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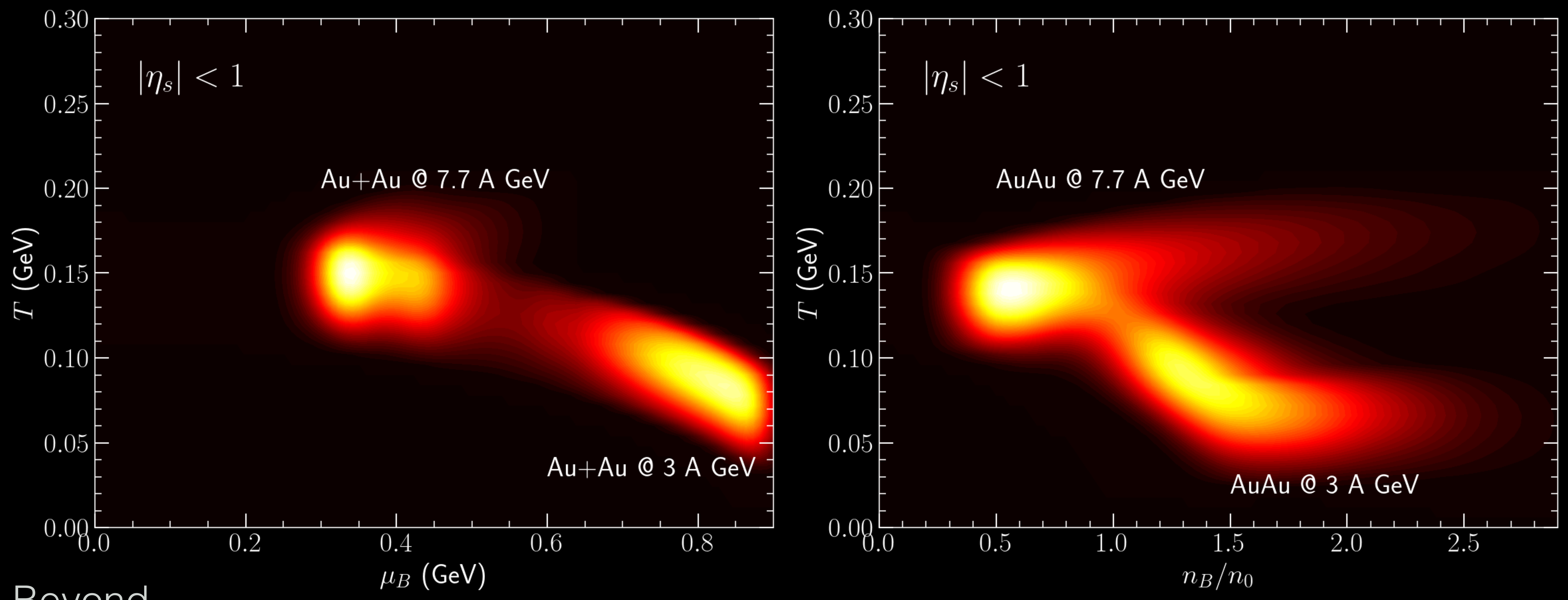
BEST COLLABORATION

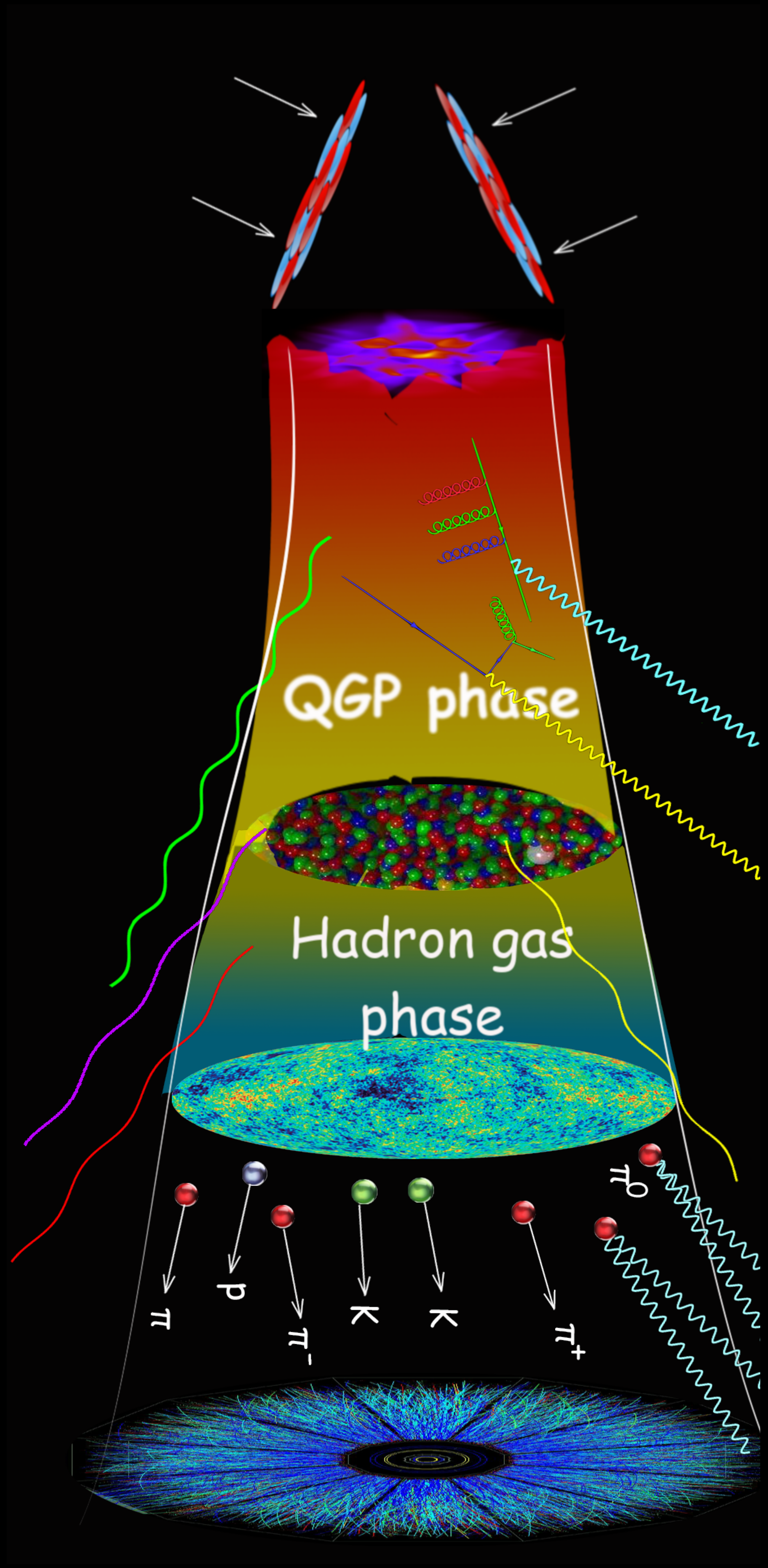
DYNAMICAL MODELING OF RHIC BES: WHAT'S THERE AND WHAT'S LEFT?

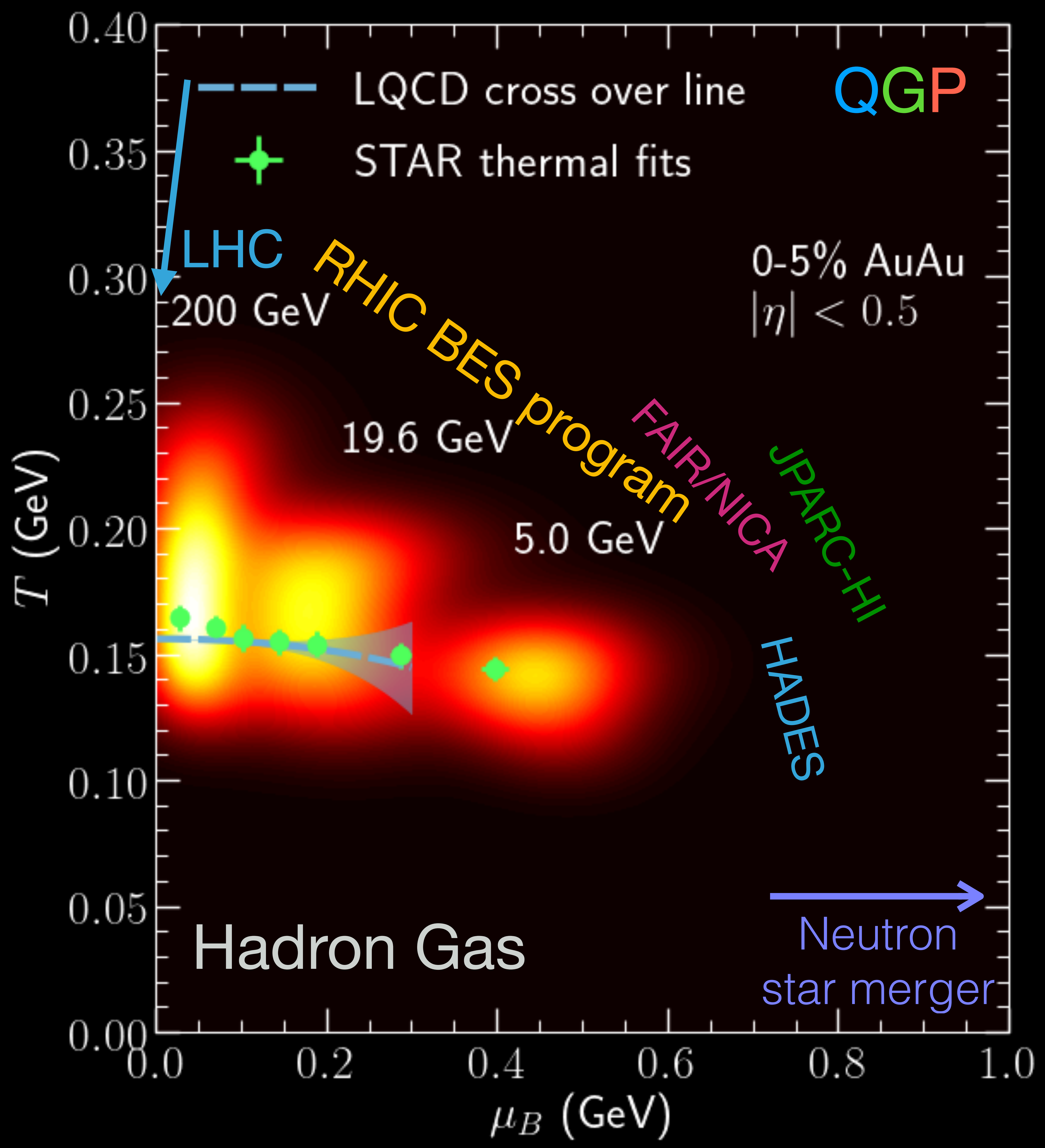
CHUN SHEN



August 17, 2021
RHIC Beam Energy Scan and Beyond

PROBING THE NUCLEAR MATTER PHASE DIAGRAM





- Search for a critical point & 1st order phase transition
- How does the QGP transport property change with baryon doping?

