LIPEI DU

McGILL U / UC BERKELEY / LBNL

THEORY OVERVIEW ON COLLECTIVITY

THE 15TH WORKSHOP ON CRITICAL POINT AND ONSET OF DECONFINEMENT

BERKELEY, CA (MAY 20, 2024)

LIPEI DU

MCGILL U / UC BERKELEY / LBNL

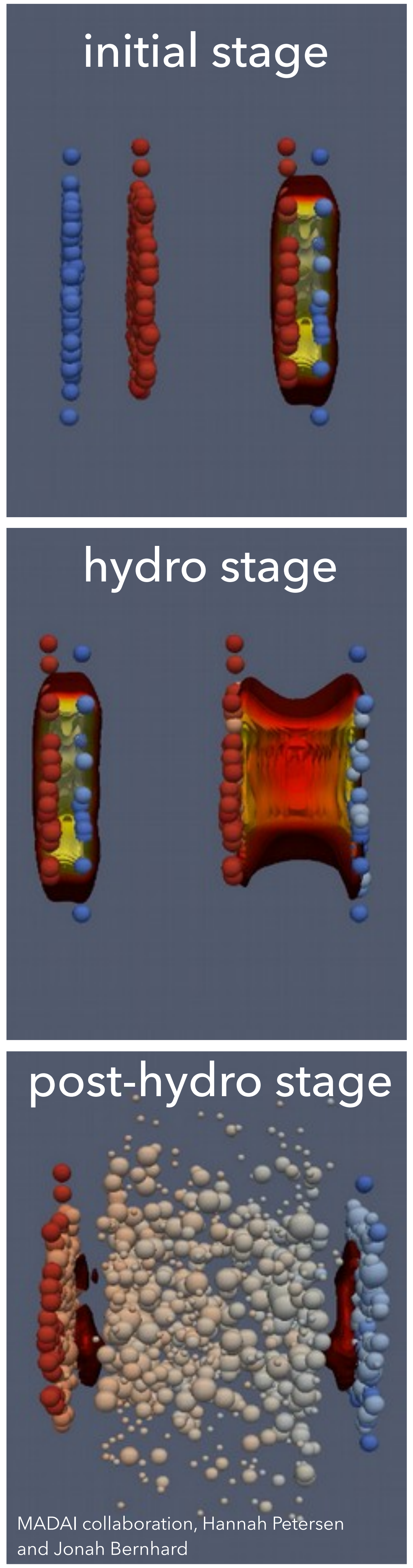
THEORY OVERVIEW ON COLLECTIVITY

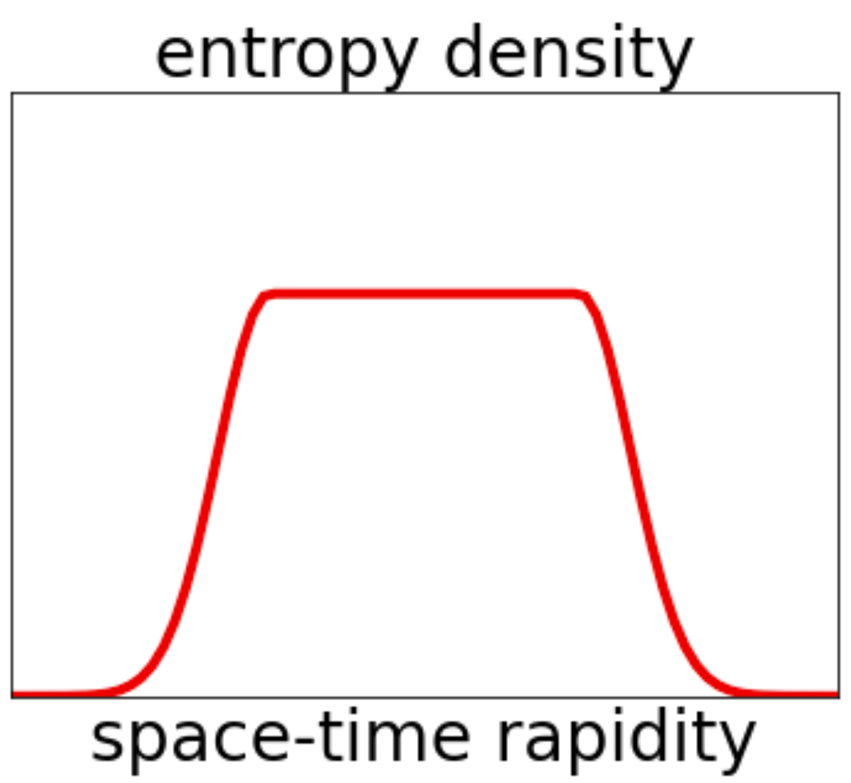
COLLECTIVITY IN THE BEAM DIRECTION

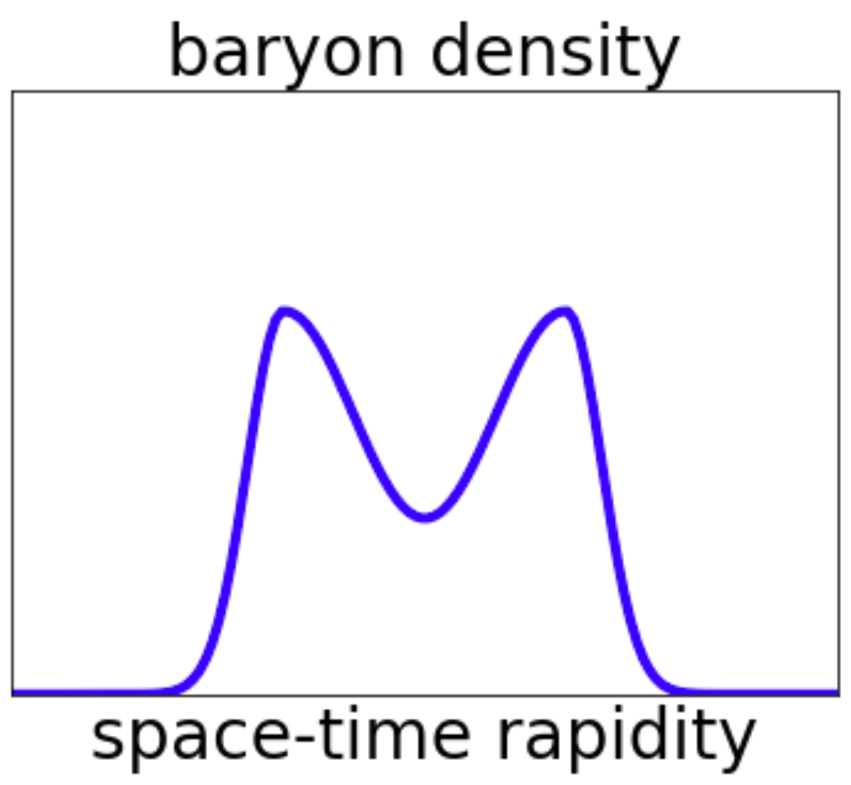
THE 15TH WORKSHOP ON CRITICAL POINT AND ONSET OF DECONFINEMENT

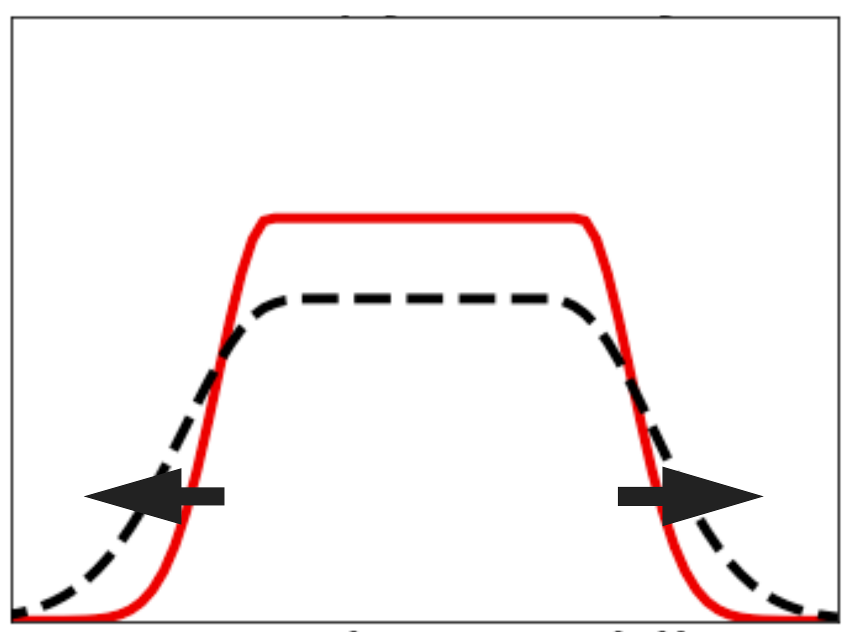
BERKELEY, CA (MAY 20, 2024)

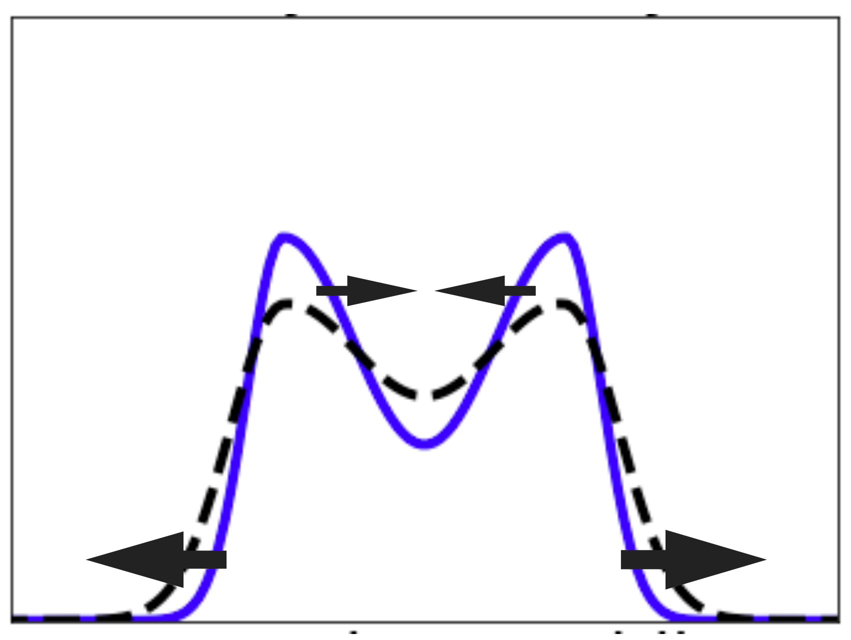
LONGITUDINAL DYNAMICS

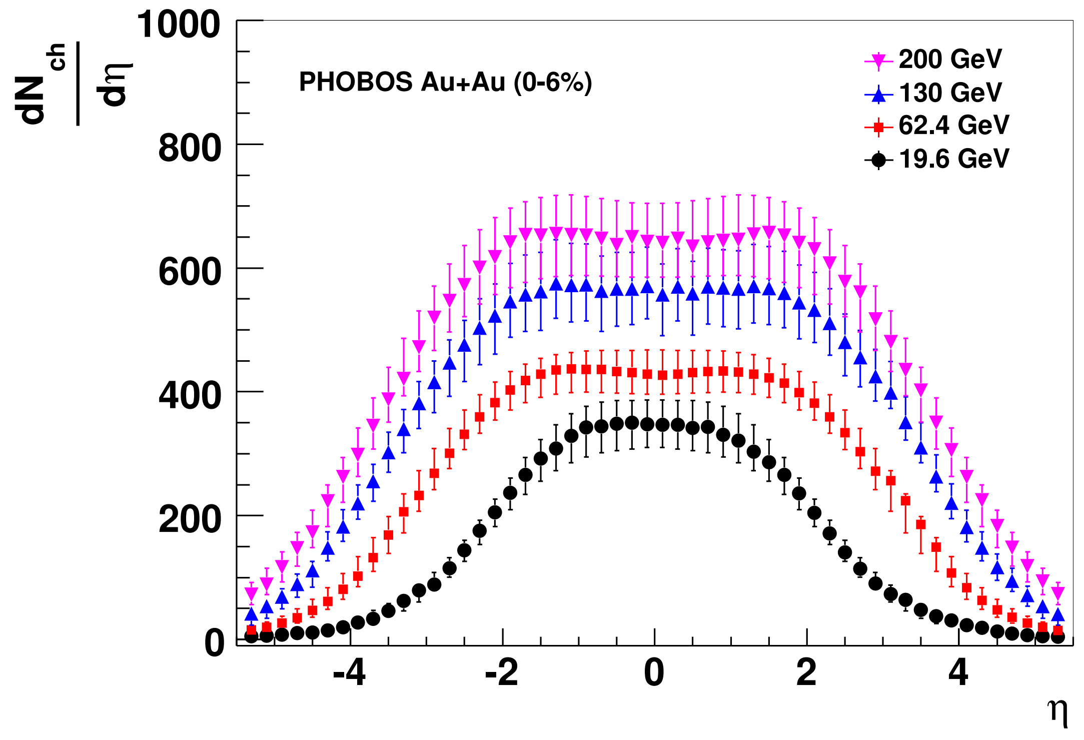


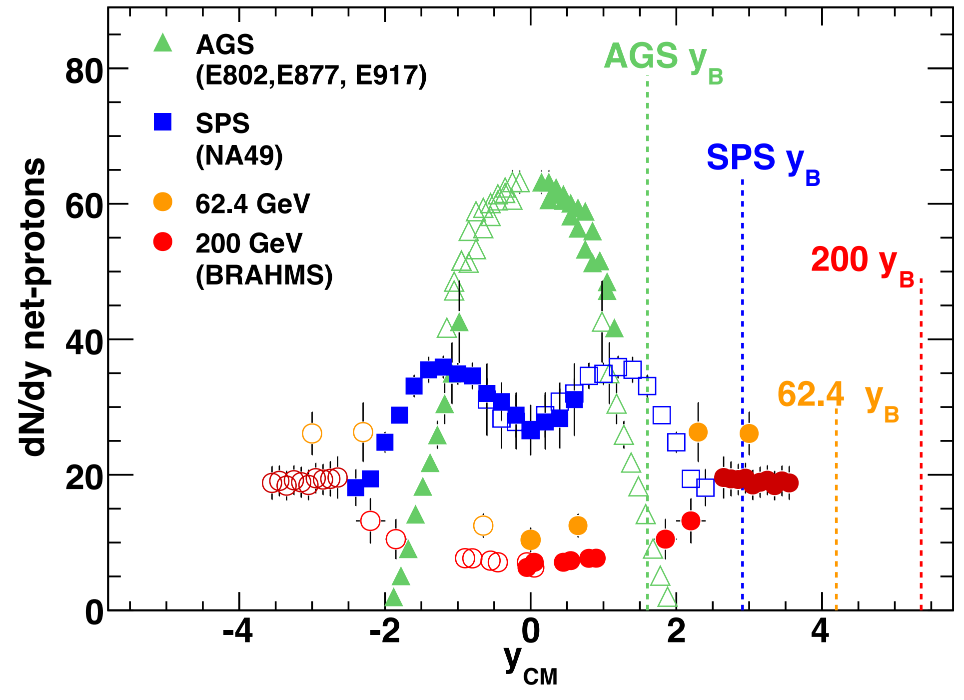












- initial energy deposition
- initial baryon stopping

+

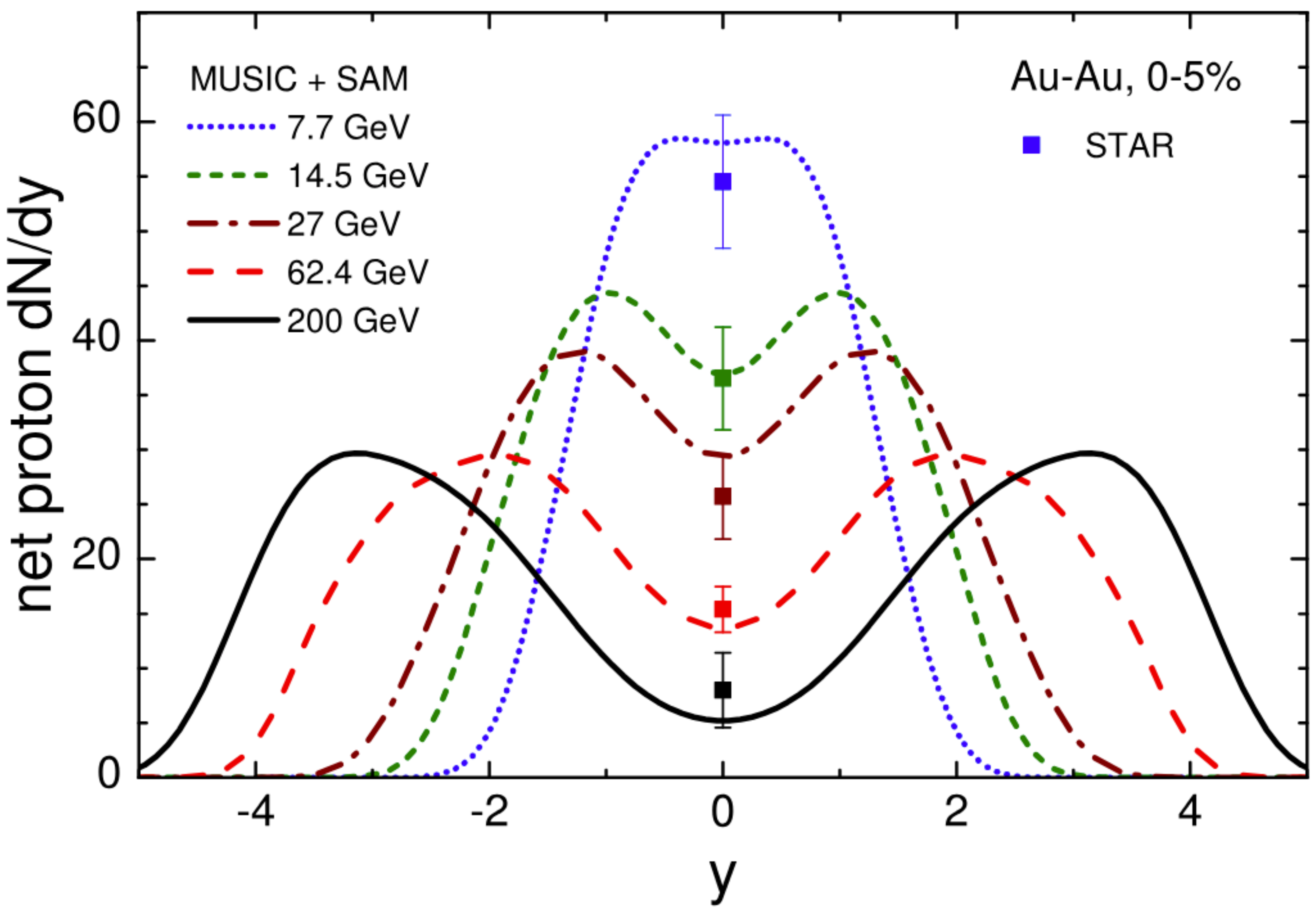
- longitudinal pressure gradient ⟹ longitudinal flow & expansion
- baryon density gradient ⟹ baryon diffusion (hydro transport)

↓

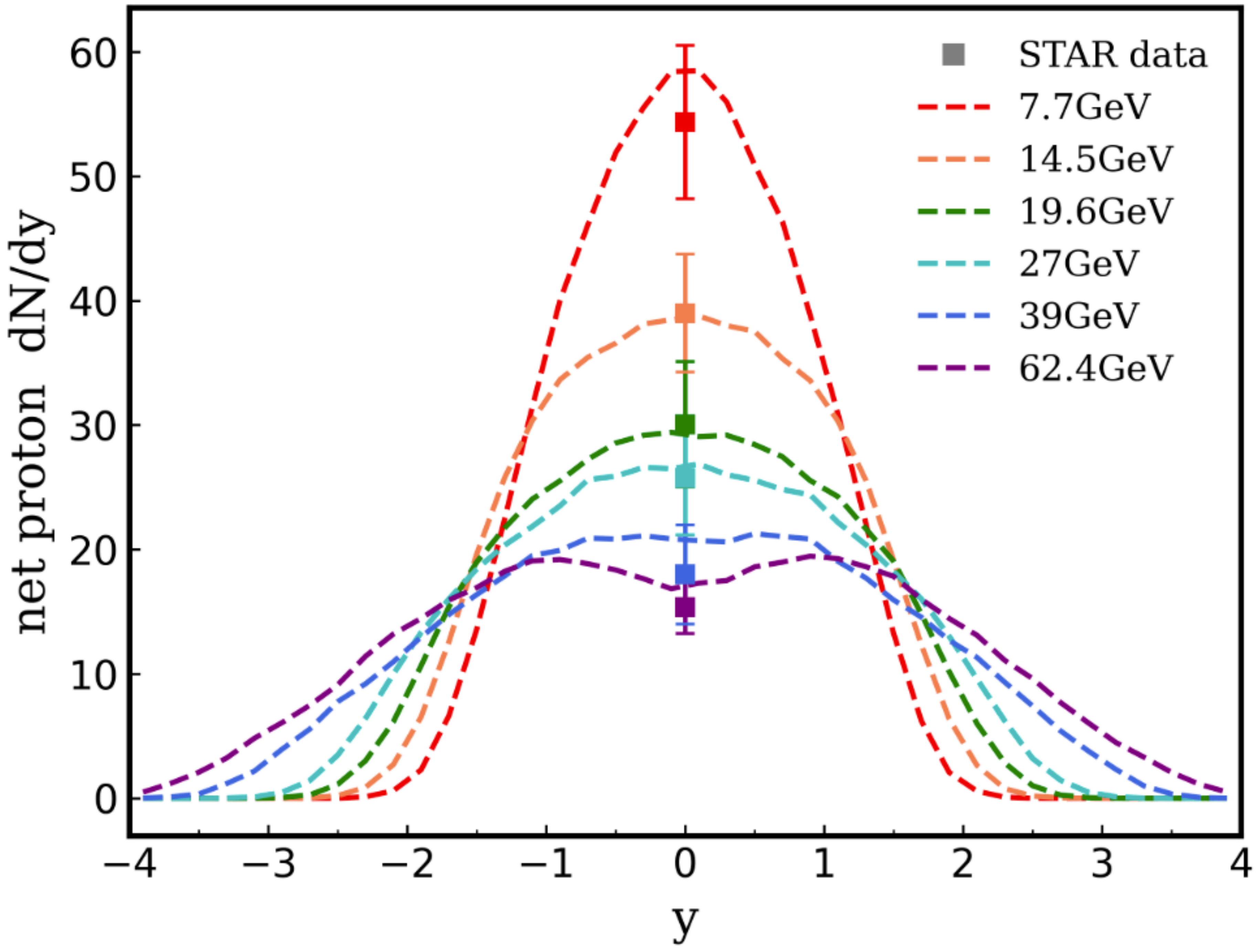
- rapidity-dependent particle distributions

LONGITUDINAL THERMODYNAMIC PROPERTIES

MID-RAPIDITY MEASUREMENTS



Vovchenko, Koch, and C. Shen, PRC 105, 014904 (2022)

