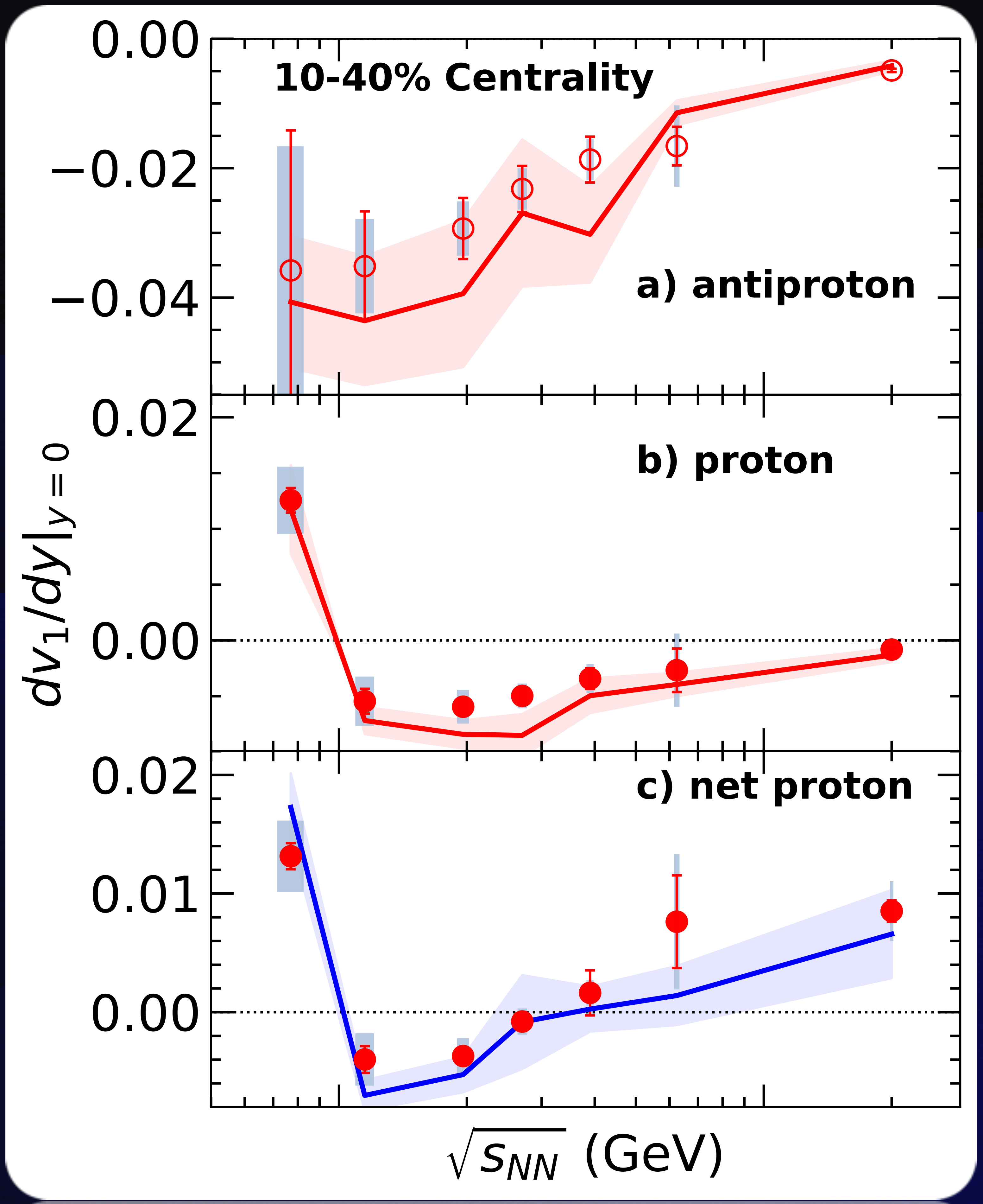
Results



STAR Collaboration PRL, 112, 163201 (2014)

Results

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



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STAR Collaboration PRL, 112, 163201 (2014)

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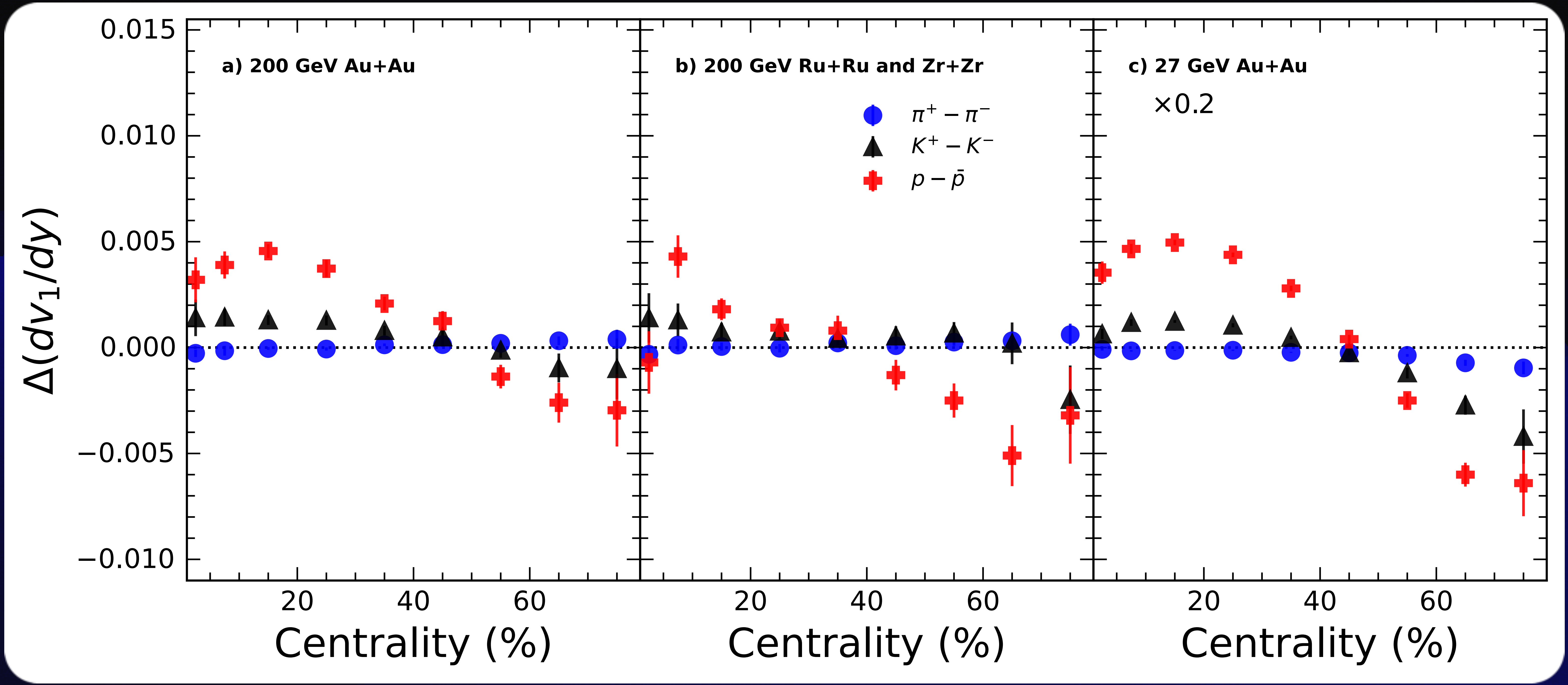
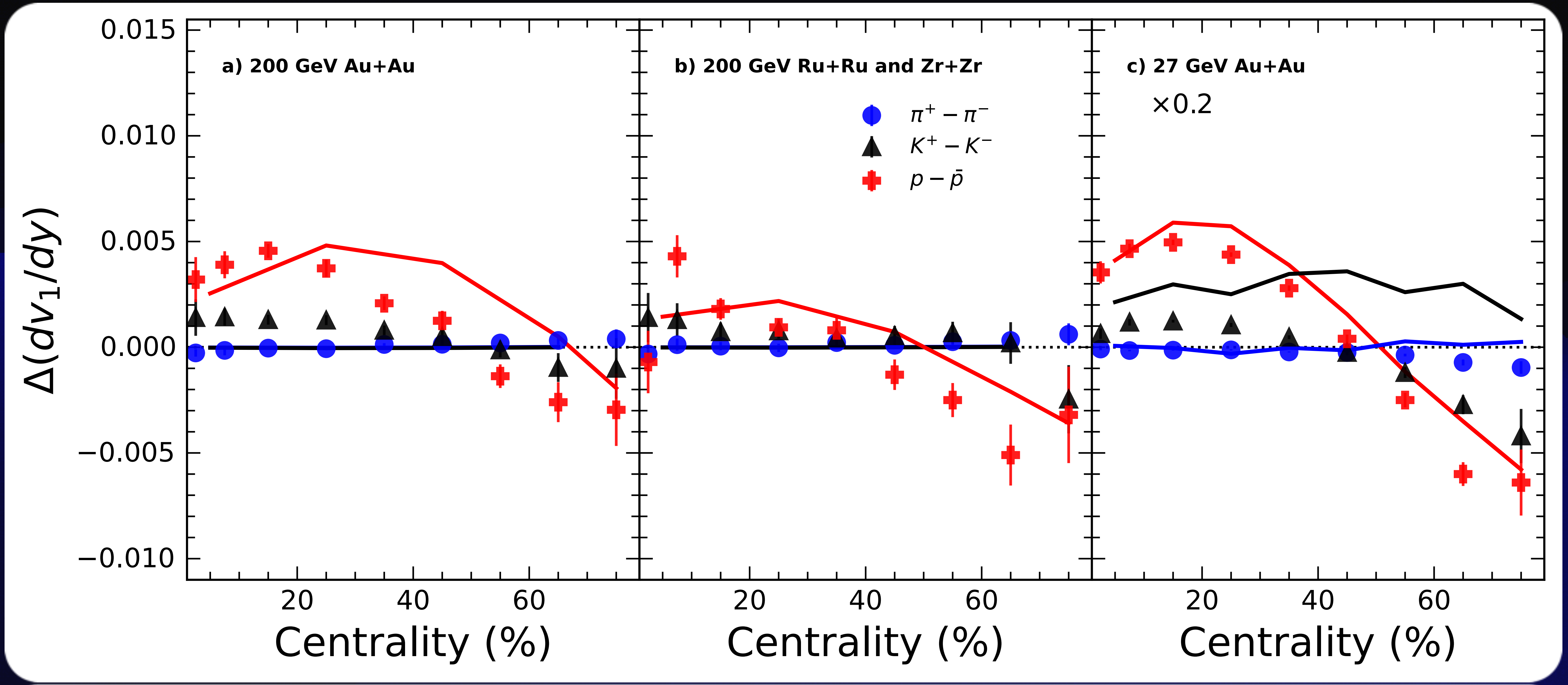


