LIPEI DU

MCGILL U. & LBNL

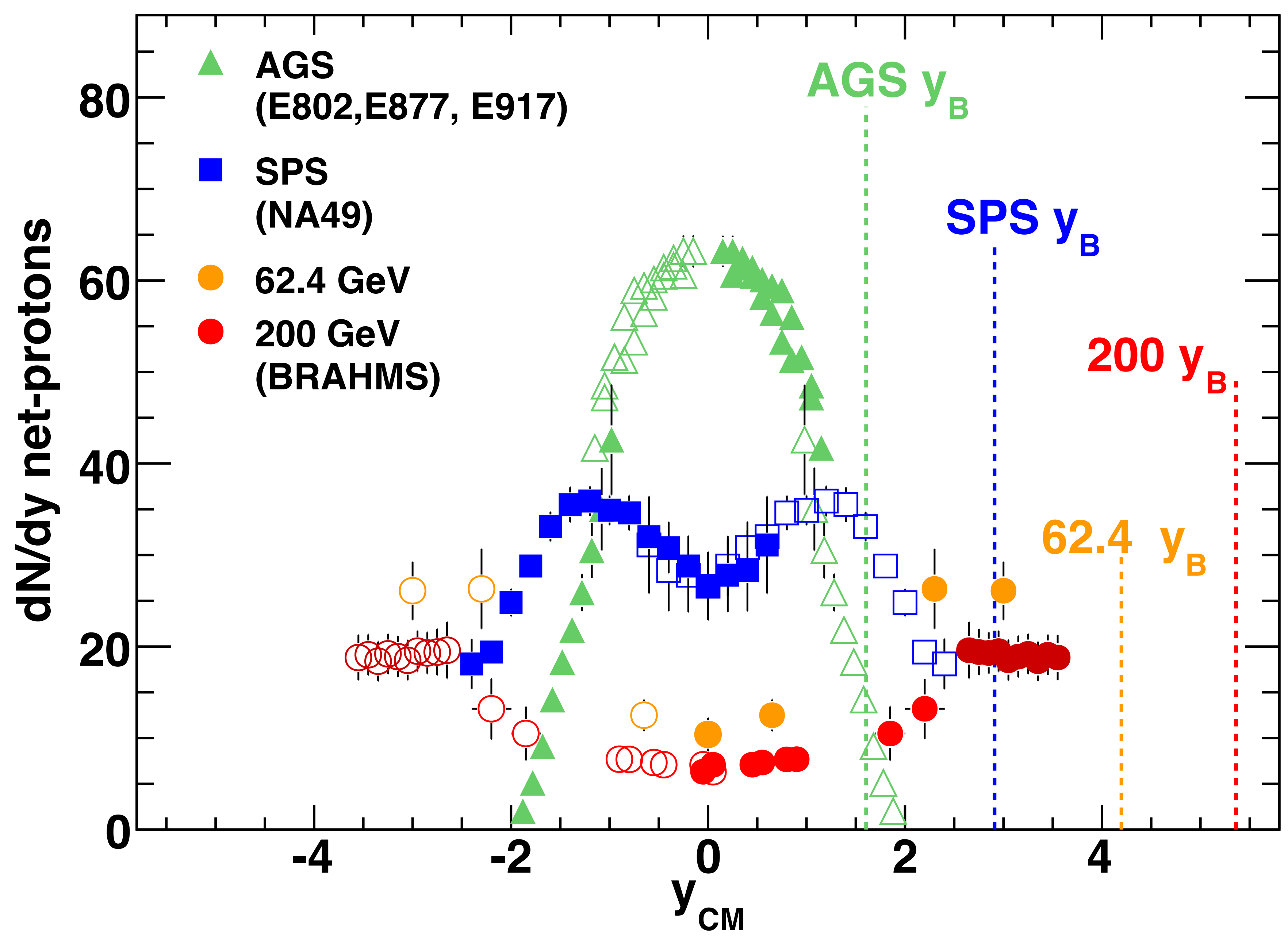
BARYON STOPPING: NUCLEON DECELERATION VS STRING JUNCTION BREAKING

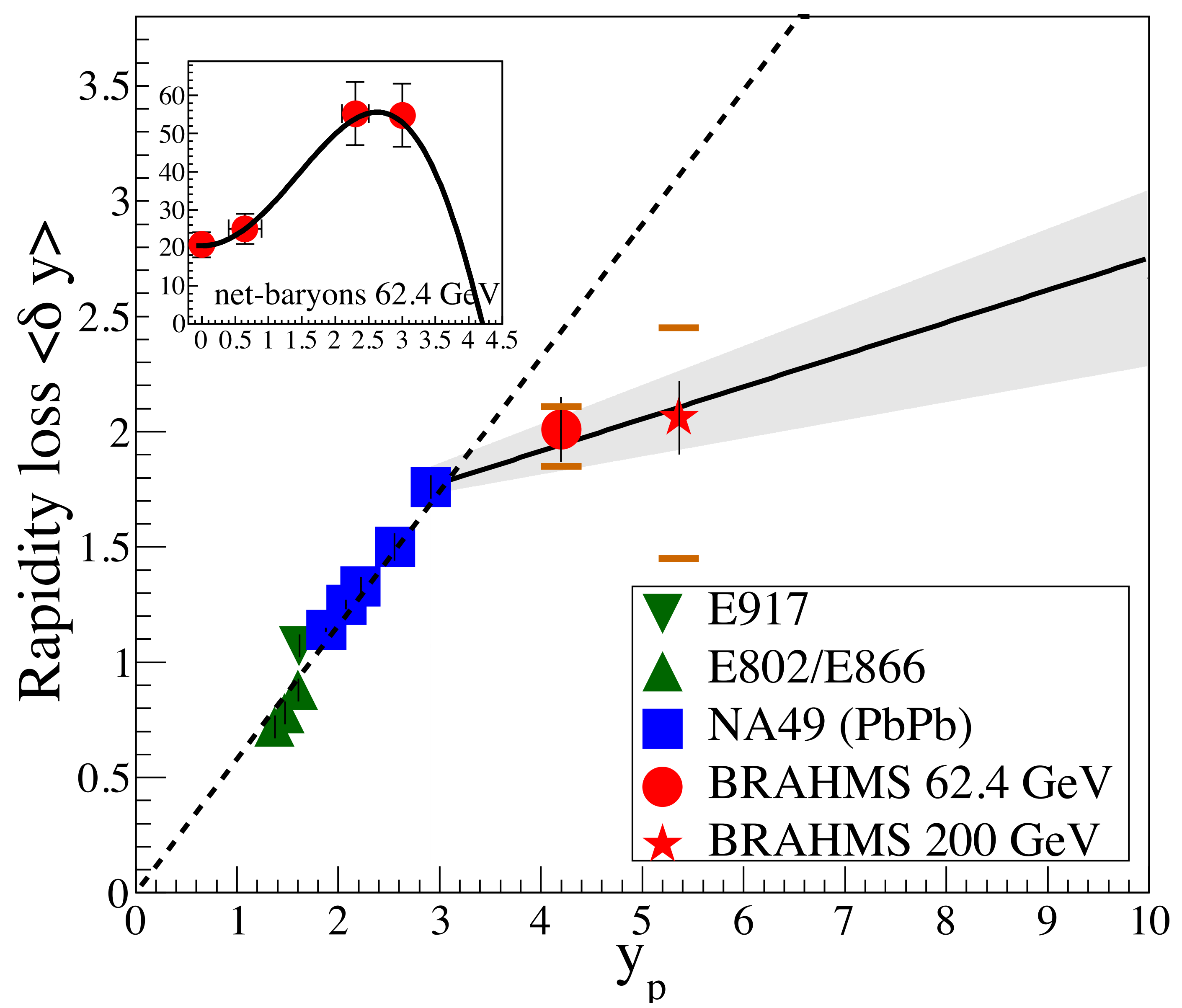
1ST WORKSHOP ON BARYON DYNAMICS FROM RHIC TO EIC

CENTER FOR FRONTIERS IN NUCLEAR SCIENCE, STONY BROOK UNIVERSITY

JANUARY 24, 2024

BARYON RAPIDITY LOSS





F. Videbaek, Nucl. Phys. A 830 (2009) 43C; BRAHMS, Phys. Lett. B677, 267-271 (2009)

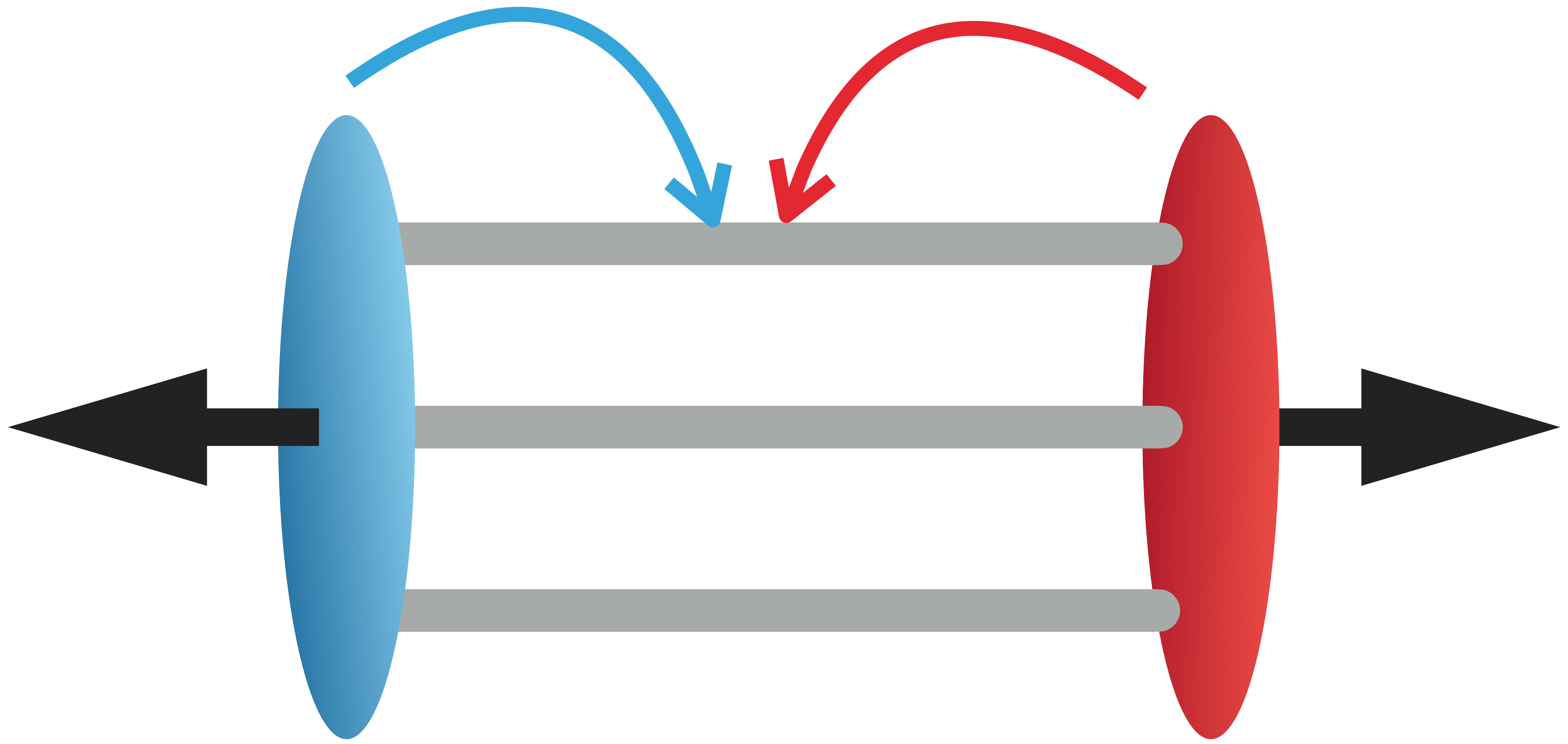
- Baryon rapidity loss

$$\delta y = y_{\mathrm{b}} - \frac{2}{N_{\mathrm{part}}} \int_0^{y_{\mathrm{b}}} y \frac{dN}{dy} \mathrm{d}y$$

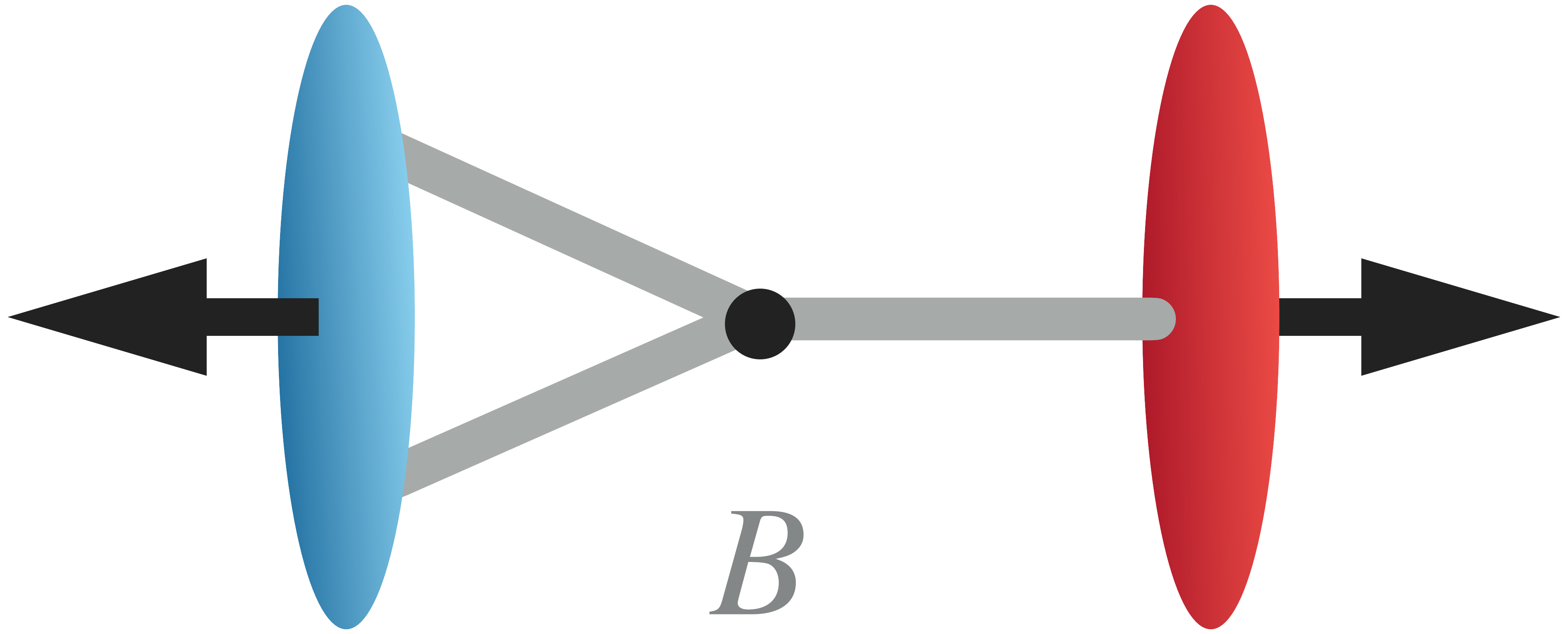
Lipei Du, arXiv: 2401.00596

BARYON STOPPING & ENERGY DEPOSITION

INITIAL BARYON “STOPPING”



Baryons get distributed in rapidity by deceleration of the incoming nucleons



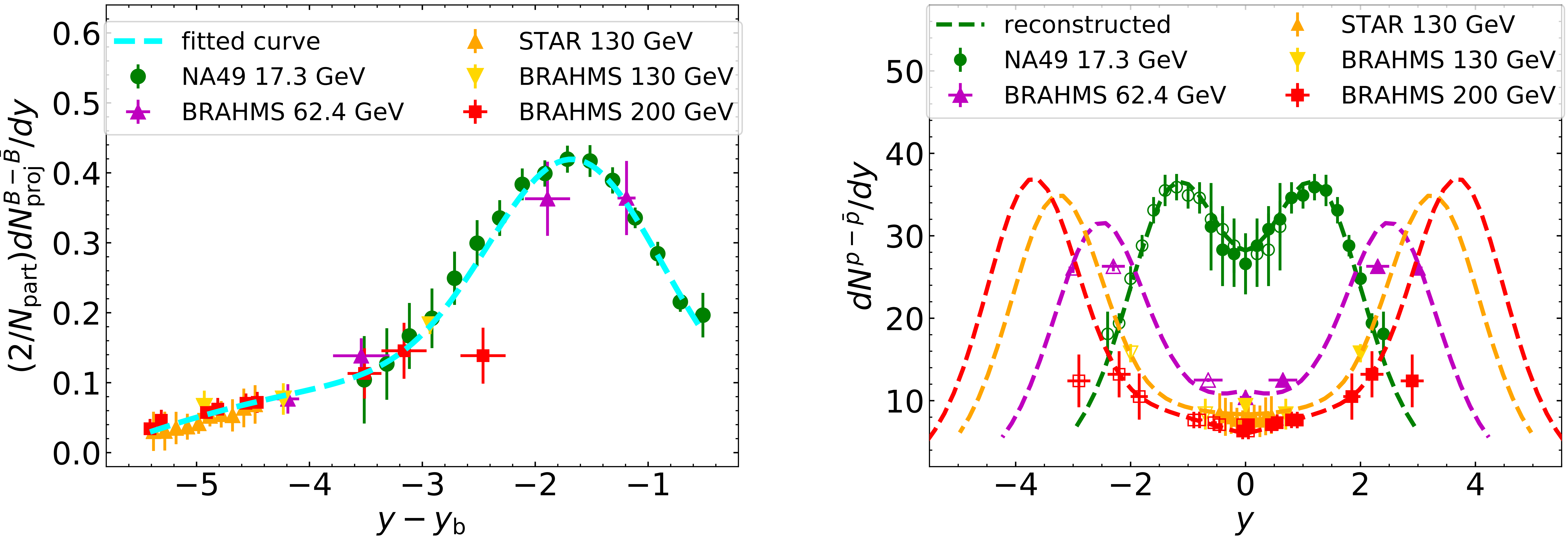
Baryons get distributed in rapidity through string junction breaking

- “Baryon deceleration” and “string junction breaking” should correspond to largely different energy loss

Kharzeev, PLB 378, 238 (1996); Sjostrand & Skands, NPB 659, 243 (2003)

