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BEST
COLLABORATION

Bayesian Inference of QGP Properties and 3D Dynamics from Beam Energy Scan Data

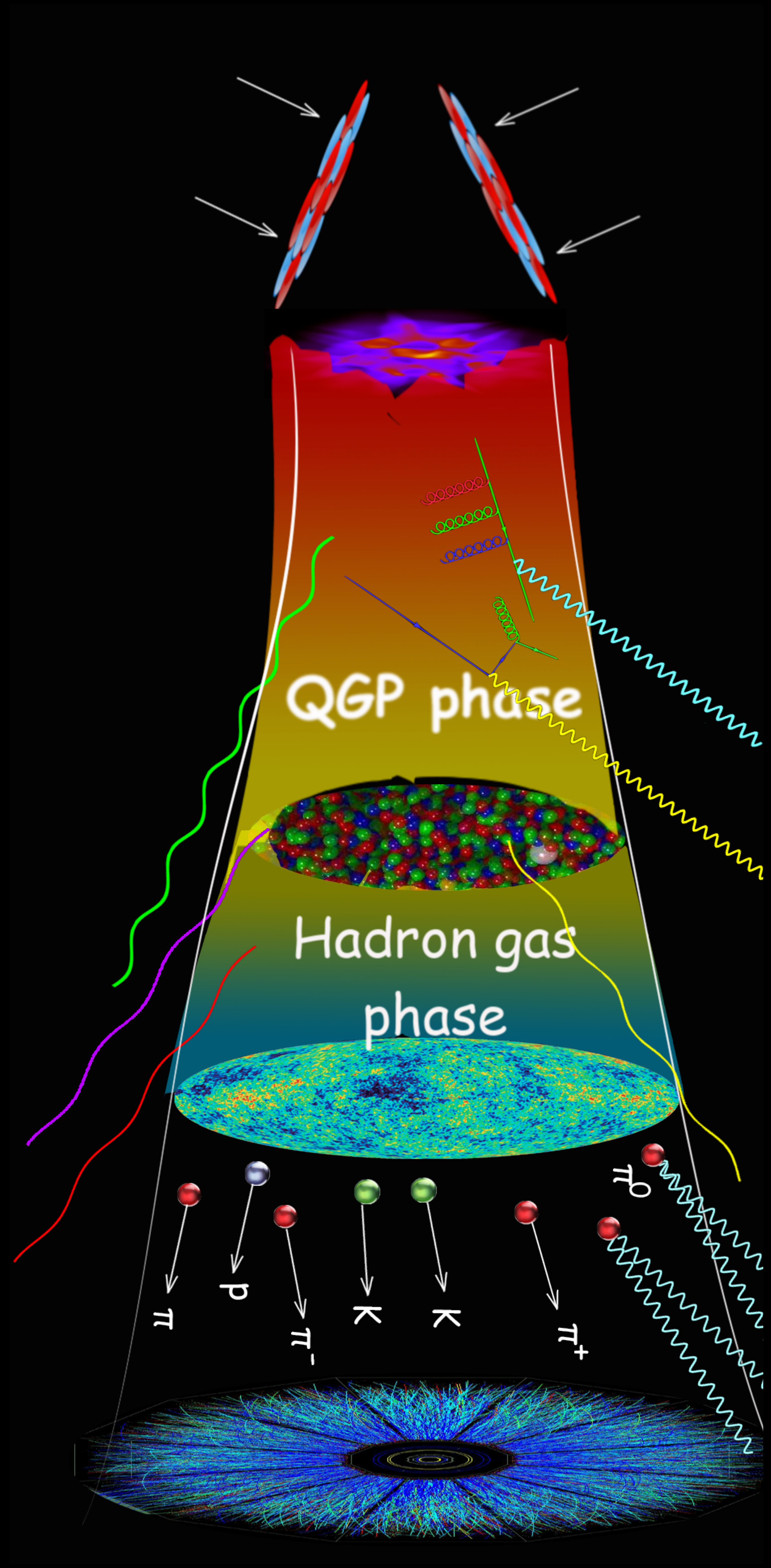
Chun Shen (Wayne State University)

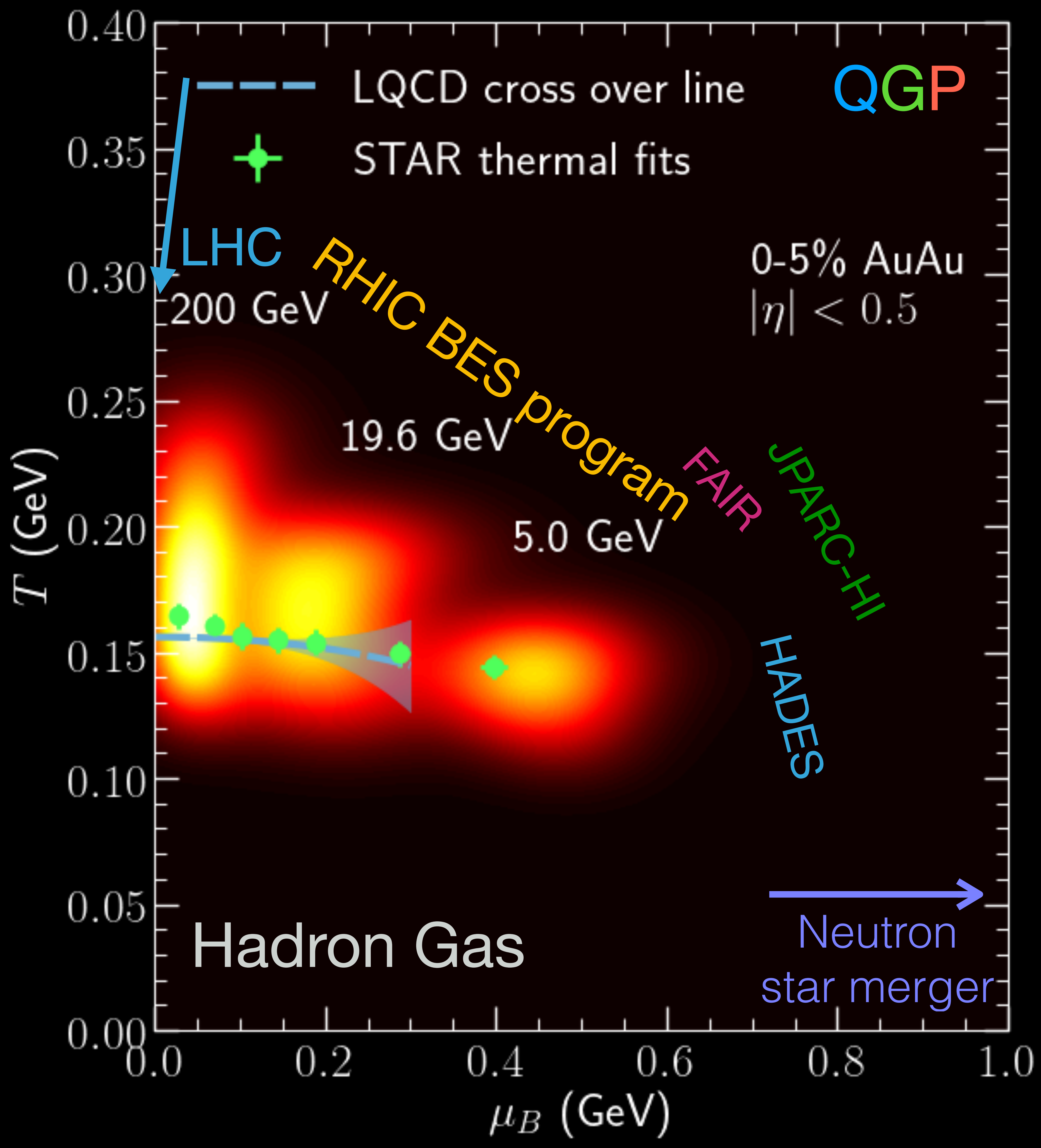
In collaboration with Björn Schenke and Wenbin Zhao

C. Shen, B. Schenke and W. Zhao, arXiv:2310.10787 [nucl-th]

Oct. 24, 2023

PROBING THE NUCLEAR MATTER PHASE DIAGRAM





- Search for a critical point & 1st order phase transition

  $c_s^2(T, \{\mu_q\})$

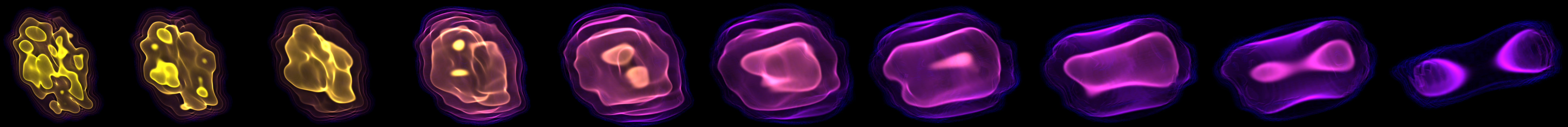
- How do the QGP transport properties change with baryon doping?

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

- Access to new transport phenomena

  Charge diffusion

THE MULTI-STAGE THEORETICAL FRAMEWORK



$T^{\mu\nu}$ 0^+ 0.5-1 τ (fm)

Initial State +
Pre-equilibrium dynamics

Hydrodynamics

Hadronic Transport

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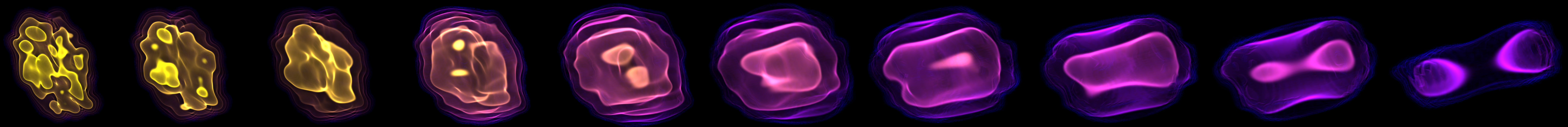