PRX (2024) 14, 011028 (STAR collaboration)

Results

PRX (2024) 14, 011028 (STAR collaboration)

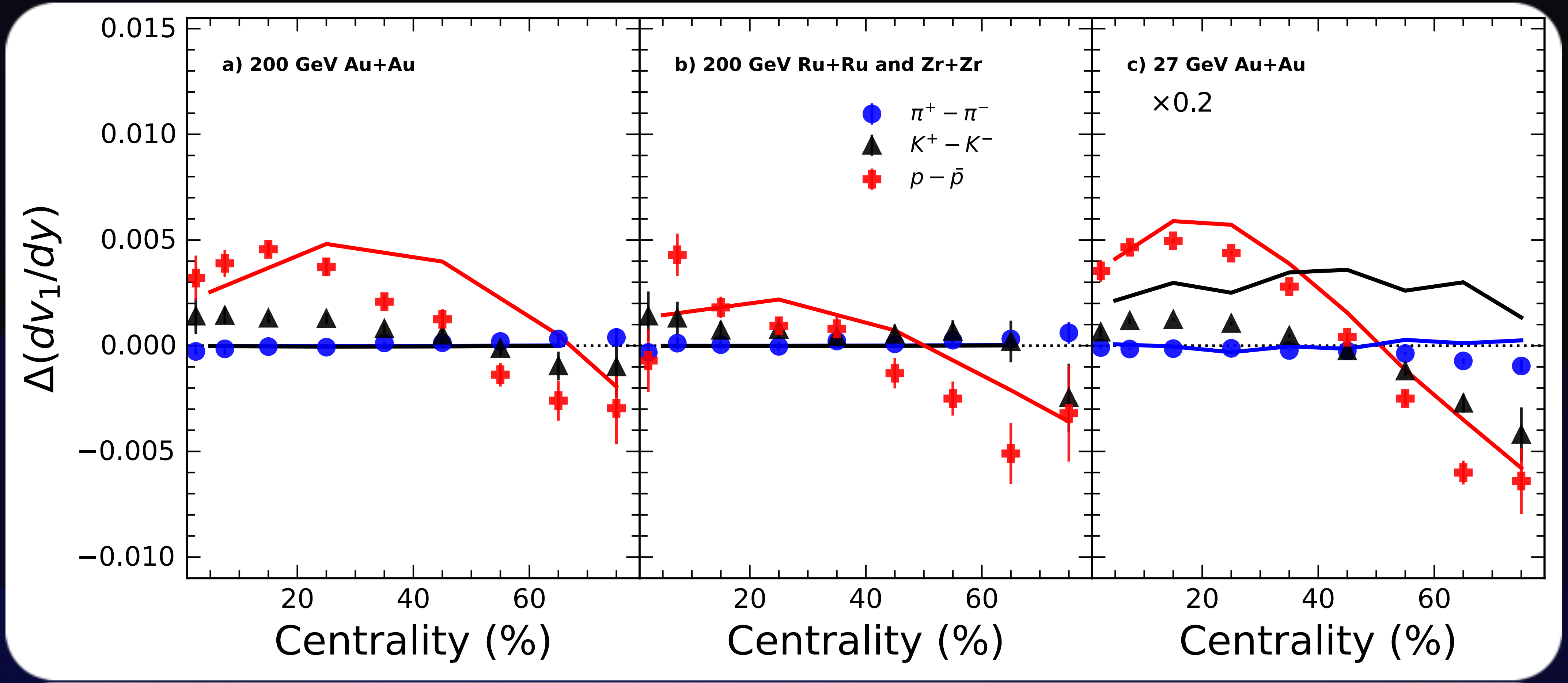
TP and Sandeep Chatterjee arxiv: 2305.08806

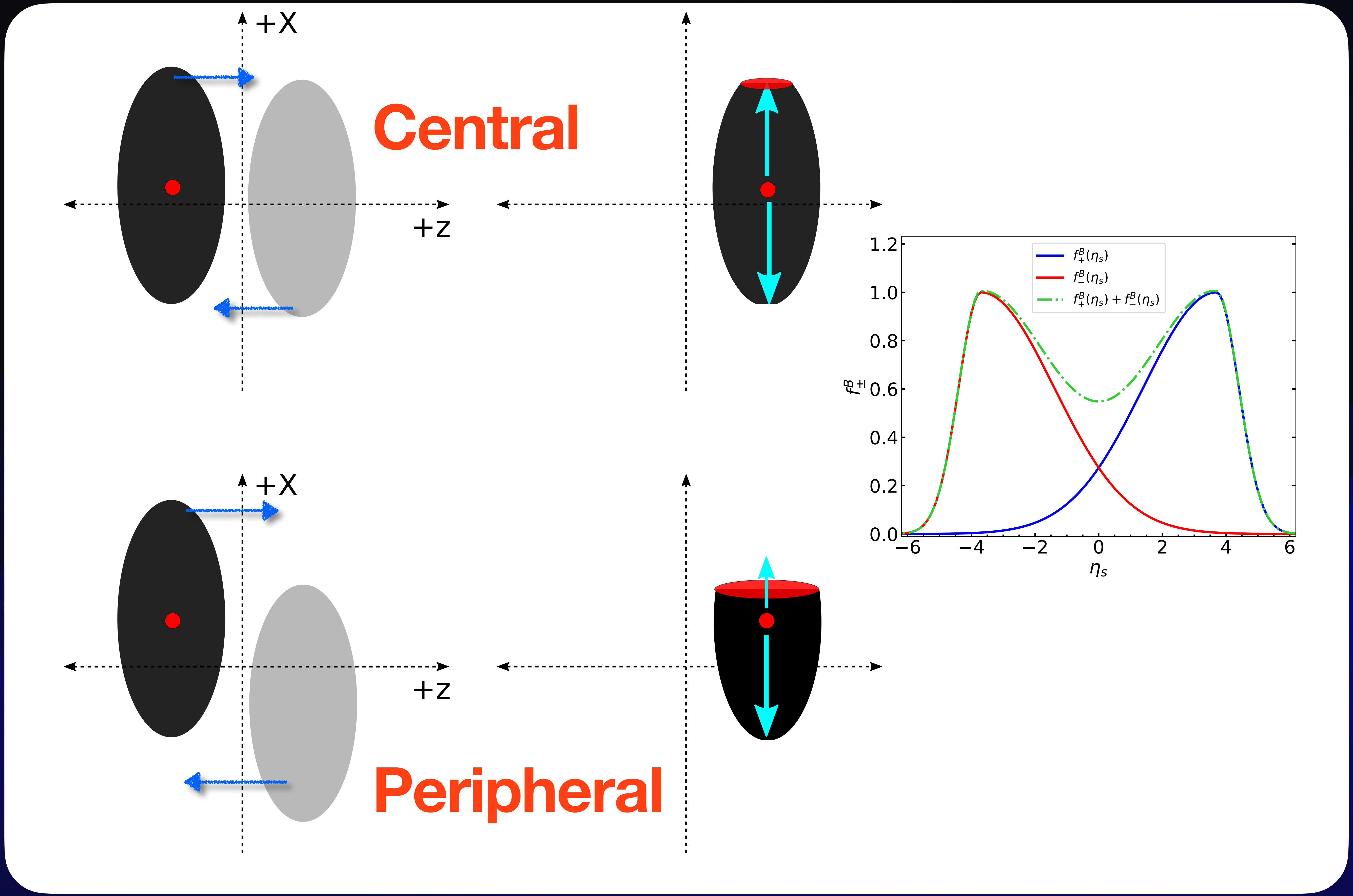


No EM field effect in our model

Background of conserved charge physics to the signals of EM field

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





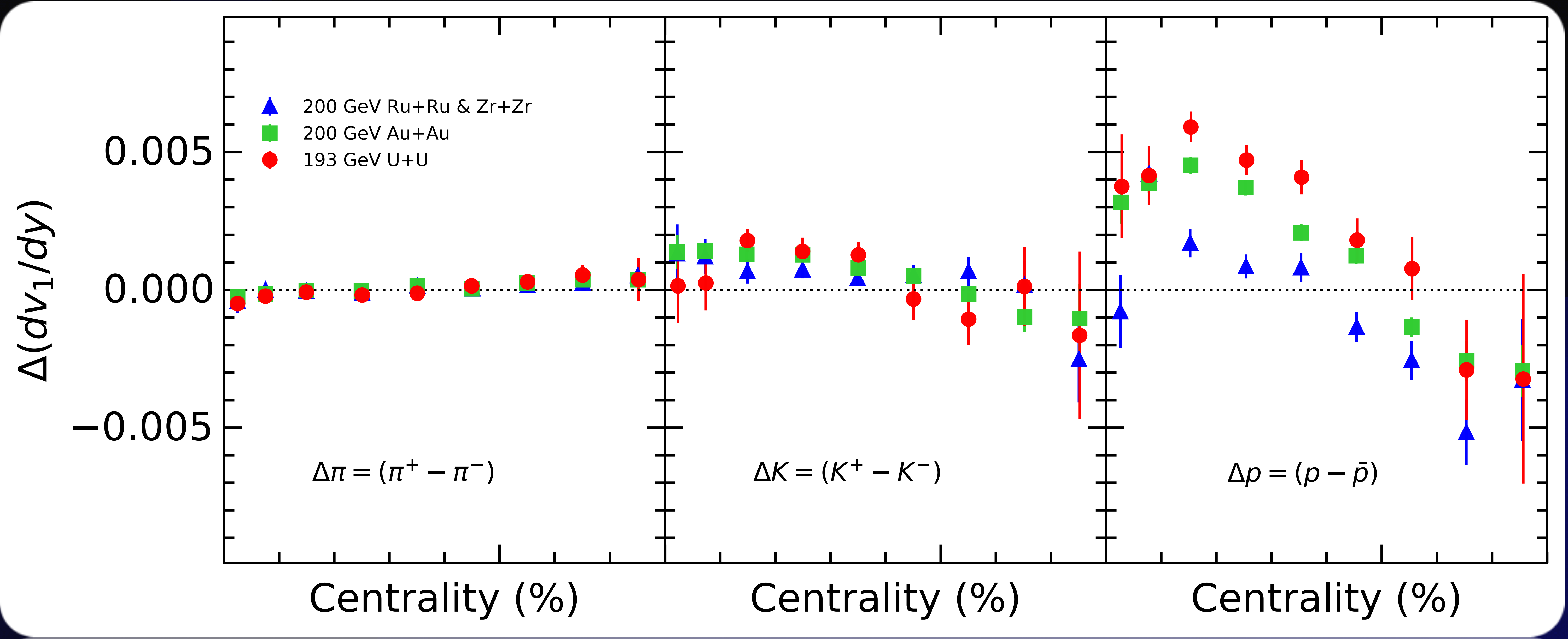
Asymmetric baryon gradient along +x to -x

$$j^\mu_B = \kappa_B \nabla^\mu (n_B)$$

TP and Sandeep Chatterjee arxiv: 2305.08806

PRX (2024) 14, 011028 (STAR collaboration)