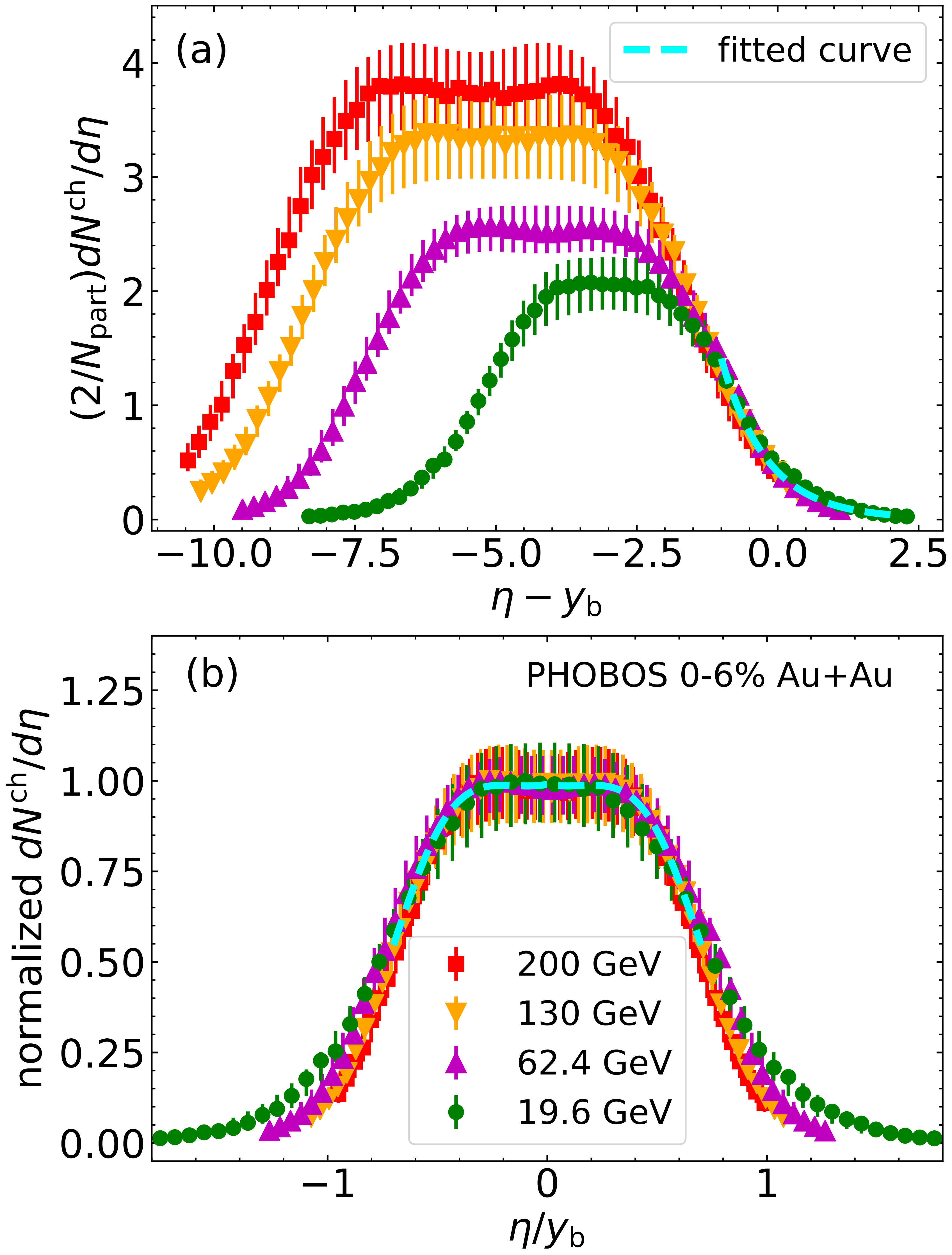


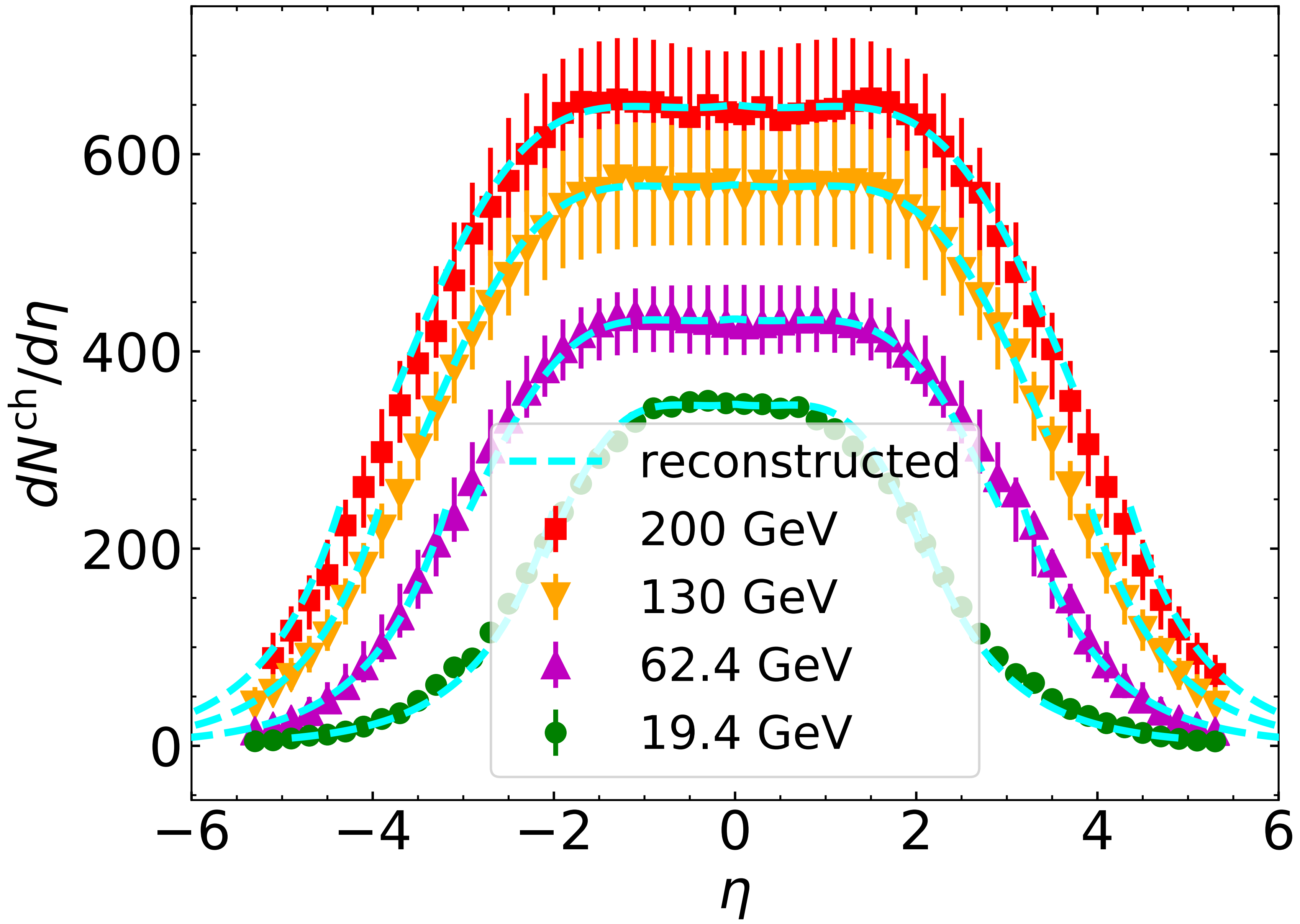
Y.-f. Shen, Chen, Wu, Xu, and Huang, 2404.02397

- If we only take measurements at mid-rapidity, the dynamics along the beam direction may not be well-constrained.

G. Denicol et al, PRC 98, 034916 (2018); LD, An and Heinz, PRC 104, 064904 (2021); LD, Gao, Jeon & Gale, PRC 109, 014907 (2024); Mendenhall and Lin, PRC 107, 034909 (2023); Cimerman, Karpenko, Tomášik, and Trzeciak, PRC 103, 034902 (2021); Cimerman, Karpenko, Tomášik, and Huovinen, PRC 107, 044902 (2023)

CONSTRUCT RAPIDITY-DISTRIBUTION: $dN^{\rm ch}/d\eta$

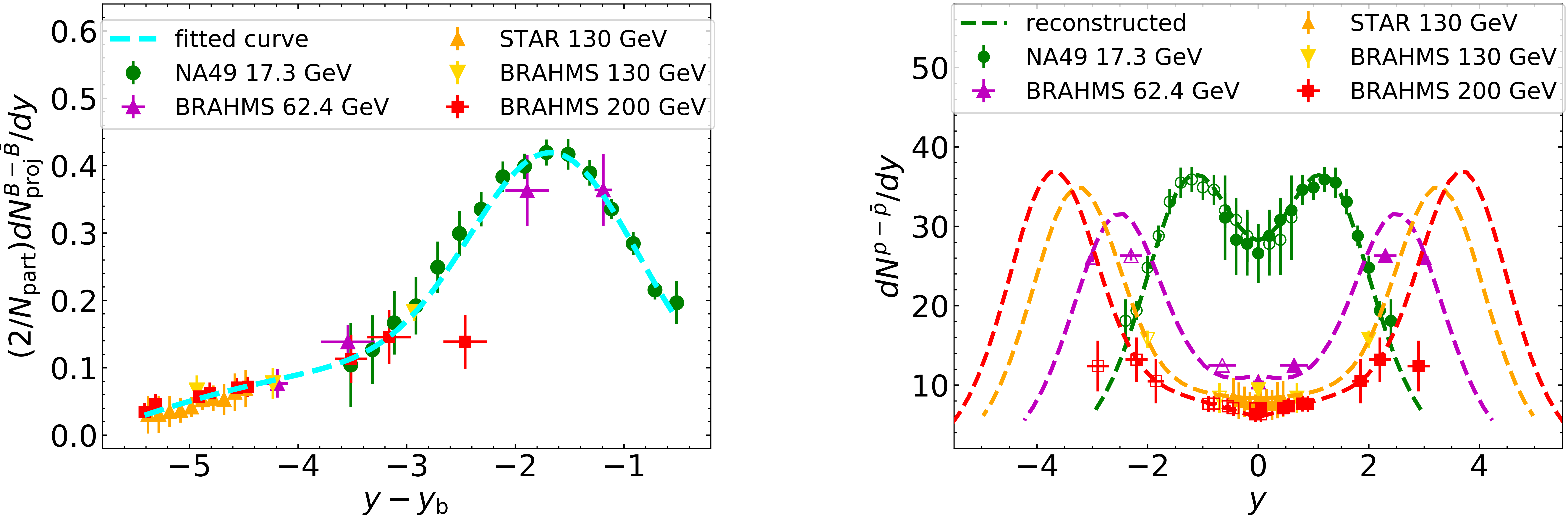




- Fit two regions separately: Lipei Du, arXiv: 2401.00596
  - forward-rapidity: limiting fragmentation
  - mid-rapidity: central plateau
- The fitted curves can be used to reconstruct $dN^{\rm ch}/d\eta$, even at energies that were not directly measured.

PHOBOS, PRL 91, 052303 (2003); PHOBOS, PRC 83, 024913 (2011); ALICE, PRL 116, 222302 (2016); Basu et al 2021 J. Phys. G: Nucl. Part. Phys. 48 025103;

CONSTRUCT RAPIDITY-DISTRIBUTION: $dN^{p-\bar{p}}/dy$

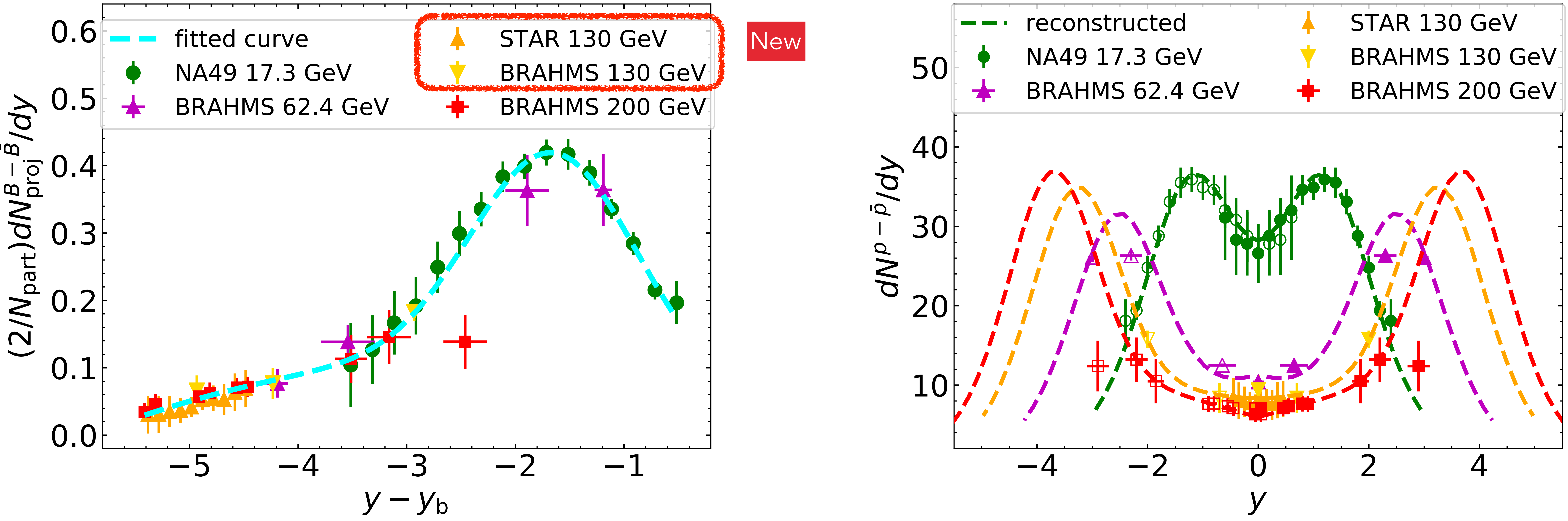


Lipei Du, arXiv: 2401.00596

- Fit the net baryon rapidity density attributed to the projectile after subtraction of the target contribution.
- The reconstructed distributions can help constrain models at BES.

BRAHMS, PLB 677, 267-271(2009); Braun-Munzinger, Friman, Redlich, Rustamov, and Stachel, NPA 1008 (2021) 122141; Hoelck, Hiyama, and Wolschin, PLB 840, 137866 (2023)

CONSTRUCT RAPIDITY-DISTRIBUTION: $dN^{p-\bar{p}}/dy$

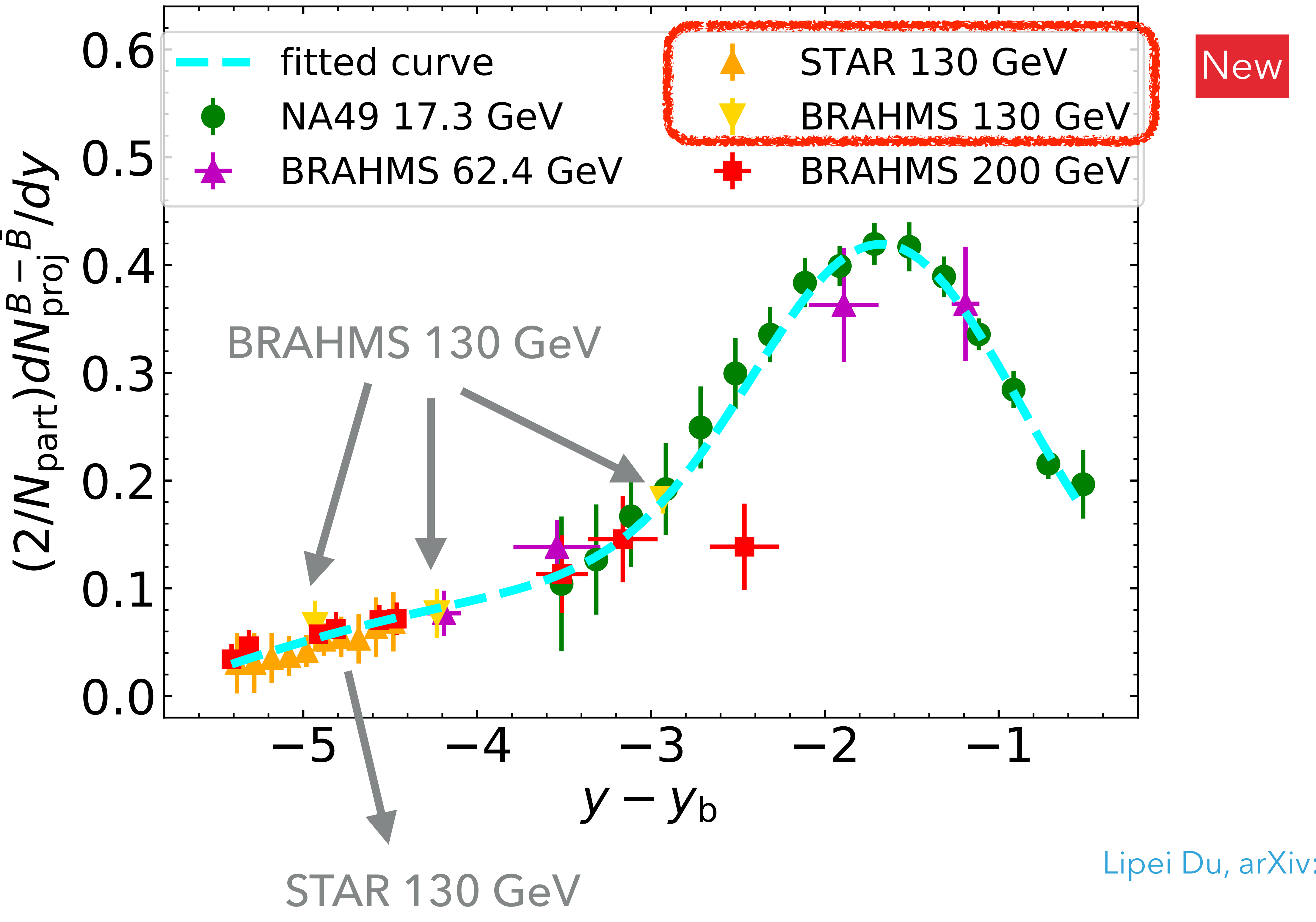


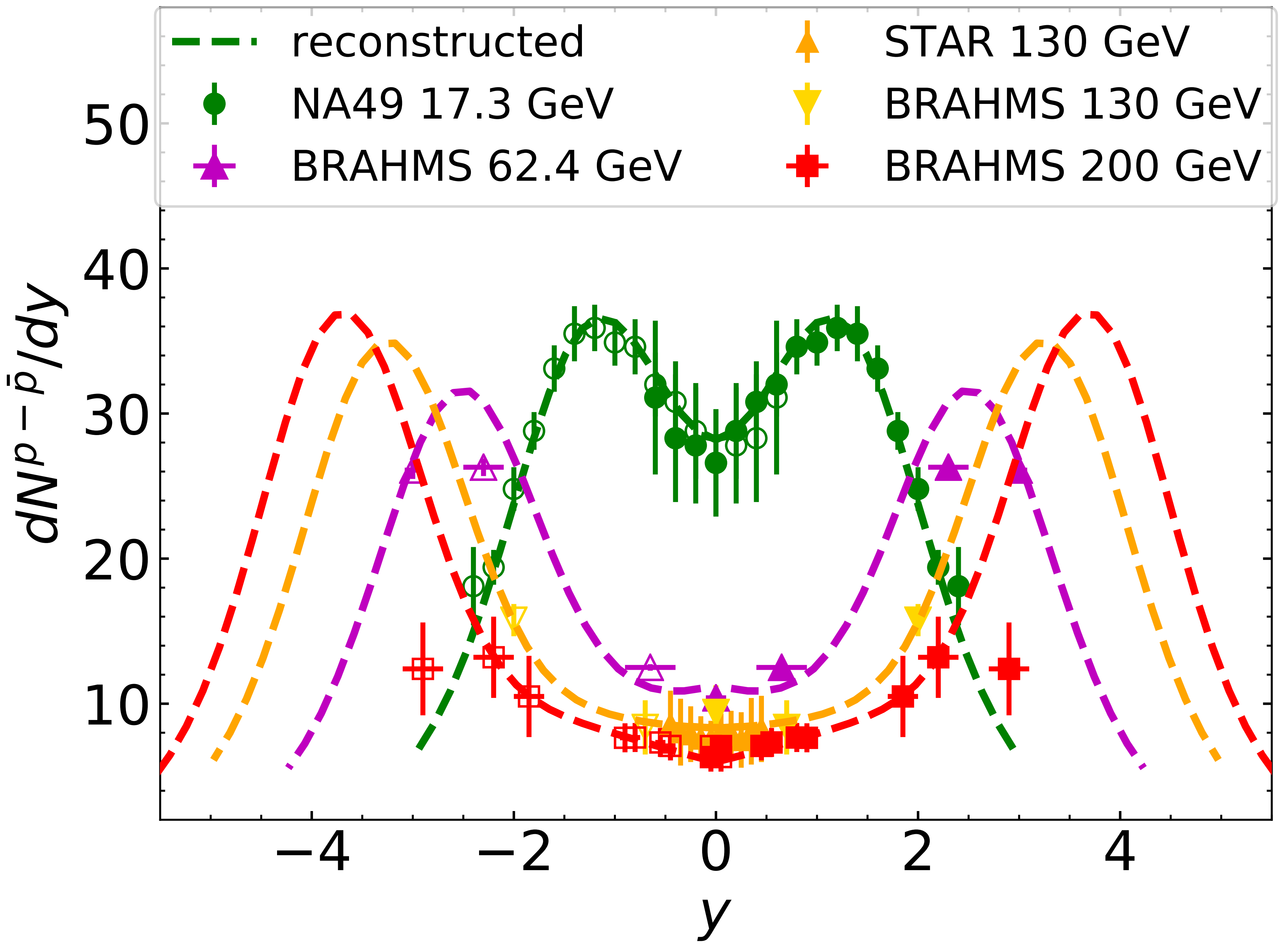
Lipei Du, arXiv: 2401.00596

- Fit the net baryon rapidity density attributed to the projectile after subtraction of the target contribution.
- The reconstructed distributions can help constrain models at BES.

BRAHMS, PLB 677, 267-271(2009); Braun-Munzinger, Friman, Redlich, Rustamov, and Stachel, NPA 1008 (2021) 122141; Hoelck, Hiyama, and Wolschin, PLB 840, 137866 (2023)

CONSTRUCT RAPIDITY-DISTRIBUTION: $dN^{p-\bar{p}}/dy$



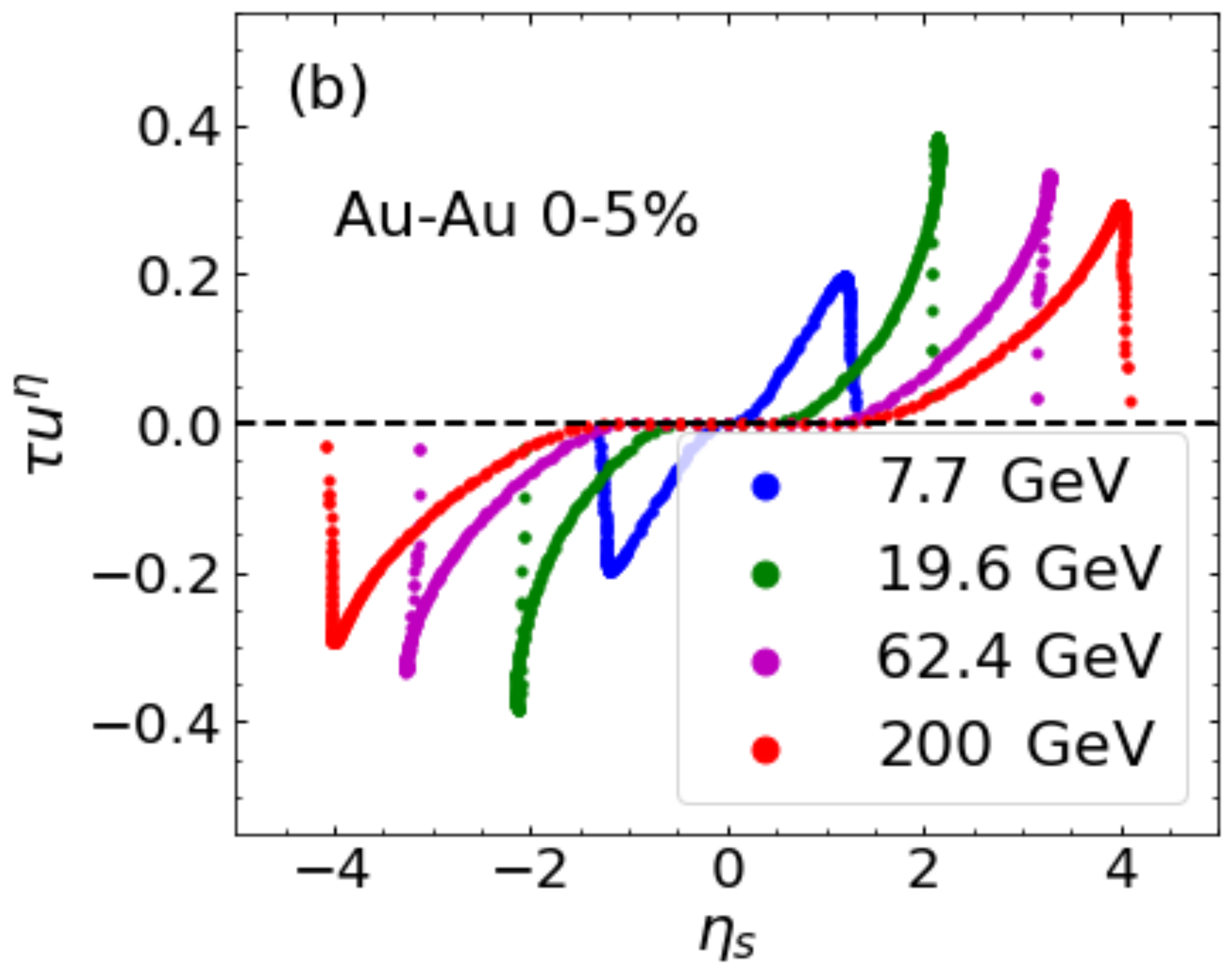


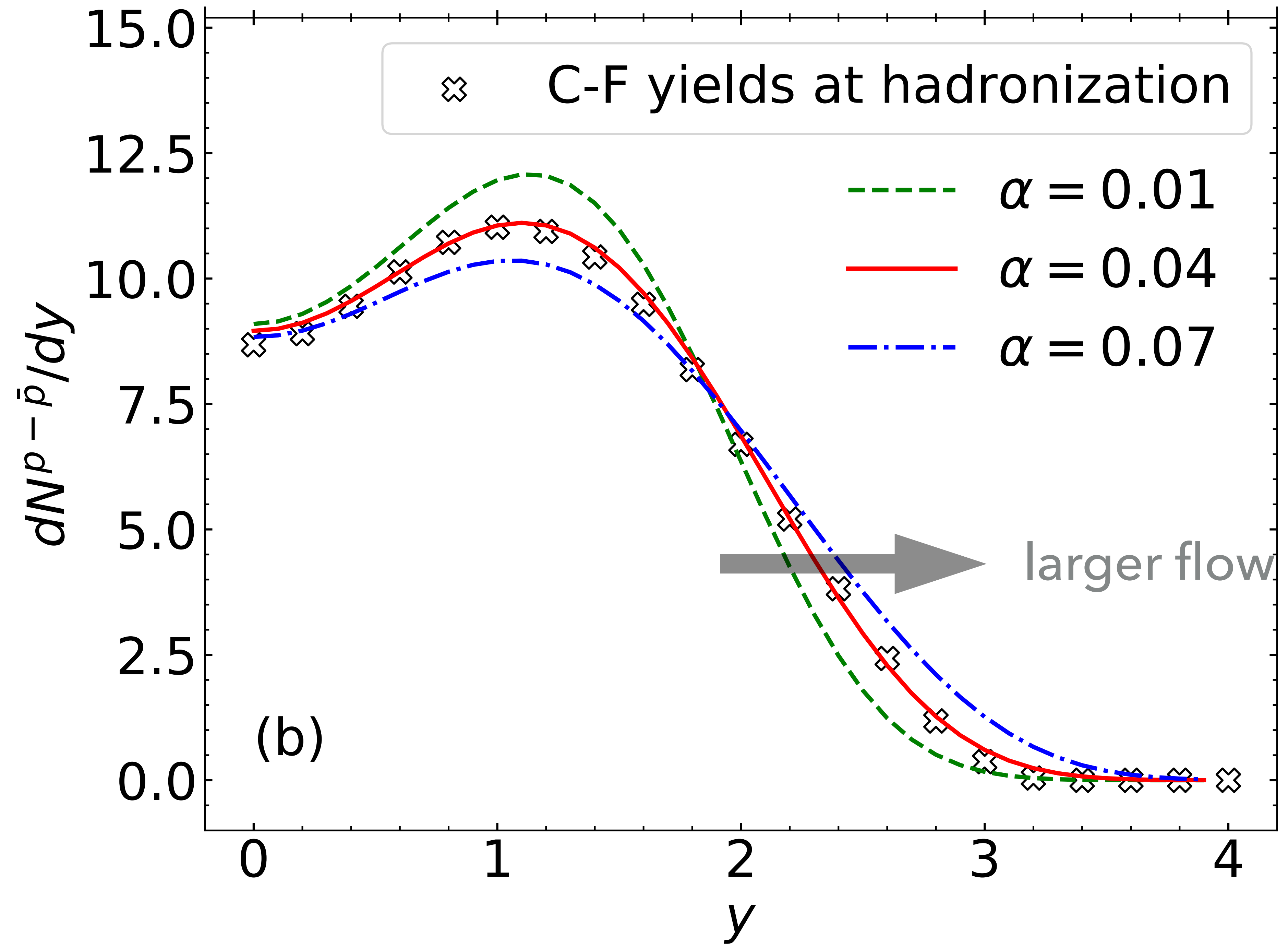
Lipei Du, arXiv: 2401.00596

- Fit the net baryon rapidity density attributed to the projectile after subtraction of the target contribution.
- The reconstructed distributions can help constrain models at BES.

