LIPEI DU

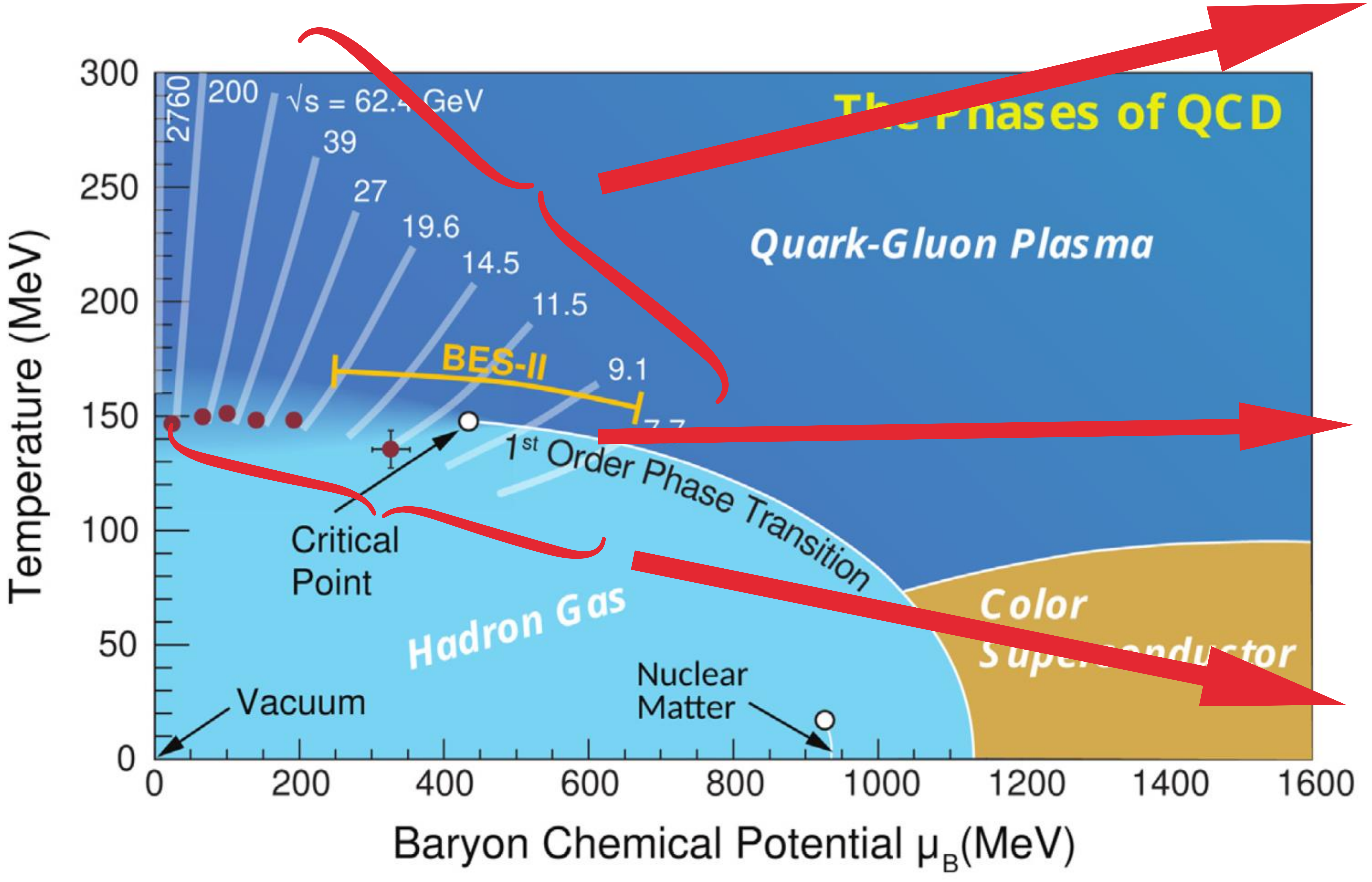
DEPARTMENT OF PHYSICS, MCGILL UNIVERSITY

LONGITUDINAL DYNAMICS OF HEAVY-ION COLLISIONS AT BEAM ENERGY SCAN

2023 RHIC/AGS ANNUAL USERS' MEETING

BNL, AUGUST 02, 2023

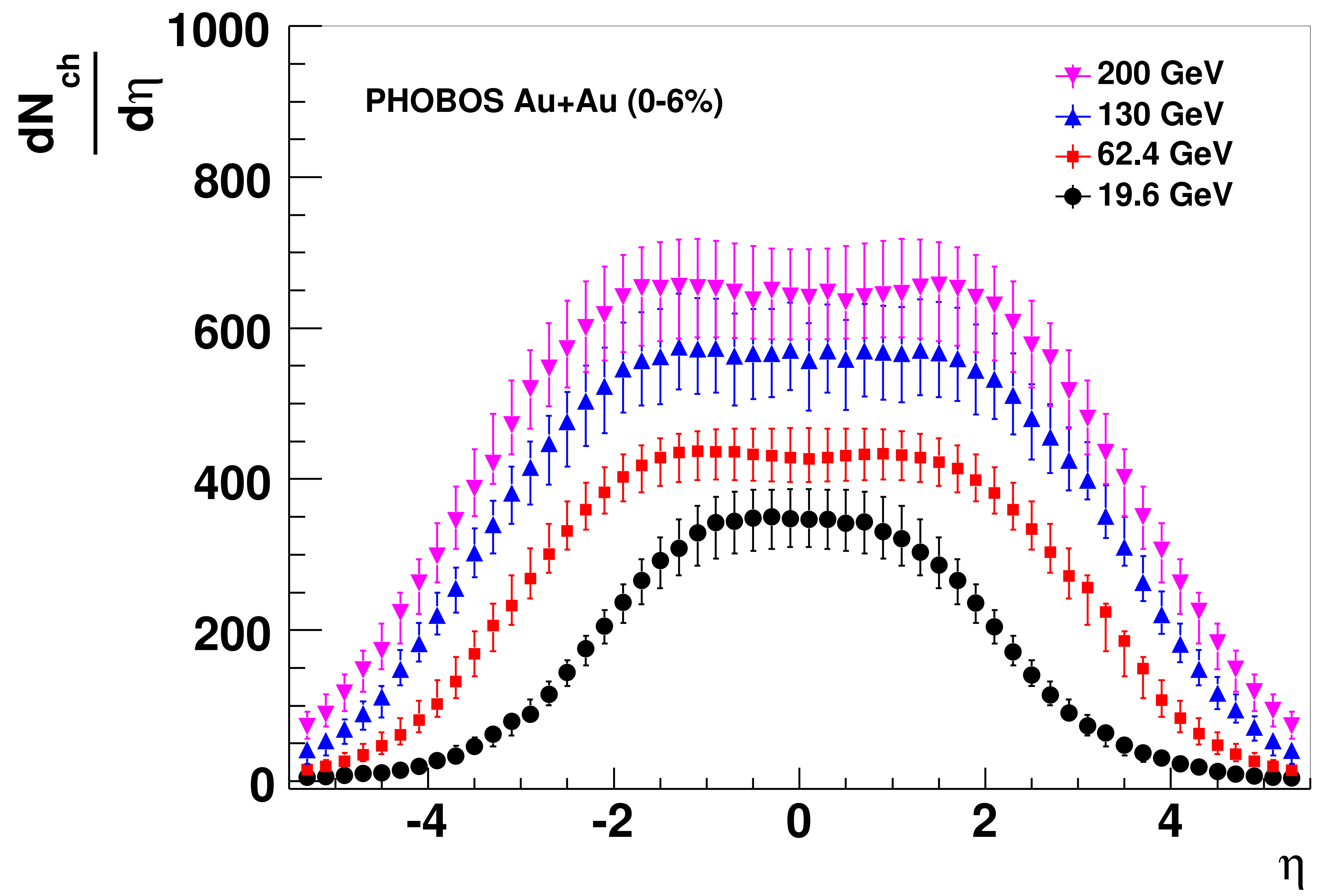
QCD PHASE DIAGRAM TRAJECTORIES

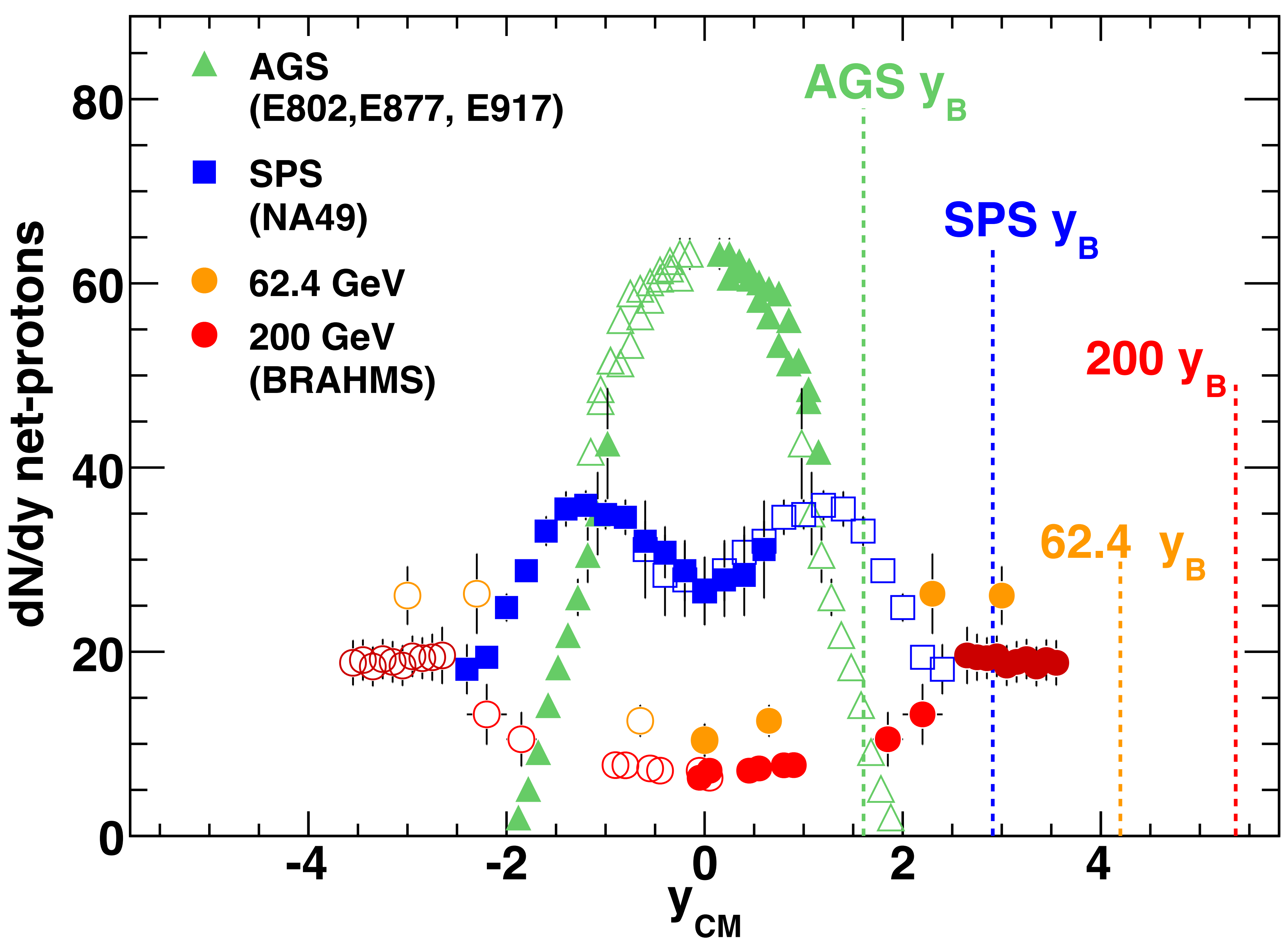


- **Starting points**: initial baryon density
- **Trajectory**: hydrodynamic evolution
- **Endpoints**: final baryon density

Bzdak, Esumi, Koch, Liao, Stephanov, and Xu, Phys. Rept. 853 (2020)

RAPIDITY-DEPENDENT MEASUREMENTS

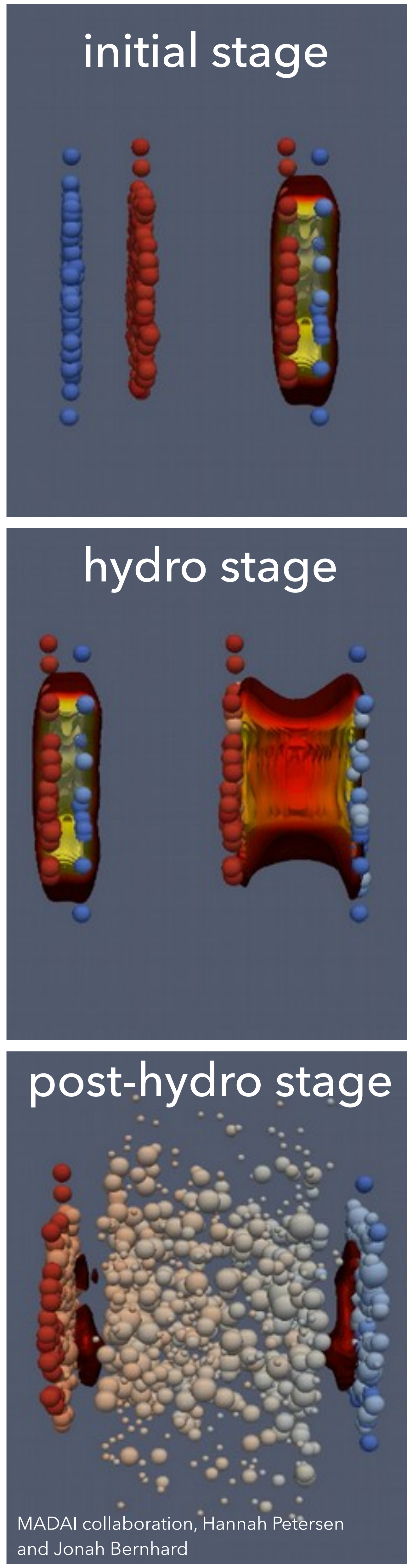


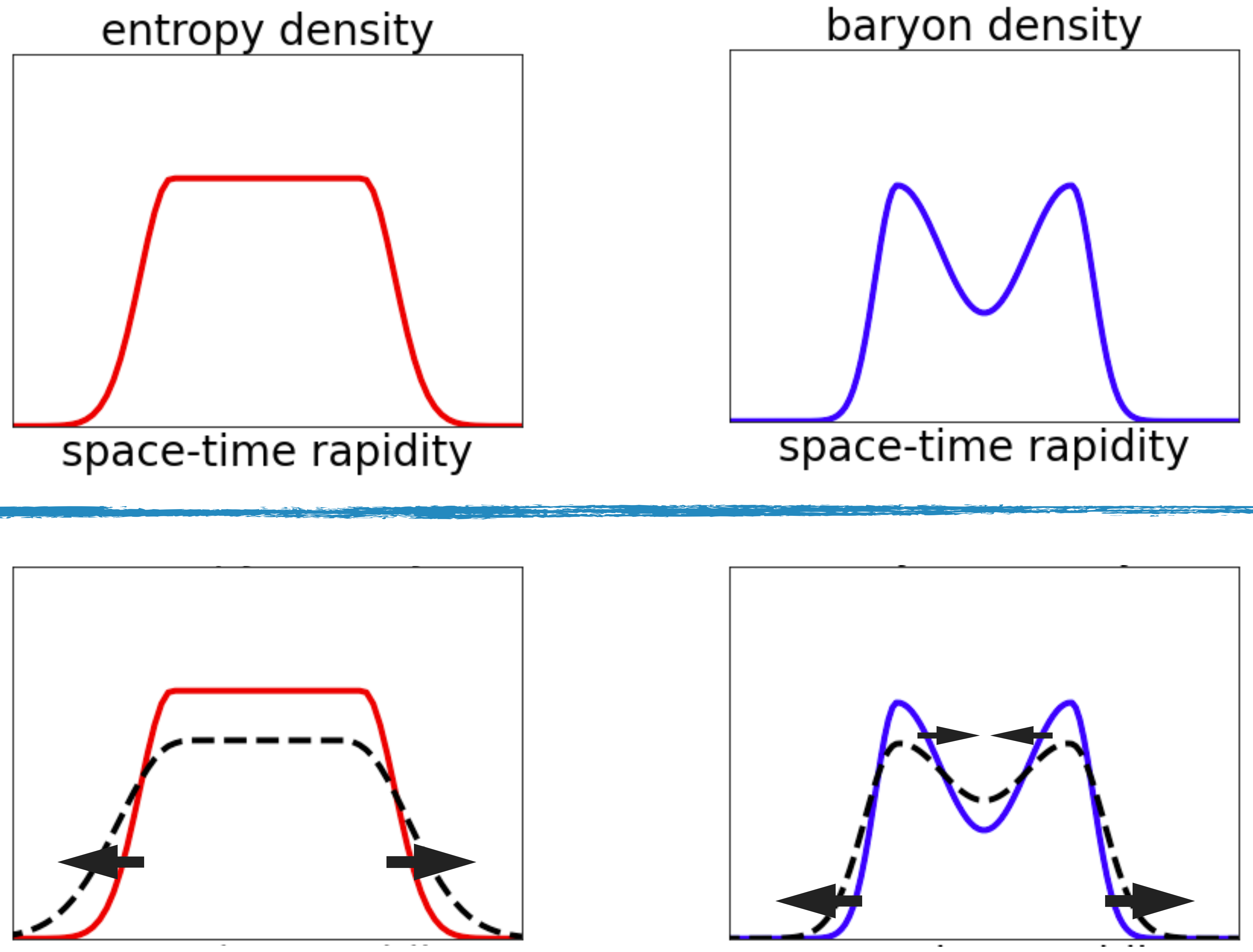


- The measurements indicate longitudinal inhomogeneity at the beam energy scan; it's essential to study the longitudinal dynamics;
- Rapidity-dependent measurements are essential for constraining theoretical models: Charged particle multiplicity → entropy/energy density; net-proton yields → baryon density