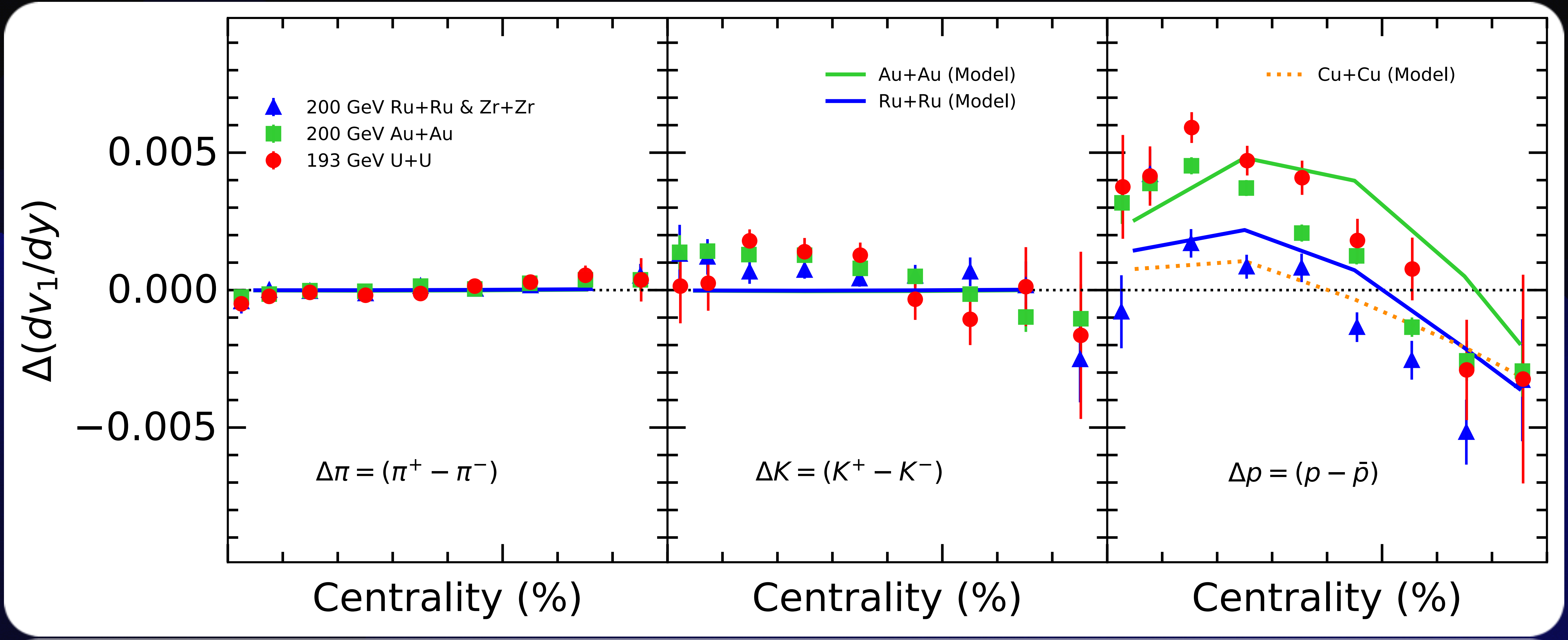
Results



STAR collab. SQM, Strasbourg, 2024

Results

TP, Sandeep Chatterjee and Subhash Singha
In preparation …



STAR collab. SQM, Strasbourg, 2024

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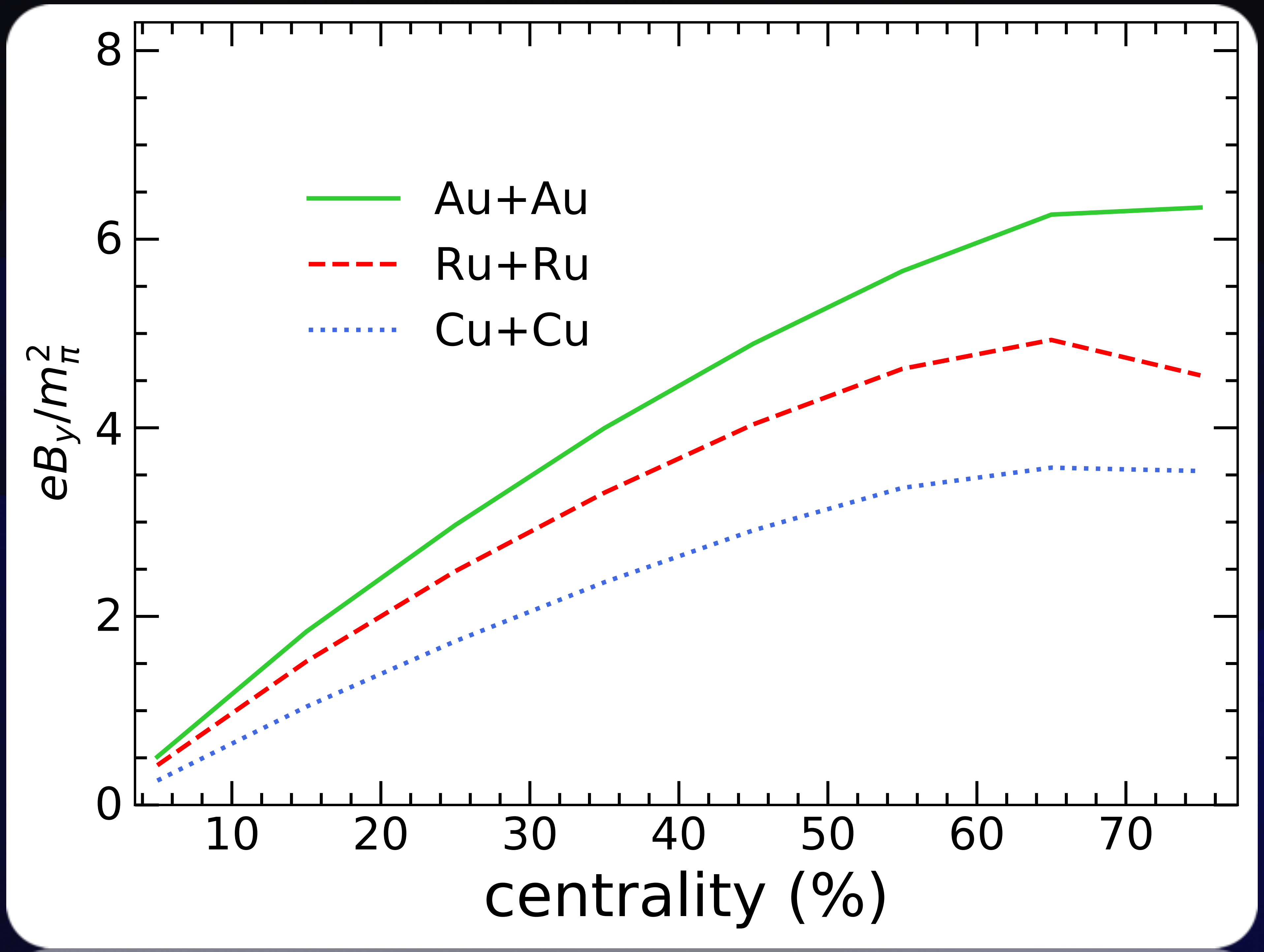
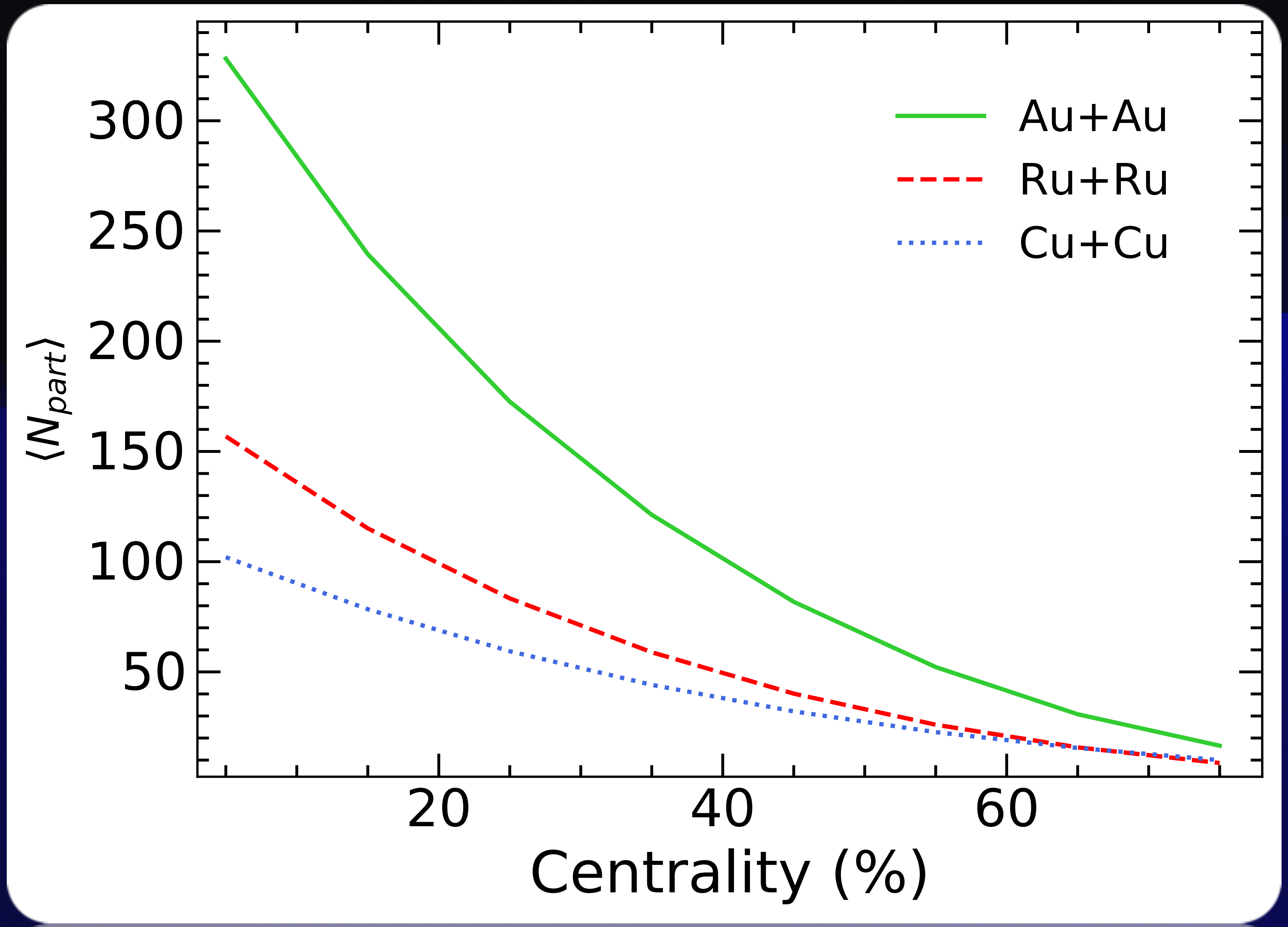
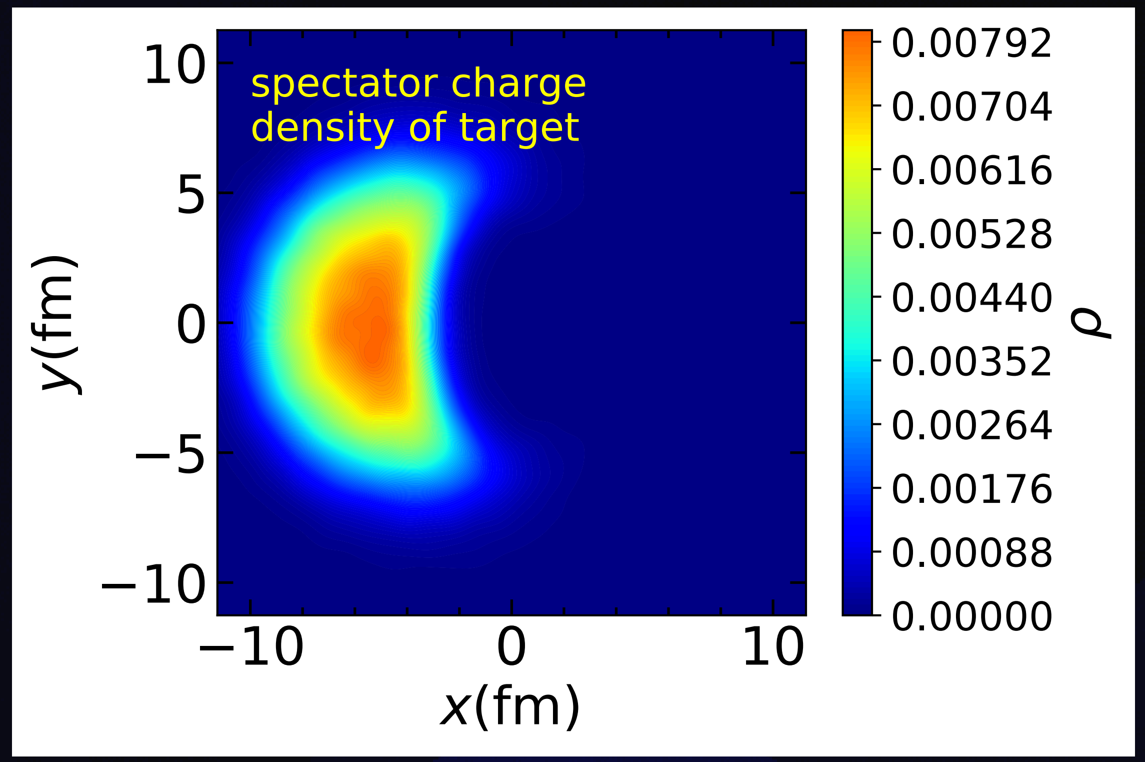
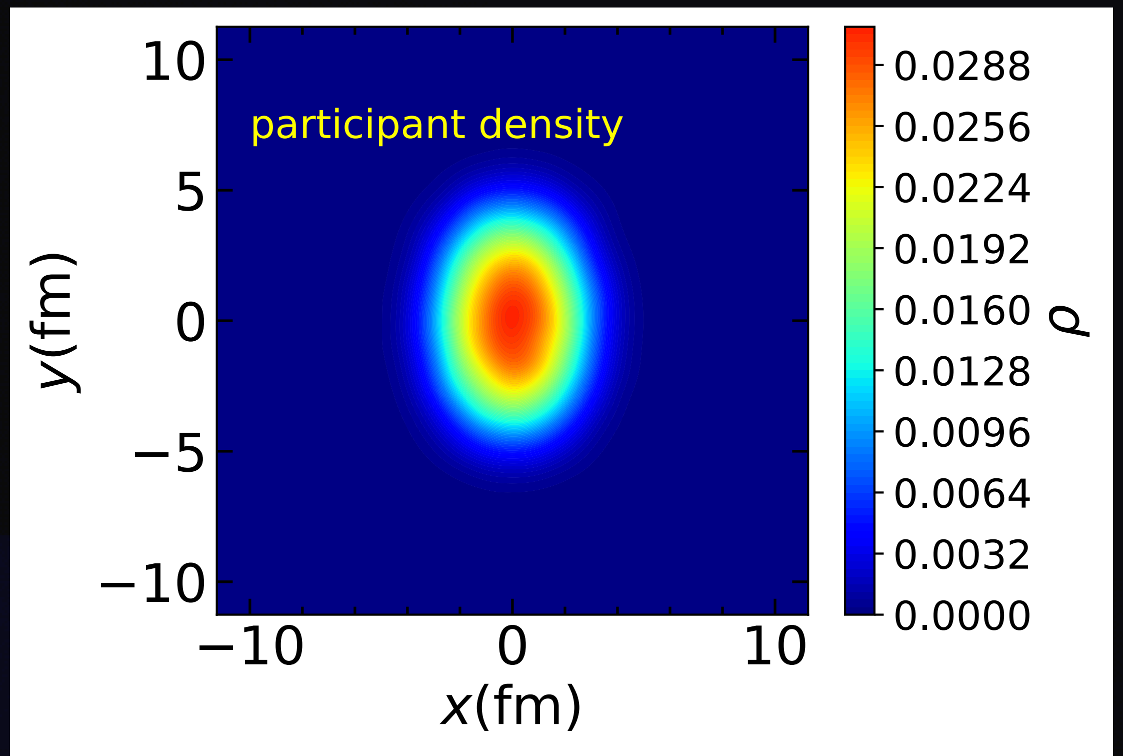
