New ansatz on baryon deposition & phenomenology of heavy ion collisions

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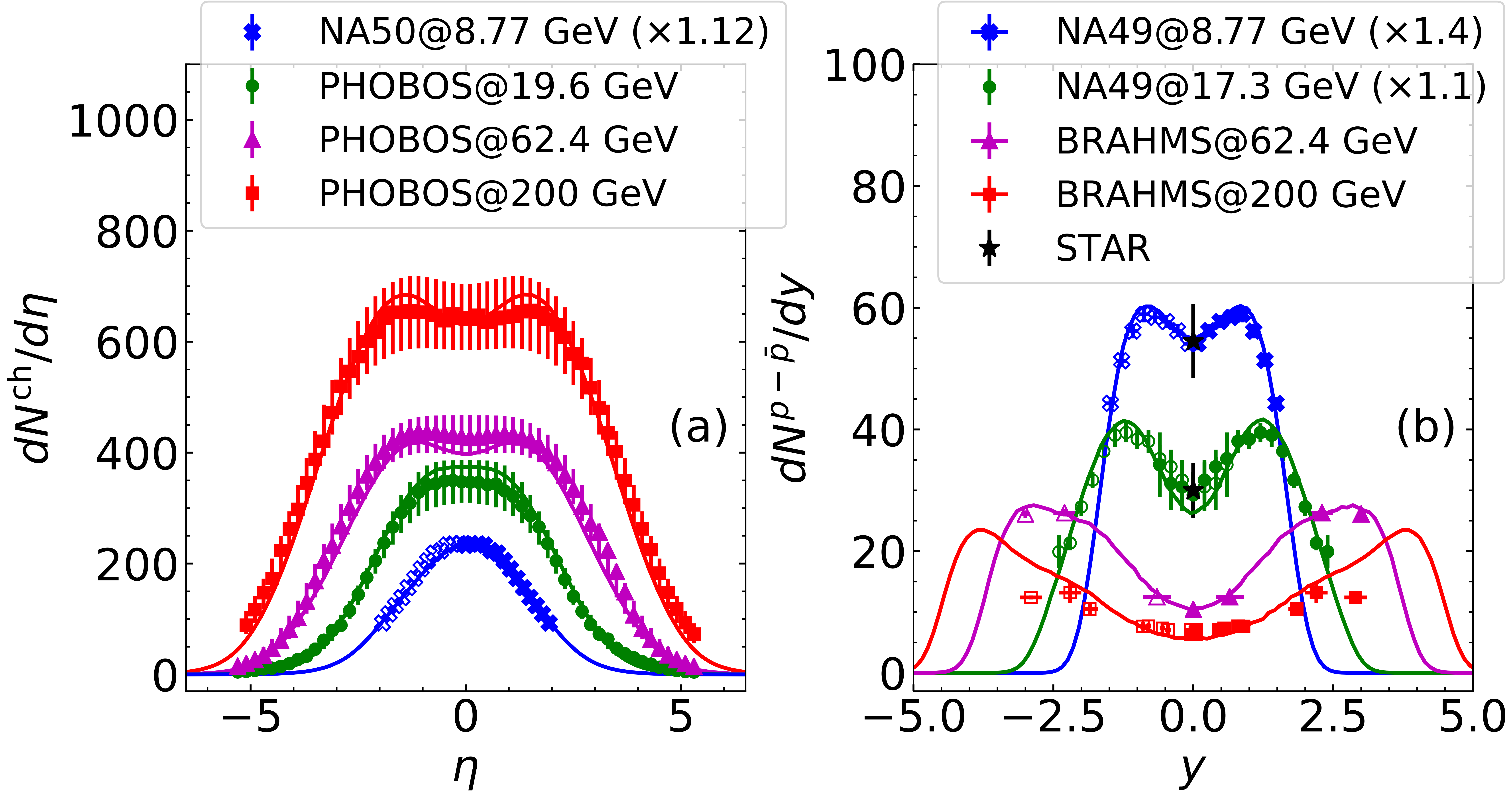
1st Workpshop on Baryon Dynamics from RHIC to EIC,
Stony Brook University, 22-24 January, 2024

Based on works done with **Tribhuban Parida**
arXiv: 2211.15729, 2211.15659, 2305.08806, 2305.10371, ...

RHIC BES is a tale of 2 currents - $T^{\mu\nu}, J_B^\mu$



$dN^{ch}/d\eta \sim T^{\mu\nu}$

$dN^{p-\bar{p}}/dy \sim J_B^\mu$

As we go to lower energies, the baryon current plays an increasingly important role: essential to understand

How well do we understand the baryon current and its consequences on RHIC phenomenology?

Lipei Du et al, 2211.16408

Understanding the baryon current: ingredients within a hydro framework

- Distribution of net baryon density (n_B) at the initial thermalised hypersurface

- Equation of state of the QCD medium at non-zero n_B

- Baryon transport coefficient (κ_B) as a medium response to baryon gradient; analogous to η and ζ in the case of gradients of $T^{\mu\nu}$

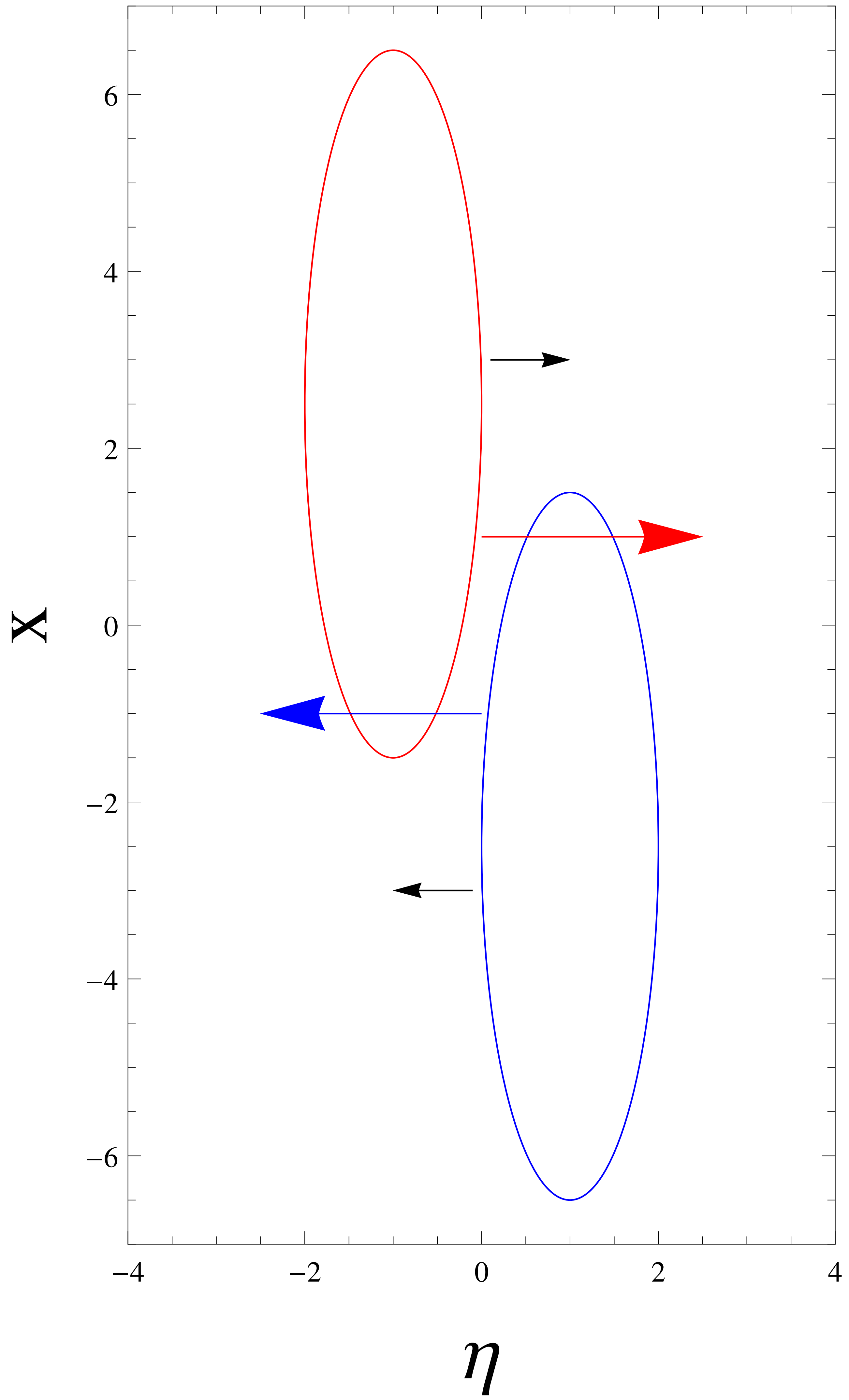
Understanding the baryon current: ingredients within a hydro framework

Distribution of net baryon density (n_B) at the initial thermalised hypersurface (educated guesses needed)

Equation of state of the QCD medium at non-zero n_B (available from Lattice QCD)

Baryon transport coefficient (κ_B) as a medium response to baryon gradient; analogous to η and ζ in the case of gradients of $T^{\mu\nu}$ (educated guesses needed)

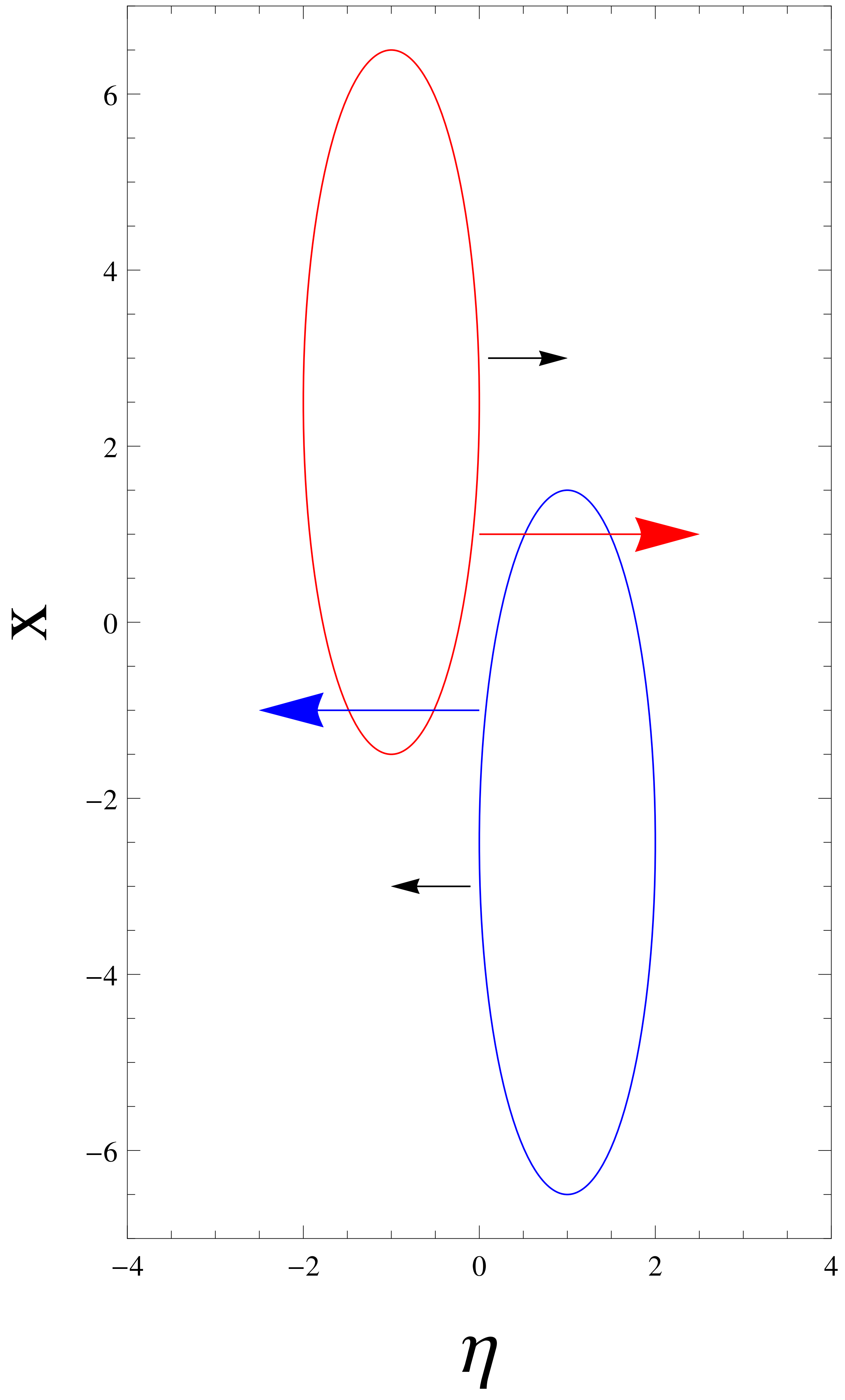
Initial condition of entropy



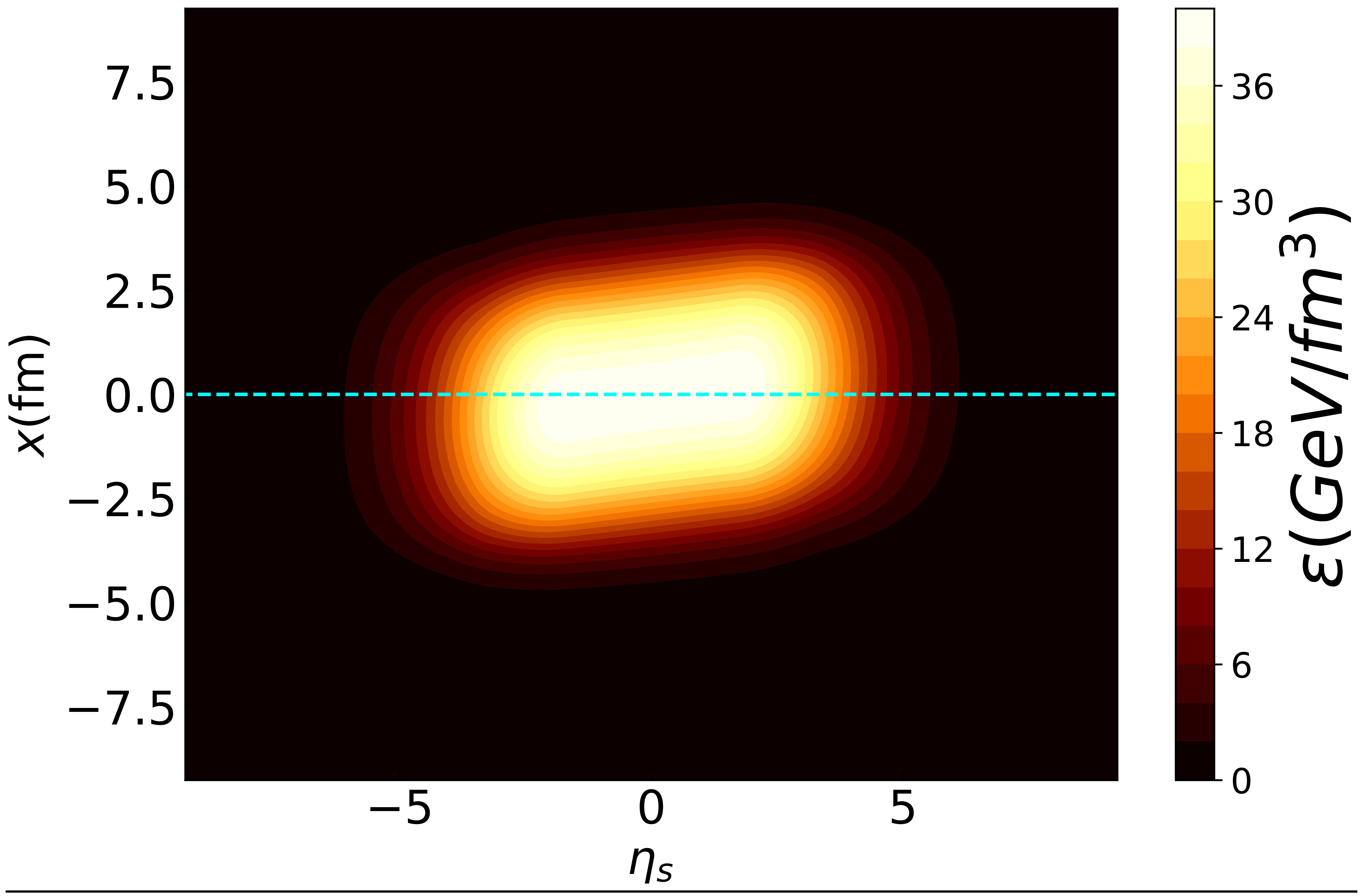
At a generic point (x, y) on the transverse plane, $N_{part}^{+}(x, y) \neq N_{part}^{-}(x, y)$ where '+' and '-' refer to positive and negative η directions.