Figs refs: R. Sahoo et al., 1408.5773; F. Videbaek, Nucl. Phys. A 830 (2009) 43C

LONGITUDINAL DYNAMICS

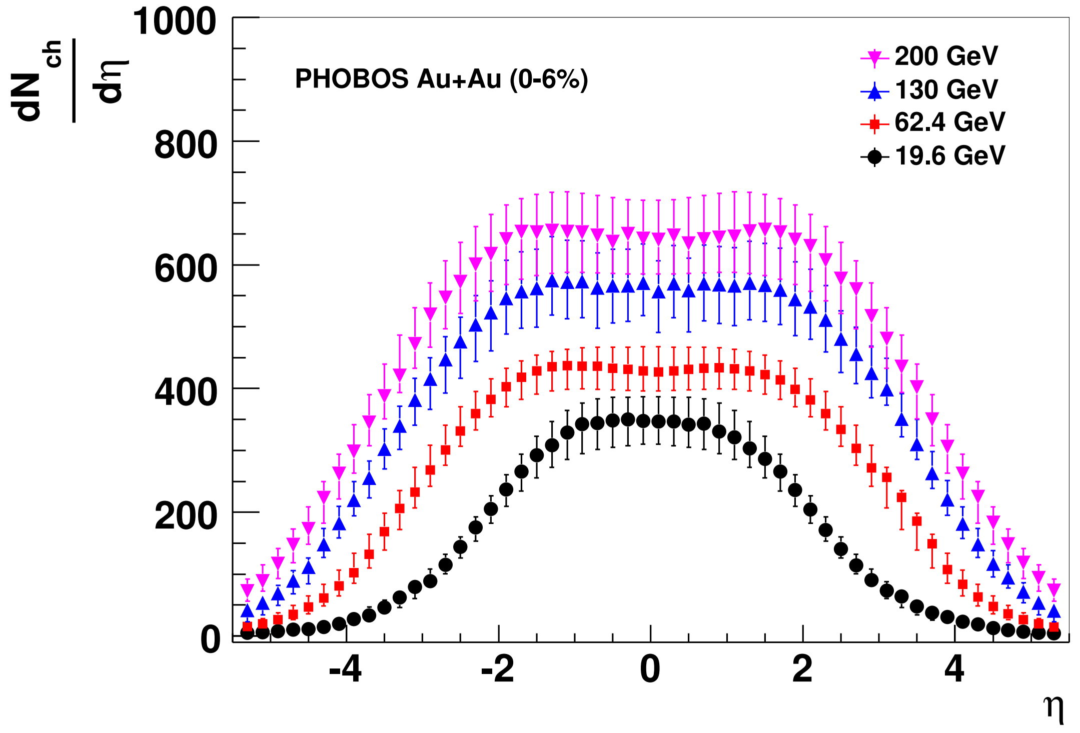


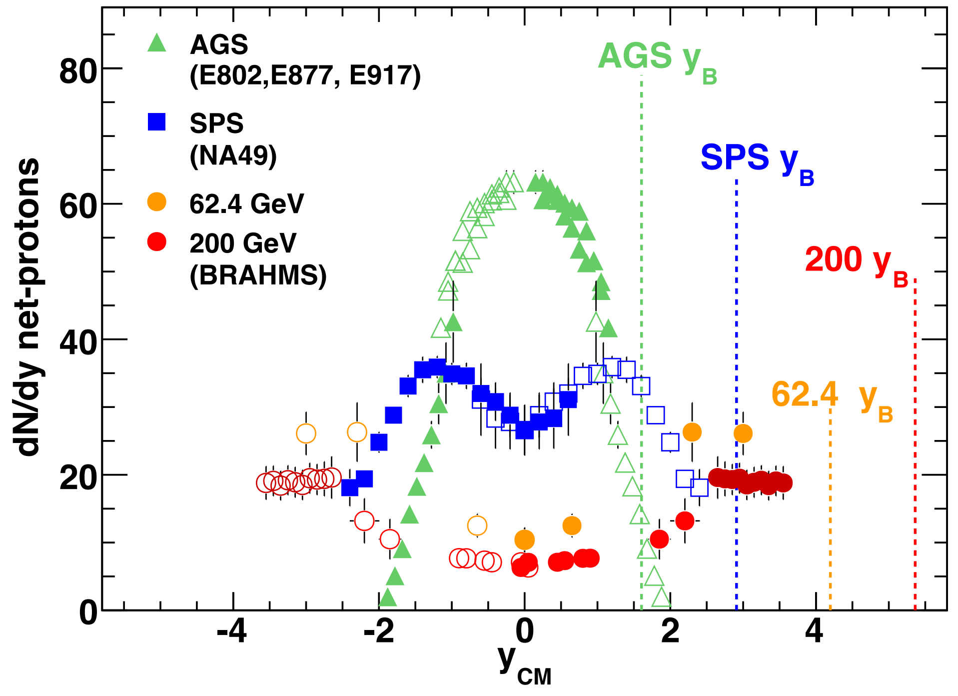


- initial energy deposition
- initial baryon stopping

\+

- longitudinal pressure gradient ⟹ longitudinal flow & expansion
- baryon density gradient ⟹ baryon diffusion (hydro transport)

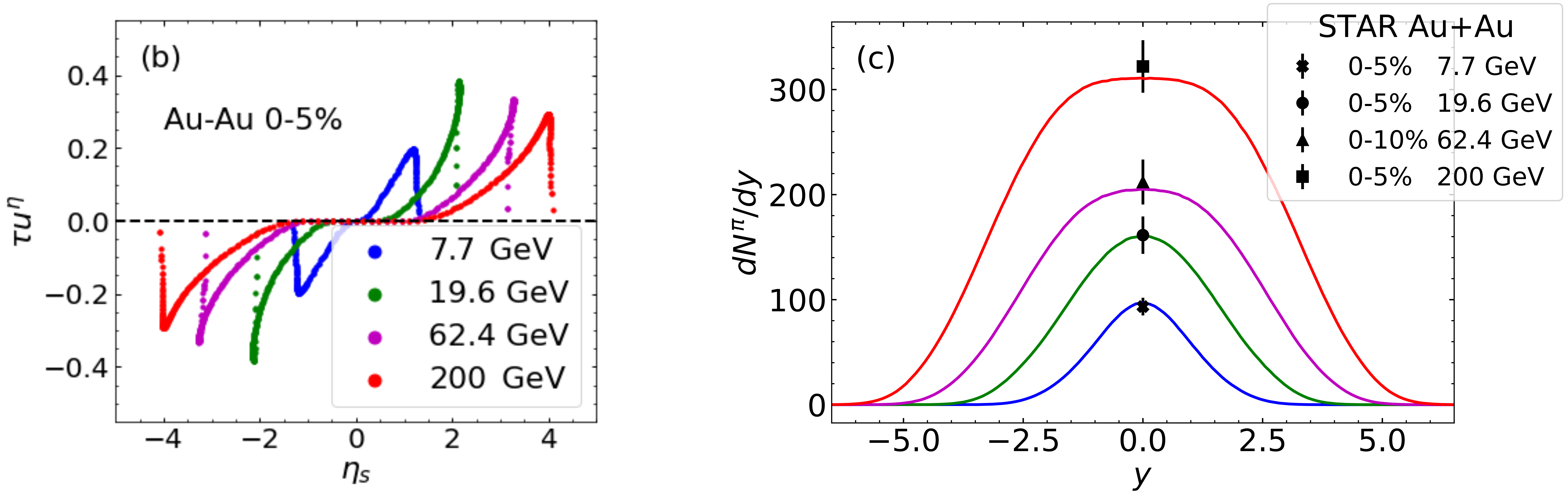




↓

- rapidity-dependent particle distributions

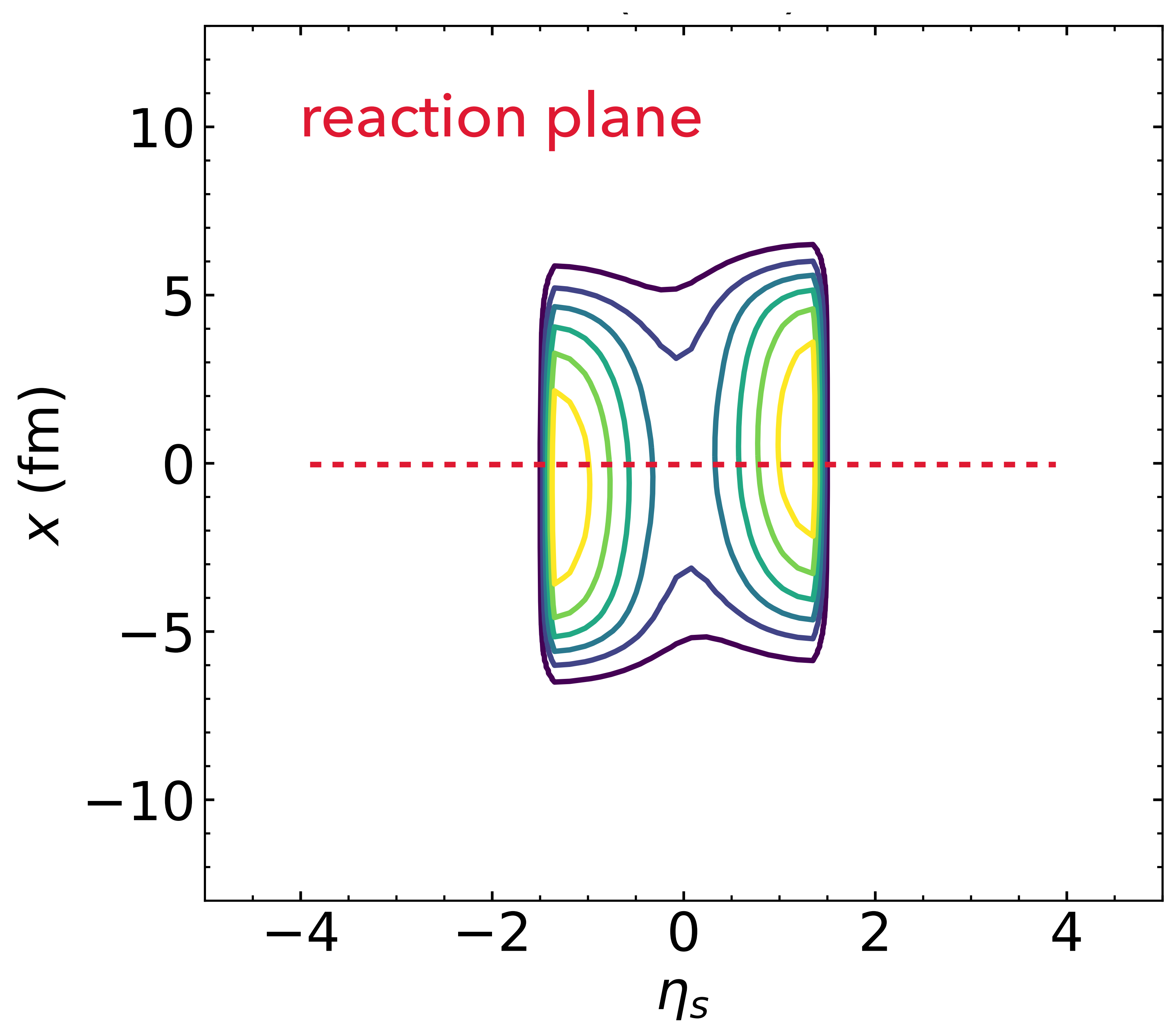
LONGITUDINAL EXPANSION



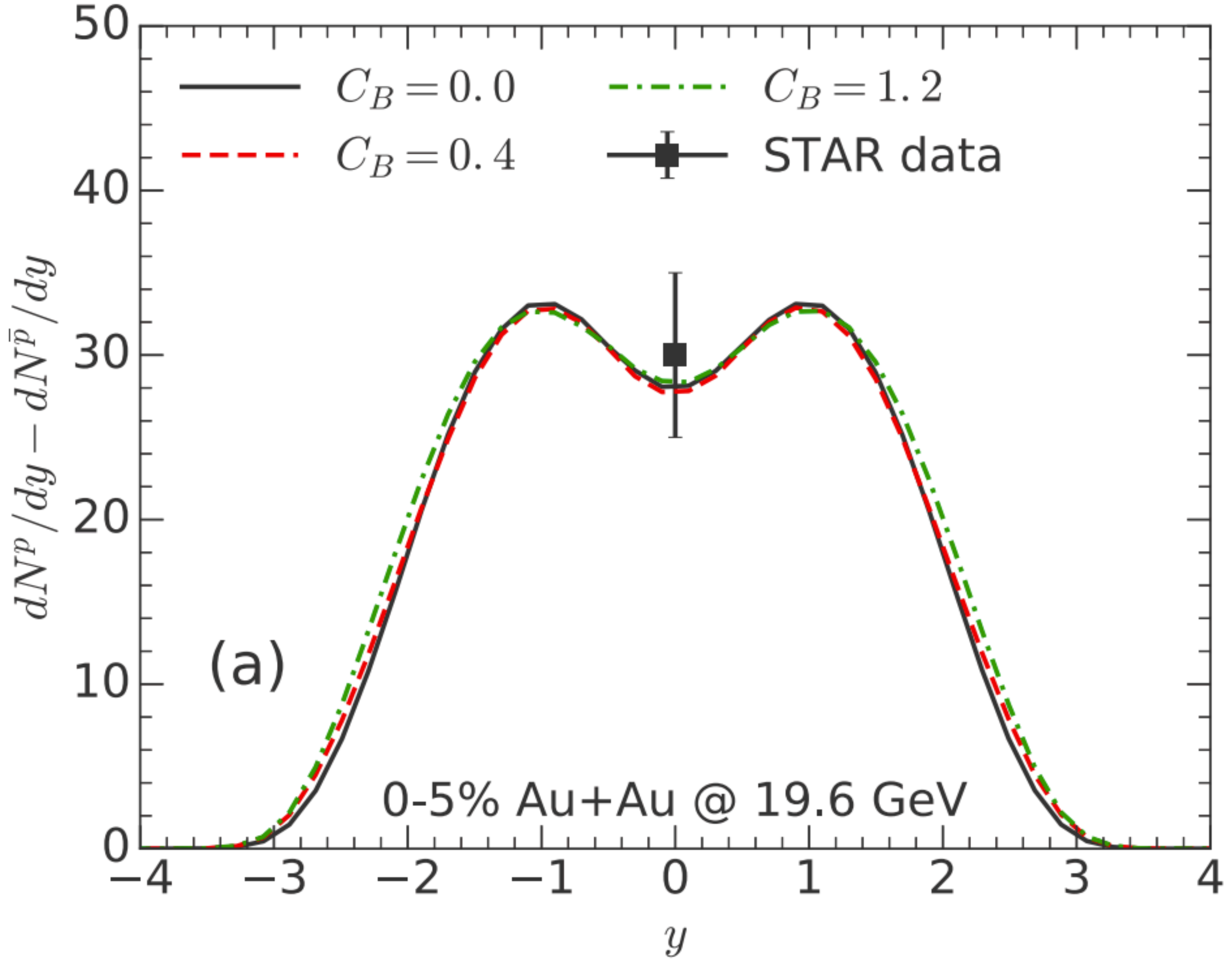
- Boost invariance is strongly broken, especially at forward-/backward rapidities;
- Particles produced at forward rapidities may be boosted from a smaller η_s.