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

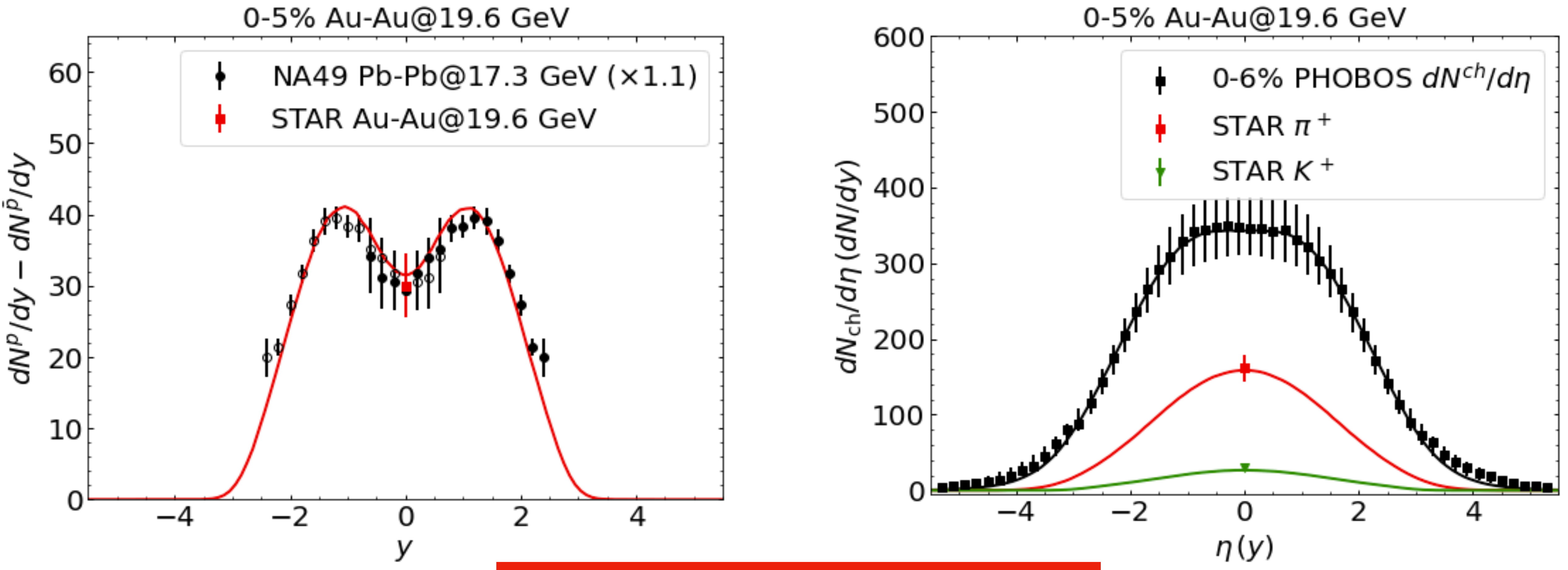
RAPIDITY-DEPENDENT NET-BARYON YIELDS



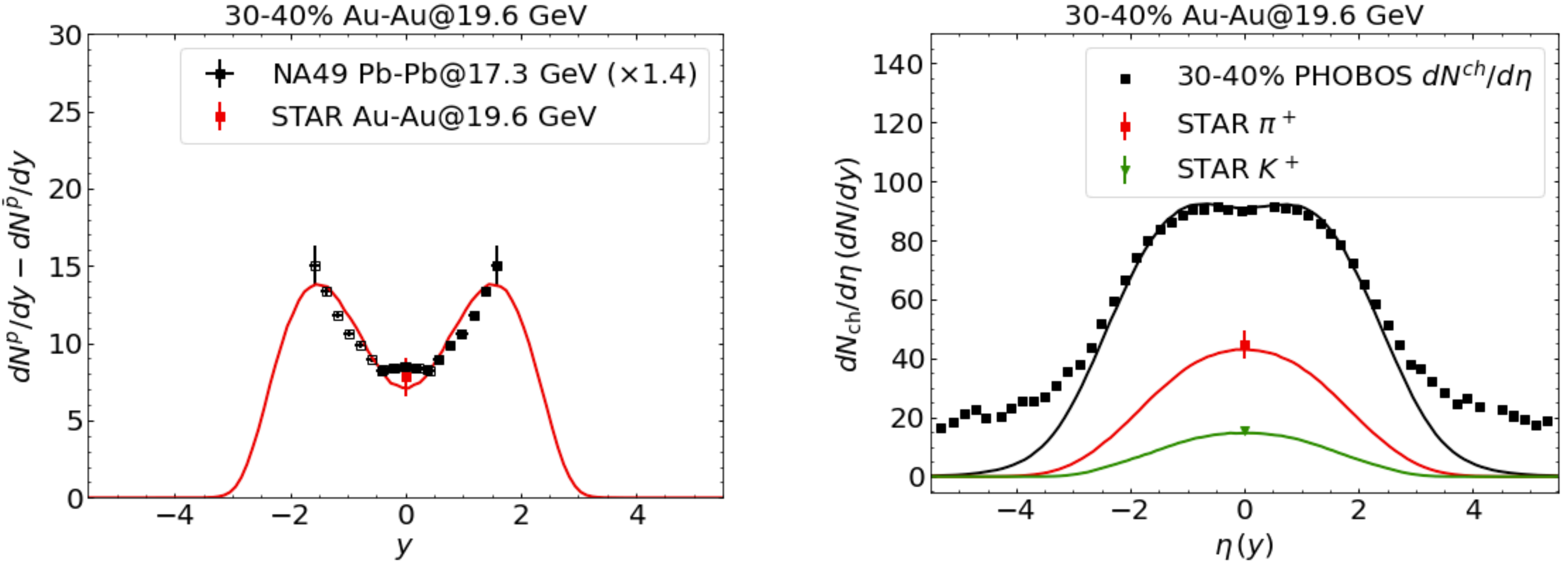
Lipei Du, arXiv: 2401.00596

- Data at 130 GeV also fall on the universal curve
- The fitted curve can be used to reconstruct the rapidity density of net protons

ENERGY DEPOSITION



0-5% Au-Au @ 19.6 GeV



30-40% Au-Au @ 19.6 GeV

Lipei Du, arXiv: 2401.00596

- Number of participants vs. total net baryon charge:

$$N^{B-\bar{B}} \stackrel{?}{=} N_{\text{part}}$$

- The energy carried by incoming participant nucleons

$$E_{\text{part}} = N_{\text{part}}\sqrt{s_{\text{NN}}}/2$$

- Total energy deposited in the fireball

$$E_{\text{hydro}} = \int d^3\Sigma_\mu T^{\mu t}(\boldsymbol{x}_\perp, \eta_s)$$

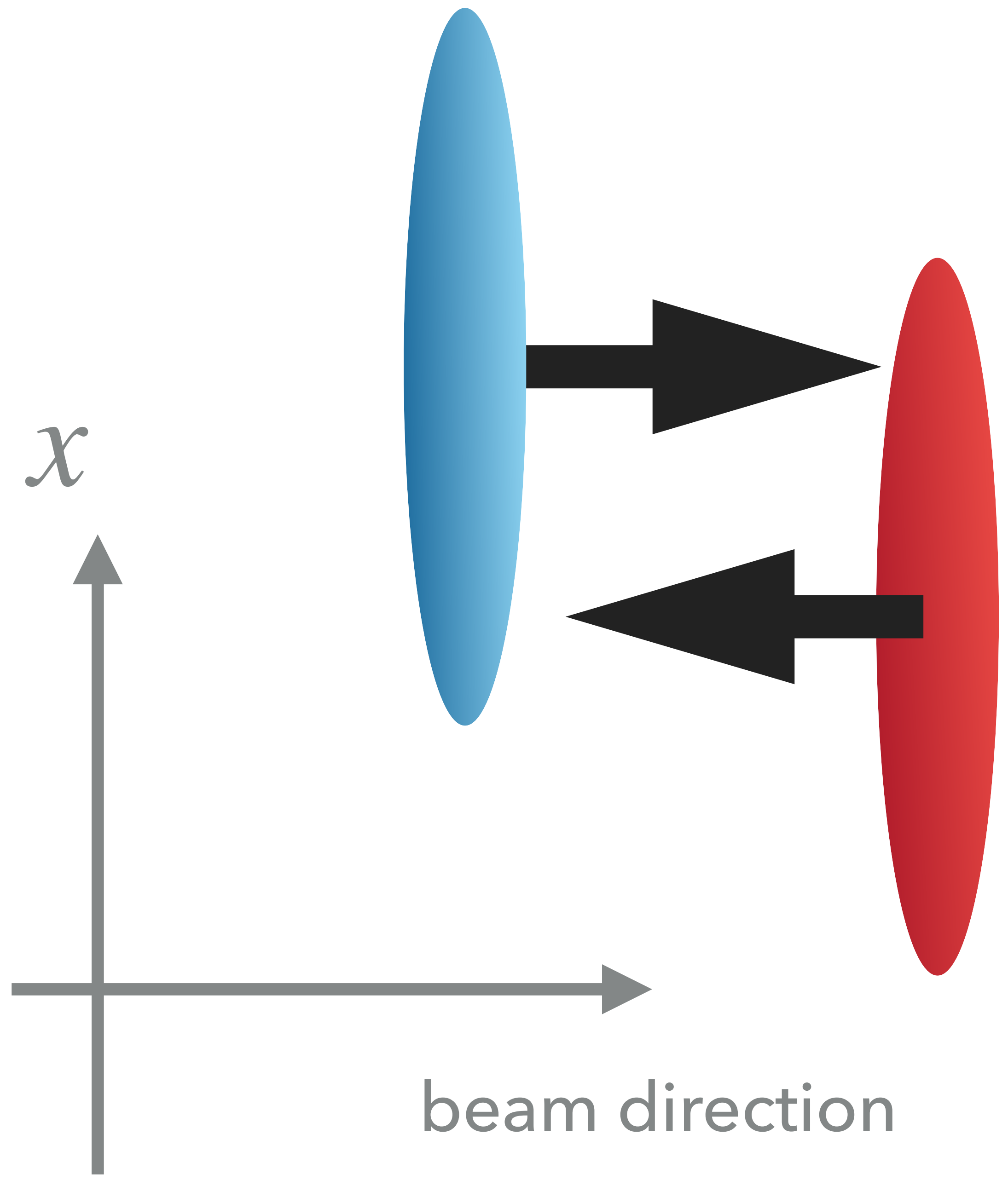
- How are the energies related

$$E_{\text{hydro}} \stackrel{?}{=} E_{\text{part}}$$

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

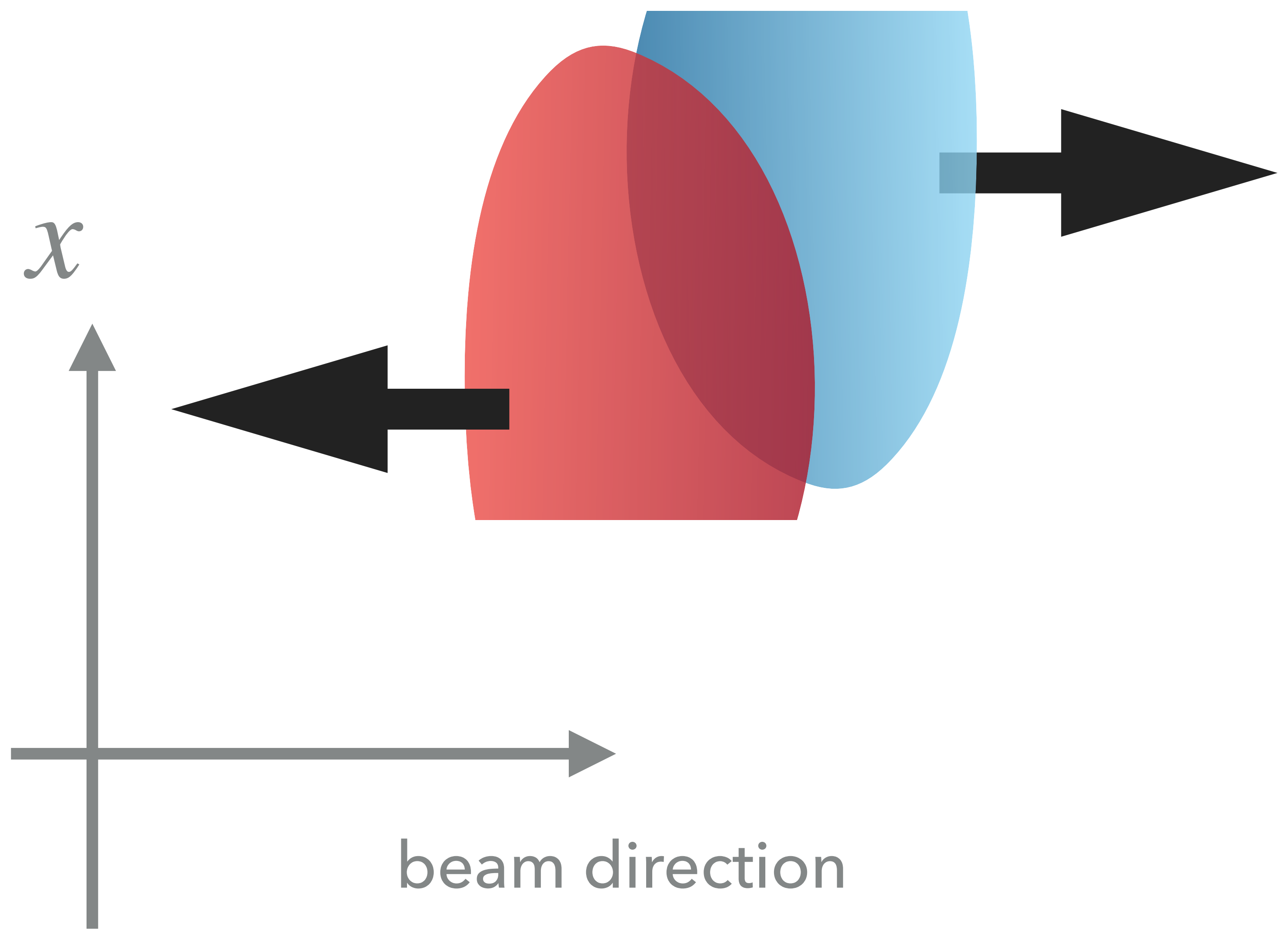
$v_1(y)$ CONSTRAINTS ON BARYON STOPPING

BARYON DECELARATION



- From the nucleon deceleration picture, the baryon density profile gets two peaks, naturally giving the double-humped net proton yields in rapidity.

BARYON DECELARATION



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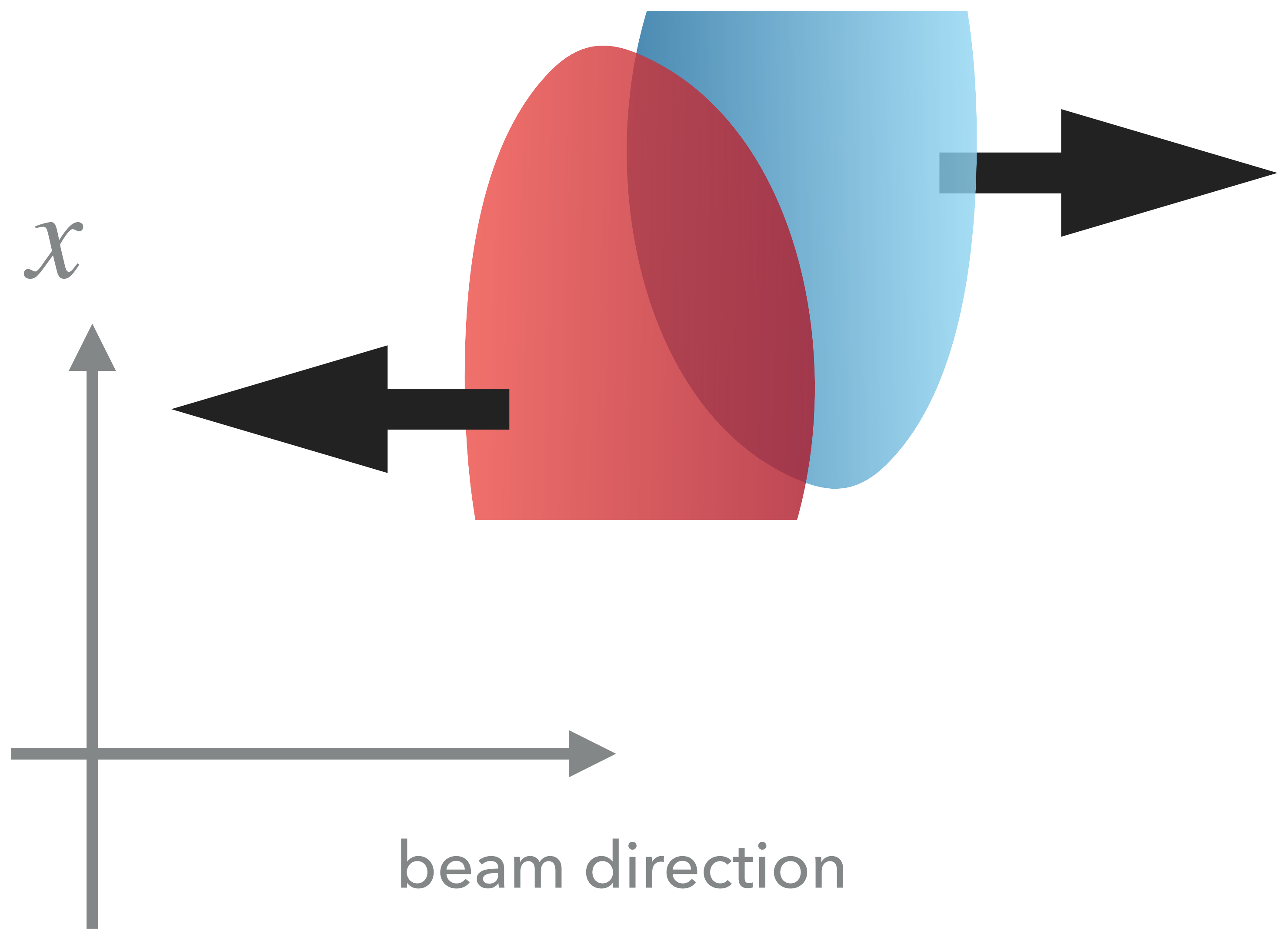
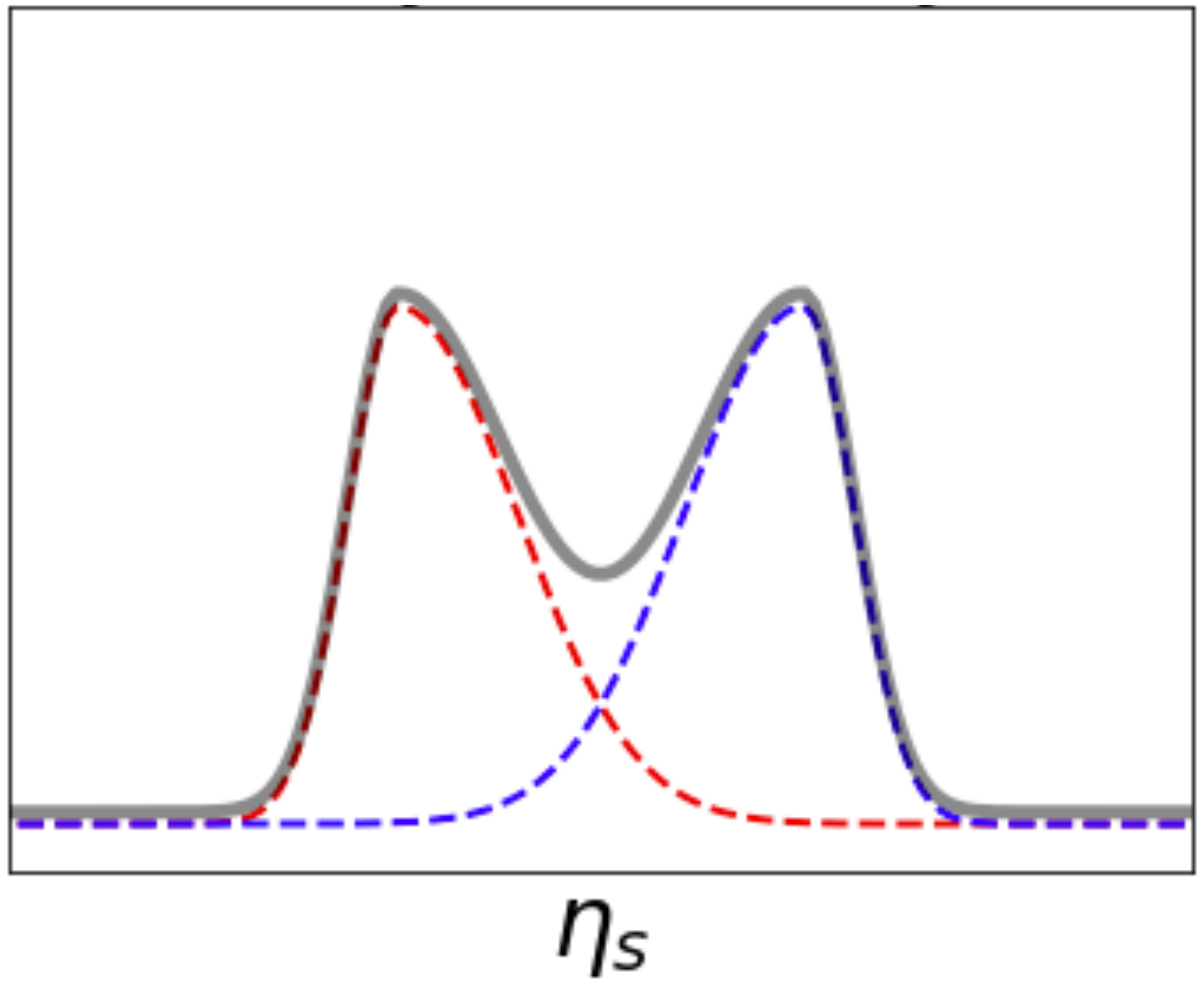
BARYON DECELARATION