$(\eta/s)(T, \{\mu_q\})$, $(\zeta/s)(T, \{\mu_q\})$

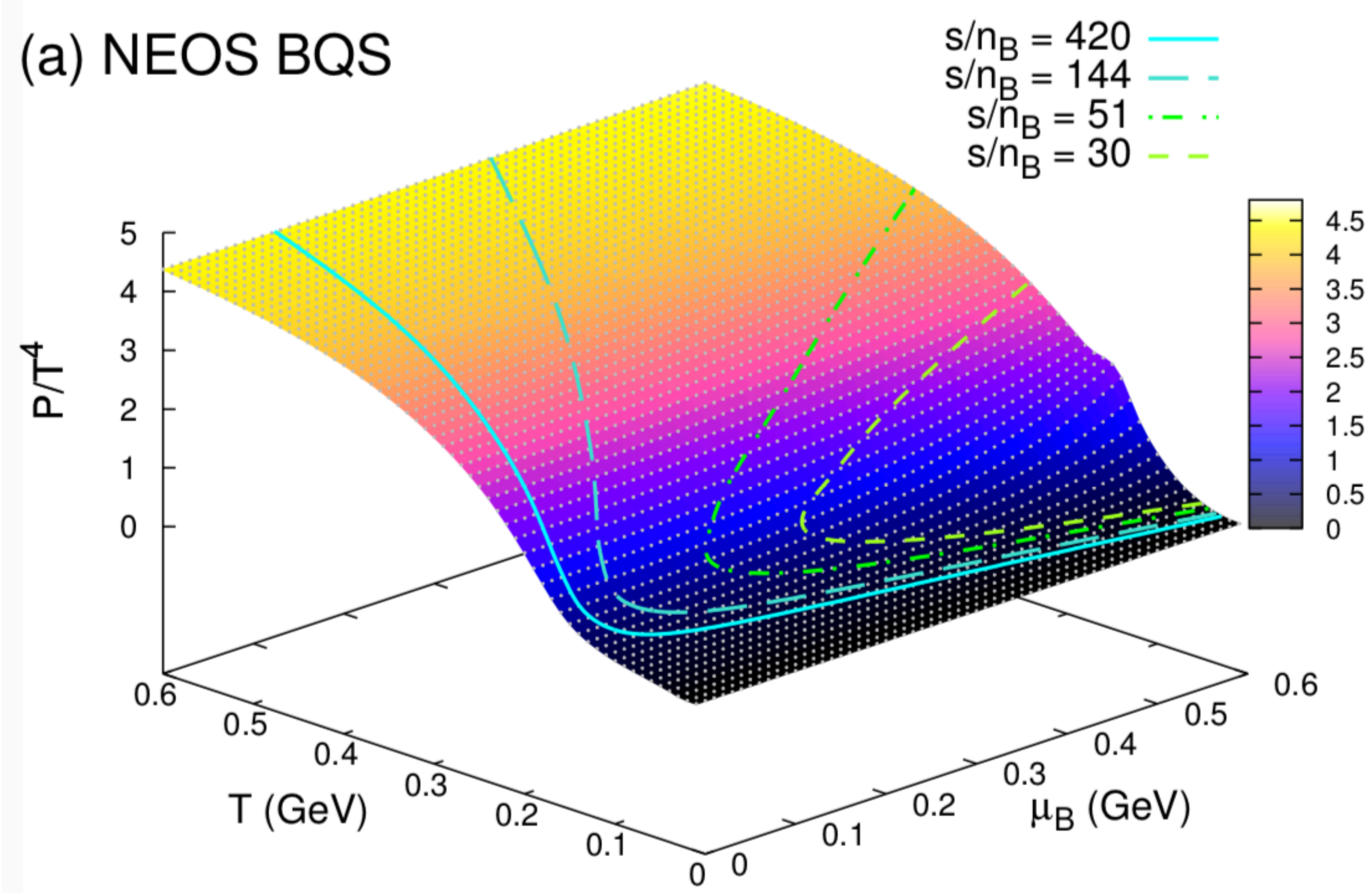
- Access to new transport phenomena

Charge diffusion

QCD EQUATION OF STATE AT FINITE DENSITIES

M. Albright, J. Kapusta and C. Young, Phys. Rev. C90, 024915 (2014)
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)
J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, Phys. Rev. C100, 064910 (2019)
J. M. Stafford *et. al*, arXiv:2103.08146 [hep-ph]

$n_s = 0 \quad n_Q = 0.4 n_B$



Lattice QCD: Taylor expansion up to the 4th order

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi^{B,Q,S}_{l,m,n}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

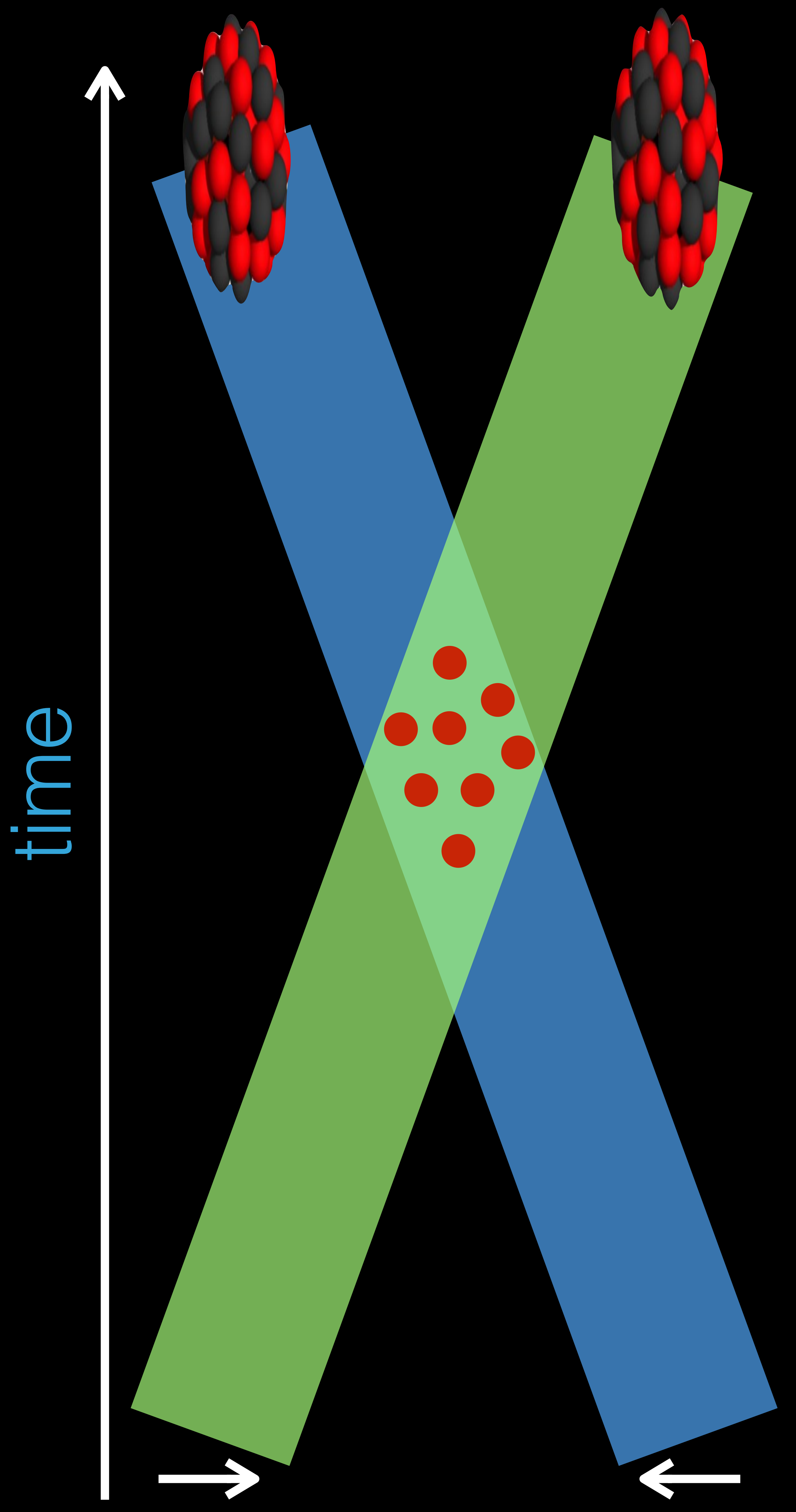
Match to Hadron Resonance Gas model at low T