LD, H. Gao, S. Jeon & C. Gale, arXiv:2302.13852

INITIAL BARYON STOPPING & BARYON TRANSPORT



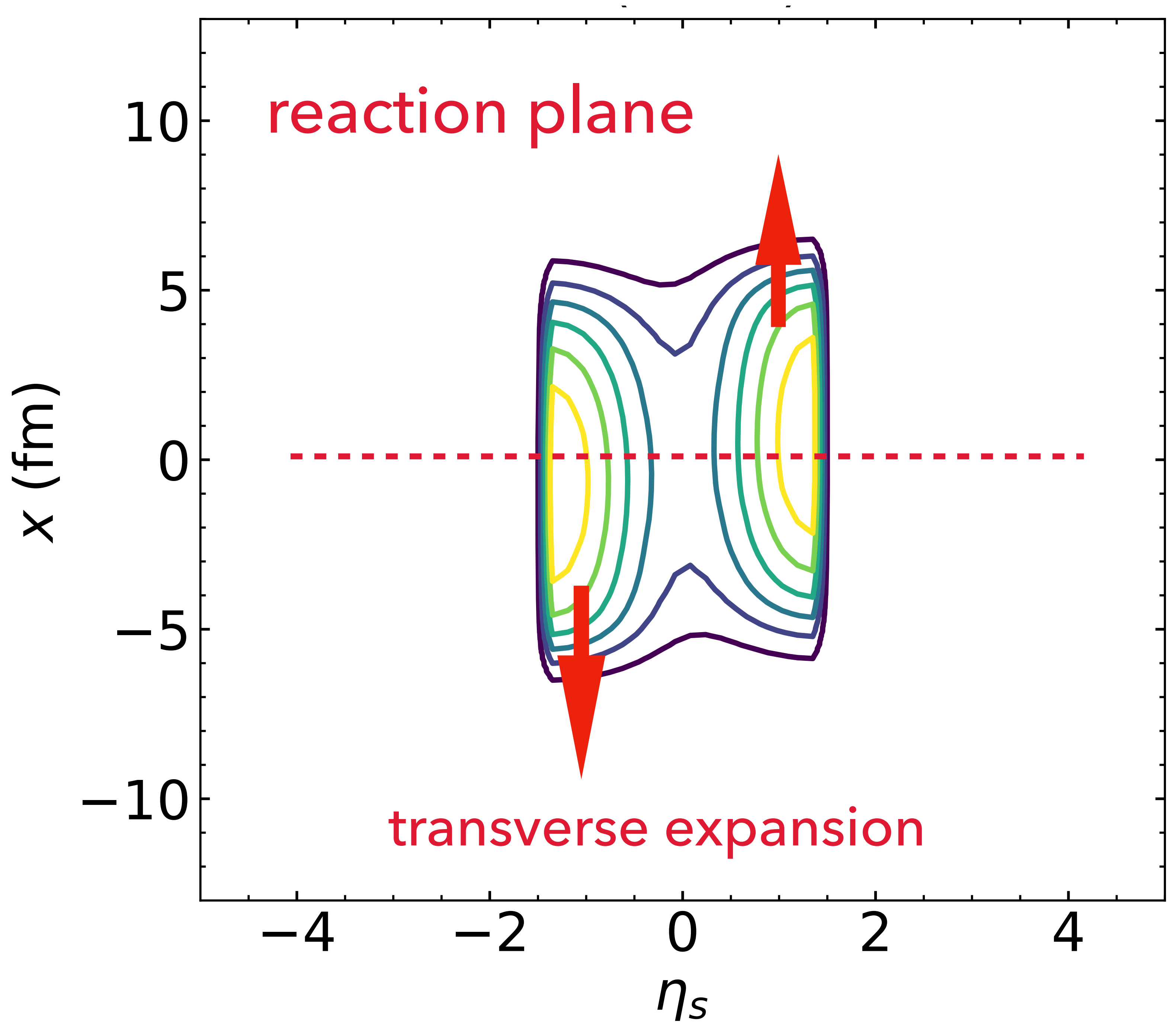
initial baryon distribution



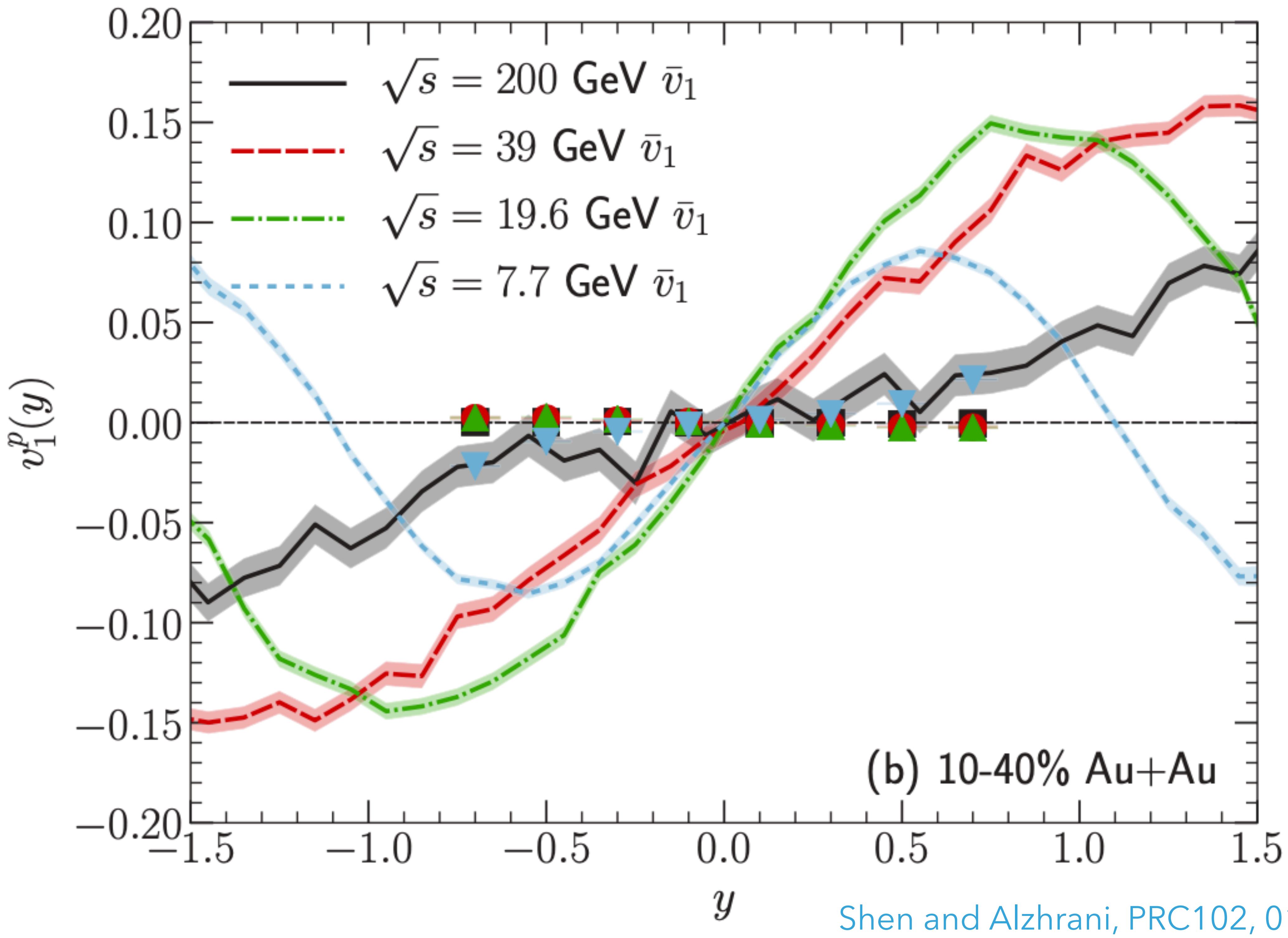
- From the nucleon deceleration picture, the baryon density gets two peaks, naturally giving the double-humped net proton yields;
- Both initial baryon stopping and diffusive transport can influence rapidity-dependent yields; probing initial baryon distribution is essential for constraining baryon diffusion.

Denicol et al, PRC 98, 034916 (2018)

DIRECTED FLOW $v_1(y)$ OF PROTONS



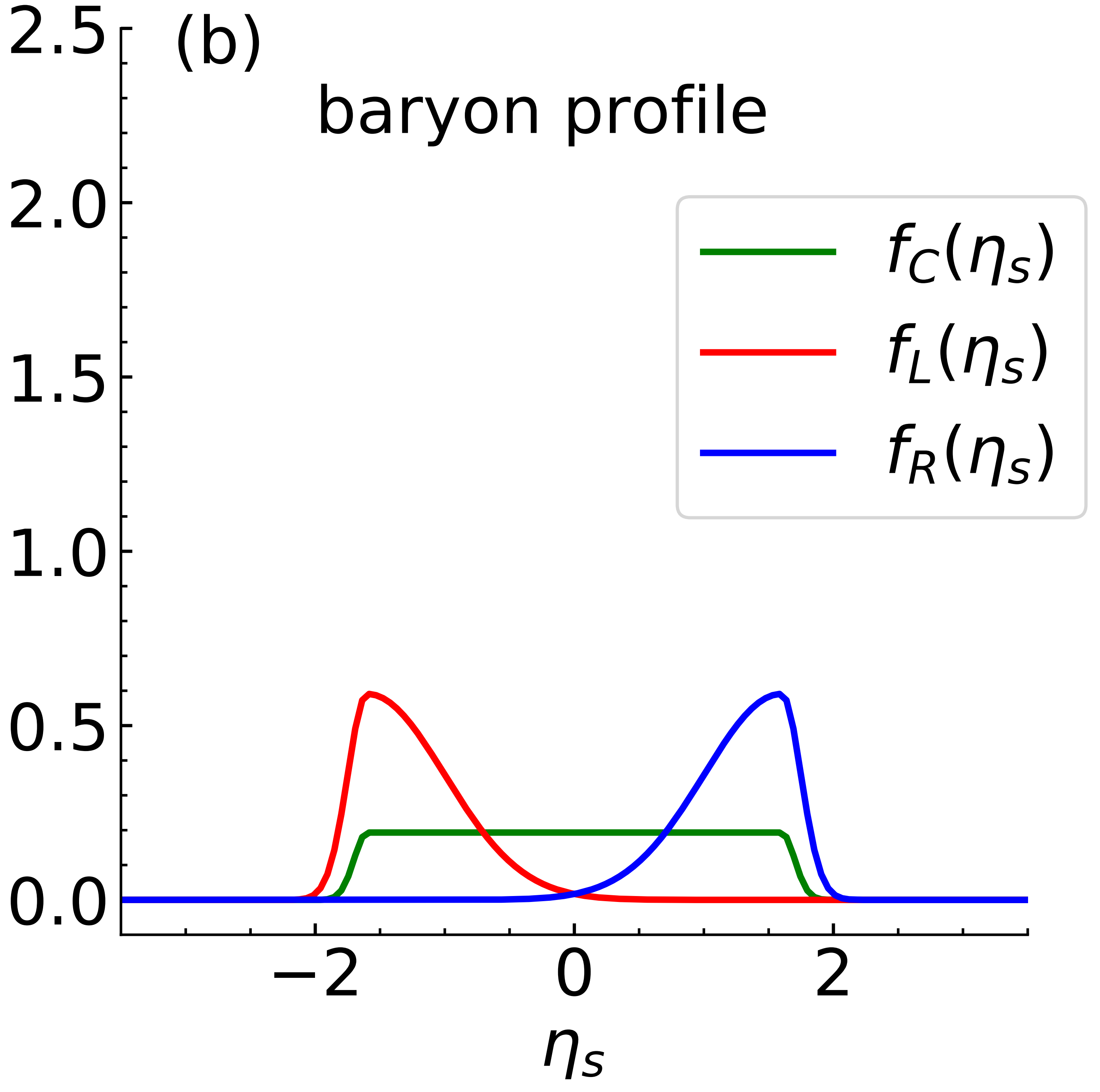
initial baryon distribution

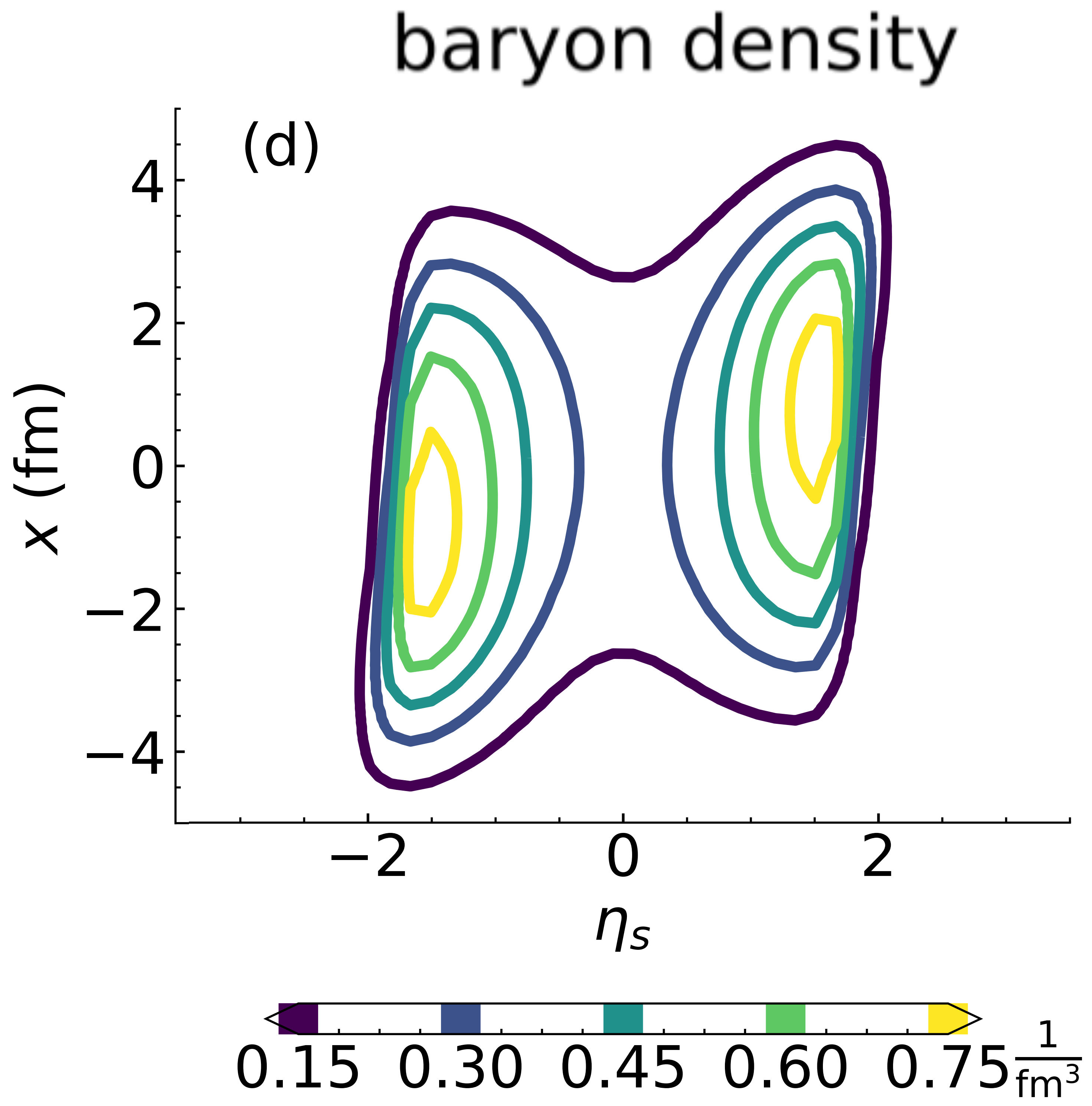


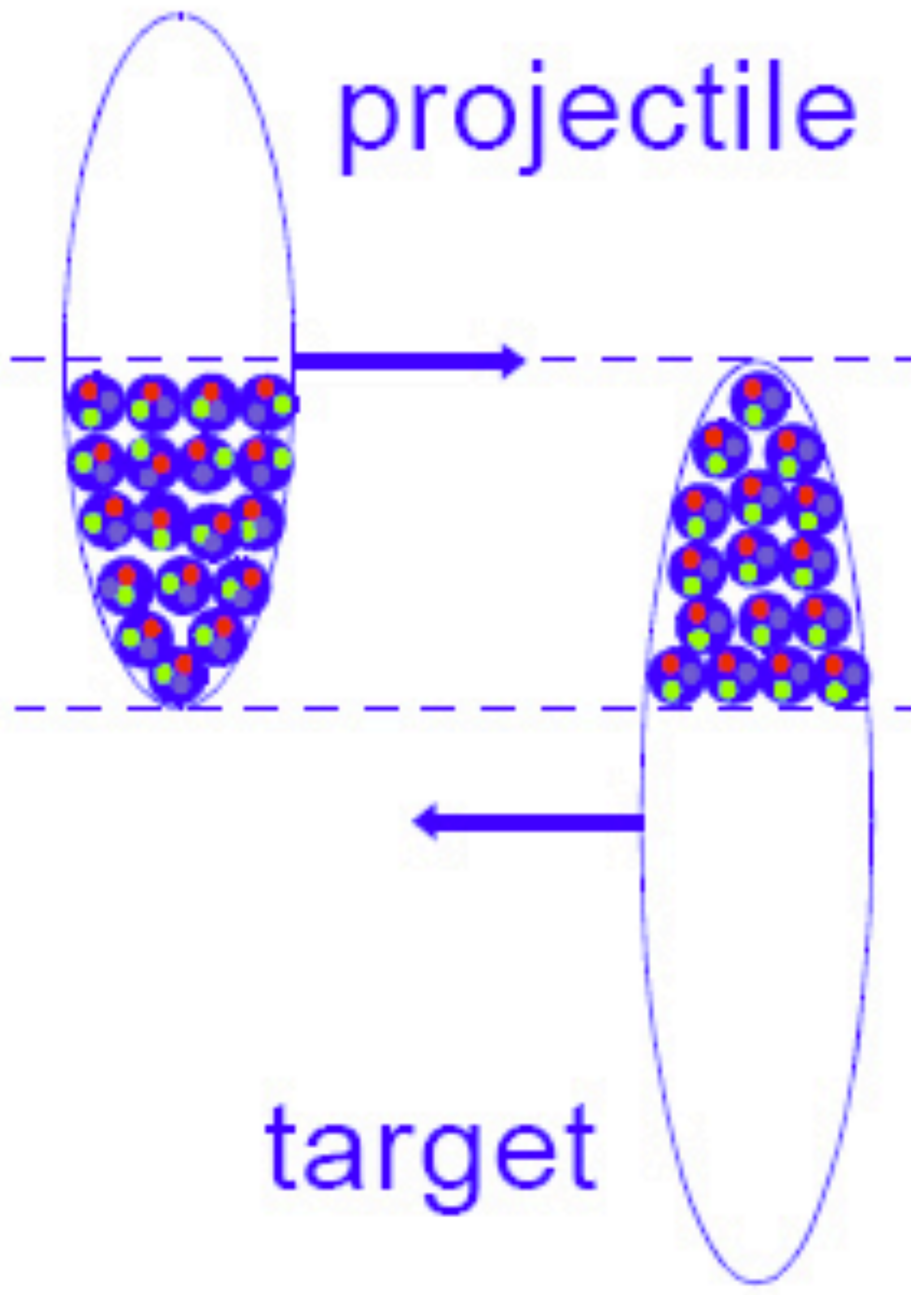
Shen and Alzhrani, PRC102, 014909 (2020)

- $v_1(y)$ of baryons is mainly driven by the asymmetric distribution of baryon density with respect to beam axis + transverse expansion;
- The widely used baryon-stopping picture results in $v_1(y)$ strongly overshooting the experimental measurements for protons at all beam energies.