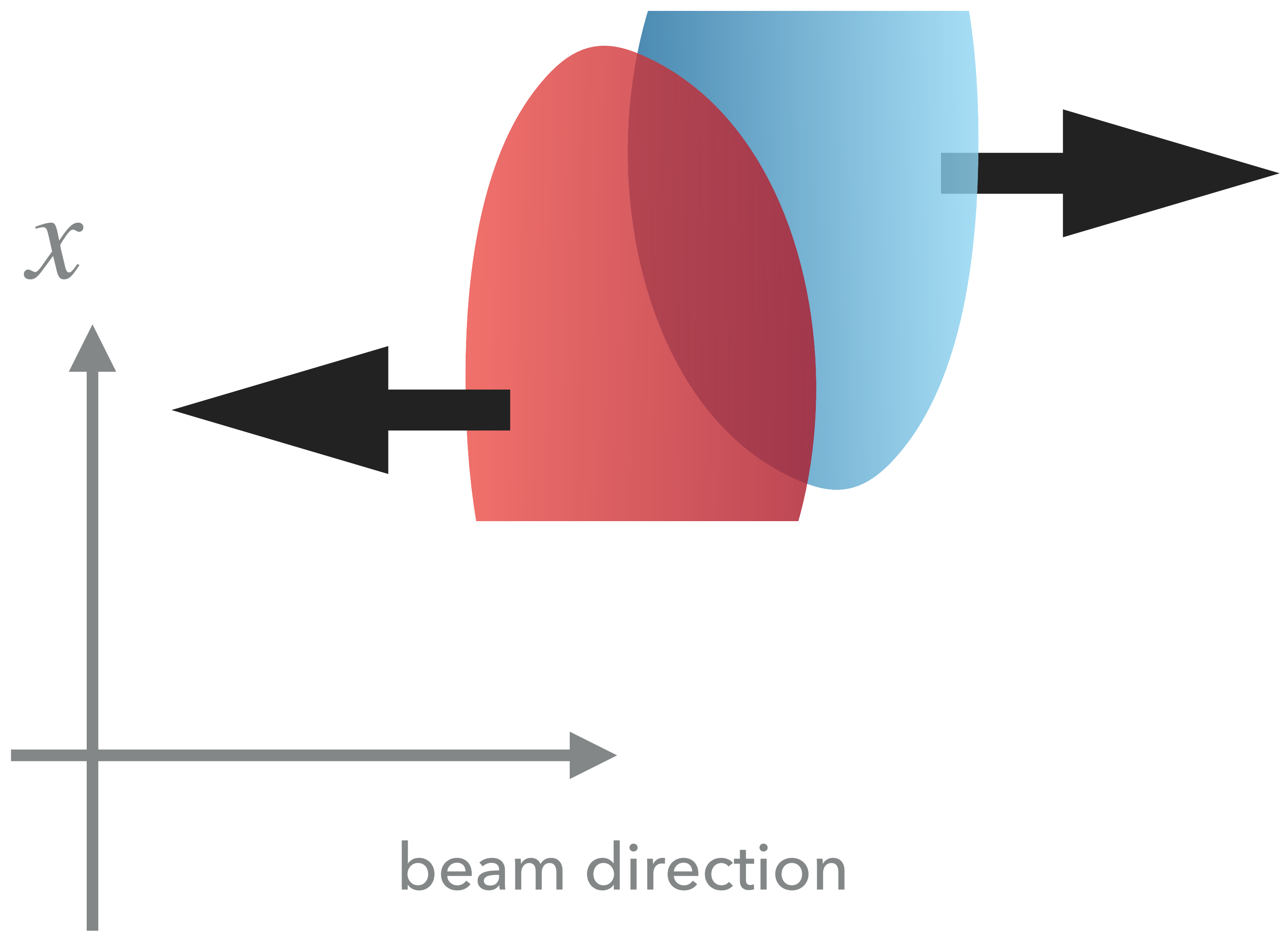


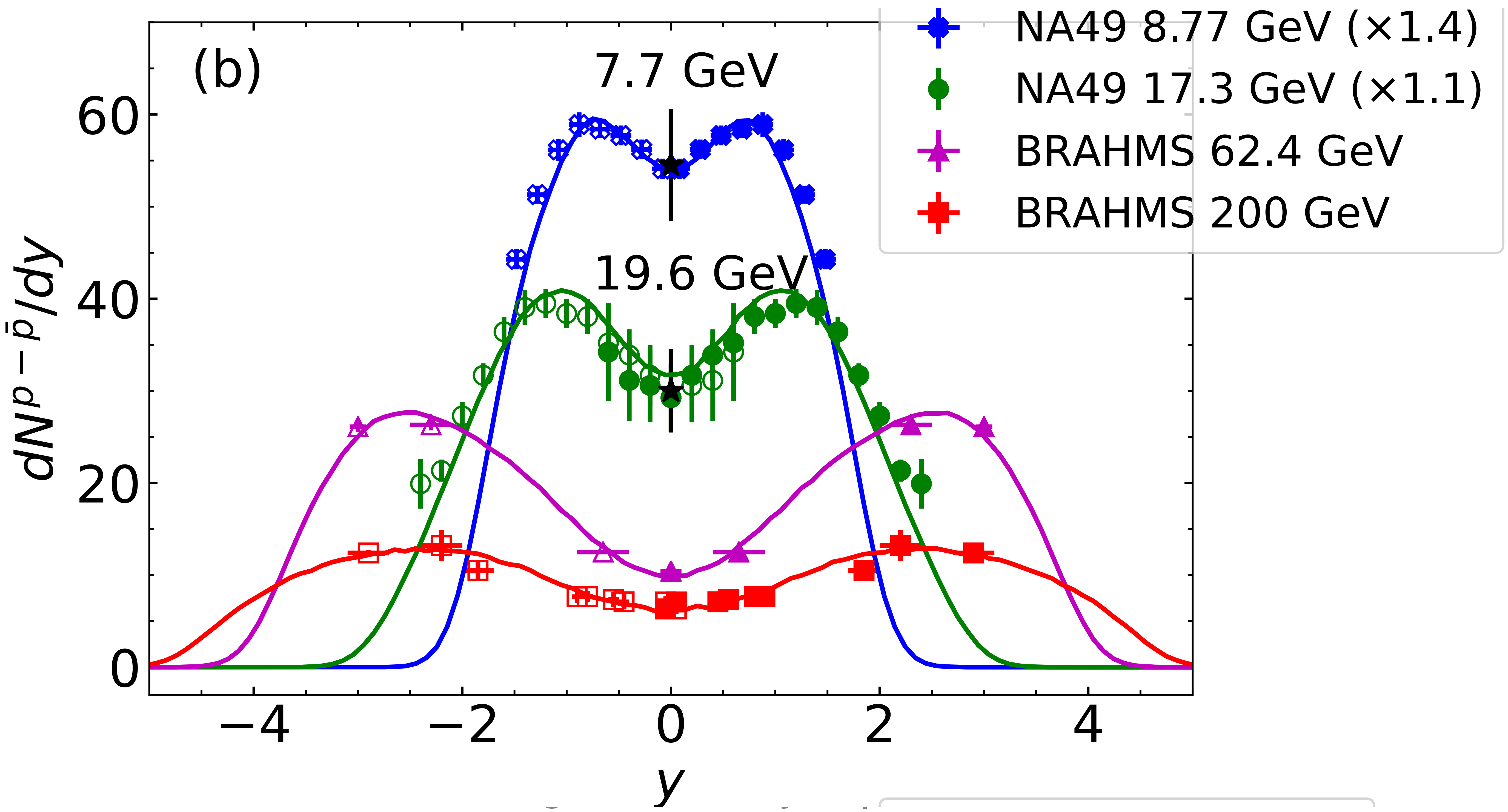
longitudinal baryon profile

- From the nucleon deceleration picture, the baryon density profile gets two peaks, naturally giving the double-humped net proton yields in rapidity.

G. Denicol et al, PRC 98, 034916 (2018); LD, H. Gao, S. Jeon & C. Gale, arXiv:2302.13852

BARYON DECELARATION





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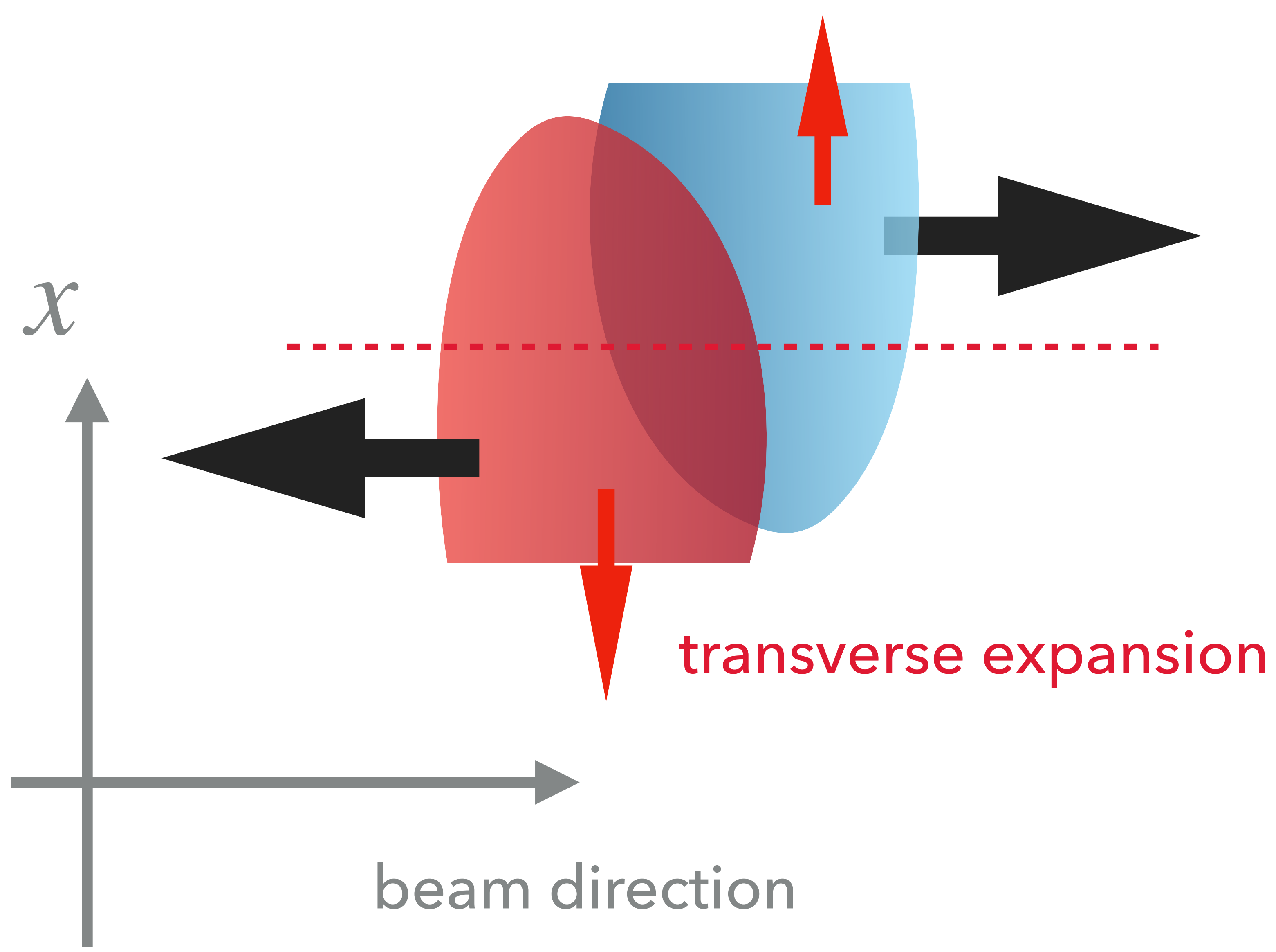
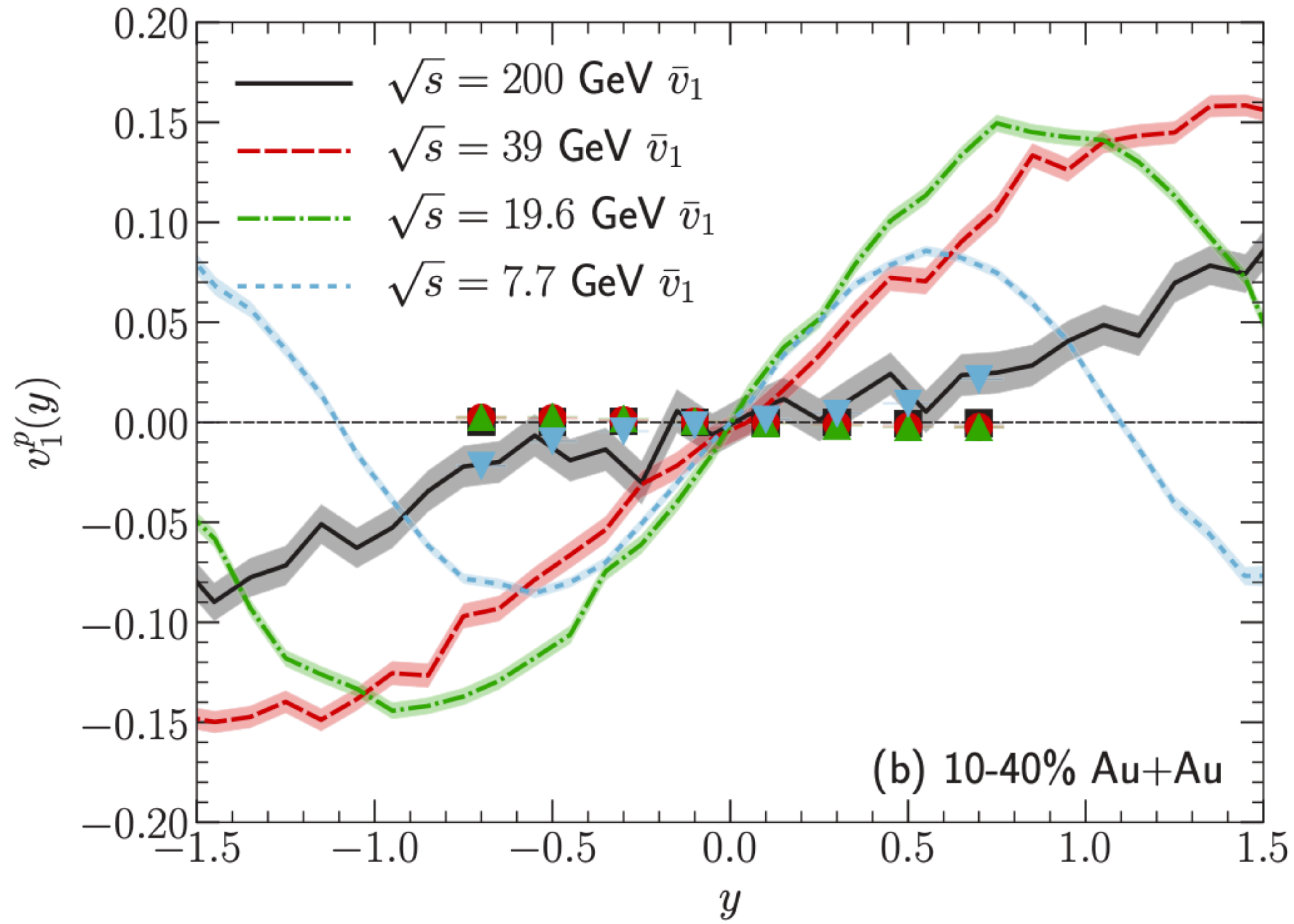
G. Denicol et al, PRC 98, 034916 (2018); LD, H. Gao, S. Jeon & C. Gale, arXiv:2302.13852