BRAHMS, PLB 677, 267-271(2009); Braun-Munzinger, Friman, Redlich, Rustamov, and Stachel, NPA 1008 (2021) 122141; Hoelck, Hiyama, and Wolschin, PLB 840, 137866 (2023)

LONGITUDINAL FLOW AT FREEZE-OUT





LD, H. Gao, S. Jeon & C. Gale, PRC 109, 014907 (2024)

- Boost invariance is strongly broken, especially at forward-/backward- rapidities;
- Starting from the same profiles, the rapidity distributions are stretched with increased longitudinal flow, with heavier particles experiencing greater stretching;
- Rapidity distributions of various species can be used to constrain the longitudinal flow. H. Gao, LD, S. Jeon & C. Gale, 2312.09103

L.K. Liu, Tue. 2:30 pm

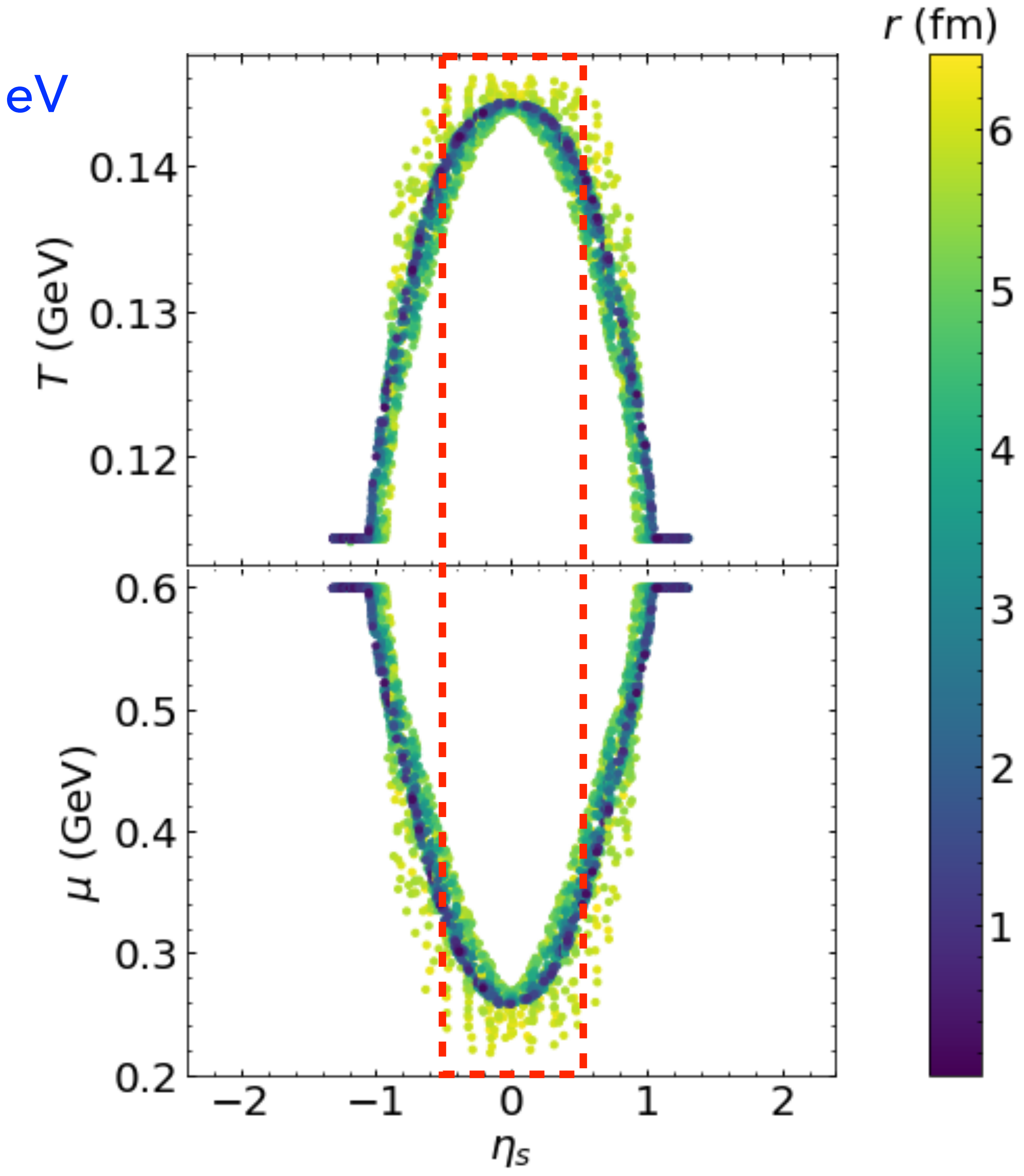
LONGITUDINAL PROPERTY VARIATION AT FREEZE-OUT

0-5% 7.7 GeV

$\Delta T/T_{\text{mid}} \sim 20\,\%$

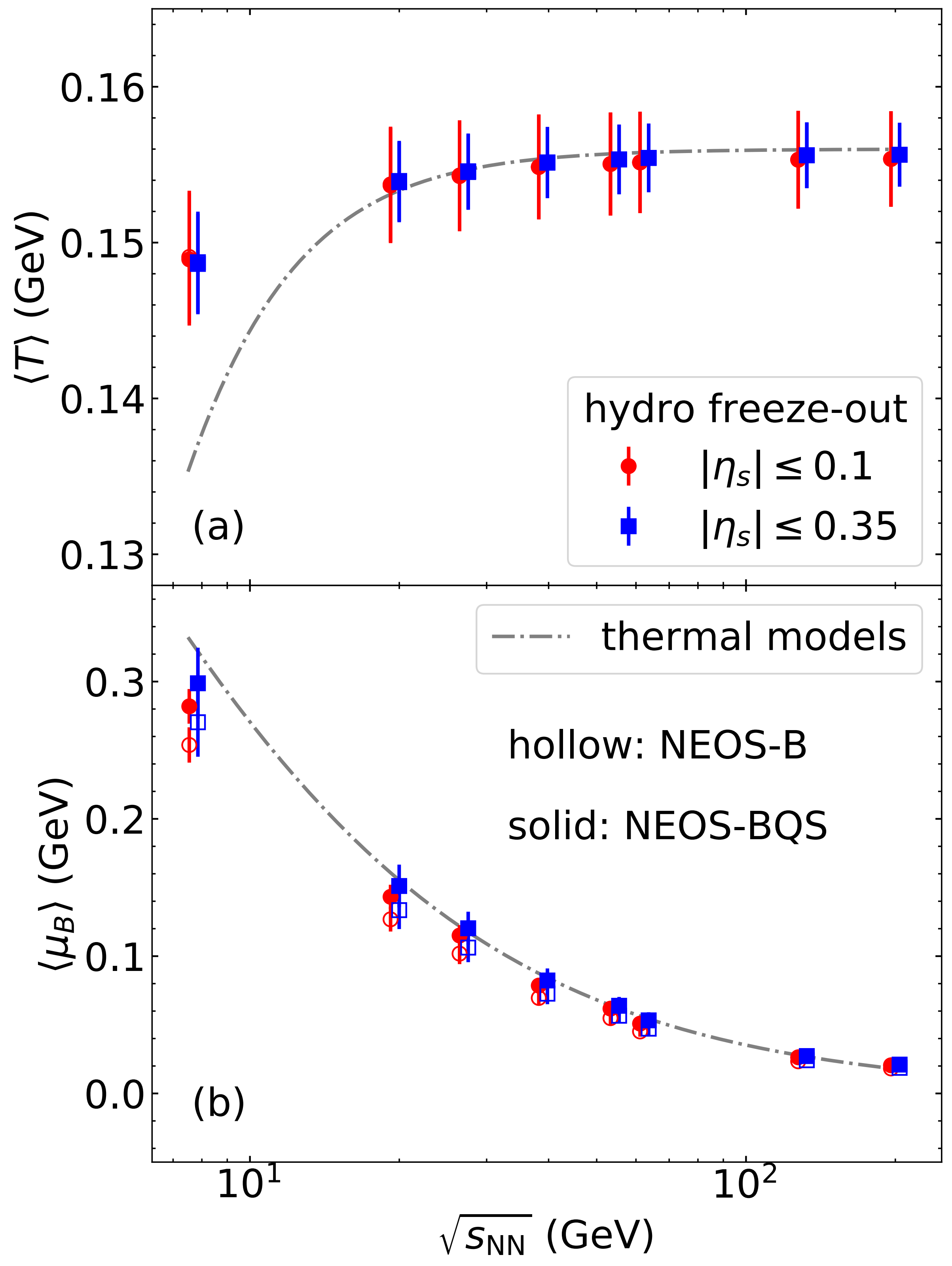
$\Delta\mu/\mu_{\text{mid}} \gtrsim 100\,\%$

thermal smearing
$\Delta y \sim \sqrt{T/\langle m \rangle}$



LD, H. Gao, S. Jeon & C. Gale, PRC 109, 014907 (2024)

0-10% BES



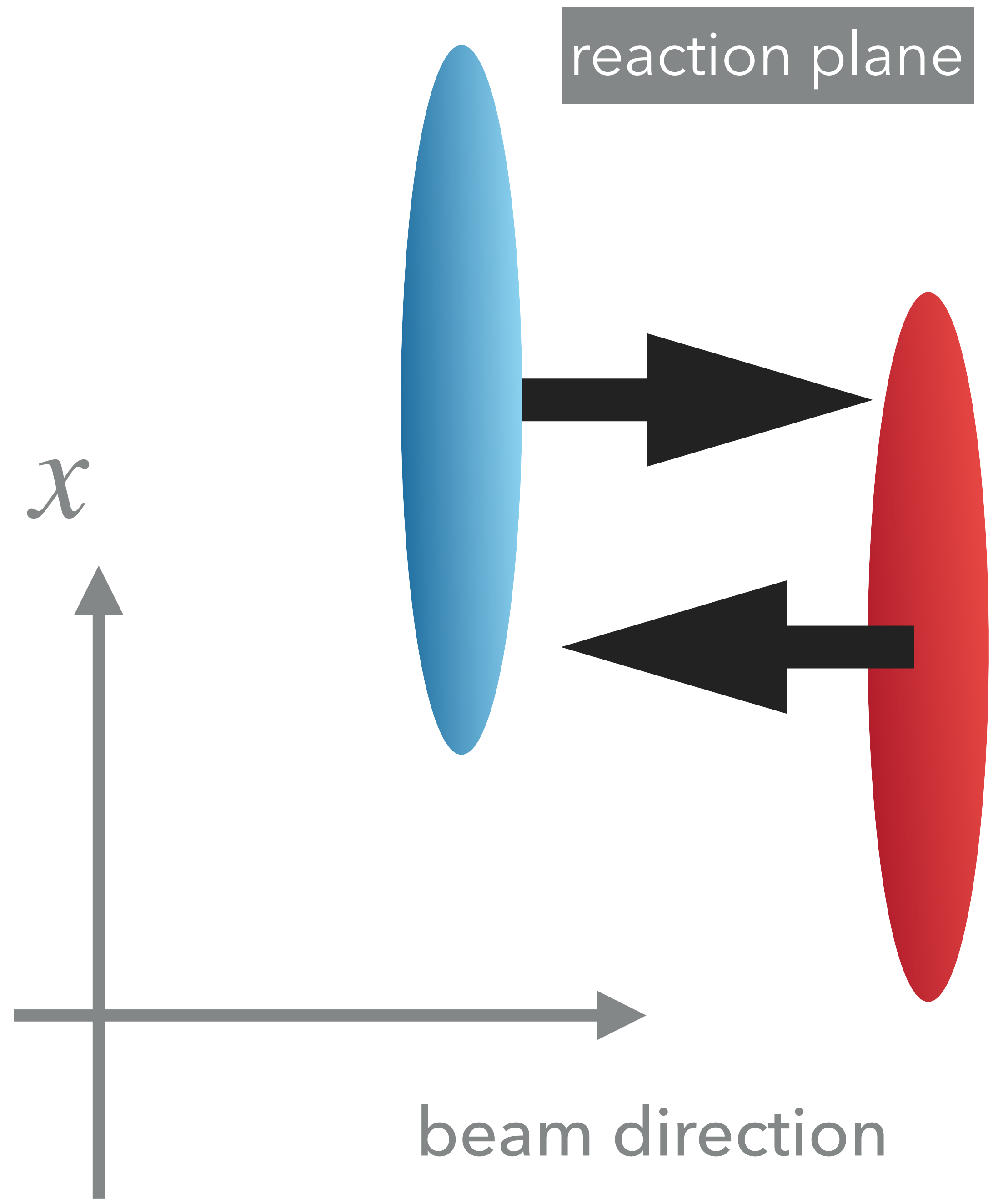
Lipei Du, arXiv: 2401.00596

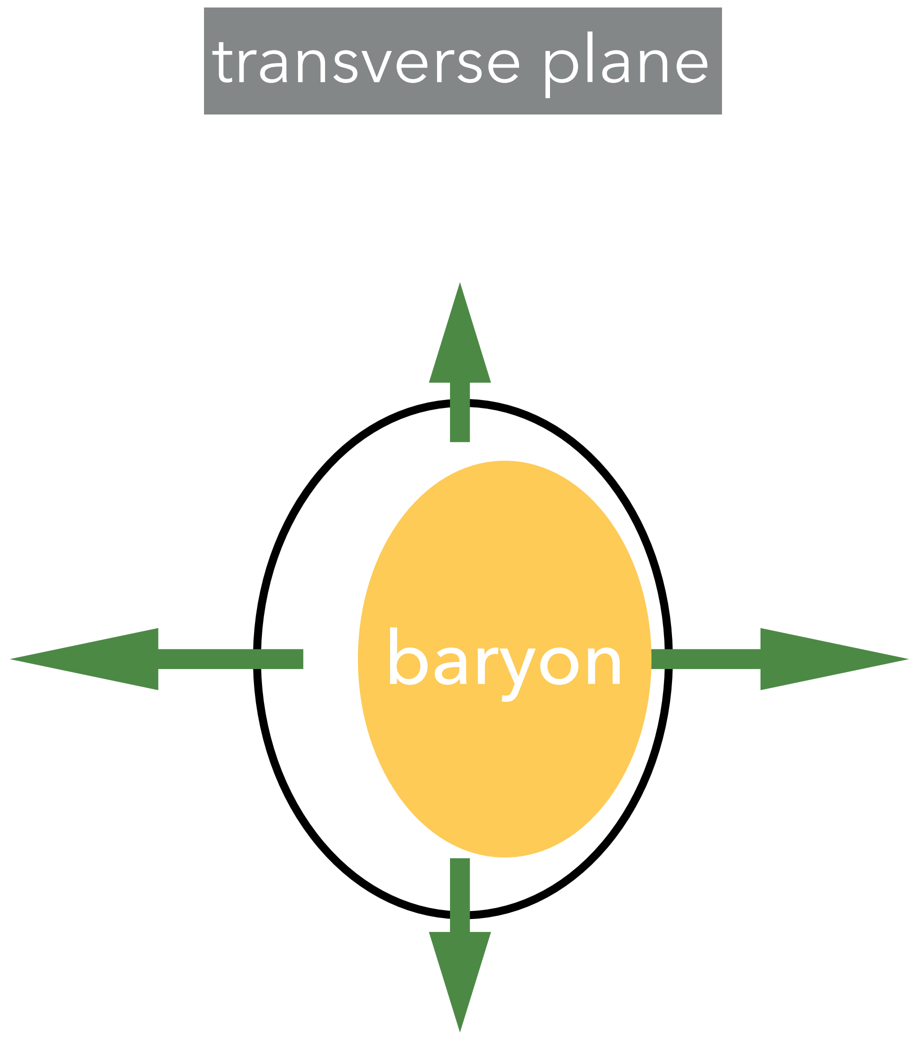
- The variation in thermodynamic properties across spacetime rapidity is strong for collisions $\lesssim$10 GeV
- Due to thermal smearing, thermal models extract (T, μ_B) averaged over a broader η_s window

Andronic, Braun-Munzinger, Redlich, and Stachel, Nature 561, 321–330 (2018); Begun, Kikoła, Vovchenko, and Wielanek, PRC 98, 034905 (2018); Karpenko, Acta Phys. Polon. B50 (2019), 141

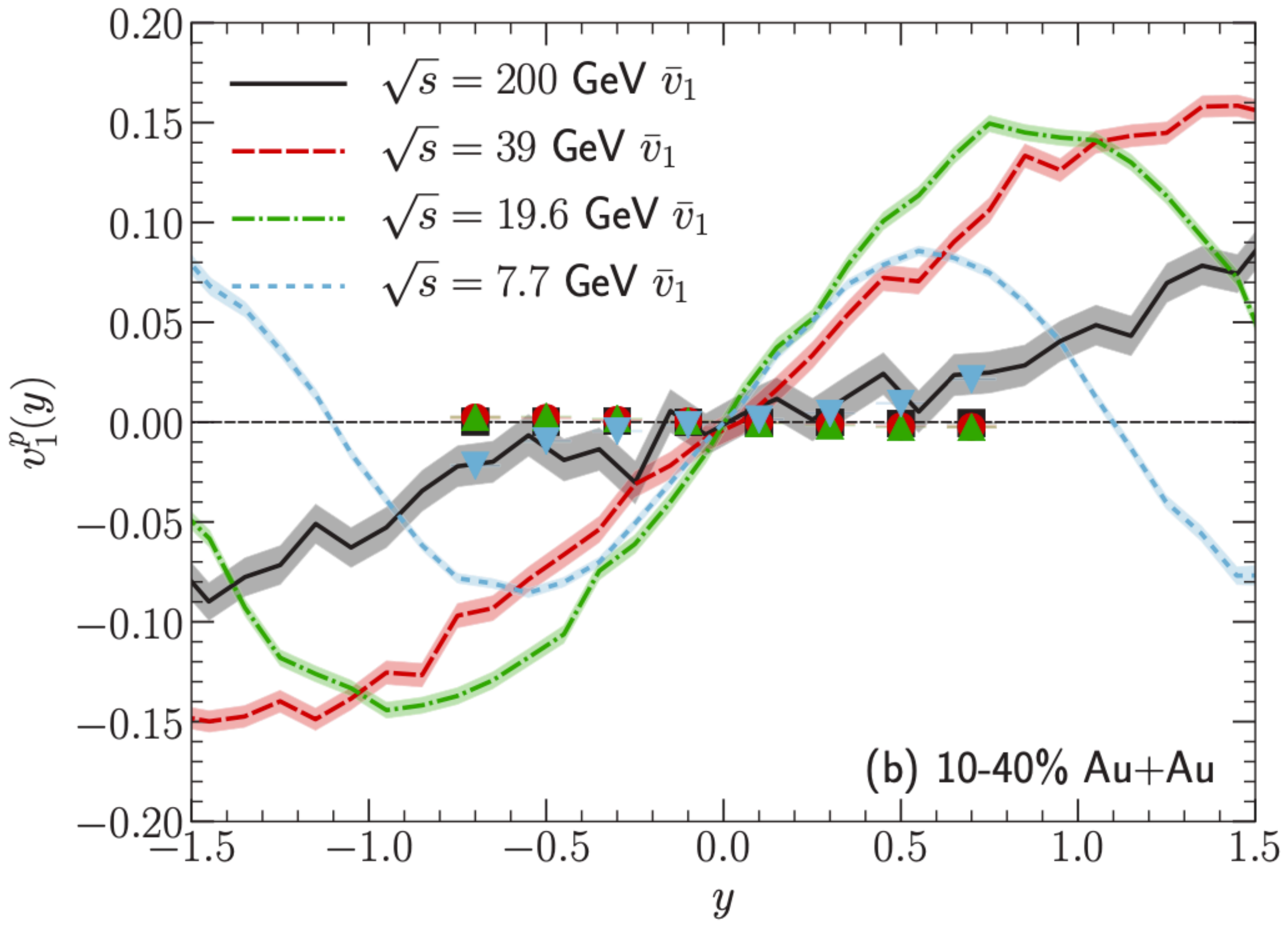
PROBING INITIAL BARYON

DIRECTED FLOW $v_1(y)$ OF PROTONS





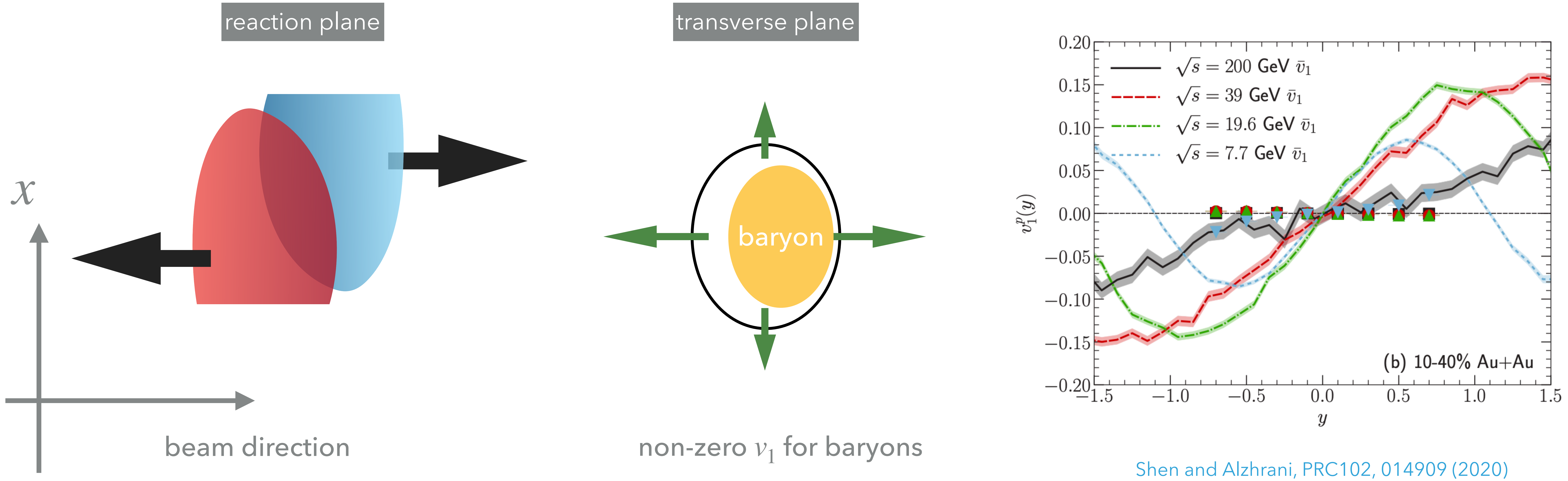
non-zero v_1 for baryons



Shen and Alzhrani, PRC102, 014909 (2020)