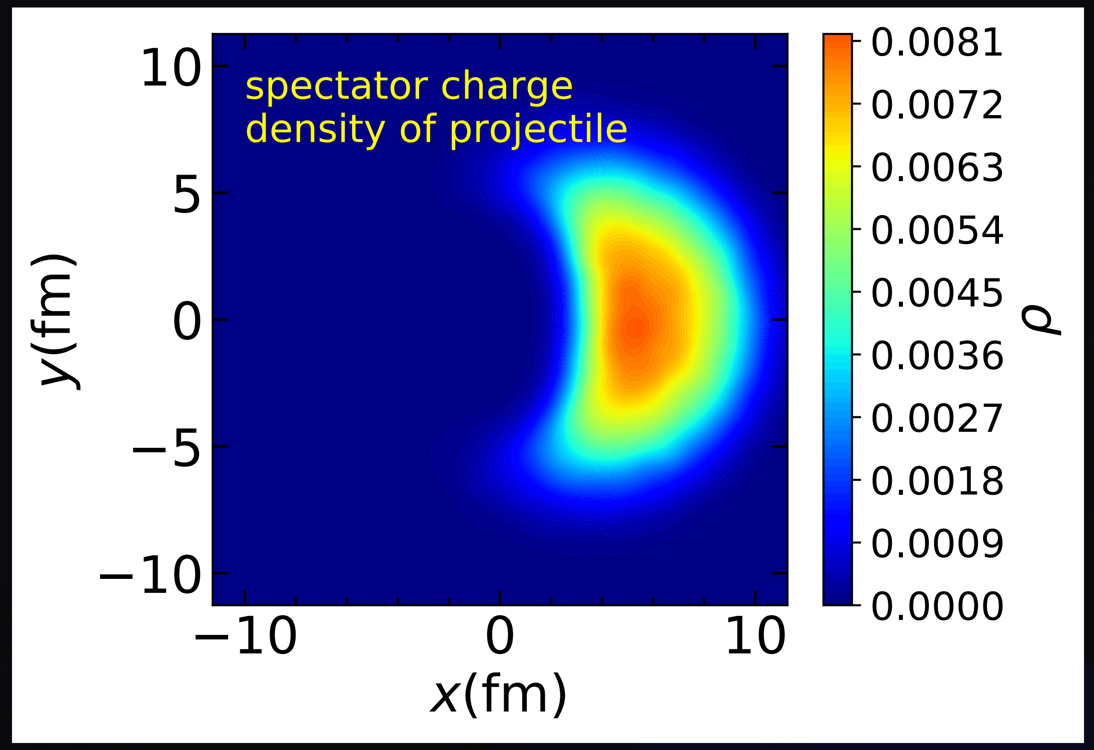


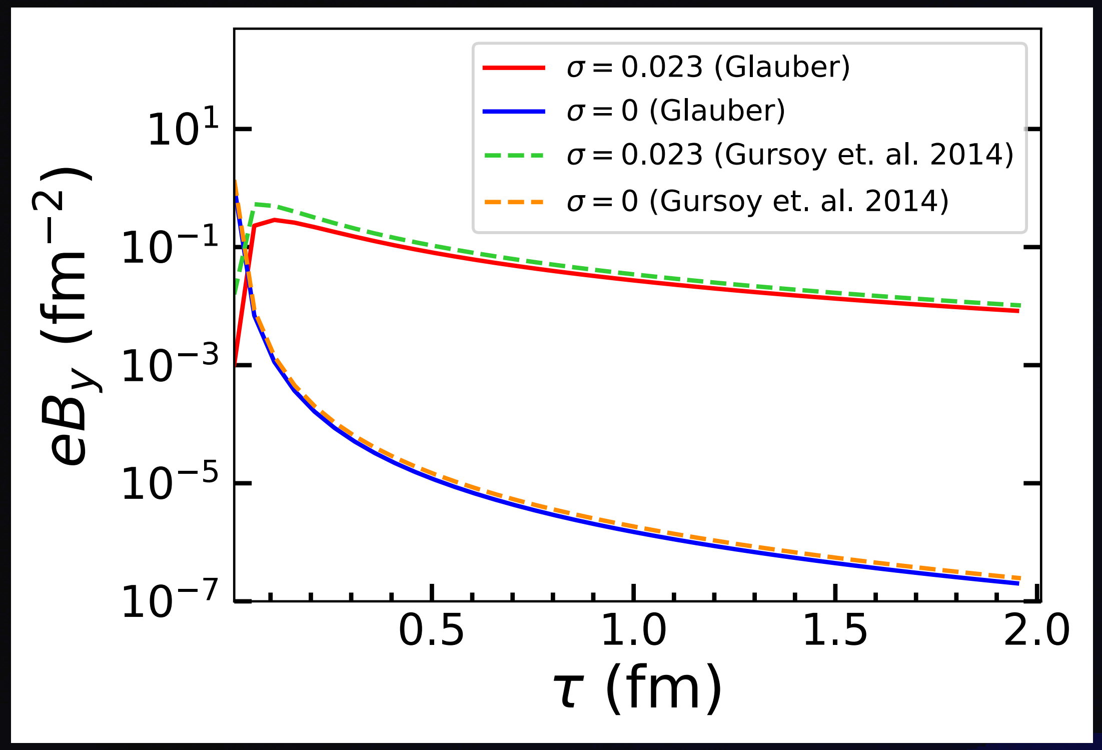


Contribution of EM field in directed flow splitting









B_y field generated at (x_T, ϕ) by a particle of charge Q moving with rapidity y_b and present at transverse position (x'_T, ϕ') is :

$$eB_y = Q\alpha \sinh y_b (x_T \cos\phi - x'_T \cos\phi') e^A \Delta^{-3/2} (1 + \sigma/2 \sinh y_b \sqrt{\Delta})$$