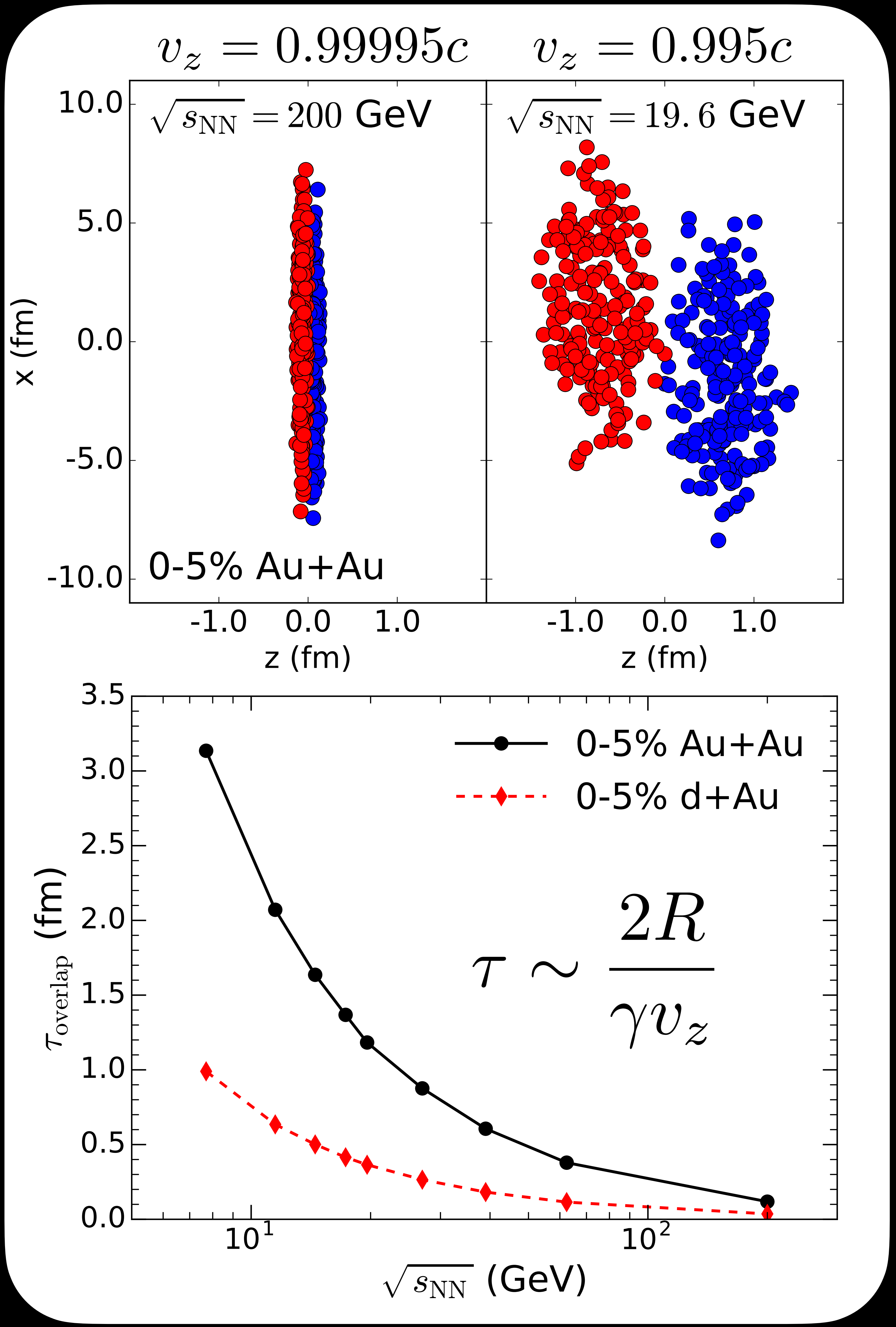
$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_J)]\frac{P_{\rm had}(T,\mu_J)}{T^4} + \frac{1}{2}[1 + f(T,\mu_J)]\frac{P_{\rm lat}(T,\mu_J)}{T^4}$$

$$f(T,\mu_B) = \tanh[(T - T_c(\mu_B)/\Delta T_c]$$

Enabled hydrodynamic simulations at finite μ_B $(\mu_B/T \leq 2.5)$

3D DYNAMICS BEYOND THE BJORKEN PARADIGM



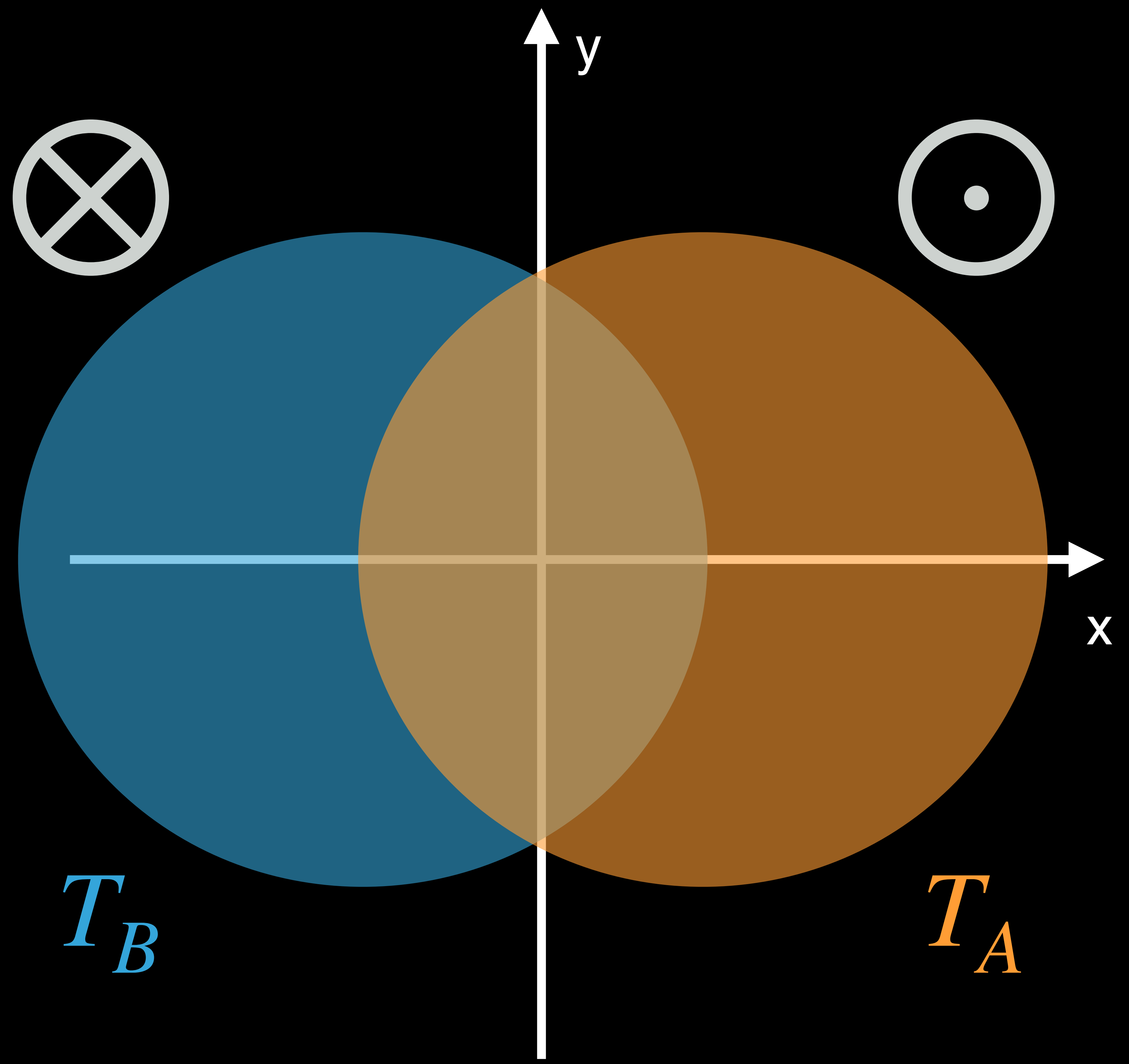


- Geometry-Based initial conditions
  - C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
  - X. Y. Wu, G. Y. Qin, L. G. Pang and X. N. Wang, arXiv:2107.04949 [hep-ph]
- Classical string-based initial conditions
  - A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)
  - C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907
- Transport model based initial conditions
  - I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
  - L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410
- Color Glass Condensate based models
  - M. Li and J. Kapusta, Phys. Rev. C 99, 014906 (2019)
  - L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)
  - M. Martinez, M. D. Sievert, D. E. Wertepny and J. Noronha-Hostler, arXiv:1911.10272 + arXiv:1911.12454 [nucl-th]
- Holographic approach at intermediate coupling
  - M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

A COLLISION-GEOMETRY-BASED 3D INITIAL CONDITION

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
S. Ryu, V. Jupic and C. Shen, arXiv:2106.08125 [nucl-th]

- Impose energy and momentum conservation on the Glauber geometry
  Assumption: All of the energy and momentum is deposited into the medium