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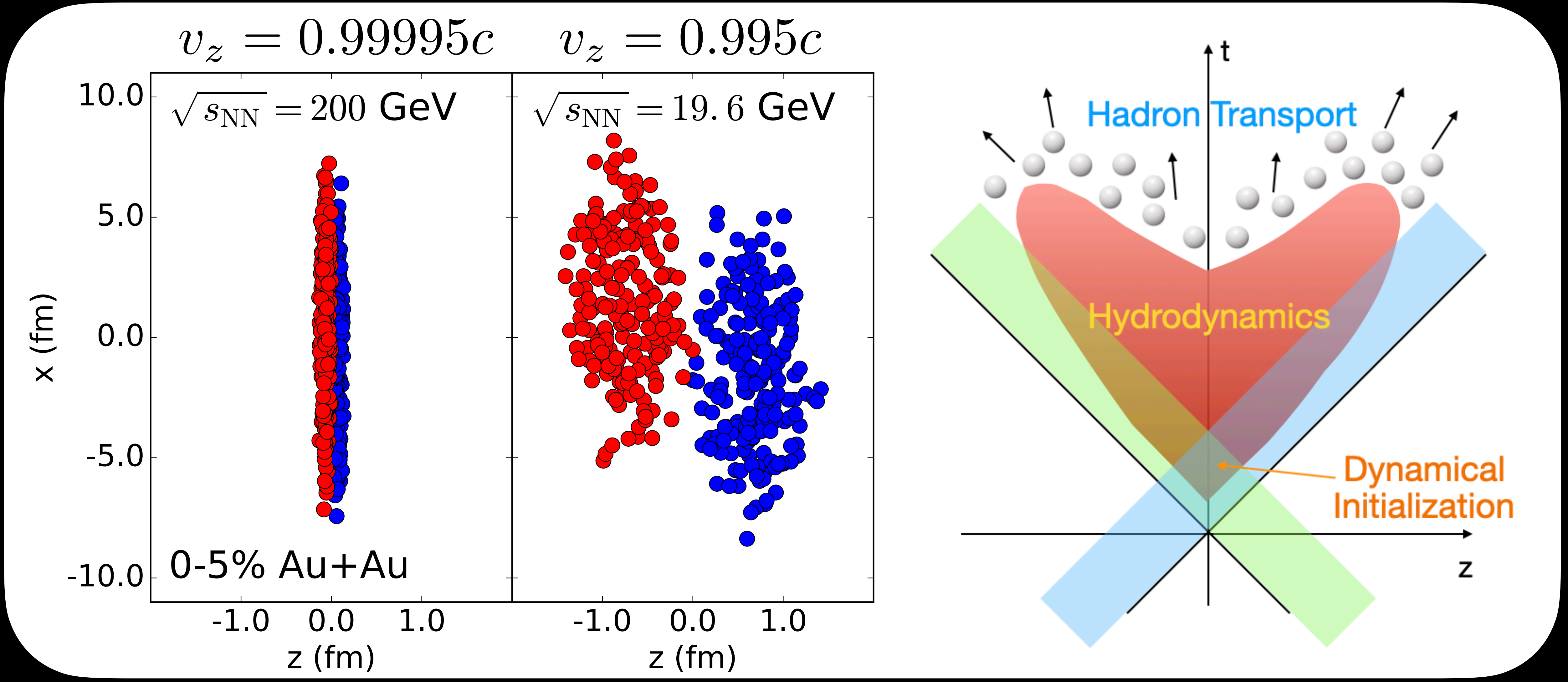
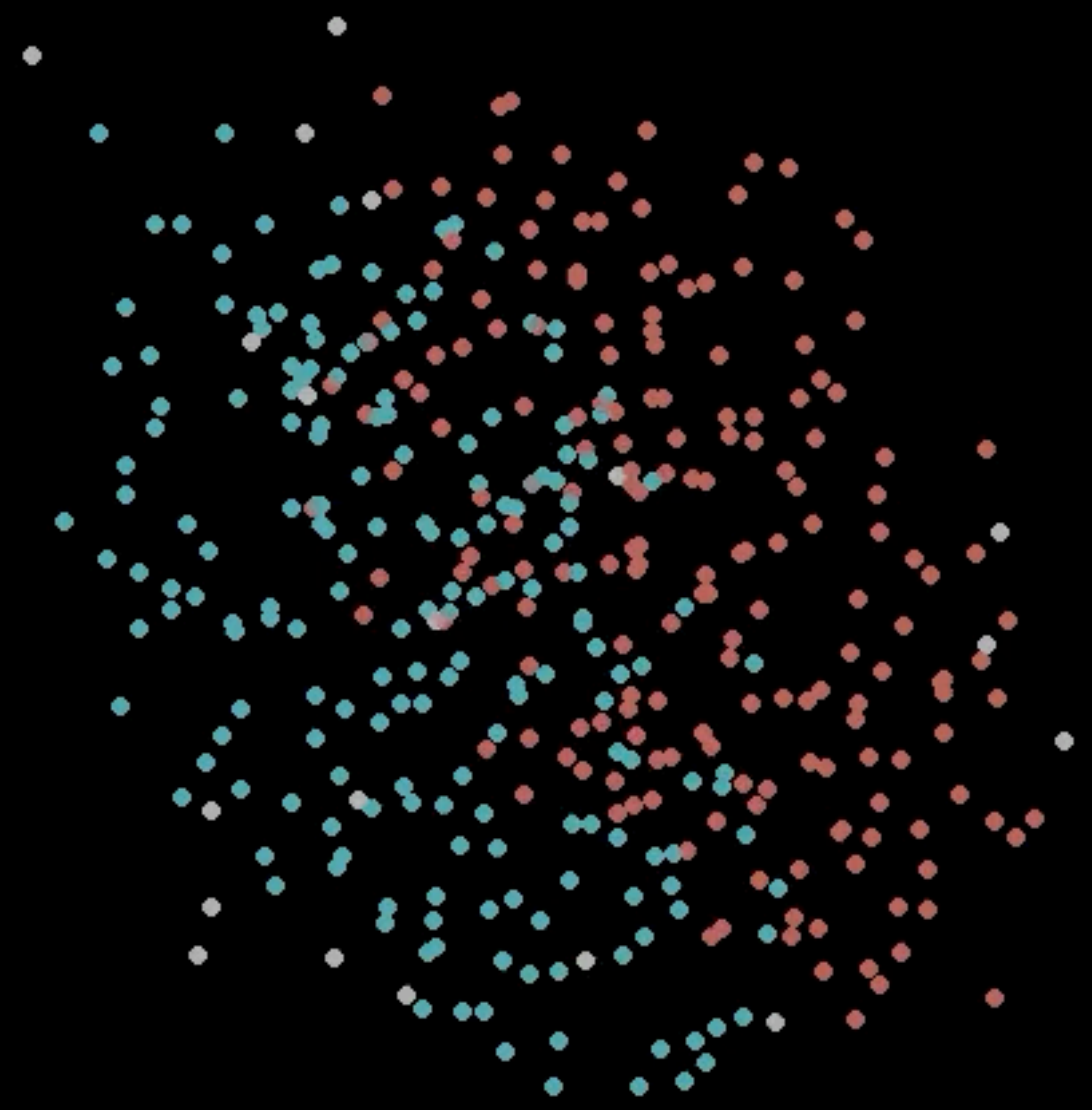
RHIC BES energies



$$\partial_\mu T^{\mu\nu} = J^\nu_{\rm source}$$

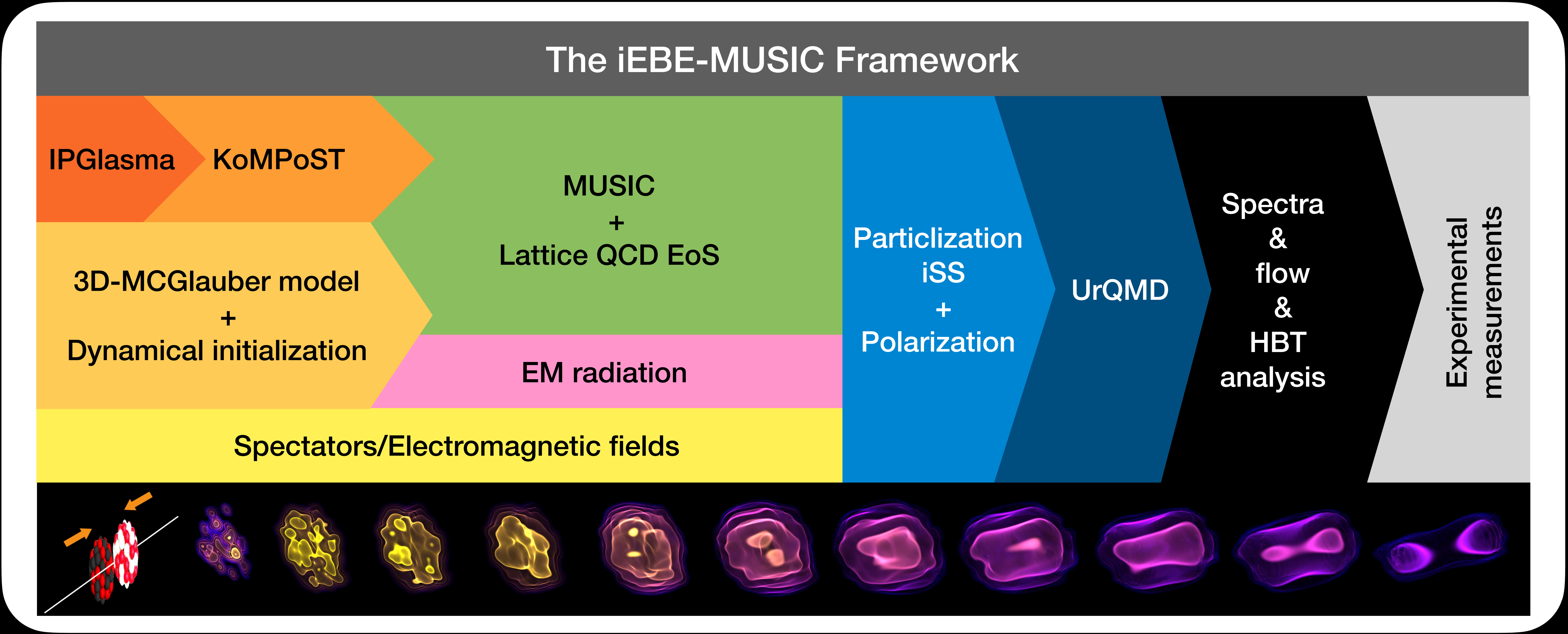
$$\partial_\mu J^\mu = \rho_{\rm source}$$

0-5% Au+Au @ 19.6 GeV



AN OPEN SOURCE HYBRID FRAMEWORK—IEBE-MUSIC

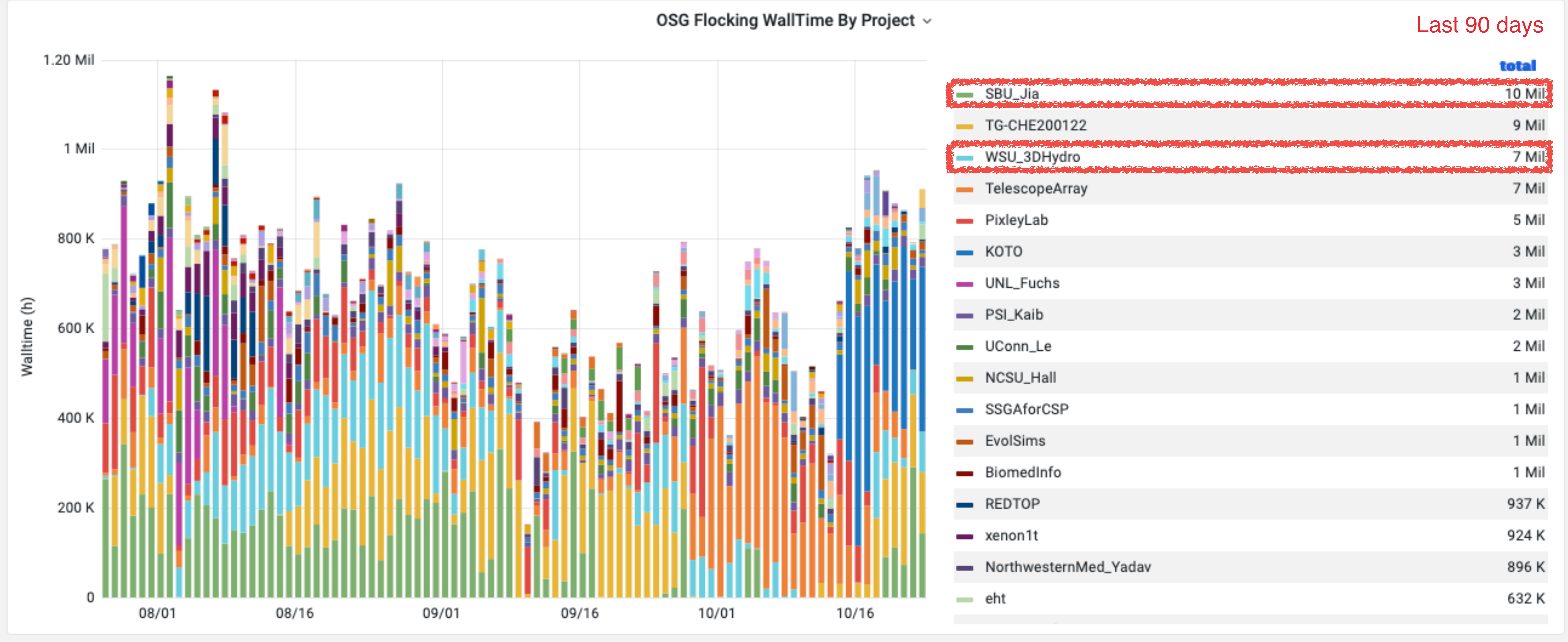
https://github.com/chunshen1987/iEBE-MUSIC



State-of-the-art event-by-event simulations for relativistic heavy-ion collisions

AN OPEN SOURCE FRAMEWORK FOR THE COMMUNITY

The iEBE-MUSIC framework takes advantage of free computing resources powered by the Open Science Grid (OSG)