Gursoy et. al. PRC,89, 054905 (2014)

Gursoy et. al. PRC,98, 055201 (2018)

In fluid rest frame

$$m\frac{d\vec{v}_{drift}}{dt} = q\vec{v}_{drift} \times \vec{B} + q\vec{E} - \mu m \vec{v}_{drift} = 0$$

→ Lorentz transform $\vec{v}_{drift}$ to Lab frame

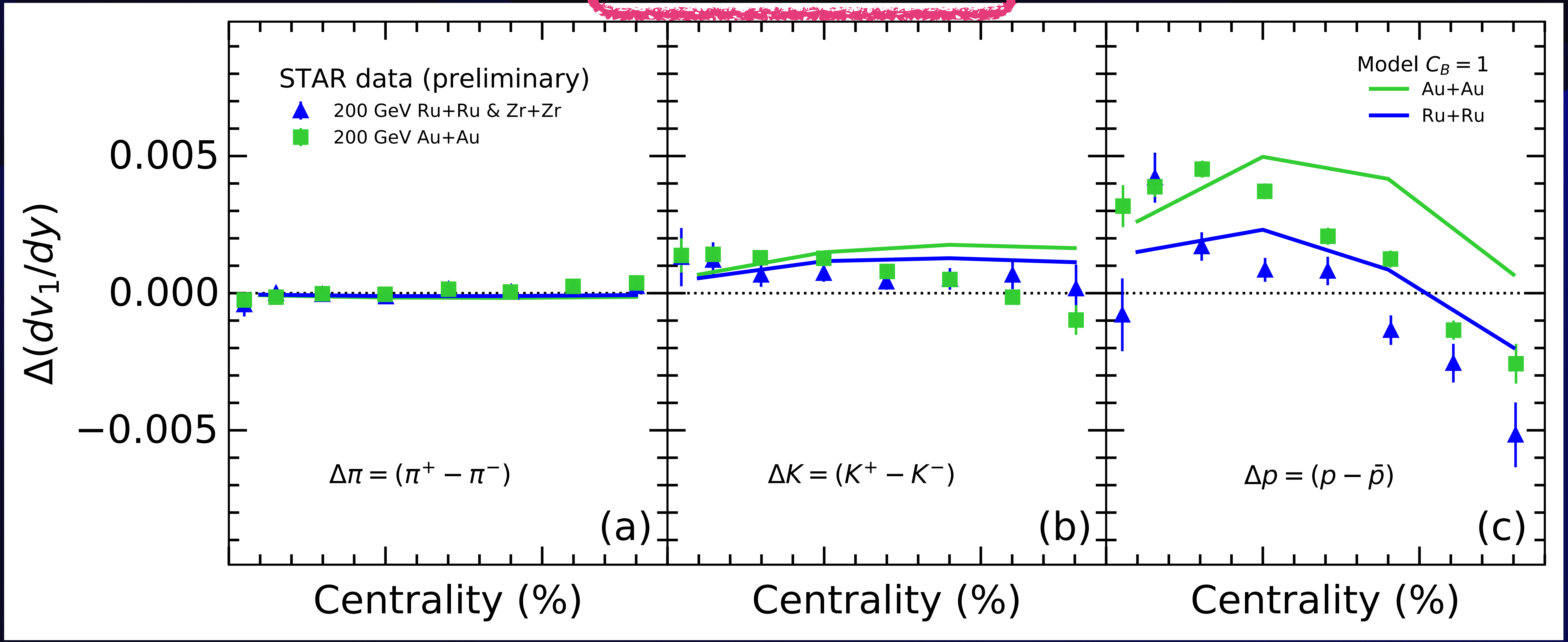
→ Modification of fluid velocity in Cooper Frye formula at freezeout hypersurface