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

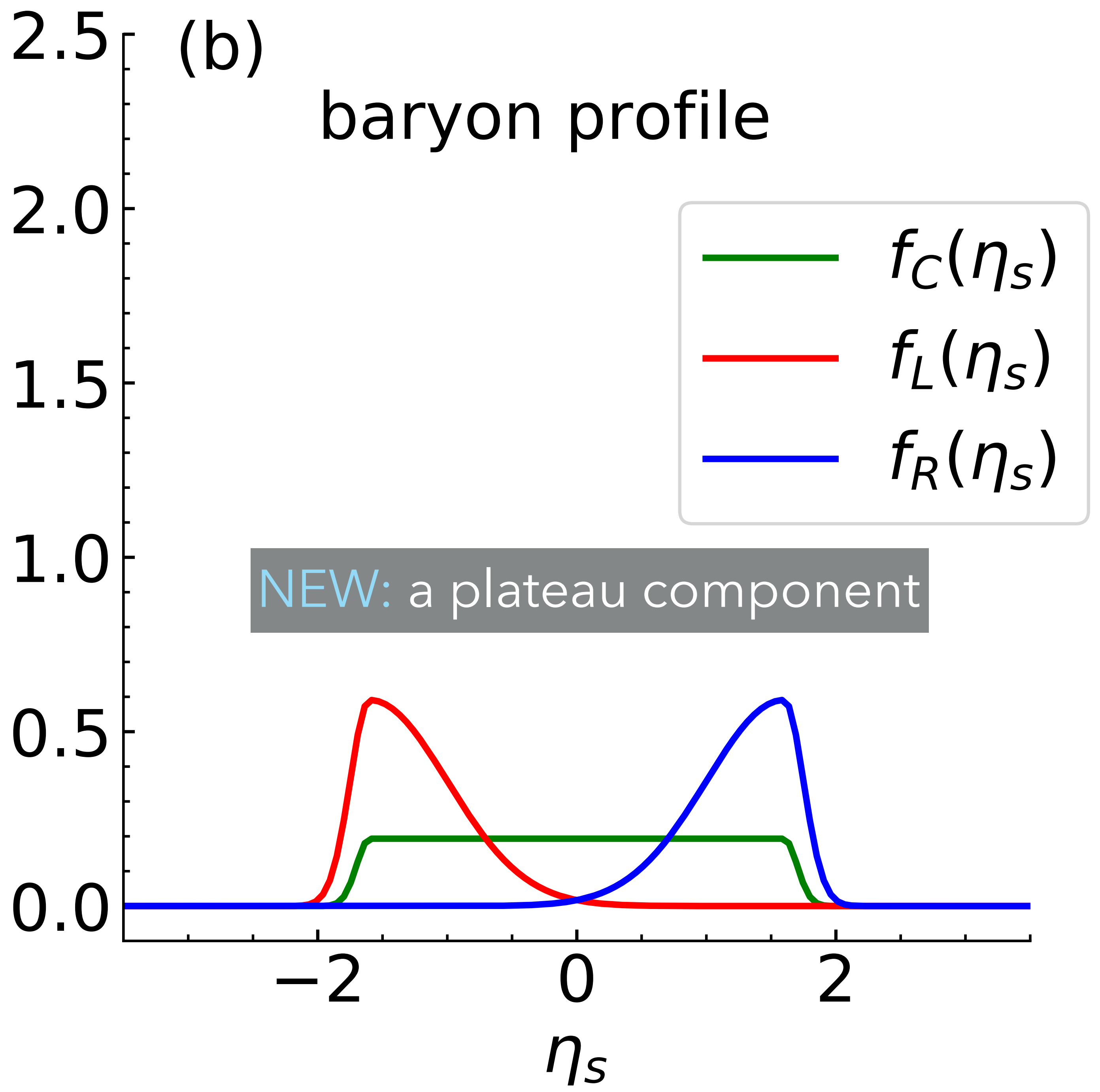
DIRECTED FLOW $v_1(y)$ OF PROTONS

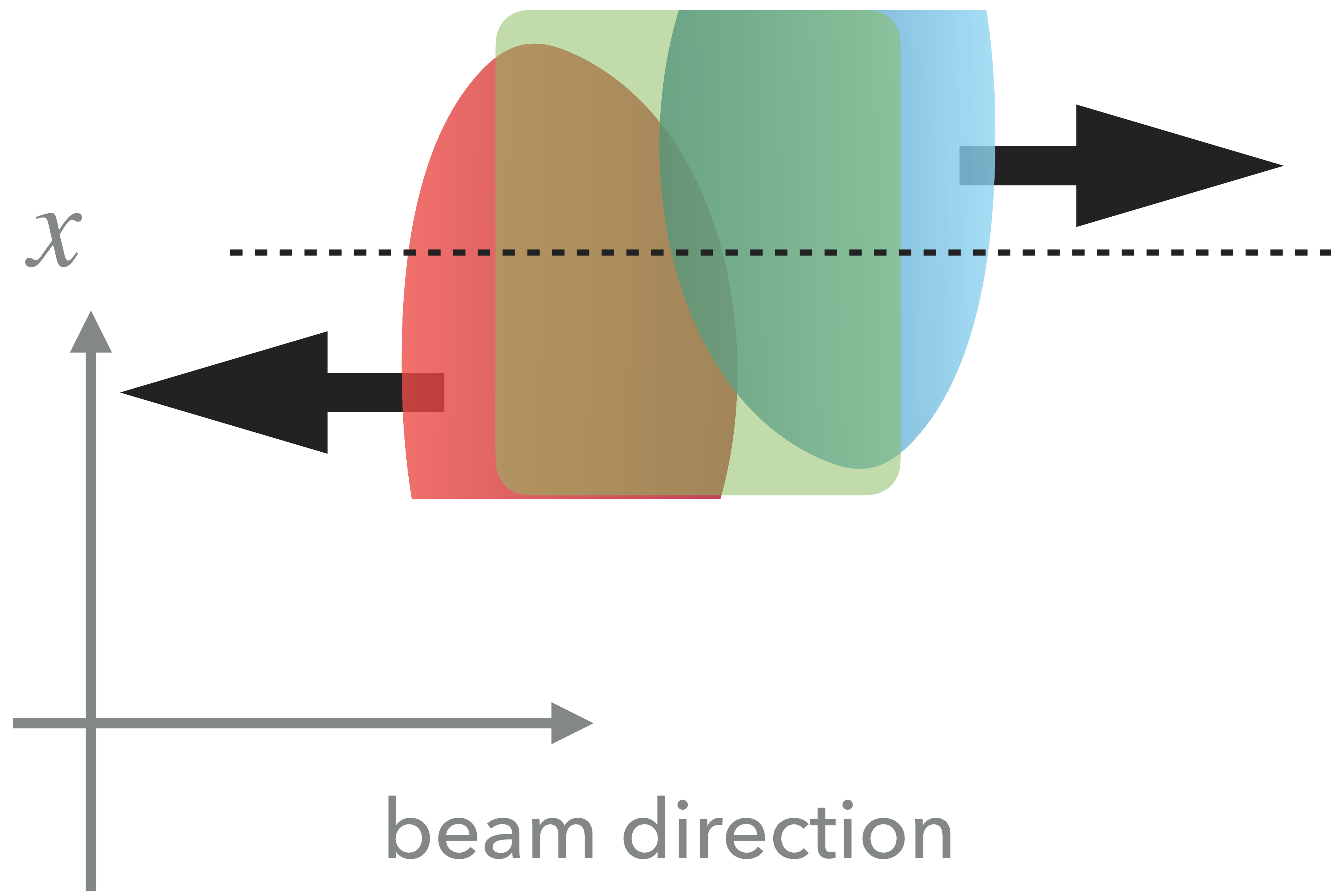


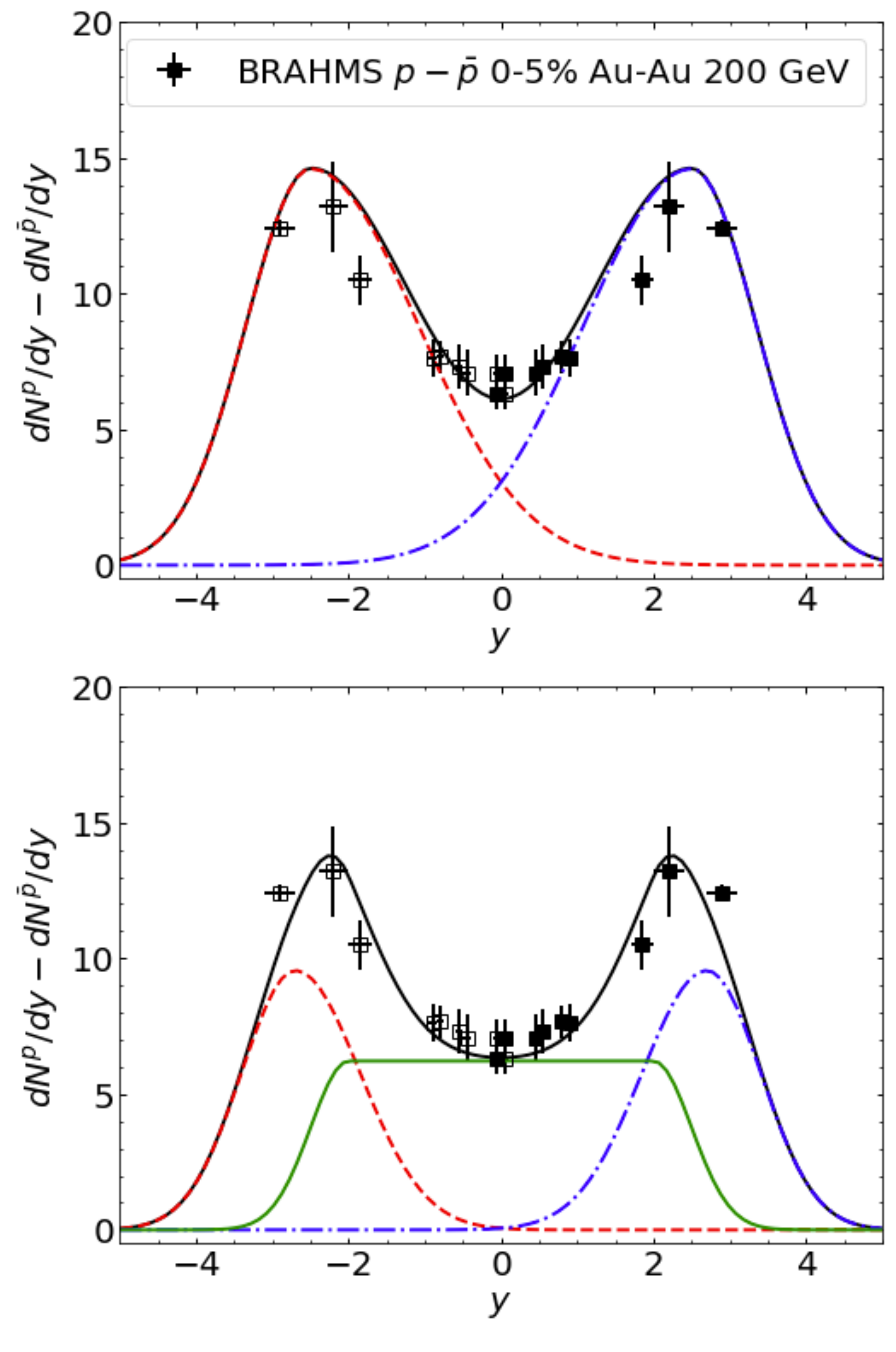
Shen and Alzhrani, PRC102, 014909 (2020)

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

NEW PARAMETRIC BARYON INITIAL CONDITION







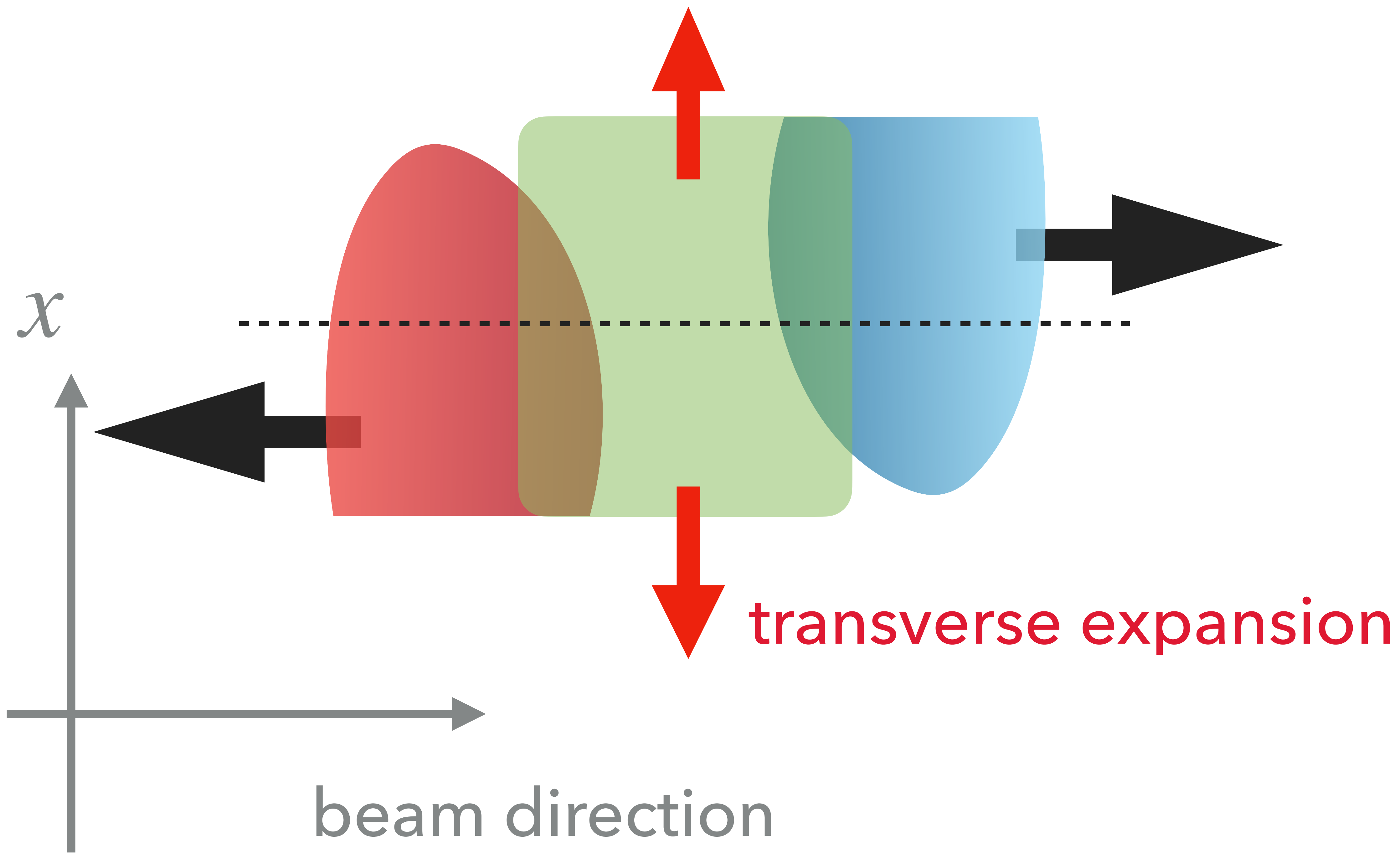
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- To explain the rapidity distributions of net proton yields and baryons' directed flows simultaneously, a plateau component is favored

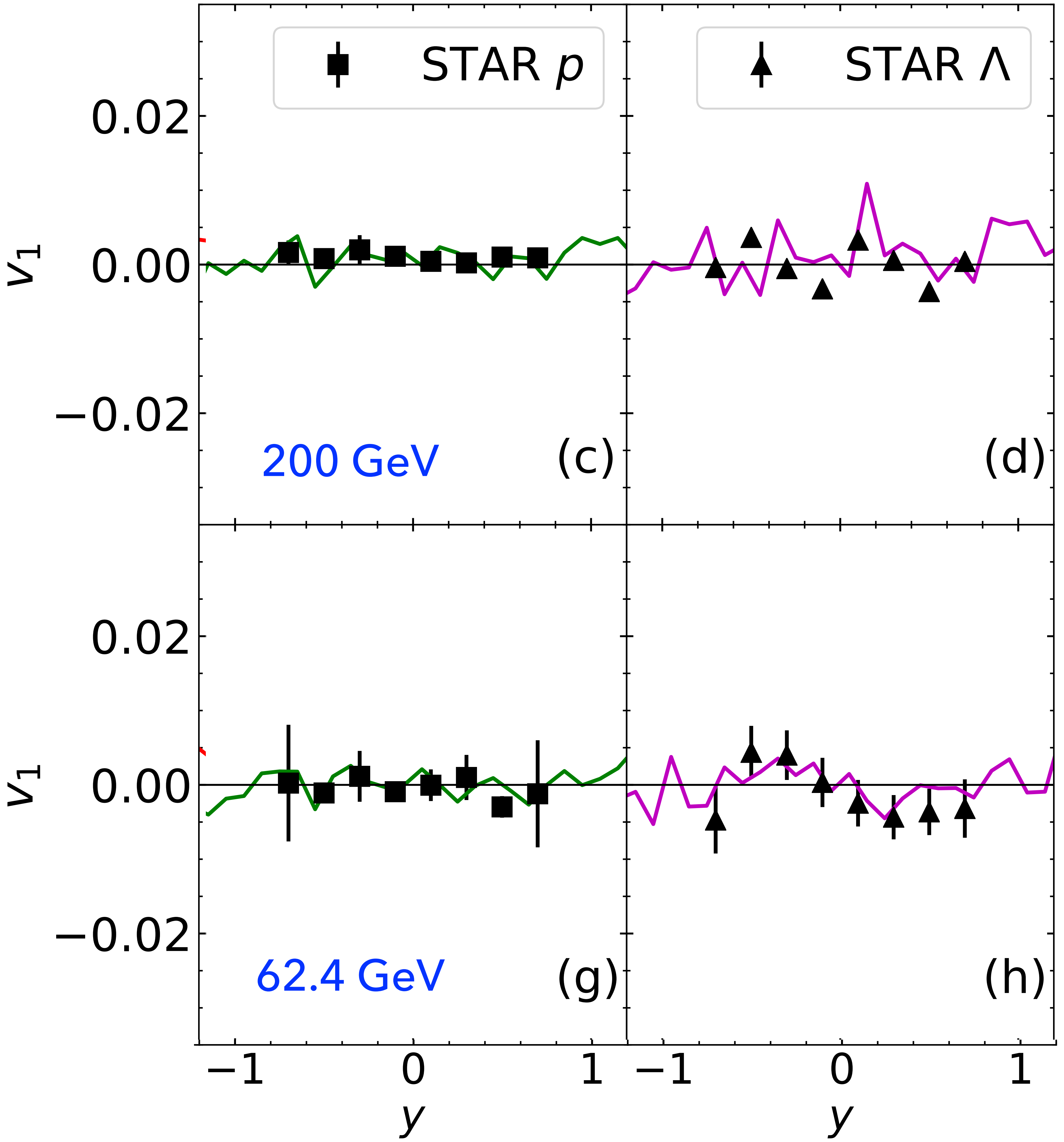
P. Tribedy, Wed. 11:50 am

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

DIRECTED FLOW OF BARYONS AT 200 AND 62.4 GEV



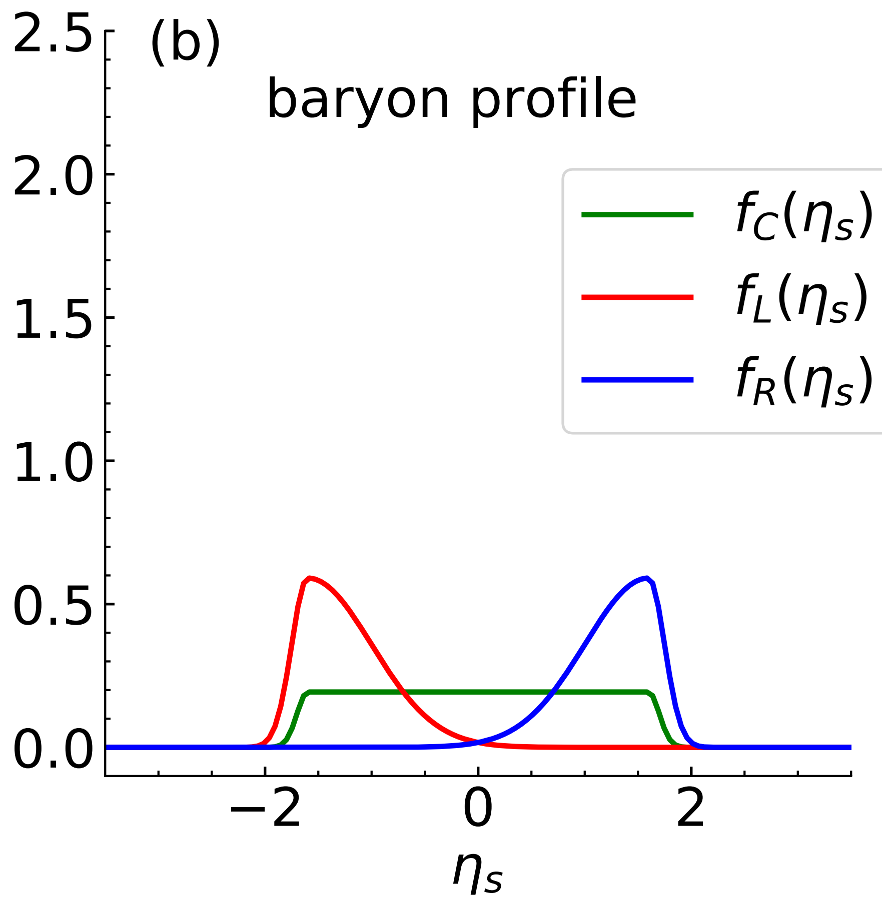
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

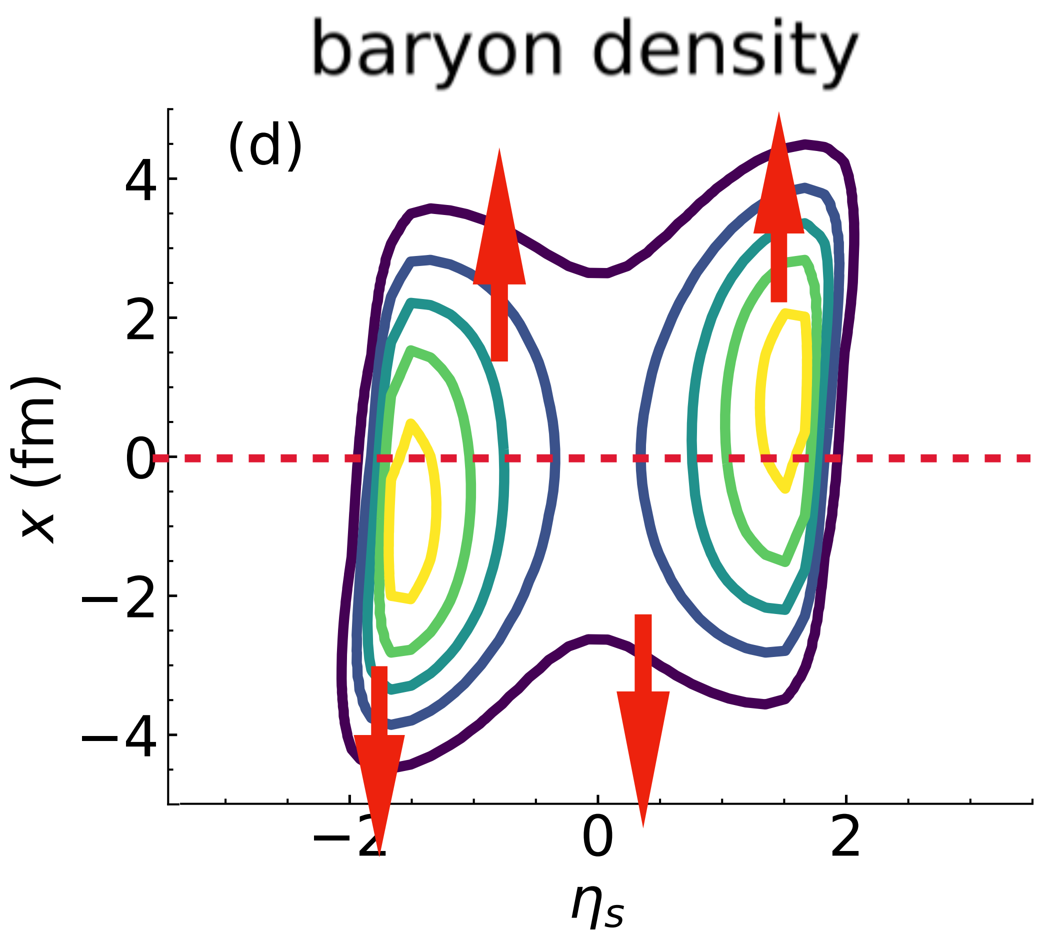


- At high beam energies with large beam rapidities, the plateau dominates around mid-rapidity and strongly reduces baryons' $v_1(y)$.