This geometric asymmetry has been utilised in Glauber type initial condition models to break boost invariance in the initial condition that can be further evolved by hydro to yield interesting rapidity dependencies in different observables.

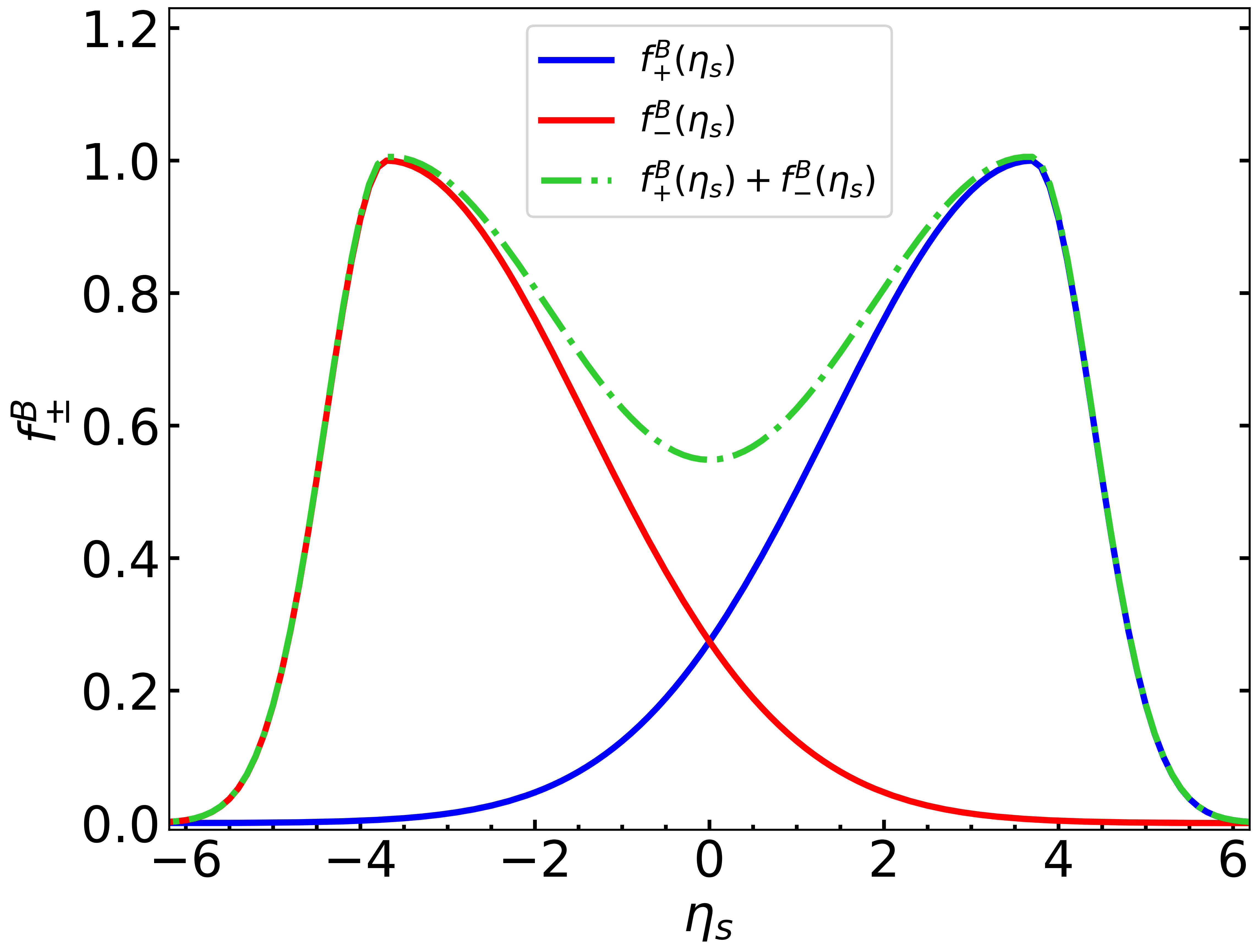
Initial condition of entropy



Tilted: assume FB asymmetric deposition by a participant source. $N_{part}^{+}(x, y) \neq N_{part}^{-}(x, y)$ gives rise to a fireball not aligned along the beam axis, tilted fireball. Bozek, Wyskiel 2010



Initial condition of n_B



$$n_B\left(x, y, \eta_s\right)$$

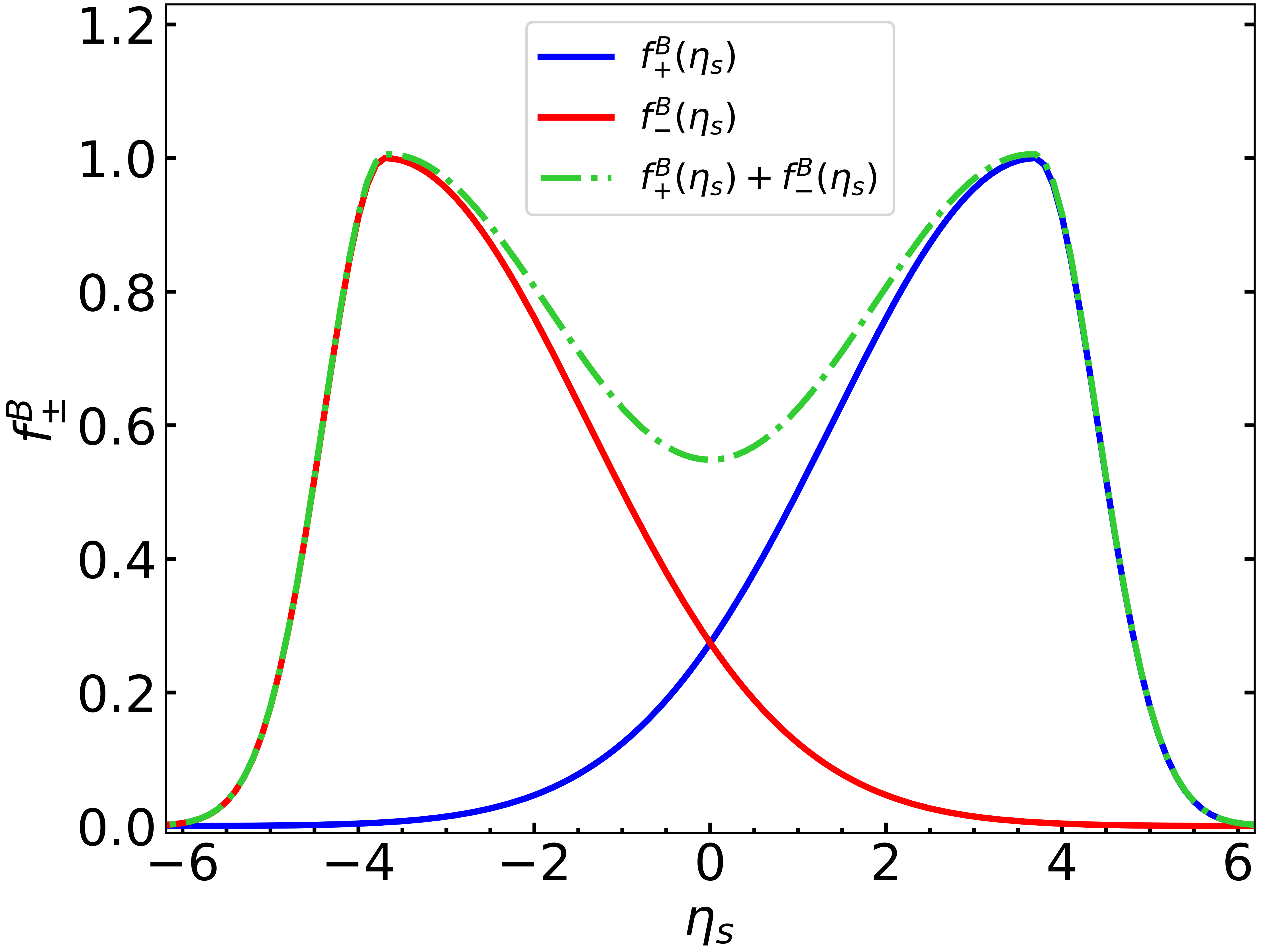
$$N_B\left[W_+^B(x, y) f_+^B(\eta_s) + W_-^B(x, y) f_-^B(\eta_s)\right]$$

$$W_\pm^B(x, y) = (1-\omega)\, N_\pm(x, y) + \omega N_{coll}(x, y)$$

$$\int \tau_0 dx dy d\eta n_B\left(x, y, \eta, \tau_0\right) = N_+ + N_-$$

The transverse profile for baryon, W^B is usually taken $\sim N_{+,-}$. We have allowed for contribution from N_{coll} to account for scenarios that arise in microscopic models like LEXUS where the rapidity loss of the depositing source depends on the number of binary collisions, thus having more baryon deposited where N_{coll} is large.

Initial condition of n_B



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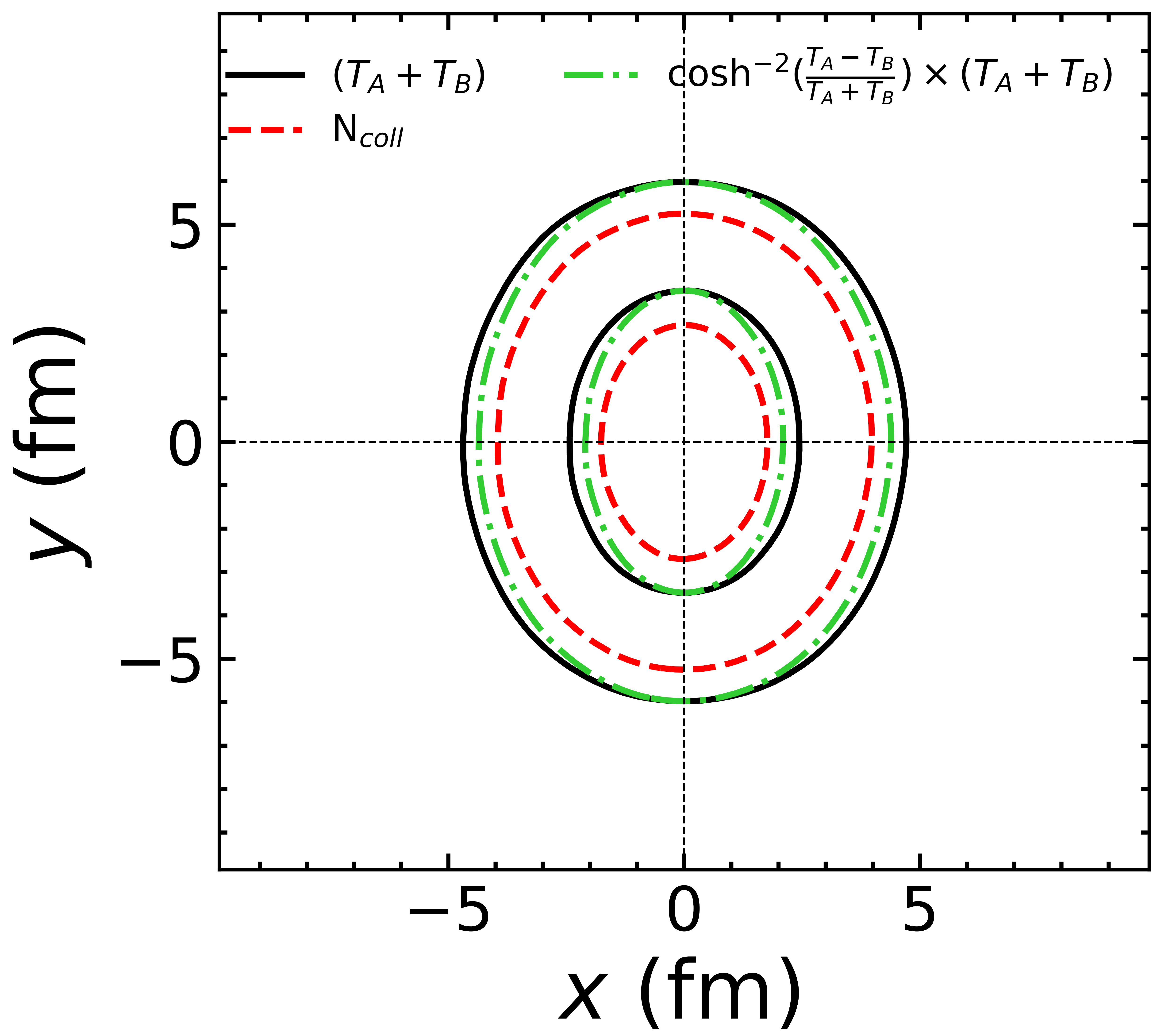
$$\int \tau_0 dxdyd\eta n_B\left(x,y,\eta,\tau_0\right)=N_++N_-$$

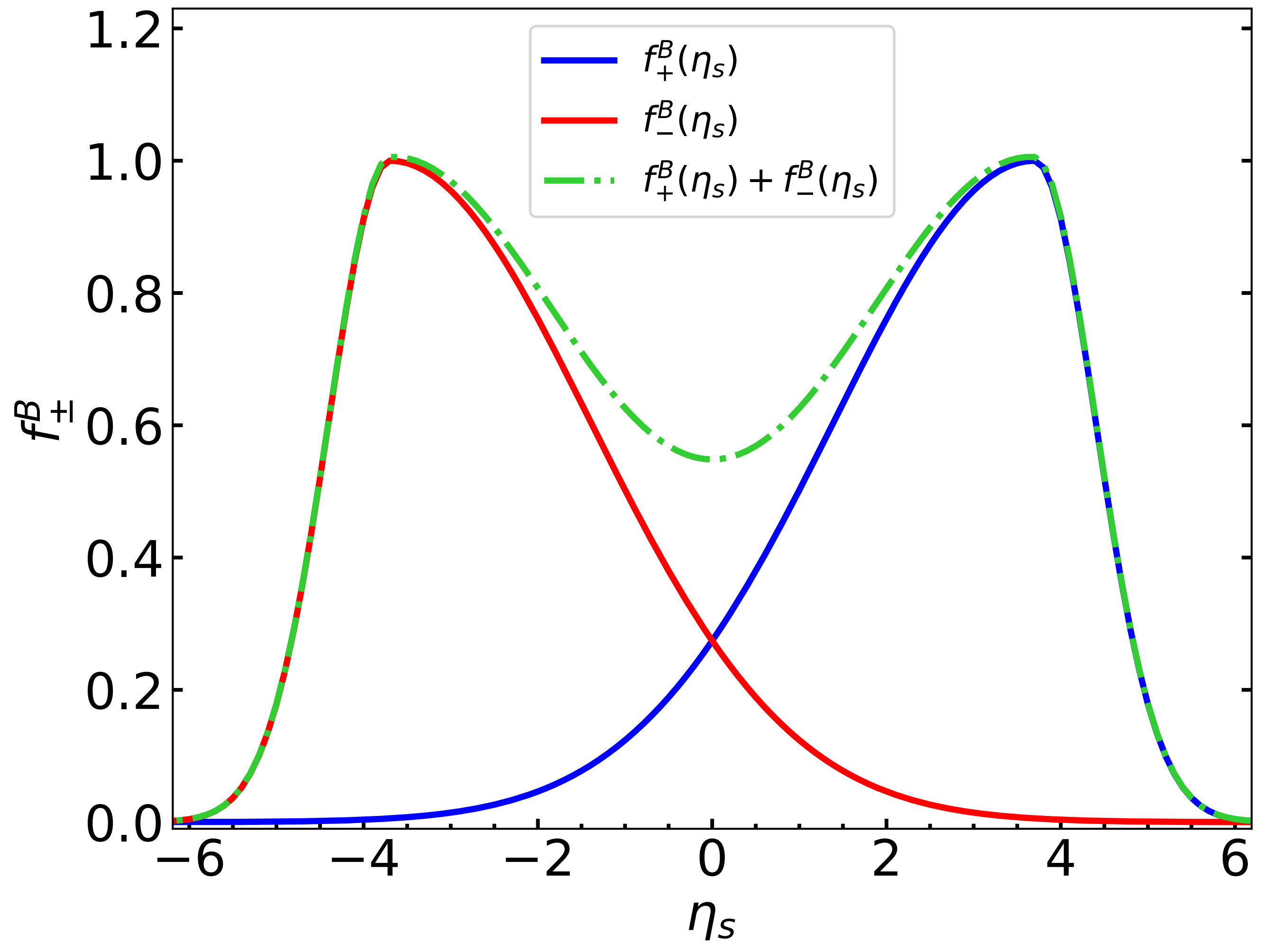
NOTE: N_{coll} multiplies rapidity even profile: $f_+^B(\eta_s)+f_-^B(\eta_s)$ which is a superposition of F/B peaks (single junction stopping) and plateau (double junction stopping) Kharzeev, 1996