Contribution of EM field in directed flow splitting

Non-zero baryon diffusion

$C_B = 1$

w/o EM field



TP, Sandeep Chatterjee and Subhash Singha

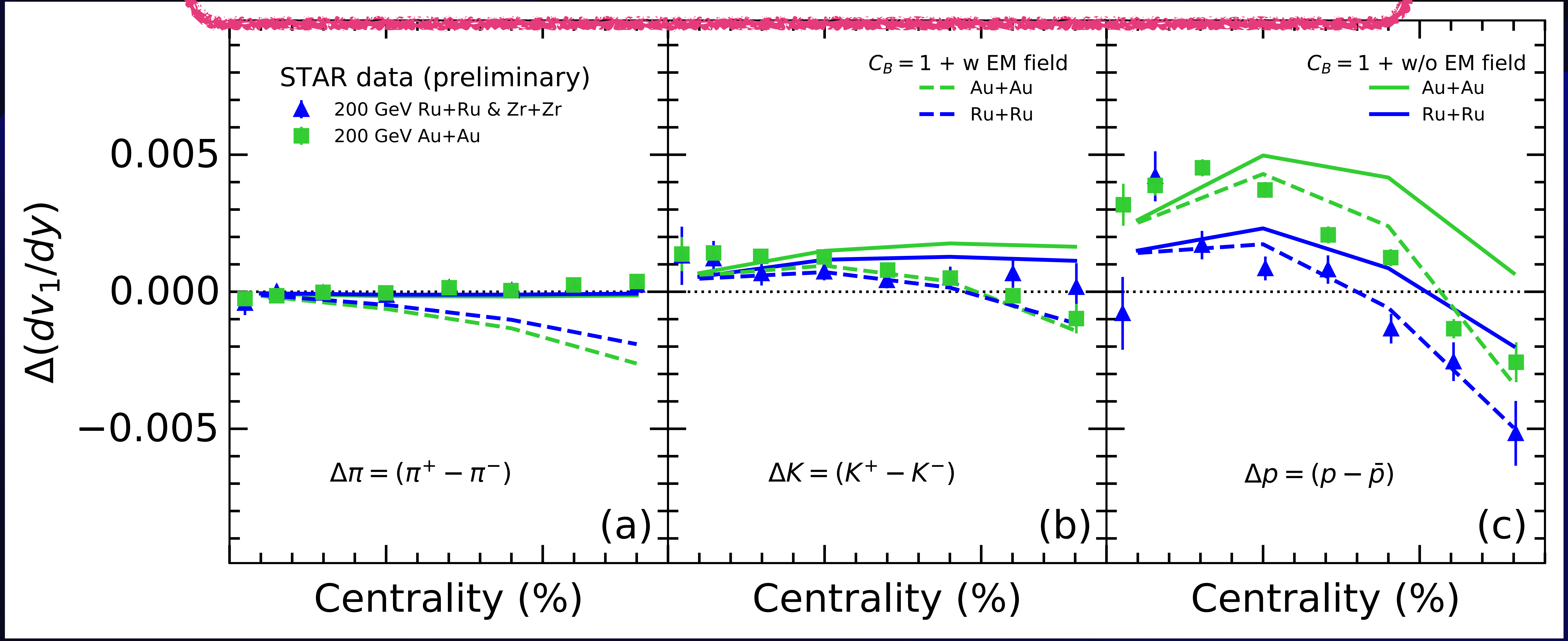
In preparation …

Contribution of EM field in directed flow splitting

Non-zero baryon diffusion

w EM field

$$C_B = 1 \quad + \quad \sigma = 0.023\ fm^{-1}$$



In preparation …

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

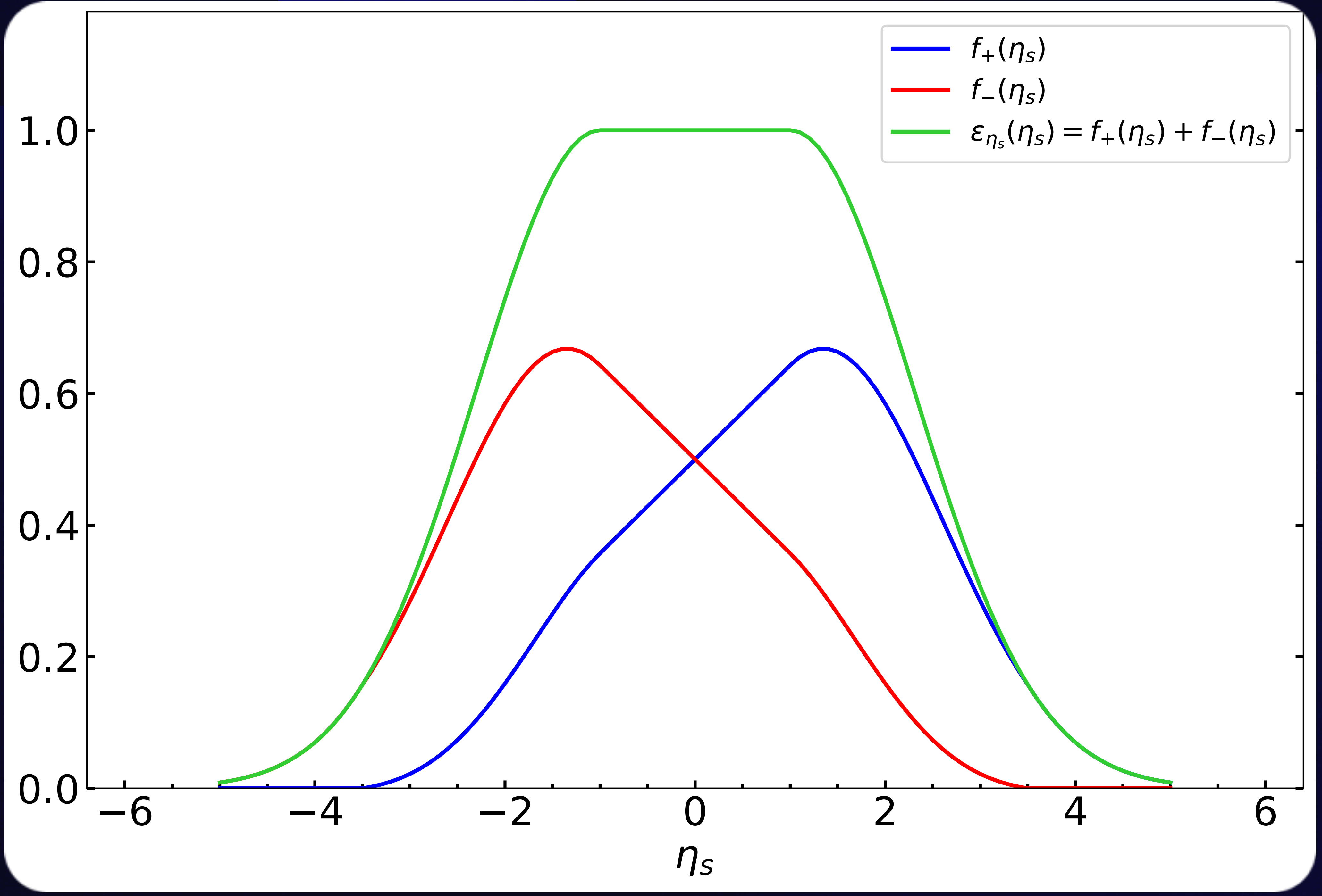
Tilted fireball

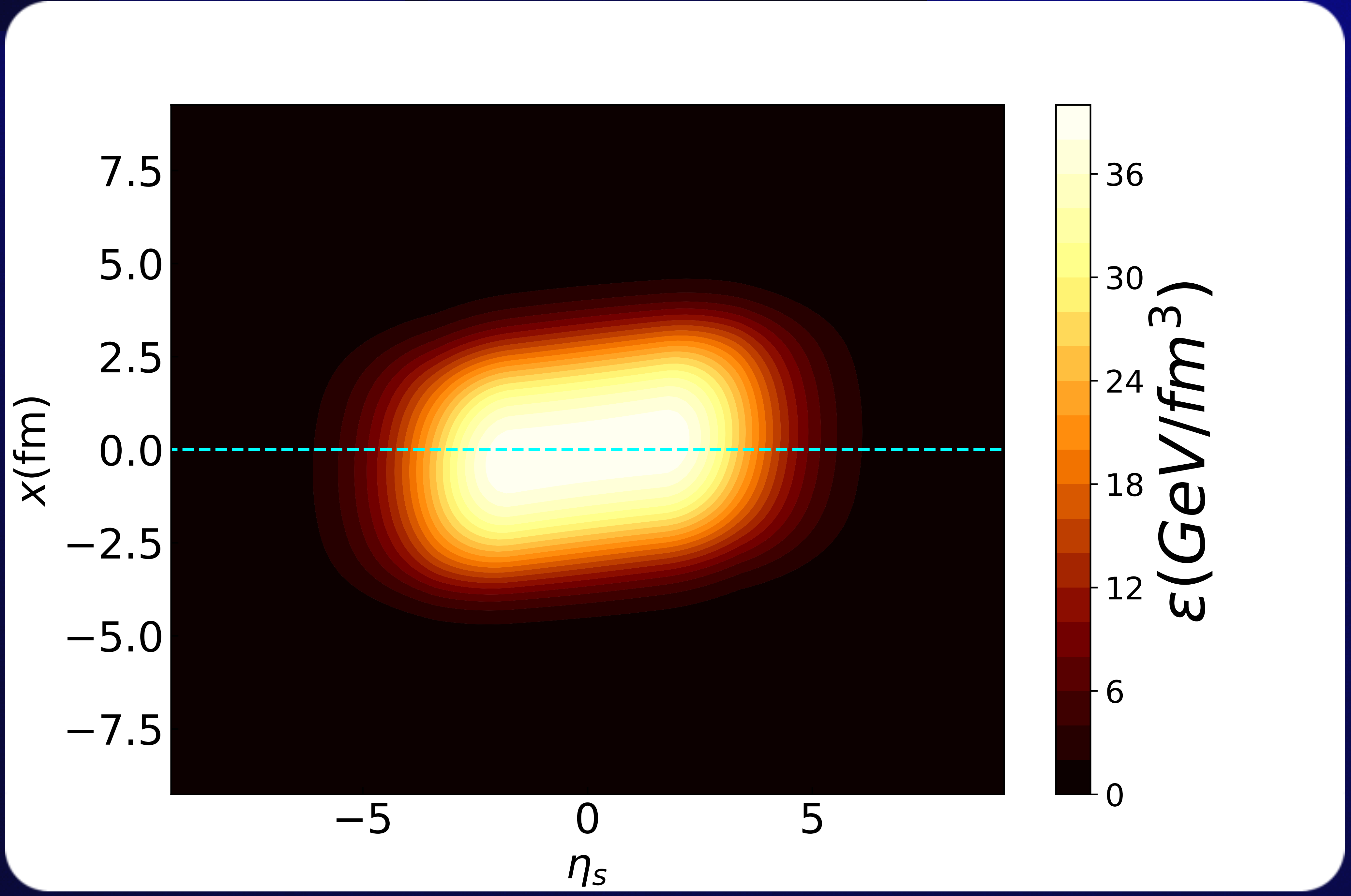
P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)