DIRECTED FLOW $v_1(y)$ OF PROTONS

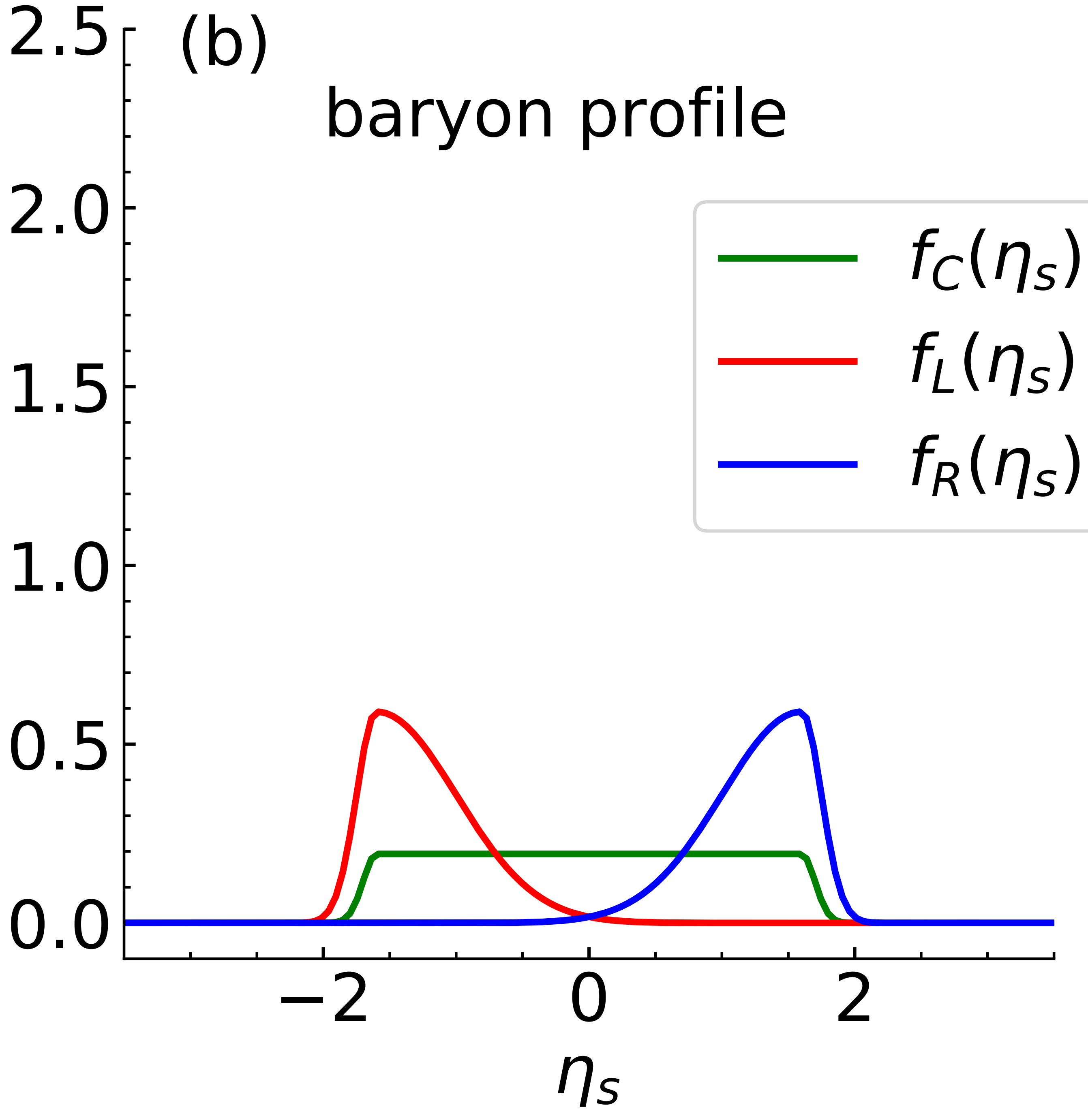


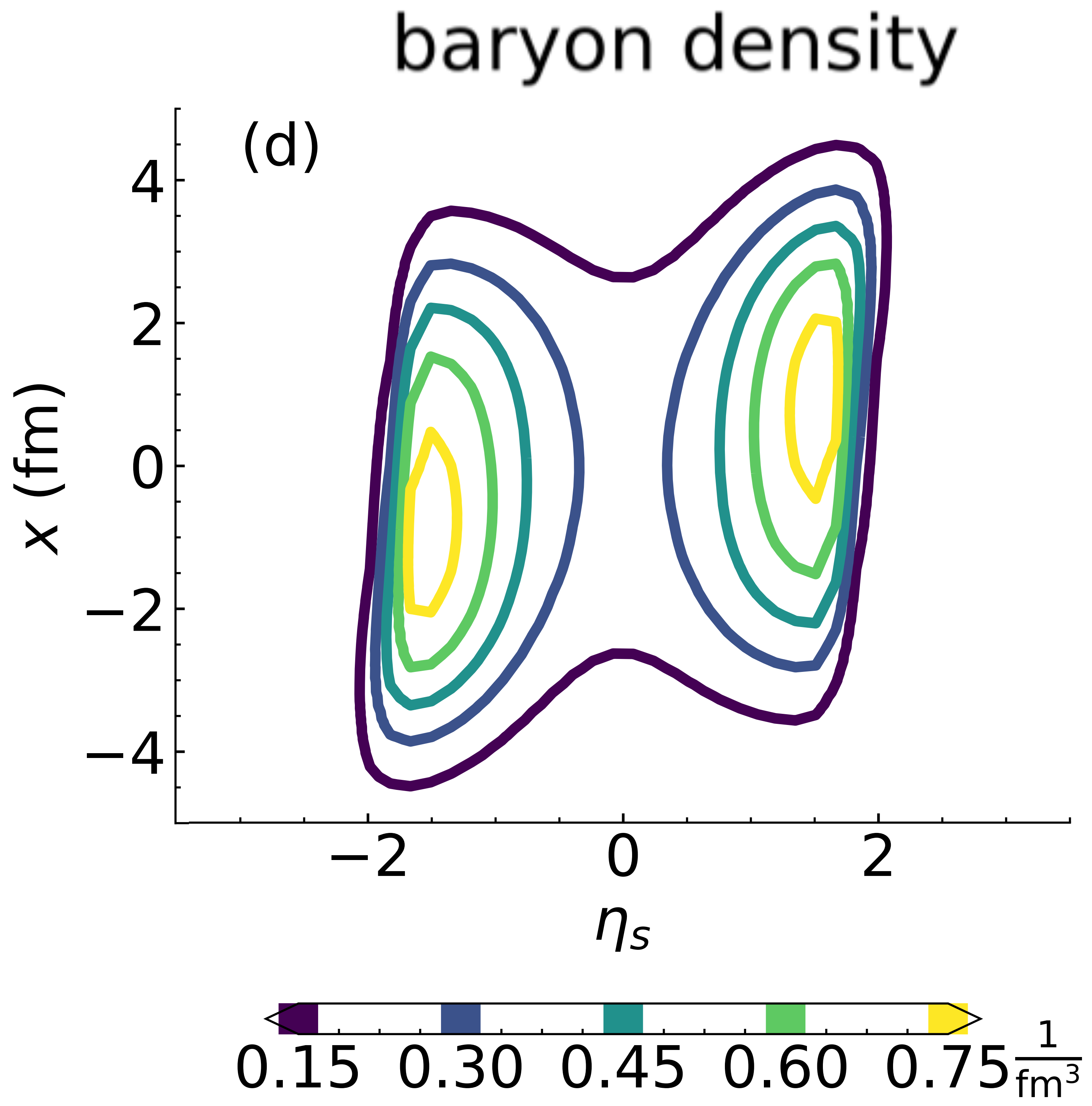


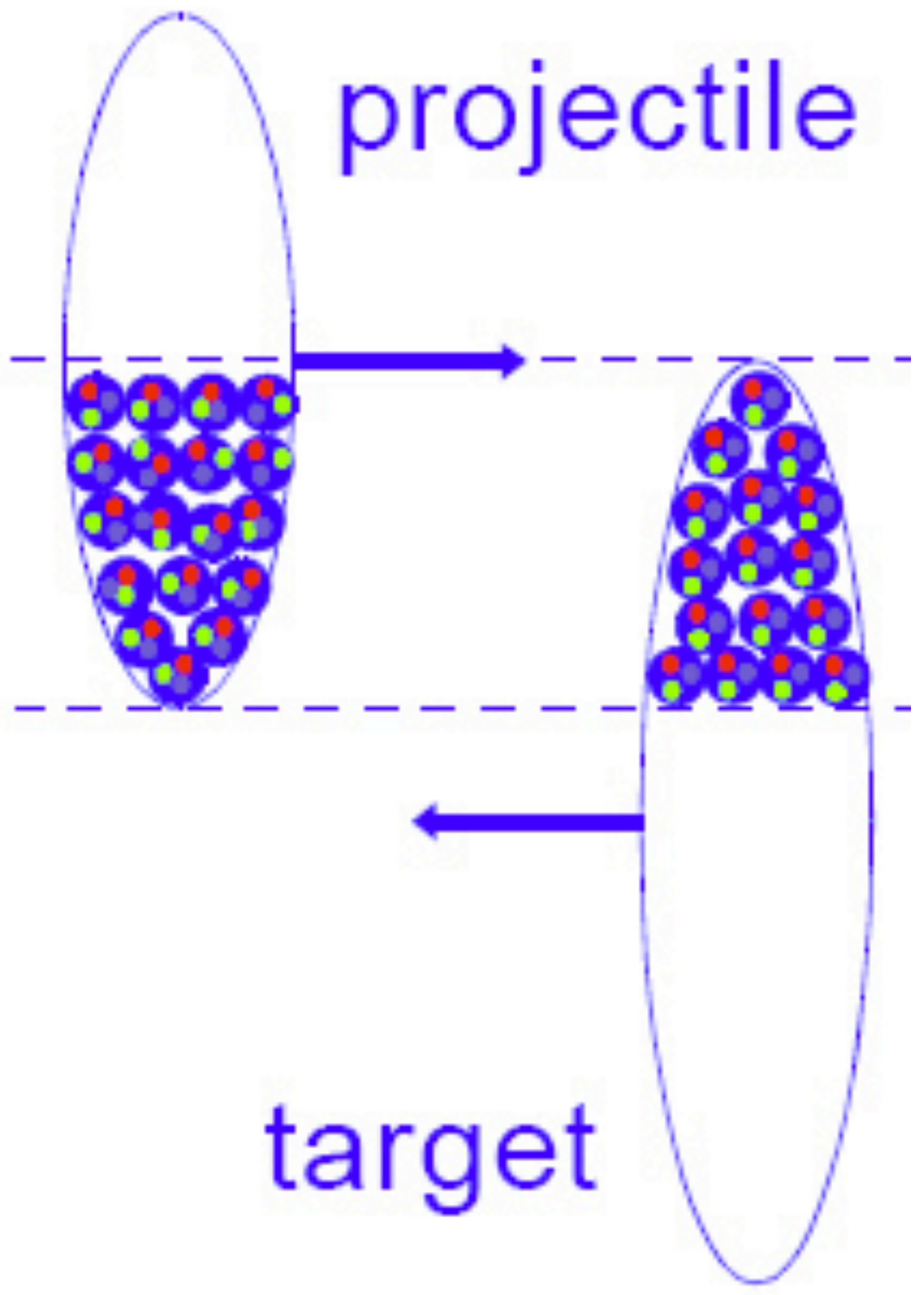
Shen and Alzhrani, PRC102, 014909 (2020)

- $v_1(y)$ 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





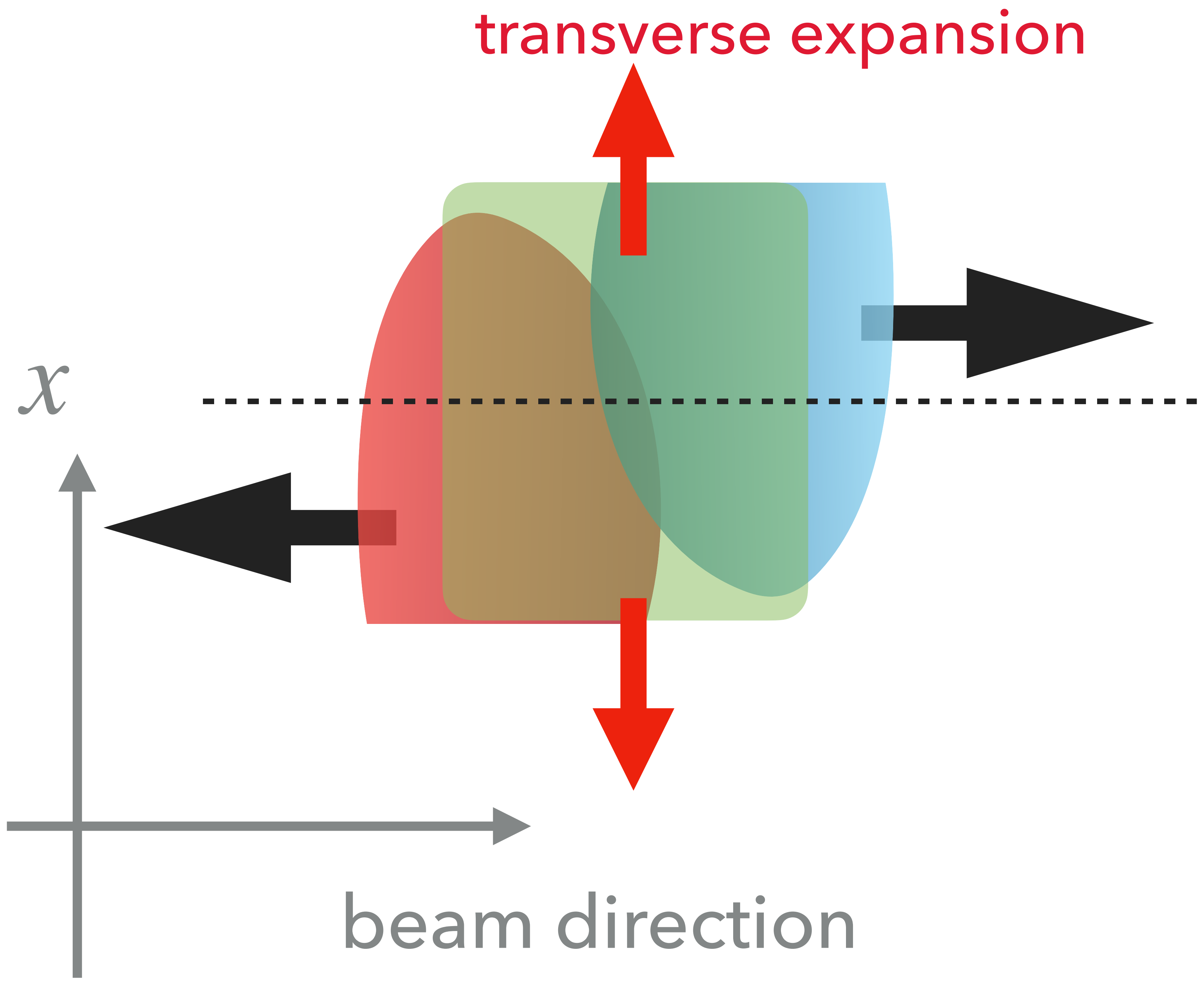


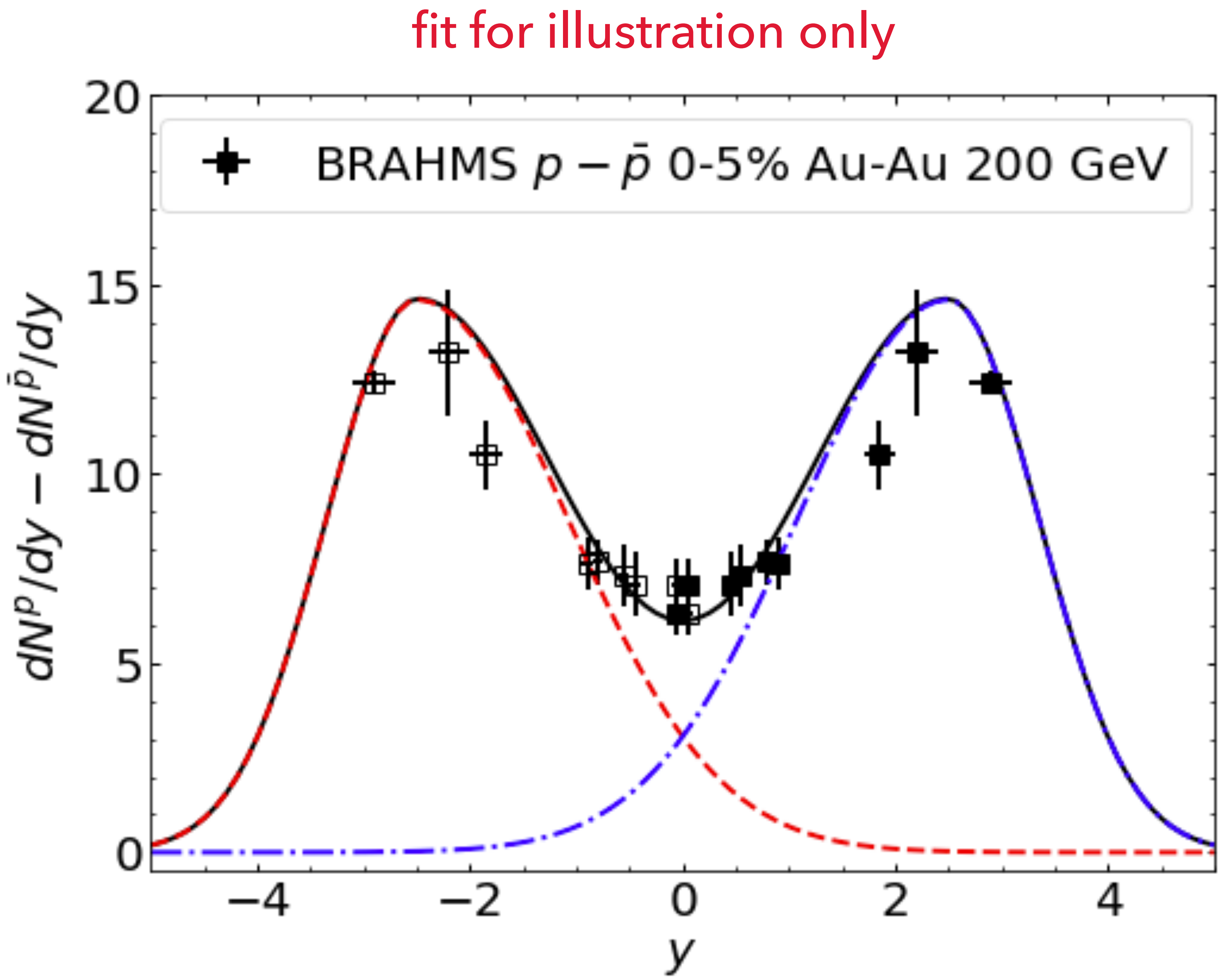
- A rapidity-independent "plateau" component in initial baryon profile & tilted baryon peaks describing the varying baryon stopping in the transverse plane

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

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

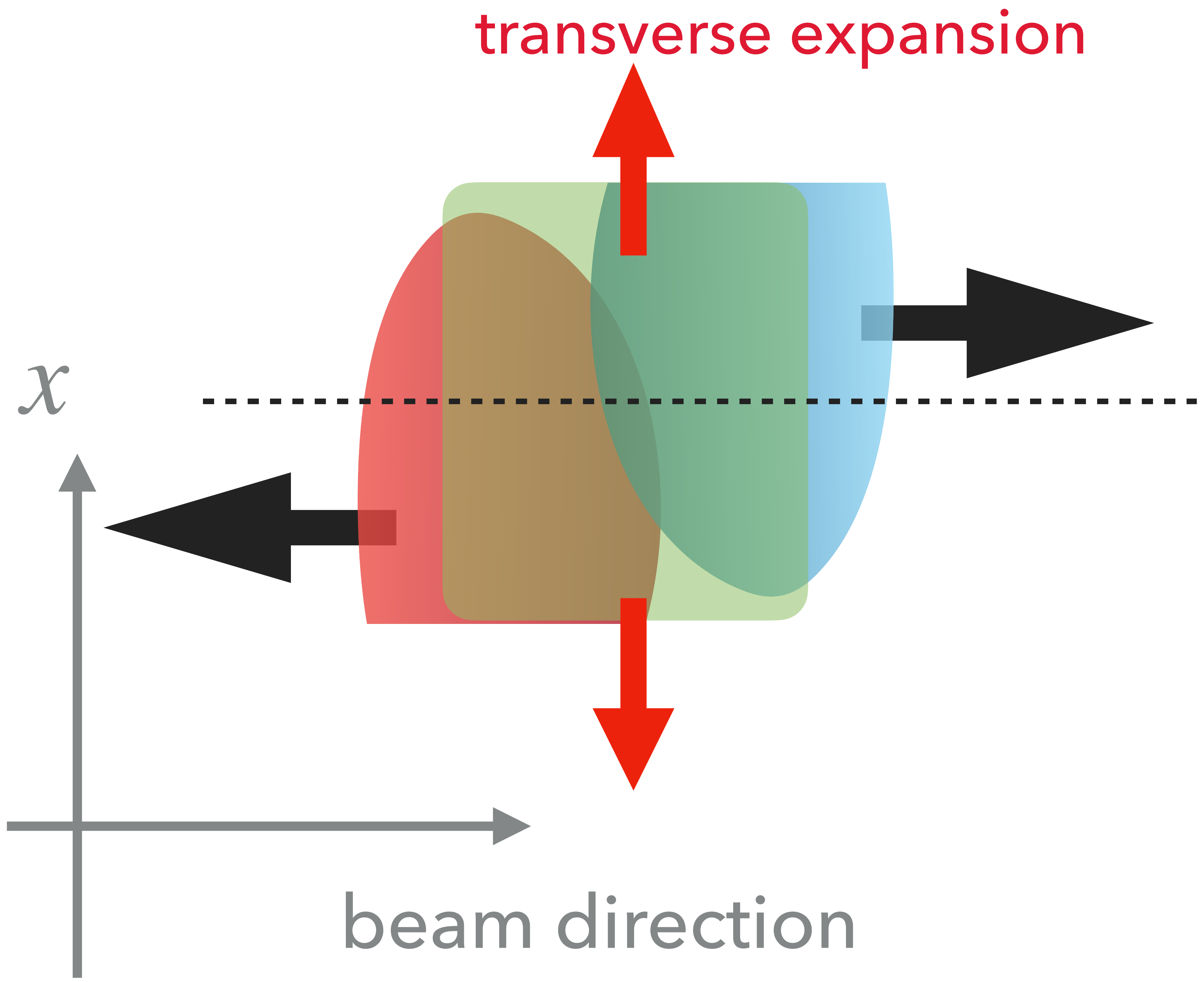
$dN^{p-\bar{p}}/dy$ AND $v_1(y)$ OF PROTONS

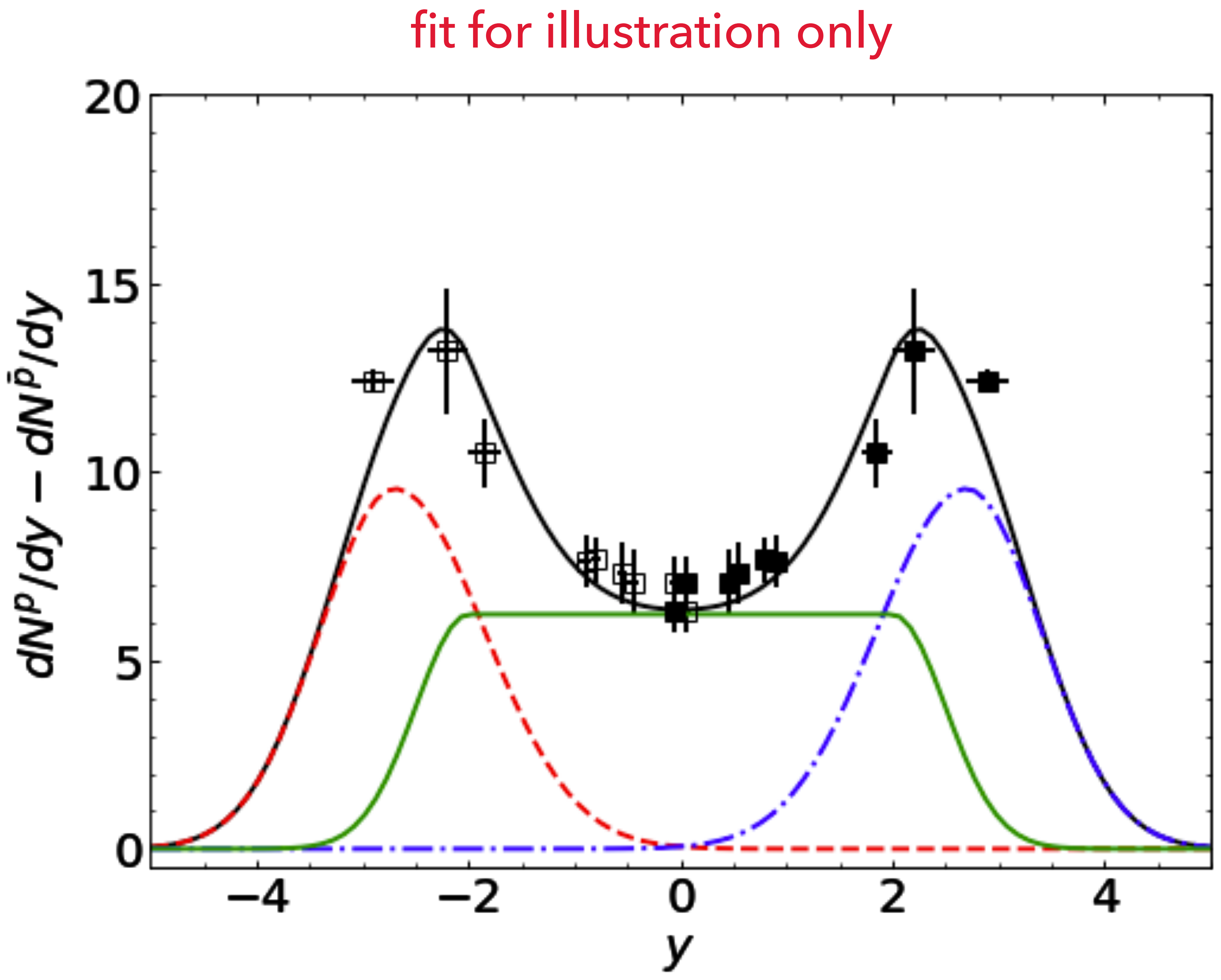




- To explain the rapidity distributions of net proton yields and baryons' directed flows simultaneously, the plateau is favored;
- It helps to reduce baryons' $v_1(y)$ while giving enough net proton yields around midrapidity.