3D MC-GLAUBER MODEL WITH STRING DECELERATION

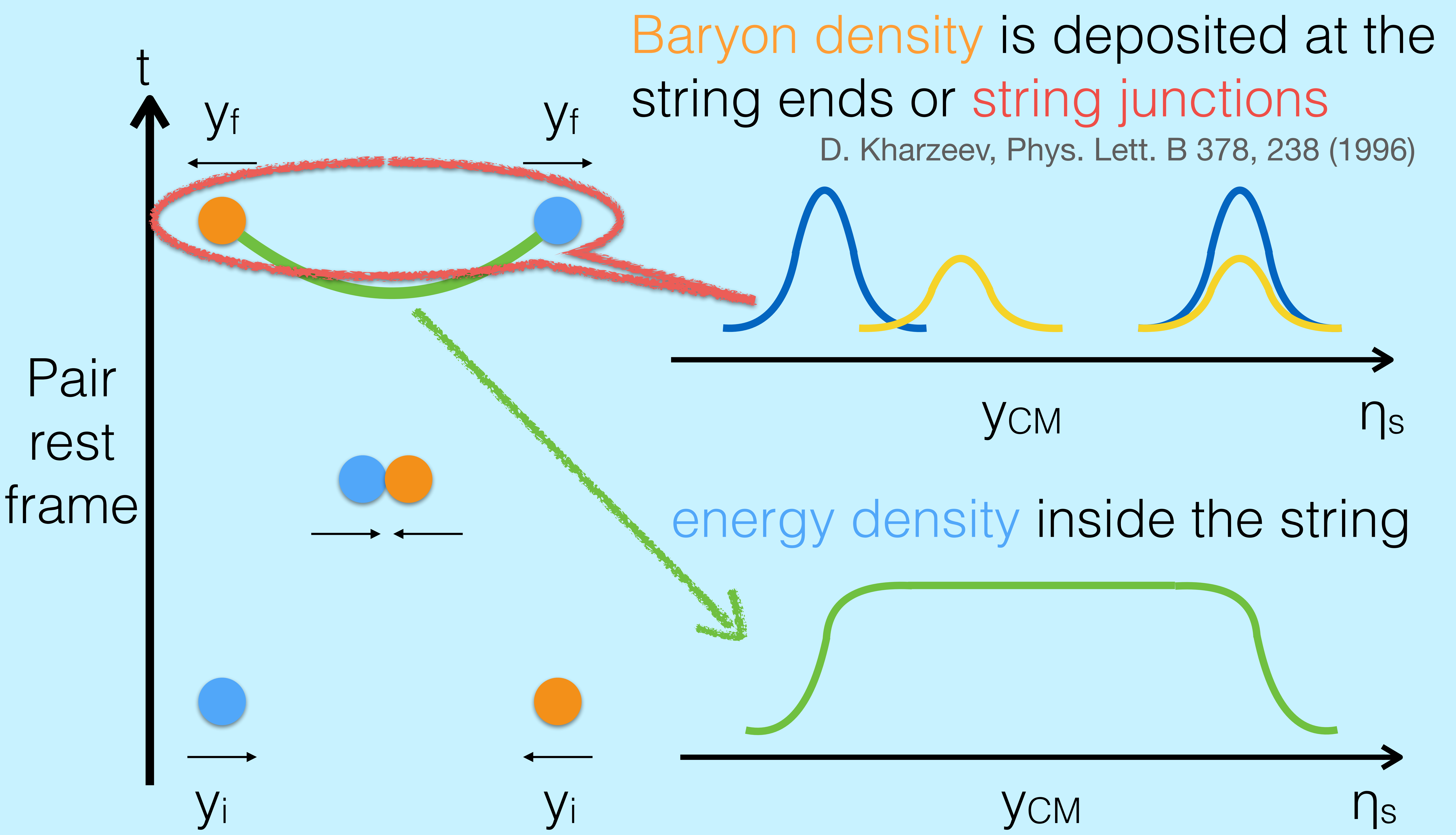
- Transverse collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF with

$$\sum_i x_i \leq 1$$

- Incoming quarks are decelerated with a string tension σ,

$$dp^z/dt = -\sigma$$

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907 + Phys.Rev.C 105 (2022) 064905



Imposed conservation for energy, momentum, and net baryon density

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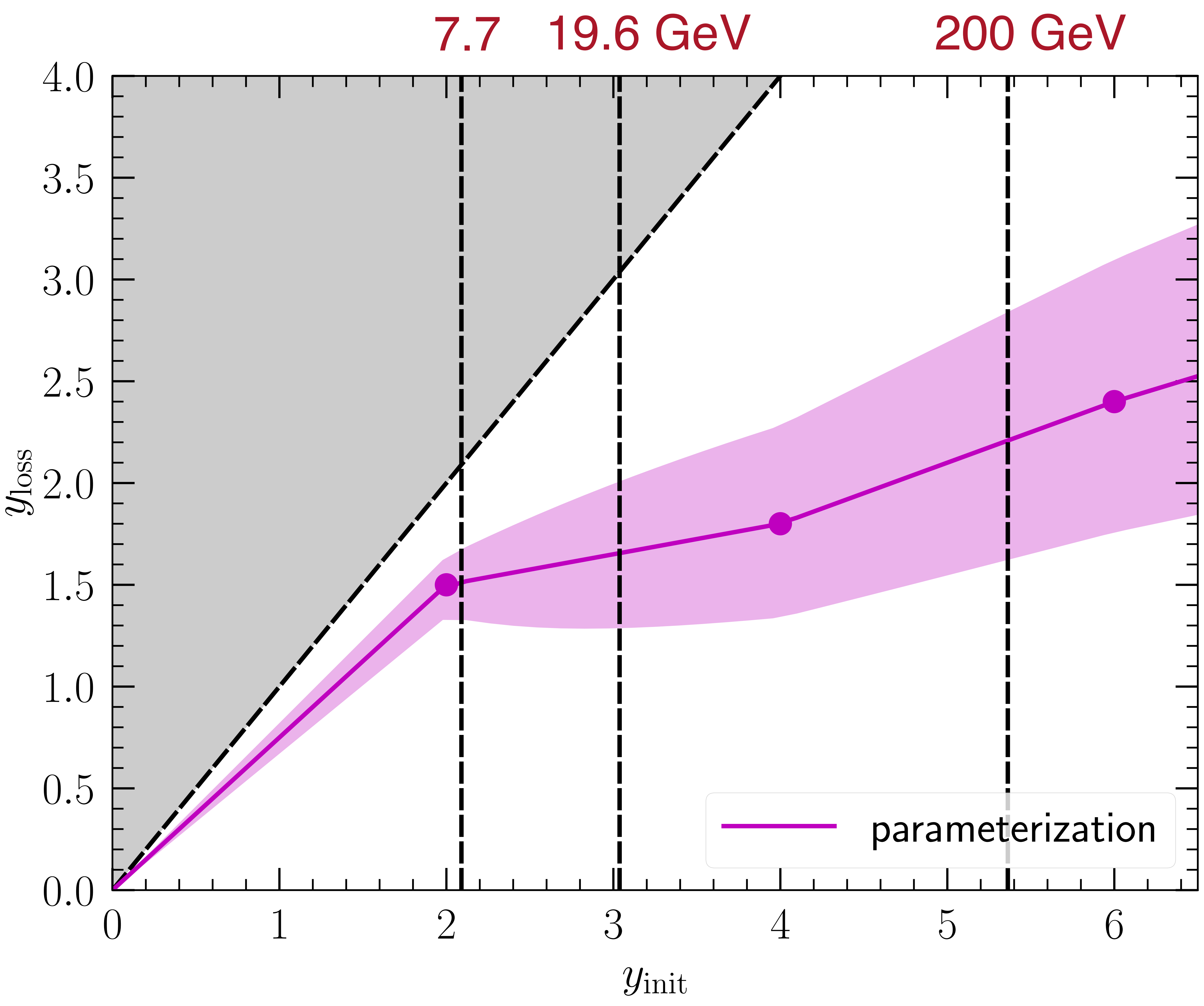


A piece-wise parameterization with

$y_{\rm loss}(y_{\rm init} = 2)$
$y_{\rm loss}(y_{\rm init} = 4)$
$y_{\rm loss}(y_{\rm init} = 6)$
$\sigma_{y_{\rm loss}}$

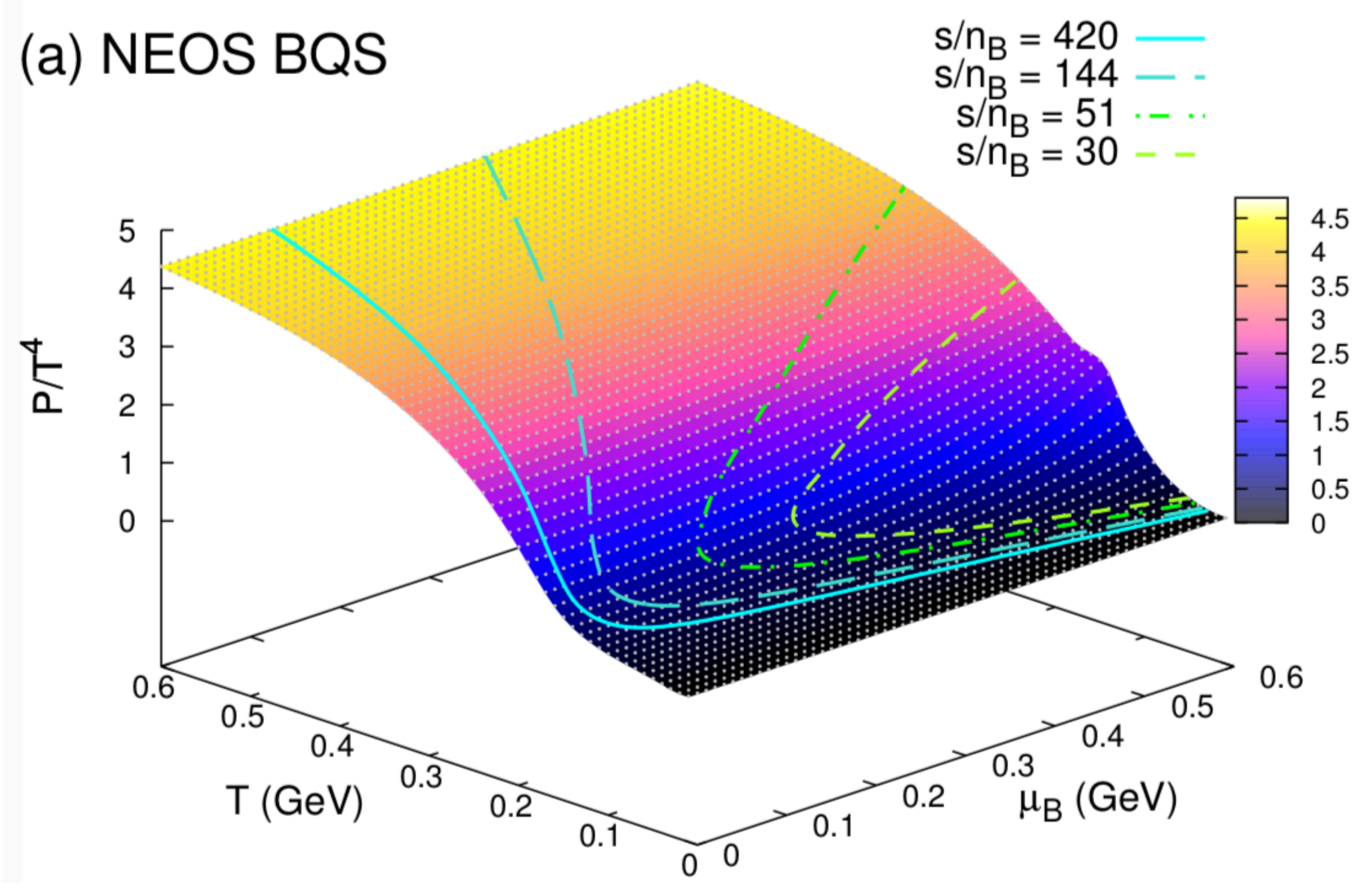
y_i y_i y_{CM} η_s

Imposed conservation for energy, momentum, and net baryon density

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

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

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

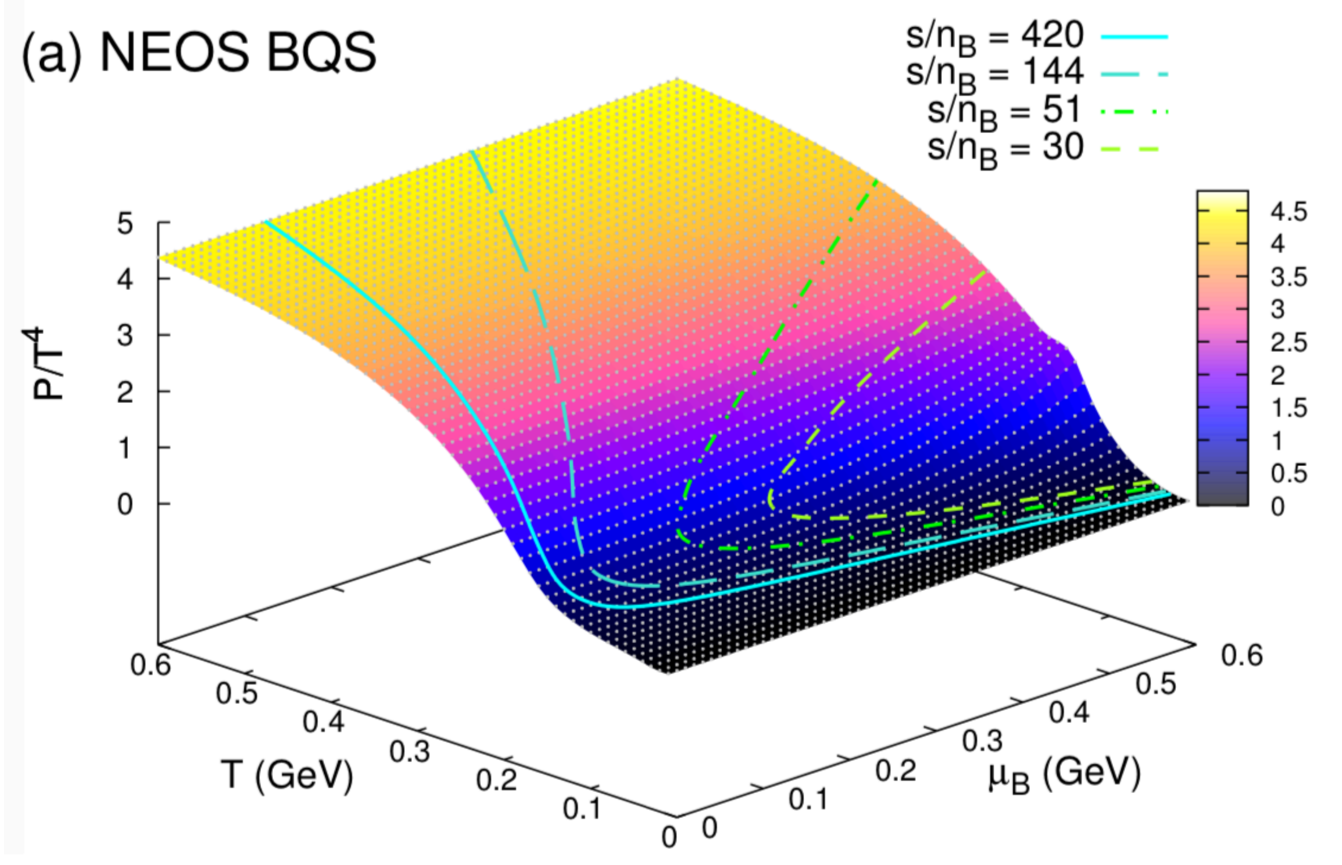
Enabled hydrodynamic simulations at finite μ