NEW PARAMETRIC BARYON INITIAL CONDITION



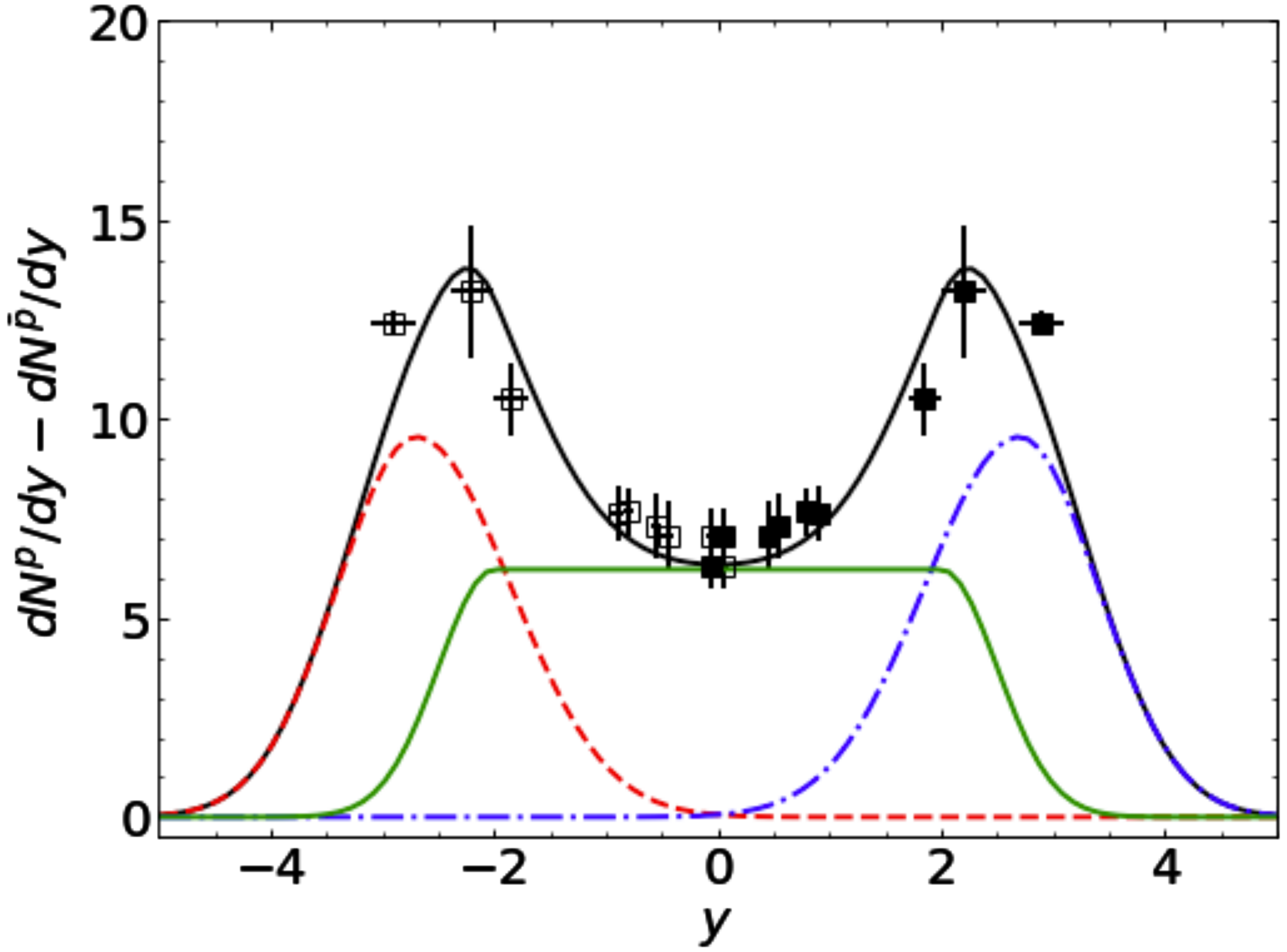


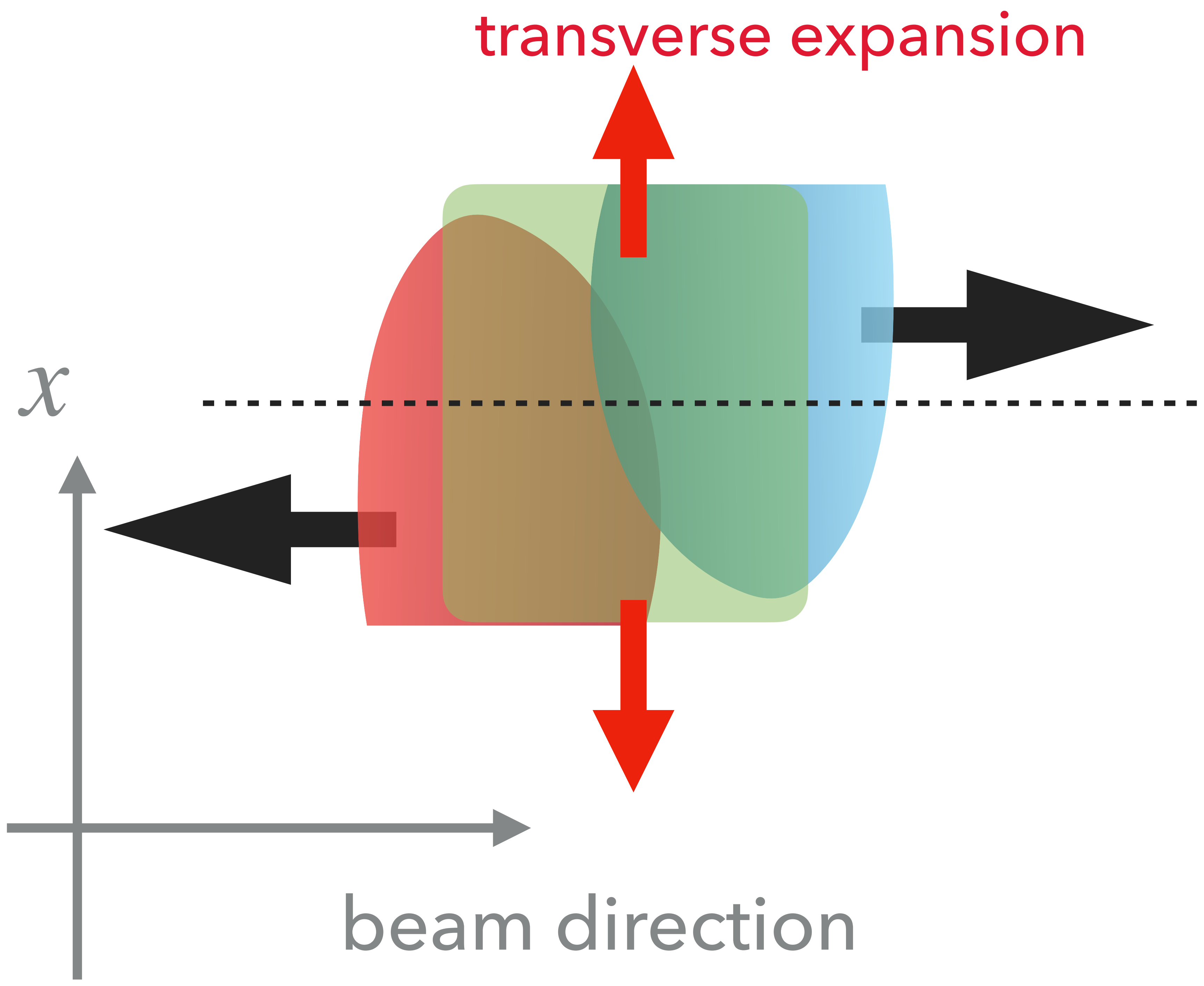


- A rapidity-independent "plateau" component in initial baryon profile & tilted baryon peaks describing the varying baryon stopping in the transverse plane

LD, C. Shen, S. Jeon & C. Gale, arXiv:2211.16408

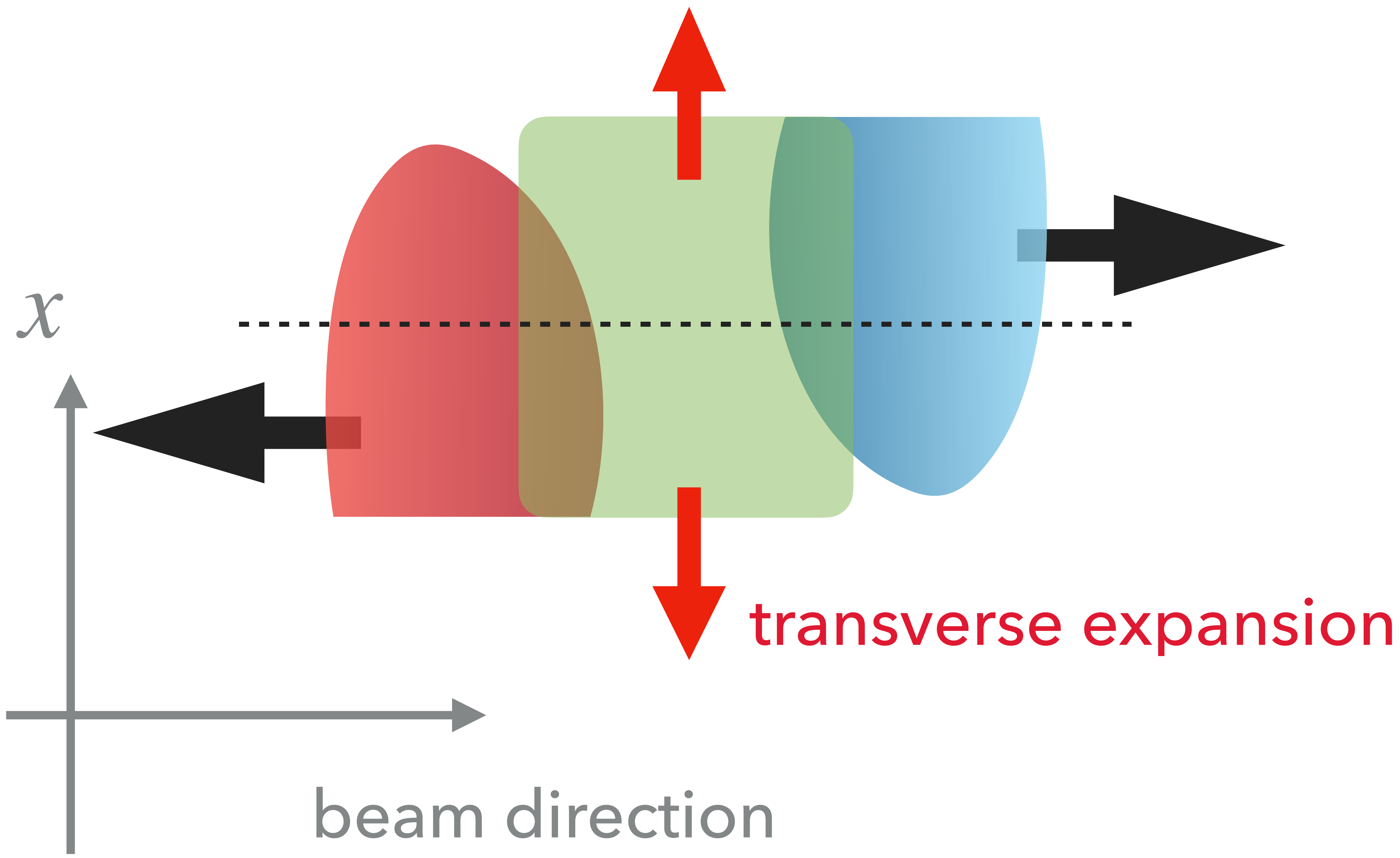
$dN^{p-\bar{p}}/dy$ AND $v_1(y)$ OF PROTONS

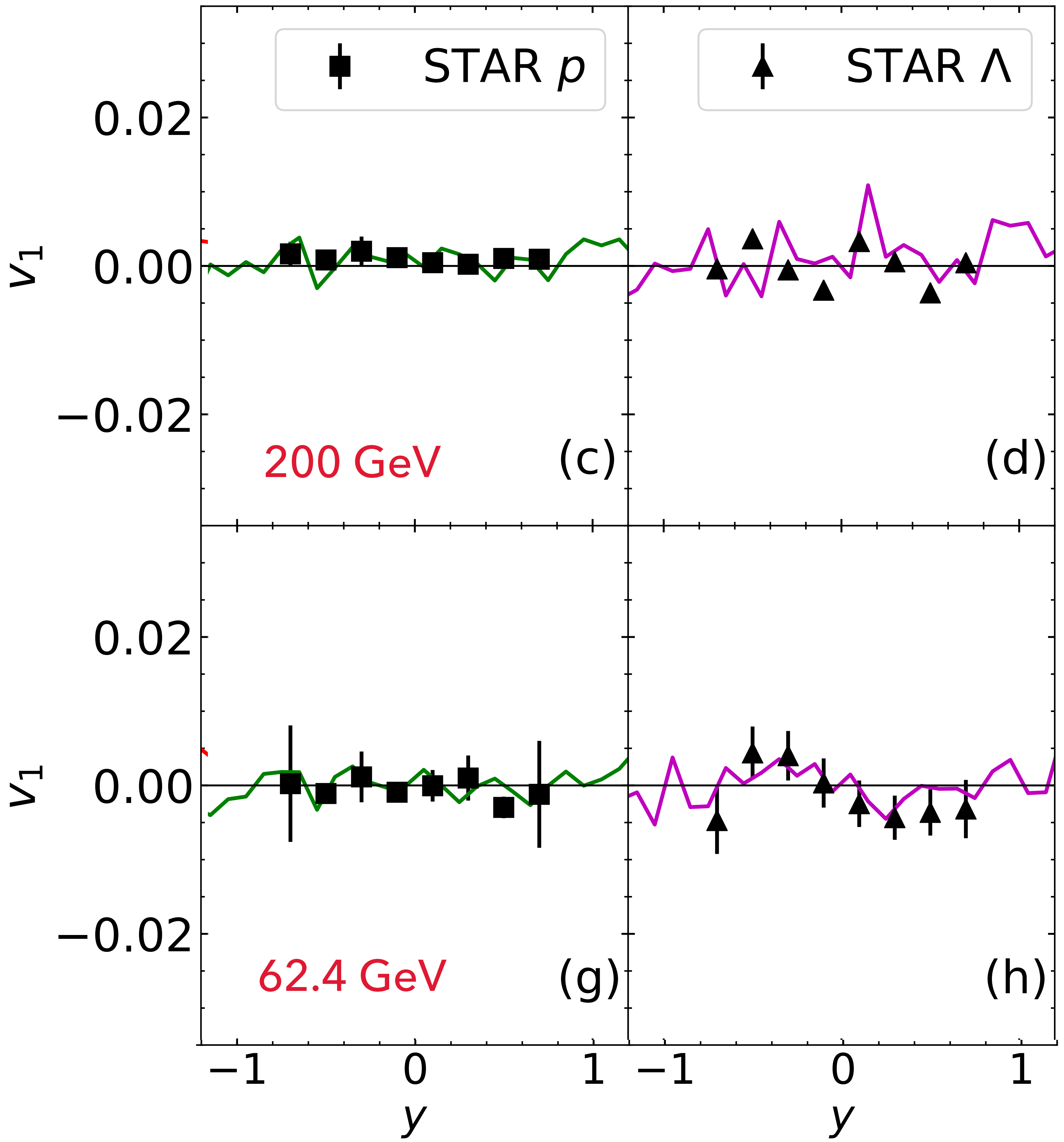




- To explain the rapidity distributions of net proton yield and proton's directed flow simultaneously, the plateau is favored;
- It helps to reduce baryons' $v_1(y)$ while giving enough net proton yields around midrapidity.