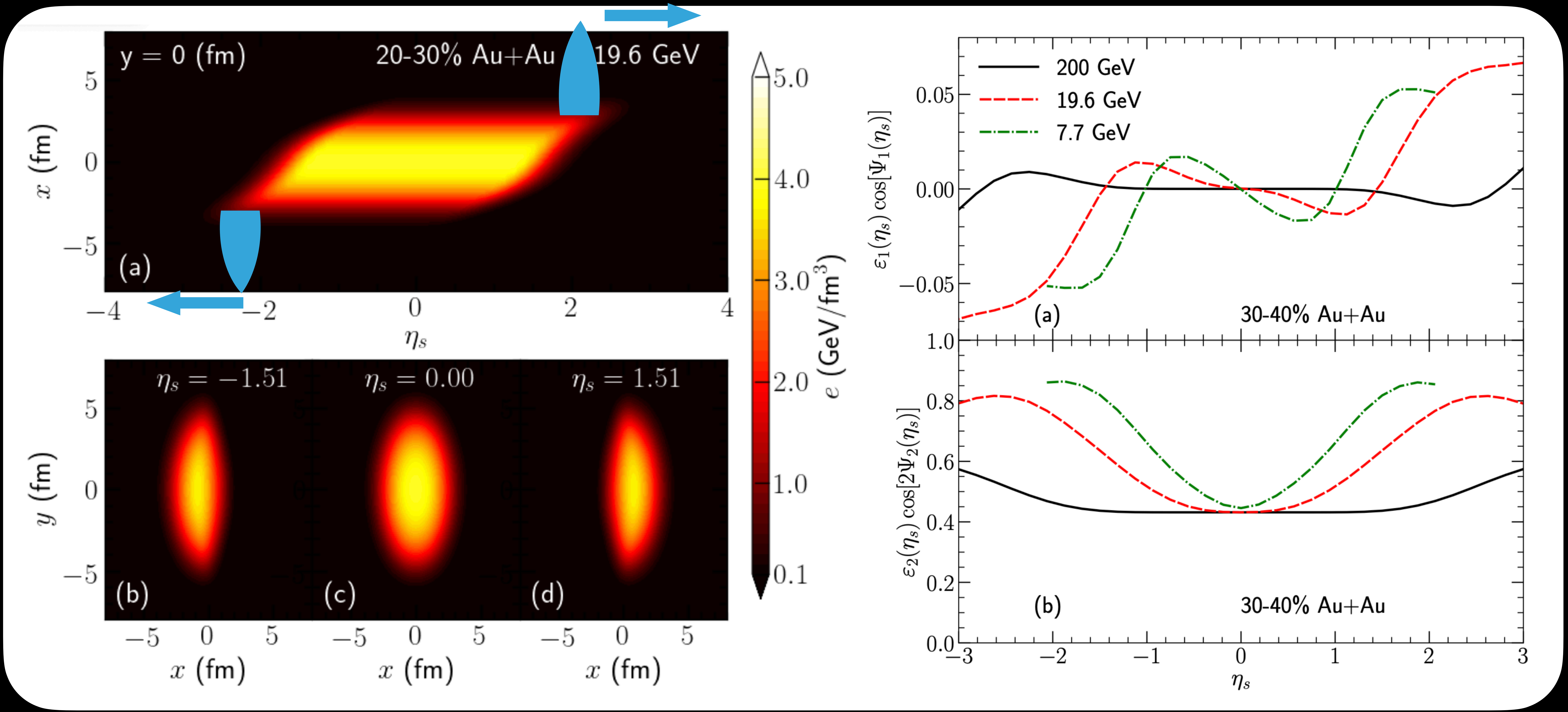


$$\frac{dE}{d^2x} = [T_A(x) + T_B(x)] m_N \cosh y_{\mathrm{beam}}$$
$$\equiv M \cosh(y_{\mathrm{CM}}) = \int \tau_0 d\eta_s T^{t\tau}(\tau_0, \eta_s, x)$$
$$\frac{dP^z}{d^2x} = [T_A(x) - T_B(x)] m_N \cosh y_{\mathrm{beam}}$$
$$\equiv M \sinh(y_{\mathrm{CM}}) = \int \tau_0 d\eta_s T^{z\tau}(\tau_0, \eta_s, x)$$

Conservations of energy, momentum, and angular momentum are ensured

A MINIMUM EXTENSION TO 3D INITIAL CONDITIONS

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

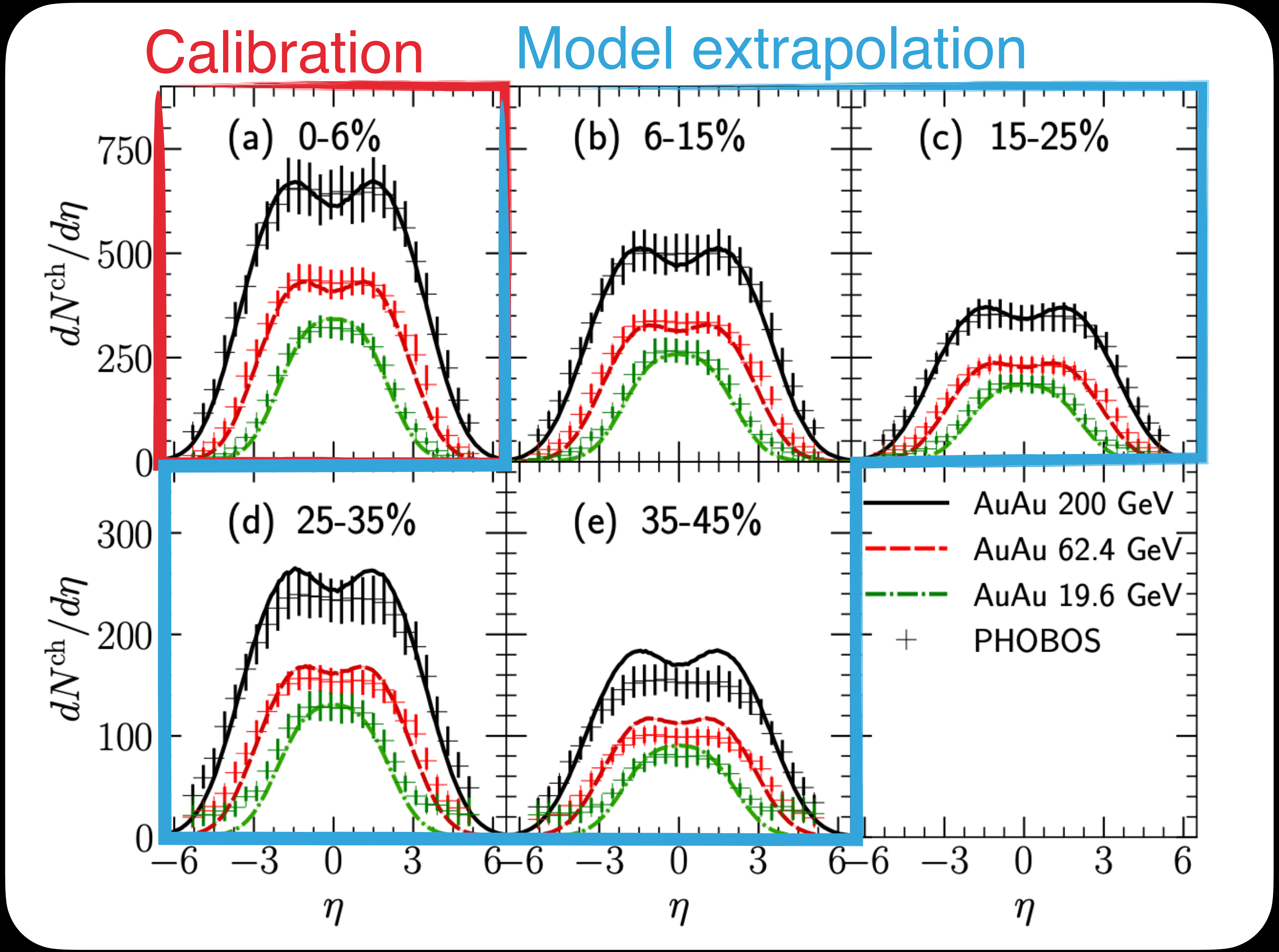


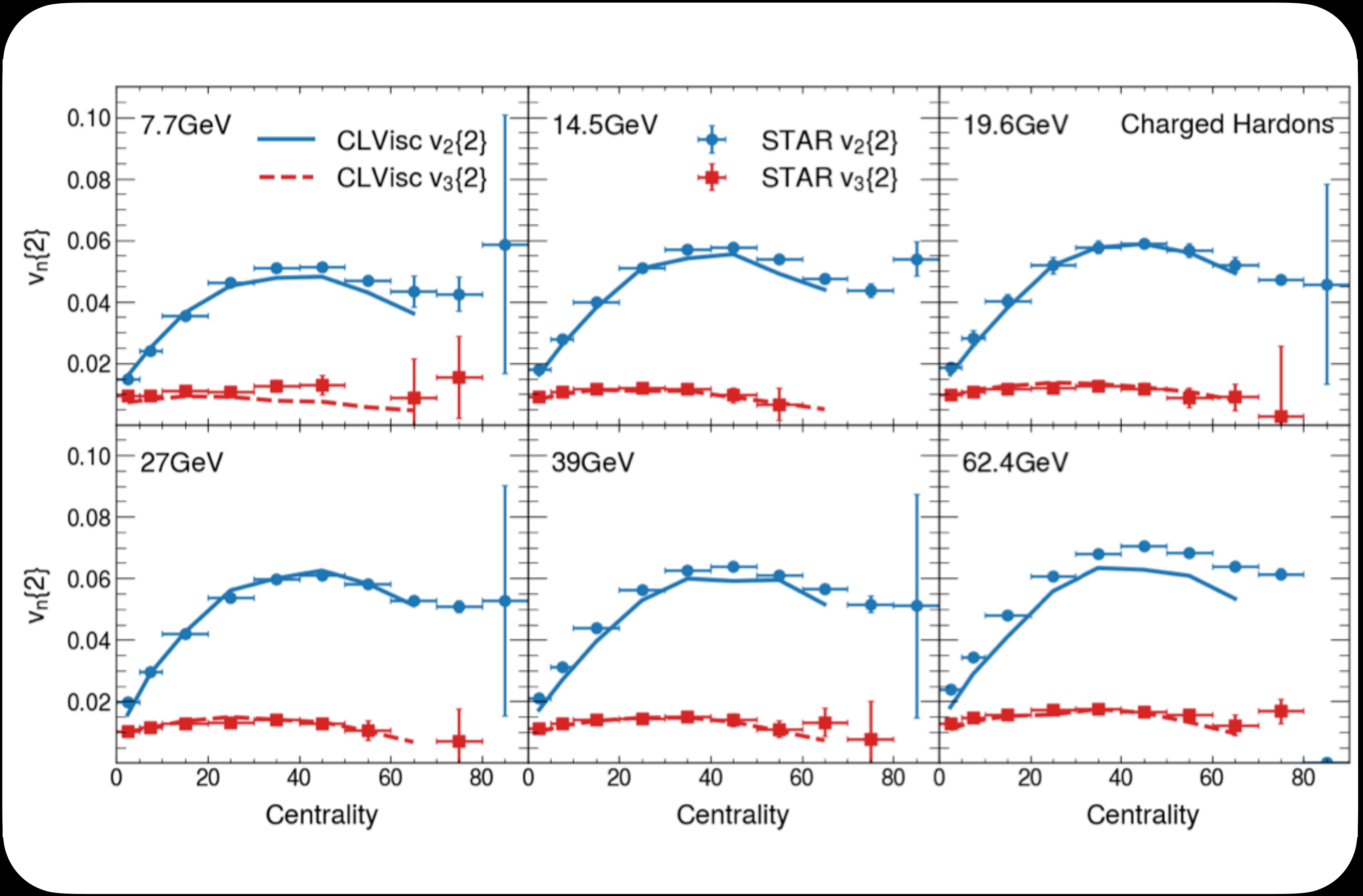
- The mid-rapidity transverse energy density profile $e(x, y) \propto \sqrt{T_A T_B}$