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

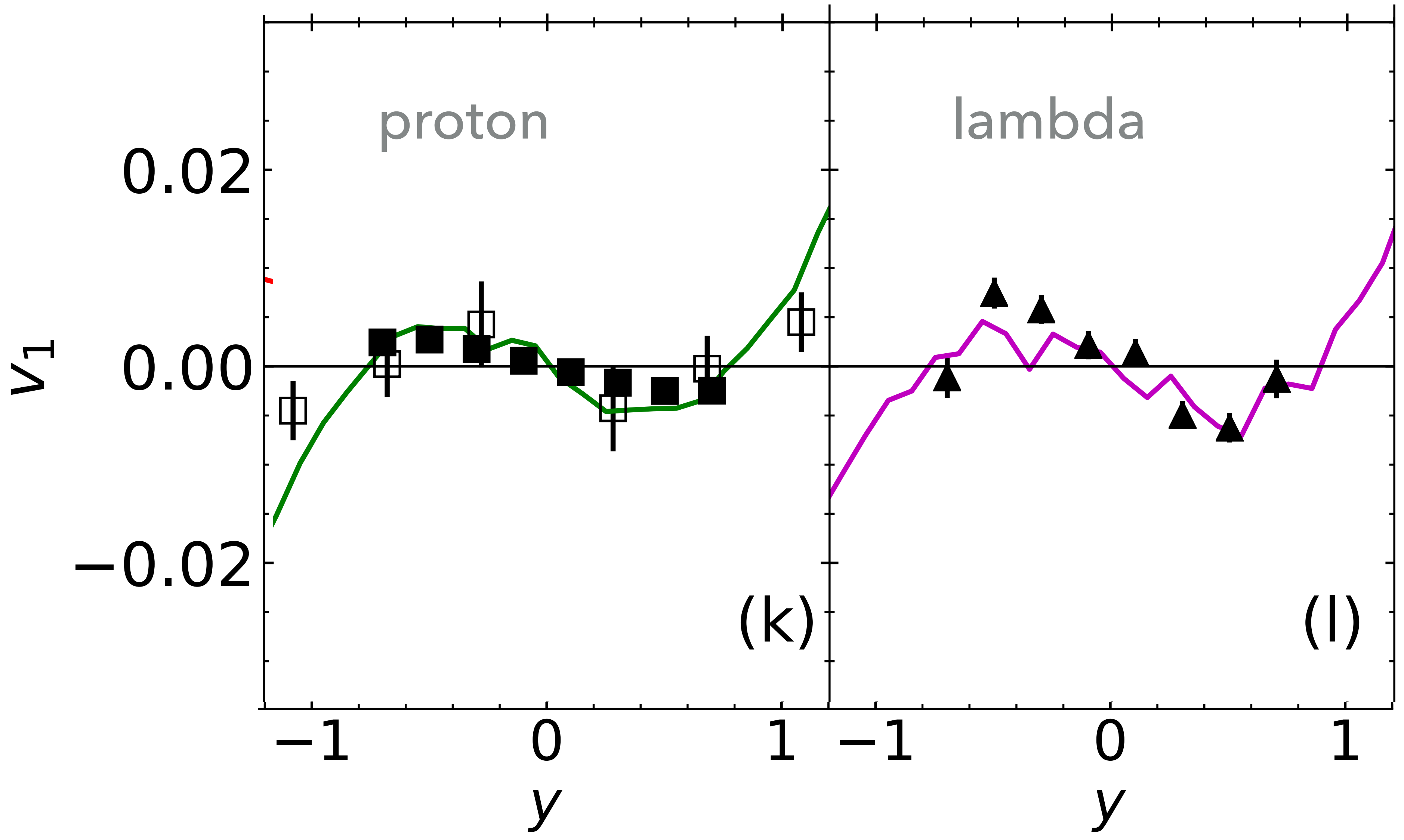
DIRECTED FLOW OF BARYONS AT 19.6 GEV





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

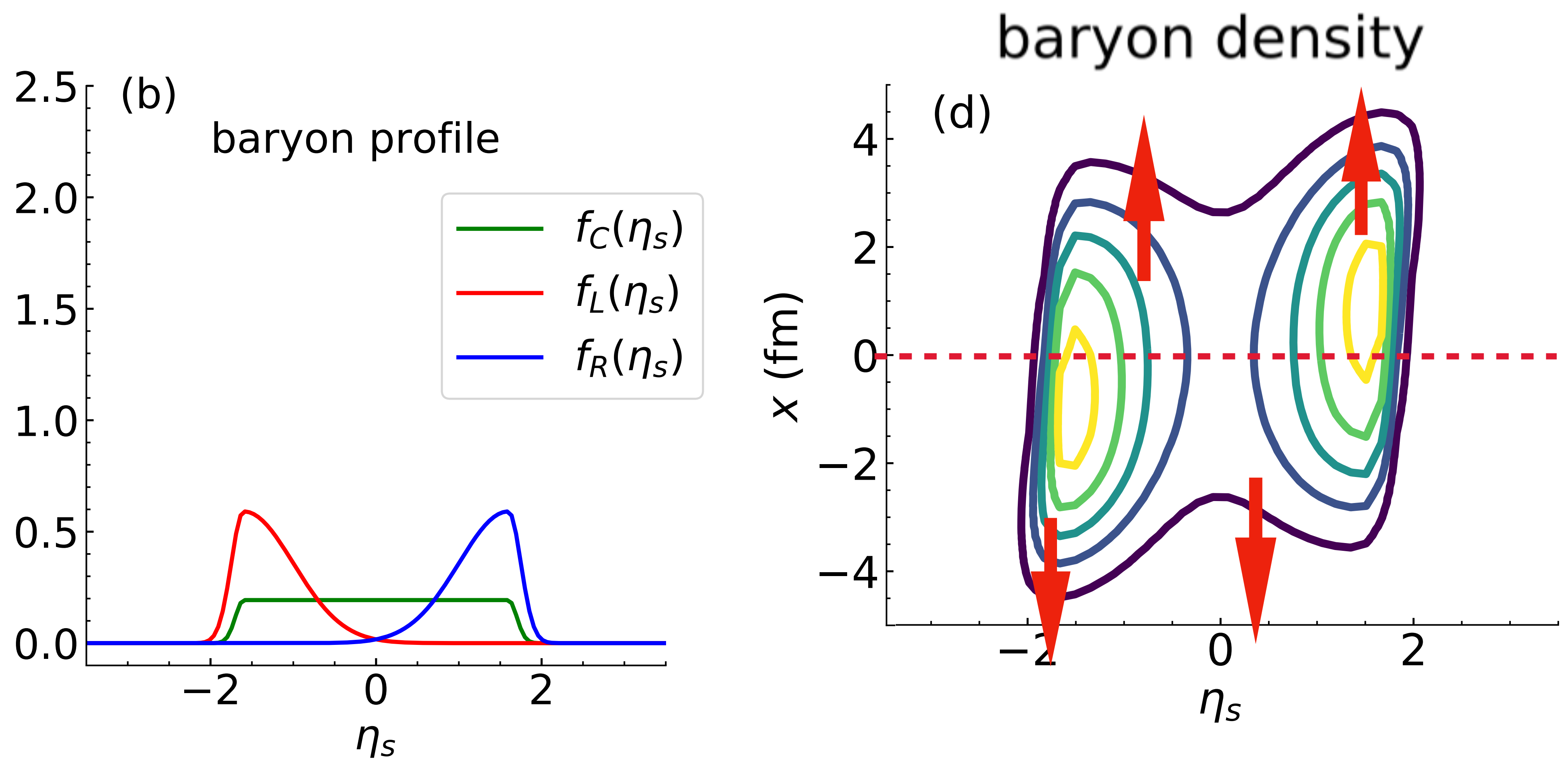
19.6 GeV



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

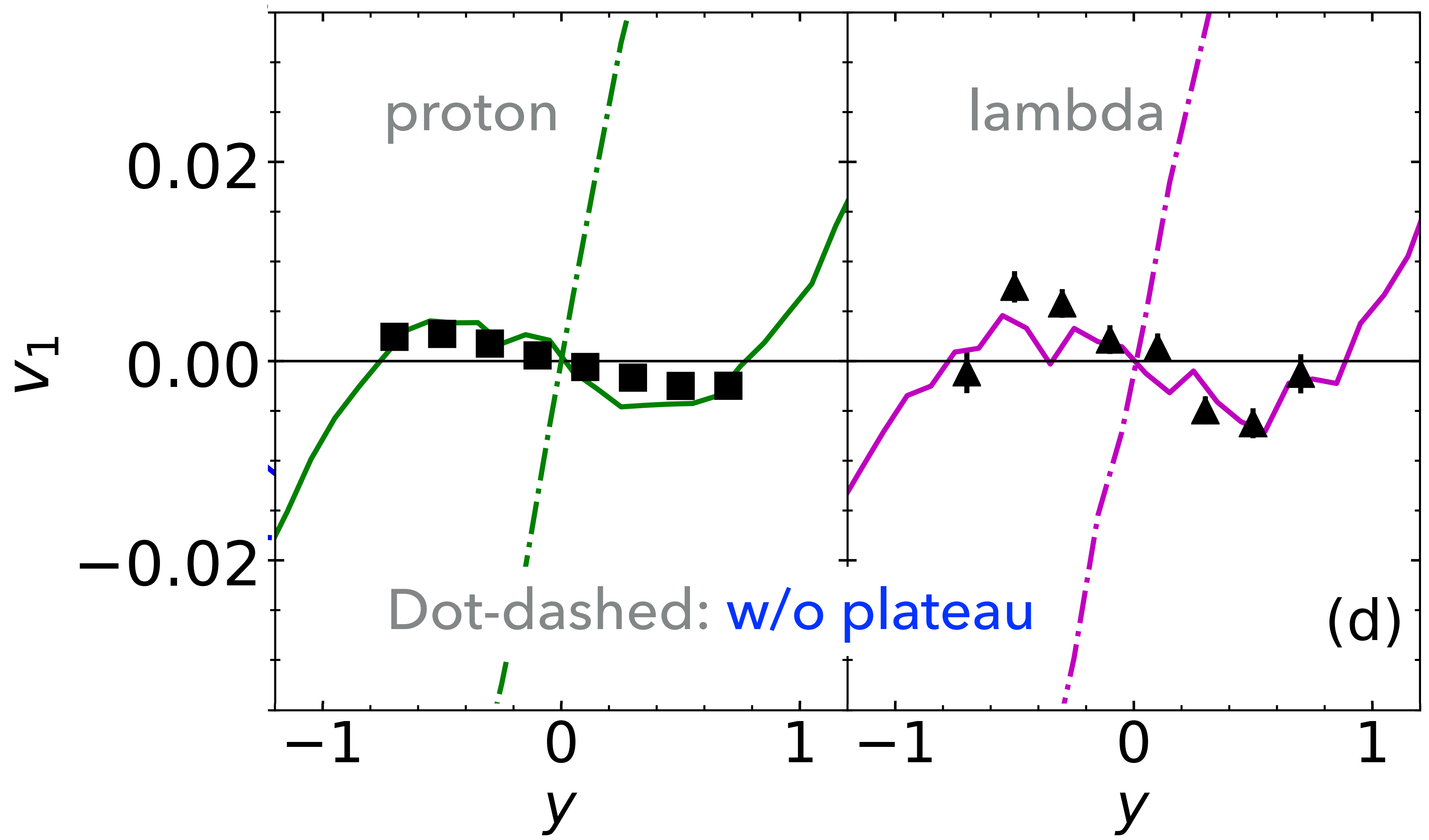
- Transverse expansion + asymmetric distribution of baryon density along x $\Longrightarrow$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV
- The sign change of $dv_1(y)/dy\,|_{y=0}$ is naturally reproduced without a 1st-order phase transition.

DIRECTED FLOW OF BARYONS AT 19.6 GEV



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

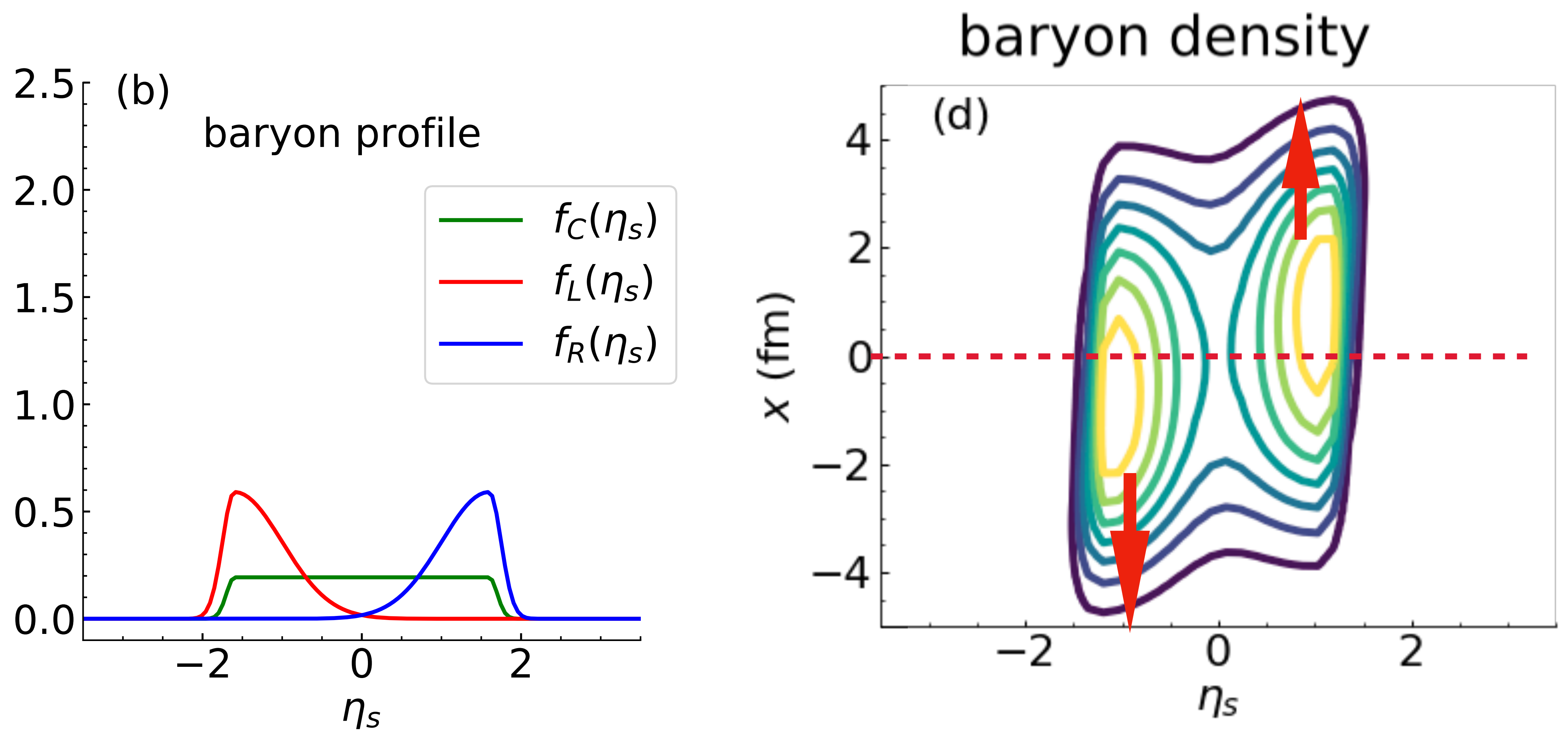
19.6 GeV



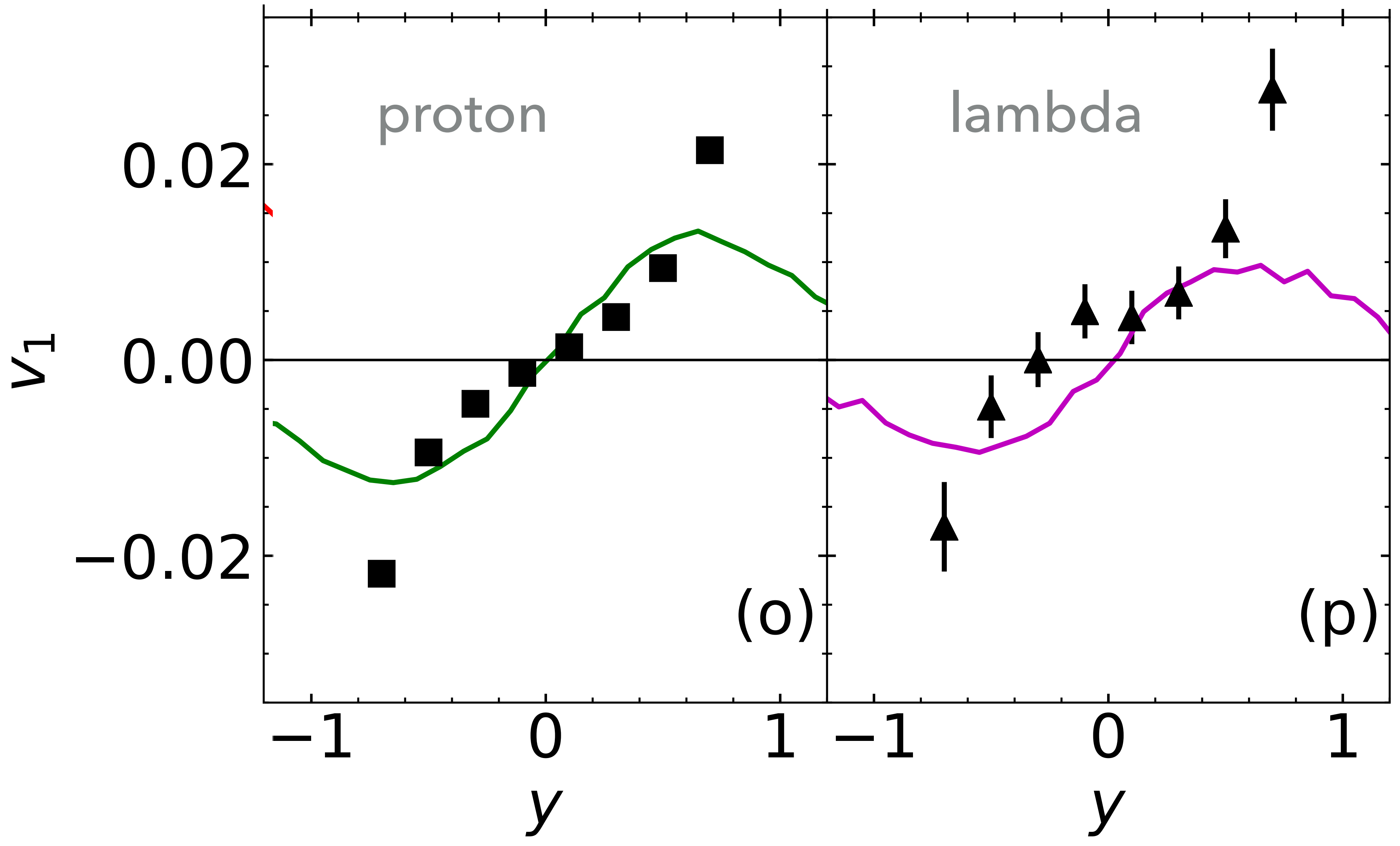
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- 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.

DIRECTED FLOW OF BARYONS AT 7.7 GEV



Initial baryon distributions in the reaction plane for 10-40% Au+Au@7.7 GeV



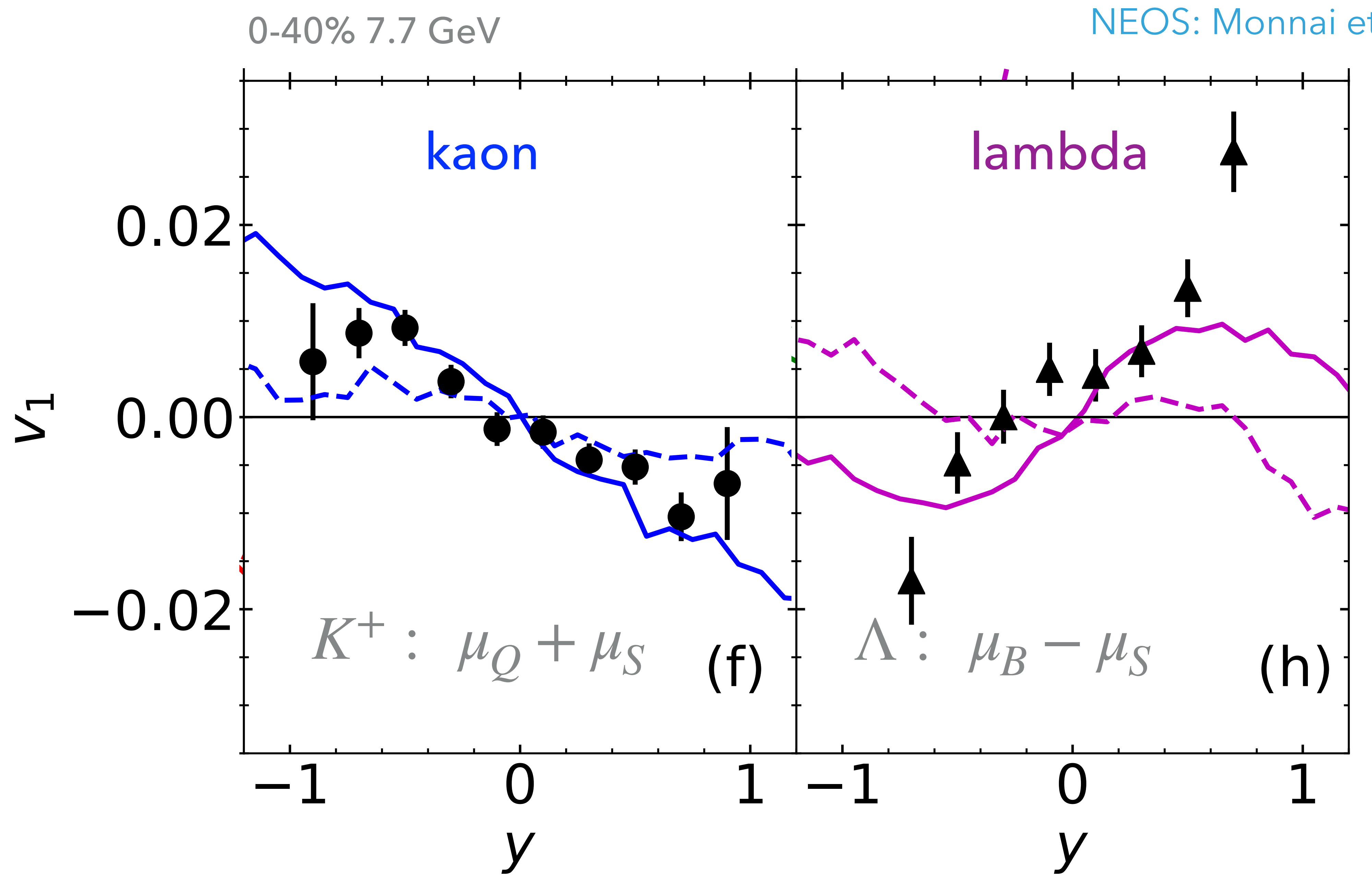
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- 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.

E. Duckworth, Fri. 9:00 am

PROBING EOS AT FINITE CHEMICAL POTENTIALS

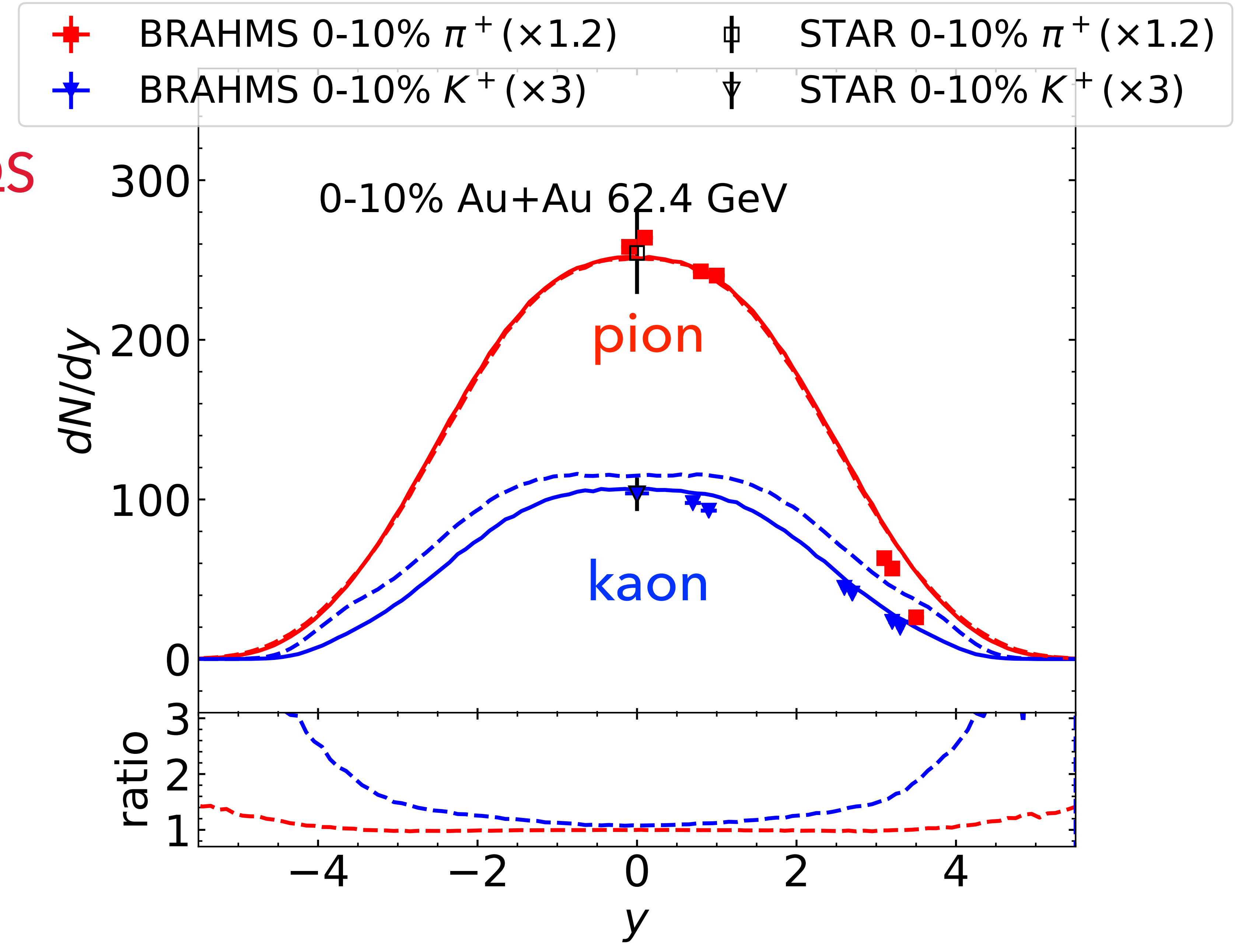
NEOS: Monnai et al, PRC 100, 024907 (2019)



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

Dashed: NEOS-BQS

Solid: NEOS-B



Lipei Du, arXiv: 2401.00596

- 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)
- Rapidity-dependent measurements of identified particles can be used to probe EoS at finite chemical potentials.