DIRECTED FLOW OF BARYONS AT 200 AND 62.4 GEV

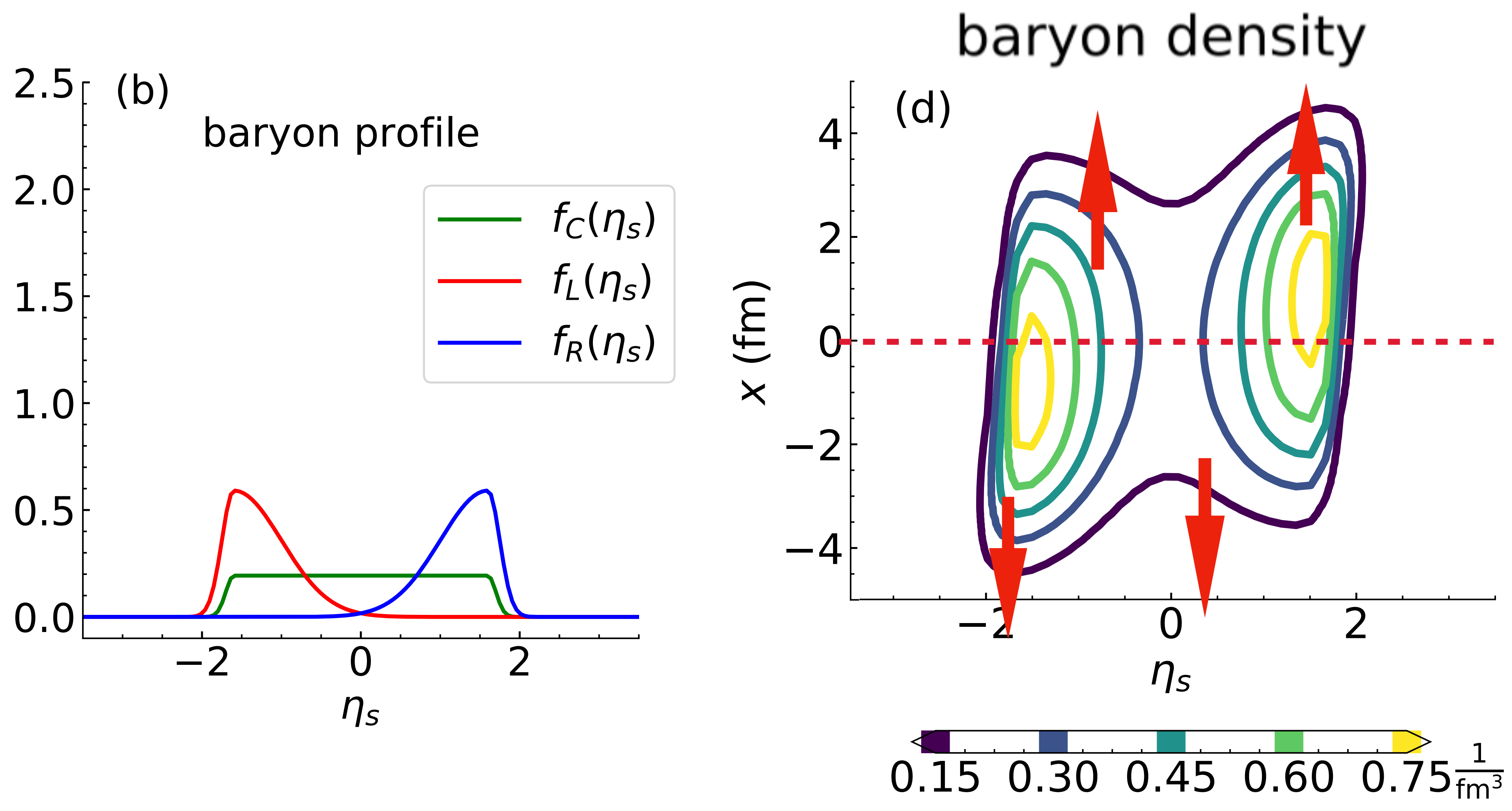




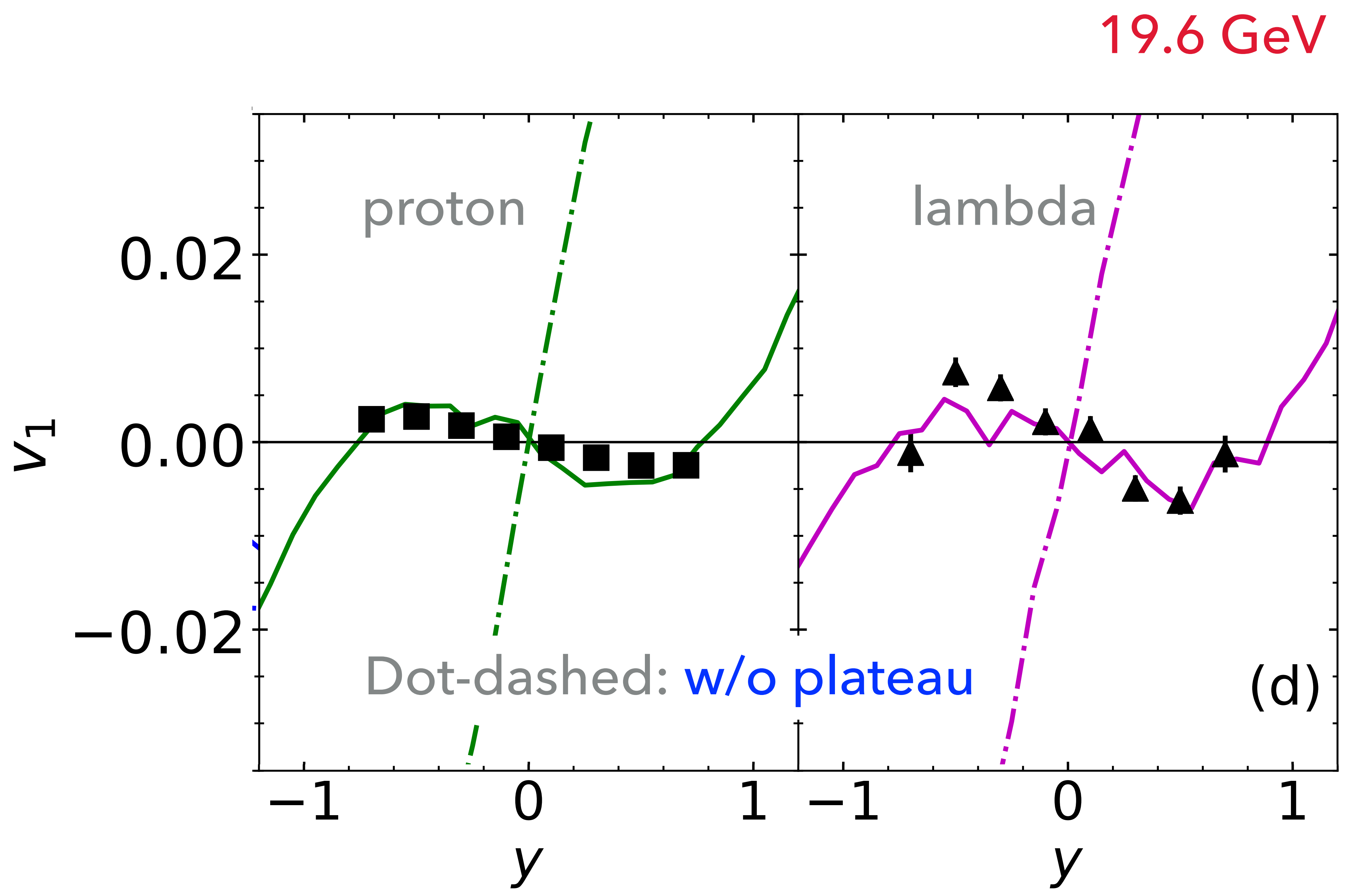
- At high beam energies with large beam rapidity, the plateau dominates and strongly reduces baryons' $v_1(y)$

Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018) LD, C. Shen, S. Jeon & C. Gale, arXiv:2211.16408

DIRECTED FLOW OF BARYONS AT 19.6 GEV

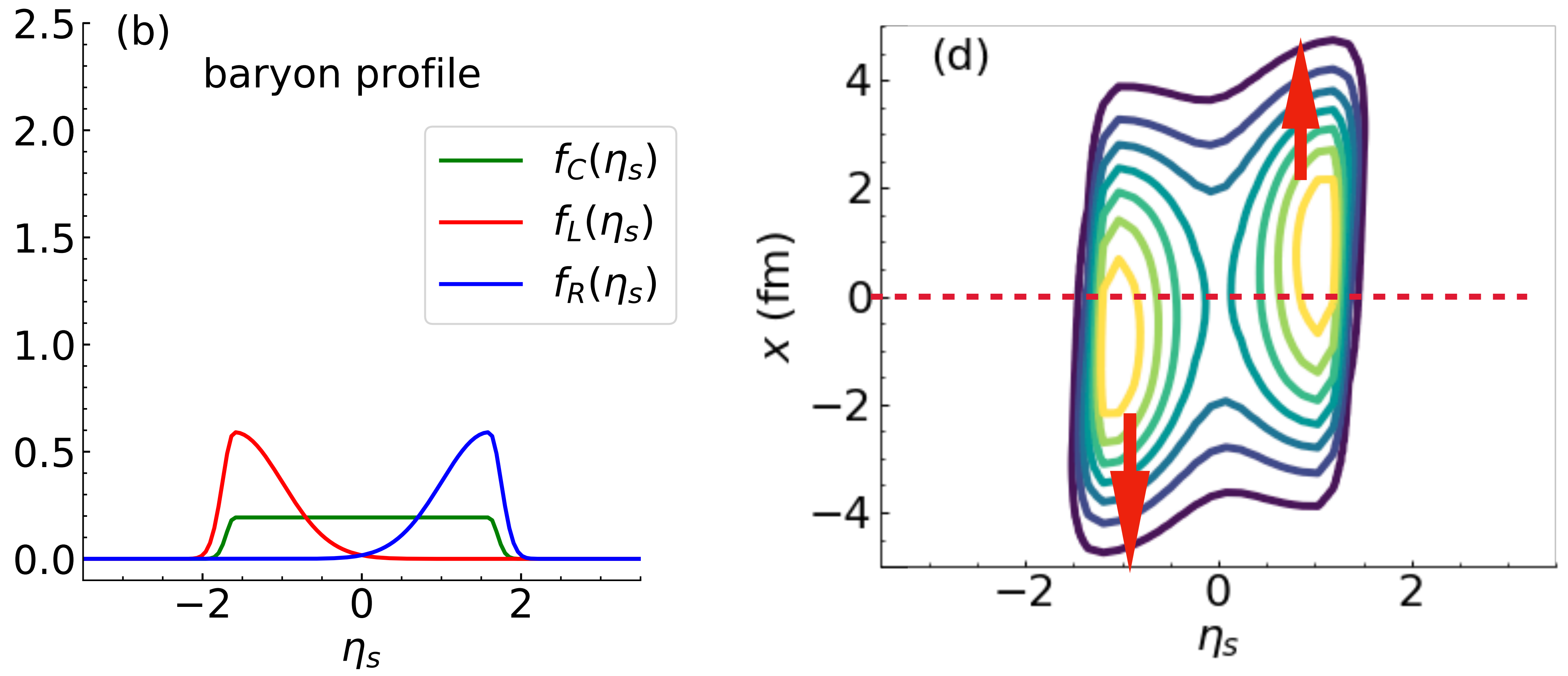


Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV



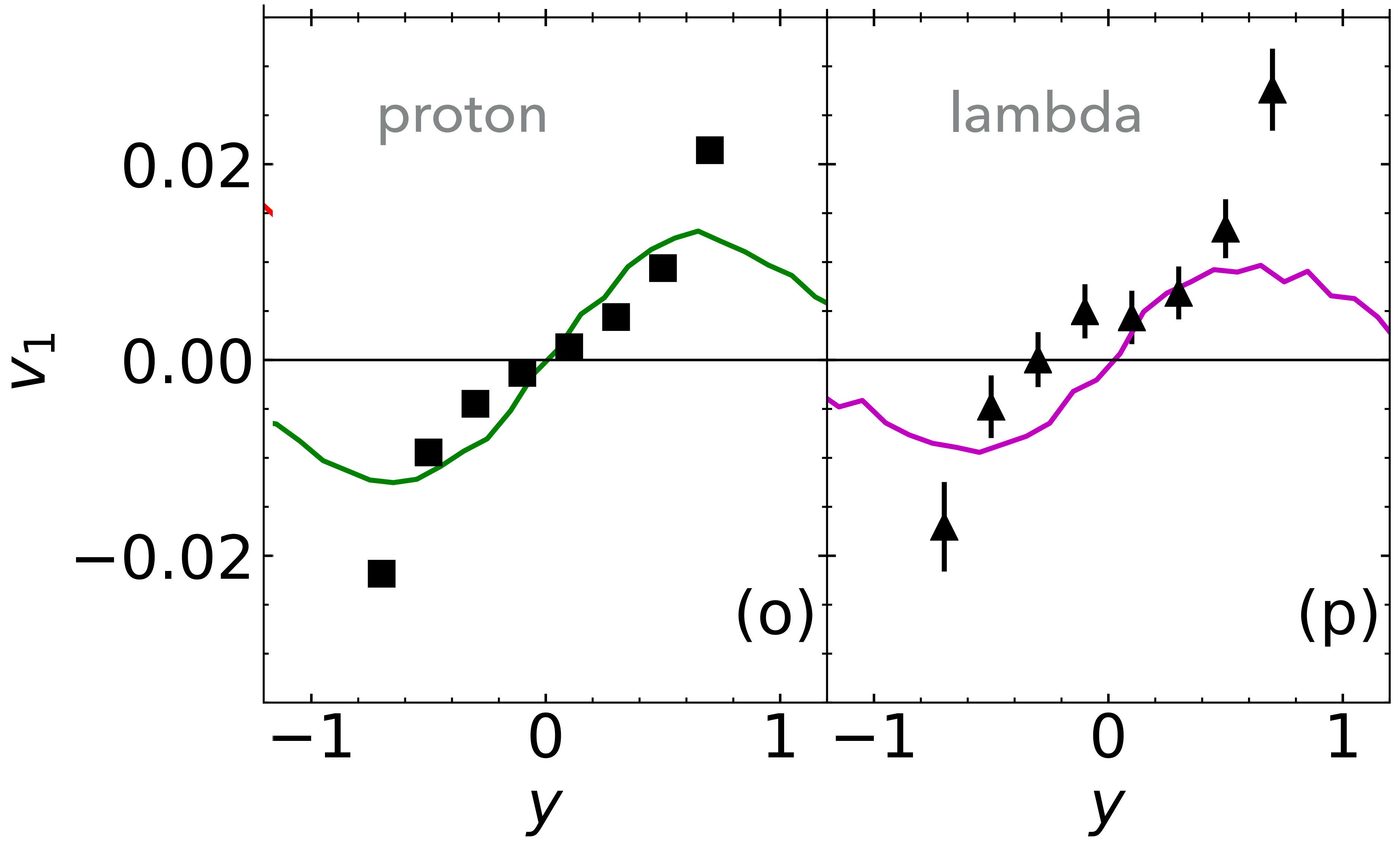
- Initial baryon distribution: central plateau + tilted peaks
- Transverse expansion + asymmetric distribution of baryon density along x ⟹ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV