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

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

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



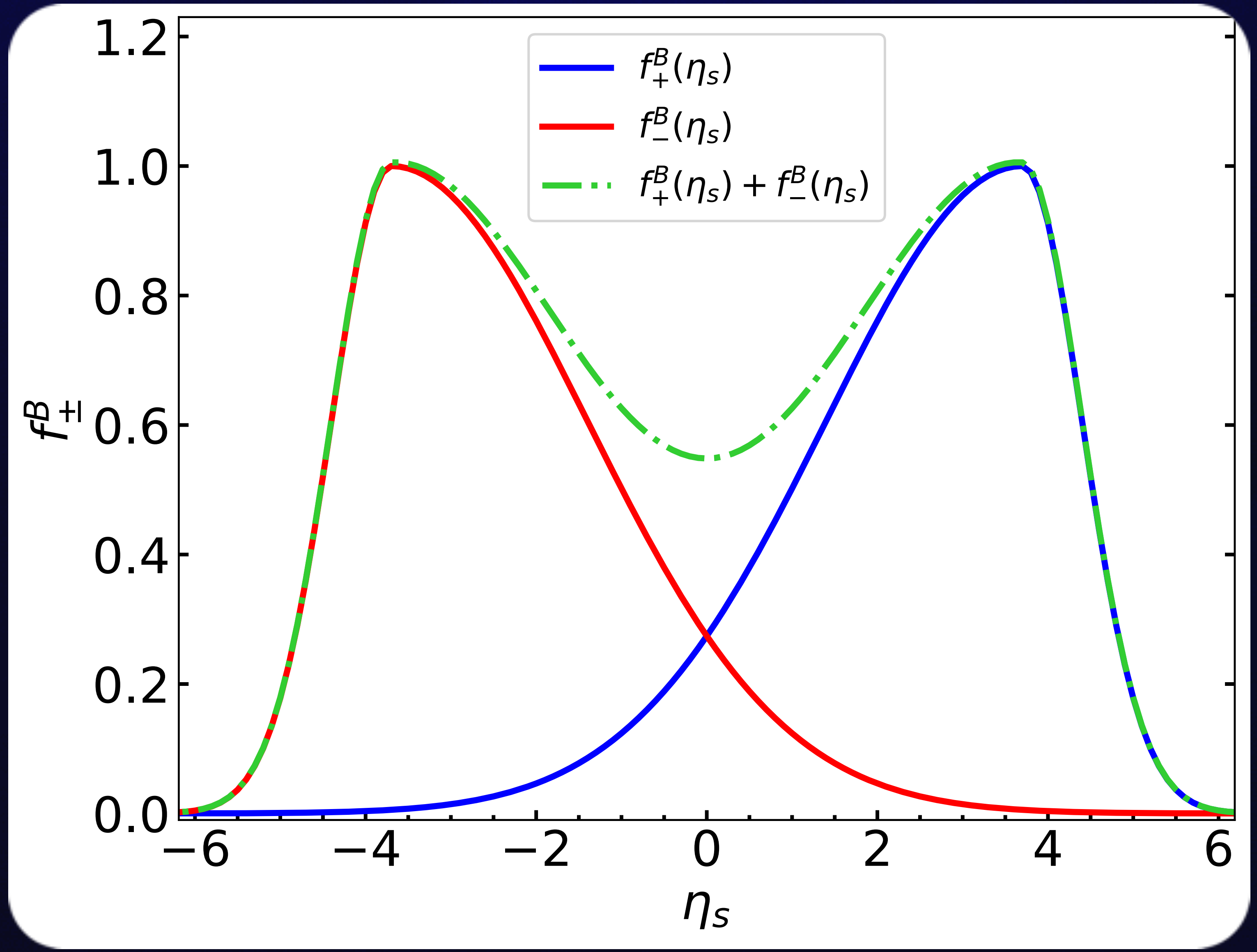


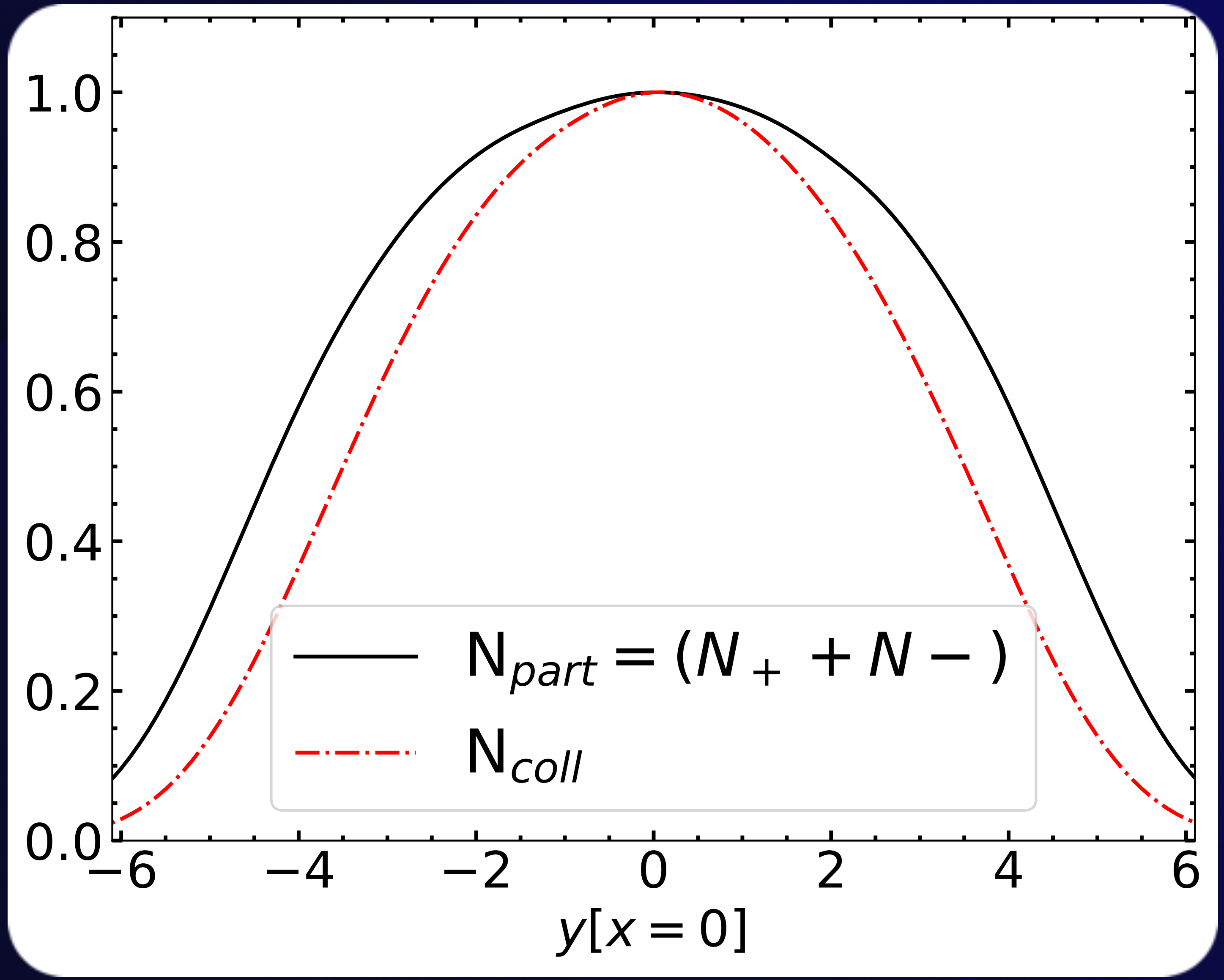
Model of the initial baryon profile

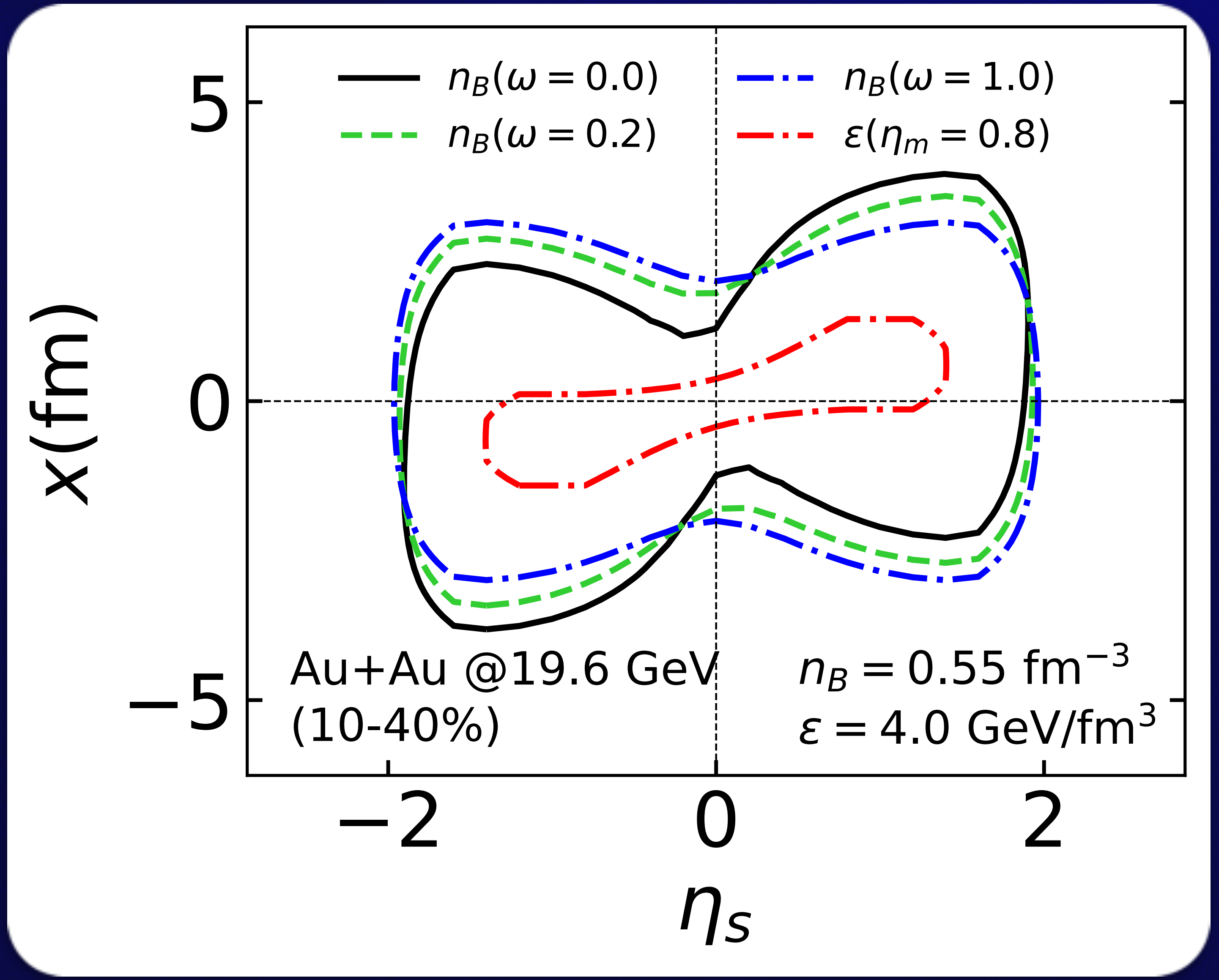
$$n_B(x,y,\eta_s) = N_B\left[(1-\omega)\Big(N_+(x,y)f_+^B(\eta_s) + N_-(x,y)f_-^B(\eta_s)\Big) + \omega N_{coll}(x,y)\Big(f_+^B(\eta_s) + f_-^B(\eta_s)\Big)\right]$$

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

- 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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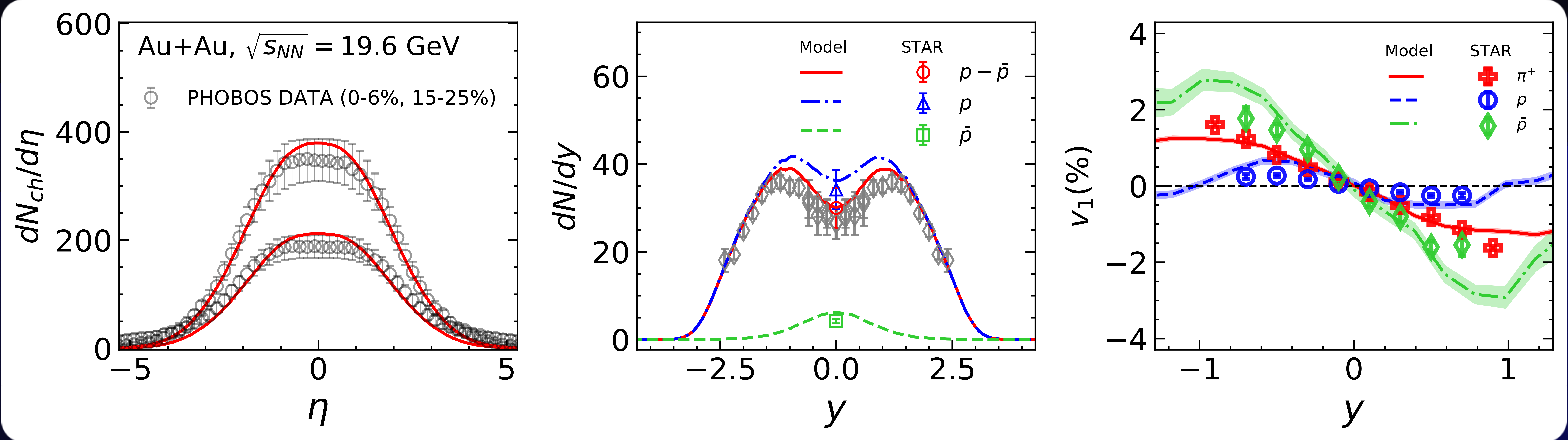
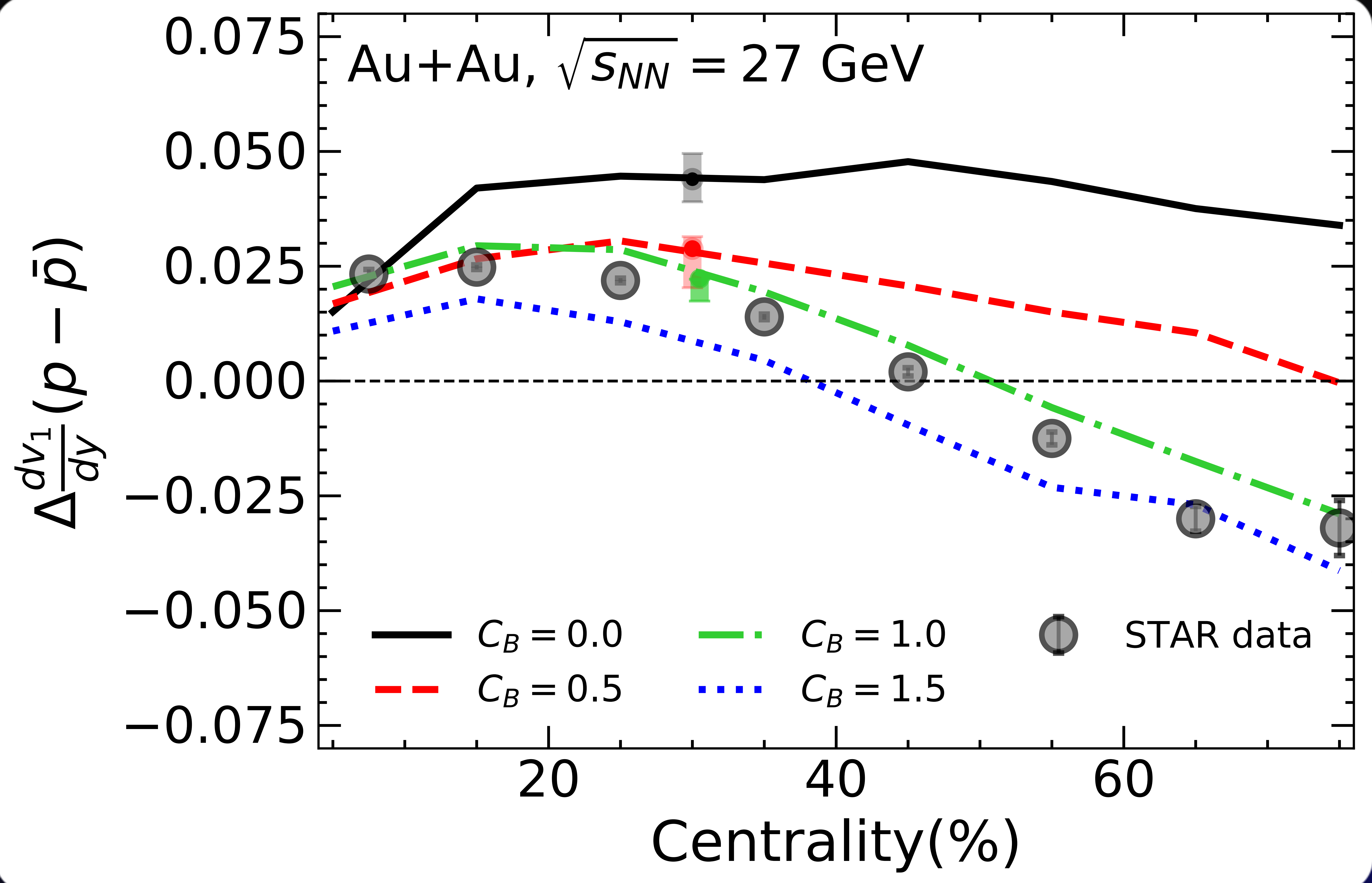
Simulation results