3D HYDRODYNAMICS WITH FINITE BARYON CURRENT

$$\partial_\mu T^{\mu\nu} = J^\nu_{\rm source}$$
$$\partial_\mu J^\mu = \rho_{\rm source}$$

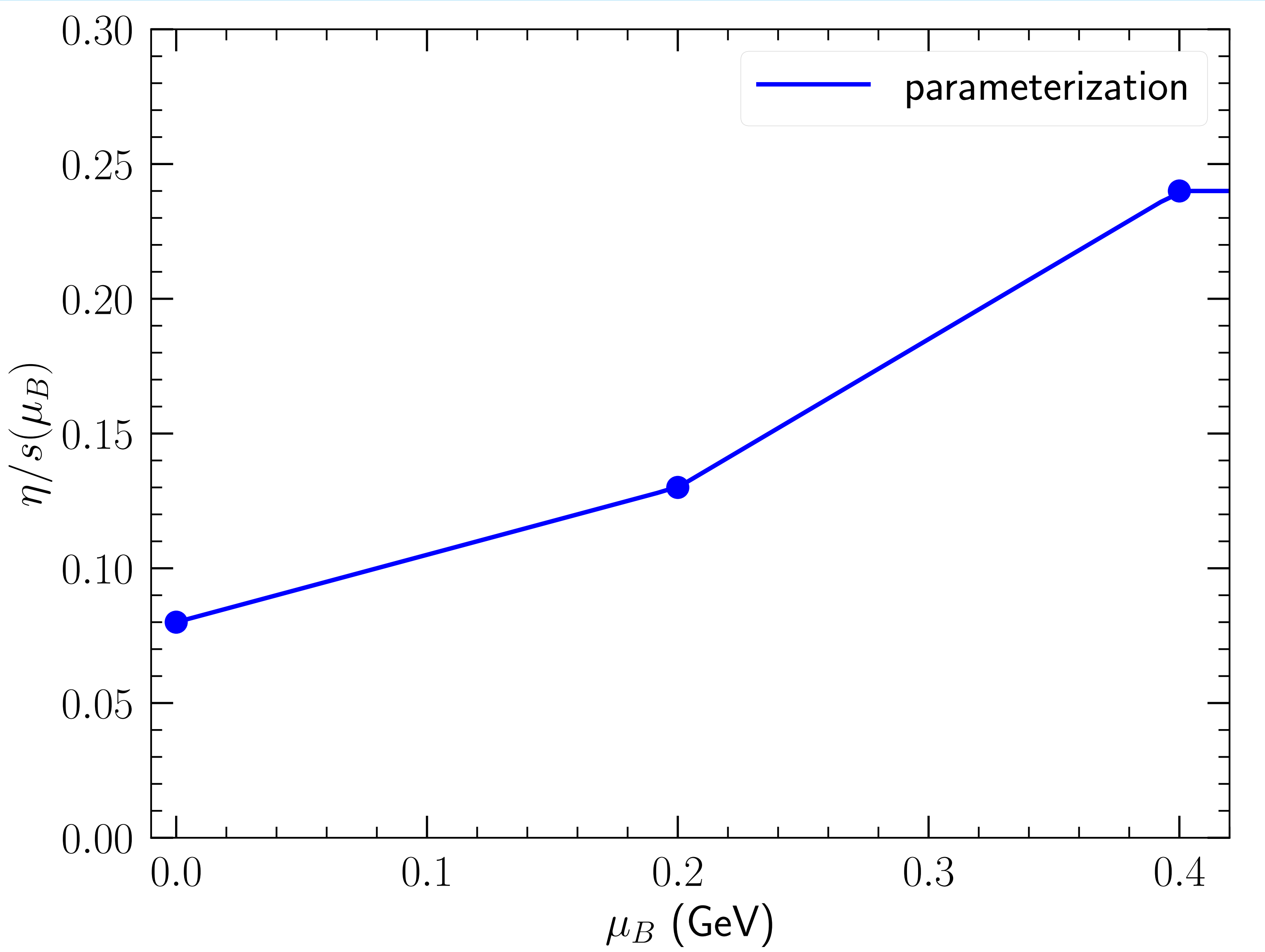
+

$n_s = 0 \quad n_Q = 0.4 n_B$

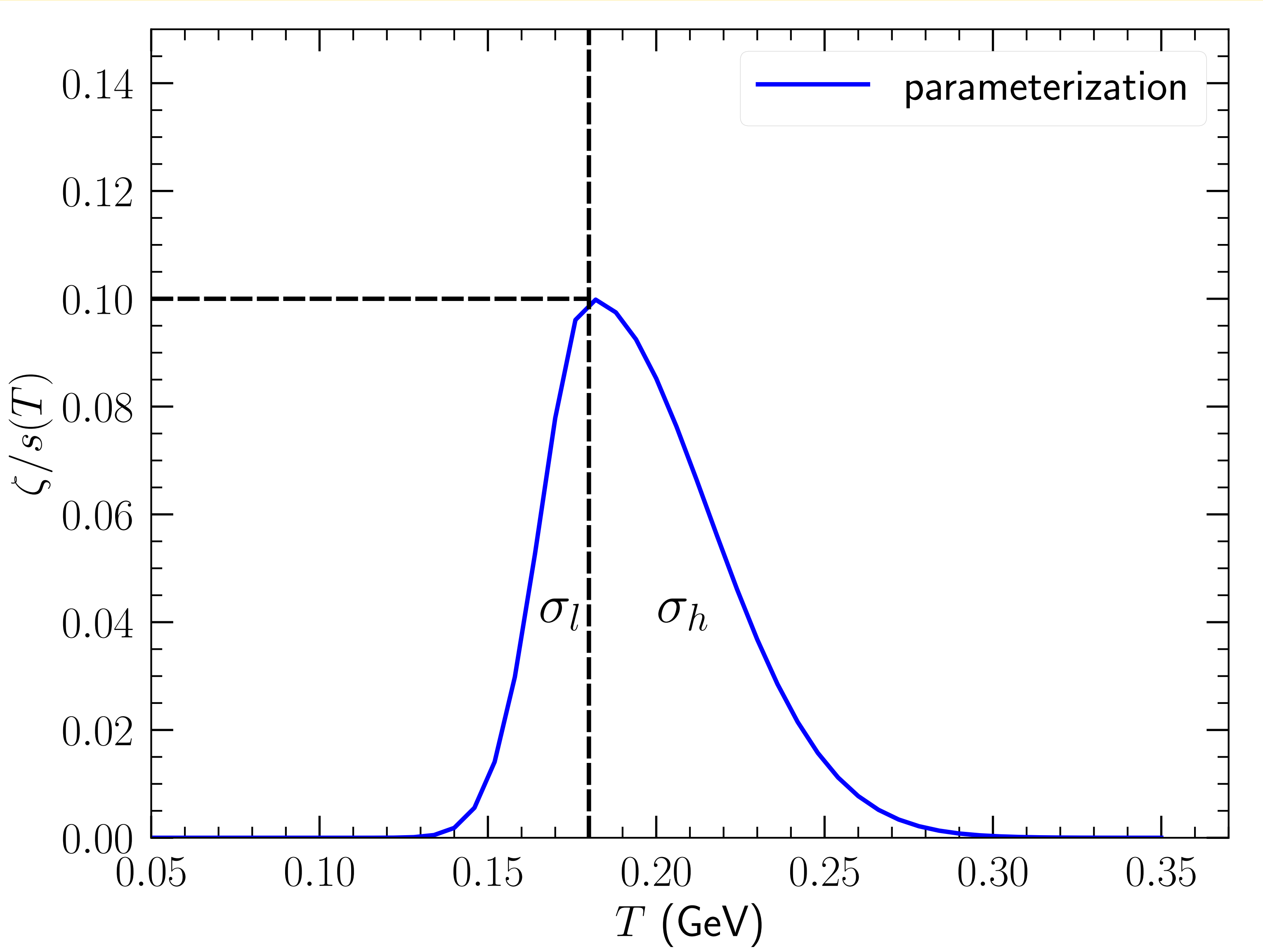


A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

$\eta/s(\mu_B)$ has a piece-wise parameterization



$\zeta/s(T)$ is parameterized with an two-piece asymmetric Gaussian



THE MODEL PARAMETERS

TABLE I. The 20 model parameters and their prior ranges.

Parameter	Prior	Parameter	Prior
B_G (GeV^{-2})	[1, 25]	$\alpha_{\mathrm{string\,tilt}}$	[0, 1]
$\alpha_{\mathrm{shadowing}}$	[0, 1]	$\alpha_{\mathrm{preFlow}}$	[0, 2]
$y_{\mathrm{loss},2}$	[0, 2]	η_0	[0.001, 0.3]
$y_{\mathrm{loss},4}$	[1, 3]	η_2	[0.001, 0.3]
$y_{\mathrm{loss},6}$	[1, 4]	η_4	[0.001, 0.3]
$\sigma_{y_{\mathrm{loss}}}$	[0.1, 0.8]	ζ_{max}	[0, 0.2]
α_{Rem}	[0, 1]	$T_{\zeta,0}$ (GeV)	[0.15, 0.25]
λ_B	[0, 1]	$\sigma_{\zeta,+}$ (GeV)	[0.01, 0.15]
$\sigma_x^{\mathrm{string}}$ (fm)	[0.1, 0.8]	$\sigma_{\zeta,-}$ (GeV)	[0.005, 0.1]
$\sigma_\eta^{\mathrm{string}}$	[0.1, 1]	e_{sw} ($\mathrm{GeV/fm^3}$)	[0.15, 0.5]

MODEL TRAINING & OBSERVABLE SELECTION

A 20-dimensional model parameter space with 1,000 training points

Au+Au	Hydro events per design	Avg. hadronic events per hydro
200 GeV	1,000	1,000
19.6 GeV	2,000	4,000
7.7 GeV	2,000	8,000

Open Science Grid delivered 5 million CPU hours for the data generation

604 experimental data points

Au+Au	STAR midrapdity data vs. centrality	PHOBOS rapidity distribtion
200 GeV	$dN/dy(\pi^+, K^+, p, \bar{p})$ $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ $v_2^{ch}\{2\}, v_3^{ch}\{2\}$	$dN^{ch}/d\eta$ $v_2(\eta)$
19.6 GeV	$dN/dy(\pi^+, K^+, p)$ $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ $v_2^{ch}\{2\}, v_3^{ch}\{2\}$	$dN^{ch}/d\eta$
7.7 GeV	$dN/dy(\pi^+, K^+, p)$ $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ $v_2^{ch}\{2\}, v_3^{ch}\{2\}$	

Phys. Rev. C79, 034909 (2009) Phys. Rev. C98, 034918 (2018)
Phys. Rev. C96, 044904 (2017) Phys. Rev. C74, 021901 (2006)

OBSERVABLE RESPONSES TO MODEL PARAMETERS

Red: Positive correlation; Blue: Negative correlation

OBSERVABLE RESPONSES TO MODEL PARAMETERS

- Particle yields provide strong constraints on initial-state energy (rapidity) loss parameters
- The opposite correlations between mid-rapidity and forward in PHOBOS pseudo-rapidity distributions can provide complement constraints to those from STAR mid-rapidity measurements at the multiple collision energies