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





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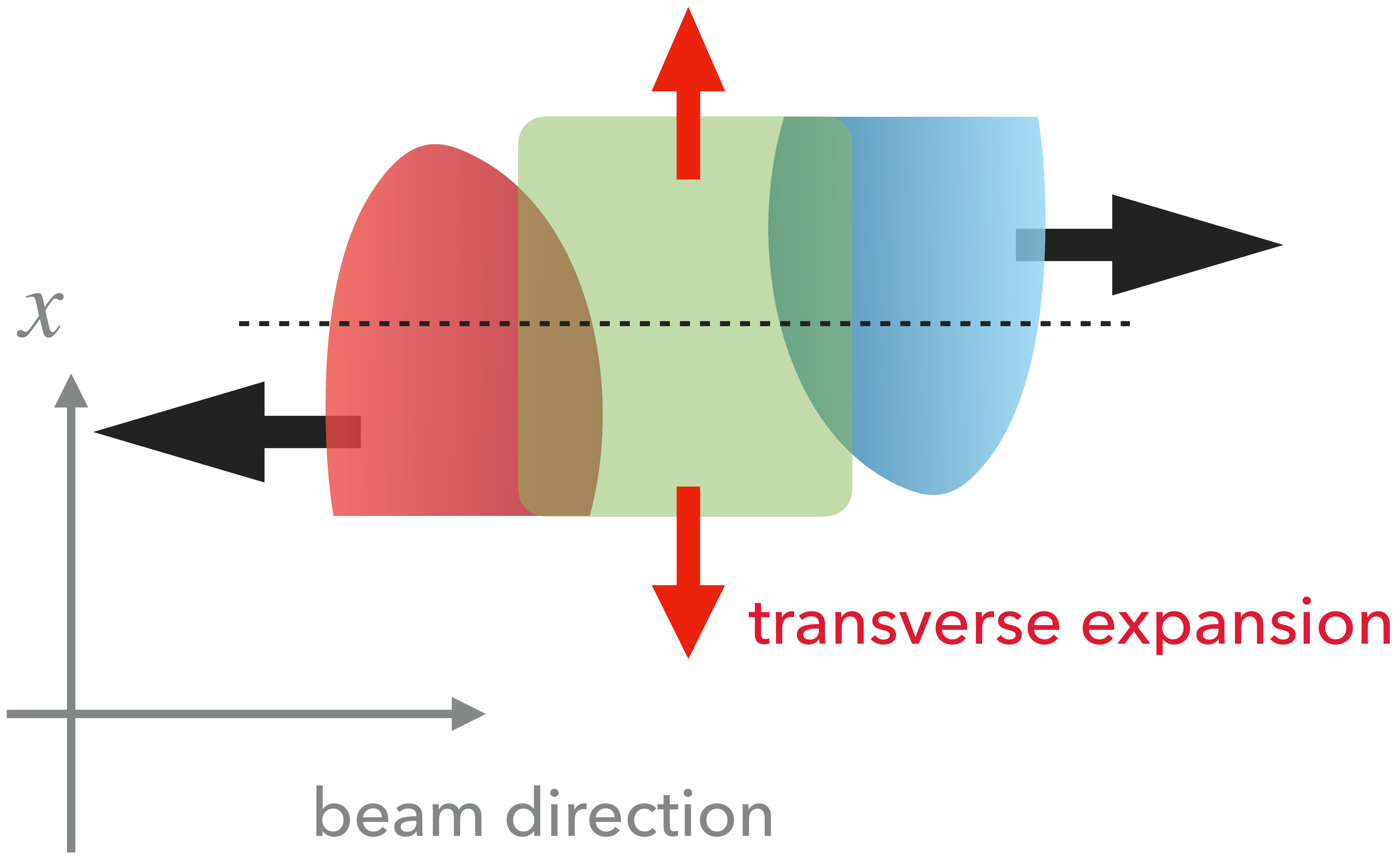
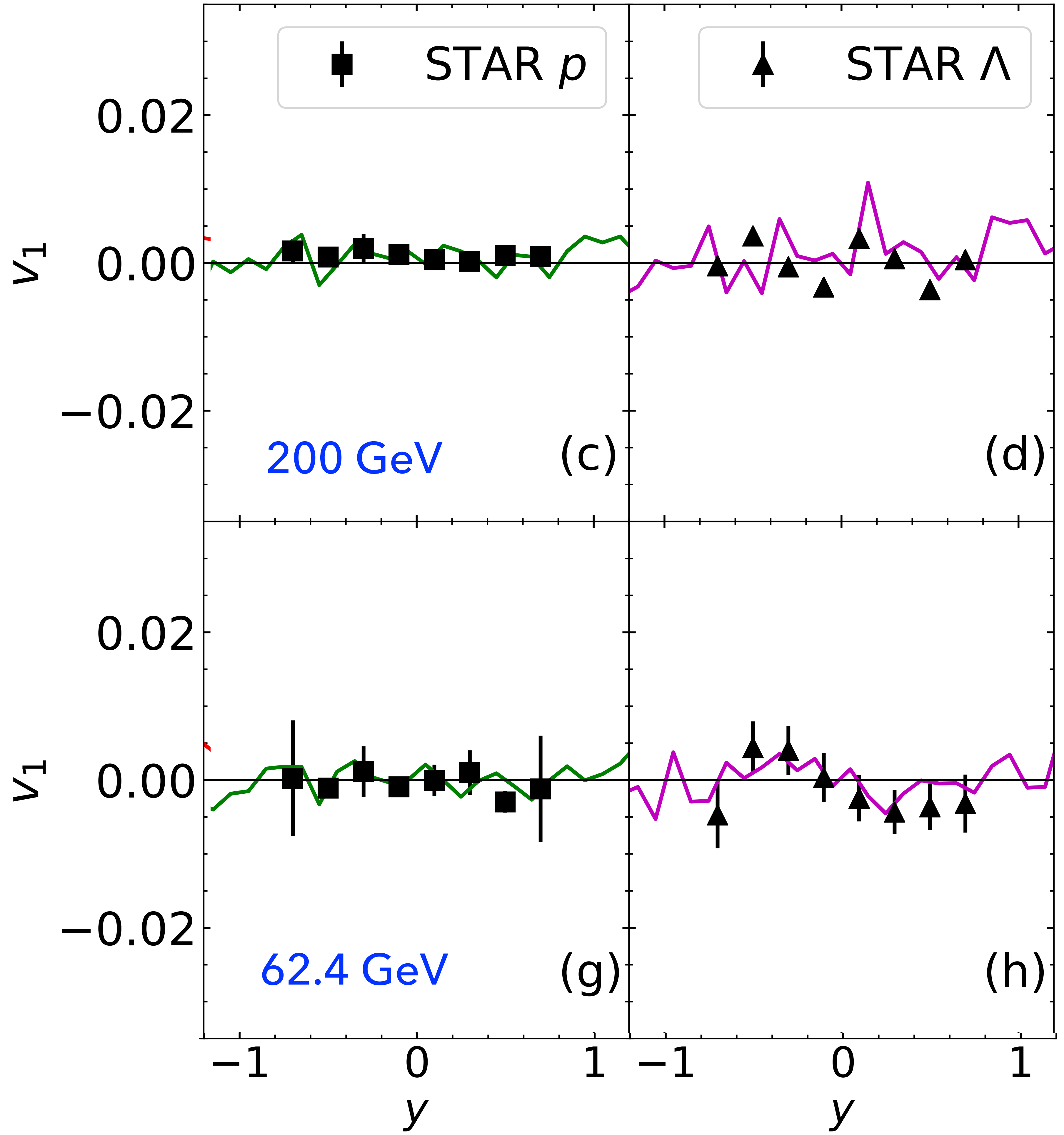
DIRECTED FLOW OF BARYONS AT 200 AND 62.4 GEV



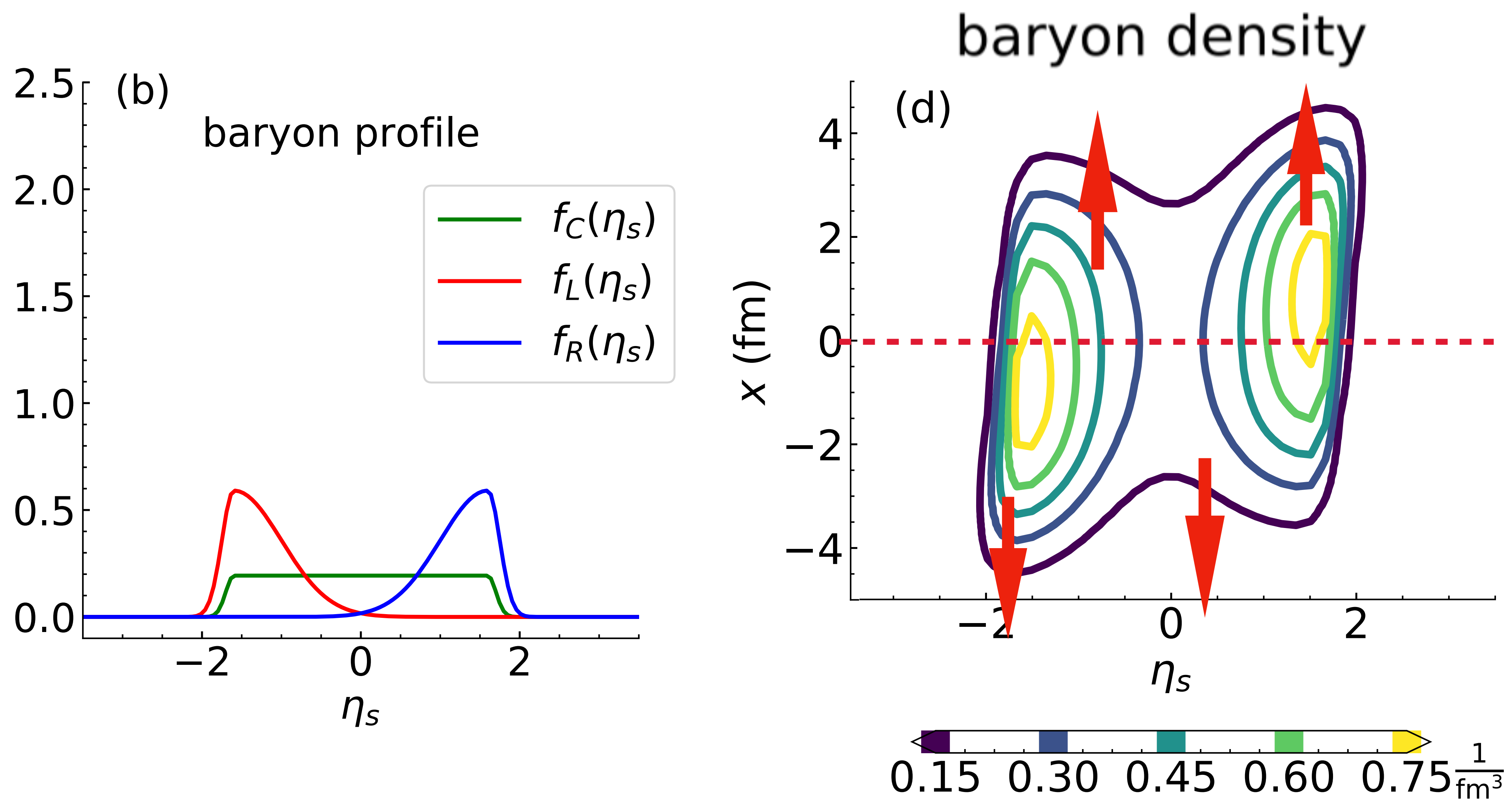


- At high beam energies with large beam rapidities, the plateau dominates and strongly reduces baryons' $v_1(y)$.

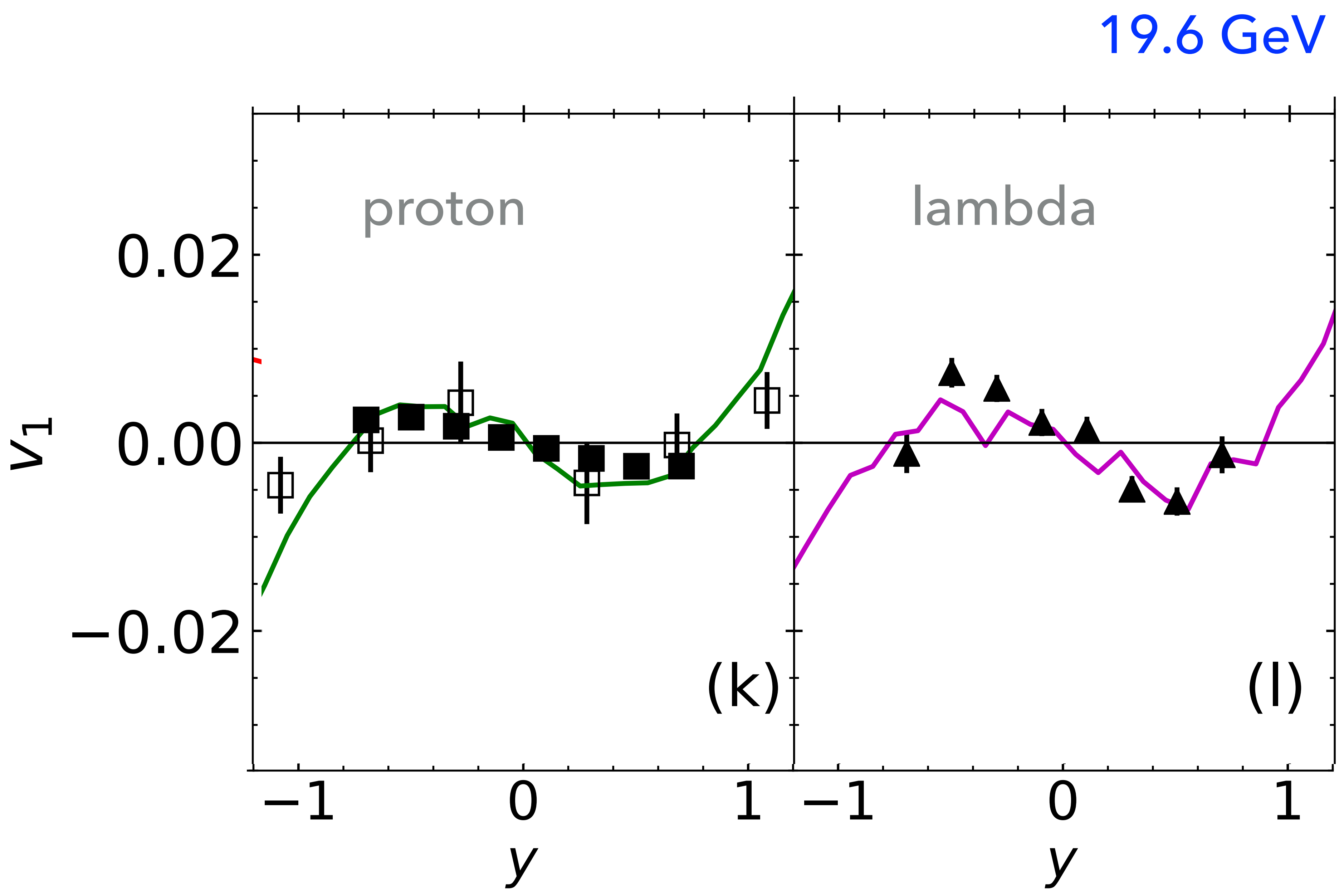
Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018)

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

DIRECTED FLOW OF BARYONS AT 19.6 GEV



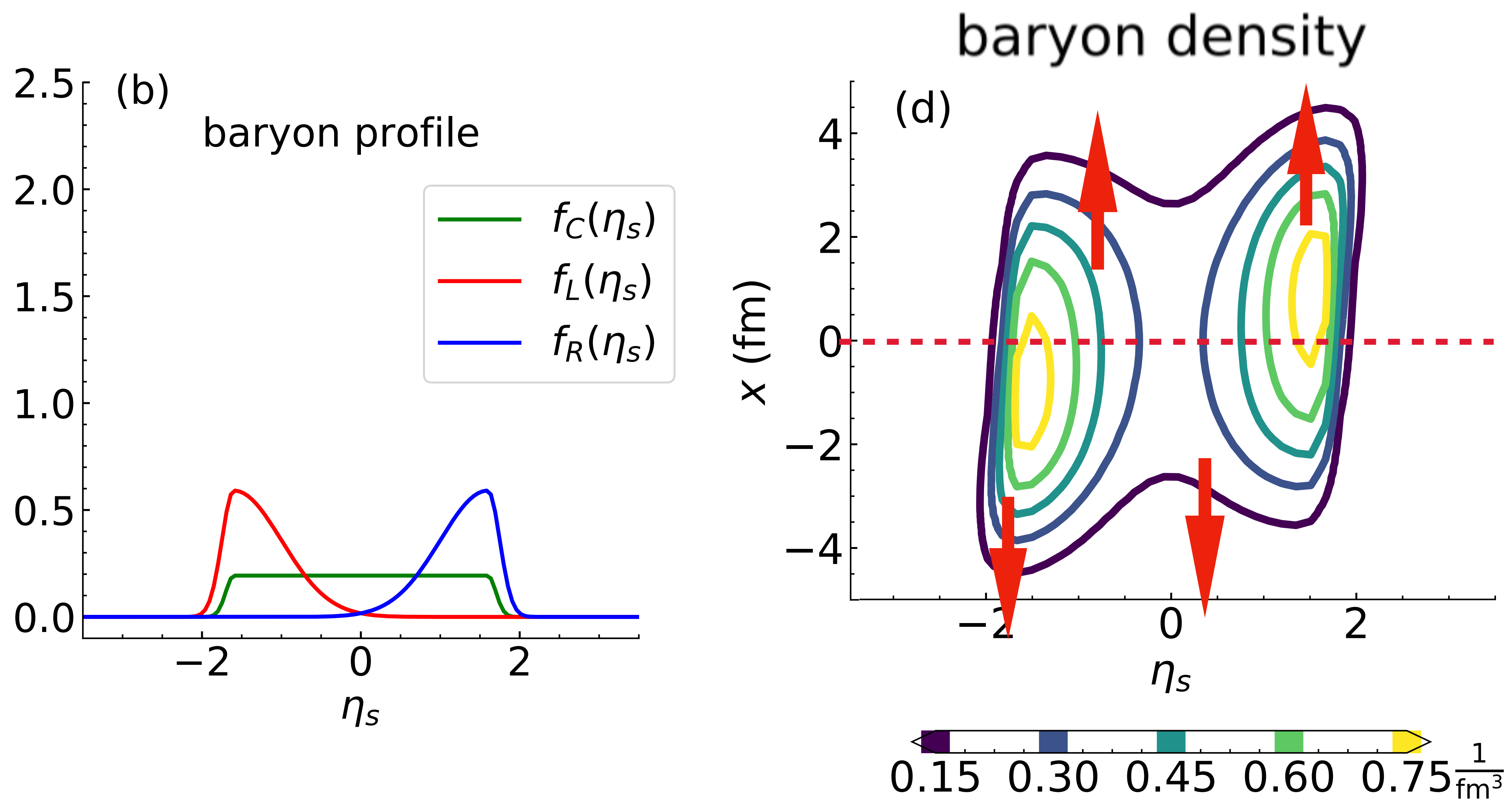
Initial distributions in reaction plane for 10-40%
Au+Au@19.6 GeV