Comparison of the weights to the rapidity even profile



Stronger at the origin than standard Npart profile

Initial condition of n_B



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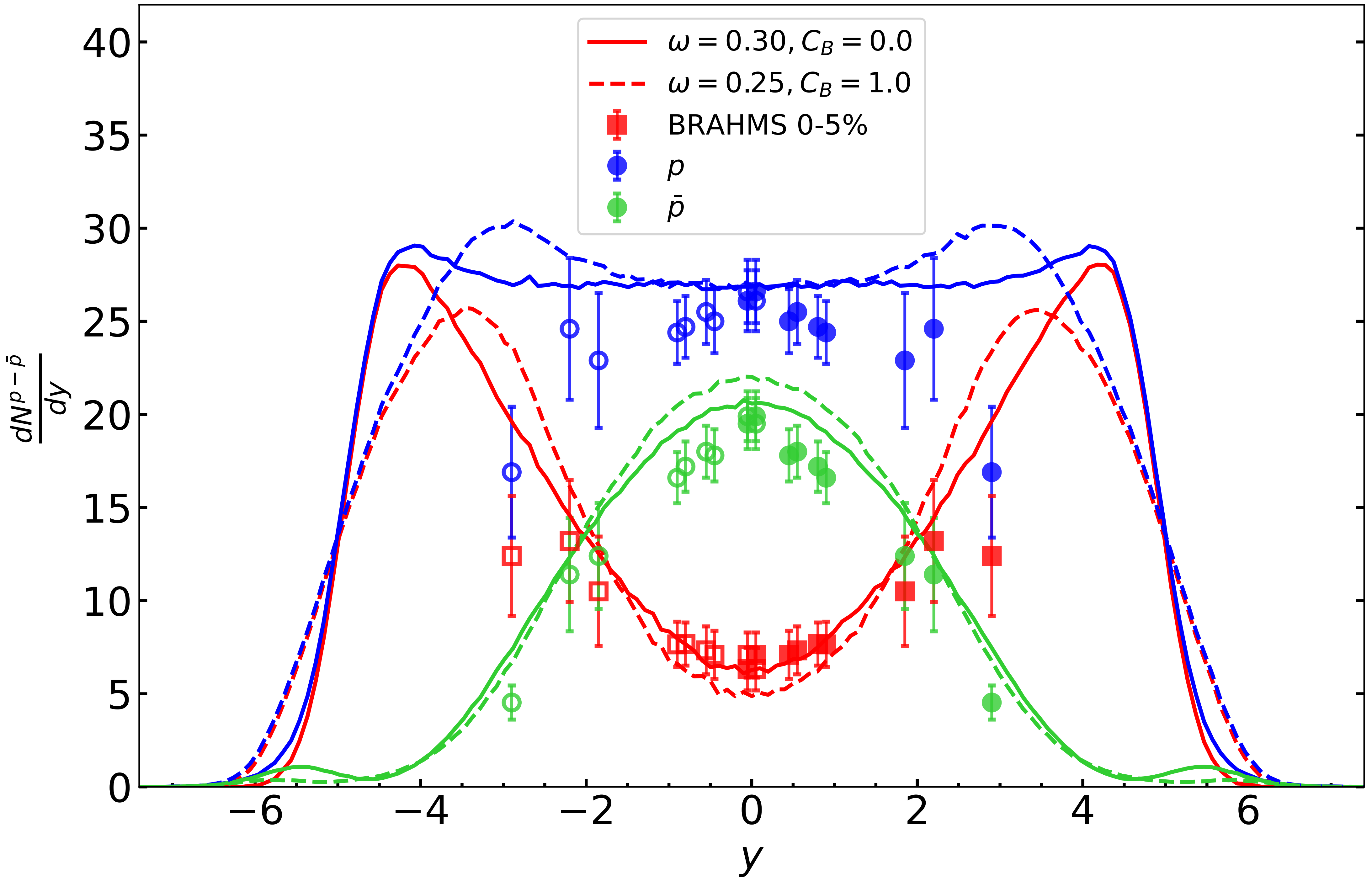
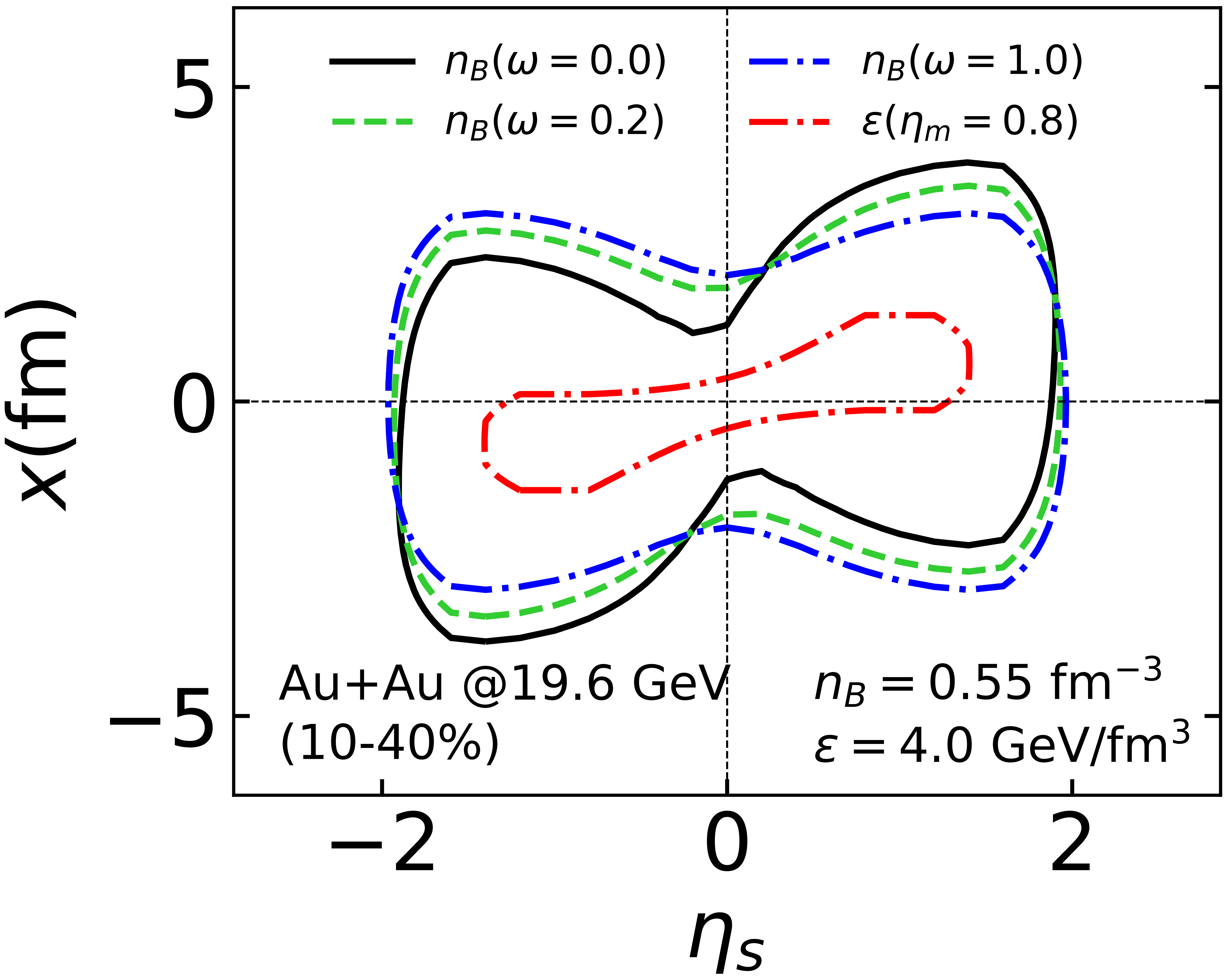


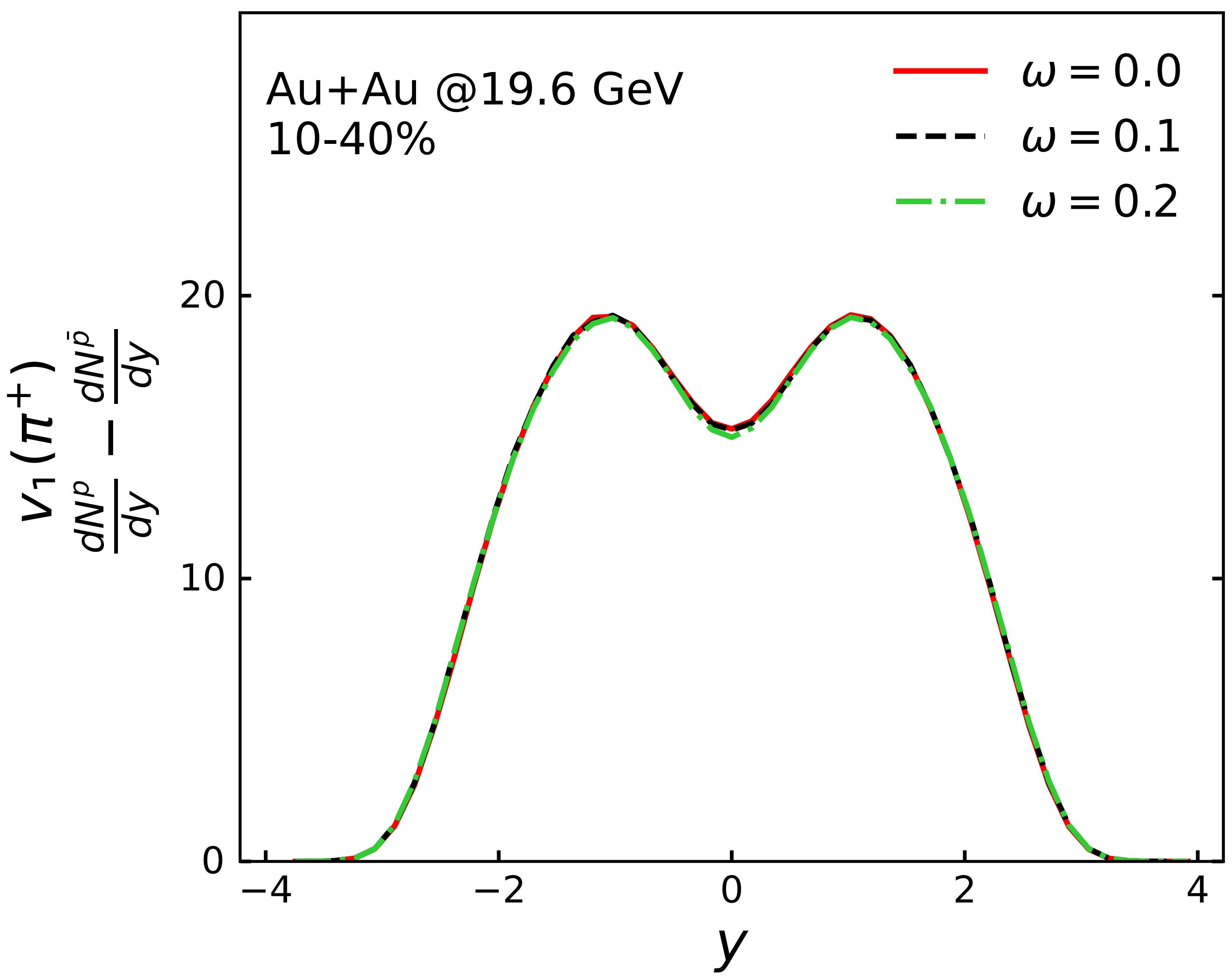
Profile parameters constrained by rapidity dependence of net proton yield

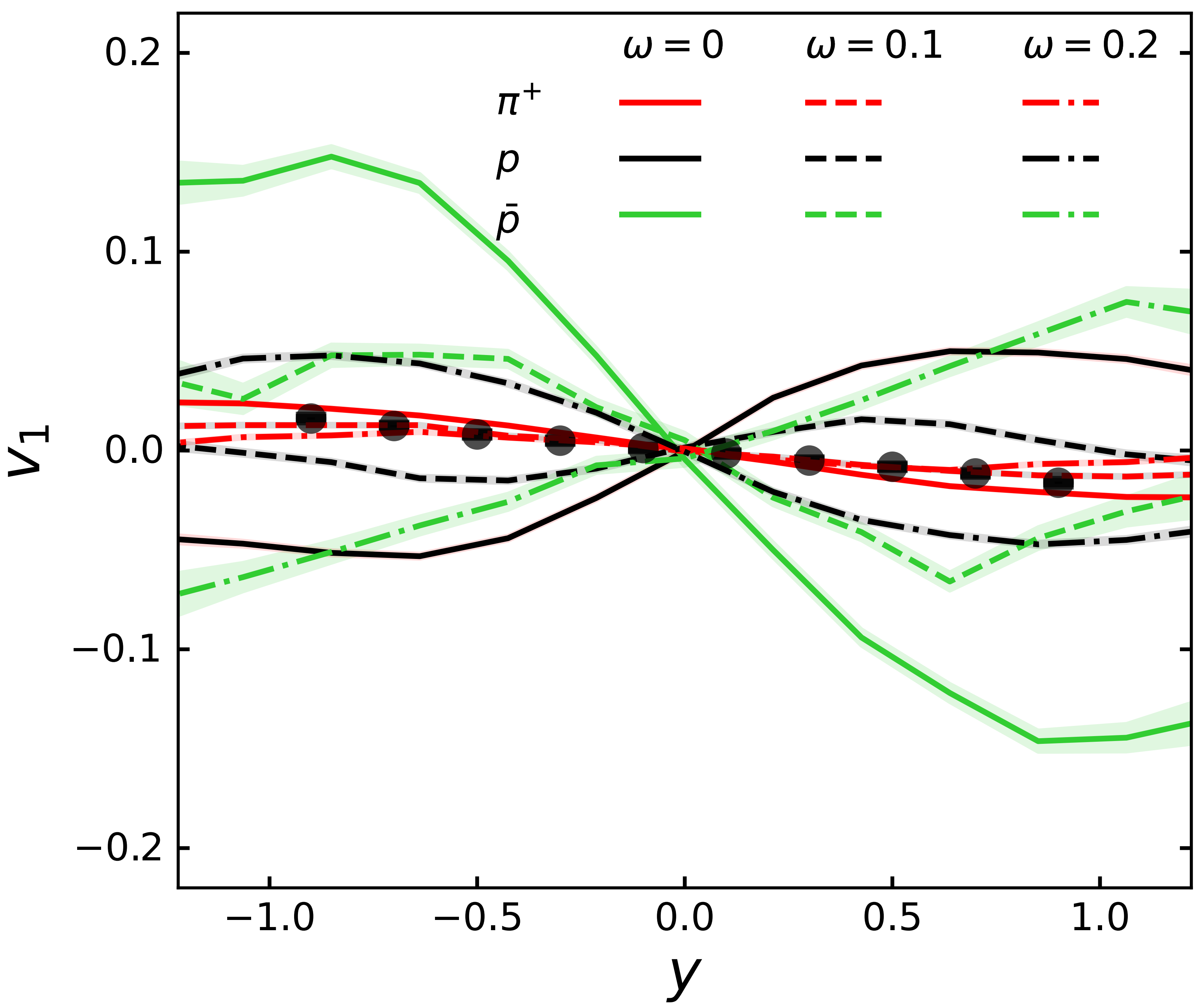
NOTE: Participant source has rapidity asymmetric profile while collision source has rapidity symmetric profile, thus ω decides relative tilt of baryon wrt matter

Role of ω



Role of ω





Does not affect rapidity distribution of net proton yield, however the net proton v1 or splitting in proton - antiproton v1 is significantly affected, including their individual slopes

Baryon transport coefficient: κ_B

Within the relaxation time approximation and in the massless limit, κ_B can be obtained from the Boltzmann equation as follows