DIRECTED FLOW OF BARYONS AT 7.7 GEV



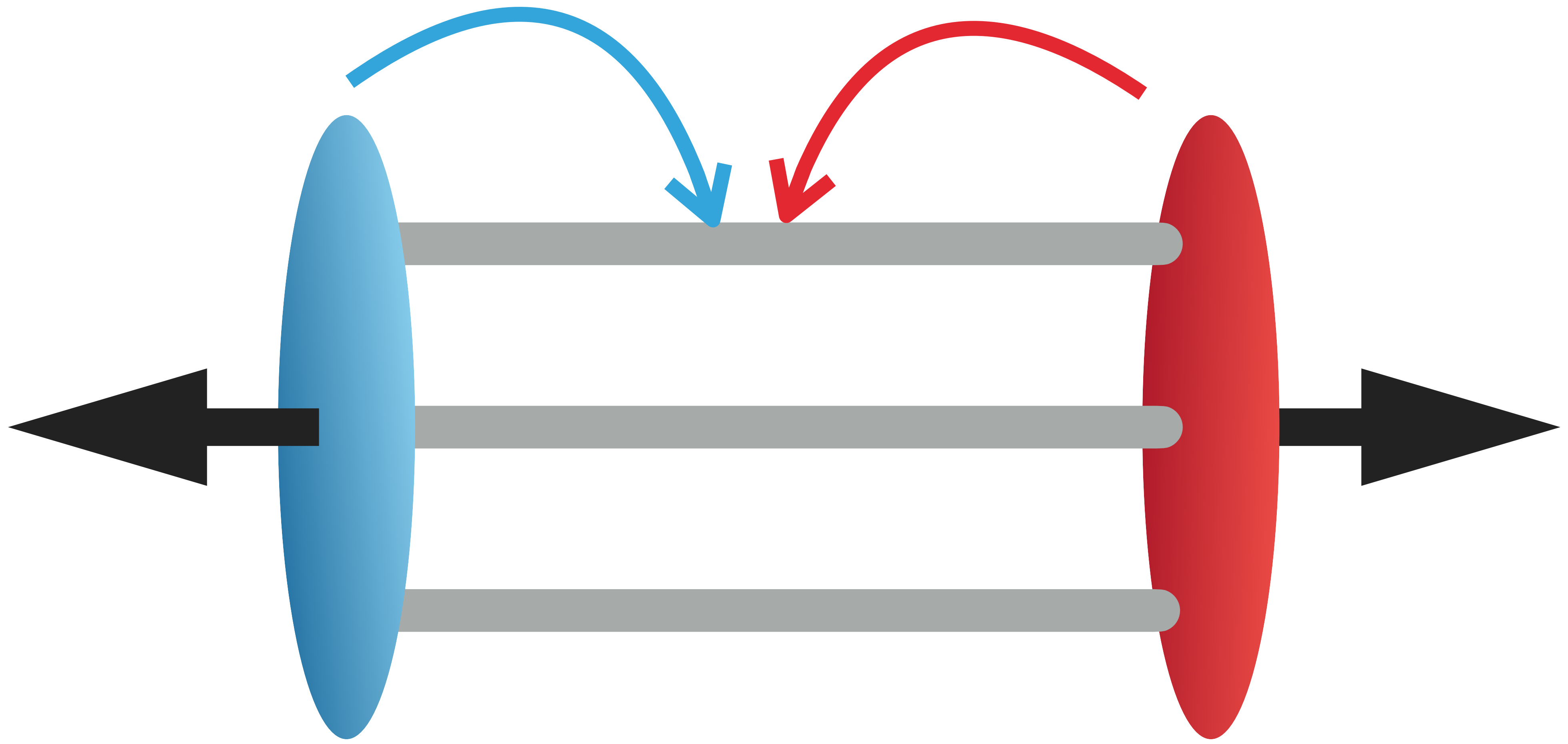
Initial distributions in reaction plane for 10-40%
Au+Au@19.6 GeV

7.7 GeV

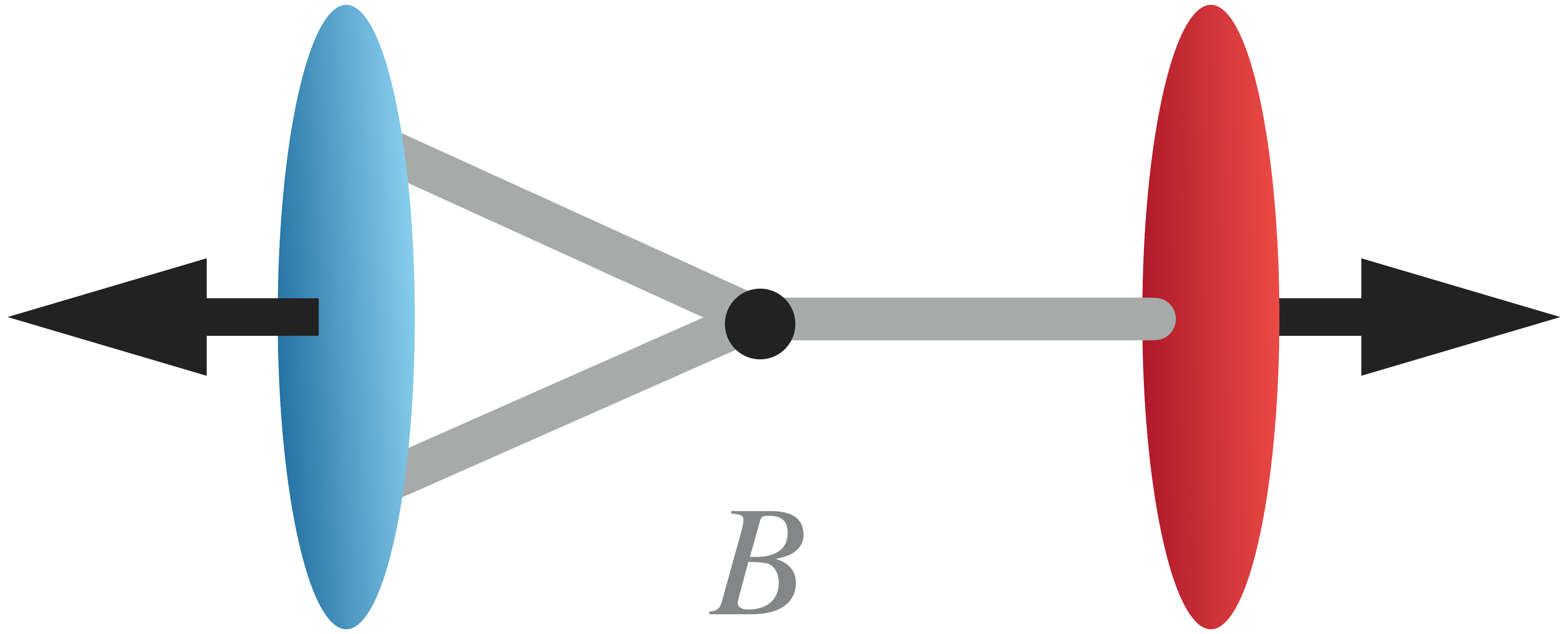


- Initial baryon distribution: central plateau + tilted peaks
- Transverse expansion + asymmetric distribution of baryon density along x $\Longrightarrow$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV

INITIAL BARYON "STOPPING"



Baryons get distributed in rapidity by deceleration of the incoming nucleons



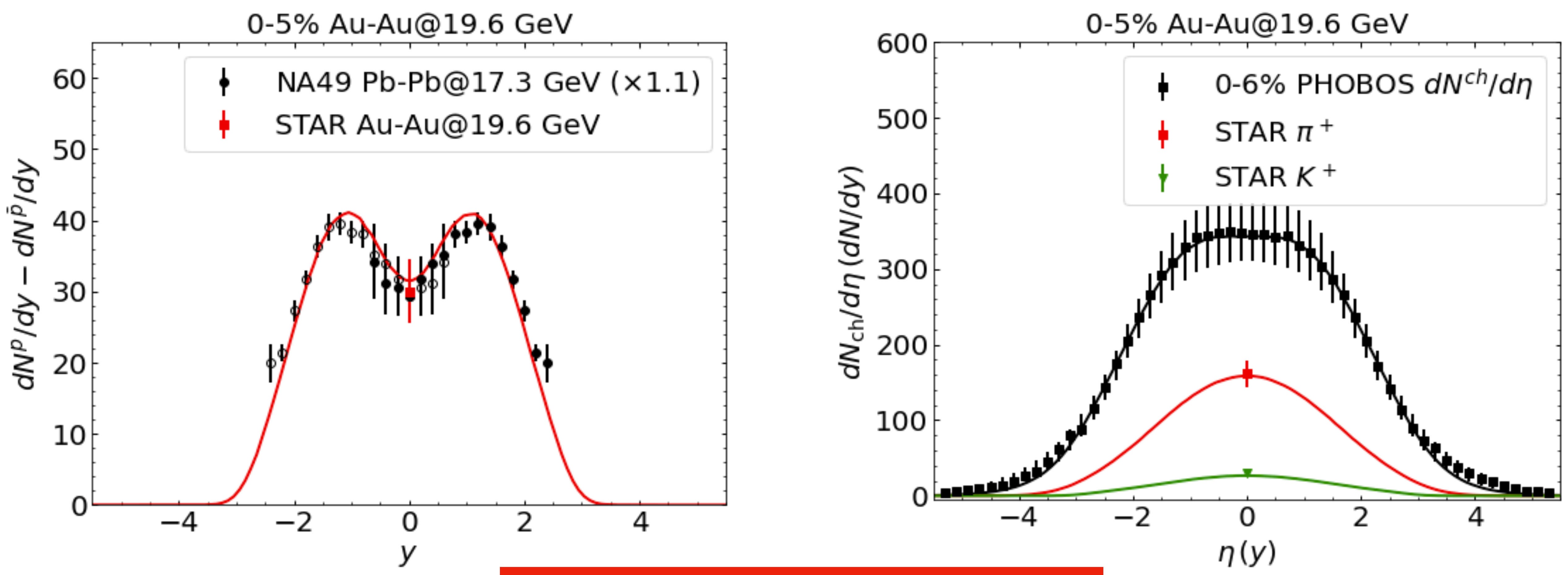
Baryons get distributed in rapidity through string junction breaking

- Profound impact on understanding initial baryon distribution and energy loss
- How to differentiate "baryon deceleration" and "string junction breaking" in the initial baryon distribution?

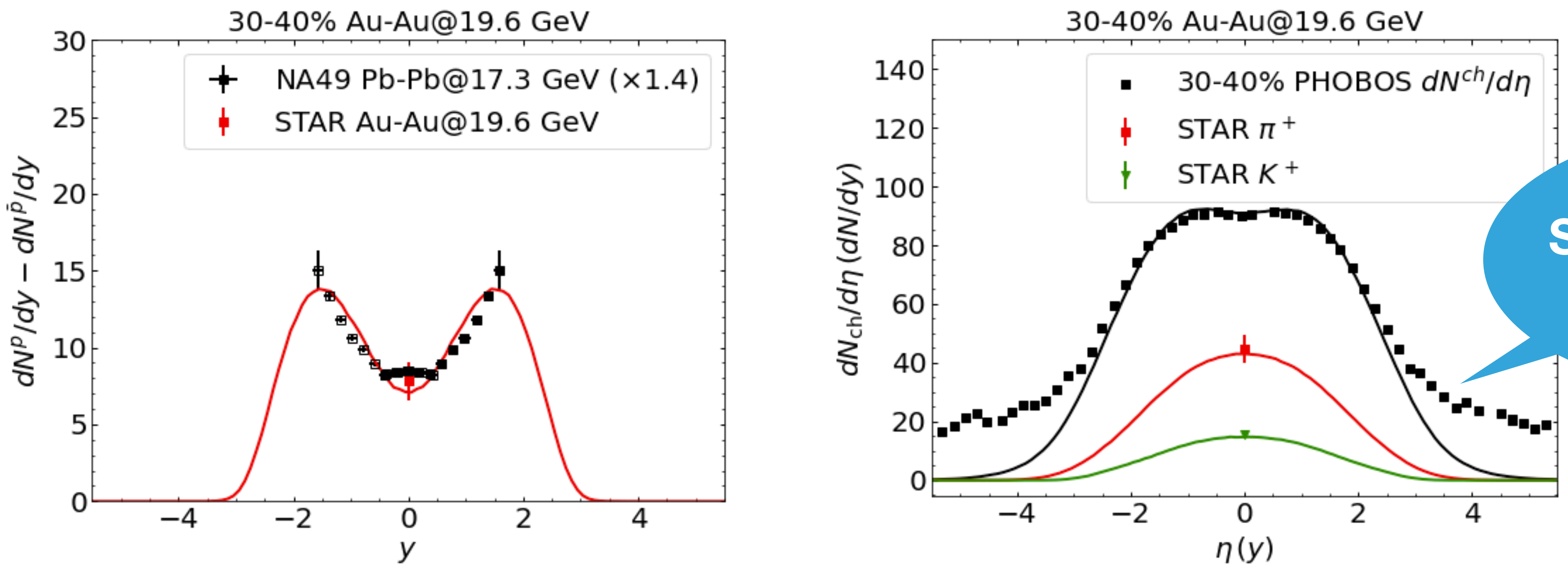
String junction: Kharzeev, PLB 378, 238 (1996); Lund string model