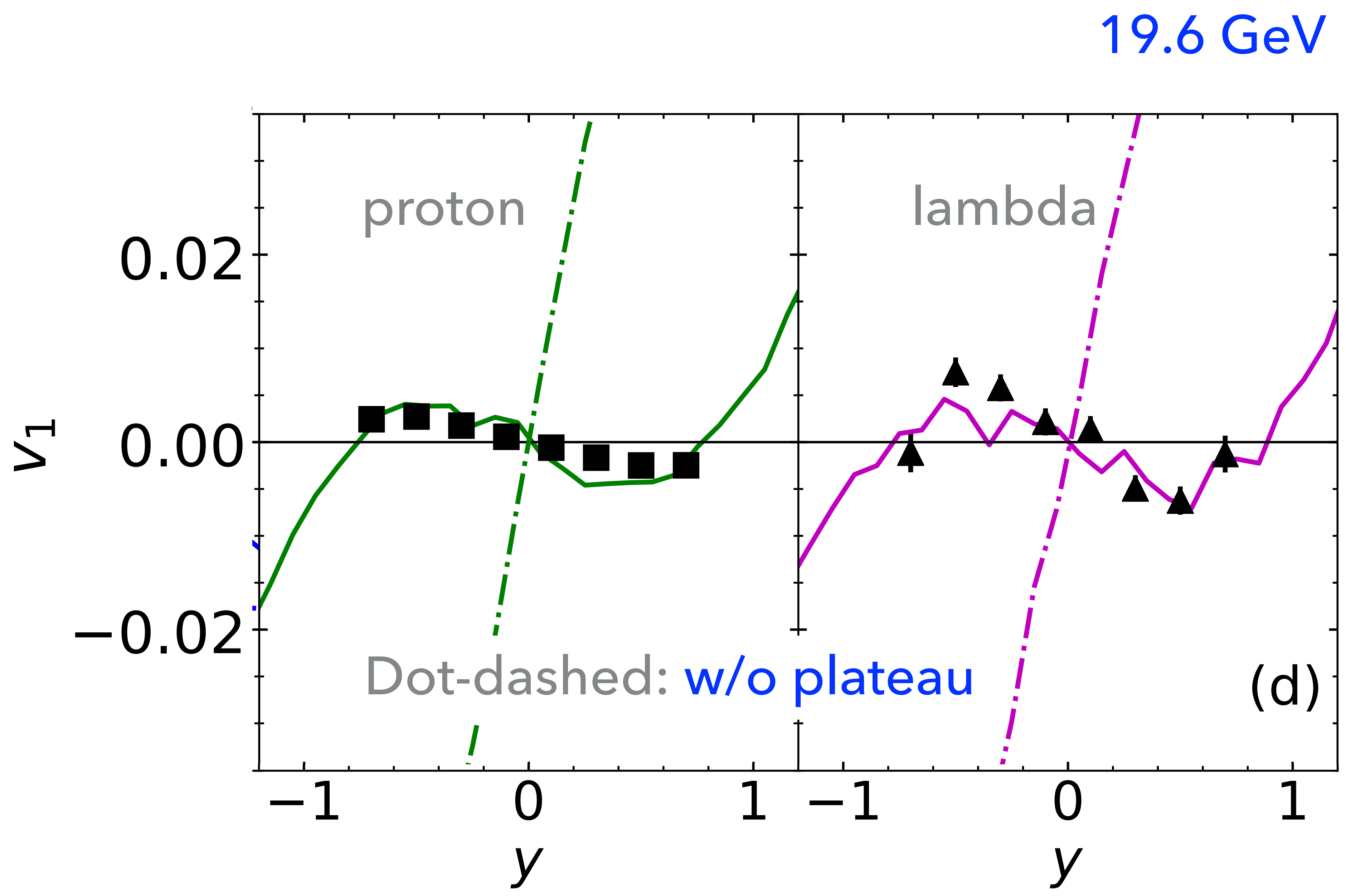
- Transverse expansion + asymmetric distribution of baryon density along x $\Longrightarrow$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV
- The sign change of $dv_1(y)/dy\,|_{y=0}$ is naturally reproduced without a 1st-order phase transition.

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

DIRECTED FLOW OF BARYONS AT 19.6 GEV



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



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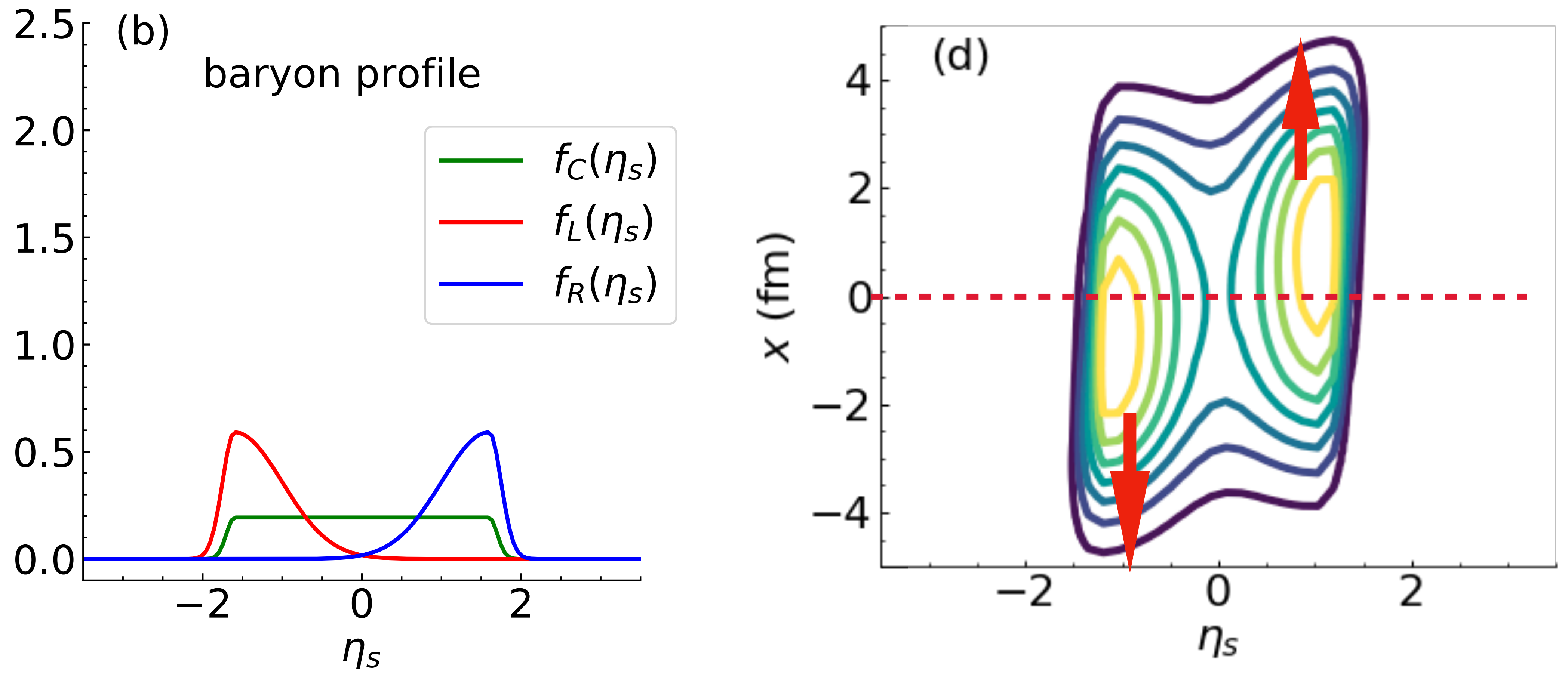
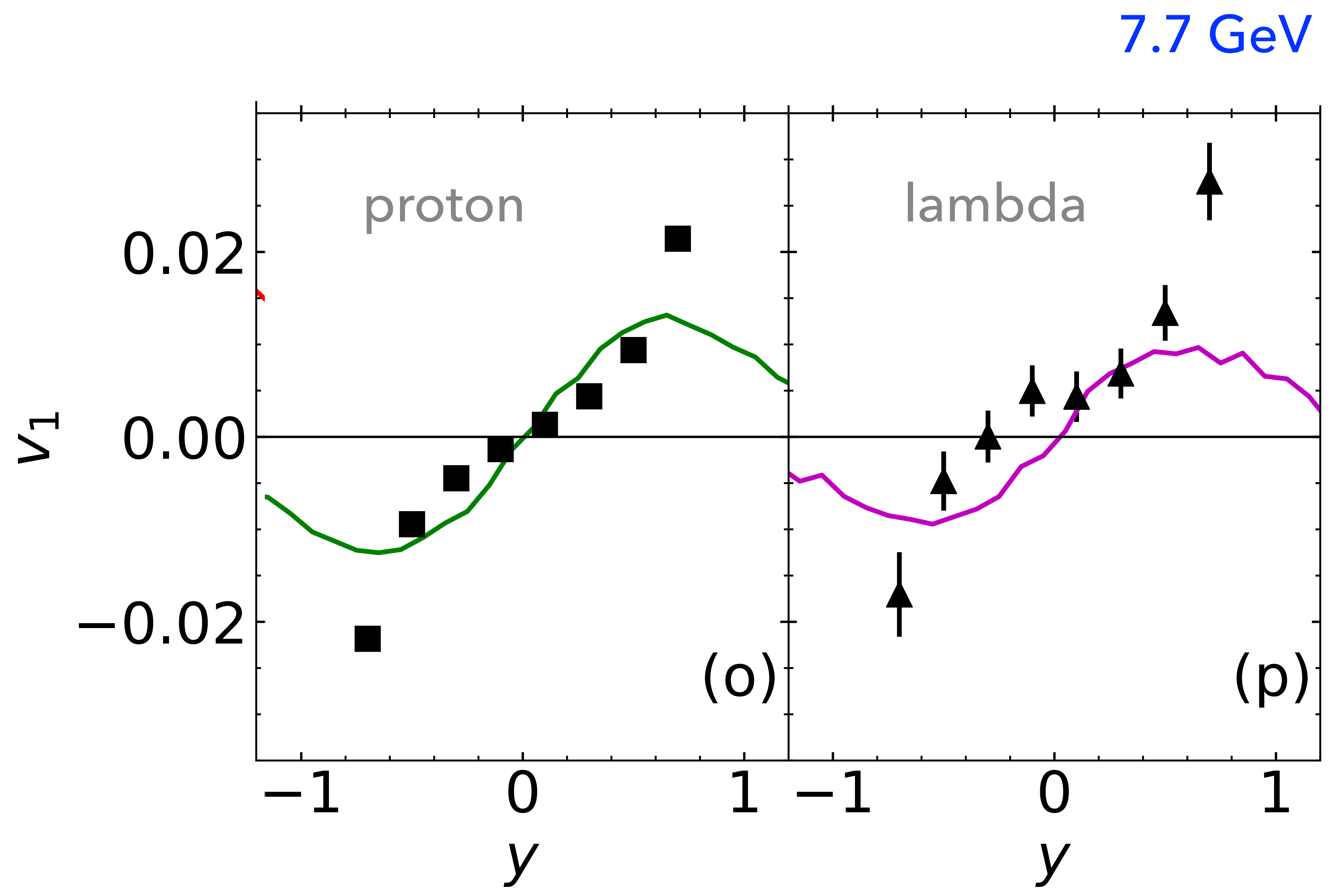
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

DIRECTED FLOW OF BARYONS AT 7.7 GEV



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



- 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
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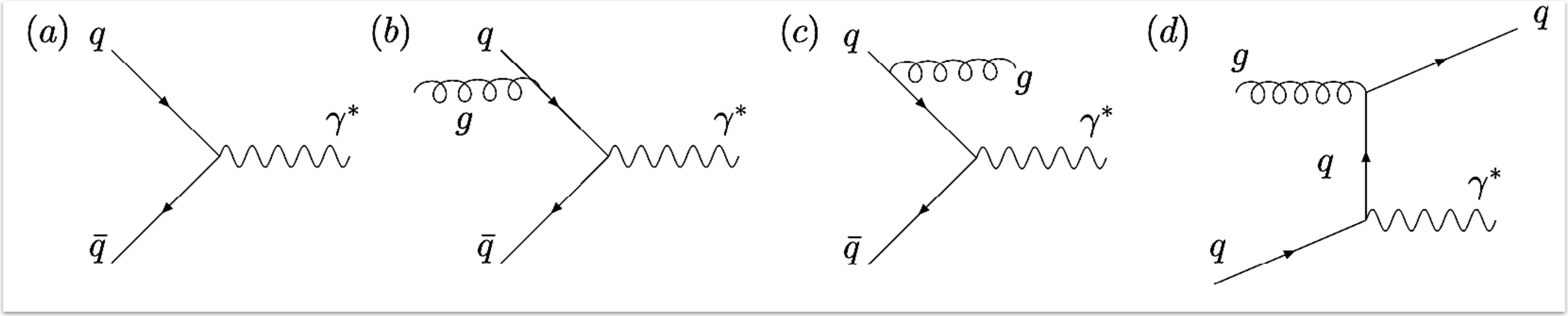
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, arXiv: 2311.06675, arXiv: 2311.06951

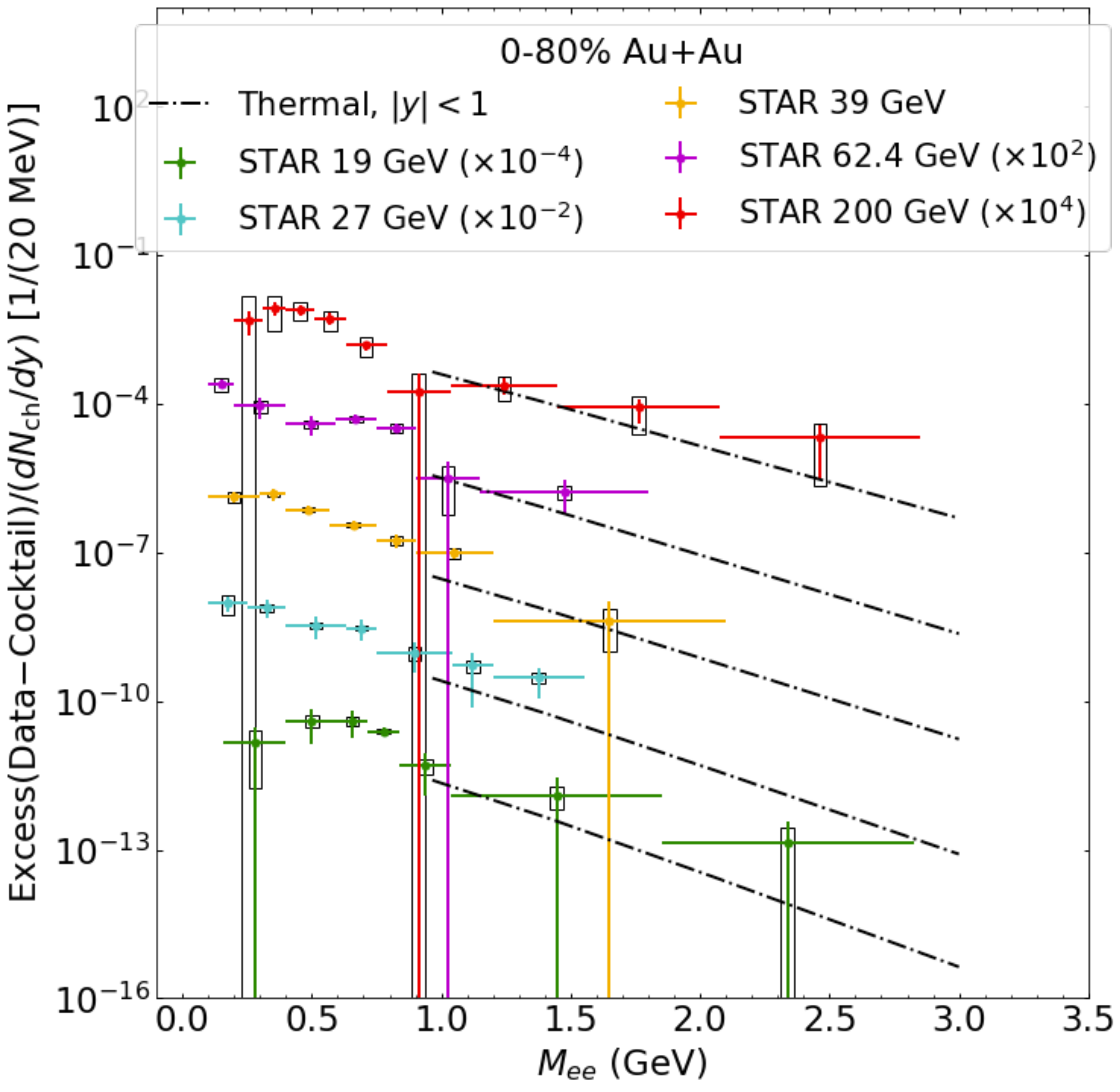
THERMAL DILEPTON AT $\mu_B \neq 0$

THERMAL DILEPTON PRODUCTION

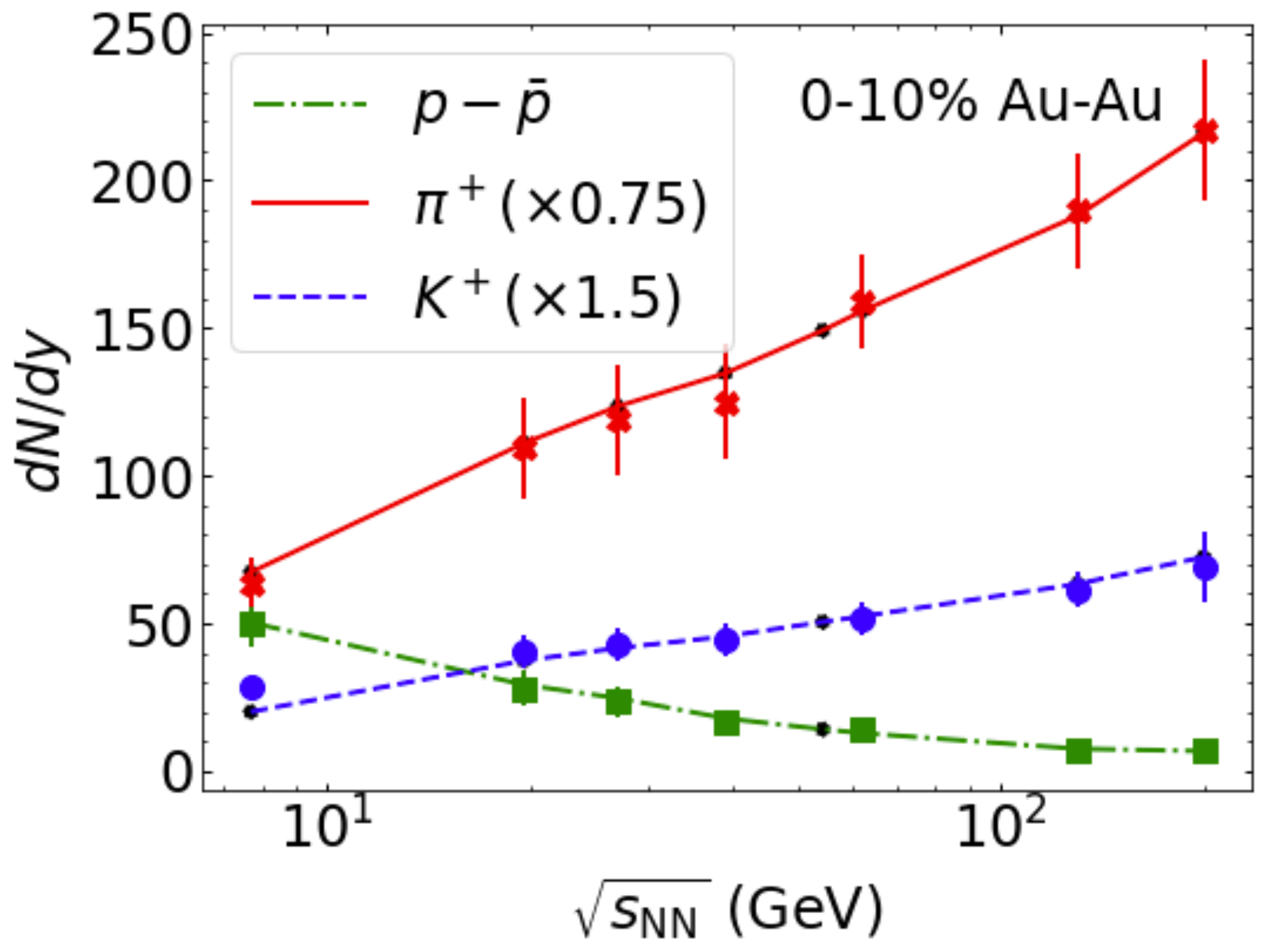


- Baryons: both quarks and string junctions could be the possible source
- Dileptons and photons production: quarks and anti-quarks are needed
- Electromagnetic probes of quarks and anti-quarks
    - μ_B-dependent emission rates assume $\mu_B = 3\mu_q$ (quarks carry baryon number)