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

Denicol et al, 1804.10557

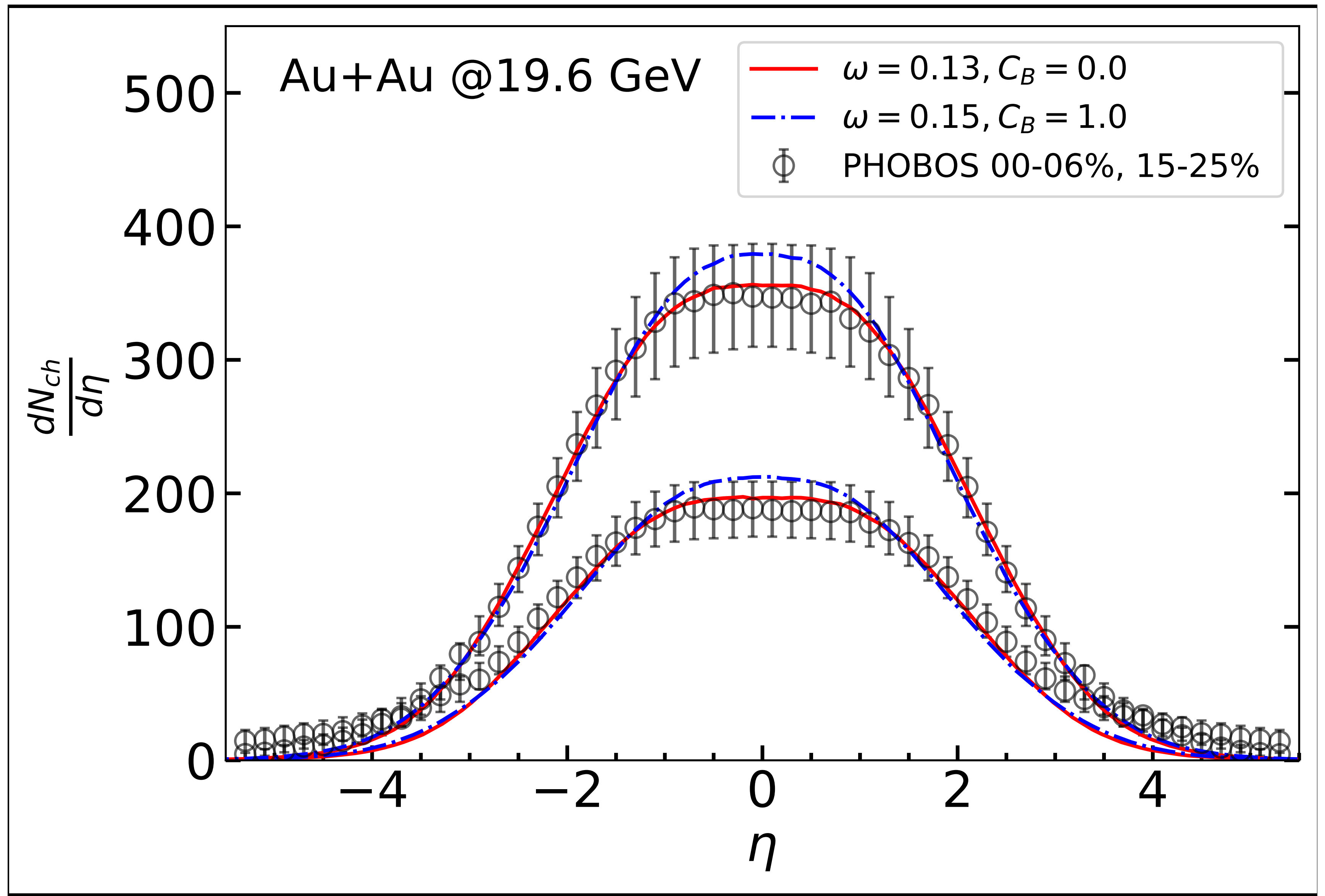
Here C_B is an arbitrary constant that may be varied to study the effect of baryon transport. To be constrained by data.

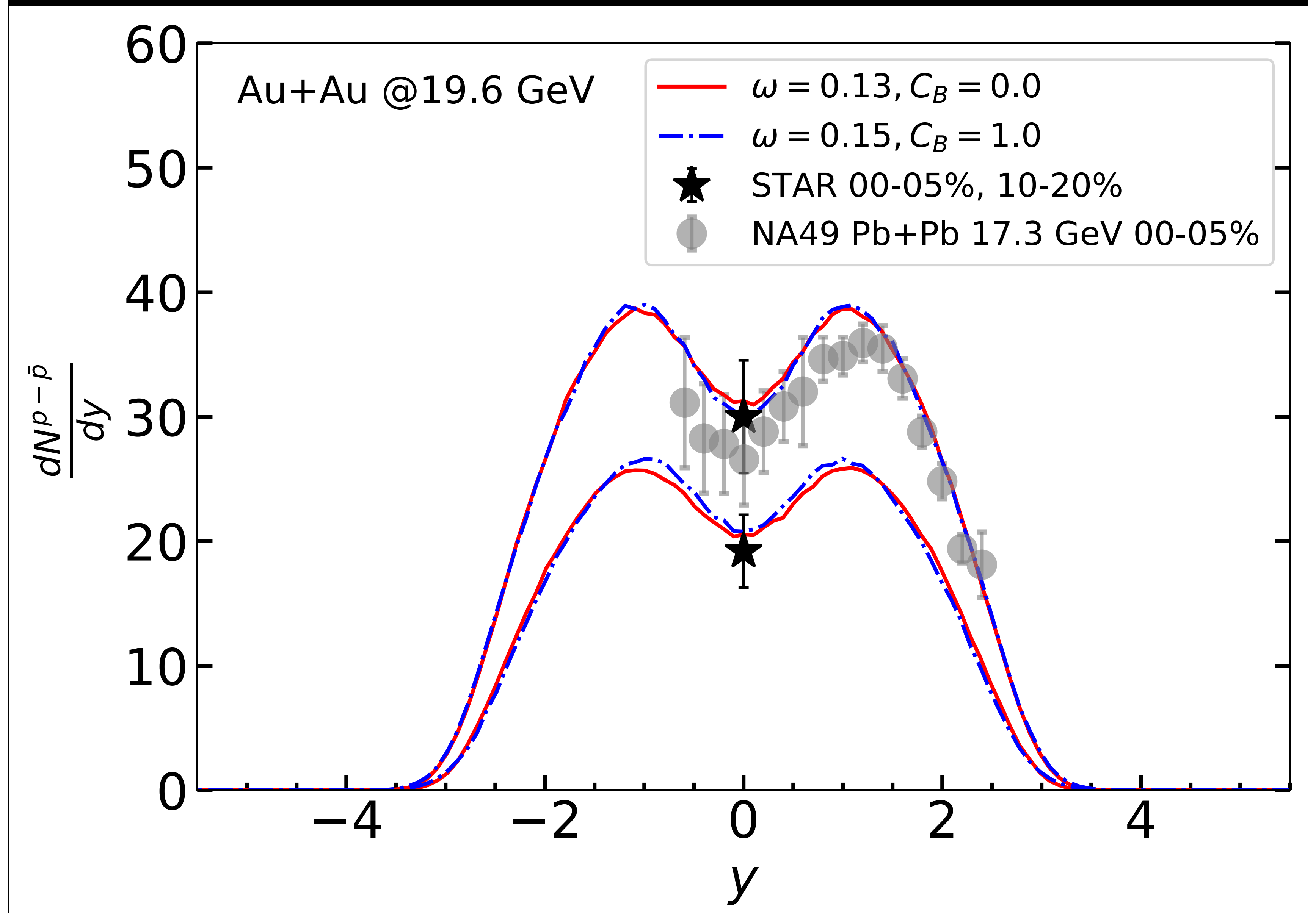
Evolution

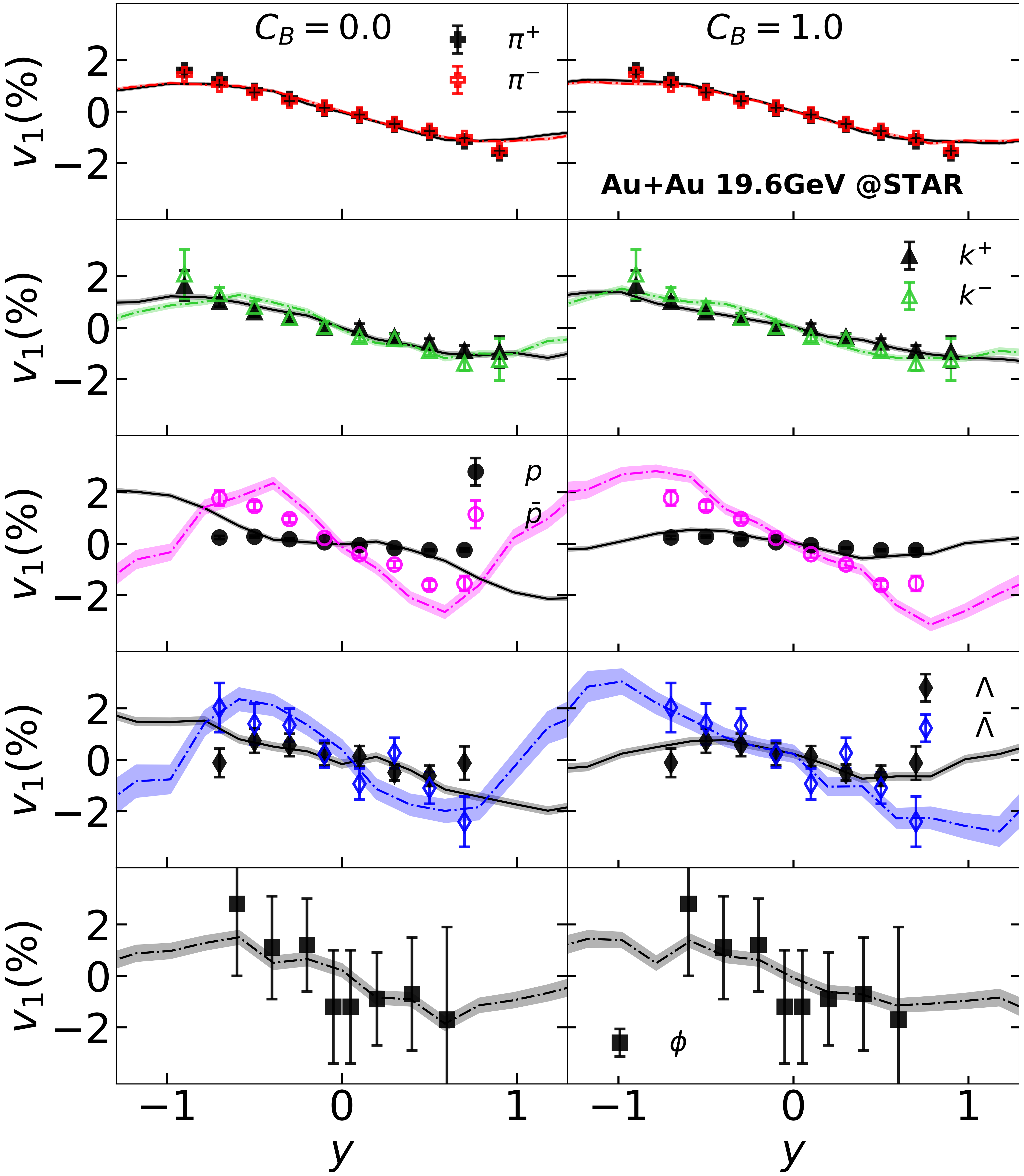
Hybrid approach

We take, $n_S = 0,\ n_Q = 0.4 n_B,\ \dfrac{\eta T}{\epsilon + P} = 0.08,\ \zeta = 0,\ \epsilon_f = 0.26$ GeV/fm^3