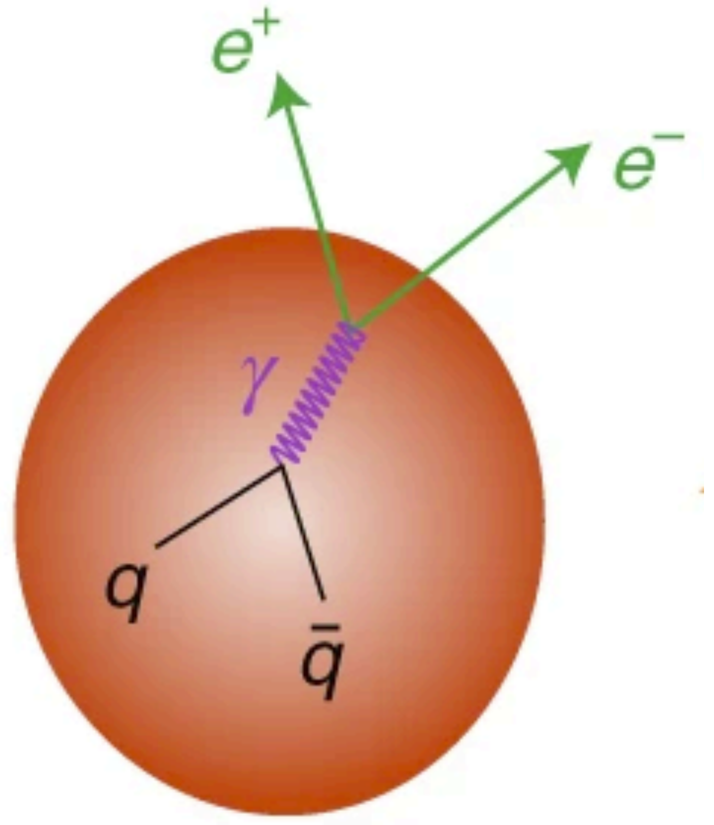
C. Plumberg, Fri. 10:10 am

H. Feng, Wed. 11:30 am

M. Kahangirwe, Wed. 12:10 pm

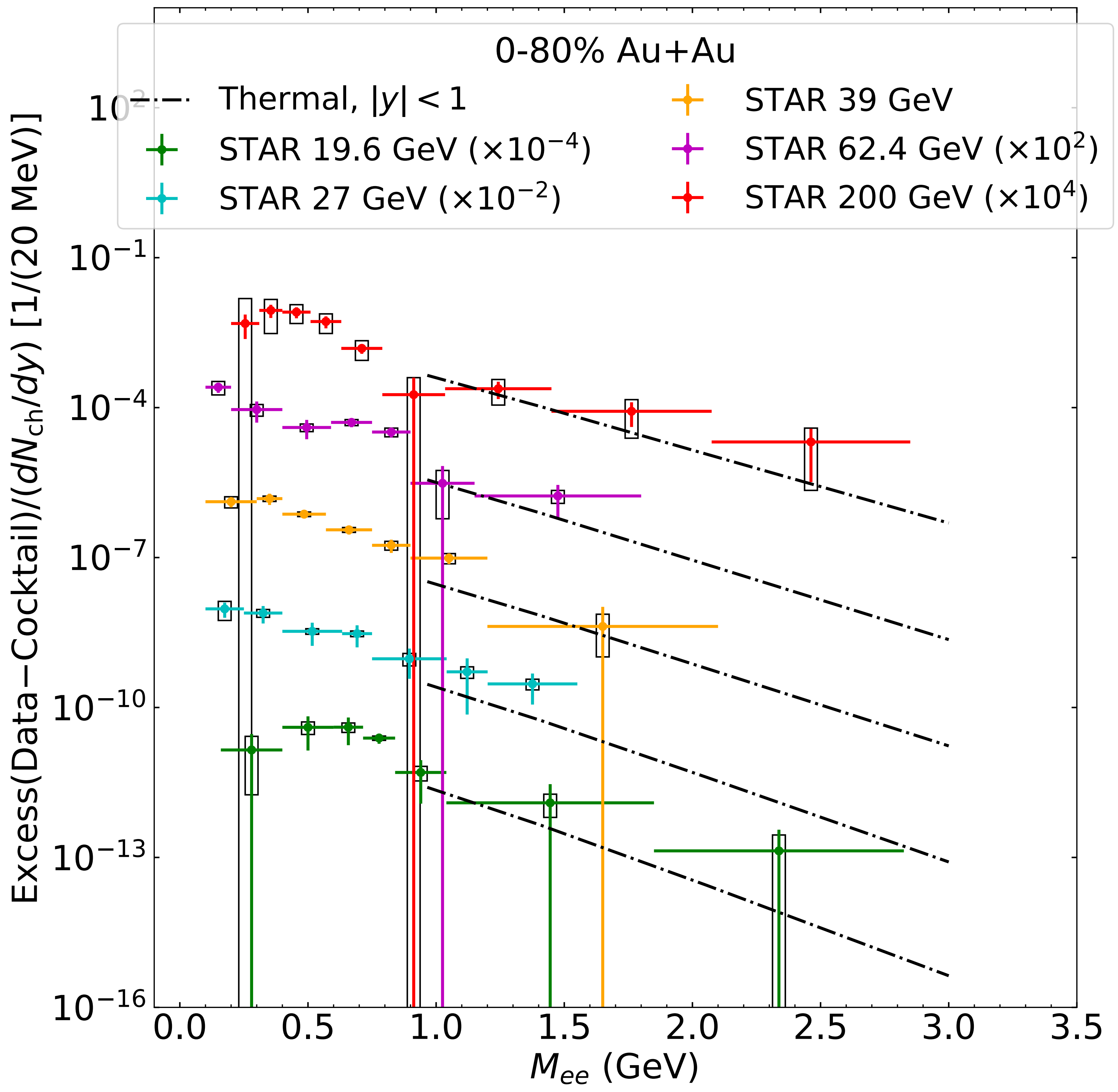
PROBING INITIAL TEMPERATURE

THERMAL DILEPTON PRODUCTION



- Dileptons & real photons: A penetrating, "clean" probe
  - emitted throughout the entire evolution of the medium
  - escape the strongly interacting medium with negligible interactions ("clean")

NA60, PRL 100, 022302 (2008); EPJC 59 607-623 (2009). STAR, PRL113, 022301 (2014); PRC 92, 024912 (2015); PLB 750 (2015) 64–71; PRC 107, L061901 (2023). HADES, Nat. Phys.,1040–1045 (2019).

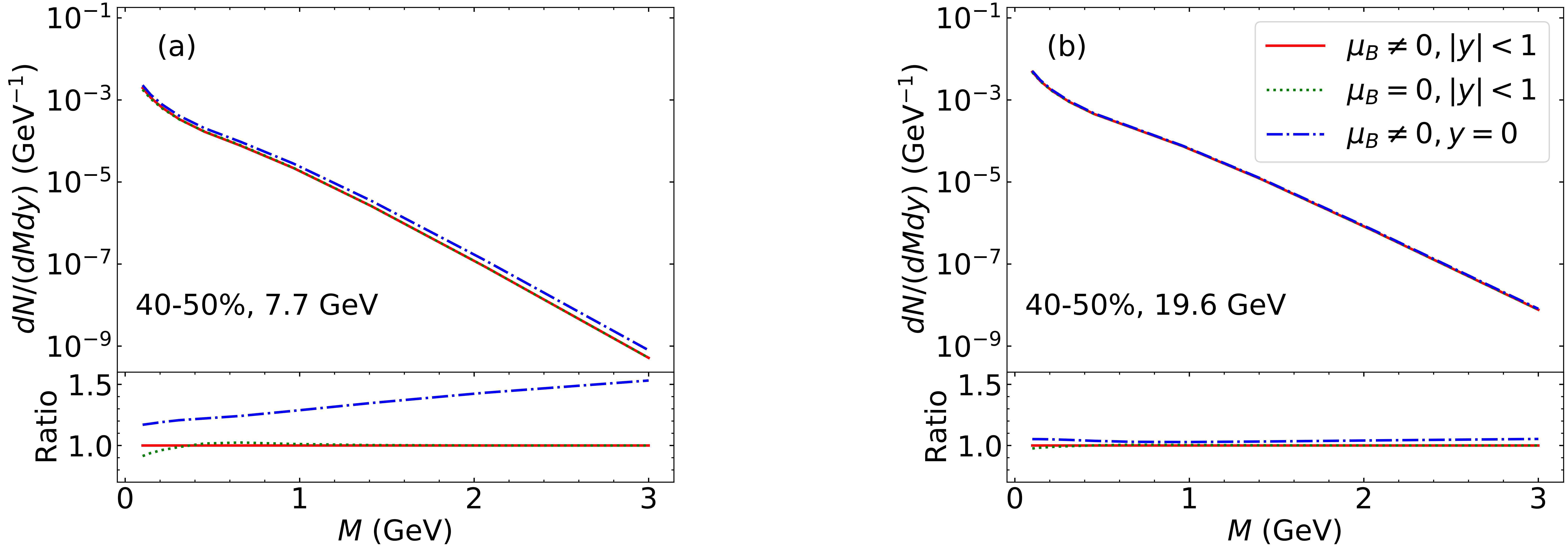


https://github.com/LipeiDu/DileptonEmission

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)

- First estimate of NLO dilepton emission at nonzero μ_B with hydrodynamics

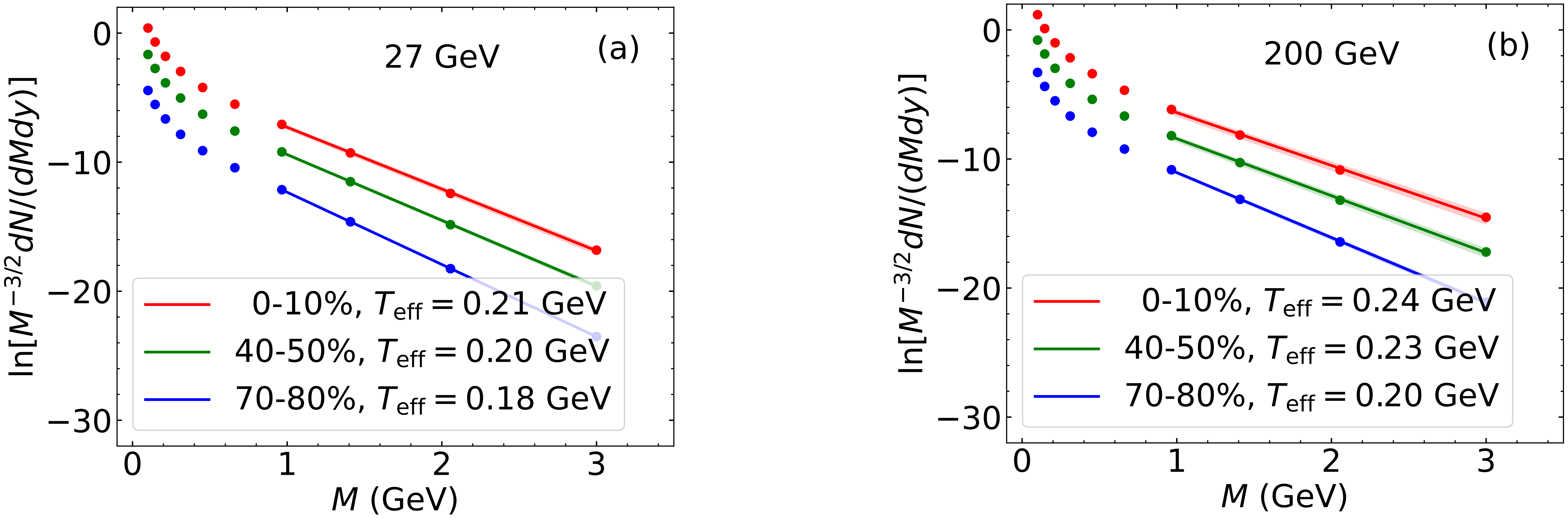
RAPIDITY AND μ_B DEPENDENCE



- μ_B-dependence is not significant for 7.7 GeV and higher beam energies
- At 7.7 GeV, a strong boost-non-invariant effect is observed

F. Seck, Fri. 9:00 am

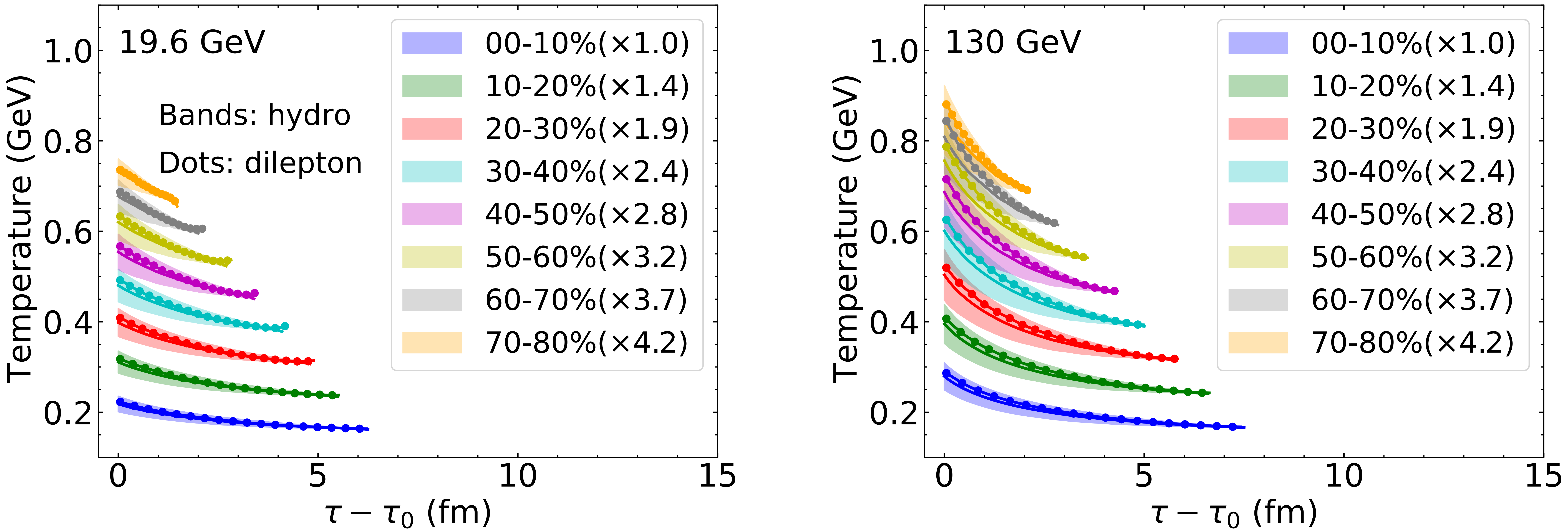
TEMPERATURE EXTRACTION



- In non-relativistic approximation, the emission rate $\dfrac{dR}{dM} \propto (MT)^{3/2}e^{-M/T}$
- Thermal dileptons within $1\text{GeV} \lesssim M \lesssim 3\text{GeV}$ for temperature extraction

NA60, PRL 100, 022302 (2008); EPJC 59 607-623 (2009). STAR, 2402.01998. HADES, Nat. Phys.,1040–1045 (2019). Rapp and van Hees, PLB 753, 586 (2016)

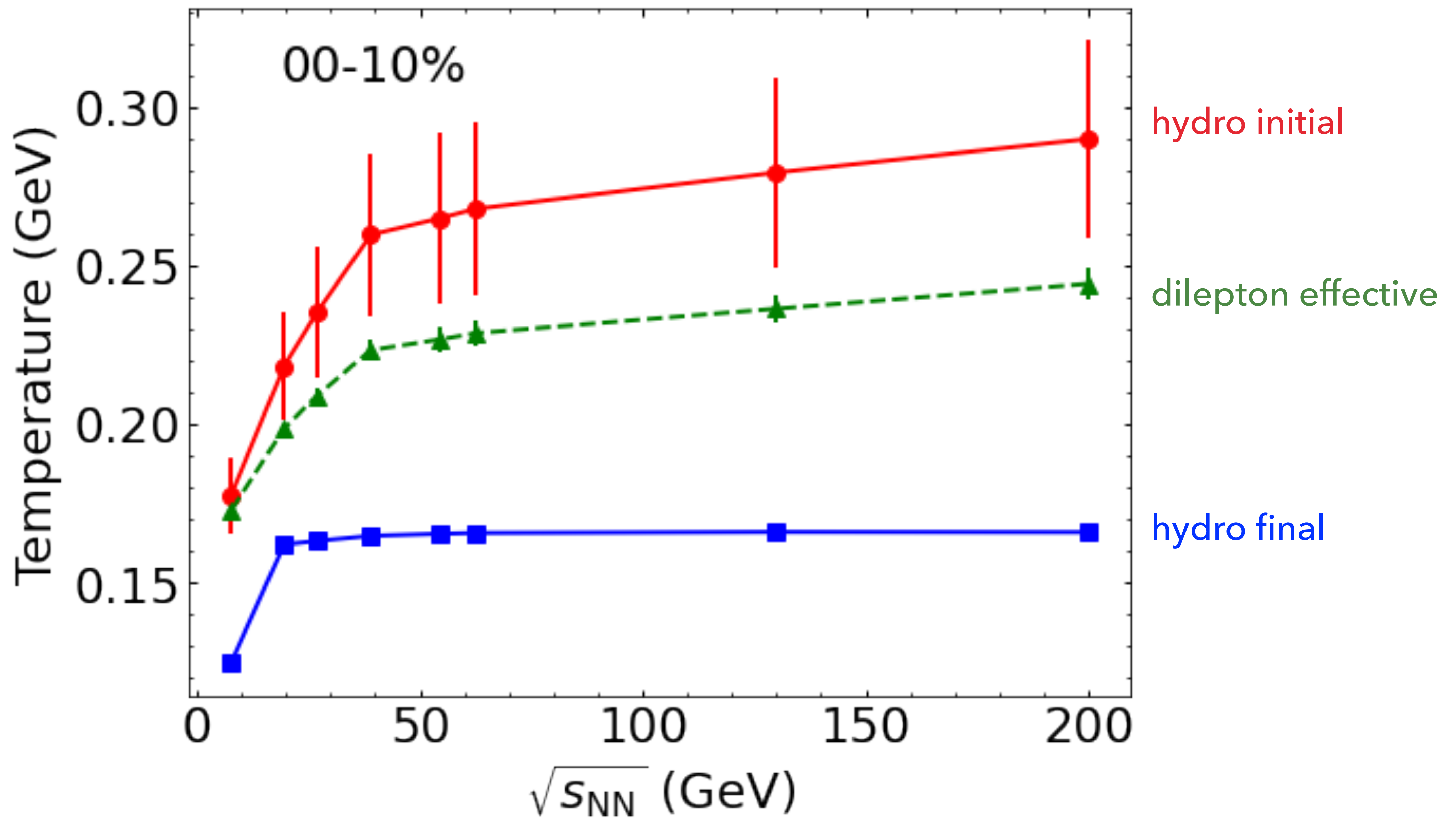
TEMPERATURE EXTRACTION IN τ

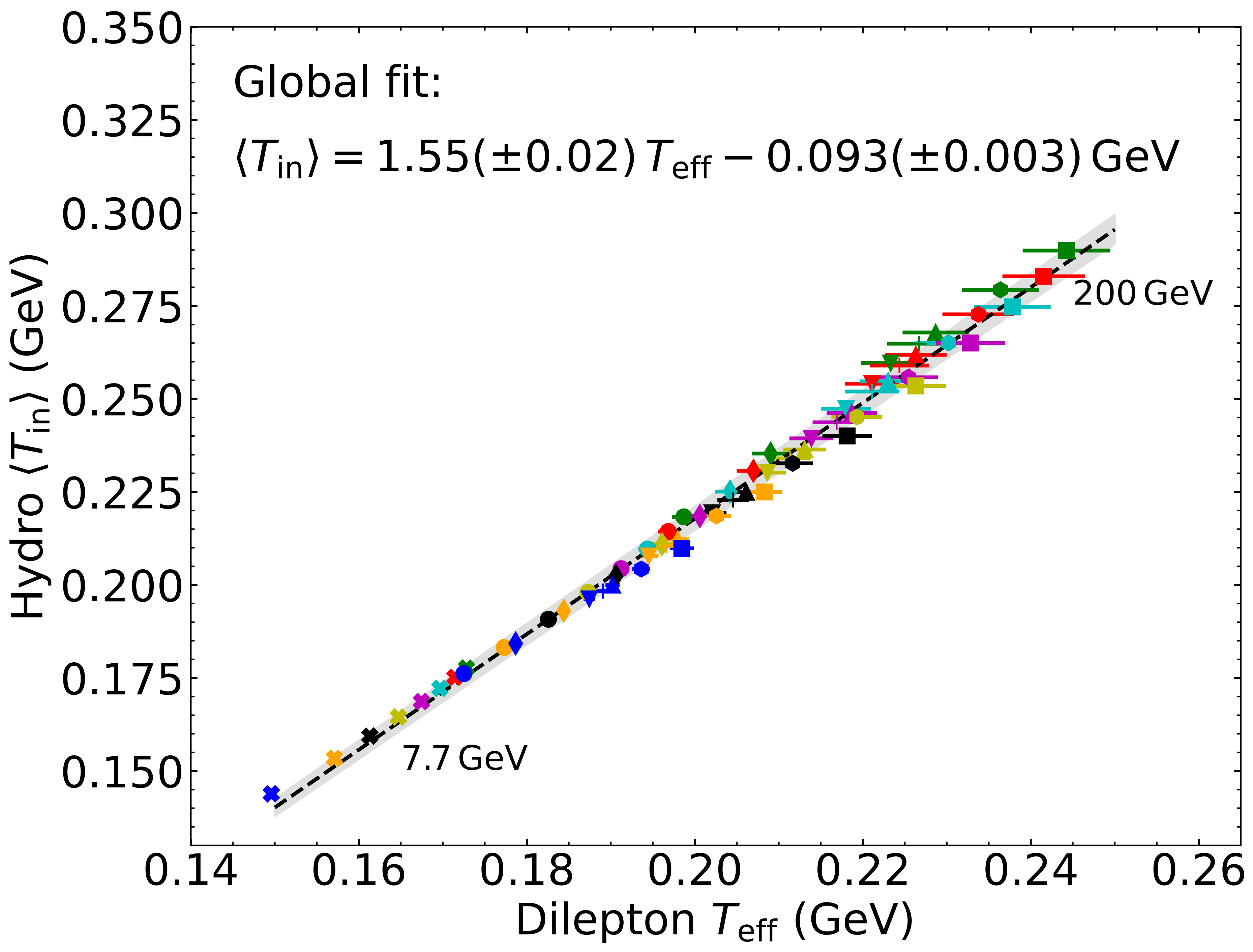


- Curves & bands: hydrodynamic temperature. curve: mean temperature; band: standard deviation
- Dots: effective temperature extracted from dilepton spectra at various time steps

Photon thermometer: Shen, Heinz, Paquet, and Gale, PRC 89, 044910 (2014)

THERMAL DILEPTON AS THERMOMETER





https://github.com/LipeiDu/DileptonEmission

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)

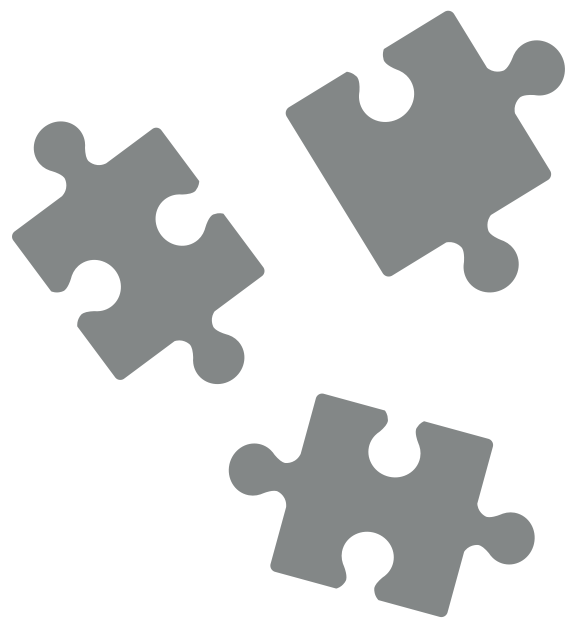
- Combining all energies and centralities, a strong correlation is observed between the initial hydro temperature and the effective temperature extracted from the dilepton spectra
- Measure the temperature of the evolving QCD fireball in a way that is unaffected by dynamical distortions

Kajantie and Miettinen, Z. Phys. C 9, 341 (1981); Hwa and Kajantie, PRD 32, 1109 (1985); Rapp and van Hees, PLB 753, 586 (2016);