Red: Positive correlation; Blue: Negative correlation

OBSERVABLE RESPONSES TO MODEL PARAMETERS

- Shear viscosity shows positive correlation with particle yields — entropy production; negative correlation with anisotropic flow — viscous damping
- PHOBOS pseudo-rapidity distributions at 200 GeV offers additional constrains on $\eta/s(\mu_B)$

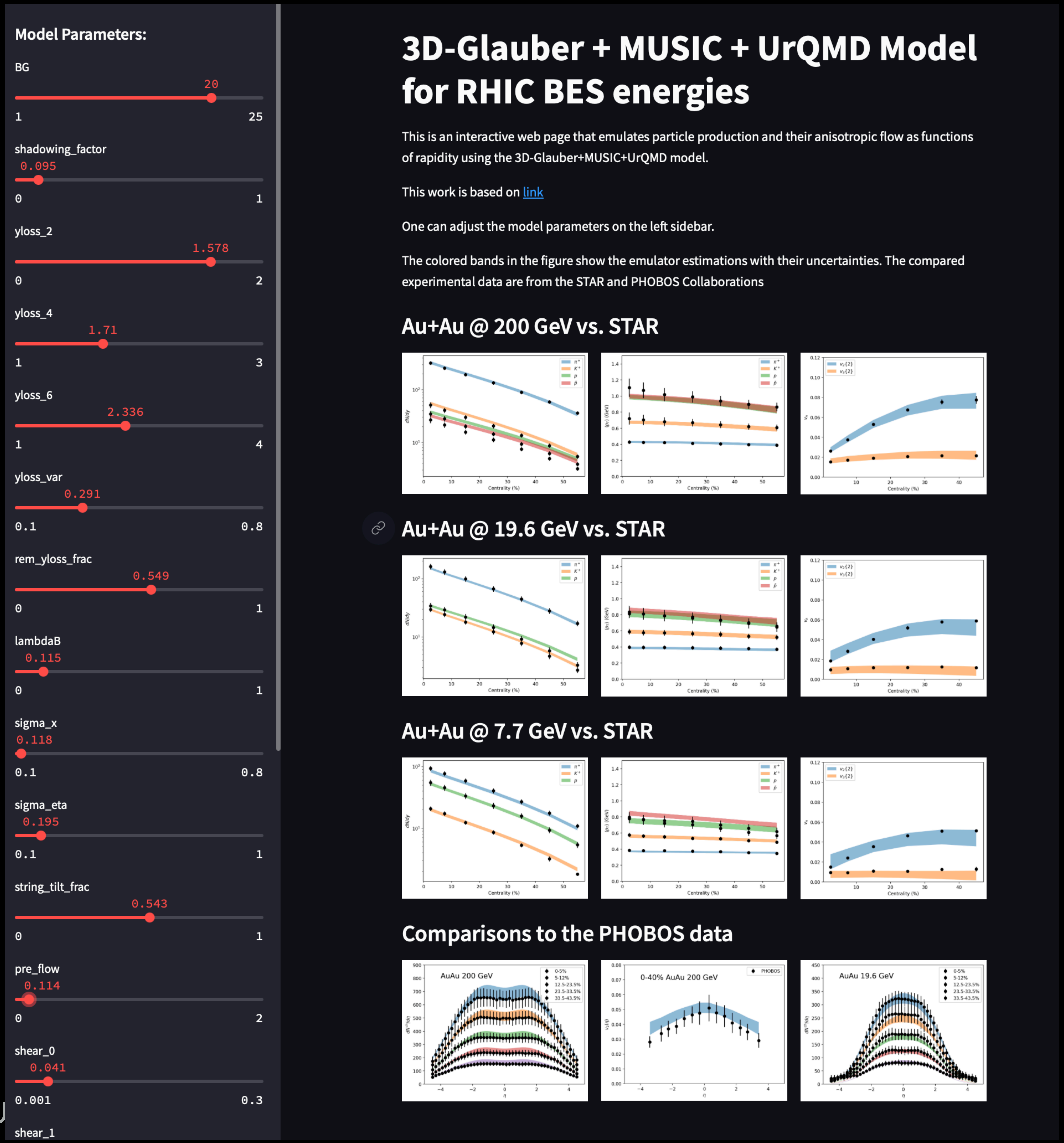
Red: Positive correlation; Blue: Negative correlation

OBSERVABLE RESPONSES TO MODEL PARAMETERS

- Bulk viscosity shows positive correlation with particle yields — entropy production; negative correlation with mean p_T — resistance to expansion
- Particle yields at forward and backward pseudo-rapidity shows stronger correlation with $(\zeta/s)_{\max}$ than those with the mid-rapidity particle yields

Red: Positive correlation; Blue: Negative correlation

PUBLIC INTERACTIVE MODEL EMULATOR

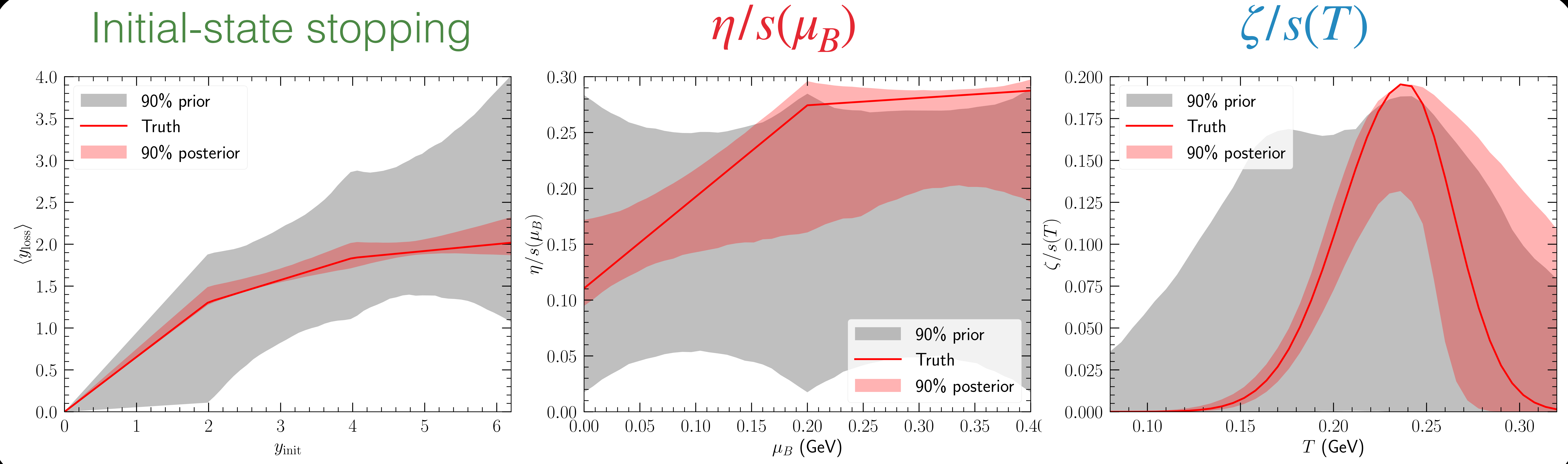


link

- An interactive webpage for emulating the full (3+1)D simulations for RHIC BES energies at real time
- Build your own intuition for heavy-ion phenomenology!

BAYESIAN VALIDATION: CLOSURE TEST

Bayes' Theorem: $P(\theta \quad y_{\rm exp}) \propto P(y_{\rm exp} \quad \theta)P(\theta)$

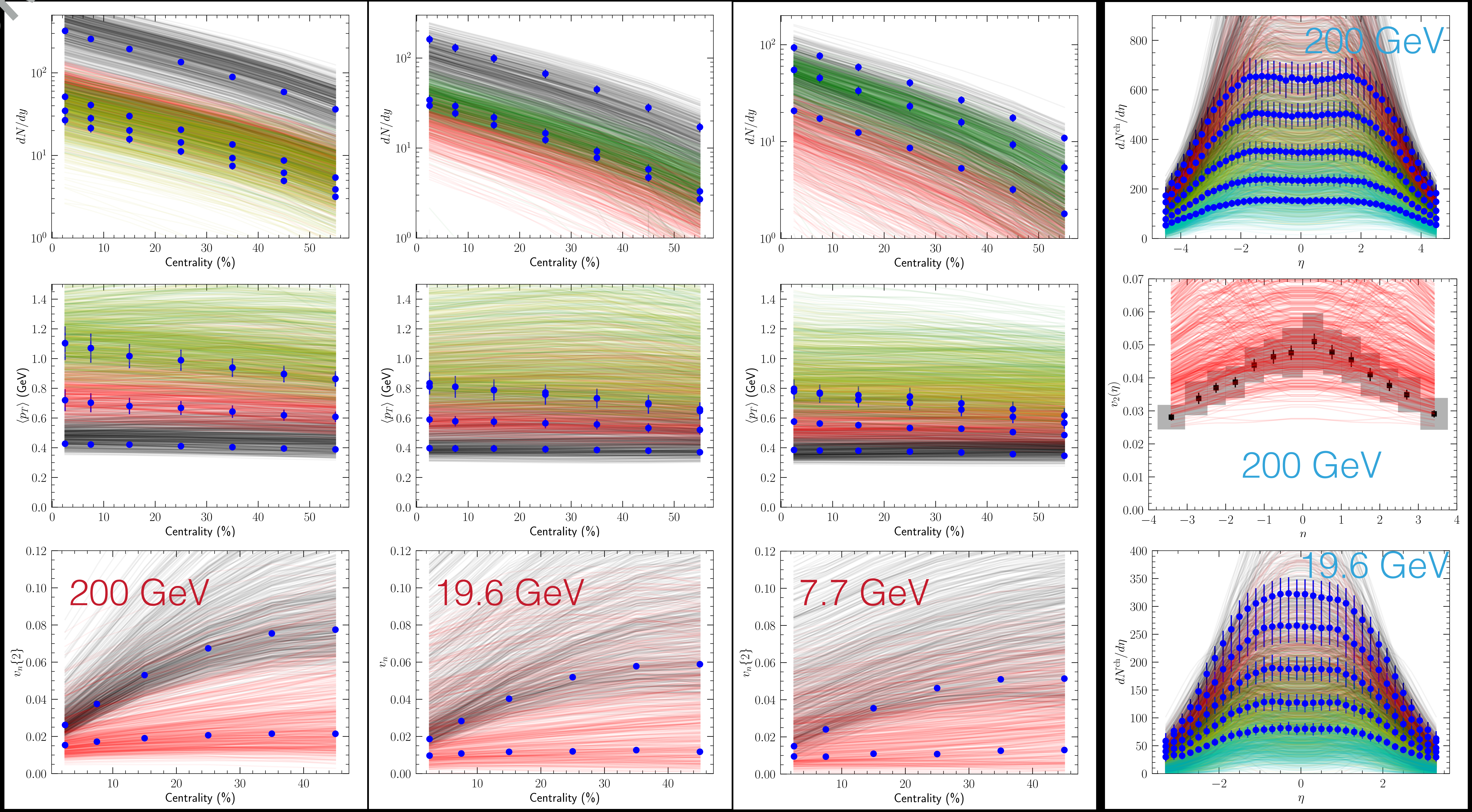


- Model emulation with Markov Chain Monte Carlo (MCMC) is verified with a closure test for initial-state stopping $y_{\rm loss}(y_{\rm init})$, $\eta/s(\mu_B)$, and $\zeta/s(T)$
- The selected observables can give strong constraints on the QGP properties at RHIC BES energies