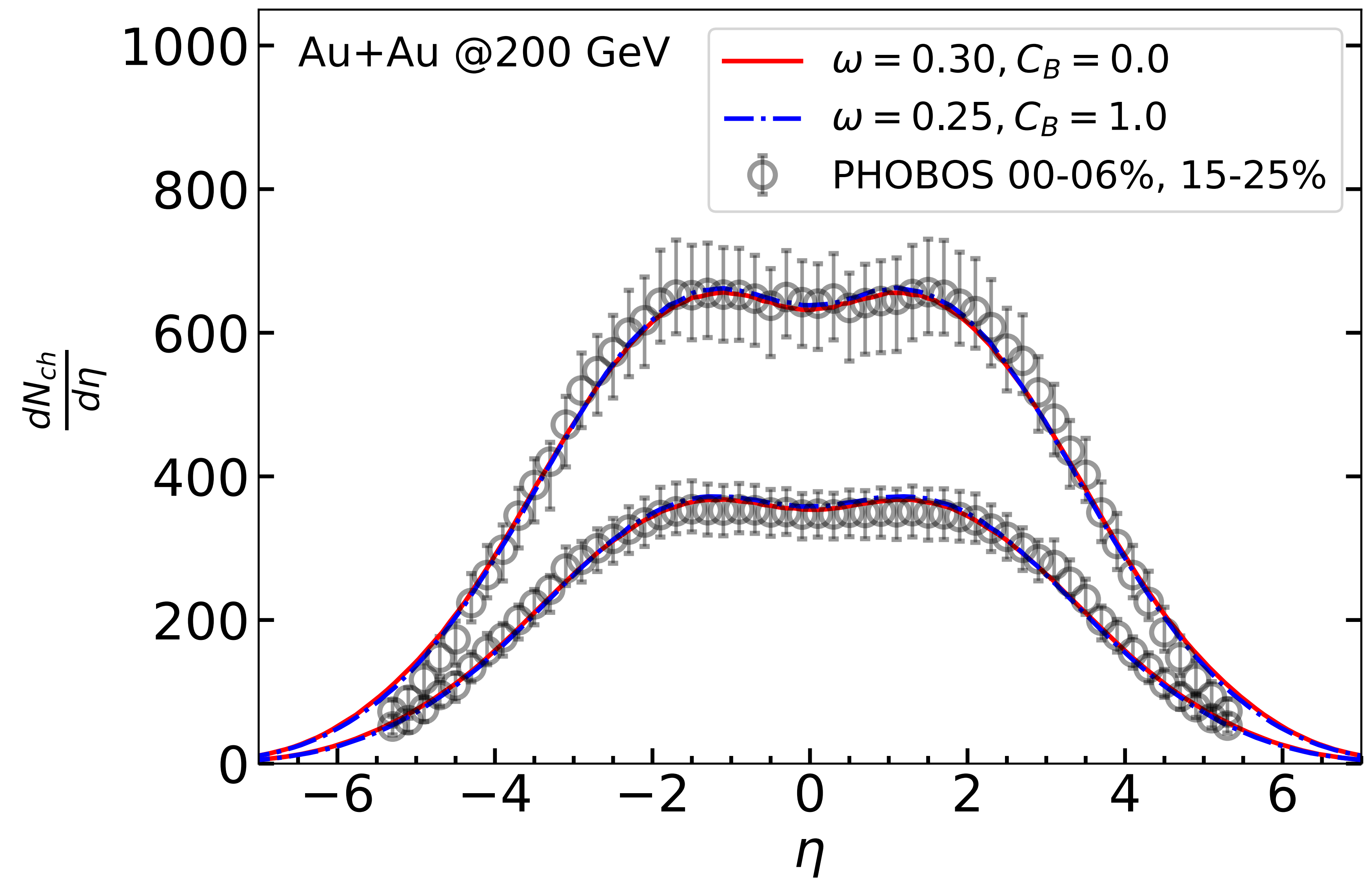
Comparison to data

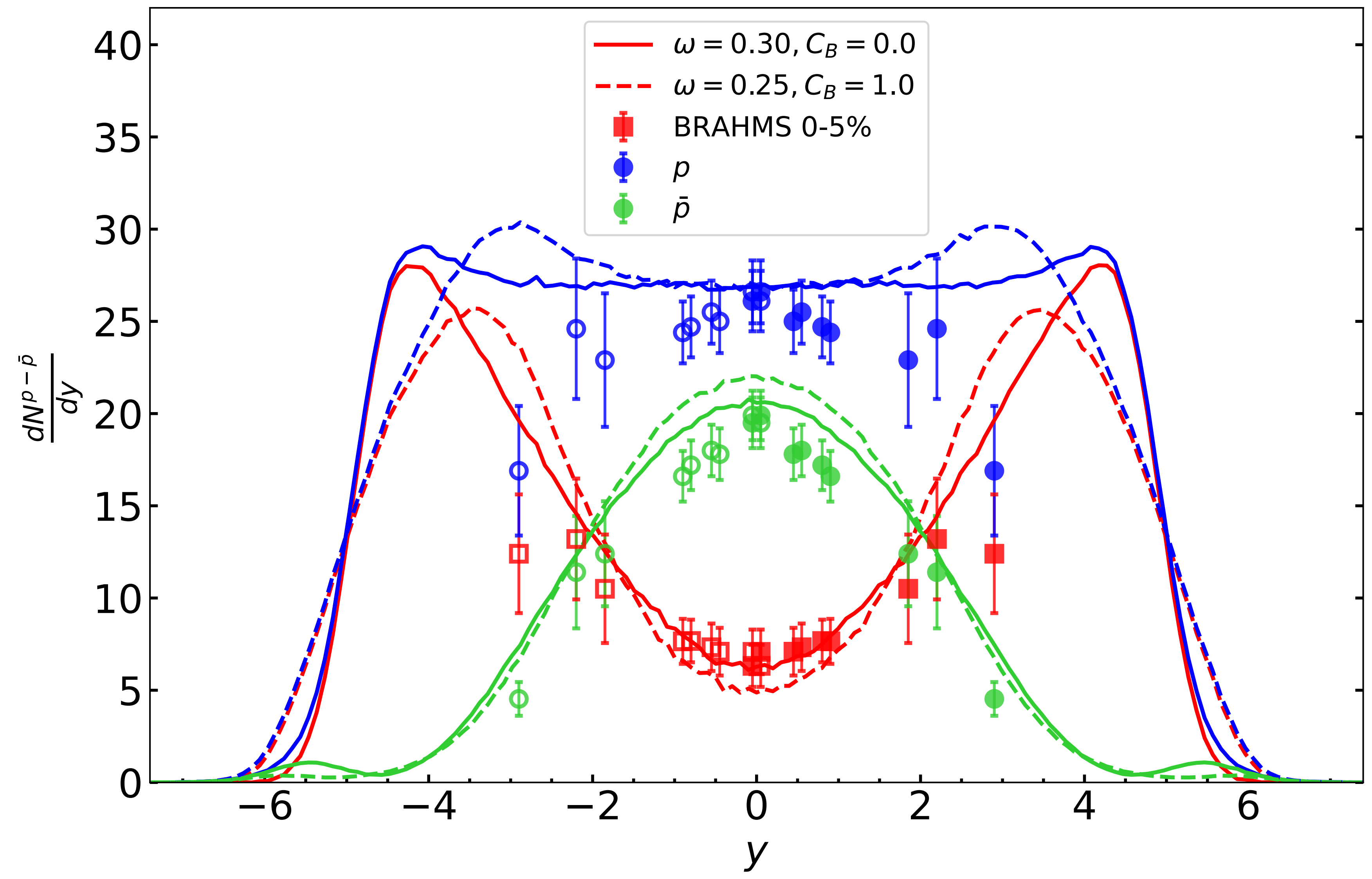


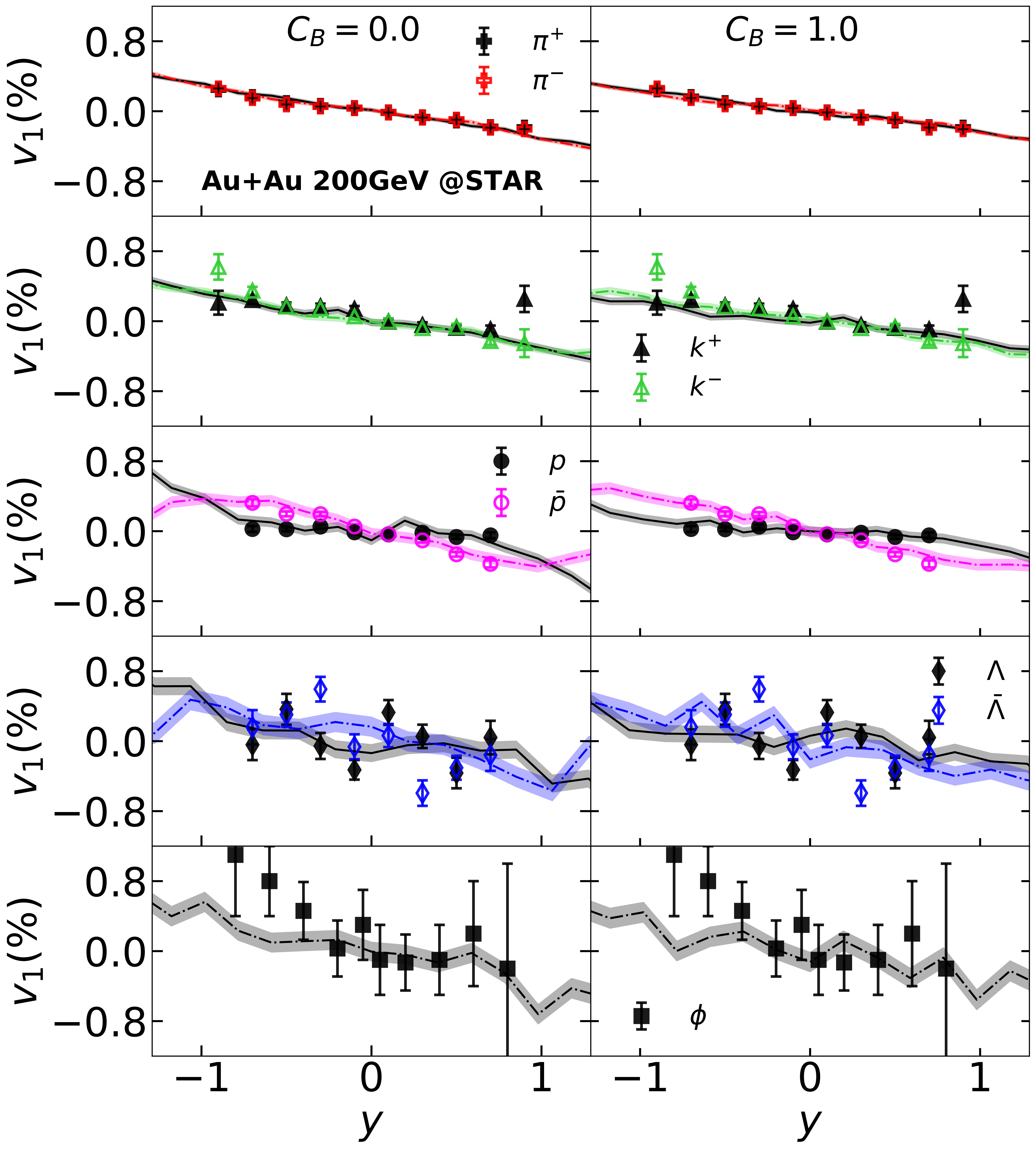


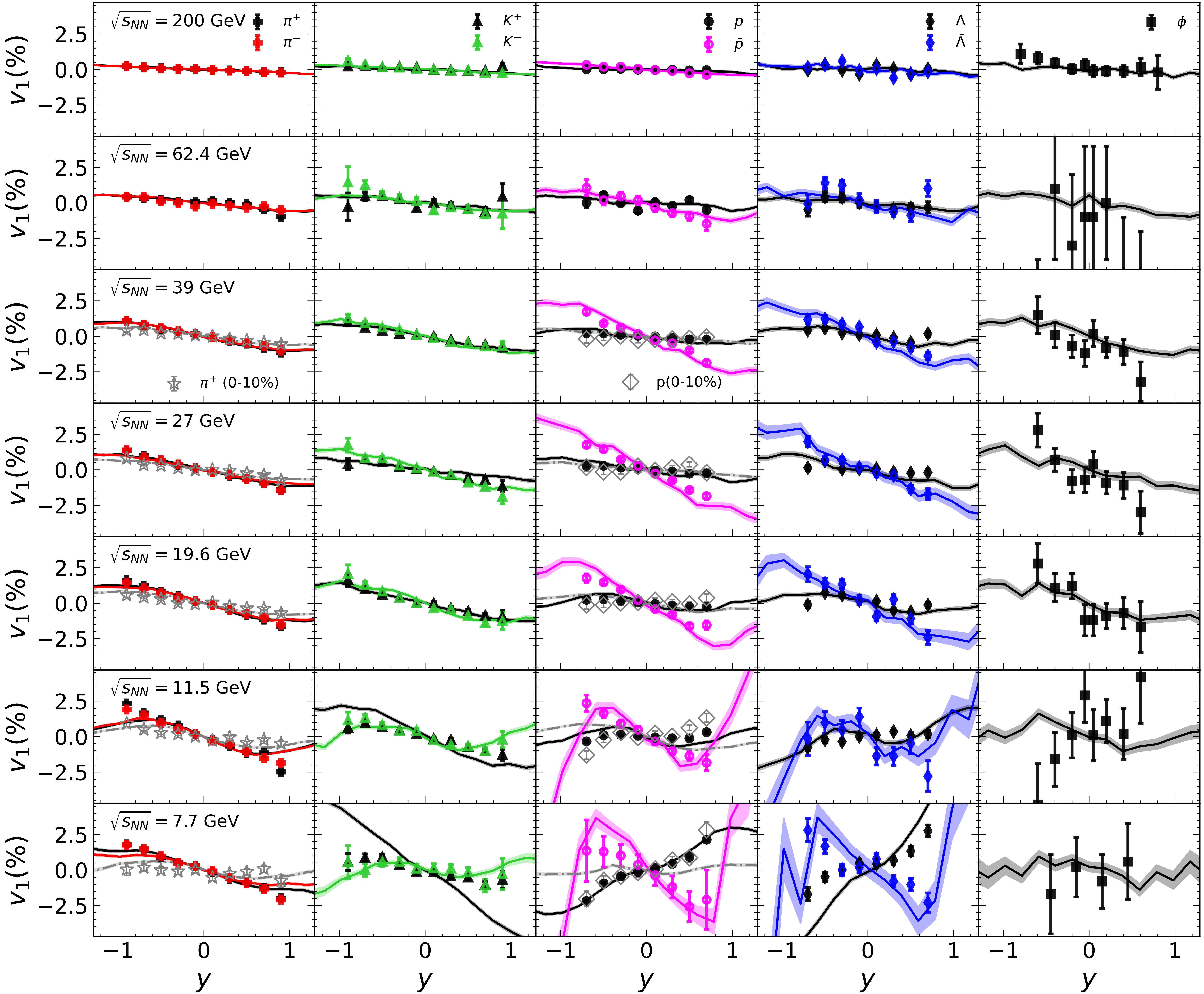


Comparison to data

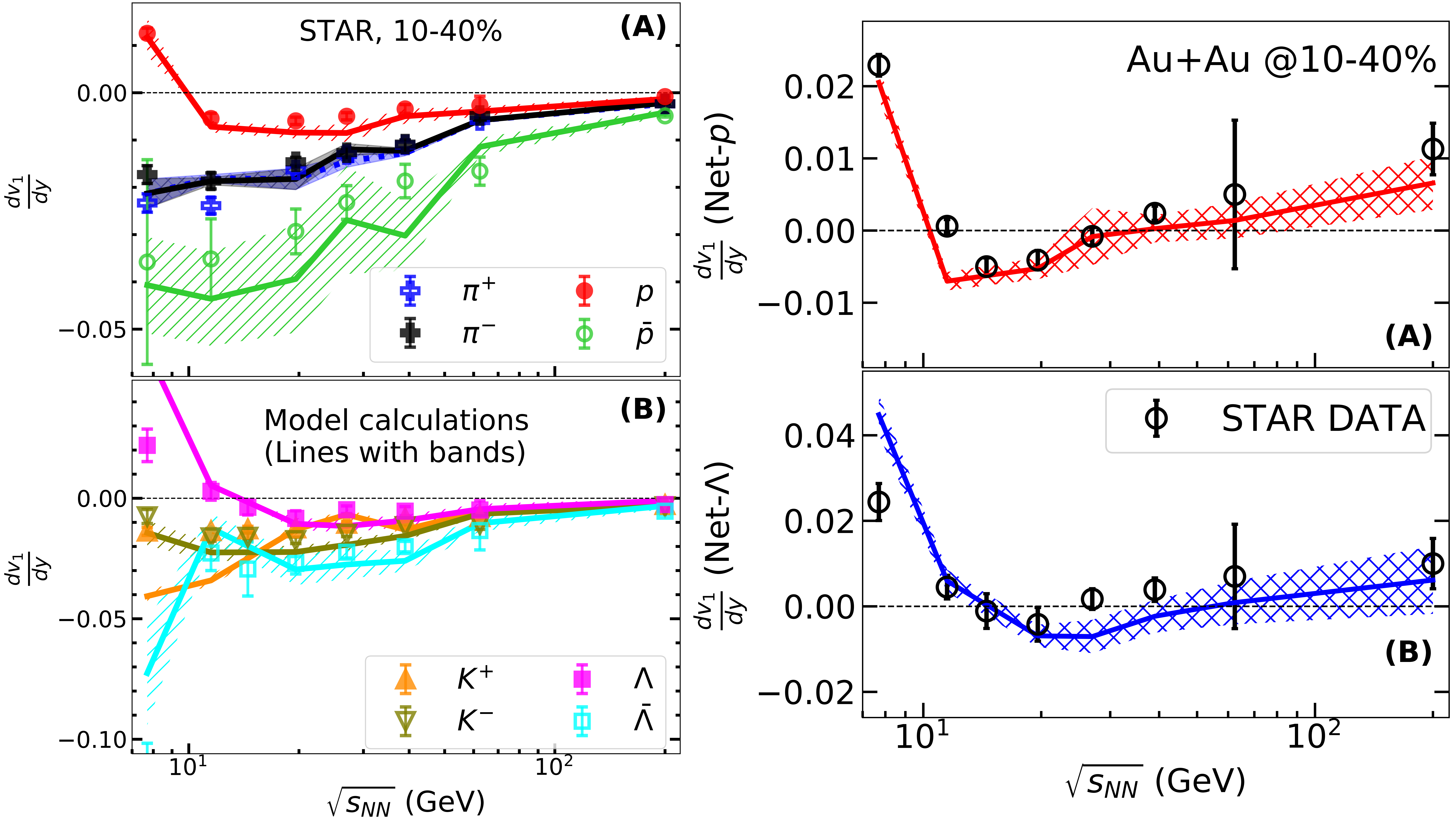








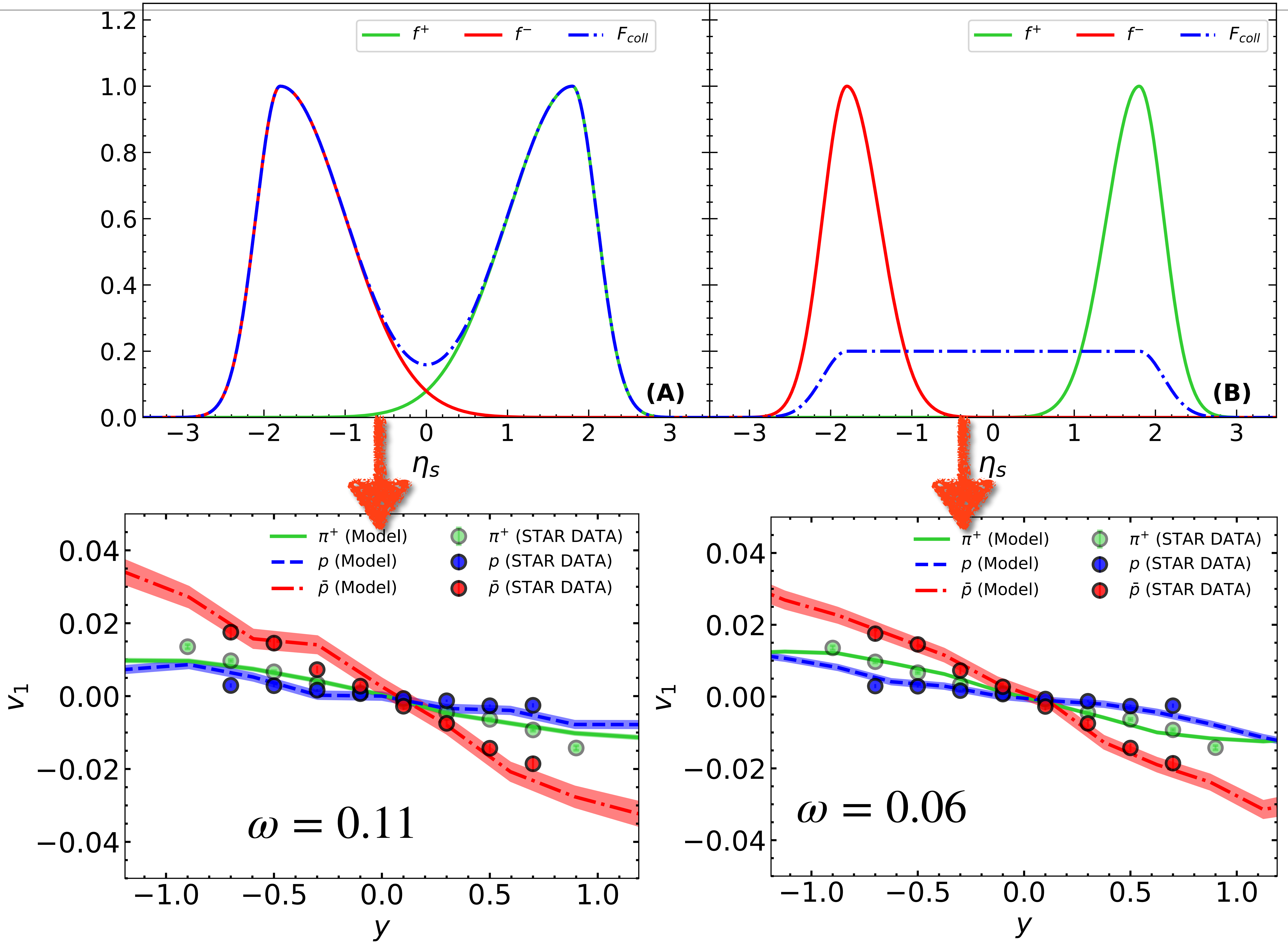
$\sqrt{s_{NN}}$ = 200 GeV
$\sqrt{s_{NN}}$ = 62.4 GeV
$\sqrt{s_{NN}}$ = 39 GeV
$\sqrt{s_{NN}}$ = 27 GeV
$\sqrt{s_{NN}}$ = 19.6 GeV
$\sqrt{s_{NN}}$ = 11.5 GeV
$\sqrt{s_{NN}}$ = 7.7 GeV
π^+
π^-
K^+
K^-
p
$\bar{p}$
Λ
$\bar{\Lambda}$
ϕ
π^+ (0-10%)
p(0-10%)
$v_1(\%)$
y