J. D. Brandenburg, N. Lewis, P. Tribedy, and Z. Xu, arXiv:2205.05685

TOTAL BARYON CHARGE AND TOTAL ENERGY



0-5% Au-Au @ 19.6 GeV

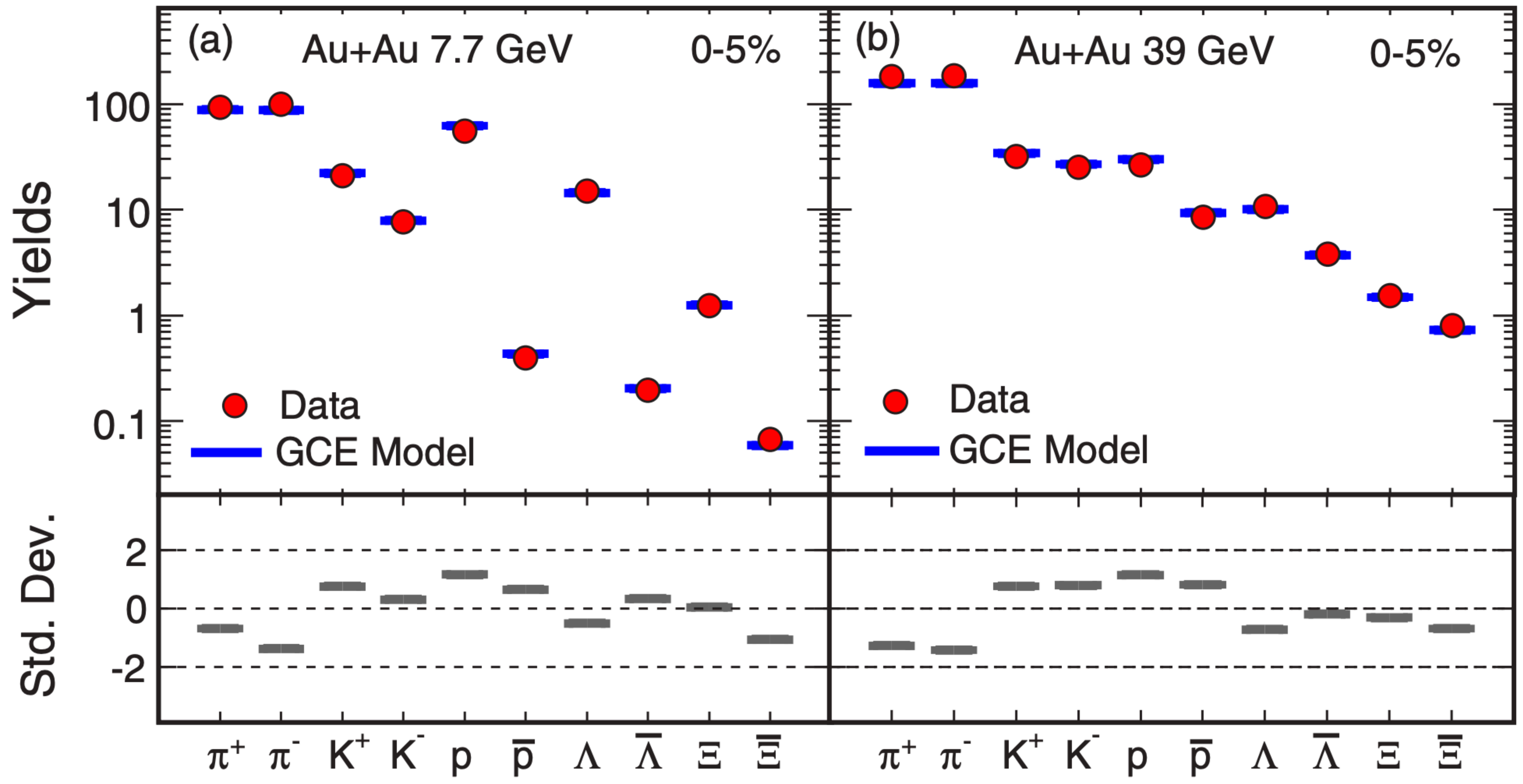


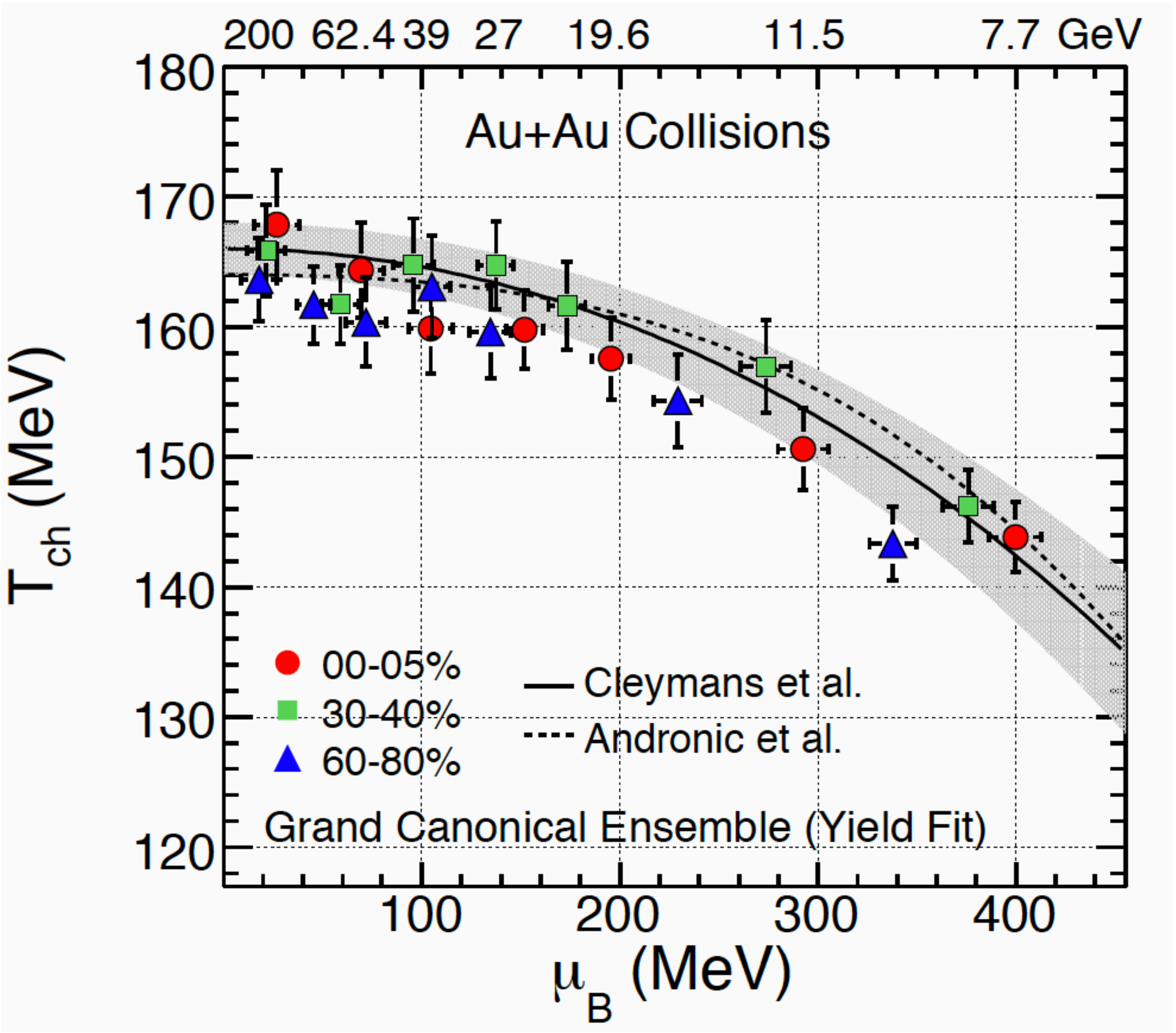
30-40% Au-Au @ 19.6 GeV

SPECTATORS? FIREBALL?

- Number of participants vs. total net baryon charge (obtained by fitting the net proton yields)
- The energy carried by incoming participant nucleons vs. total energy deposited in the fireball (obtained by fitting the charged particle multiplicity)
- Differentiate deflected spectators and hadrons emitted from the fireball; EPD can help!

EXTRACTION OF FREEZE-OUT PARAMETERS

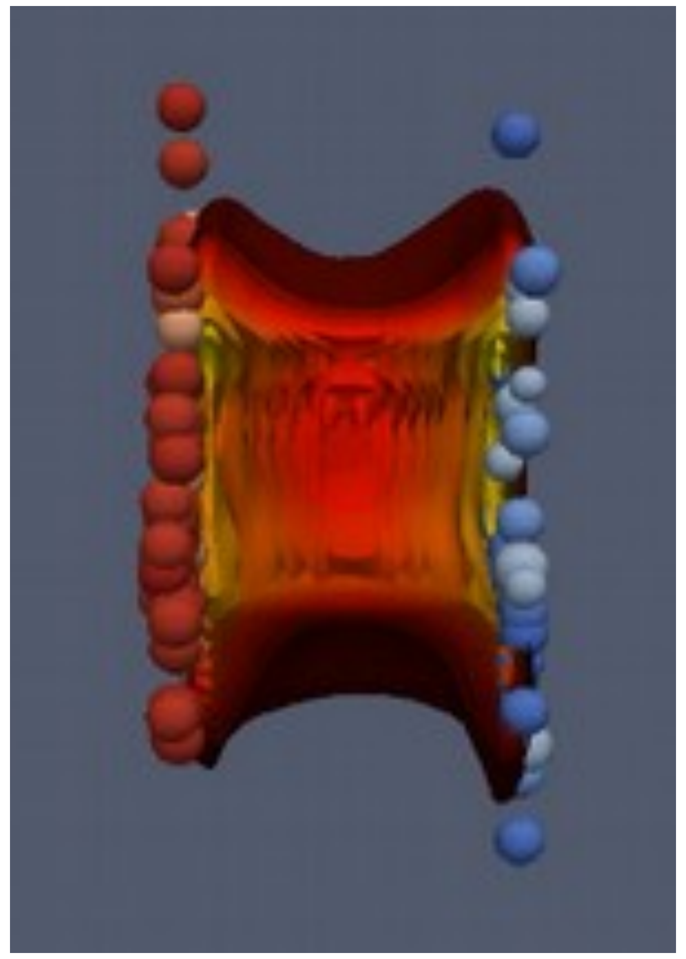


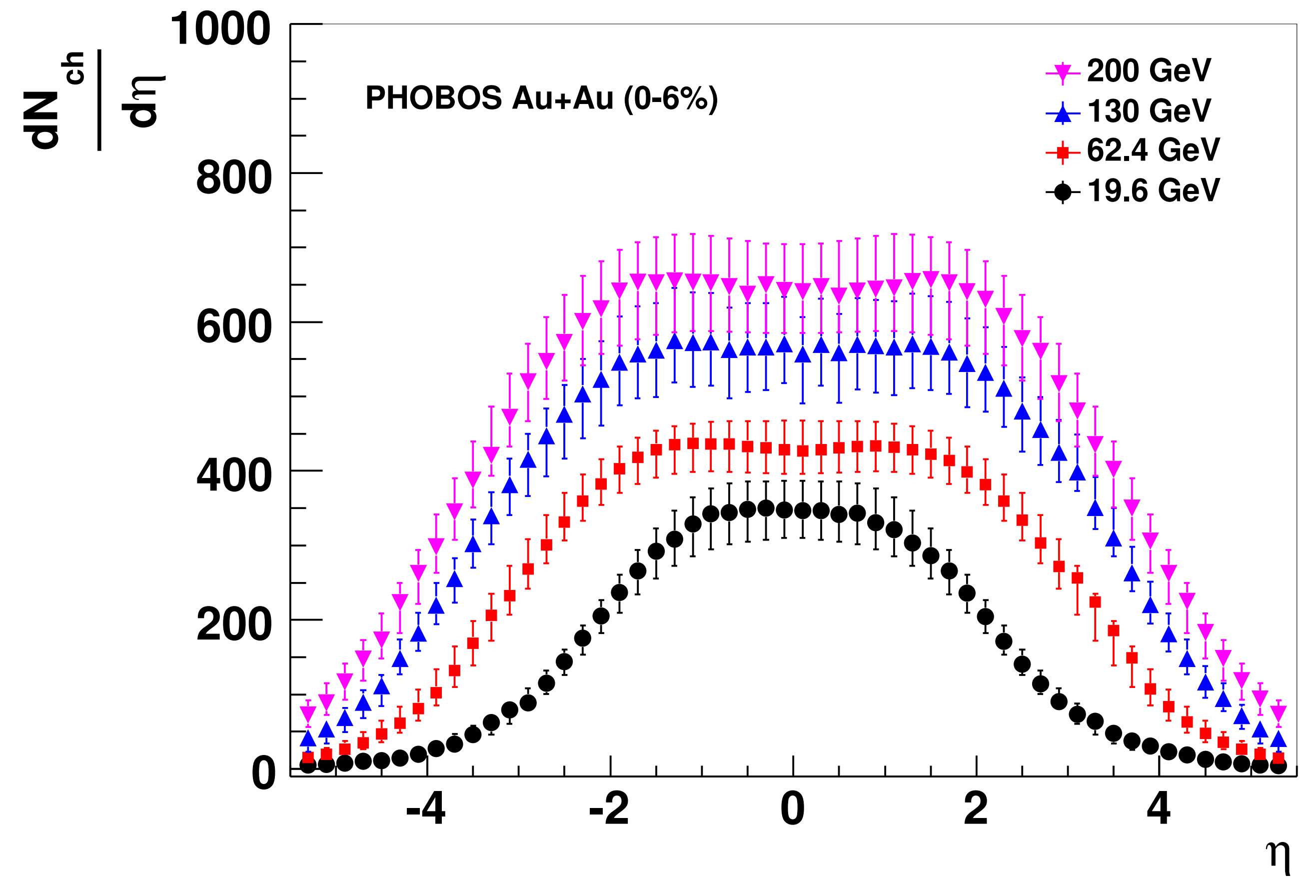


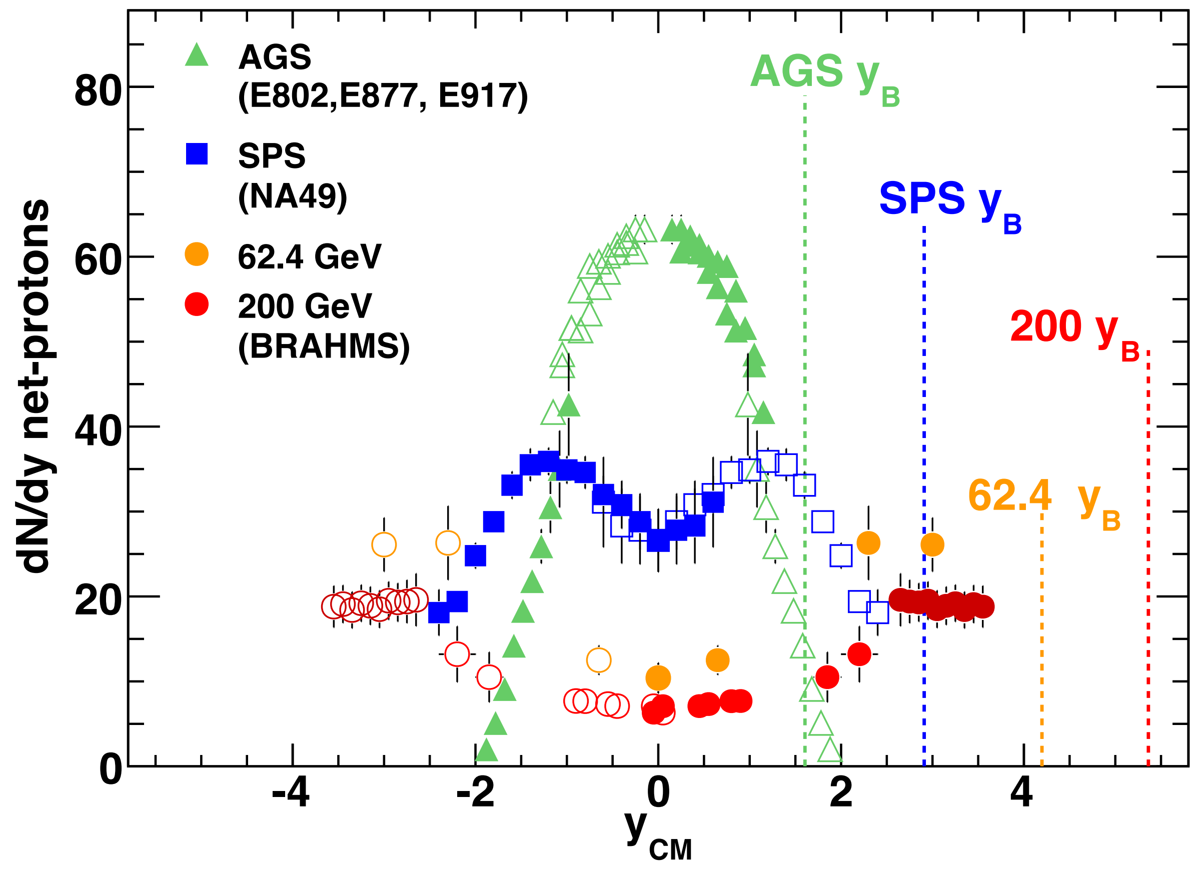
STAR, PRC 96, 044904 (2017)

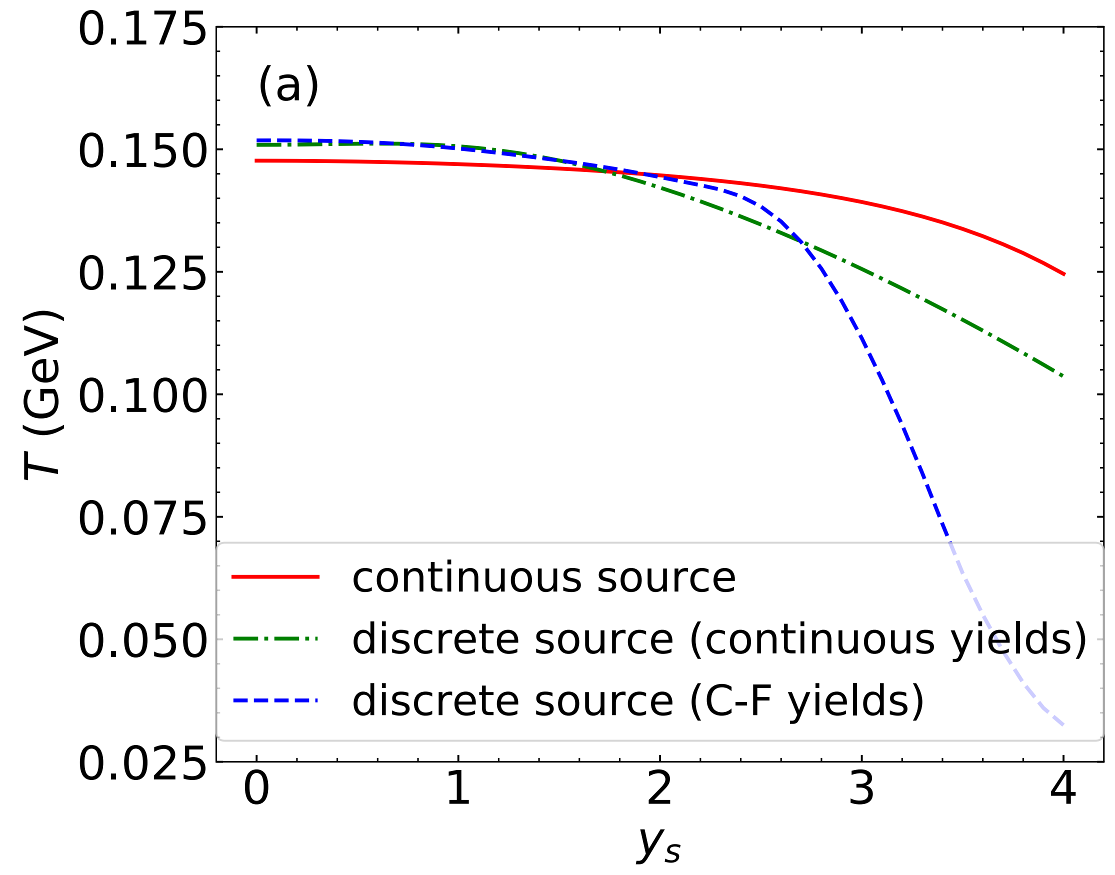
- Statistical thermal models have been applied to hadron yields for extracting freeze-out parameters around midrapidity [Andronic, Braun-Munzinger, Stachel and Winn, PLB 718 (2012) 80]