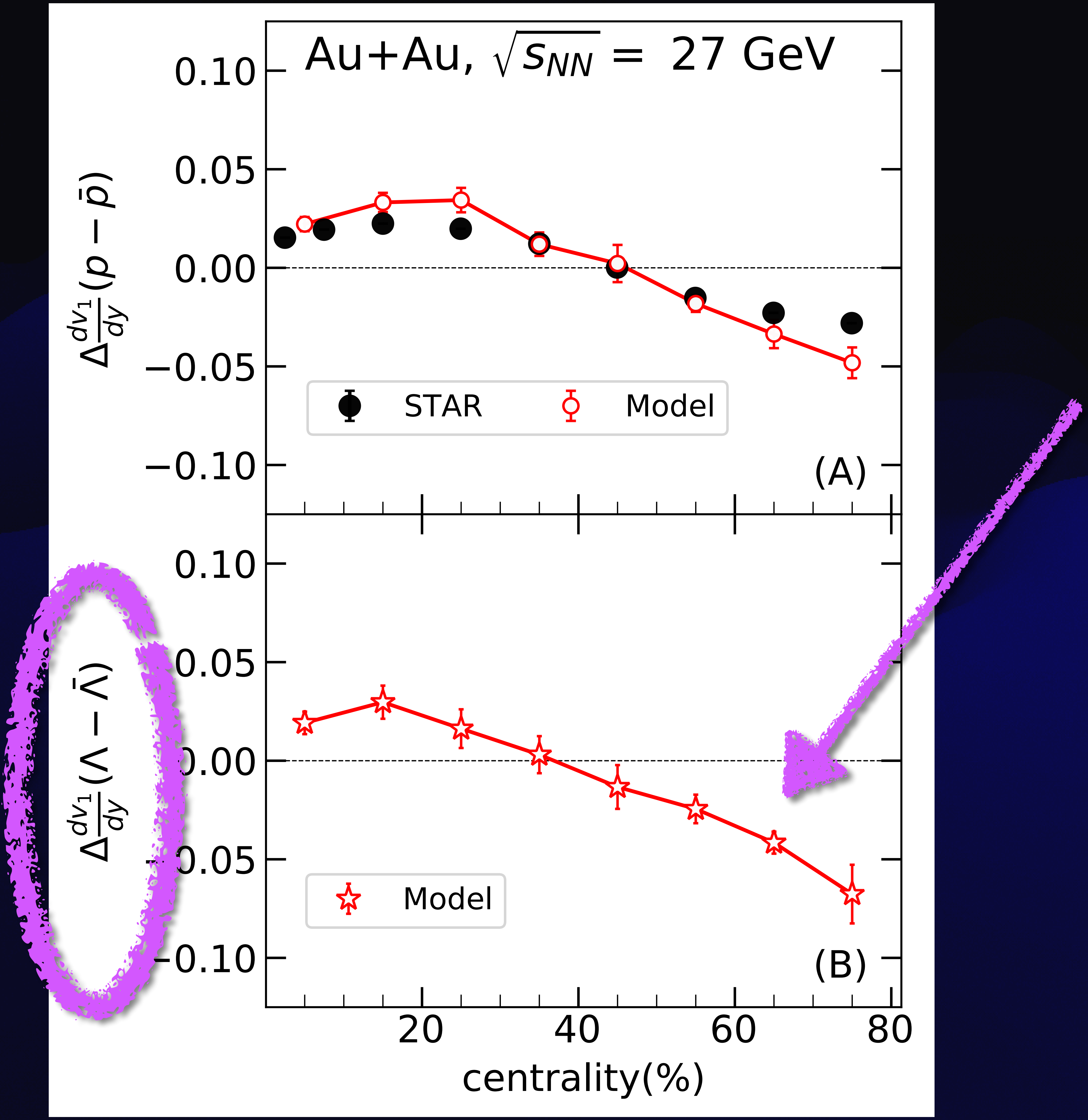
$$\eta_m = 0.8,\ \omega = 0.15$$

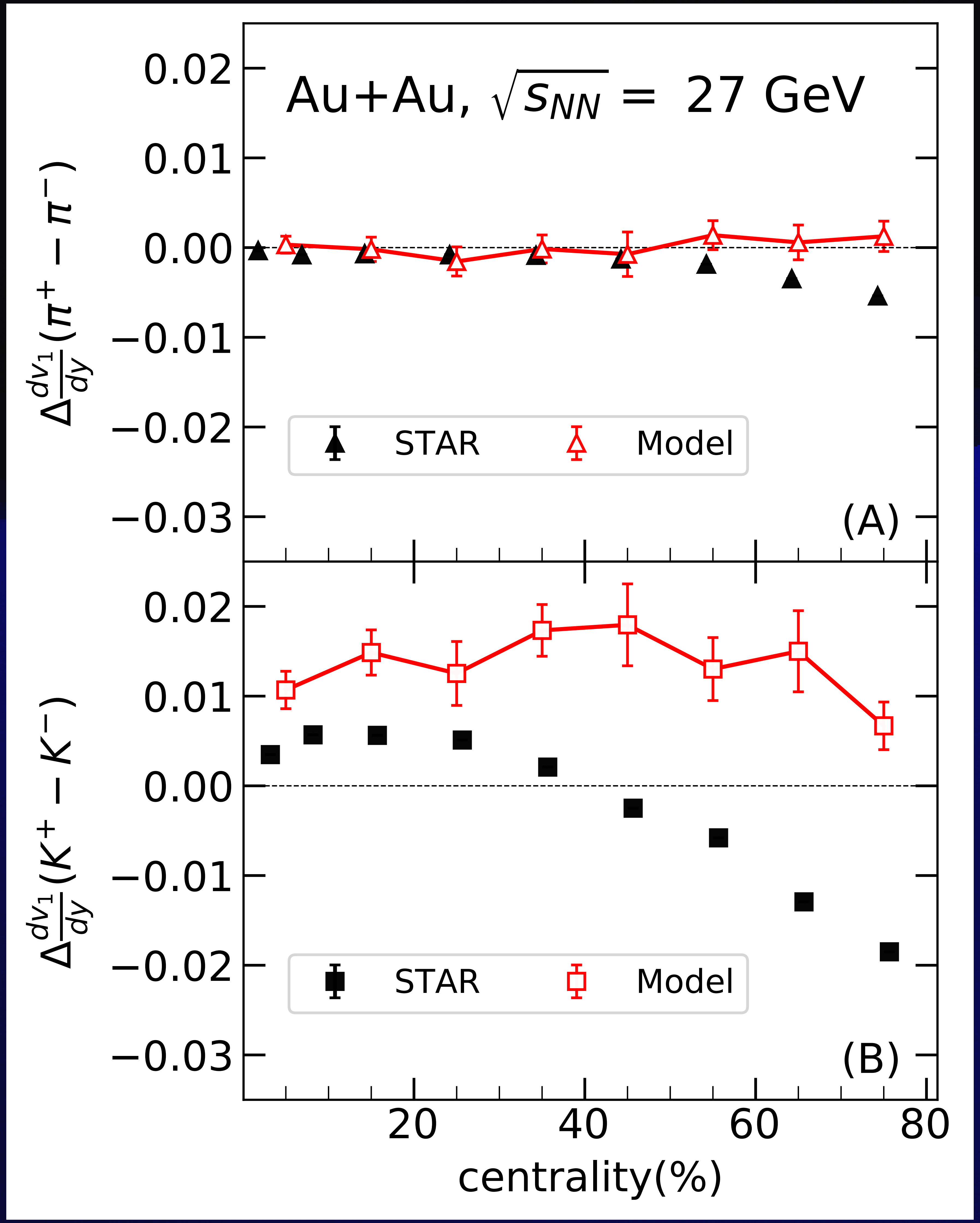


our model parameters are tuned to capture the above observables simultaneously



Au+Au, $\sqrt{s_{NN}}$ = 27 GeV
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
$\Delta \frac{dv_1}{dy}(p-\bar{p})$
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
$\Delta\frac{dv_1}{dy}(p-\bar{p})$
0.10
0.05
0.00
−0.05
−0.10
STAR
Model
(A)
$\Delta\frac{dv_1}{dy}(\Lambda-\bar{\Lambda})$
Model
(B)
20
40
60
80
centrality(%)


Au+Au, $\sqrt{s_{NN}}$ = 27 GeV
$\Delta\frac{dv_1}{dy}(\pi^+-\pi^-)$
0.02
0.01
0.00
−0.01
−0.02
−0.03
STAR
Model
(A)
$\Delta\frac{dv_1}{dy}(K^+-K^-)$
STAR
Model
(B)
20
40
60
80
centrality(%)