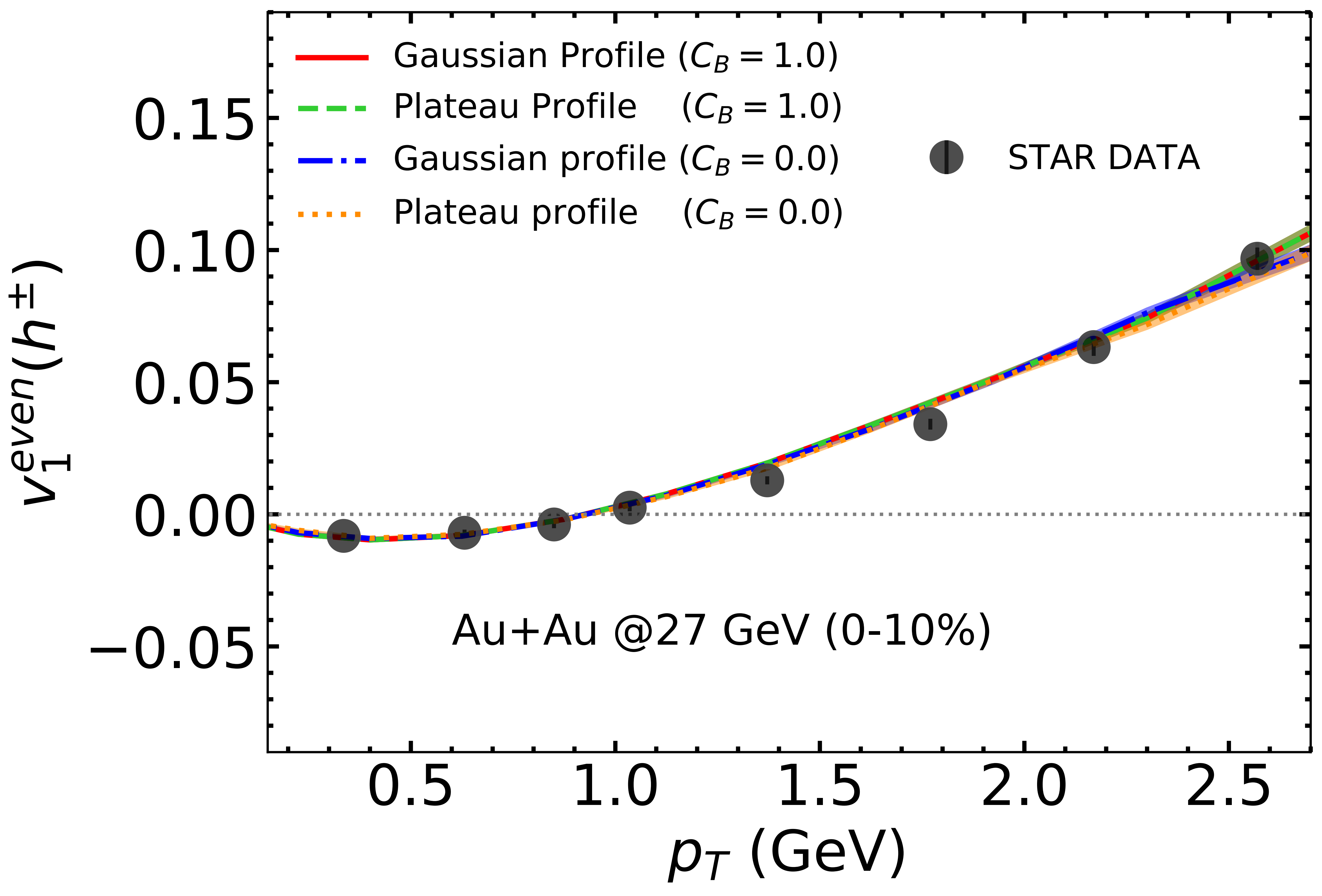
STAR, 10-40%
(A)
(B)
Model calculations
(Lines with bands)
π+
π−
p
p̄
K+
K−
Λ
Λ̄
dv1/dy
√sNN (GeV)
Au+Au @10-40%
dv1/dy (Net-p)
dv1/dy (Net-Λ)
STAR DATA

Constraining the rapidity even profile: v_1^{odd} fails

$$n_B(x, y, \eta_s; \tau_0) = N_B \left((1-\omega)\left(N_+(x,y) f_+(\eta_s) + N_-(x,y) f_-(\eta_s)\right) + \omega N_{coll}(x,y) F_{coll}(\eta_s) \right)$$



Constraining the rapidity even profile: use rapidity even v_1



STAR Collab., PLB 784 (2018) 26-32

$$v_1^{even}(p_T) = \frac{\langle Q \cos(\phi_j - \Psi_{EP,1}) \rangle}{\sqrt{\langle Q^2 \rangle}}$$

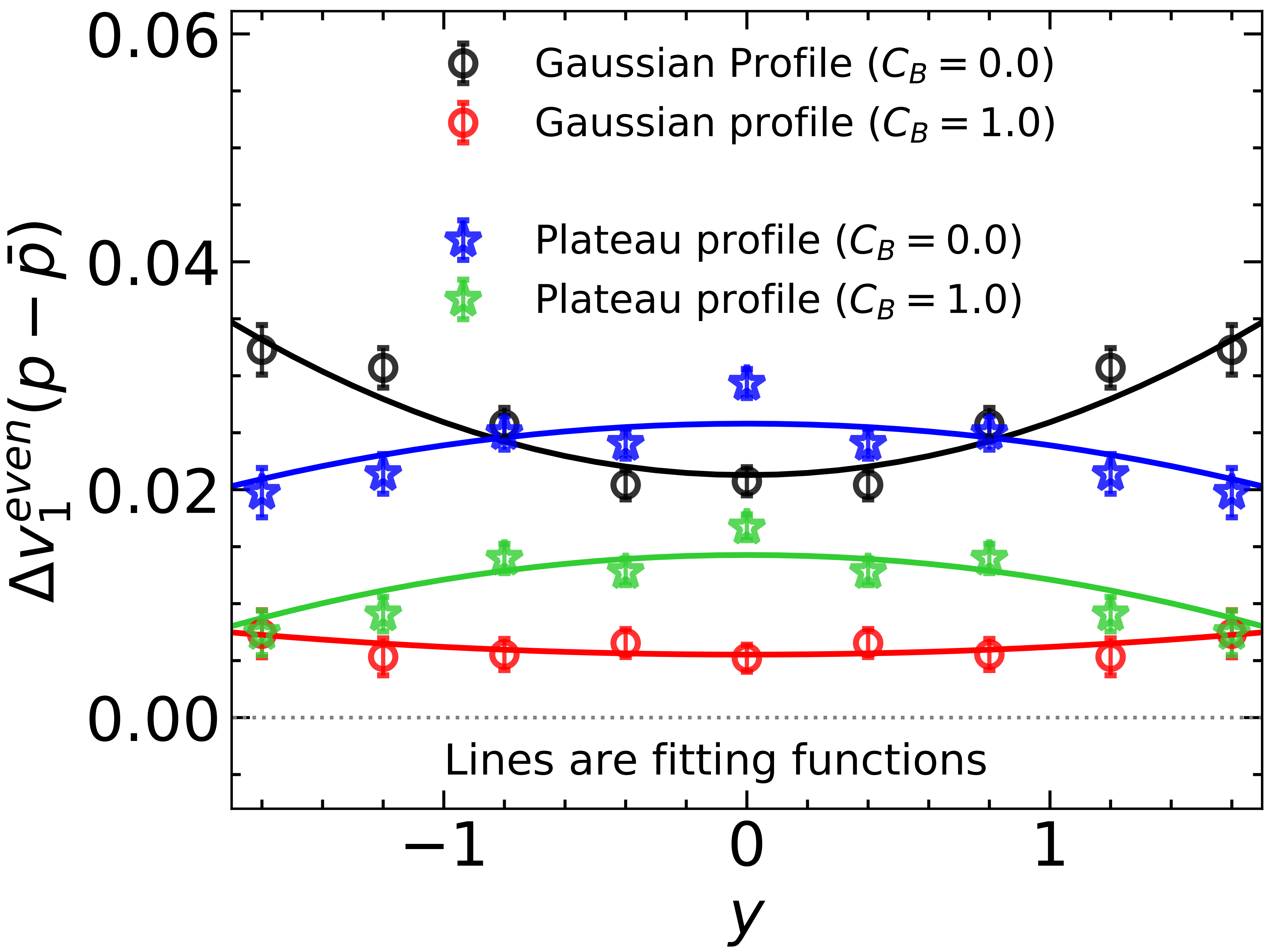
$$Q \exp\left(i\Psi_{EP,1}\right) = \langle w_j \exp(i\phi_j) \rangle$$

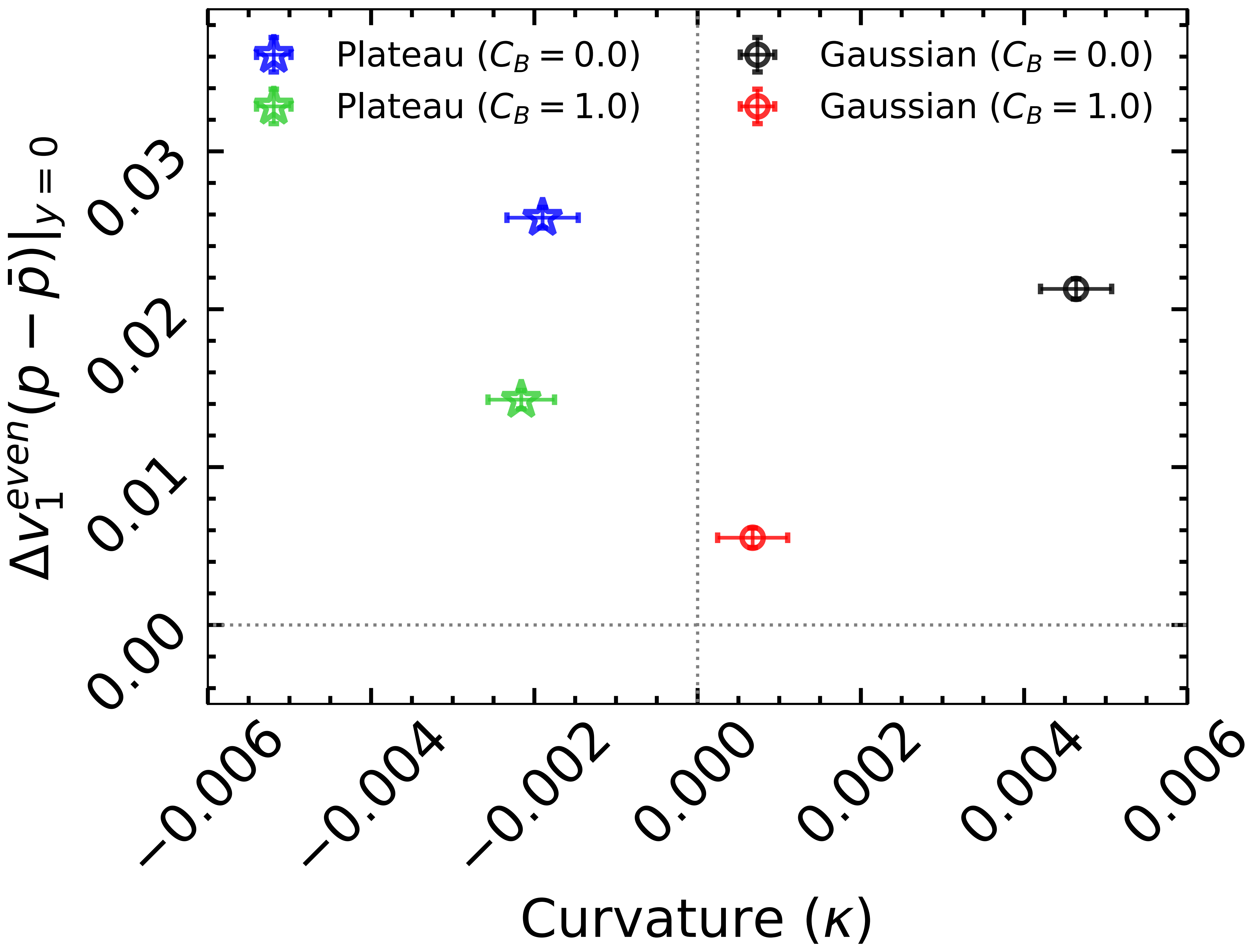
$$w_j = (p_T)_j \frac{\langle p_T^2 \rangle}{\langle p_T \rangle}$$

Gardim et al, PRC 83 (2011) 064901

Bozek, PLB, 717 (2012) 287

Constraining the rapidity even profile: use rapidity even v_1





Contribution of baryon stopping to signals of EM field

Electric charge and strangeness-dependent directed flow splitting of produced quarks in Au+Au collisions

The STAR Collaboration
(Dated: April 7, 2023)

We report directed flow (v_1) of multistrange baryons (Ξ and Ω) and improved v_1 data for K^-, $\bar{p}$, $\bar{\Lambda}$ and ϕ in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ =27 and 200 GeV from the STAR at the Relativistic Heavy Ion Collider (RHIC). We focus on particles whose constituent quarks are not transported from beam rapidity rather produced in the collisions. In midcentral collisions, we observe a coalescence sum rule for hadron combinations with identical quark content and a difference ("splitting") in the slope of v_1 vs. rapidity for combinations having nonidentical quark content. The splitting strength appears to increase with the electric charge difference and strangeness content difference of the constituent quarks in the combinations, consistent with an electromagnetic effect. The peripheral collision statistics are insufficient to draw firm conclusions.

STAR, 2304.02831

Observation of the electromagnetic field effect via charge-dependent directed flow in heavy-ion collisions at the Relativistic Heavy Ion Collider

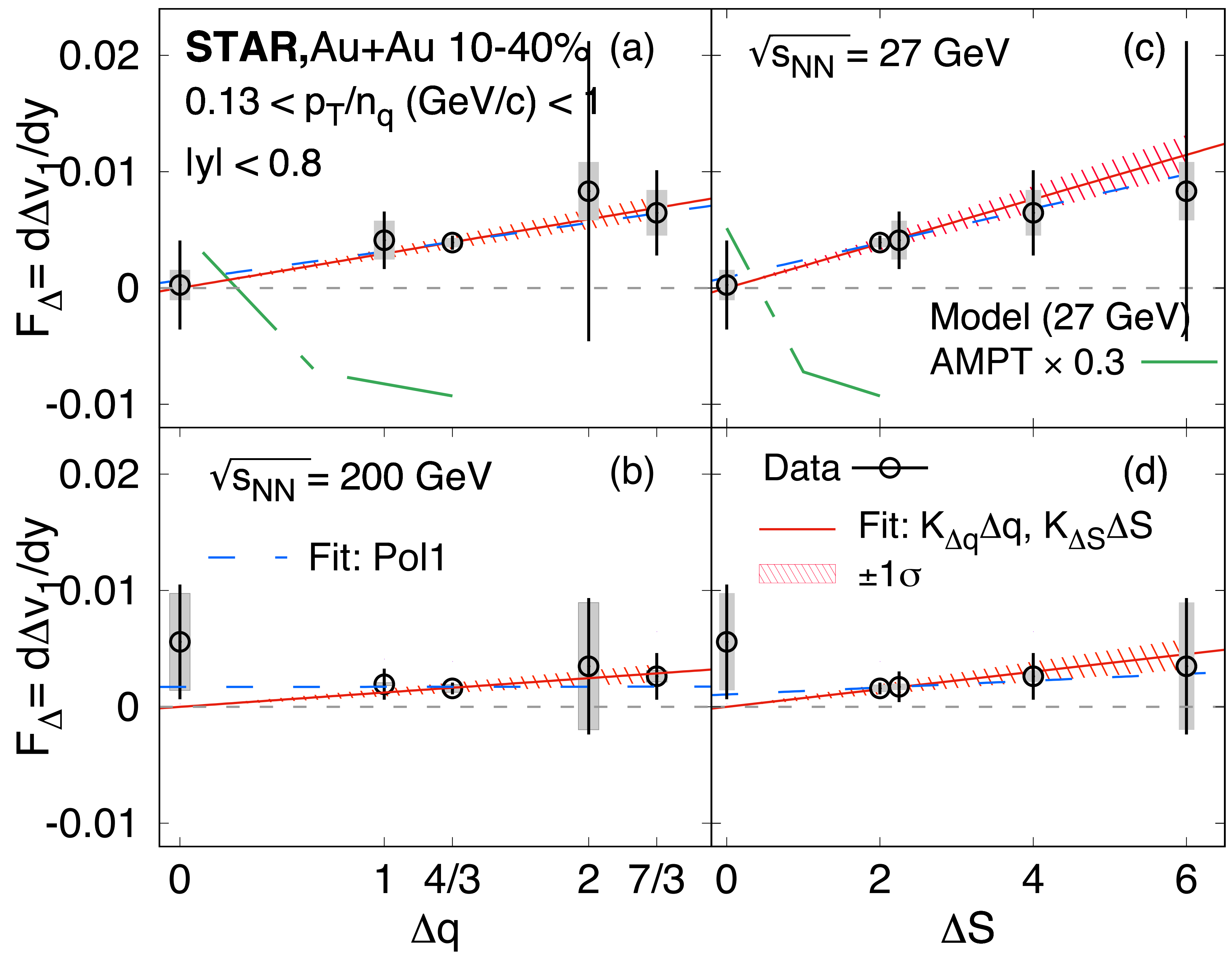
The STAR Collaboration

Non-central collisions between ultra-relativistic heavy nuclei can produce strong magnetic fields on the order of 10^{18} Gauss, and the evolution of the electromagnetic field could leave an imprint on the final-state particles. In particular, particles and anti-particles with opposite charges will receive opposite contributions to their rapidity-odd directed flow, $v_1(\mathrm{y})$. Here we present the charge-dependent measurements of $dv_1/d\mathrm{y}$ near midrapidity for $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ in Au+Au and isobar ($^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV, and in Au+Au at 27 GeV, recorded by the STAR detector at the Relativistic Heavy Ion Collider. The combined dependence of the v_1 signal on collision system, particle species, and collision centrality can be qualitatively and semi-quantitatively understood as several effects on constituent quarks. While the results in central events can be explained by the u and d quarks transported from initial-state nuclei, those in peripheral events reveal the contributions from the Faraday induction and Coulomb effect for the first time in heavy-ion collisions.