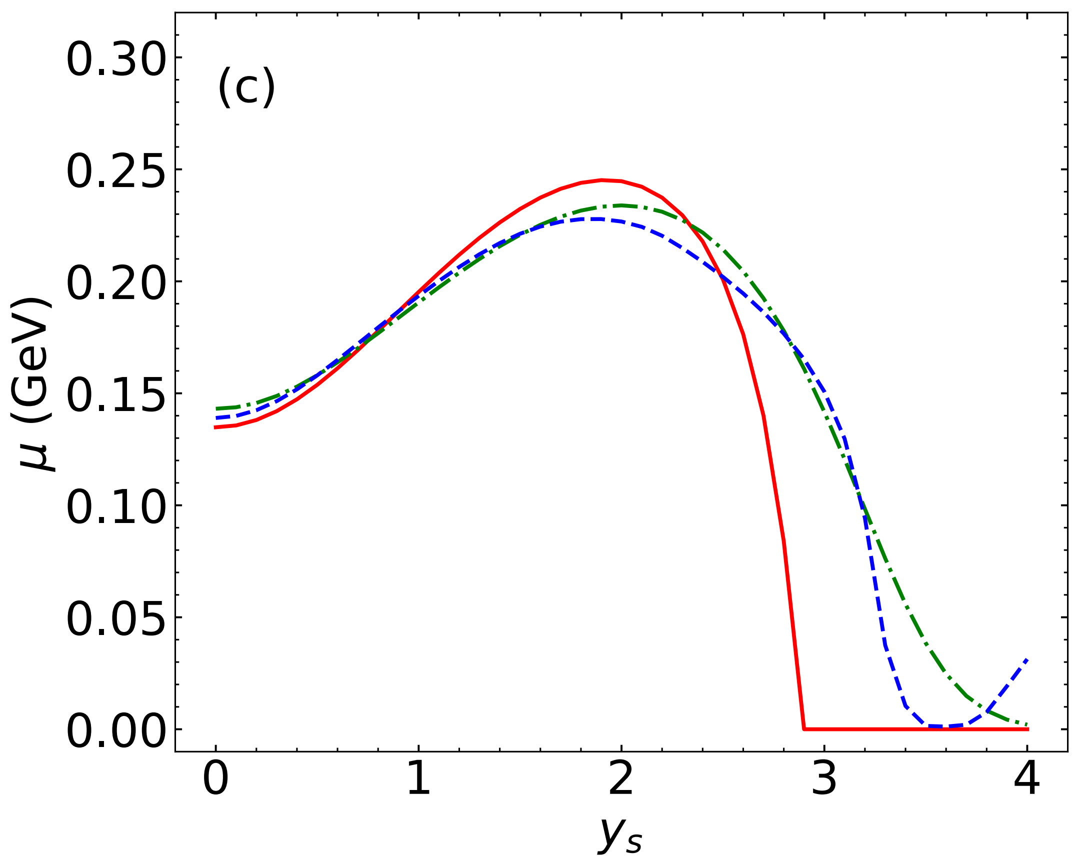
EXTRACTION OF FREEZE-OUT PARAMETERS











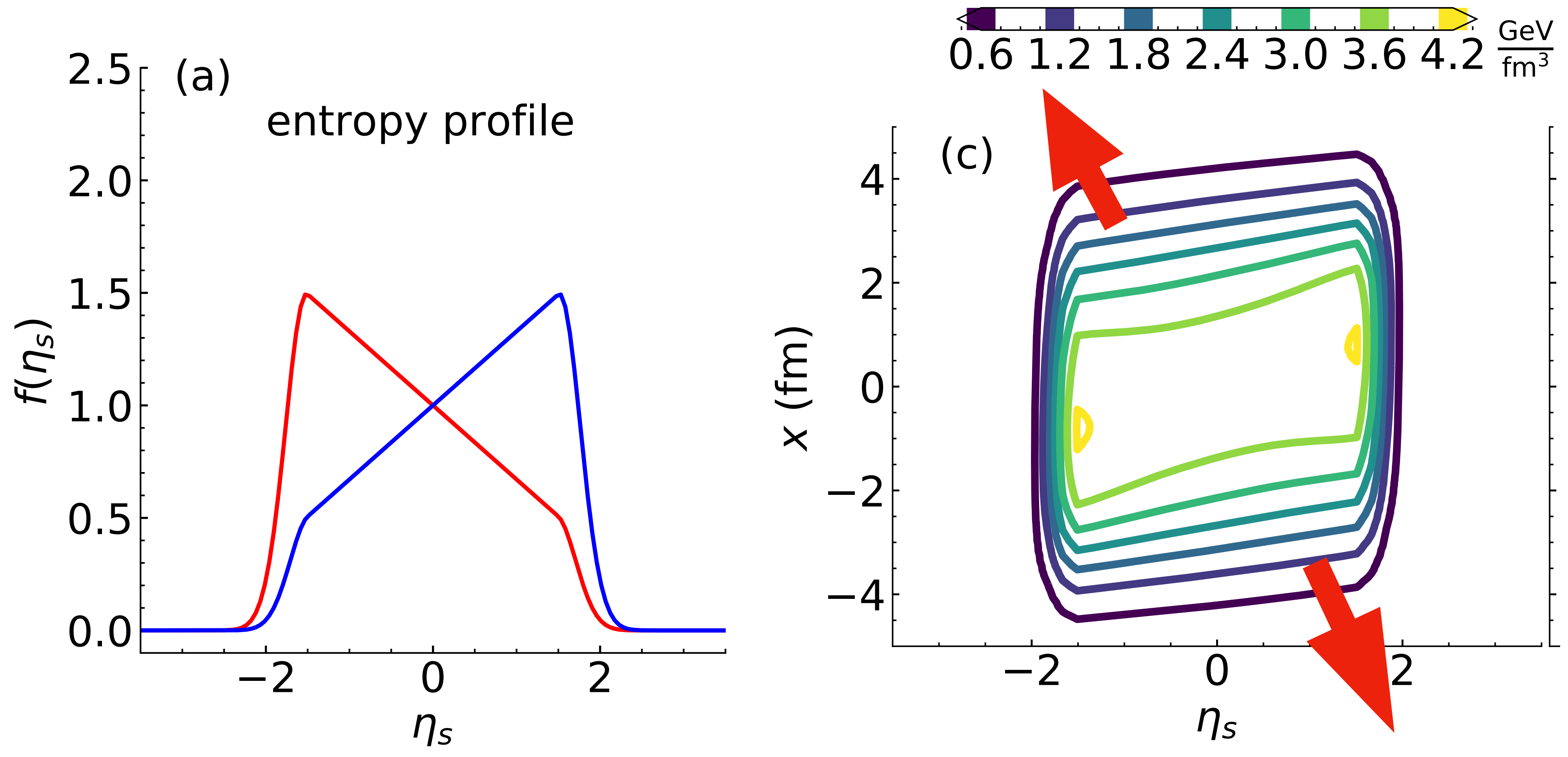
- Extracting rapidity-dependent freeze-out parameters of boost-non-invariant inhomogeneous systems at beam energy scan

LD, H. Gao, S. Jeon & C. Gale, arXiv:2302.13852

- Longitudinal pressure gradients drive flows faster than the Bjorken flow. Boost invariance is strongly broken at beam energy scan, especially at forward-/backward rapidities;
- A central plateau component in the initial baryon distribution is essential for simultaneously explaining characteristic features of $v_1(y)$ at various beam energies and net proton yields.
- Baryon distributions from incoming nucleon deceleration and string junction breaking correspond to different energy losses. Probing the total energy deposited in the fireball helps differentiate these two mechanisms.

THANK YOU!

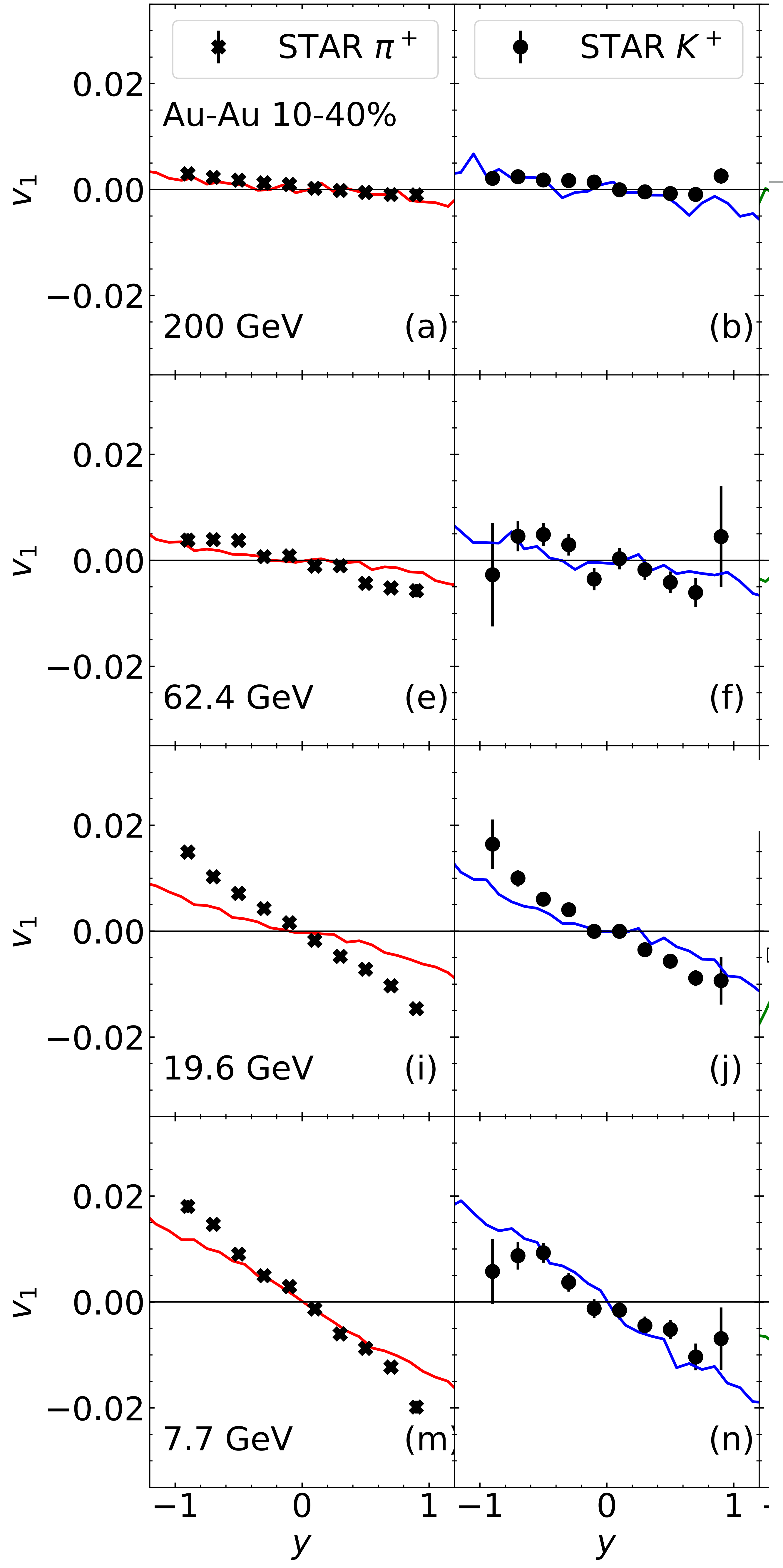
DIRECTED FLOW OF MESONS



Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV

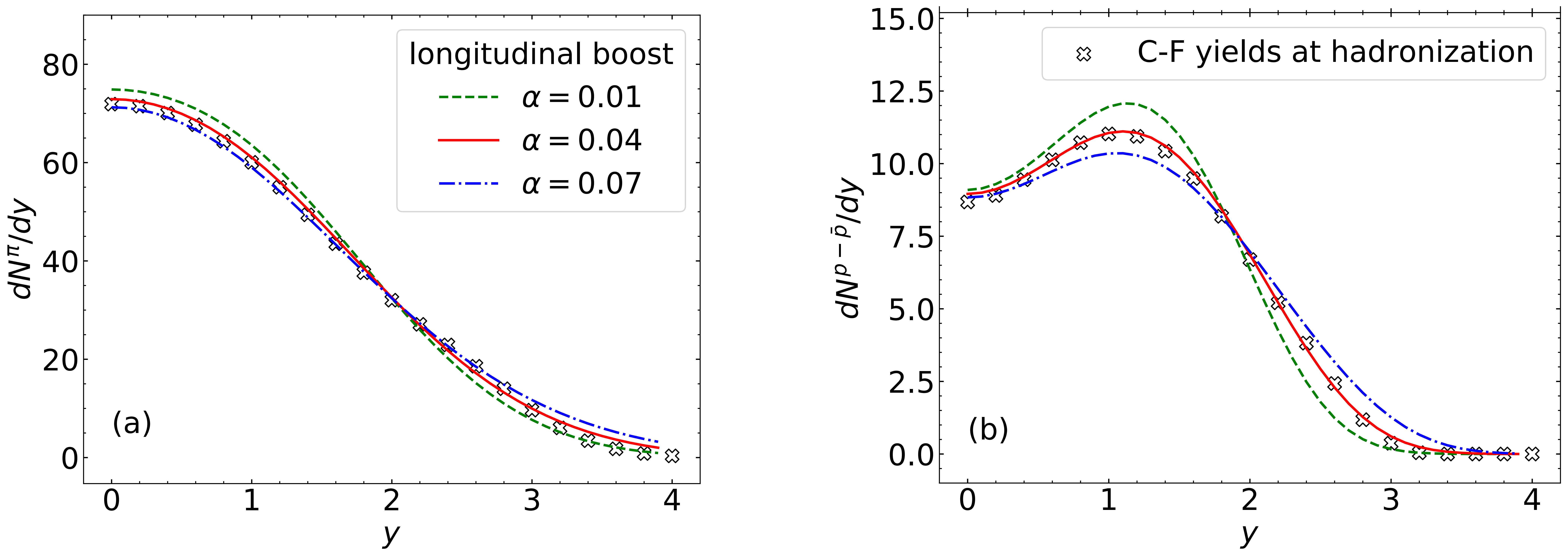
- $v_1(y)$ of mesons with negative slope at all beam energies; slope increases when beam energy decreases
- Slight shift of energy density along x (tilted structure) generates sideward pressure gradient

see also: Bożek & Wyskiel Phys. Rev. C 81, 054902 (2010)



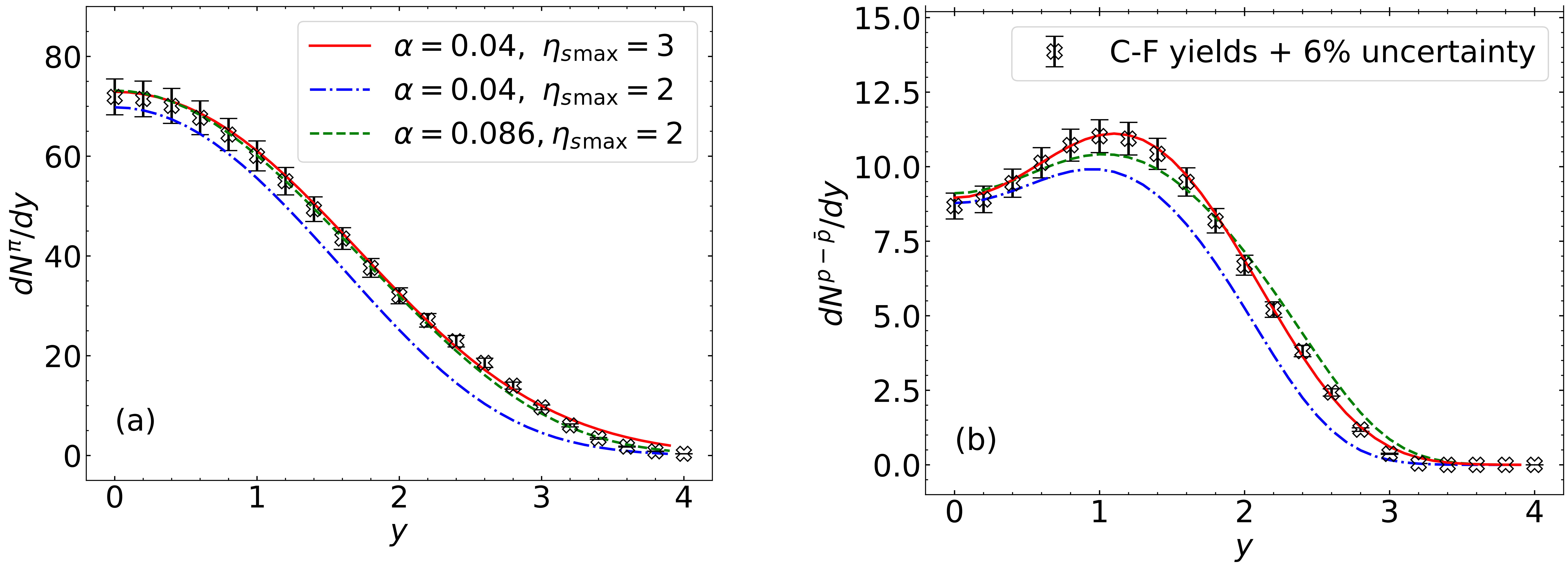
Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018)

LONGITUDINAL FLOW



- Starting from the same $T(\eta_s), \mu_B(\eta_s)$ profiles, the distributions get stretched in with a larger longitudinal flow y, which is more strongly for heavier species.

LONGITUDINAL SYSTEM SIZE



- A smaller system size in η_s can be compensated by a more considerable longitudinal boost and a larger volume.