THERMAL DILEPTON PRODUCTION



Data: STAR, PRL 113 (2014) 022301, PLB 750 (2015) 64–71, PRC 107 (2023) L061901

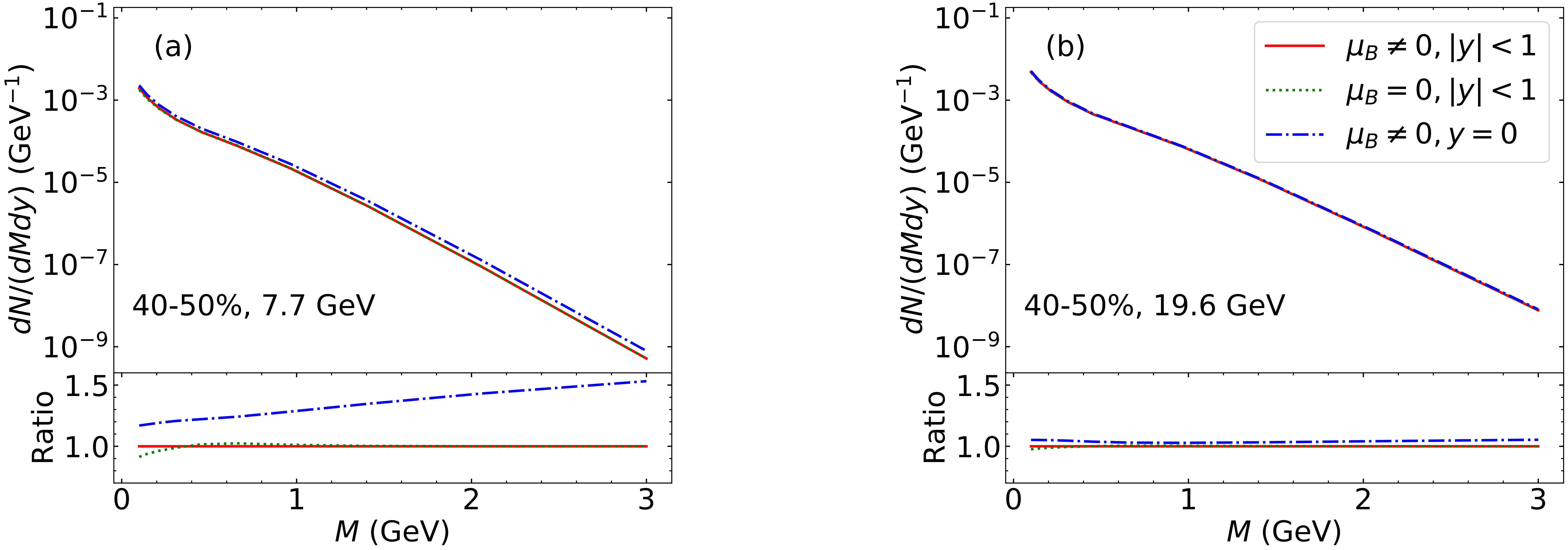


https://github.com/LipeiDu/DileptonEmission

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, arXiv: 2311.06675, 2311.06951

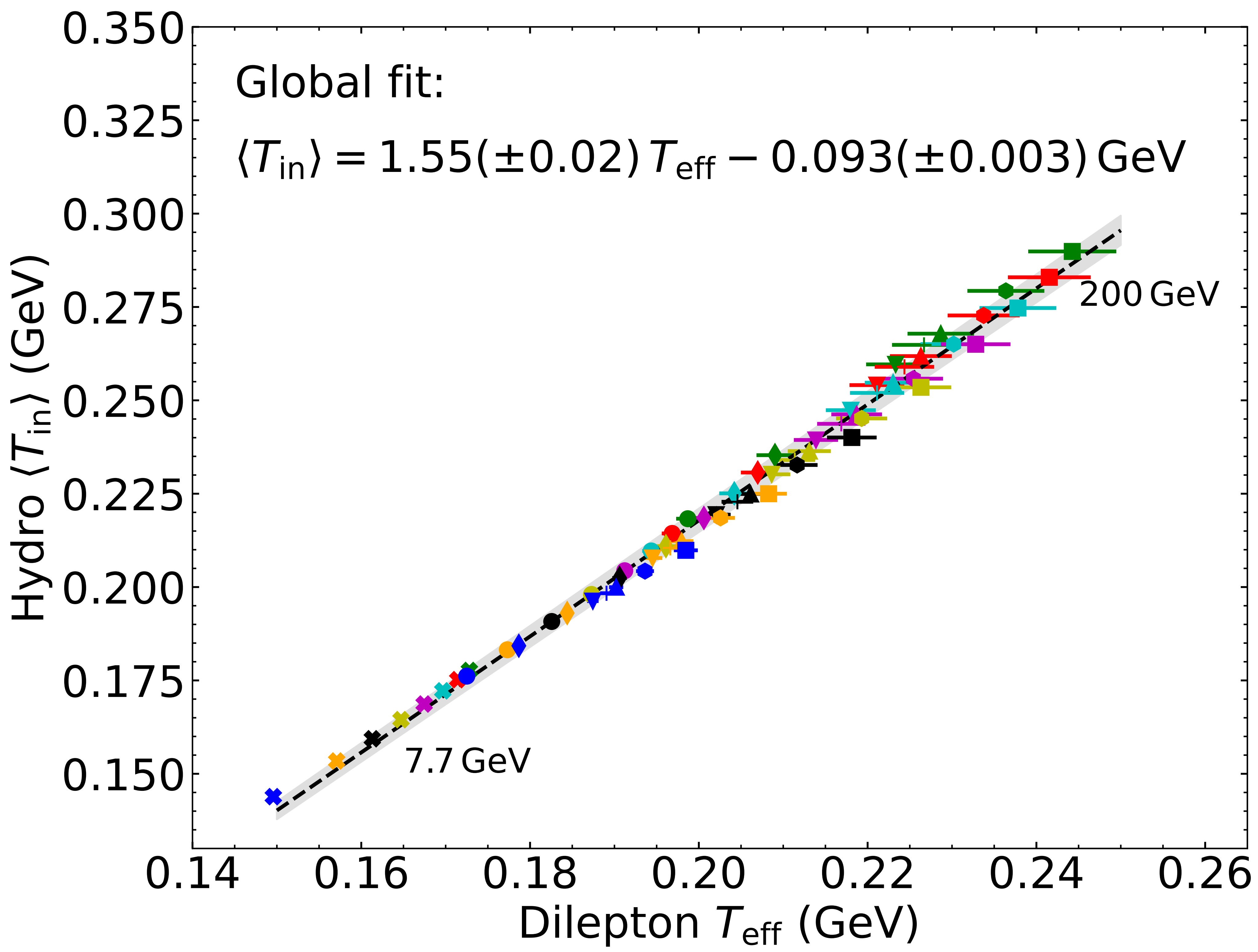
- First estimate of NLO dilepton emission at $\mu_B \neq 0$ with hydrodynamics

RAPIDITY AND μ_B DEPENDENCE



- μ_B-dependence is not significant for 7.7 GeV and higher beam energies
- Sensitivity of real photons to μ_B (excess of q to $\bar{q}$) might be stronger

THERMAL DILEPTON AS THERMOMETER



- Extract the initial QGP temperature from the effective temperature derived from the dilepton spectrum
- Not about μ_B extraction, but very useful!

SUMMARY

SUMMARY

I. Rapidity distributions

- Nucleon deceleration and string junction breaking correspond to different energy losses.
- Probing the total energy deposited in the fireball helps differentiate these two mechanisms.

II. Baryonic $v_1(y)$

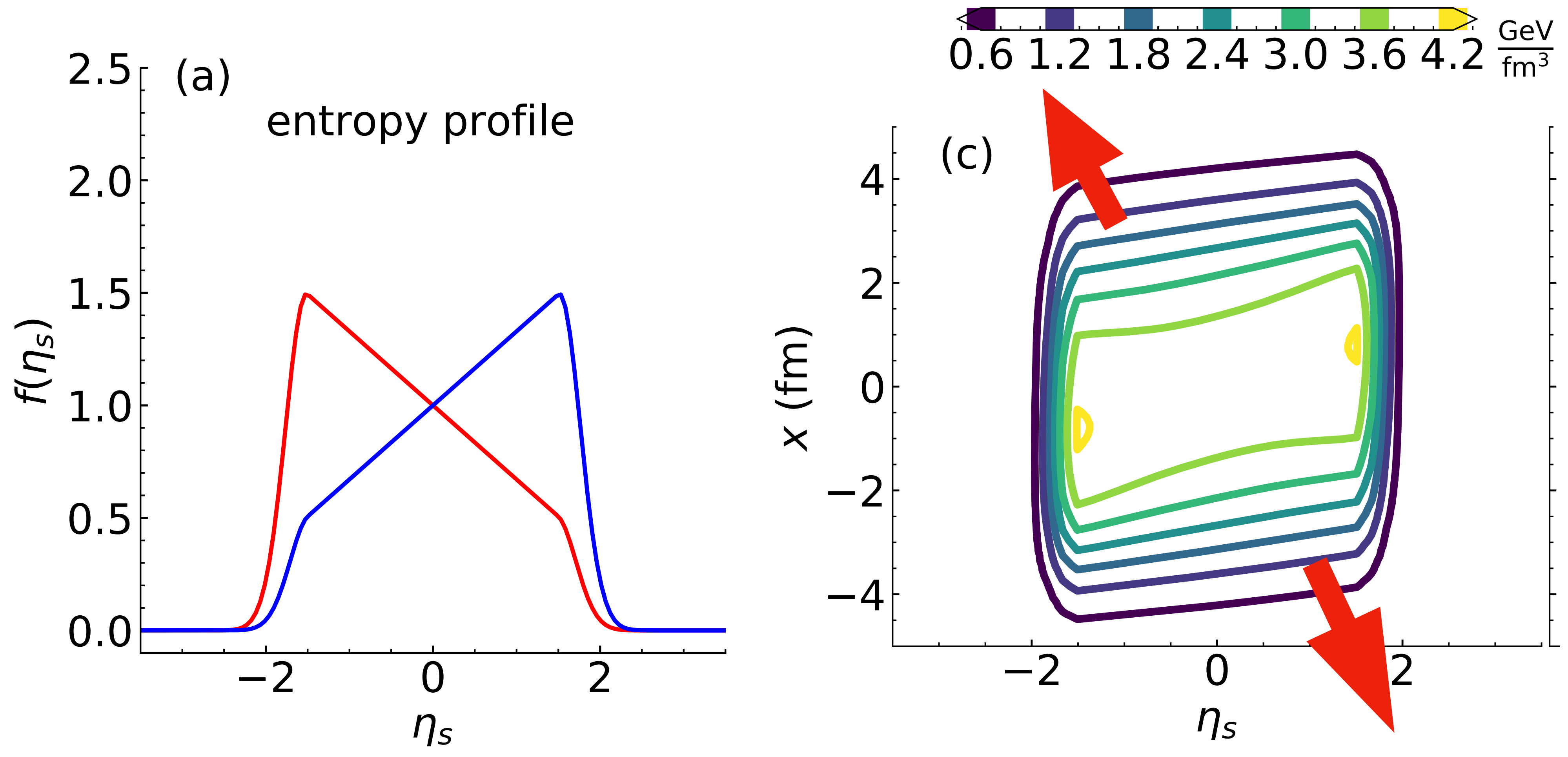
- We introduced a central plateau component in the initial baryon distribution, essential for explaining characteristic features of $v_1(y)$ at various beam energies.
- The plateau component may originate from string junctions.

III. Thermal dilepton

- Electromagnetic probes help to measure quarks and anti-quarks.

THANK YOU FOR YOUR ATTENTION!

DIRECTED FLOW OF MESONS

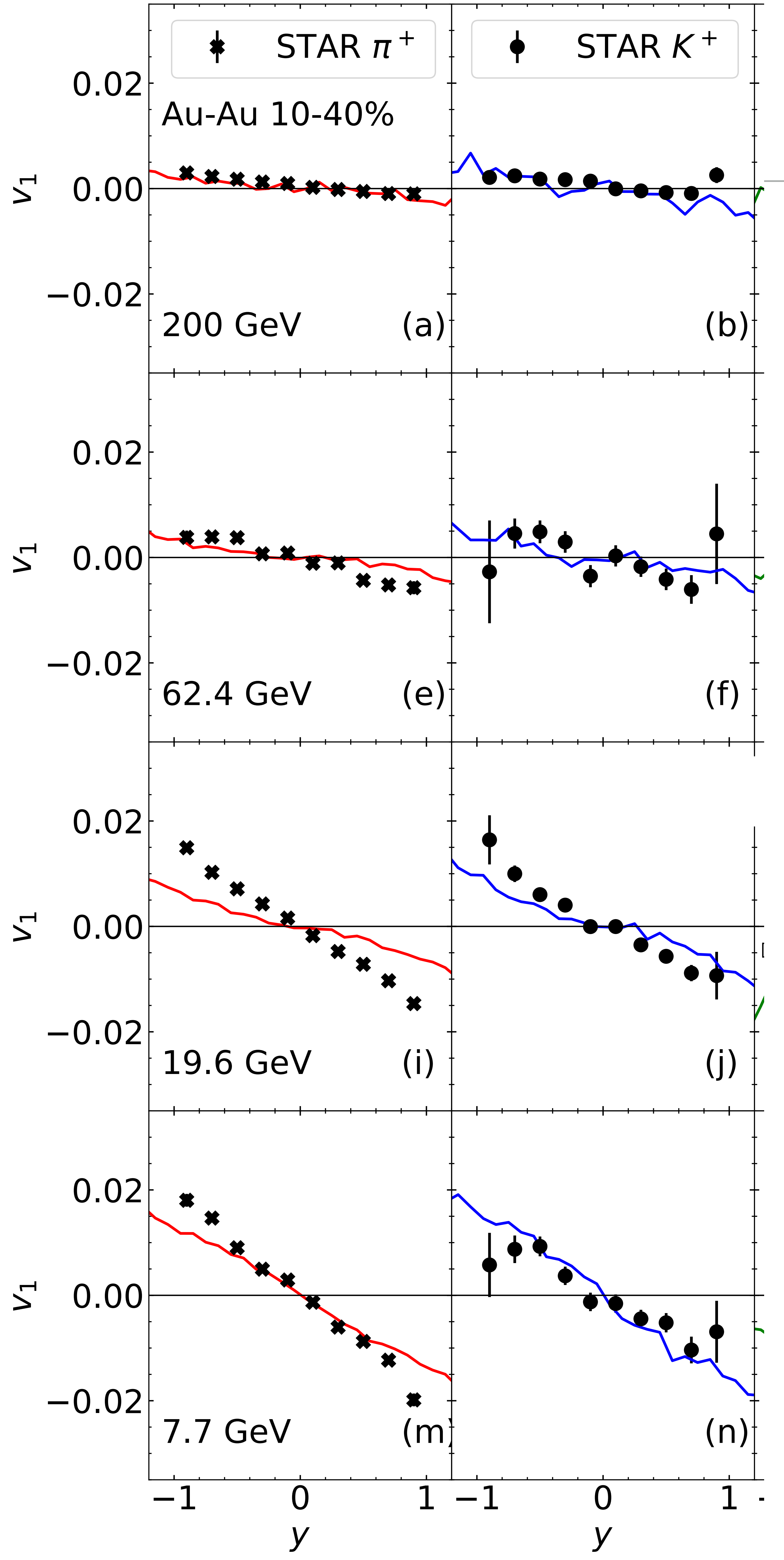


Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV

- $v_1(y)$ of mesons with negative slope at all beam energies; slope increases when beam energy decreases

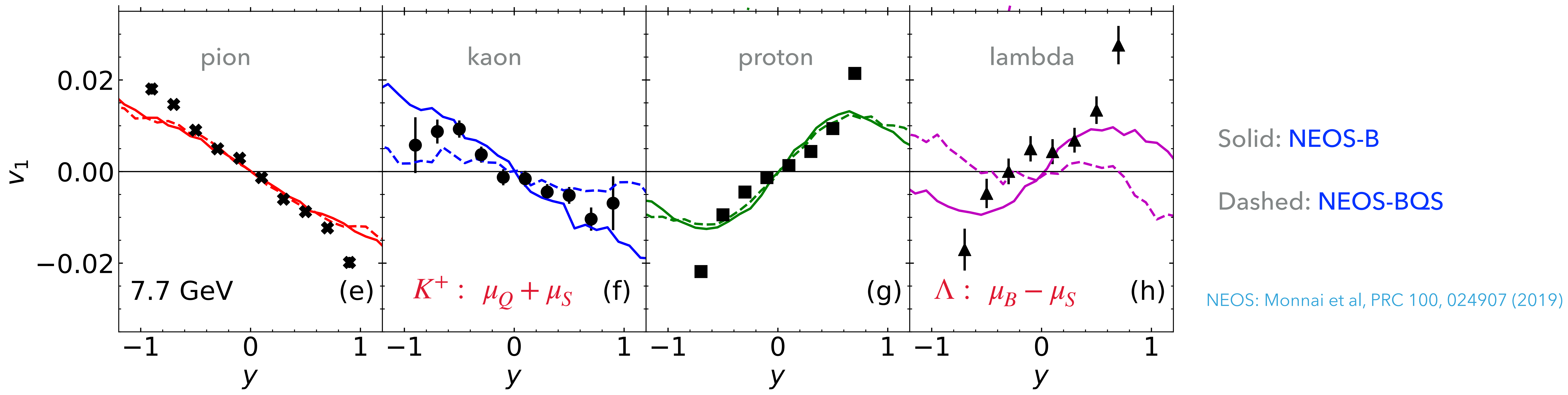
- Slight shift of energy density along x (tilted structure) generates sideward pressure gradient

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



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

PROBING EOS AT FINITE CHEMICAL POTENTIALS

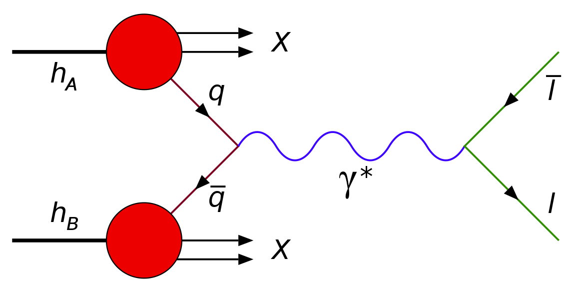


- Two limits of EoS: NEOS-B, $\mu_S = \mu_Q = 0$ and NEOS-BQS, $n_S = 0, n_Q = 0.4n_B$ (2D projection of a 4D EOS)
- Local strangeness neutrality suppresses the $v_1(y)$ of K^+ and Λ around midrapidity, and even alters the sign of Λ's $v_1(y)$ beyond $|y| \gtrsim 0.6$
- The $v_1(y)$ of identified particles can be used to probe EoS at finite chemical potentials.