STAR, 2304.03430

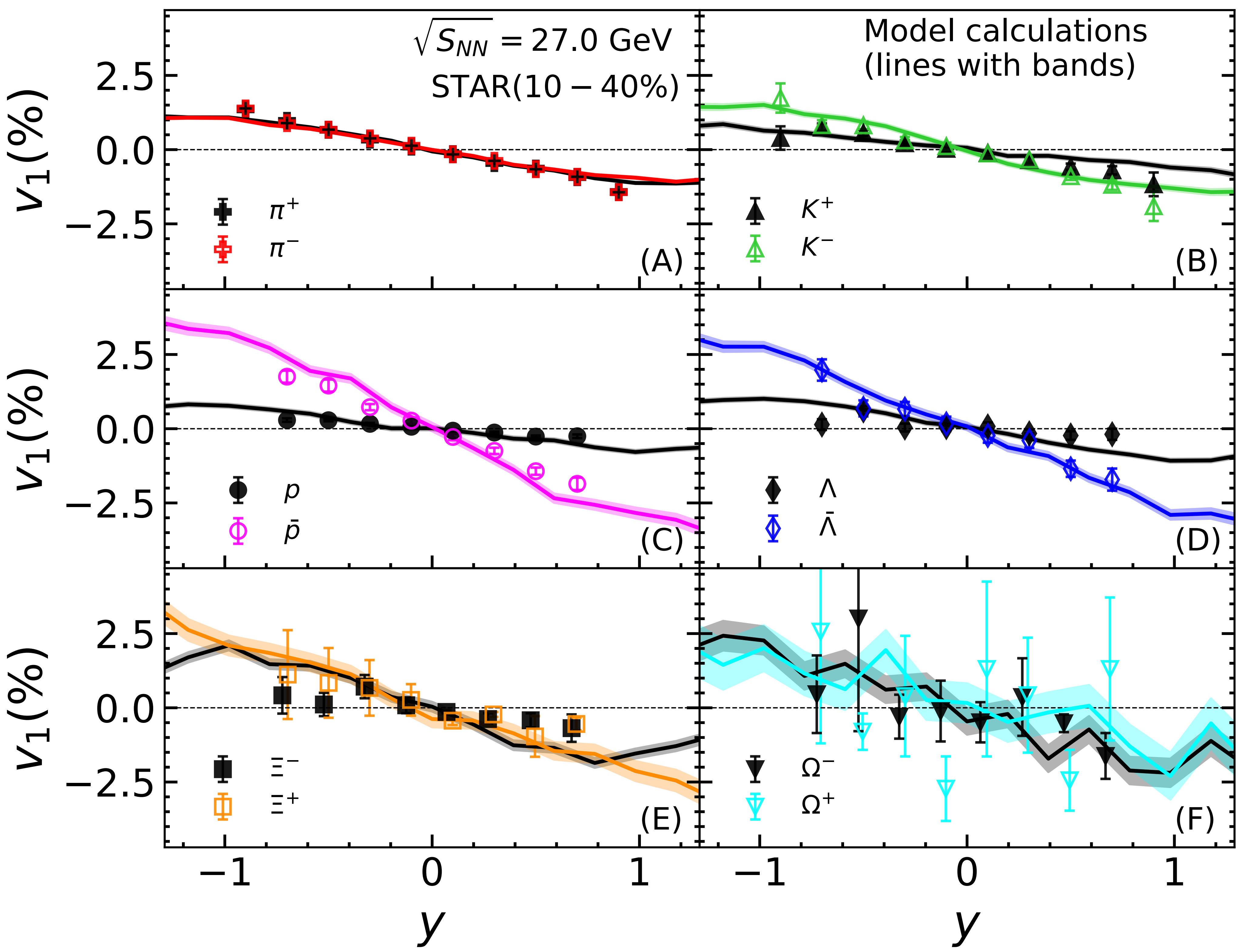
Q driven flow?

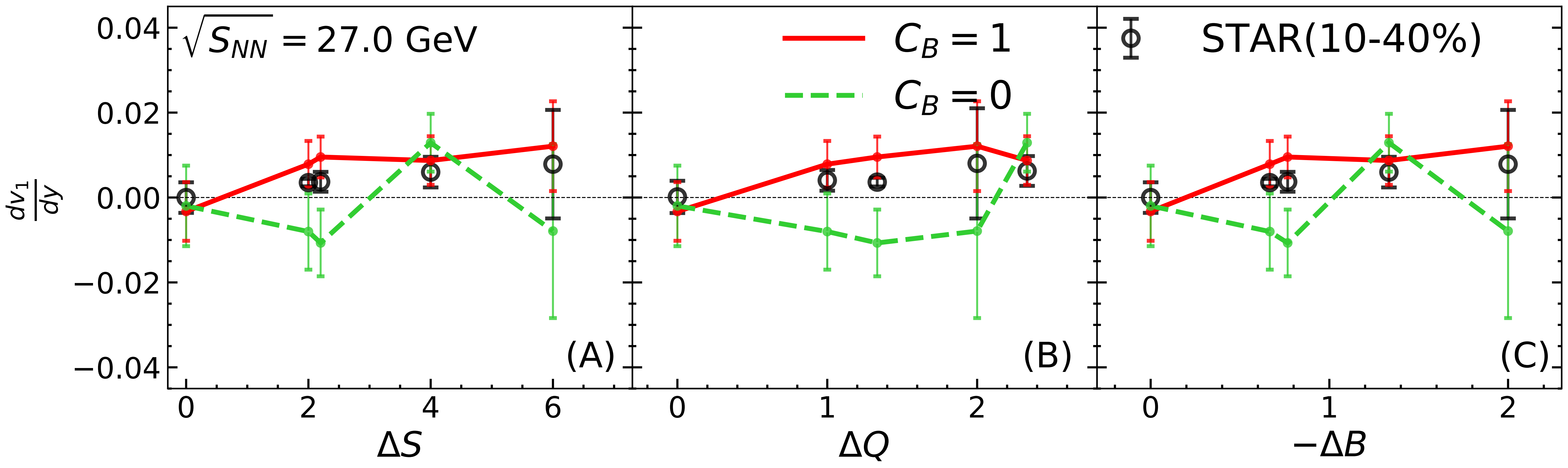
Index	Quark mass	Charge	Strangeness	Δv_1 combination
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^{-}(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^{-}(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^{+}(\bar{s}\bar{s}\bar{s})] - [\Omega^{-}(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^{+}(\bar{d}\bar{s}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\Omega^{-}(sss)]$



STAR, 2304.02831

Dominantly baryon stopping





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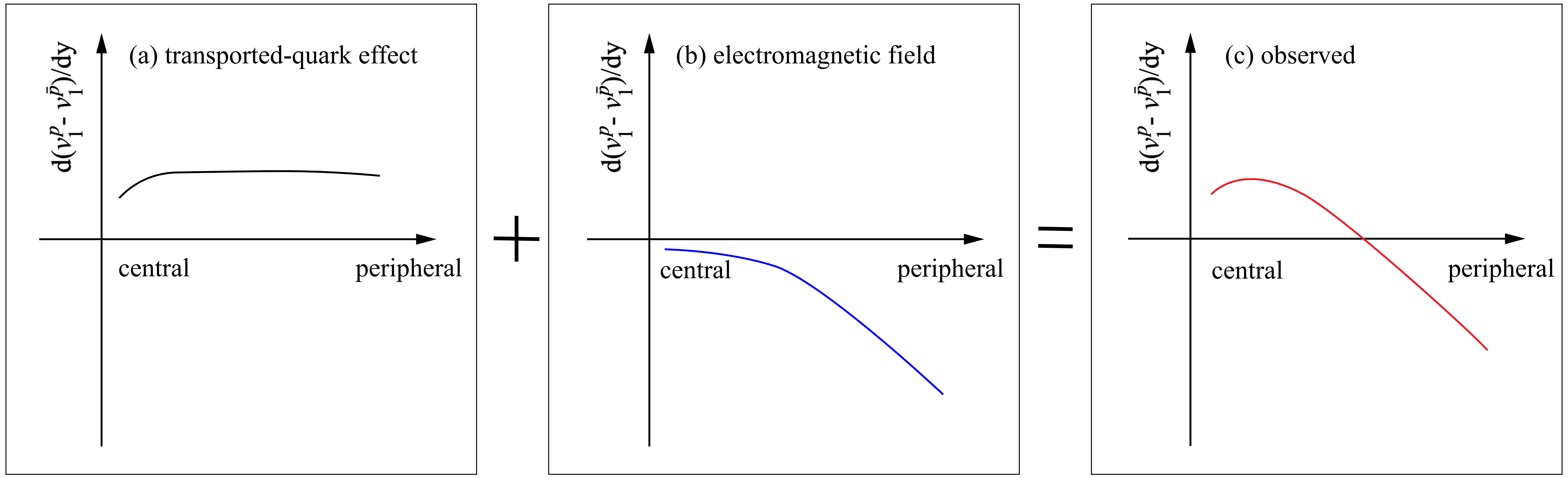
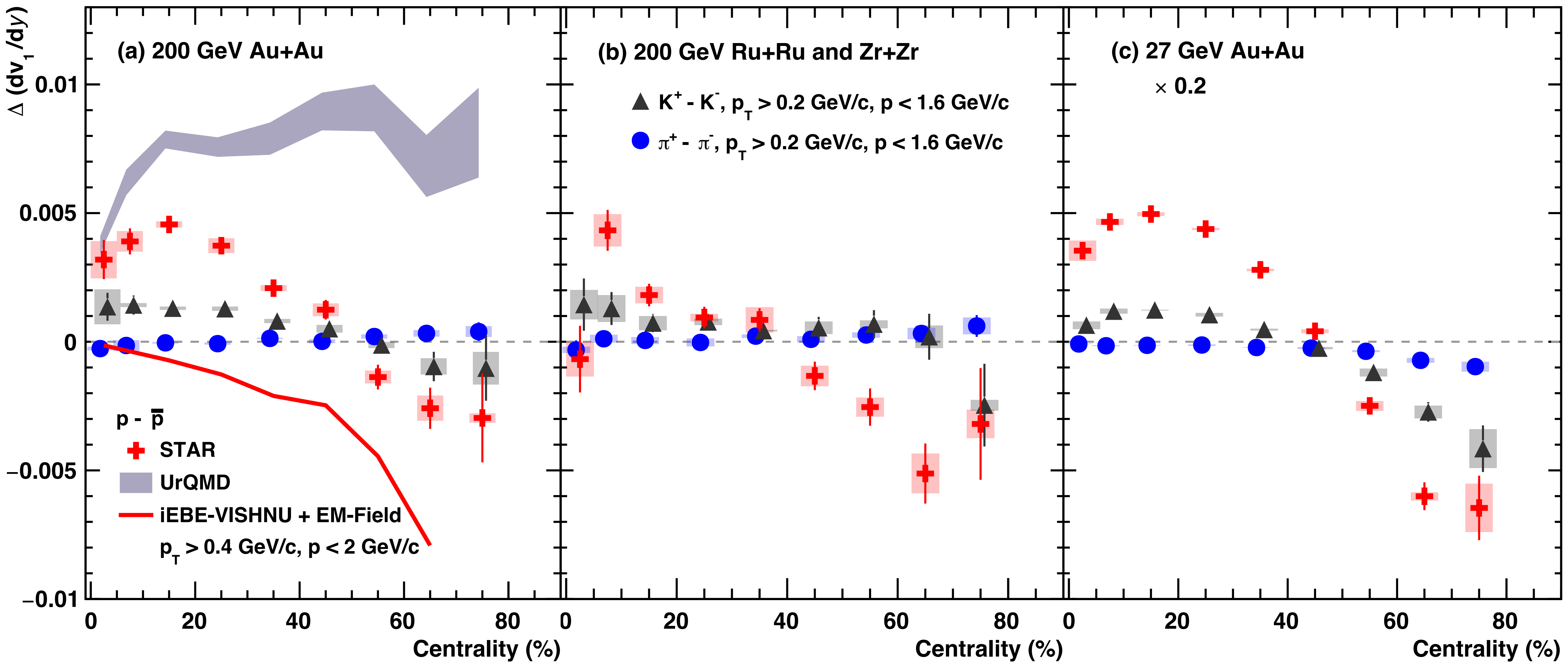
Interplay of baryon stopping vs EM field effects?