SUMMARY AND OUTLOOK

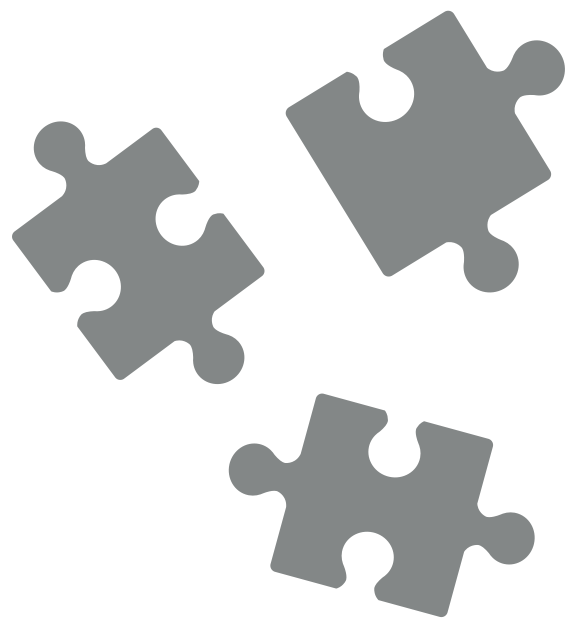
CHALLENGES AT BEAM ENERGY SCAN

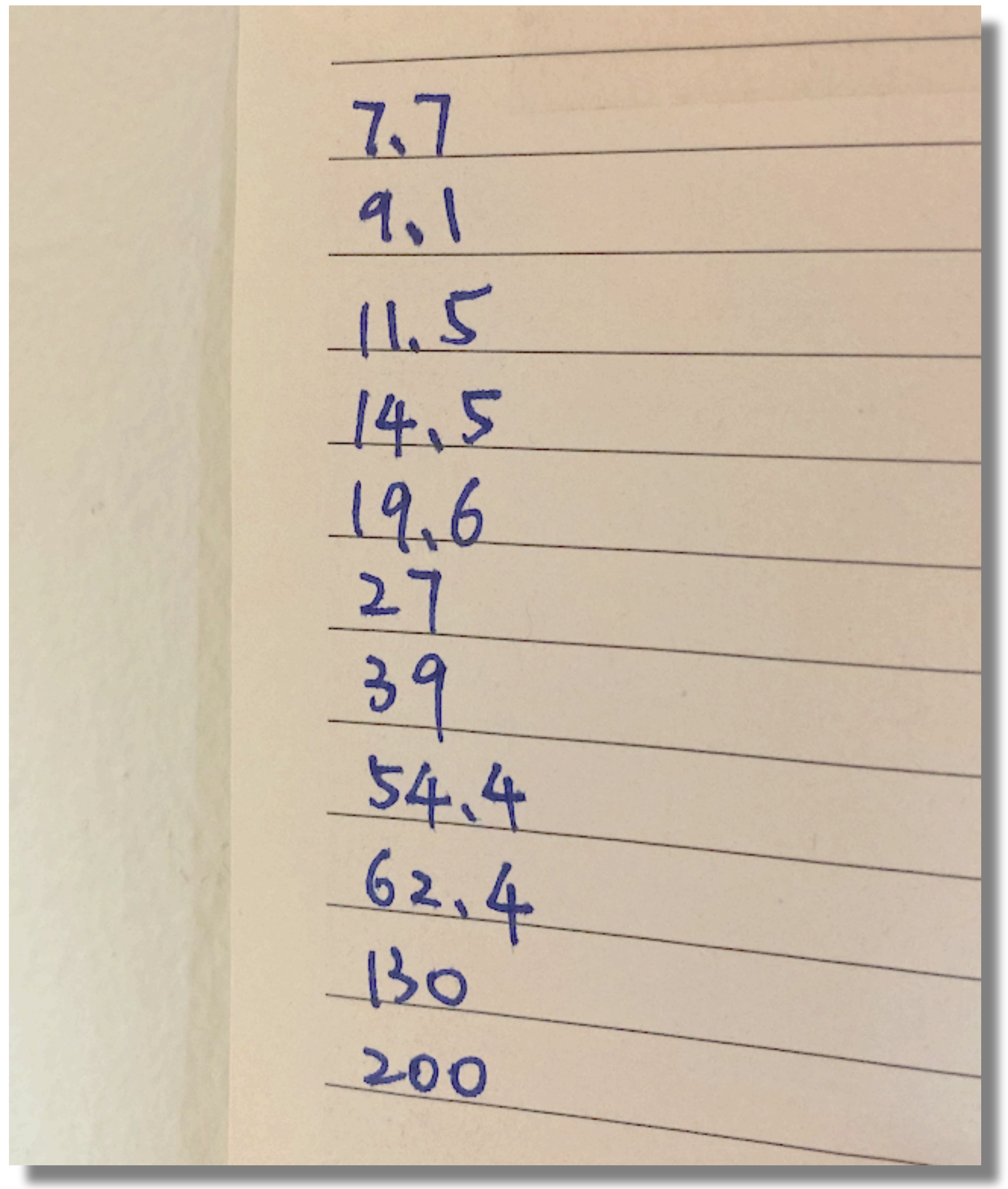
- Physics Complexity:
  - Complicated longitudinal dynamics
  - Transport of conserved charges (baryon, electric and strangeness)
  - Critical effects
- Computational Demands:
  - More physics ingredients
  - (3+1)-dimensional simulations
  - A broad range of beam energies
- Limitations in Rapidity-dependent Measurements:
  - Detector coverage
  - Scheduled shutdown of RHIC



CHALLENGES AT BEAM ENERGY SCAN

- Physics Complexity:
    - Complicated longitudinal dynamics
    - Transport of conserved charges (baryon, electric and strangeness)
    - Critical effects
- Computational Demands:
    - More physics ingredients
    - (3+1)-dimensional simulations
    - A broad range of beam energies
- Limitations in Rapidity-dependent Measurements:
    - Detector coverage
    - Scheduled shutdown of RHIC





OPPORTUNITIES

- Unique Physics:
  - Region to search for the QCD critical point
  - QCD at high baryon density (especially, multi-messenger at $\mu_B \neq 0$)
  - Connection to neutron star physics
  - Stronger constraints from rapidity-dependent measurements
    - EOS, baryon stopping, energy deposition, etc.
- Urgent Questions:
  - Constraining the longitudinal flow (both initial and final)
  - Transport coefficients of charges
  - Quantitative studies with limited rapidity data

A THEORY OVERVIEW

Chapter 1

The QCD phase diagram and Beam Energy Scan physics: a theory overview

Lipei Du,[1,2*] Agnieszka Sorensen,[3†] and Mikhail Stephanov[4,5‡]

[1]*Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada*

[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94270, USA*

[3]*Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*

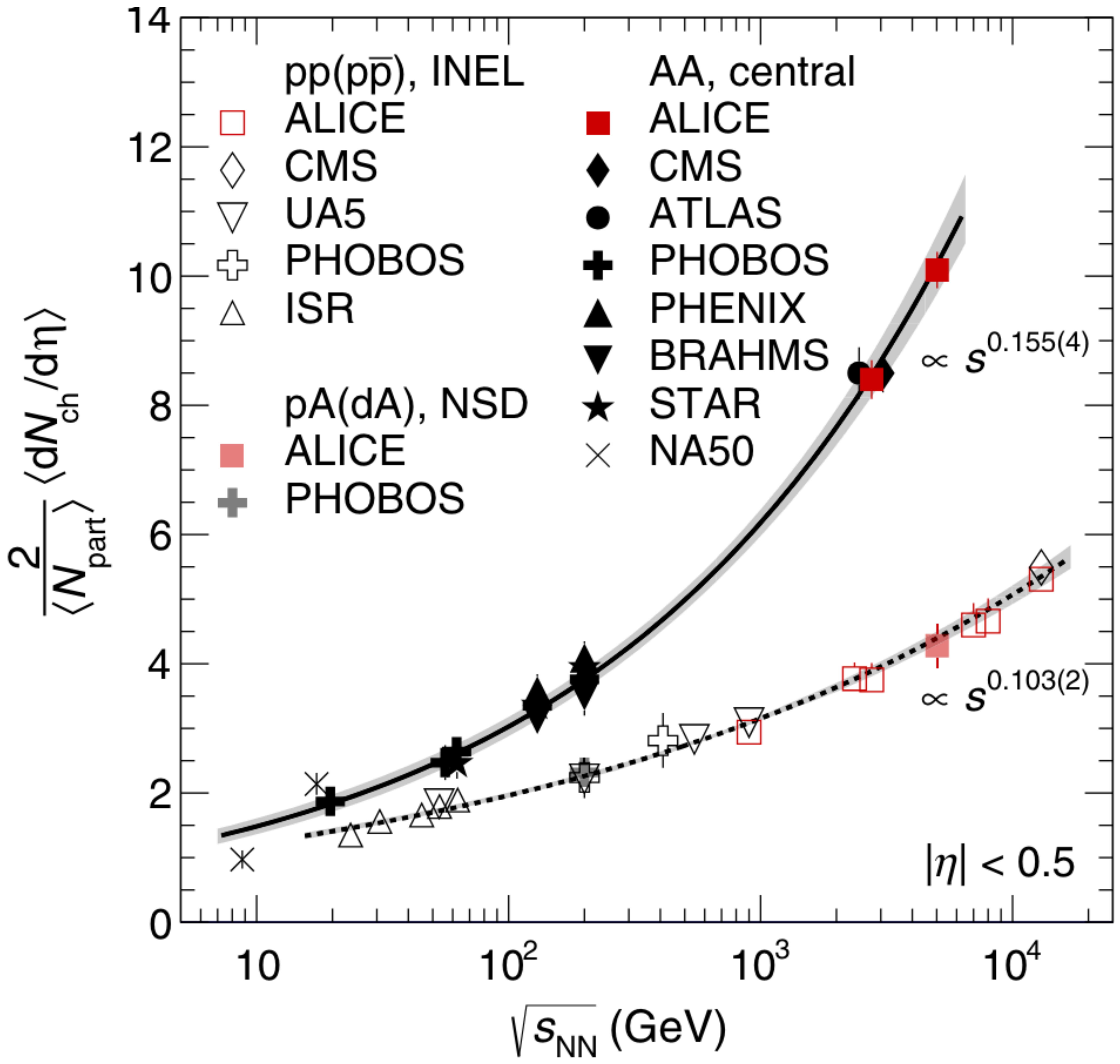
[4]*Department of Physics and Laboratory for Quantum Theory at the Extremes, University of Illinois, Chicago, IL 60607, USA*

[5]*Kadanoff Center for Theoretical Physics, University of Chicago, Chicago, Illinois 60637, USA*

L. Du, A. Sorensen, and M. Stephanov, 2402.10183 (a contribution to Quark-Gluon Plasma 6)

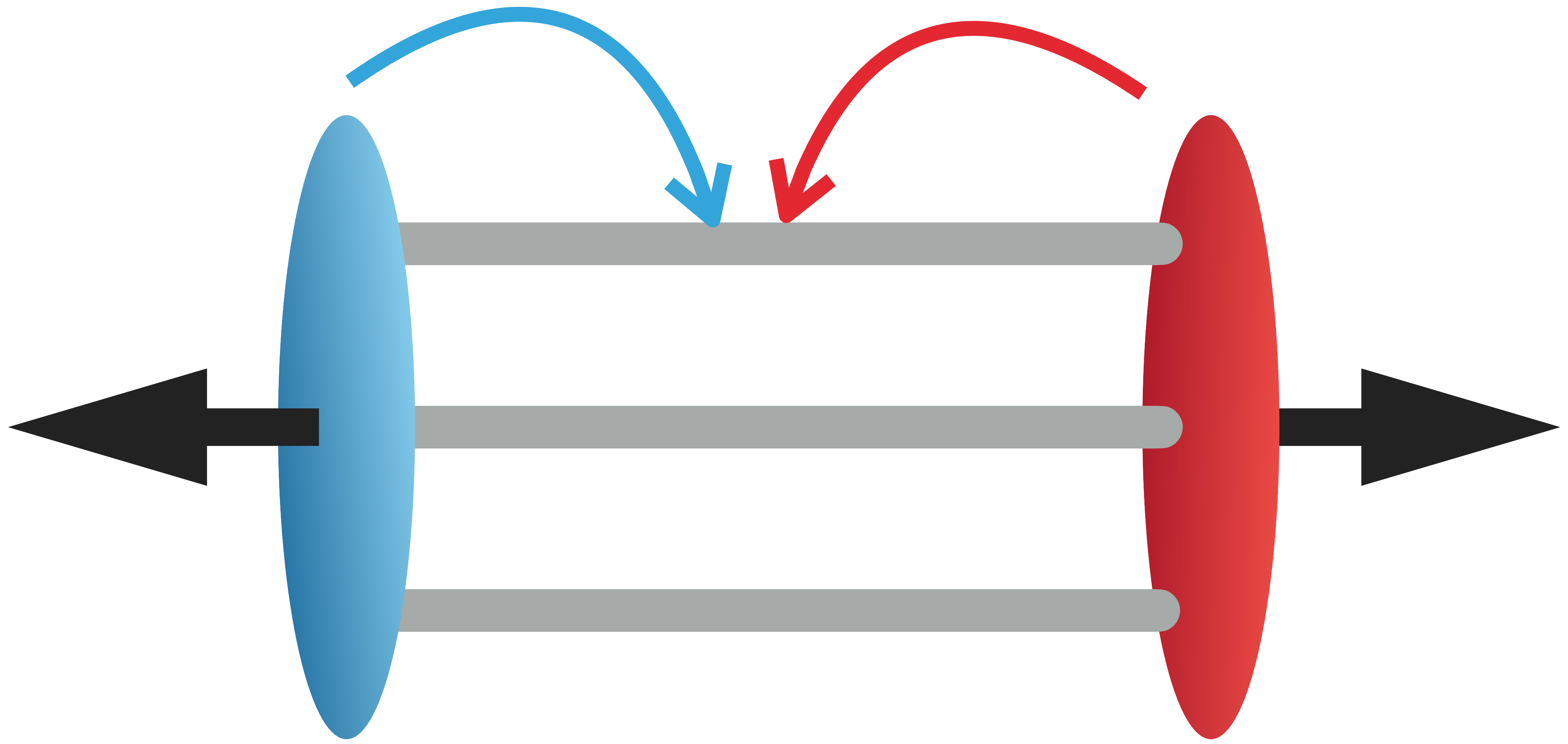
THANK YOU FOR YOUR ATTENTION!

CHARGED MULTIPLICITY SCALING

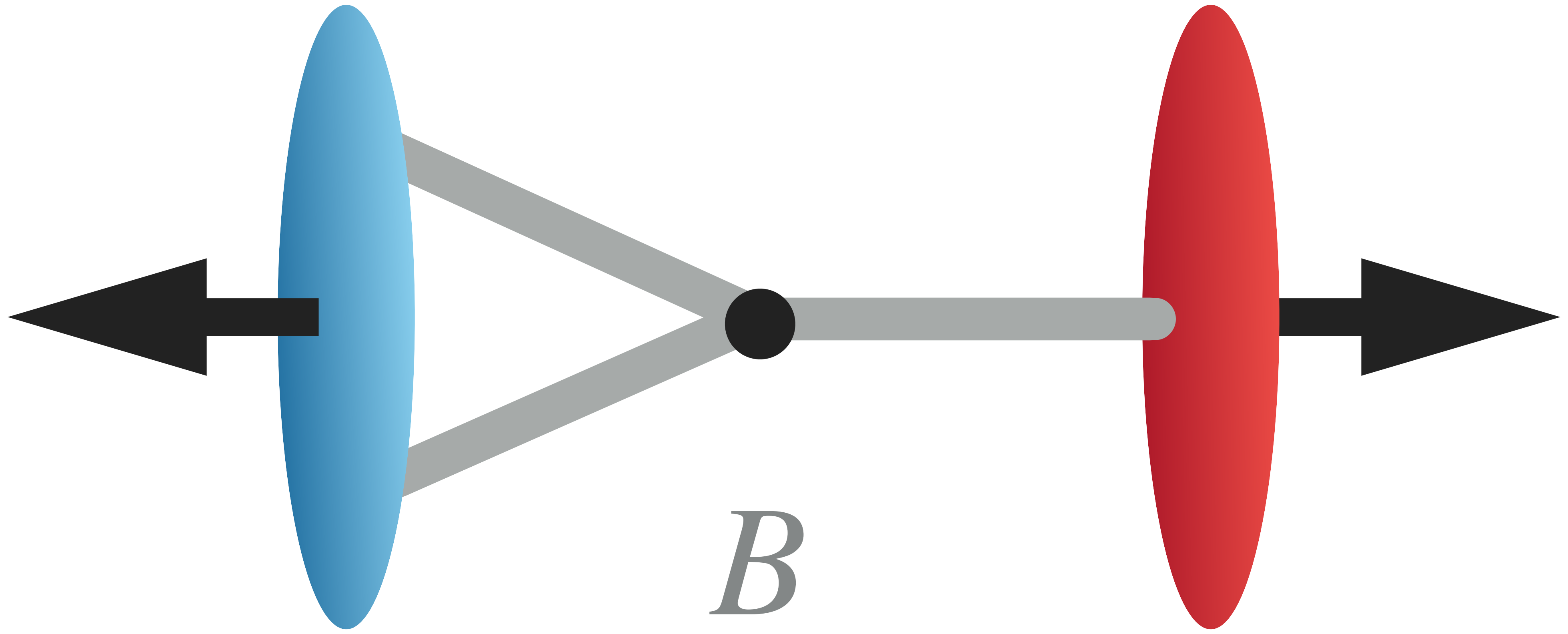


ALICE, PRL 116, 222302 (2016)

INITIAL BARYON "STOPPING"



Baryons get distributed in rapidity by deceleration of the incoming nucleons



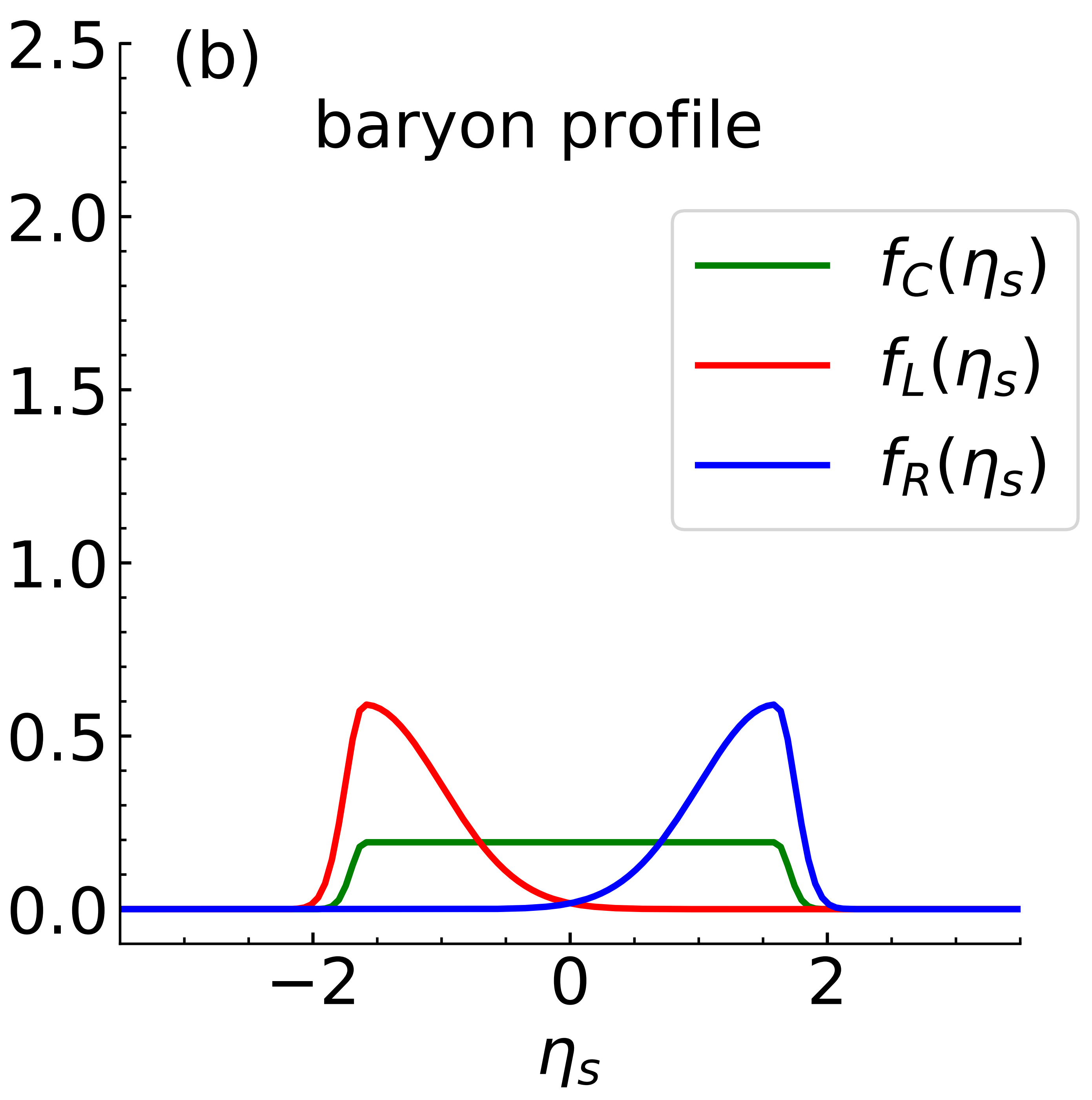
Baryons get distributed in rapidity through string junction breaking

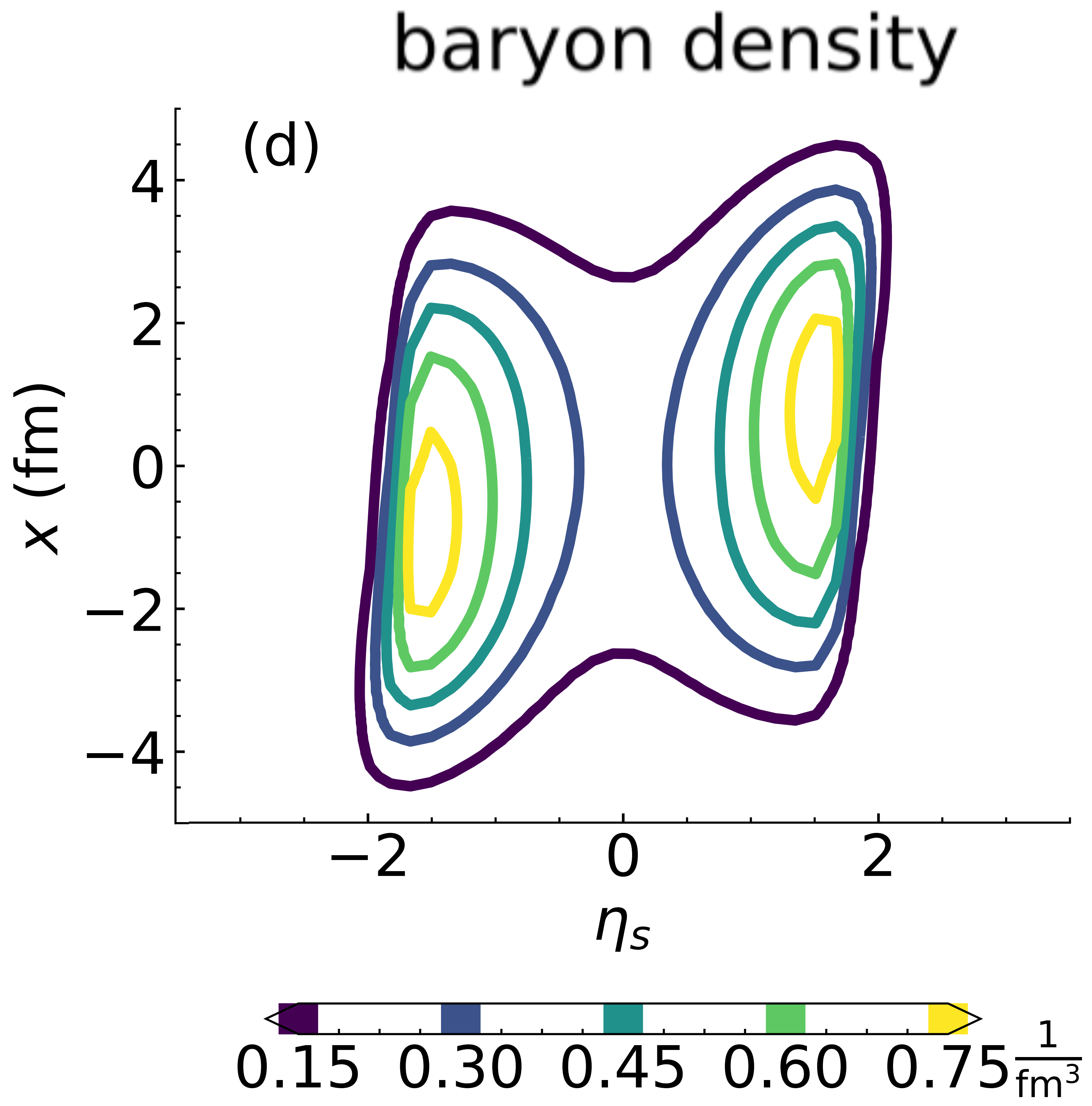
- Profound impact on understanding initial baryon distribution and energy loss
- How to differentiate "baryon deceleration" and "string junction breaking" in the initial baryon distribution?