PARTICLE PRODUCTIONS AT RHIC BES AND SPS

C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

X. Y. Wu, G. Y. Qin, L. G. Pang and X. N. Wang, arXiv:2107.04949 [hep-ph]





- The rapidity dependence of particle production and mid-rapidity anisotropic flow are well described by the parametric models

ELLIPTIC FLOW AT RHIC BES AND SHEAR VISCOSITY

I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)

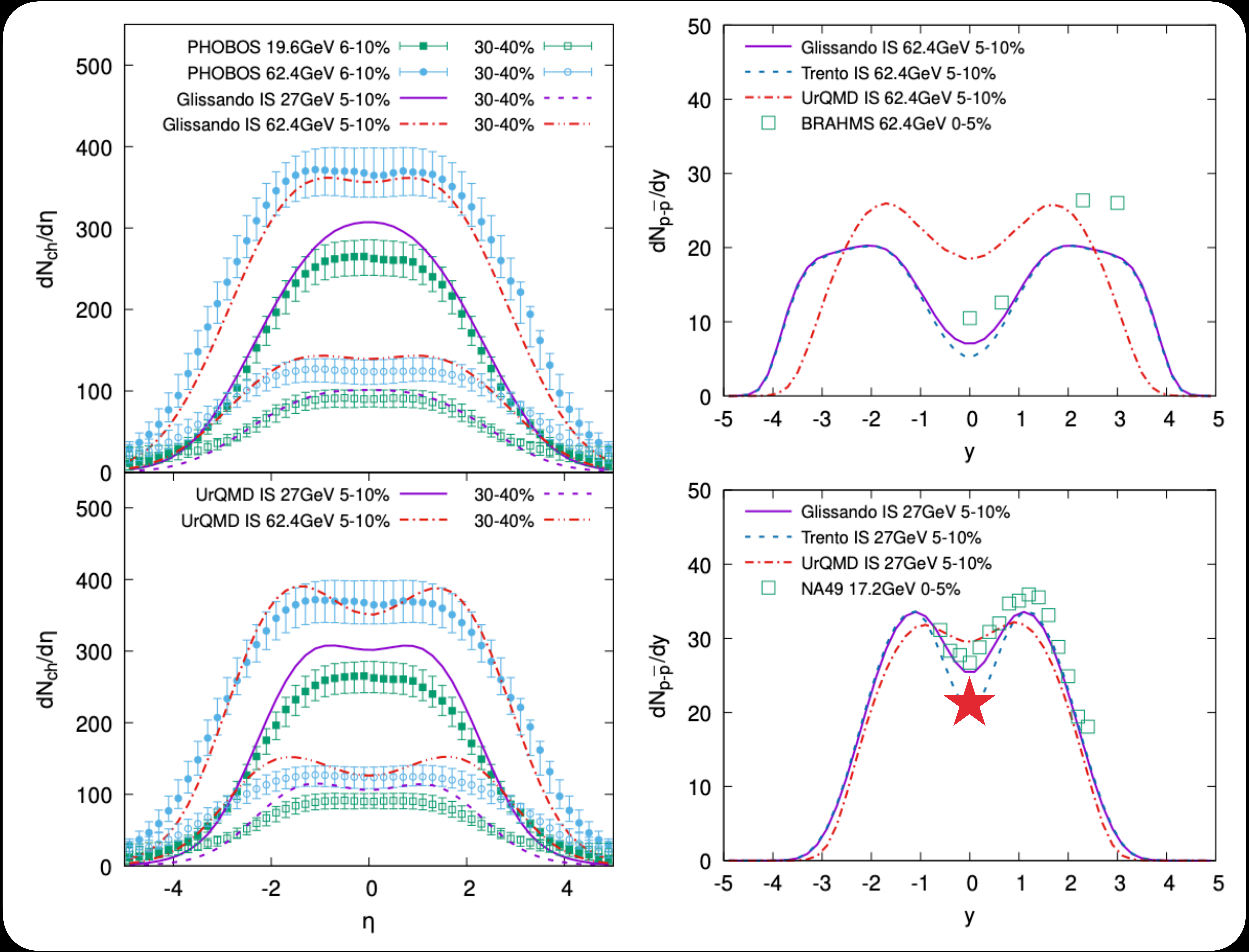
- The rapidity and centrality dependence of v_2 can set strong constraints on the $(\eta/s)(T, \mu_B)$

LIMITATIONS OF PARAMETRIC MODELS

- The model calibrations need to be performed for individual collision energy; their predictive power is limited
- The constrained model parameters usually fold many physics together — hard to interpret
- The early-stage dynamics is difficult to constrain — important for vorticity and EM probes

$\sqrt{s_{\rm NN}}$ (GeV)	τ_0 (fm/c)	η_0	σ_η	$\eta_{B,0}$	$\sigma_{B,\rm in}$	$\sigma_{B,\rm out}$
AuAu & dAu @ 200	1.0	2.5	0.6	3.5	2.0	0.1
AuAu & dAu @ 62.4	1.0	2.25	0.3	2.7	1.9	0.2
AuAu & dAu @ 39	1.3	1.9	0.3	2.2	1.6	0.2
AuAu@27	1.4	1.6	0.3	1.8	1.5	0.2
AuAu & dAu @ 19.6	1.8	1.3	0.3	1.5	1.2	0.2
AuAu@14.5	2.2	1.15	0.3	1.4	1.15	0.2
AuAu@7.7	3.6	0.9	0.2	1.05	1.0	0.1
PbPb@17.3	1.8	1.25	0.3	1.6	1.2	0.2
PbPb@8.77	3.5	0.95	0.2	1.2	1.0	0.1

TRANSPORT MODEL BASED INITIAL CONDITIONS



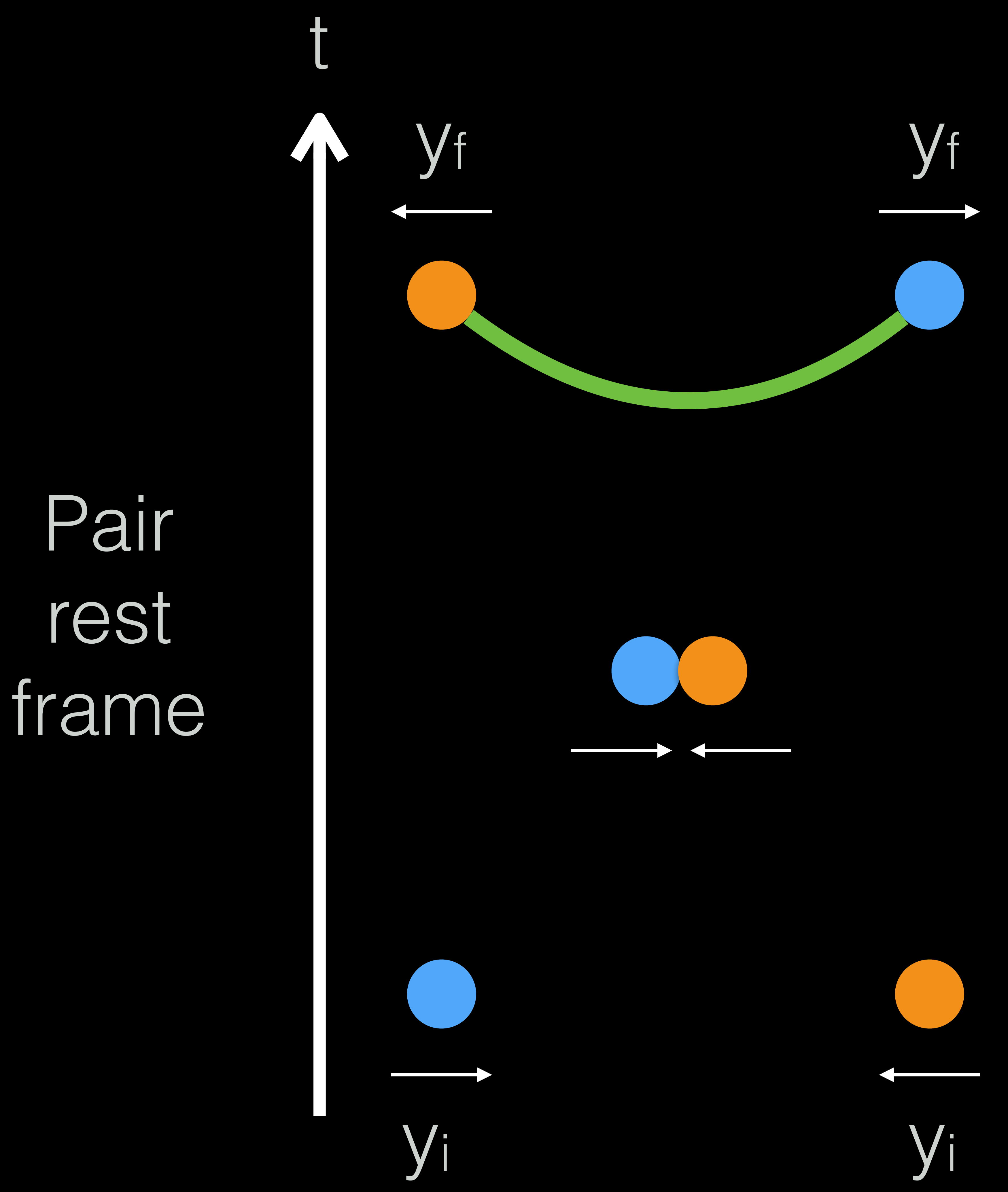
J. Cimerman, I. Karpenko, B.Tomavsik and B. A. Trzeciak, Phys. Rev. C103, 034902 (2021)