BAYESIAN INFERENCE AT RHIC BES ENERGIES

PRIOR

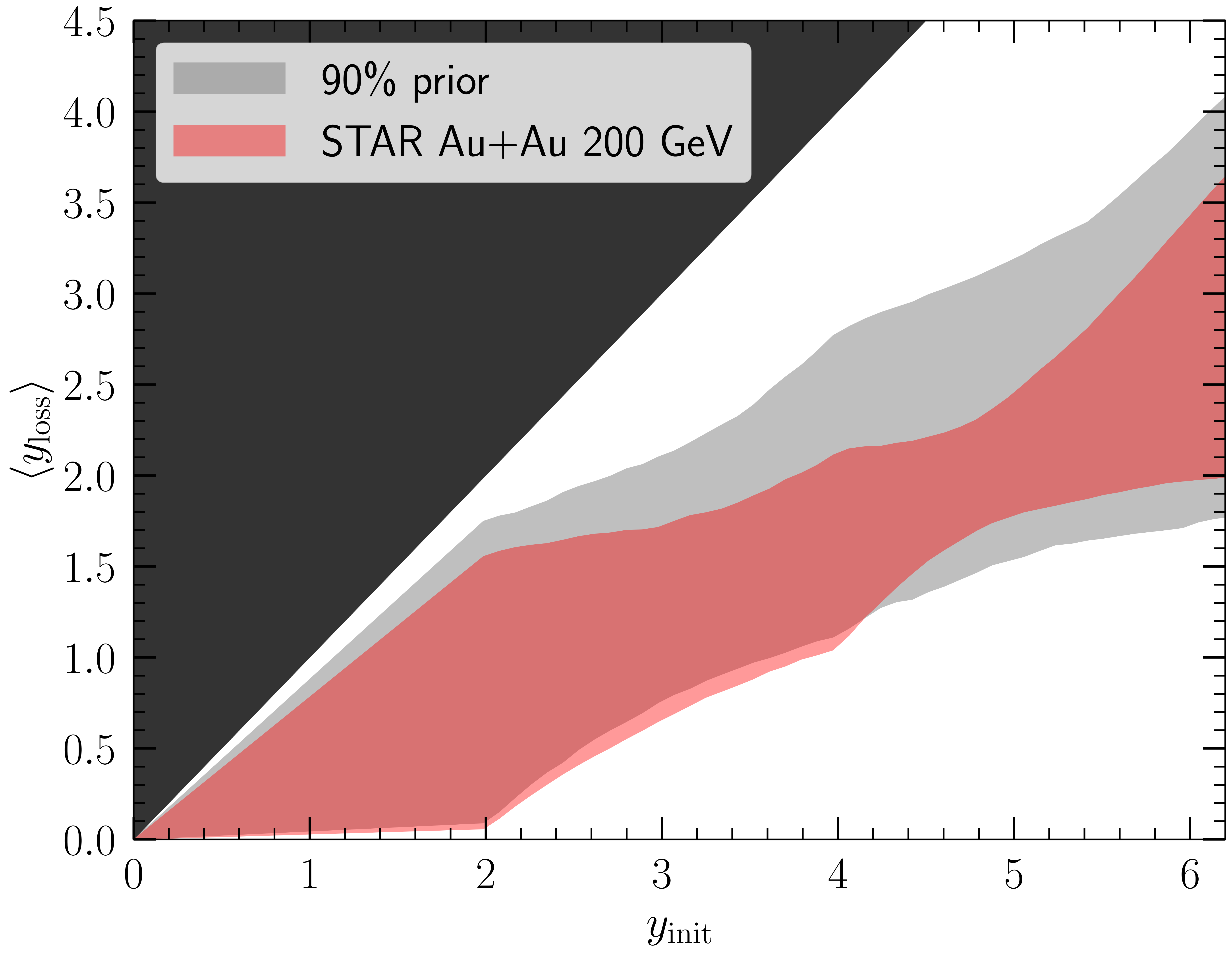
STAR



PHOBOS

BAYESIAN INFERENCE AT RHIC BES ENERGIES

INITIAL-STATE STOPPING



- Mid-rapidity particle productions at 200 GeV yields $y_{loss} \sim 2$ for $y_{init} \sim 5$

color bands indicate 90% credible interval in the posterior

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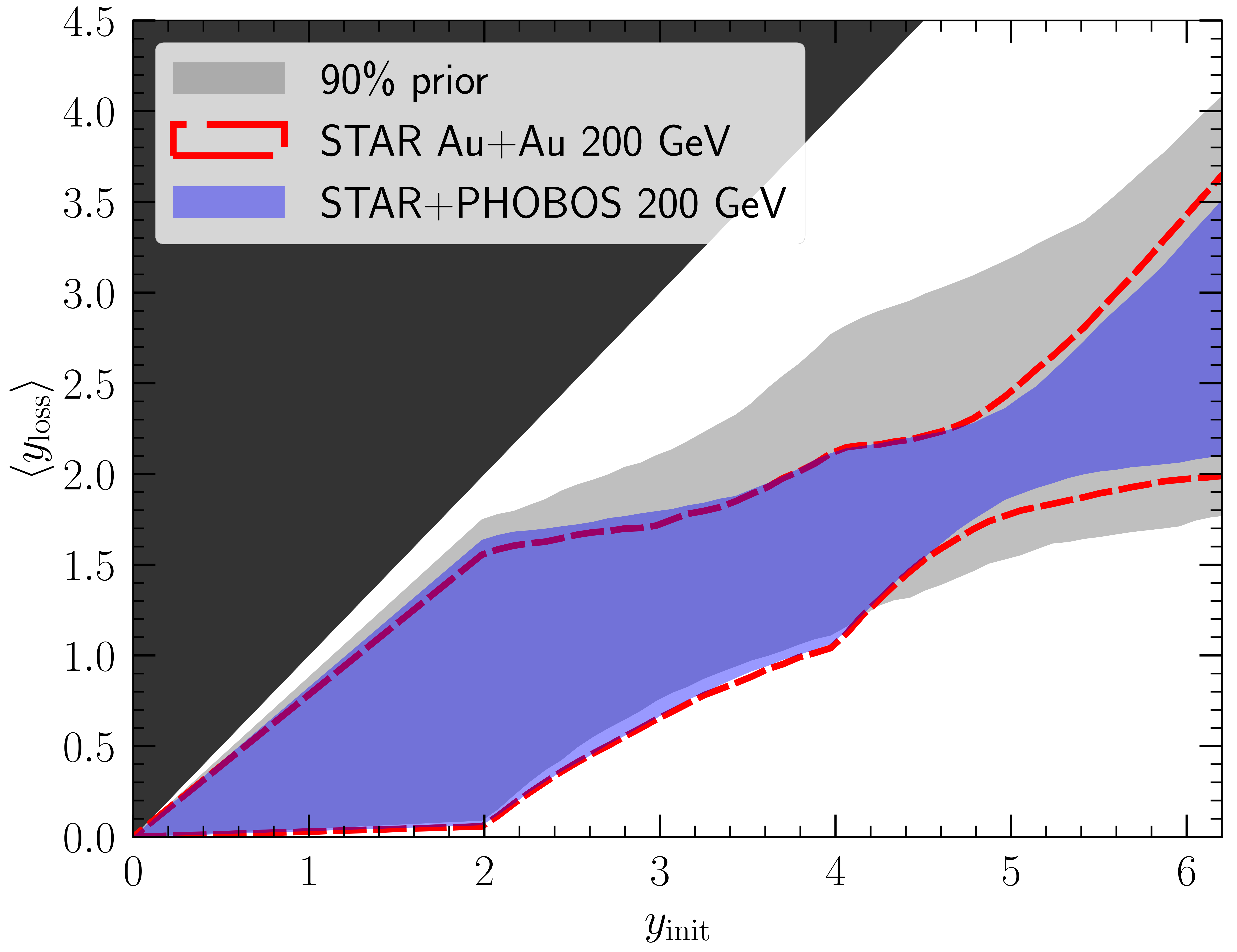

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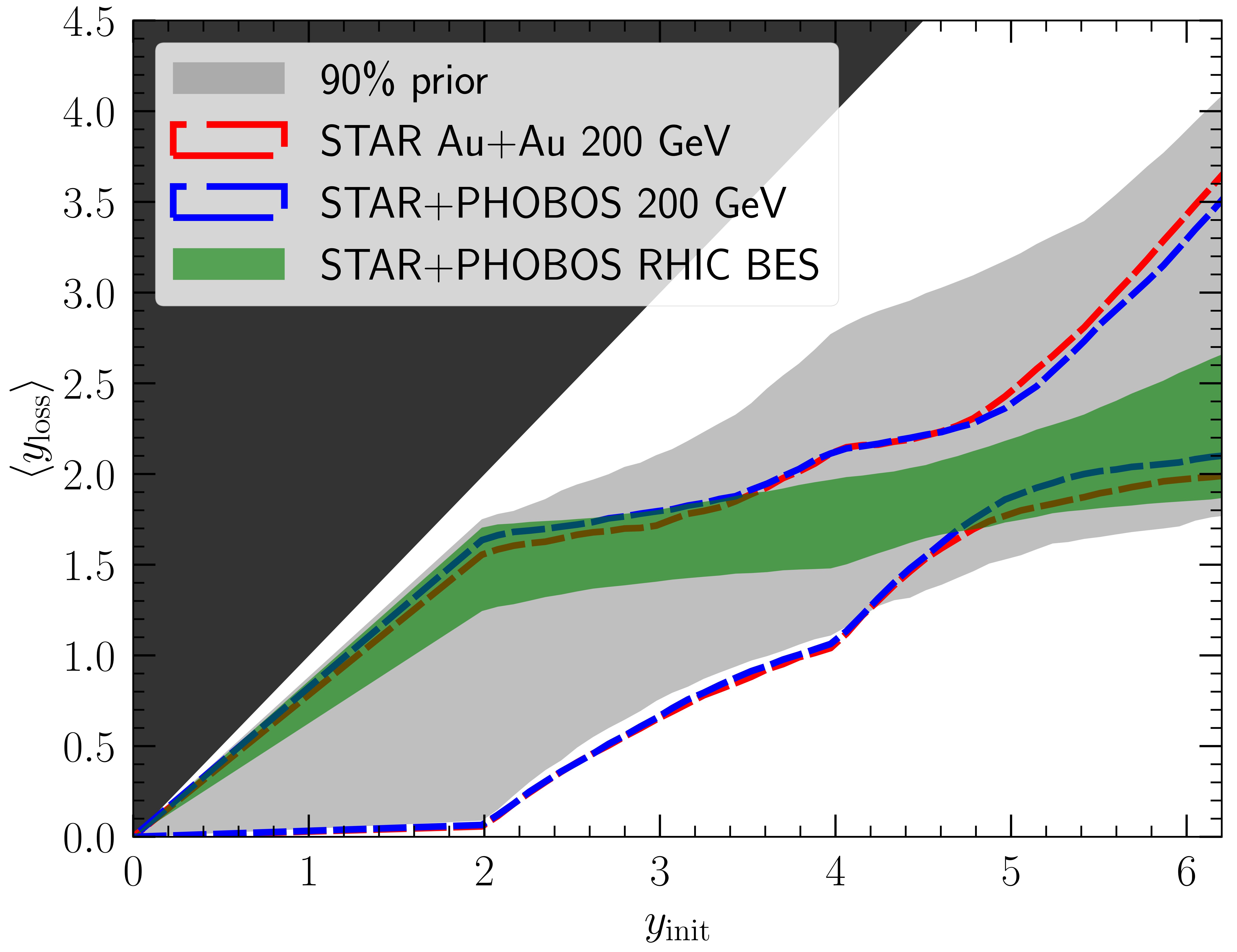

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- Particle production from 7.7, 19.6, and 200 GeV sets strong constrain on $y_{\rm loss}(y_{\rm init})$ for $y_{\rm init} \in [0,6]$

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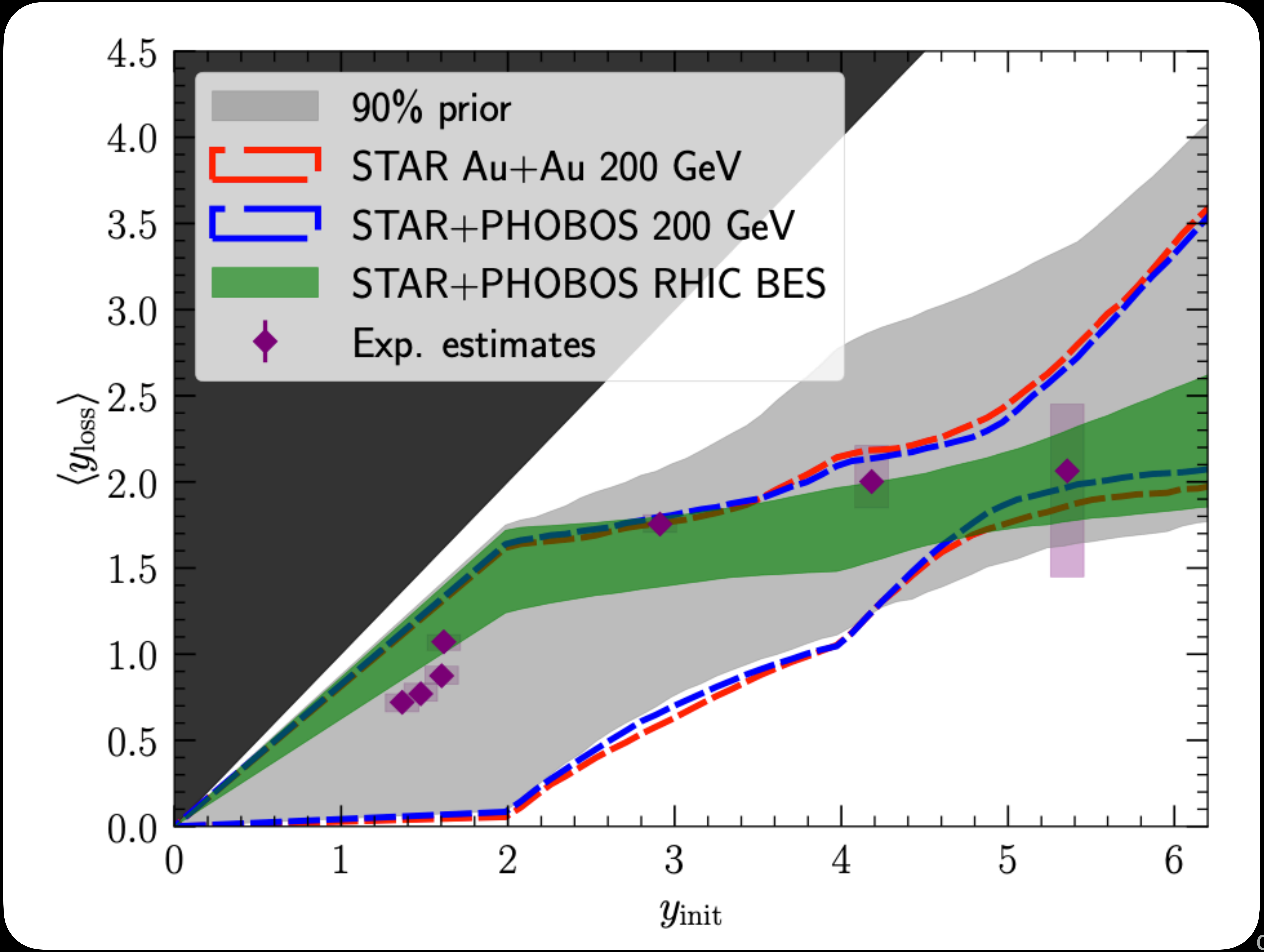
INITIAL-STATE STOPPING