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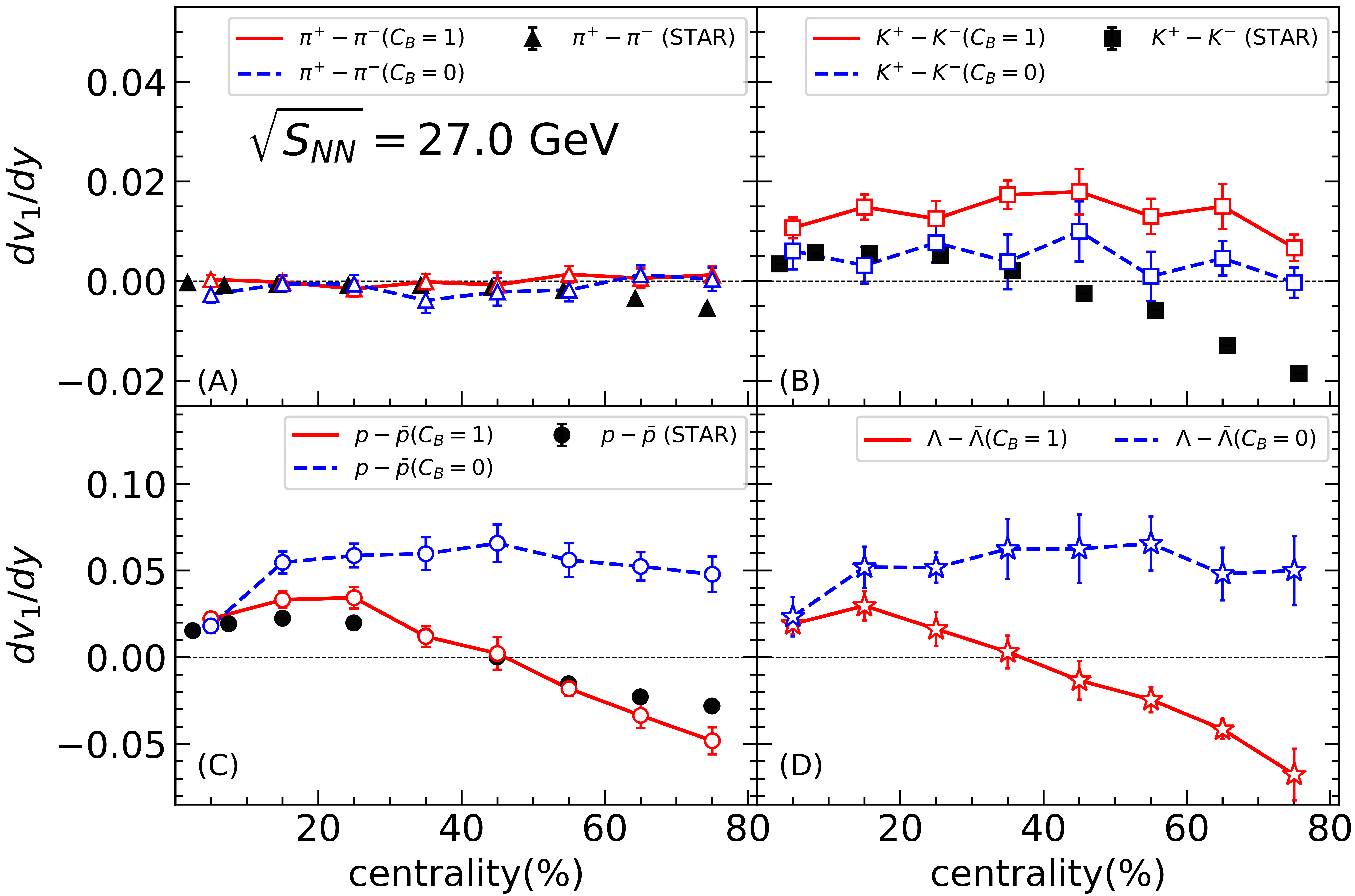
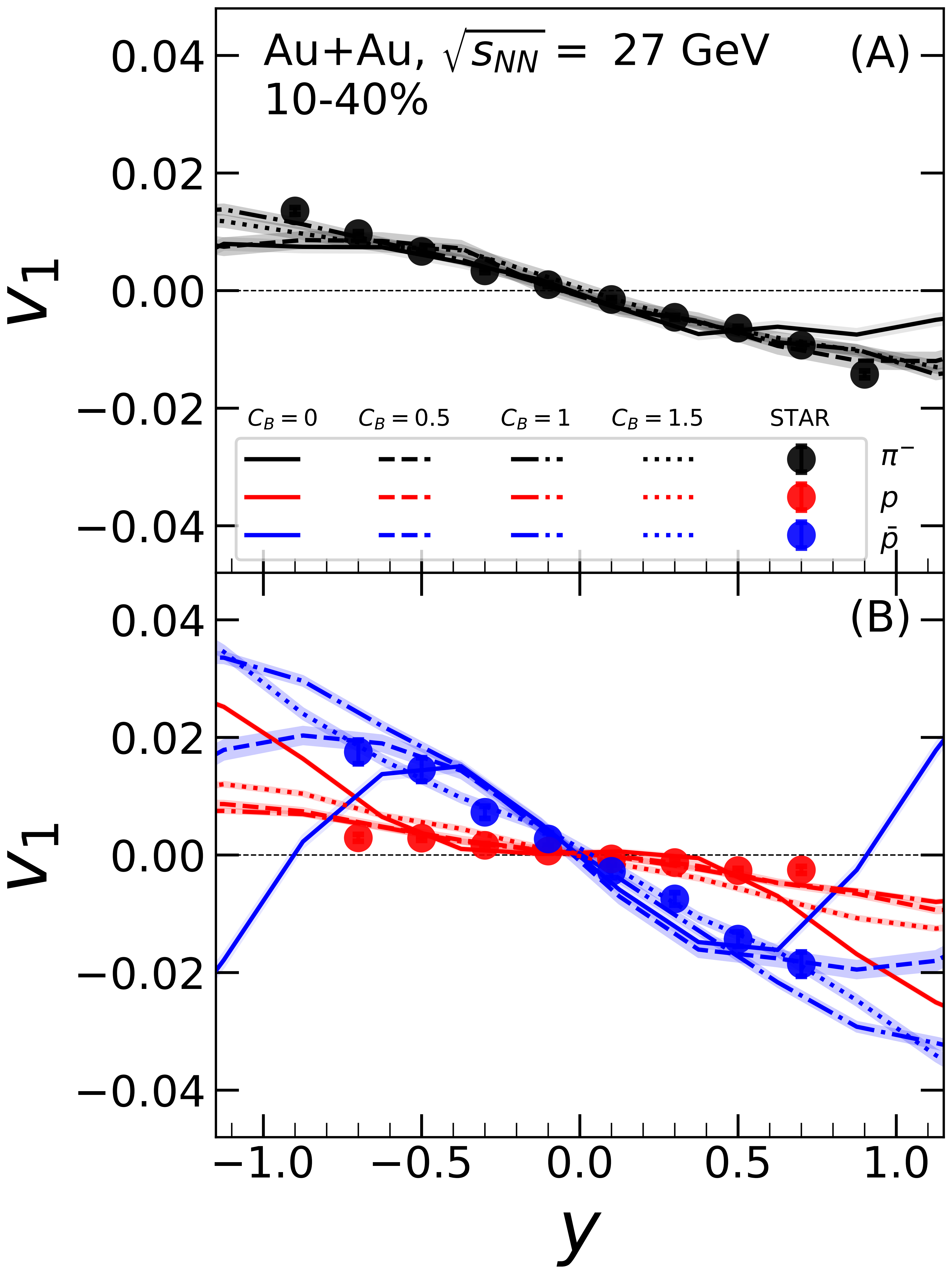


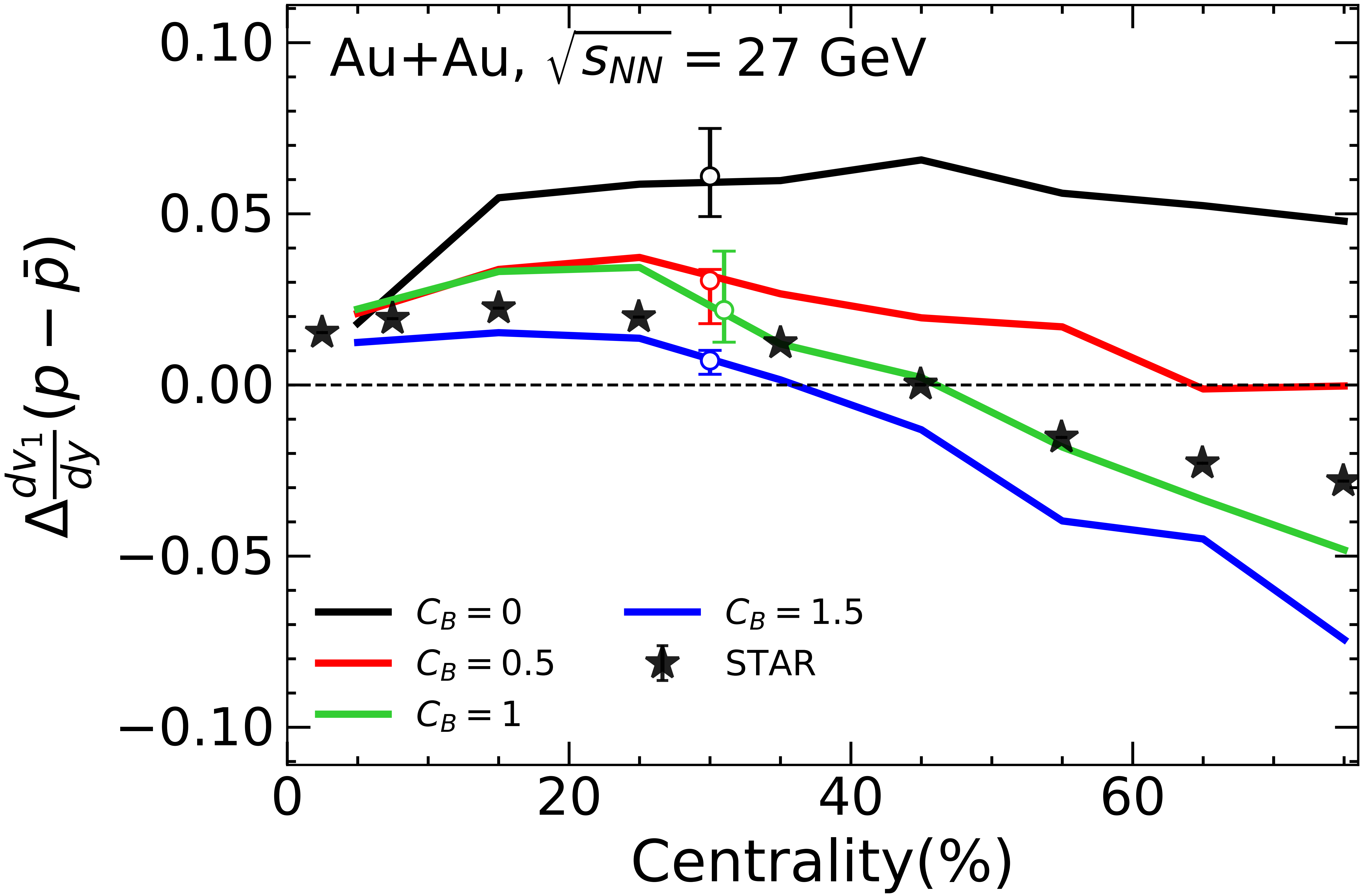
Dominant contribution from baryon stopping to baryons

Will be very interesting to measure $\Lambda - \bar{\Lambda}$; EM driven $s - \bar{s}$ should give opposite sign

Interesting observation in mesons: EM field vs transport of Q, S

Extracting baryon diffusion coefficient: C_B





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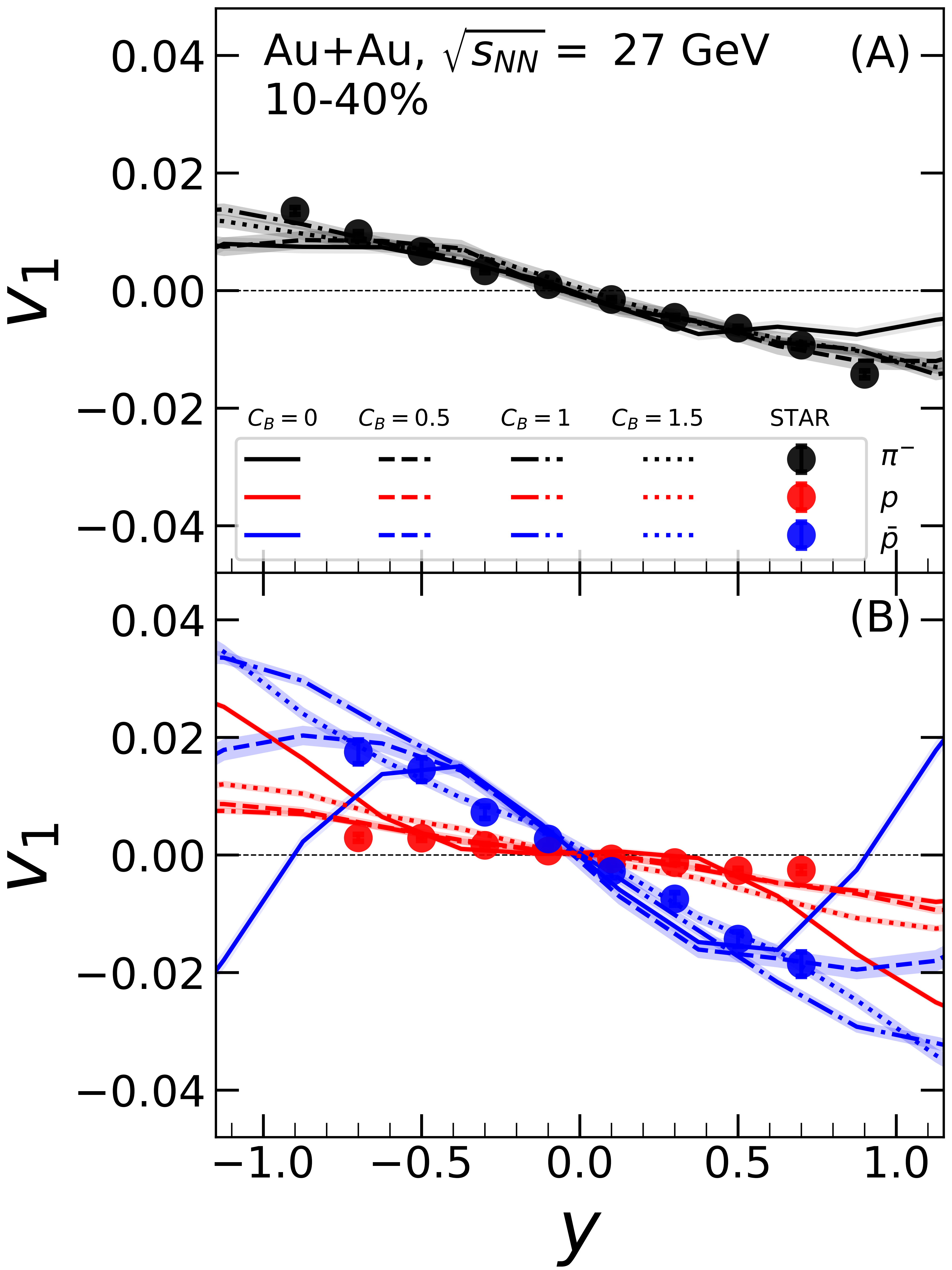

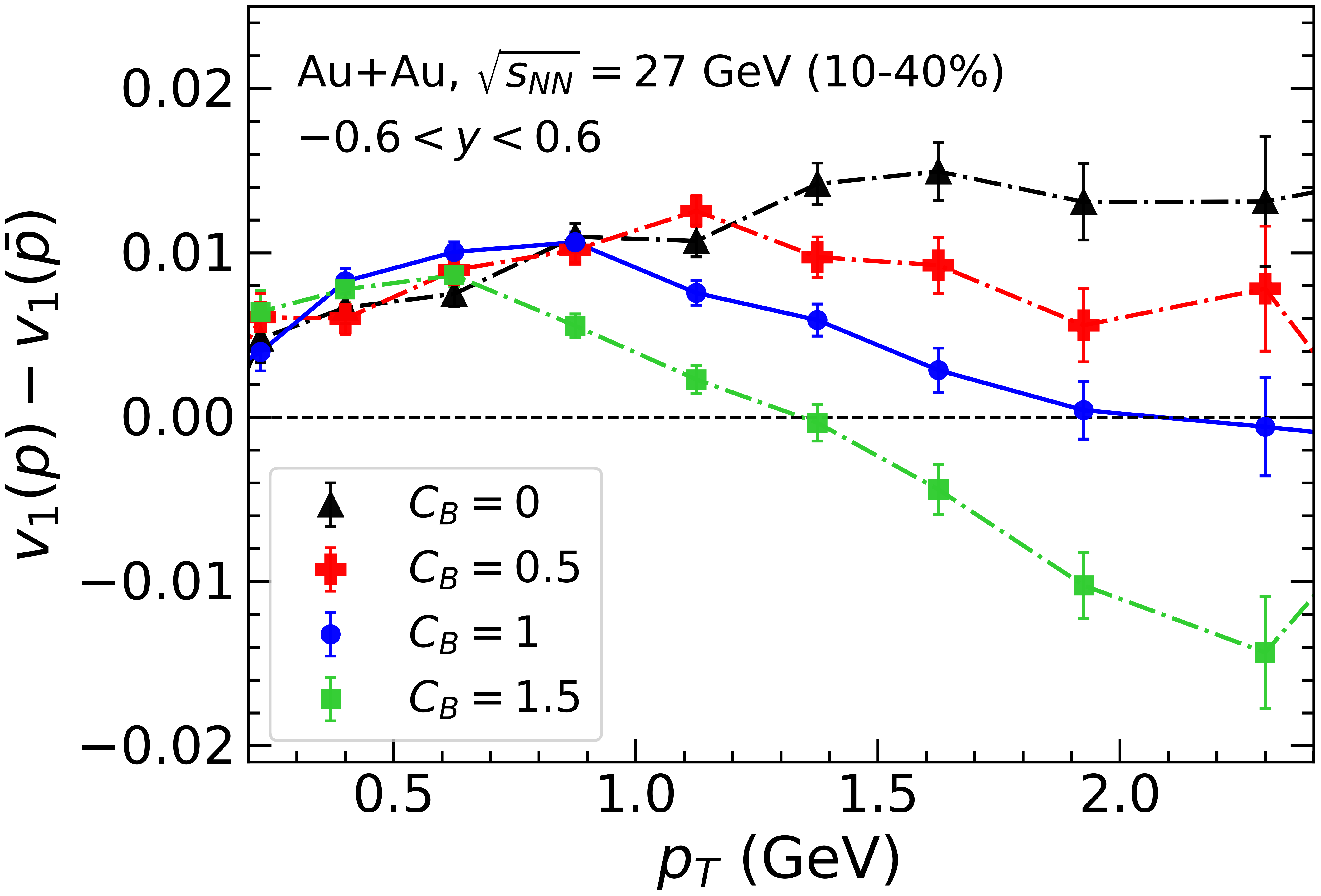

Summarising…

A phenomenologically successful model of initial baryon deposition proposed

Qualitative agreement across beam energies with data on yield, v_1; Independent evolution of strangeness, electric charge important at $\sqrt{s_{NN}} < 20$ GeV

A first estimate of baryon diffusion coefficient; Implications to astrophysics and cosmology?

Measurement of even v_1 is proposed to probe the rapidity even baryon deposition

- **single vs double baryon junction stopping**

Helps in estimating background driven by baryon stopping across beam energies in signals of other physics like that of the EM field; Useful to provide baseline estimates of QCD critical point observables like higher moments of conserved charge fluctuations

Thank You