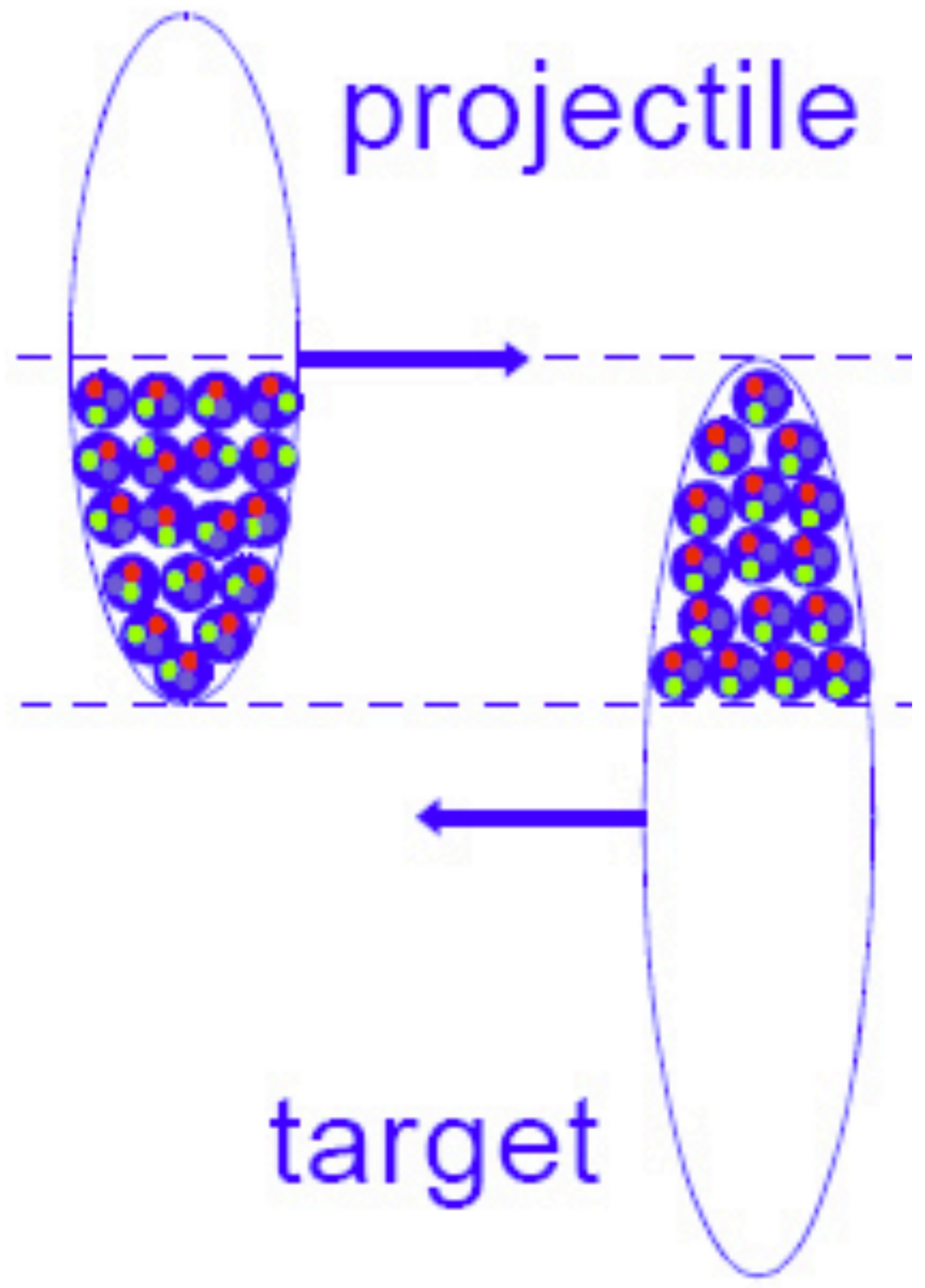
String junction: Kharzeev, PLB 378, 238 (1996); Sjostrand & Skands, NPB 659, 243 (2003)

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

NEW PARAMETRIC BARYON INITIAL CONDITION



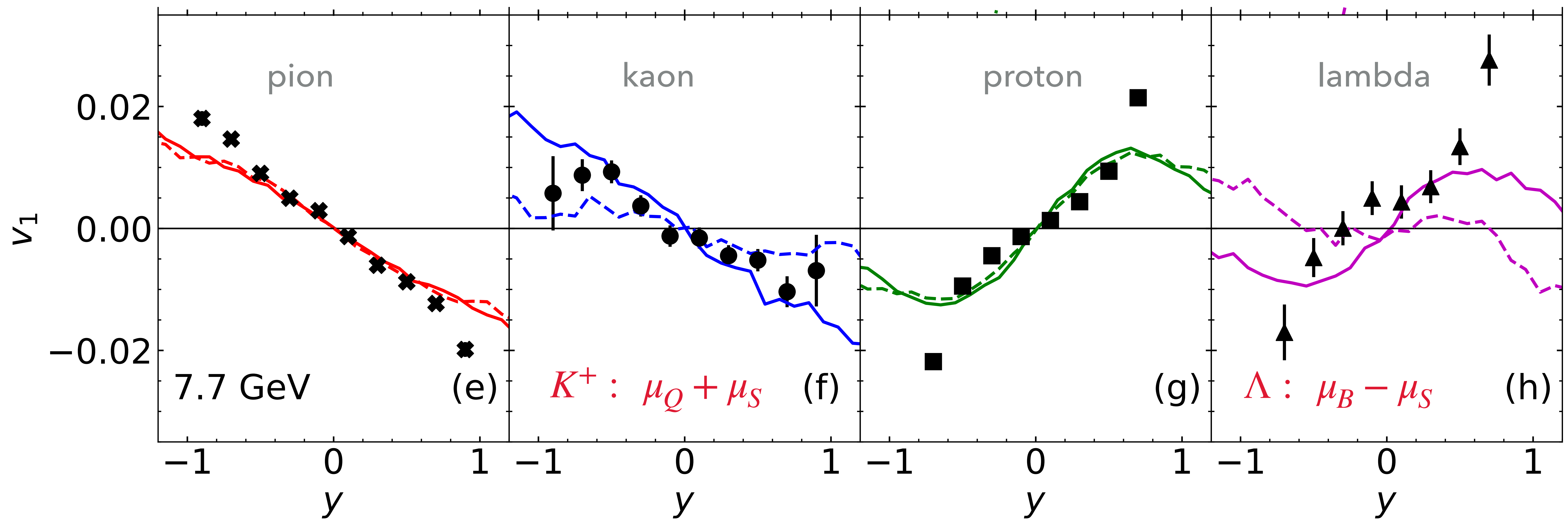




- A rapidity-independent "plateau" component in initial baryon profile & tilted baryon peaks describing the varying baryon stopping in the transverse plane

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

PROBING EOS AT FINITE CHEMICAL POTENTIALS



Solid: NEOS-B

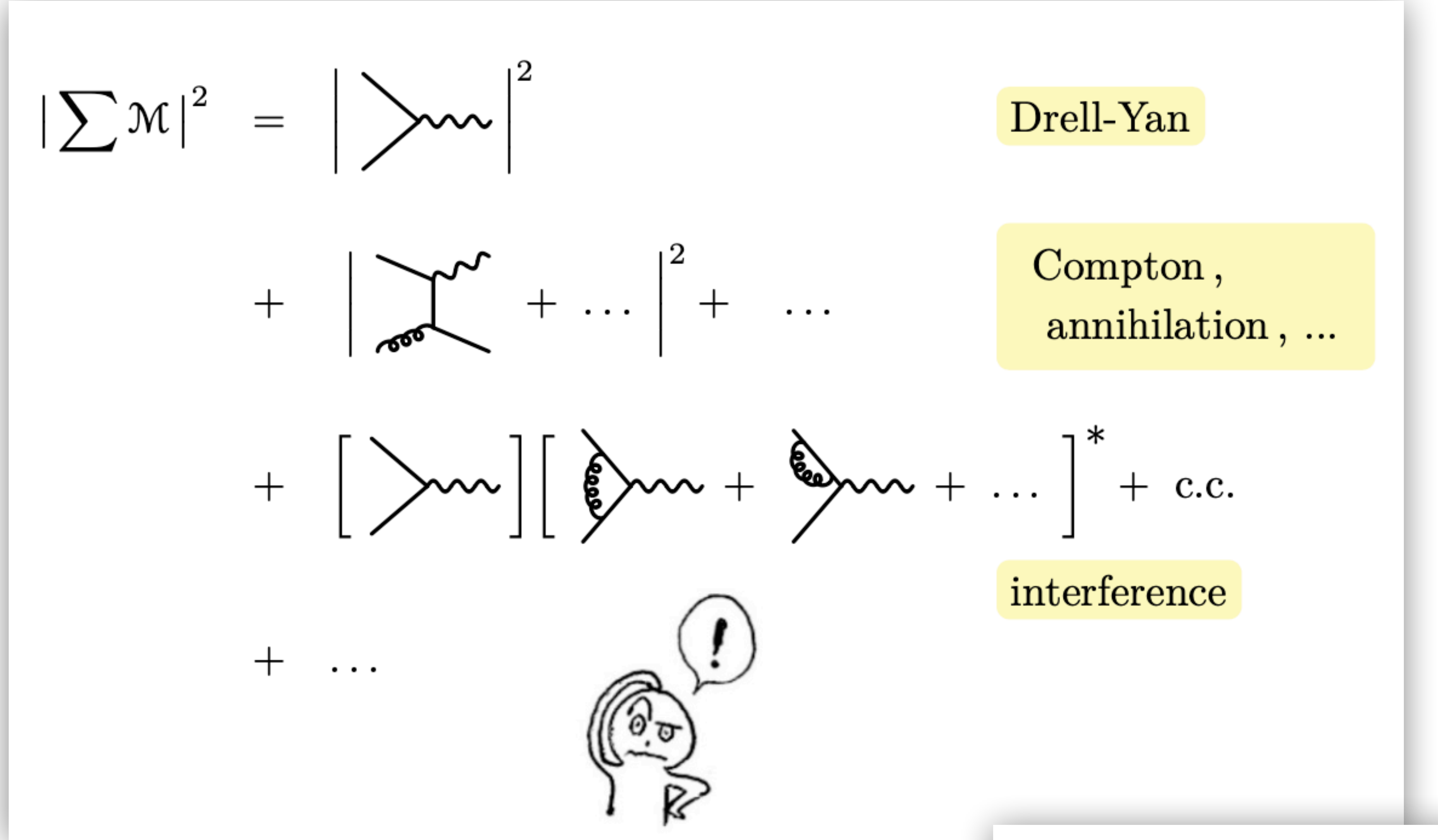
Dashed: NEOS-BQS

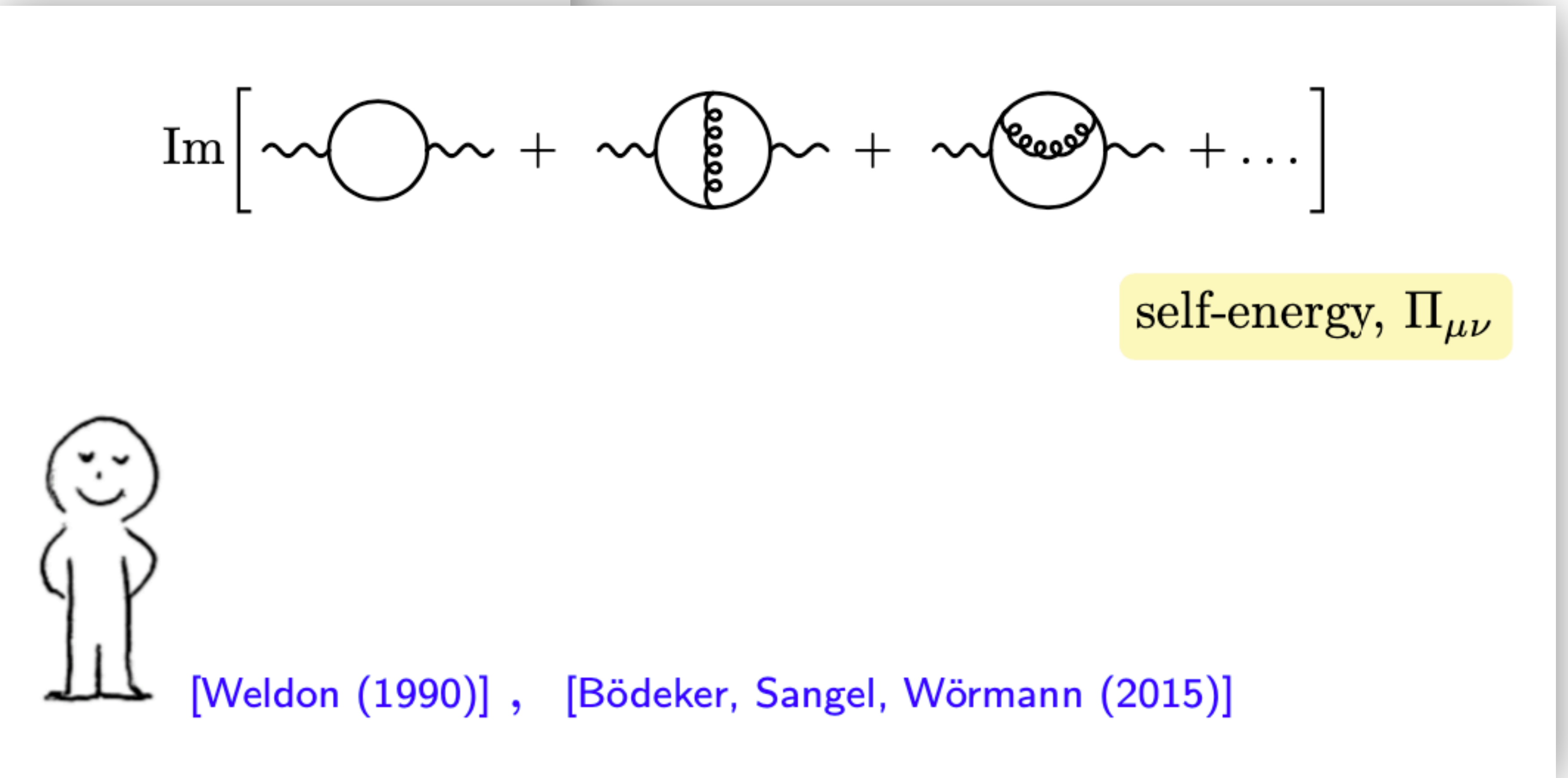
NEOS: Monnai et al, PRC 100, 024907 (2019)

- Two limits of EoS: NEOS-B, $\mu_S = \mu_Q = 0$ and NEOS-BQS, $n_S = 0, n_Q = 0.4 n_B$ (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

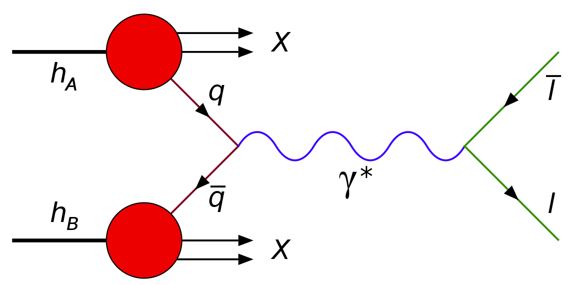
APPLICATION OF PERTURBATIVE QCD



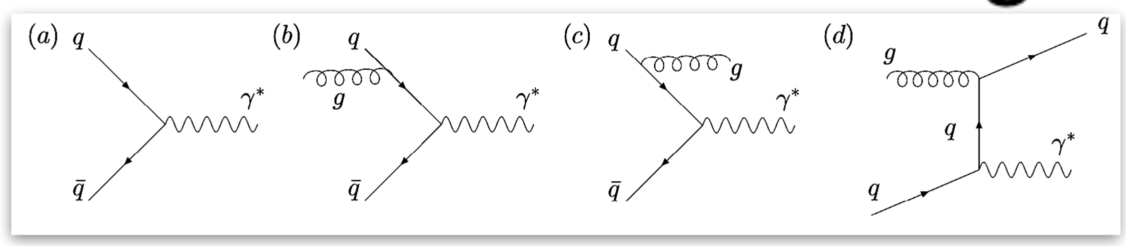


DILEPTON SPECTRA

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



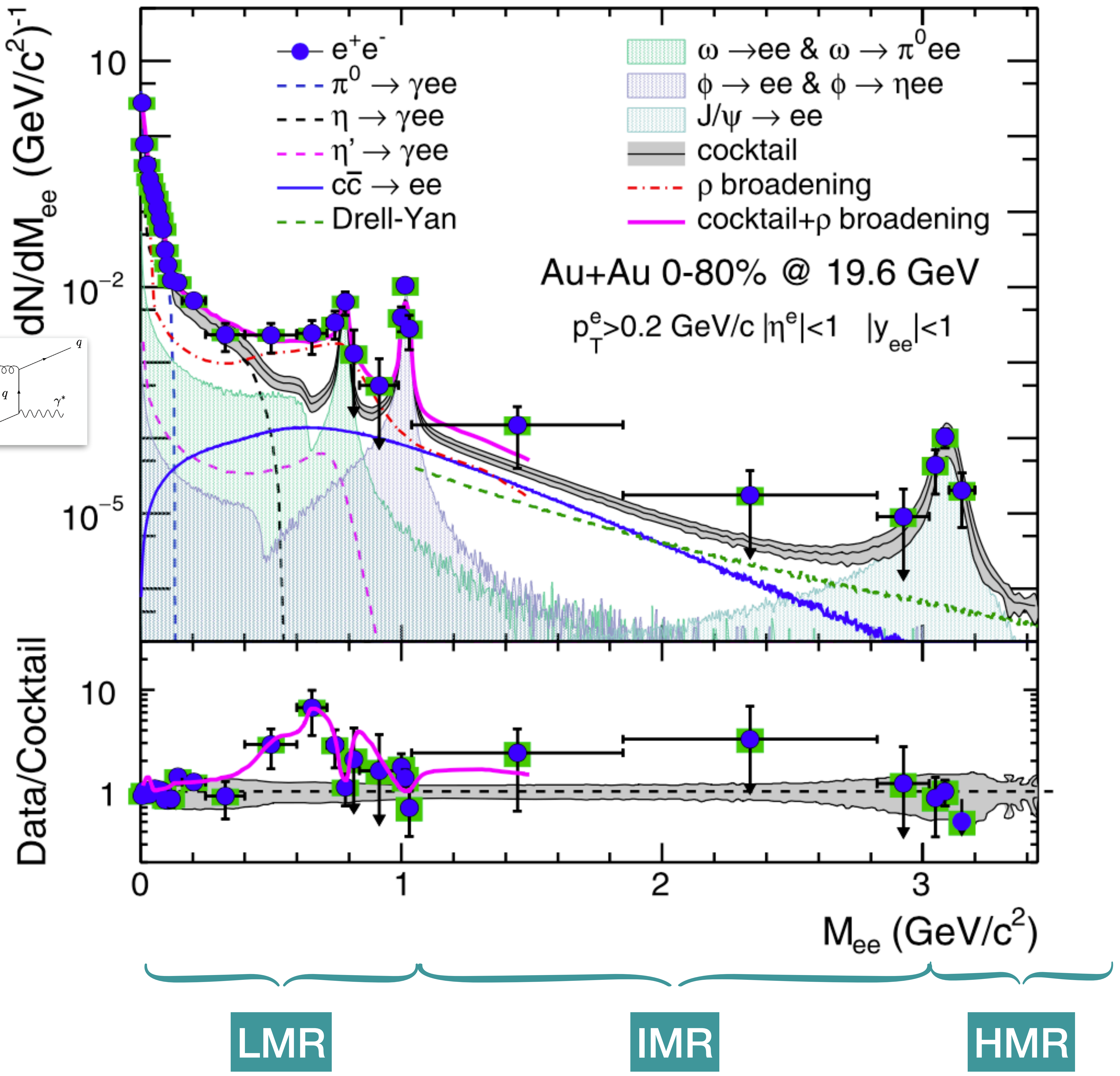
  - decays of J/ψ
- Intermediate-mass region (IMR)
  - thermal emission from QGP



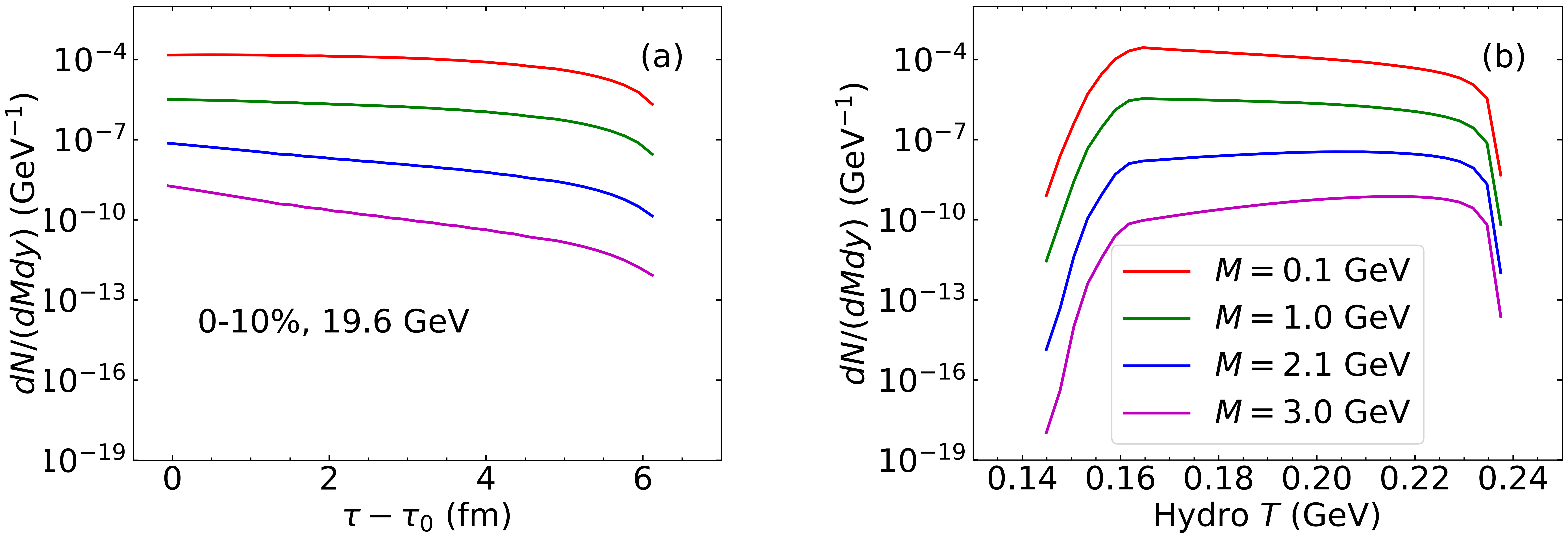
  - semileptonic decays from open heavy flavor-antiflavor pair, e.g. $D/\bar{D}$
- Low-mass region (LMR)
  - thermal emission from hadronic matter
  - direct decays of $\rho/\omega/\phi$ (ρ is short-lived)
  - Dalitz (three body) decays of $\pi^0/\eta/\eta'$

Dilepton cocktail: late decays of hadrons

STAR, PLB 750 (2015) 64–71



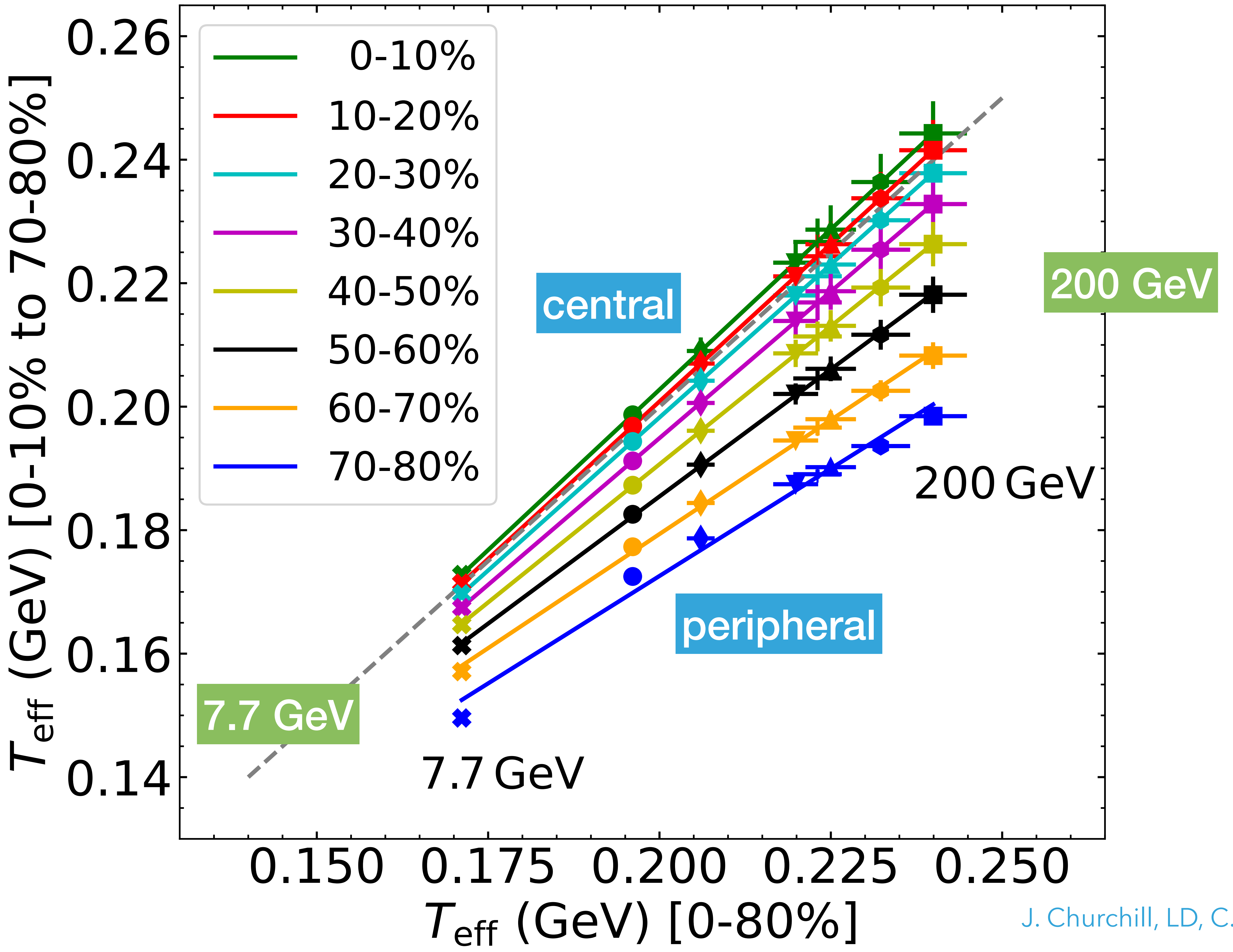
DILEPTON PRODUCTION IN T AND τ



- Two effects at play:
  - The emission rate decreases as the temperature decreases
  - The volume of the system increases with time

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)

THERMAL DILEPTON AS THERMOMETER



- The effective temperatures extracted from the dilepton spectra in 0-80% centrality are quite close to those in 10-20% centrality across all beam energies

J. Churchill, LD, C. Gale, G. Jackson & S. Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)