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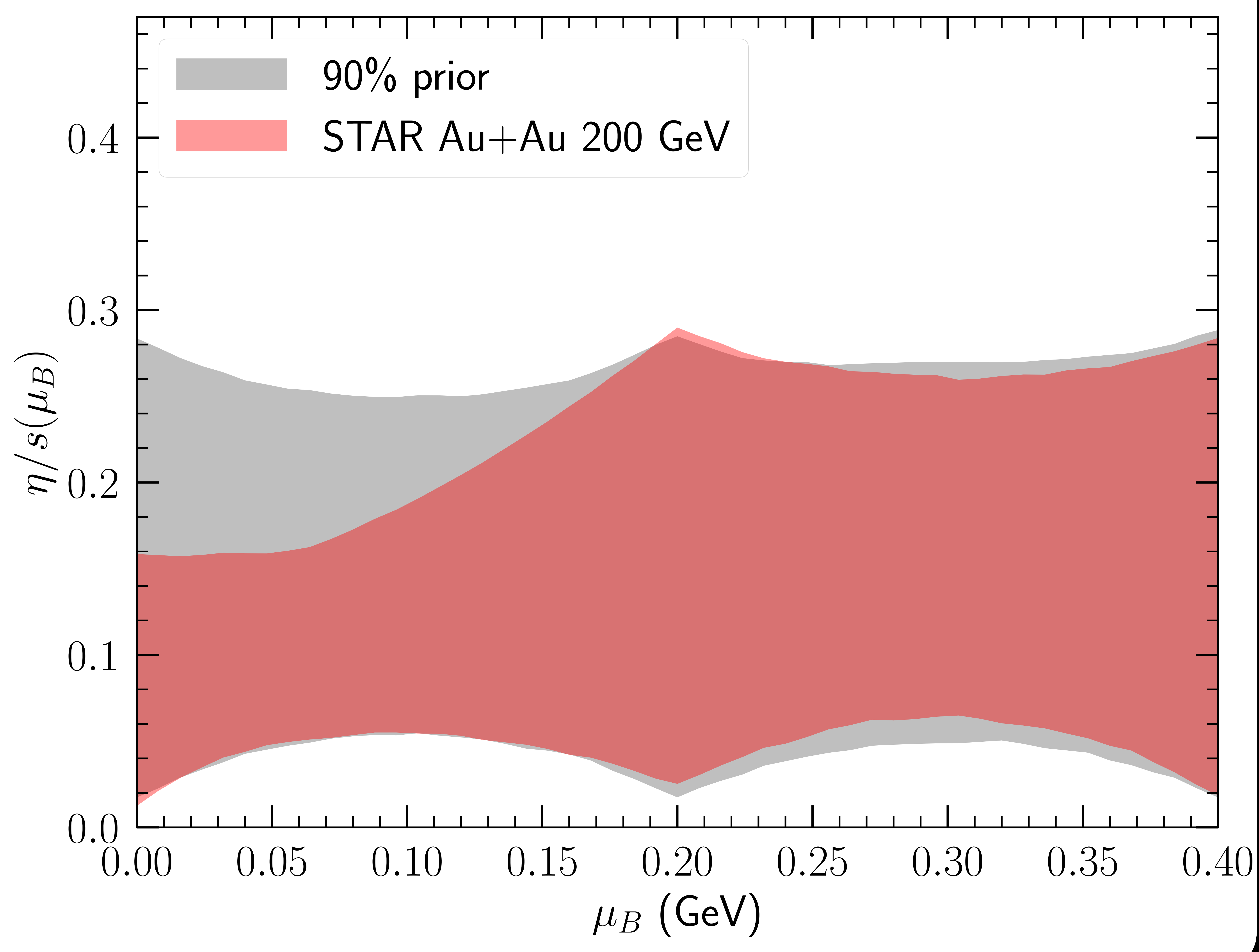
SHEAR VISCOSITY $\eta/s(\mu_B)$



- Mid-rapidity data at 200 GeV can constrain η/s around $\mu_B = 0$

color bands indicate 90% credible interval in the posterior

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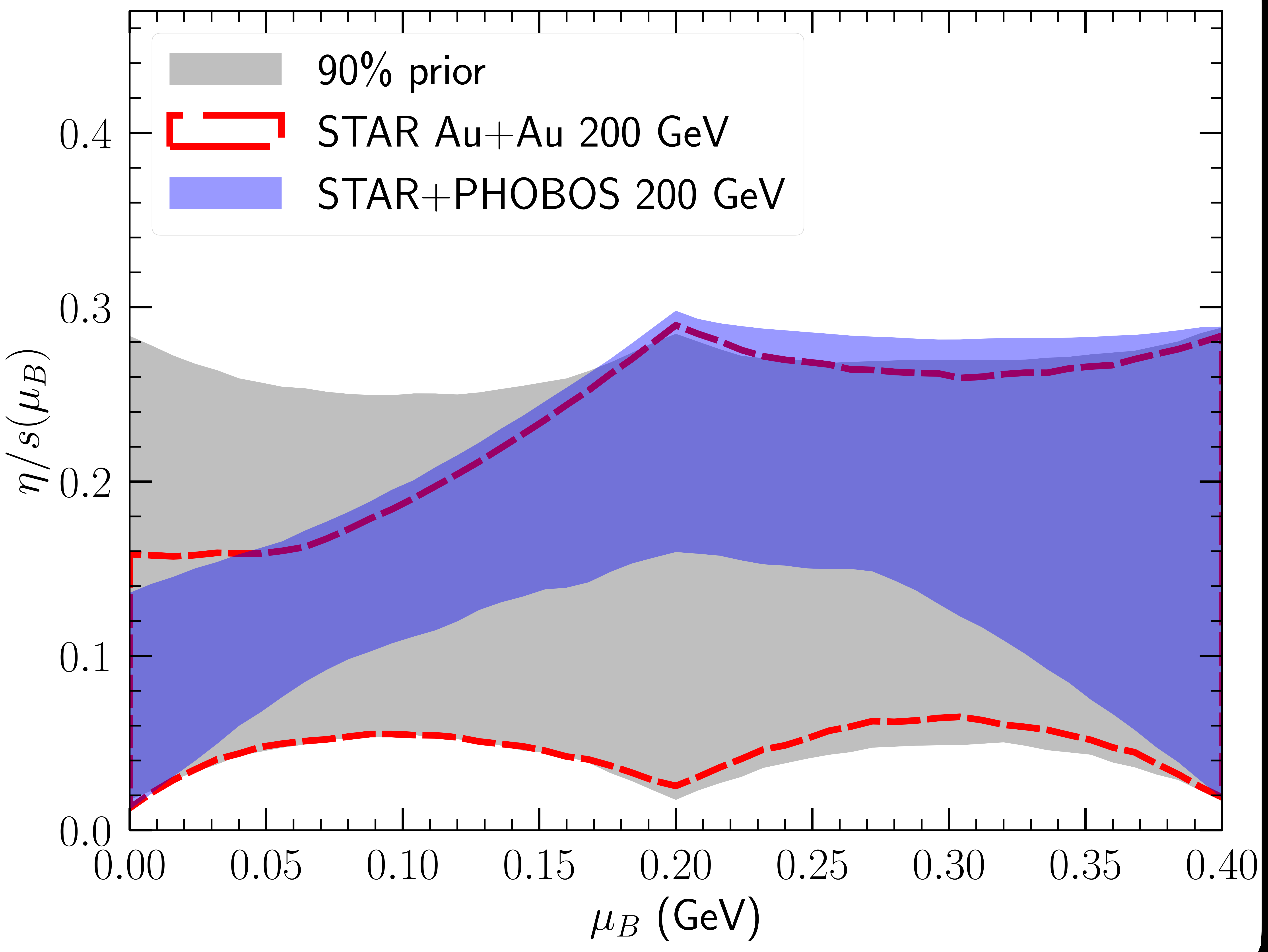

- Mid-rapidity data at 200 GeV can constrain η/s around $\mu_B = 0$
- The $dN^{\mathrm{ch}}/d\eta$ and $v_2(\eta)$ at 200 GeV *significantly* improve the η/s constraint at $\mu_B \sim 0.2$ GeV