- The UrQMD initial condition shows a wider boost-invariant plateau near mid-rapidity than the parametric Glissando model

- The UrQMD initial condition overestimates the initial baryon stopping compare to what the data suggests

THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



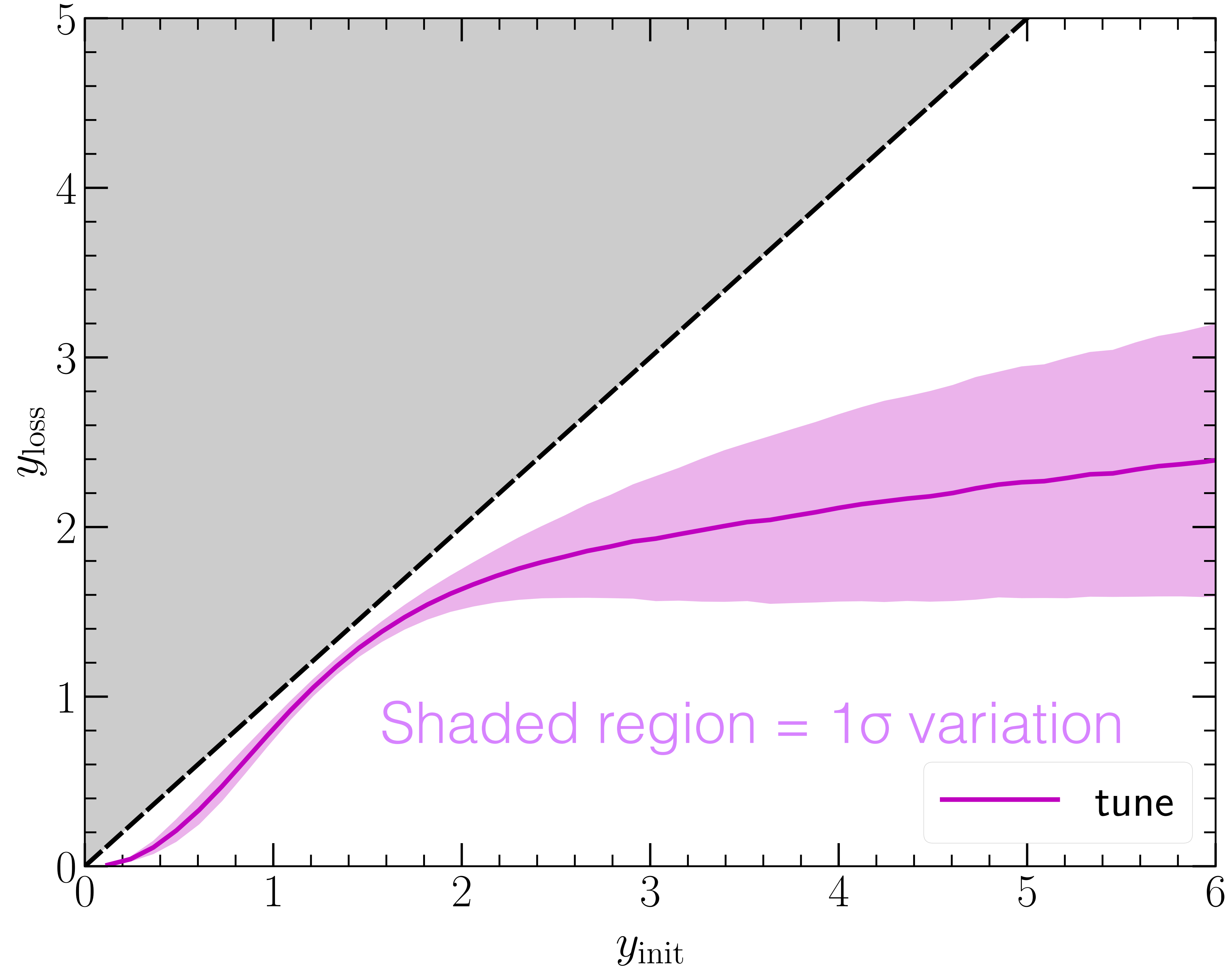
- Collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF and randomly picked to lose energy during a collision $\left(\sum_i x_i \leq 1\right)$
- Incoming quarks are decelerated with a classical string tension,

$$dp^\mu = -T^{\mu\nu} d\Sigma_\nu$$

$$T^{\mu\nu} = \begin{pmatrix} \sigma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sigma \end{pmatrix} \qquad d\Sigma_\nu = (dz, 0, 0, -dt)$$

PARAMETERIZE THE VALENCE QUARK ENERGY LOSS

B. Schenke and C. Shen, in preparation



$$\langle y_{\rm loss} \rangle = A y_{\rm init}^{\alpha_2} [\tanh(y_{\rm init})]^{\alpha_1 - \alpha_2}$$

- A: the slope
- At small y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_1}$
- At large y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_2}$
- Std of $y_{\rm loss}$ fluctuations: σ_y ($y_{\rm loss} \in [0, y_{\rm init}]$)

PARTICLE PRODUCTION AT THE RHIC BES

B. Schenke and C. Shen, in preparation

- Calibrated with charged particle pseudo-rapidity distribution in minimum bias p+p collisions
- Rapidity loss fluctuations are essential to reproduce the p+p multiplicity distribution

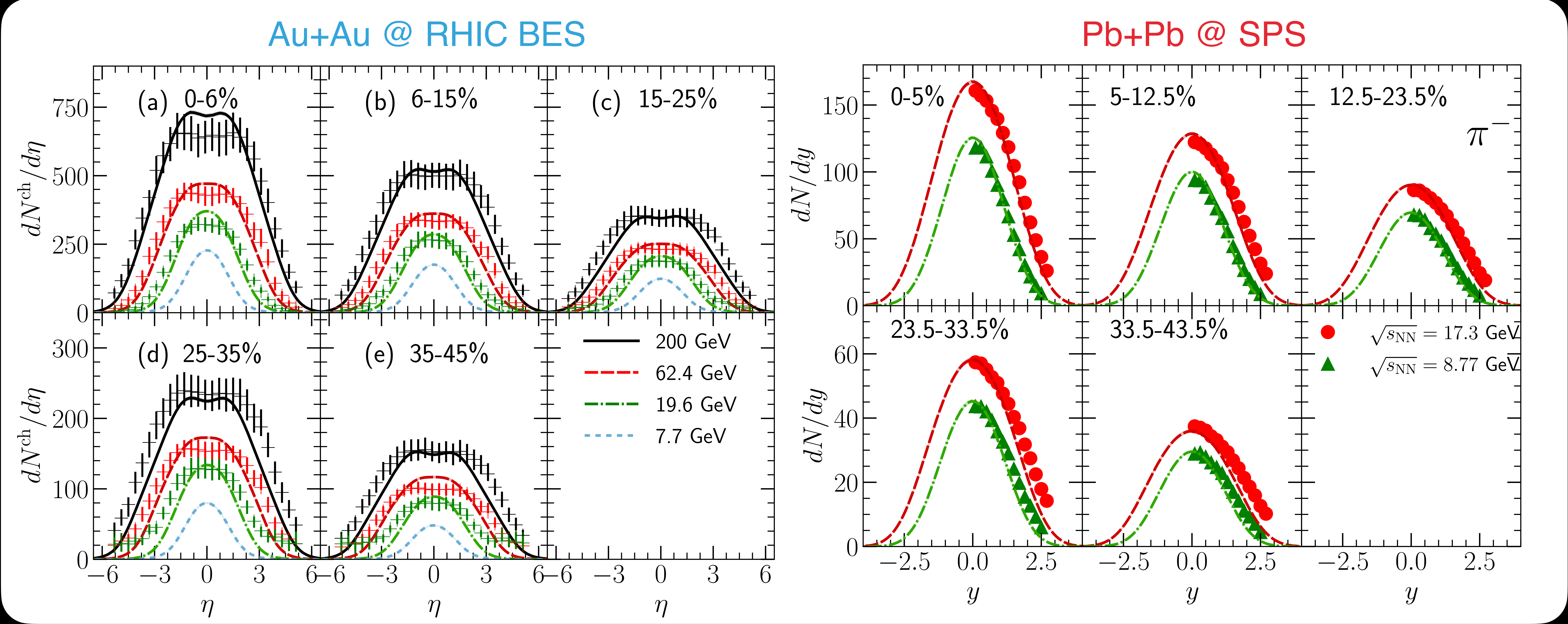
EXTEND 3D DESCRIPTION TO SMALL SYSTEMS AT BES

B. Schenke and C. Shen, in preparation

- Our model reproduces the STAR multiplicity distribution in the d+Au collisions at 200 GeV
- The predicted charged hadron rapidity distribution agrees well with the PHENIX measurements from central to peripheral collisions
- The role of spectators in the forward rapidity need further investigation at low energies