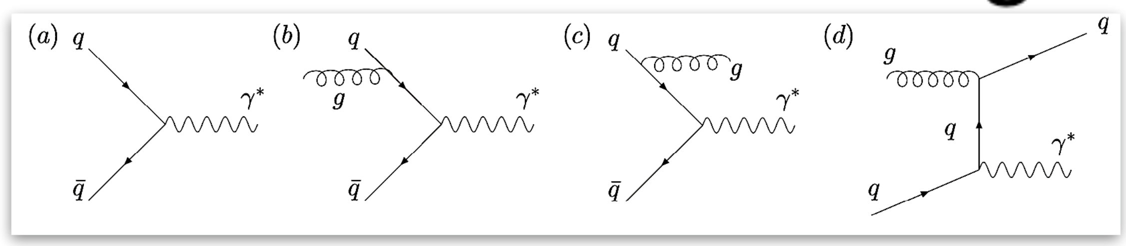
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

DILEPTON SPECTRA

- High-mass region (HMR)
  - Drell-Yan process



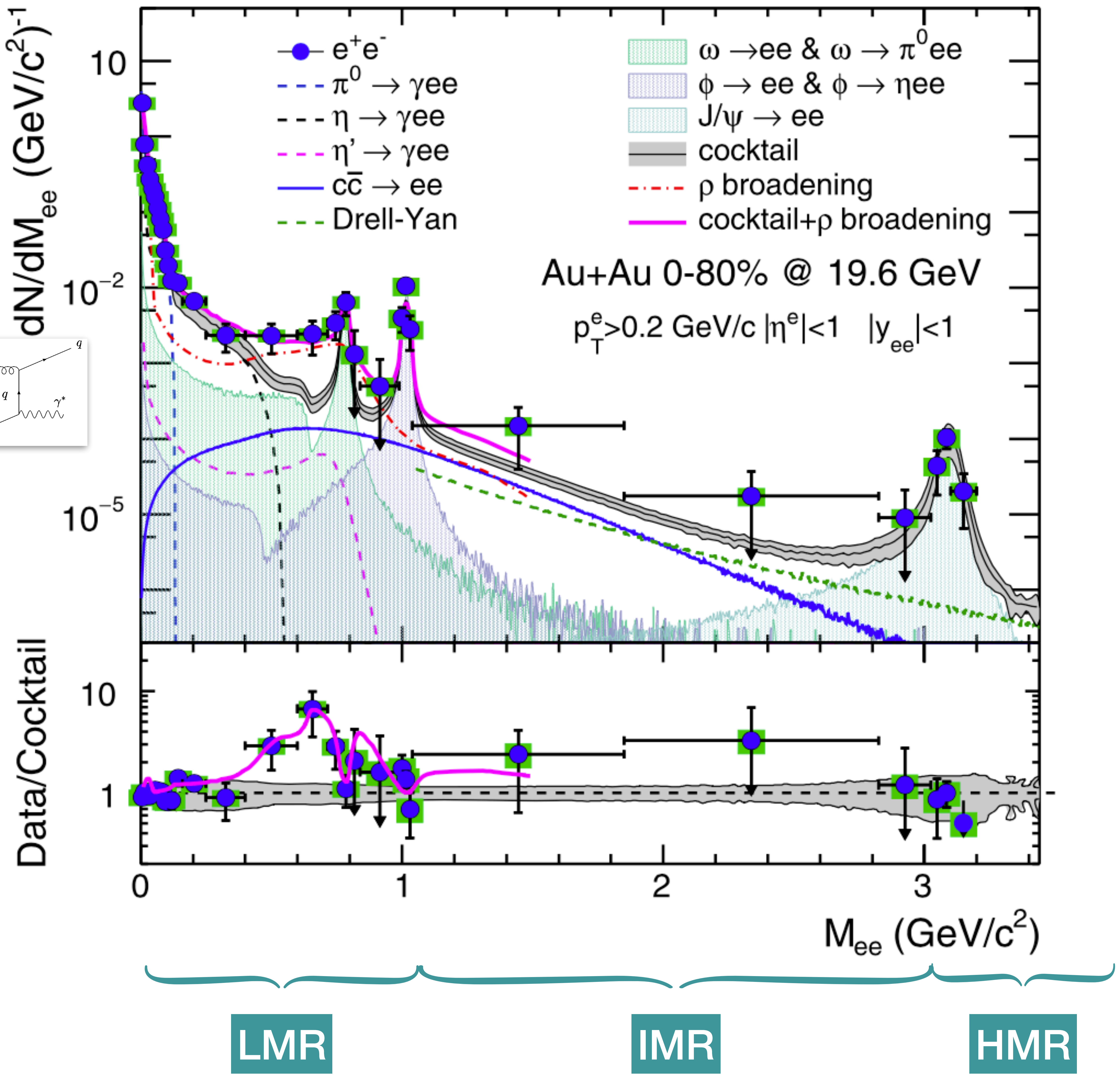
  - decays of J/ψ
- Intermediate-mass region (IMR)
  - thermal emission from QGP



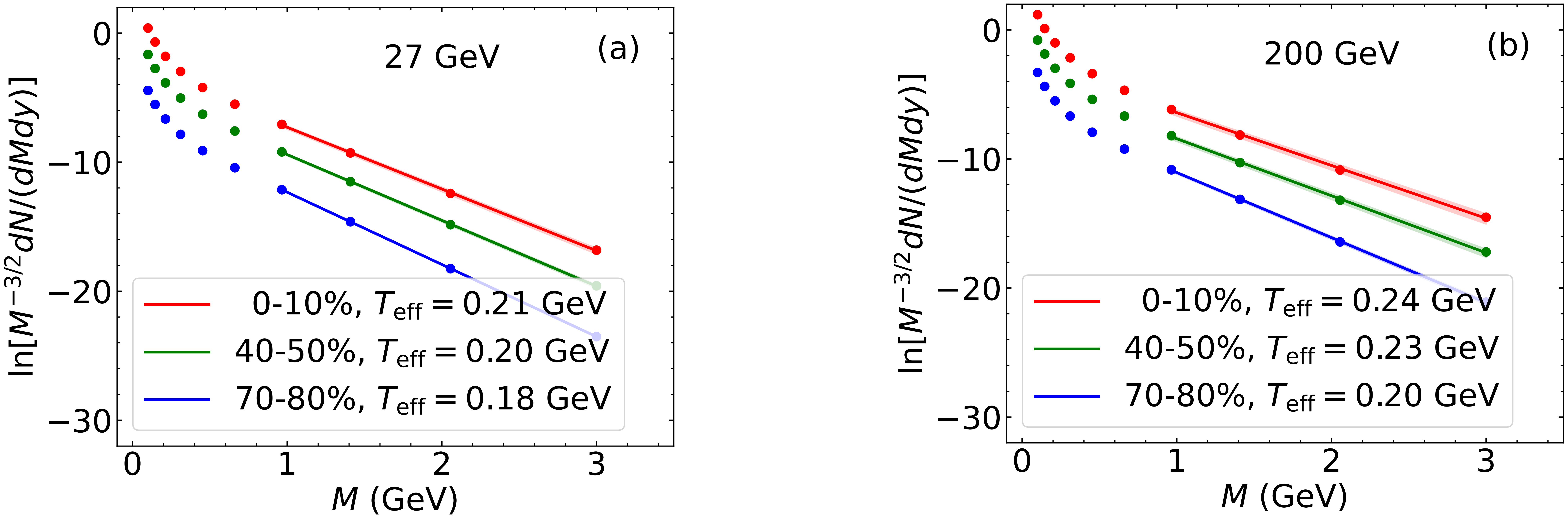
  - semileptonic decays from open heavy flavor-antiflavor pair, e.g. $D/\bar{D}$
- Low-mass region (LMR)
  - thermal emission from hadronic matter
  - direct decays of $\rho/\omega/\phi$ (ρ is short-lived)
  - Dalitz (three body) decays of $\pi^0/\eta/\eta'$

Dilepton cocktail: late decays of hadrons

STAR, PLB 750 (2015) 64–71

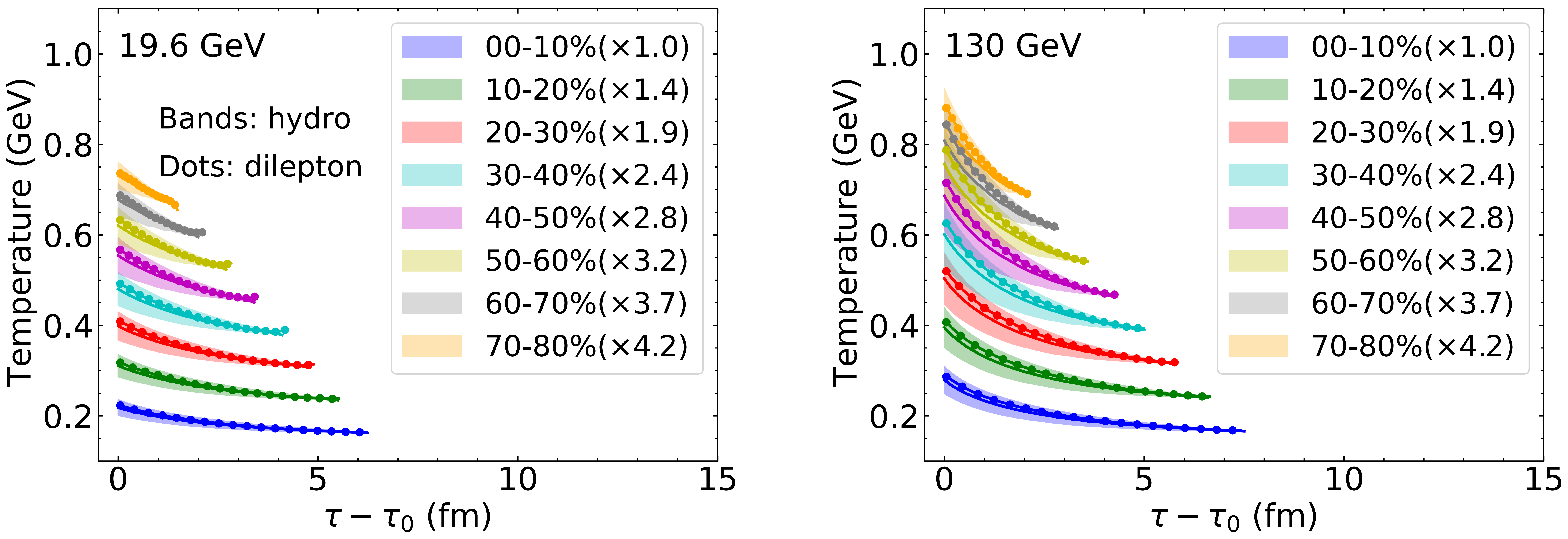


TEMPERATURE EXTRACTION



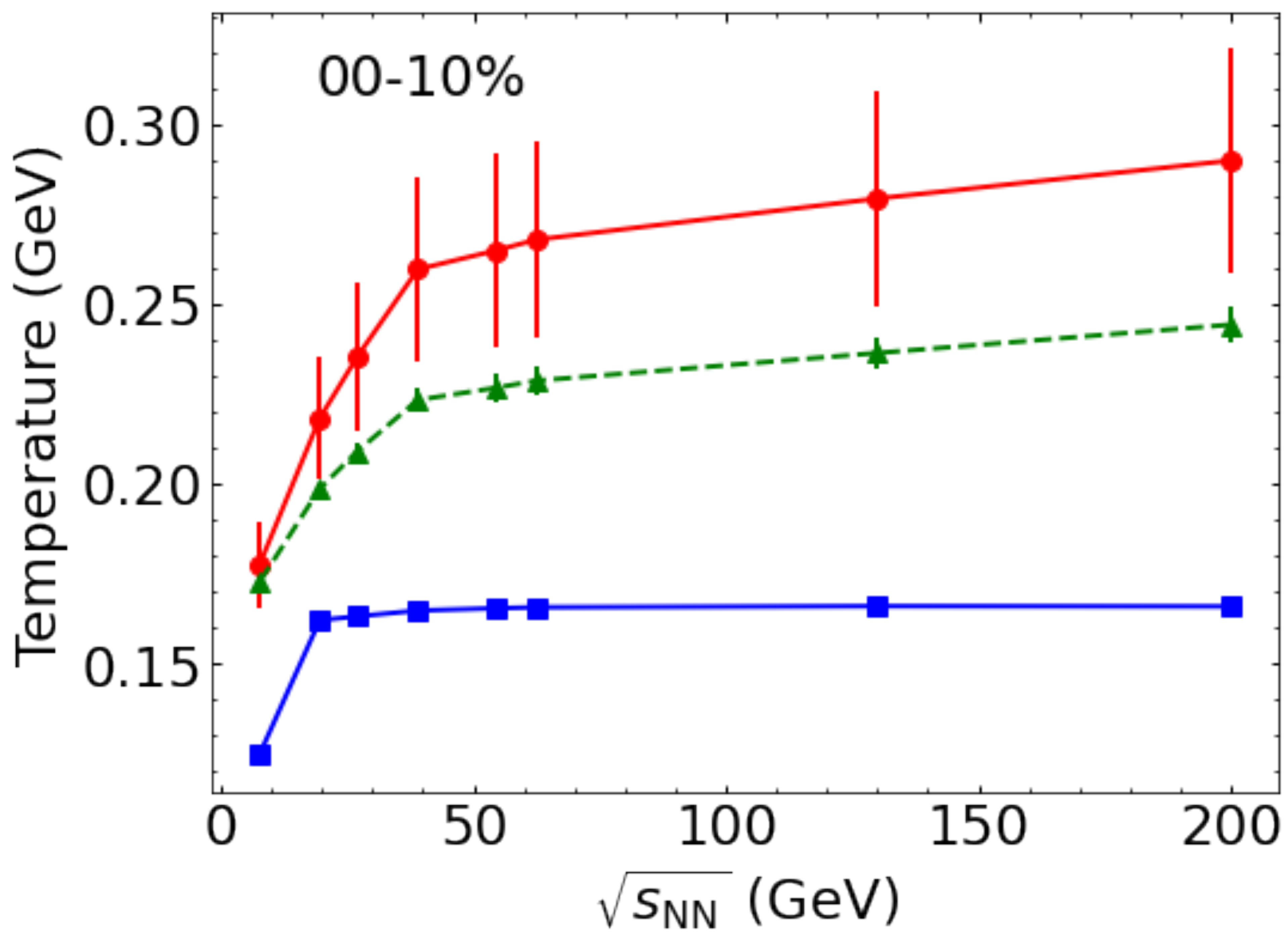
- In non-relativistic approximation, the emission rate $\dfrac{dR}{dM} \propto (MT)^{3/2} e^{-M/T}$
- Use thermal dileptons within $1\text{GeV} \lesssim M \lesssim 3\text{GeV}$ for temperature extraction
$$\ln\left(\frac{dN}{dM}M^{-3/2}\right) \propto \ln(T^{3/2}e^{-M/T}) = -\frac{M}{T} + \dots$$

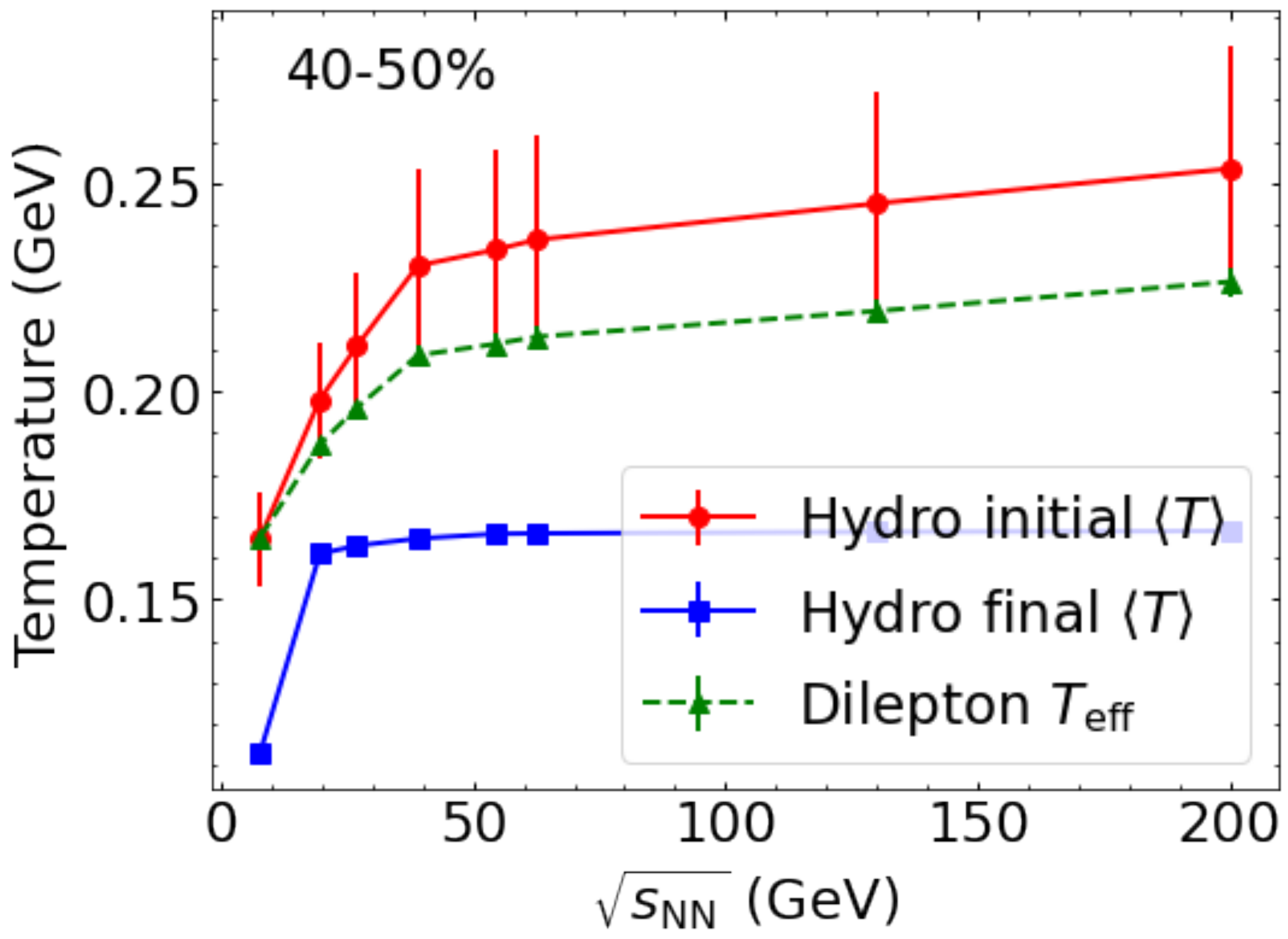
TEMPERATURE EXTRACTION IN τ



- To obtain hydrodynamic temperature distribution, the temperature of each fluid cell is weighted by its energy density. curve: mean temperature; band: standard deviation
- Dots: effective temperature extracted from dilepton spectra

THERMAL DILEPTON AS THERMOMETER





- The final temperature is approximately a constant for $\sqrt{s_{NN}} \gtrsim 19.6$ GeV and much smaller at $\sqrt{s_{NN}} = 7.7$ GeV because of the baryon chemical potential
- A correlation between the hydro initial temperature and effective temperature can be observed