PARTICLE PRODUCTION IN AA COLLISIONS

B. Schenke and C. Shen, in preparation



- Extension to AA collisions gives reasonable descriptions of the exp. data

INITIAL STATE BARYON STOPPING

C. Shen and B. Schenke, in preparation

- Allowing the initial baryon charges to fluctuate to string junctions provides a consistent description of net proton rapidity distribution from 7.7 to 200 GeV

D. Kharzeev, Phys. Lett. B 378, 238 (1996)

Quantify the early-stage baryon stopping at RHIC

IDENTIFIED PARTICLE YIELDS AT RHIC BES

B. Schenke and C. Shen, in preparation

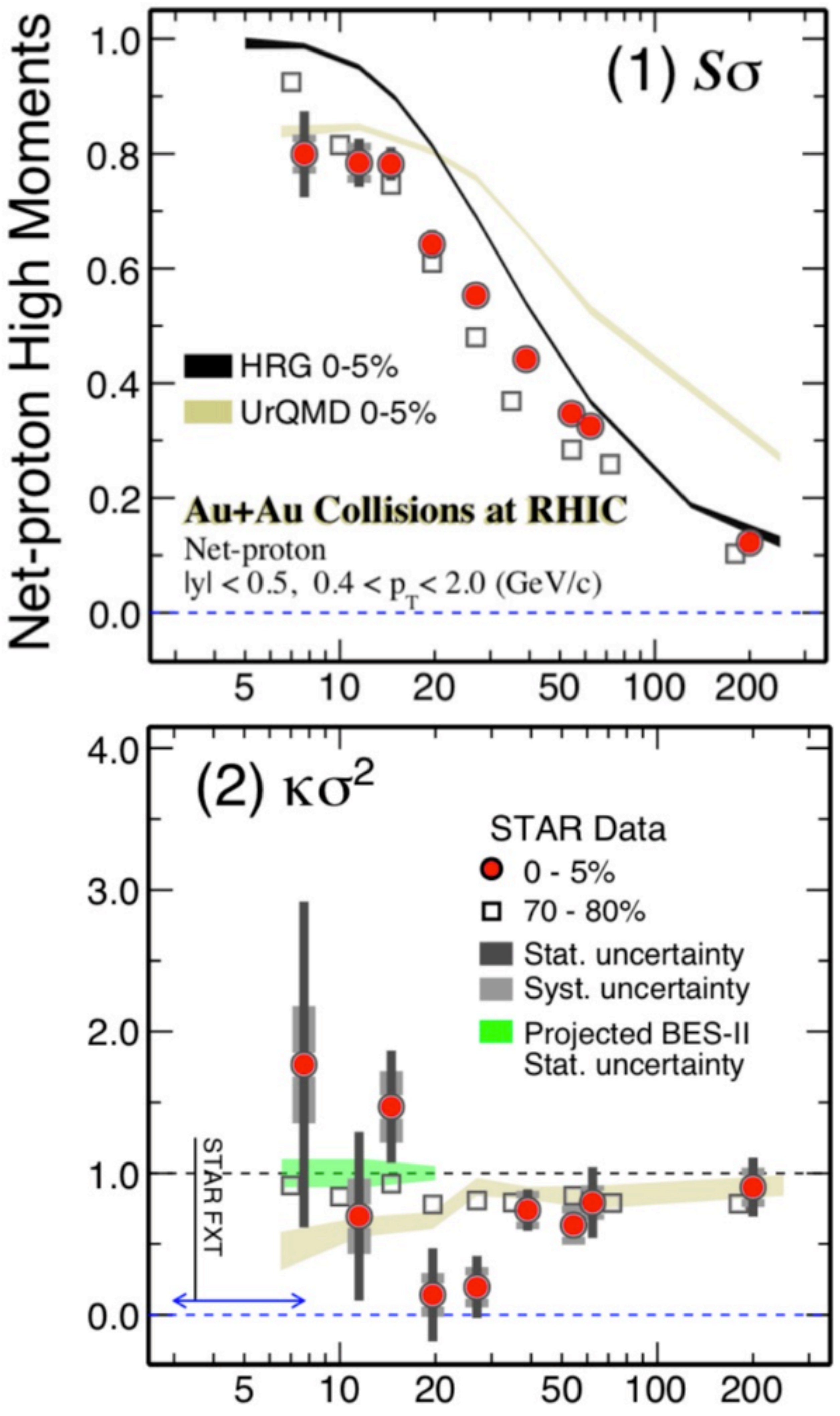
C. Shen, arXiv:2108.04987 [nucl-th]

- Collision energy dependence of identified particle ratios can be reasonably reproduced

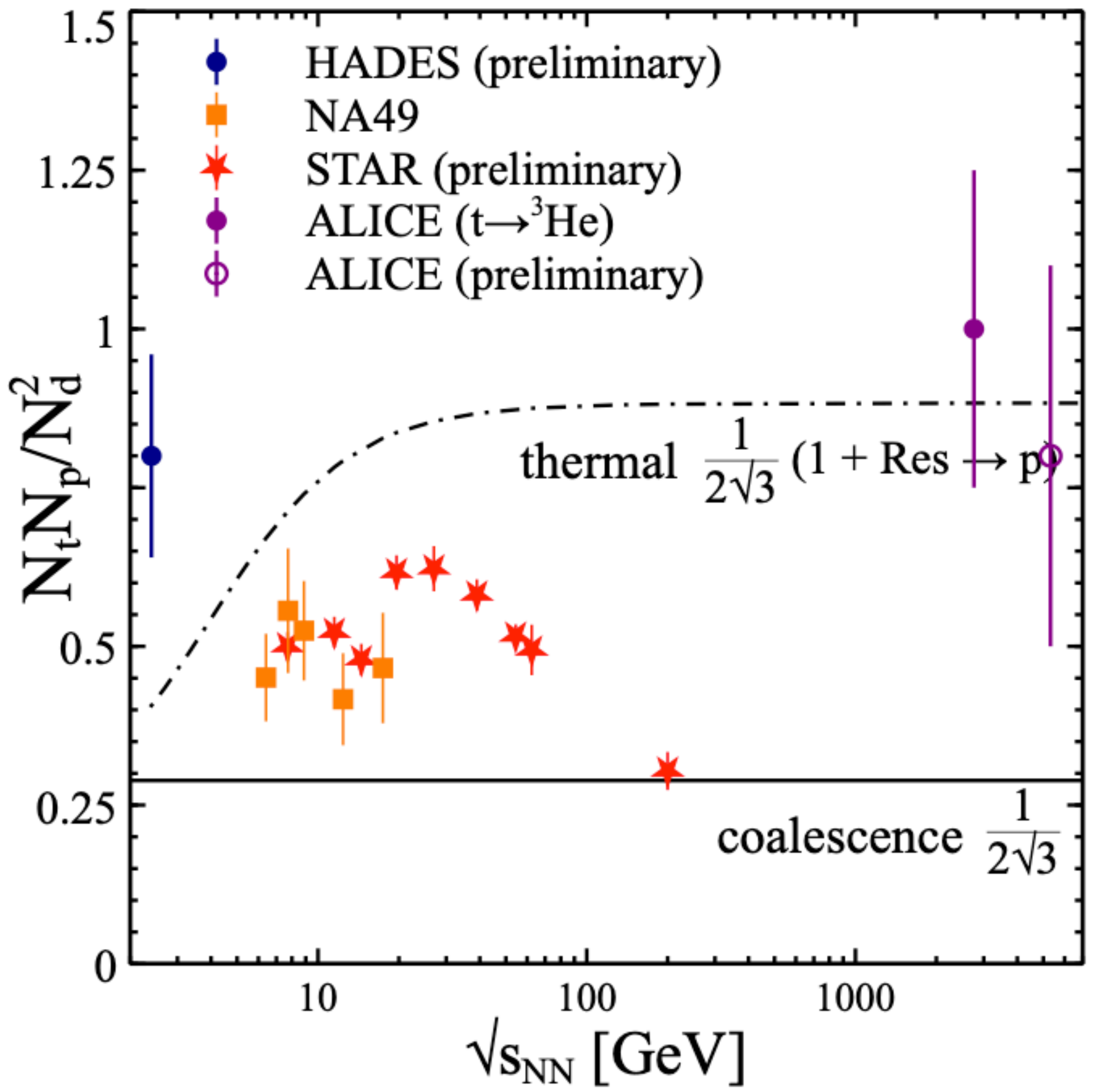
Grand canonical ensemble + baryon stopping + $n_s = 0$ **and** $n_Q = 0.4 n_B$

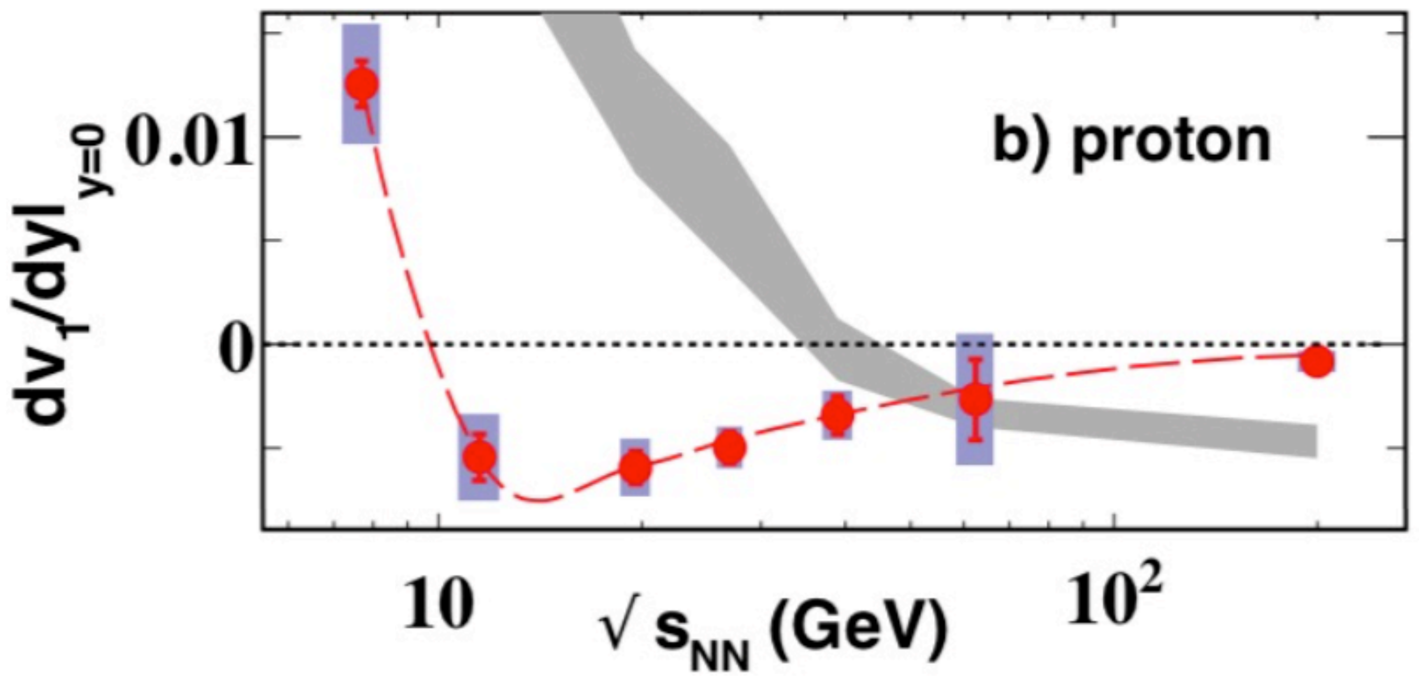
OUTSTANDING CHALLENGES AT RHIC BES

STAR, Phys. Rev. Lett. 126,092301 (2021)



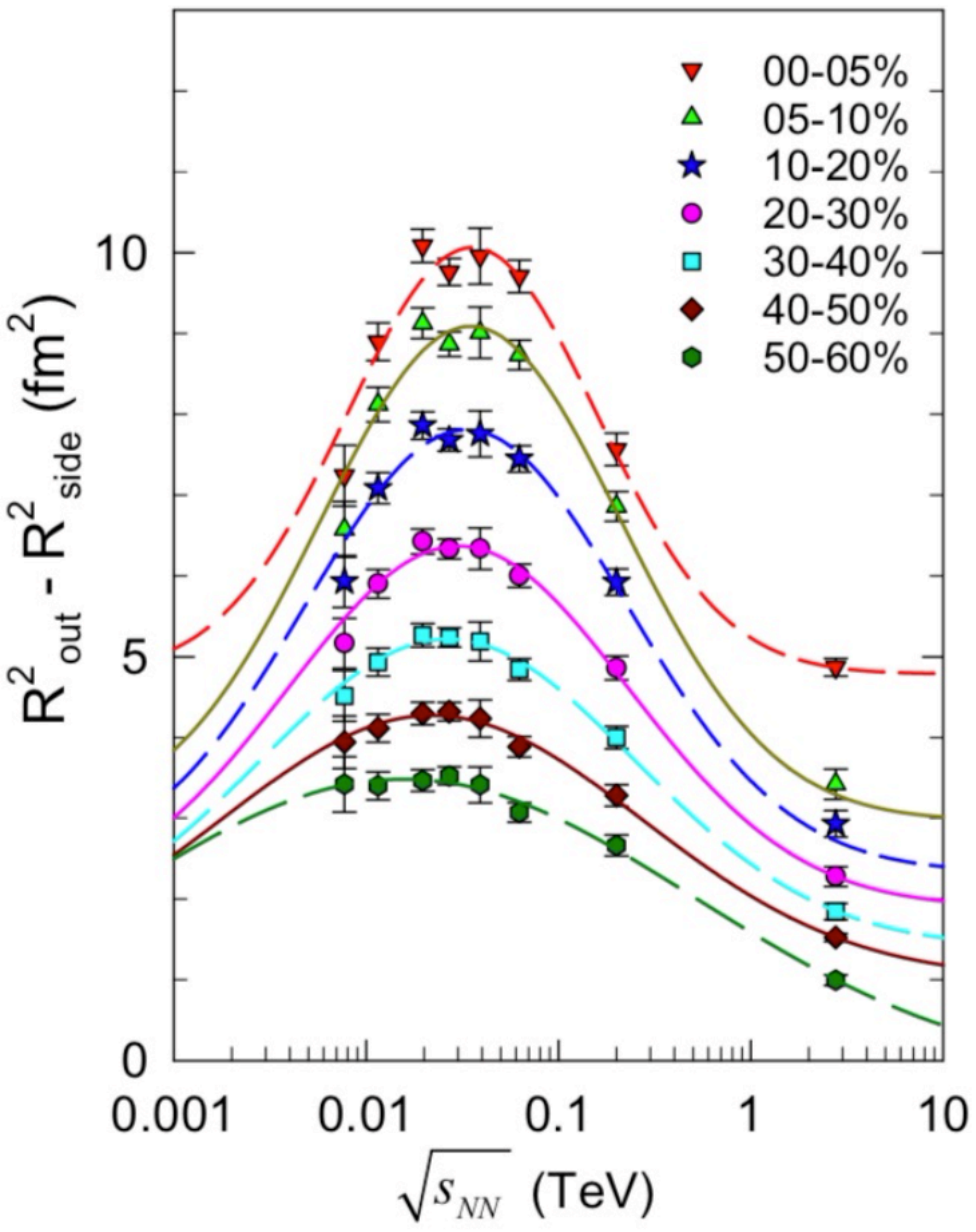
D. Oliinychenko, Nucl. Phys. A1005, 121754 (2021)





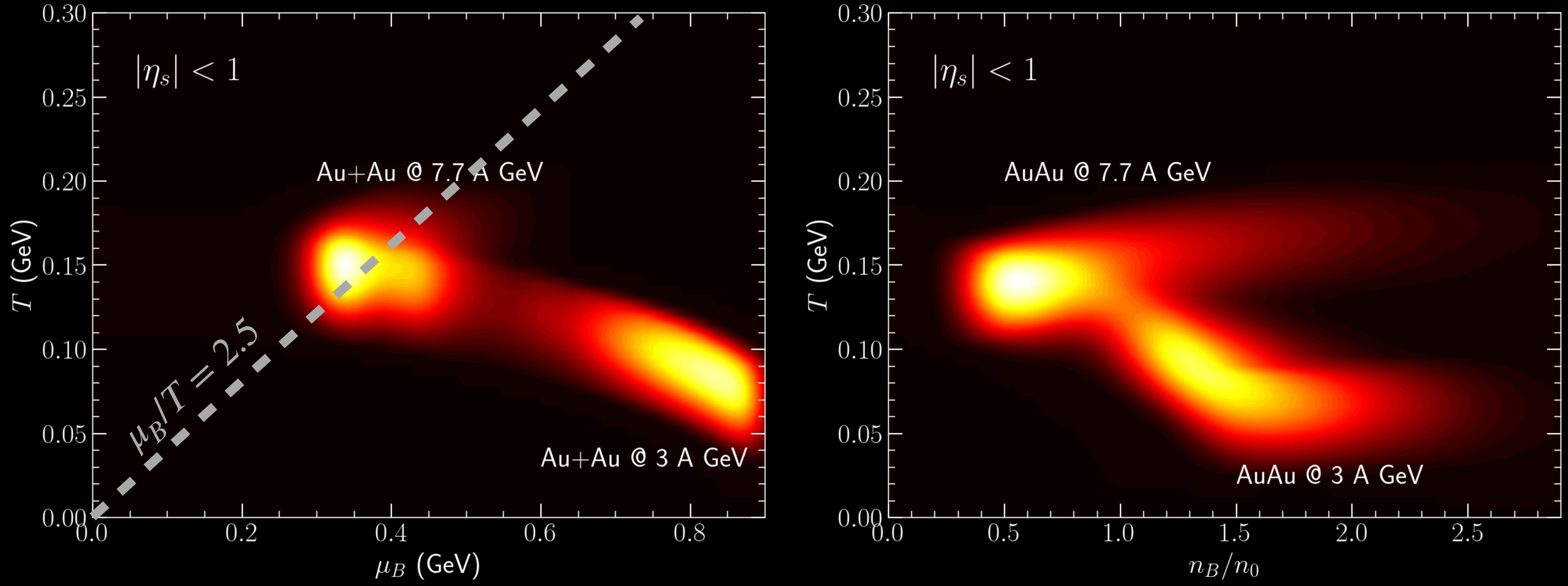
STAR, Phys. Rev. Lett. **112**,162301 (2014)

R. A. Lacey, Phys. Rev. Lett. **114**,142301 (2015)



compiled by A. Sorensen

OPPORTUNITIES AT THE RHIC FIXED TARGET EXP.



- Probing equation of state and dissipations at 1.5-2 times of nuclear saturation density (little guidance from lattice QCD)
- No distinctive dominance of single-phase evolution during the collisions

SUMMARY

- Dynamical frameworks are effective to understand particle production and flow in relativistic heavy-ion collisions at the RHIC Beam Energy Scan (BES) and the CERN SPS programs

  First principles inputs from lattice QCD for EoS

  The strangeness neutrality condition plays a crucial role on identified particle production at the RHIC BES

  Elucidating the initial baryon stopping, charge diffusion, and transport properties of QGP in a baryon rich environment

- Explore the phase structure (critical point & 1st-order phase transition) of hot QCD matter with RHIC BES II & fixed target experiments

  Parametric EoS for $\mu_B > 400$ MeV and many model updates …