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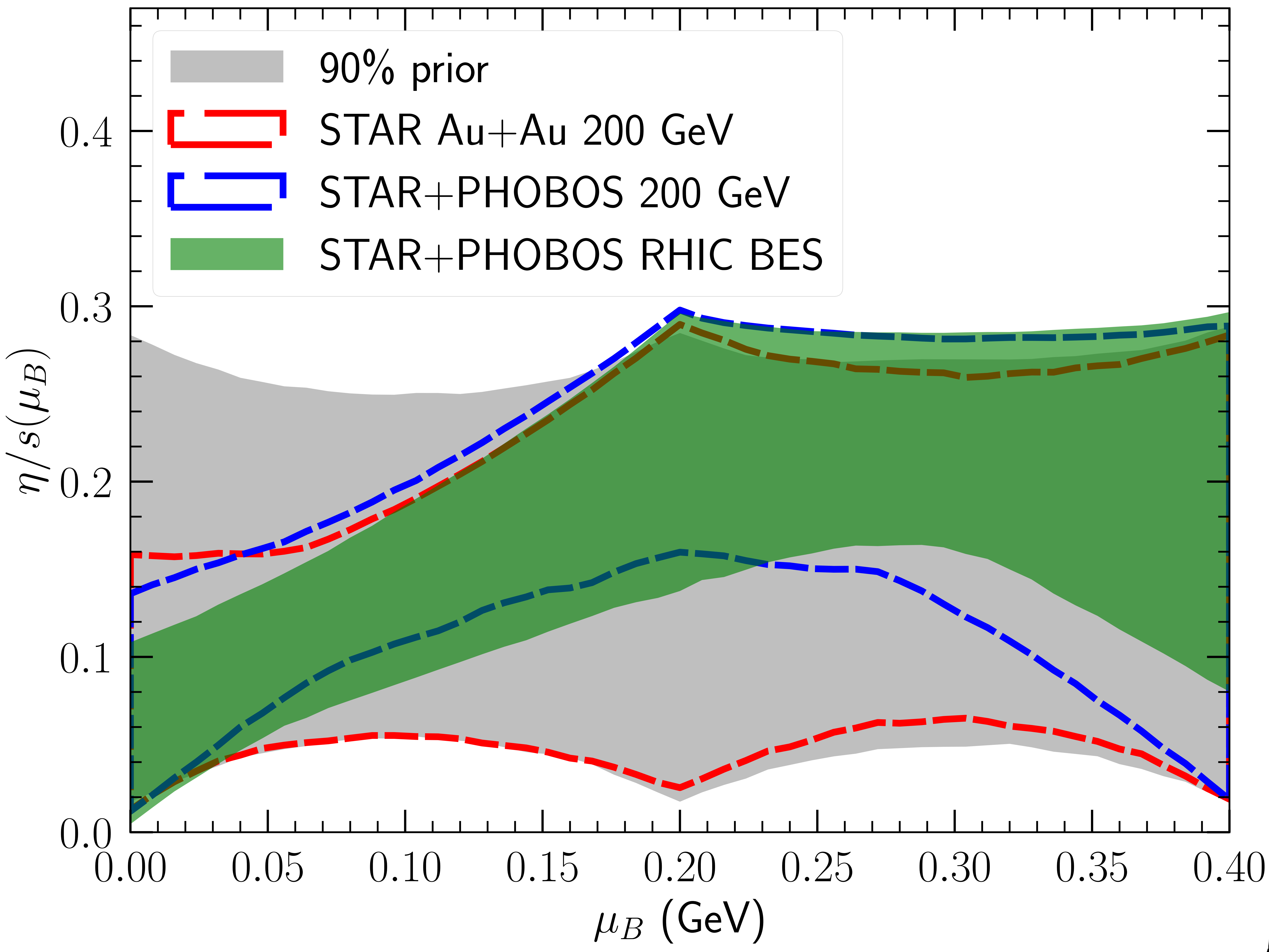
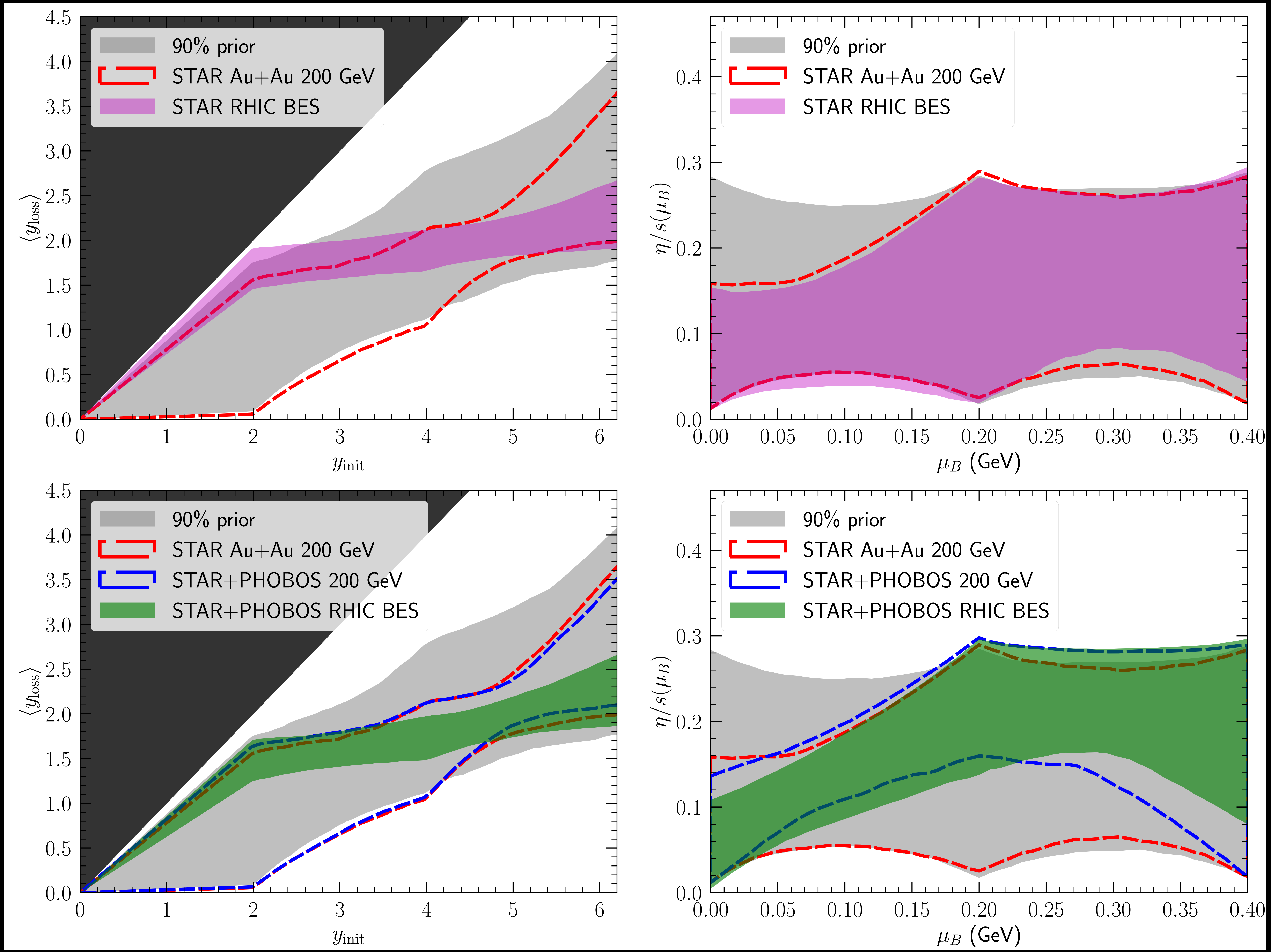


- Mid-rapidity data at 200 GeV can constrain η/s around $\mu_B = 0$
- The $dN^{ch}/d\eta$ and $v_2(\eta)$ at 200 GeV *significantly* improve the η/s constraint at $\mu_B \sim 0.2$ GeV
- The full RHIC BES data (STAR+PHOBOS) shows that the QGP η/s is **larger** at finite μ_B than that at $\mu_B = 0$

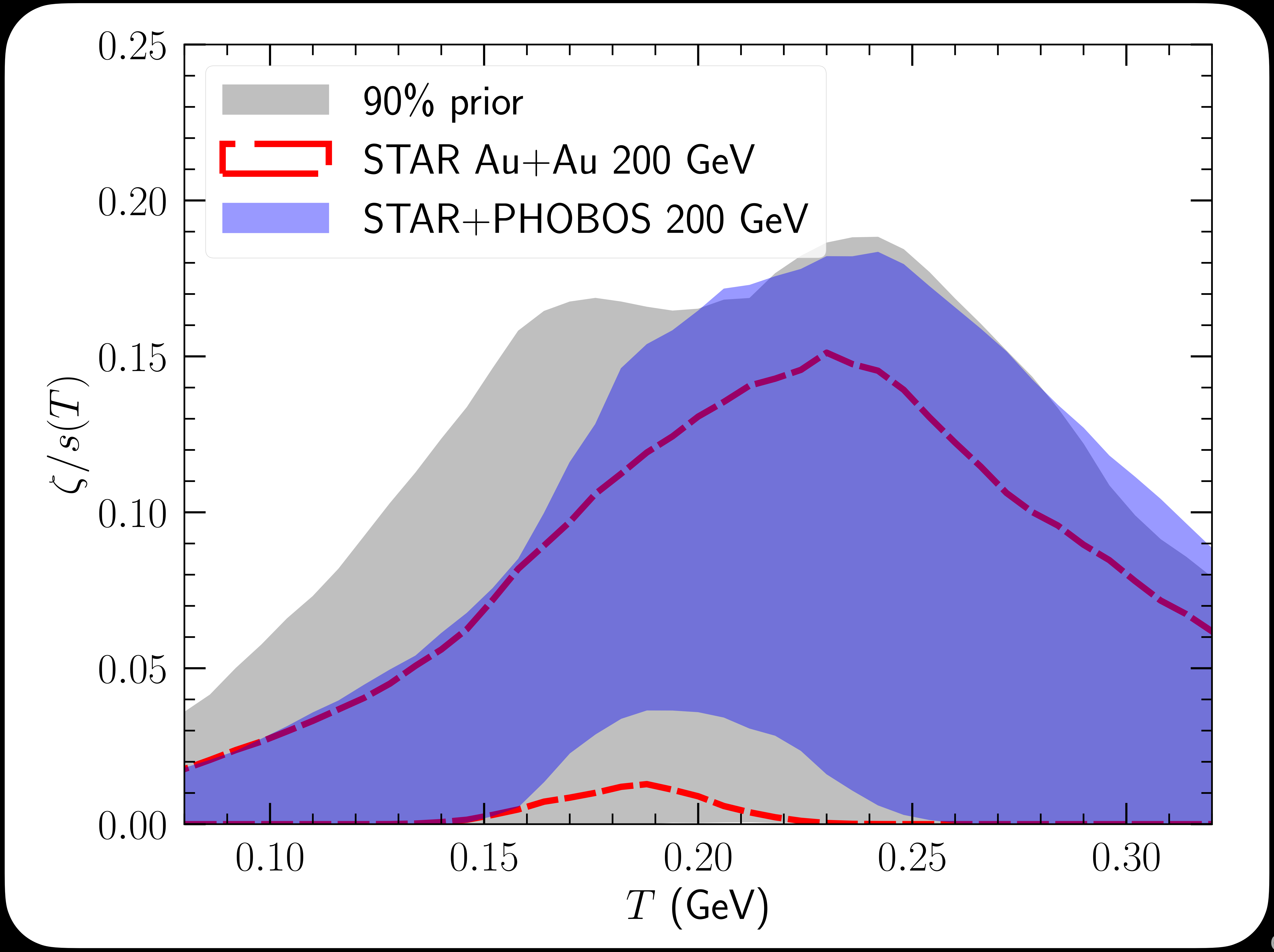
color bands indicate 90% credible interval in the posterior

INFERENCE WITH ONLY STAR MID-RAPIDITY DATA



- The mid-rapidity data from STAR BES energies can set a good constraint on $y_{\rm loss}(y_{\rm init})$
- The rapidity dependent $v_2(\eta)$ measurement imposes strong constraints on $\eta/s(\mu_B)$

BULK VISCOSITY $\zeta/s(T)$

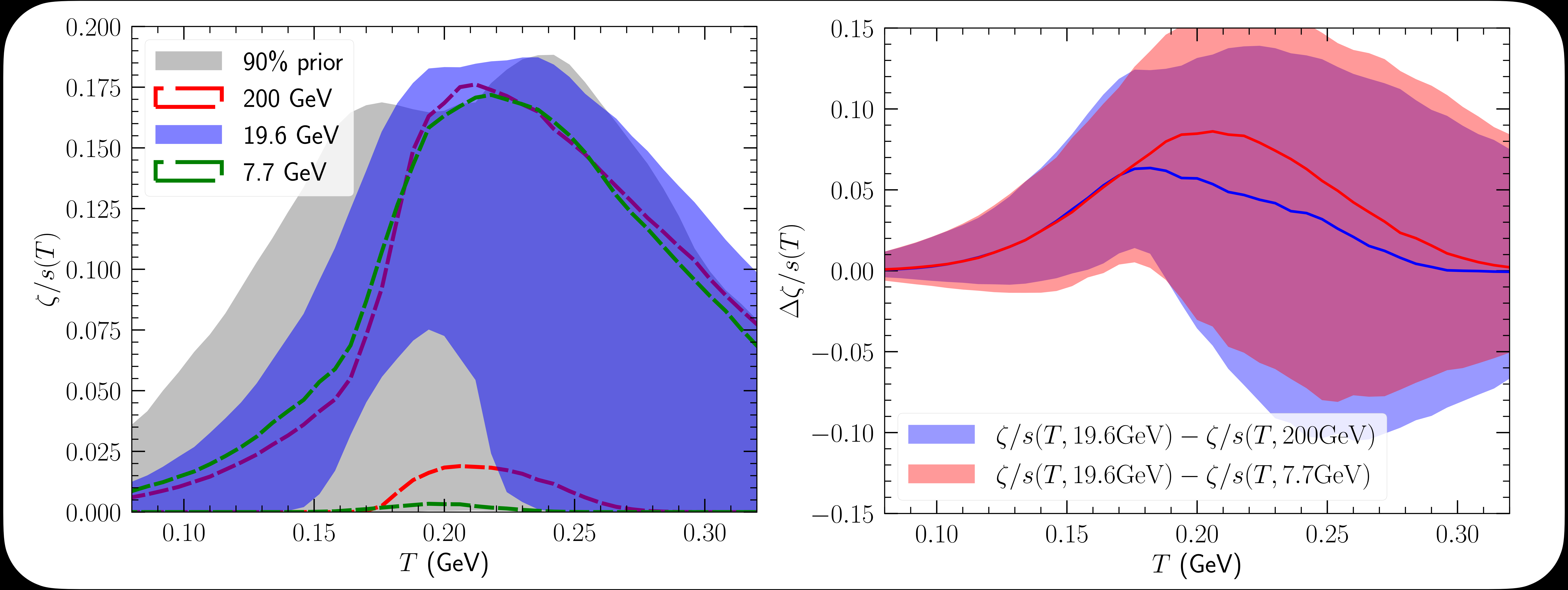


- Mid-rapidity identified particle yields and their $\langle p_T \rangle$ at 200 GeV set constraints on the temperature dependence of the QGP bulk viscosity

- The additional PHOBOS data shifts the posterior $\zeta/s(T)$ to larger values

color bands indicate 90% credible interval in the posterior

BULK VISCOSITY $\zeta/s(T, \sqrt{s})$



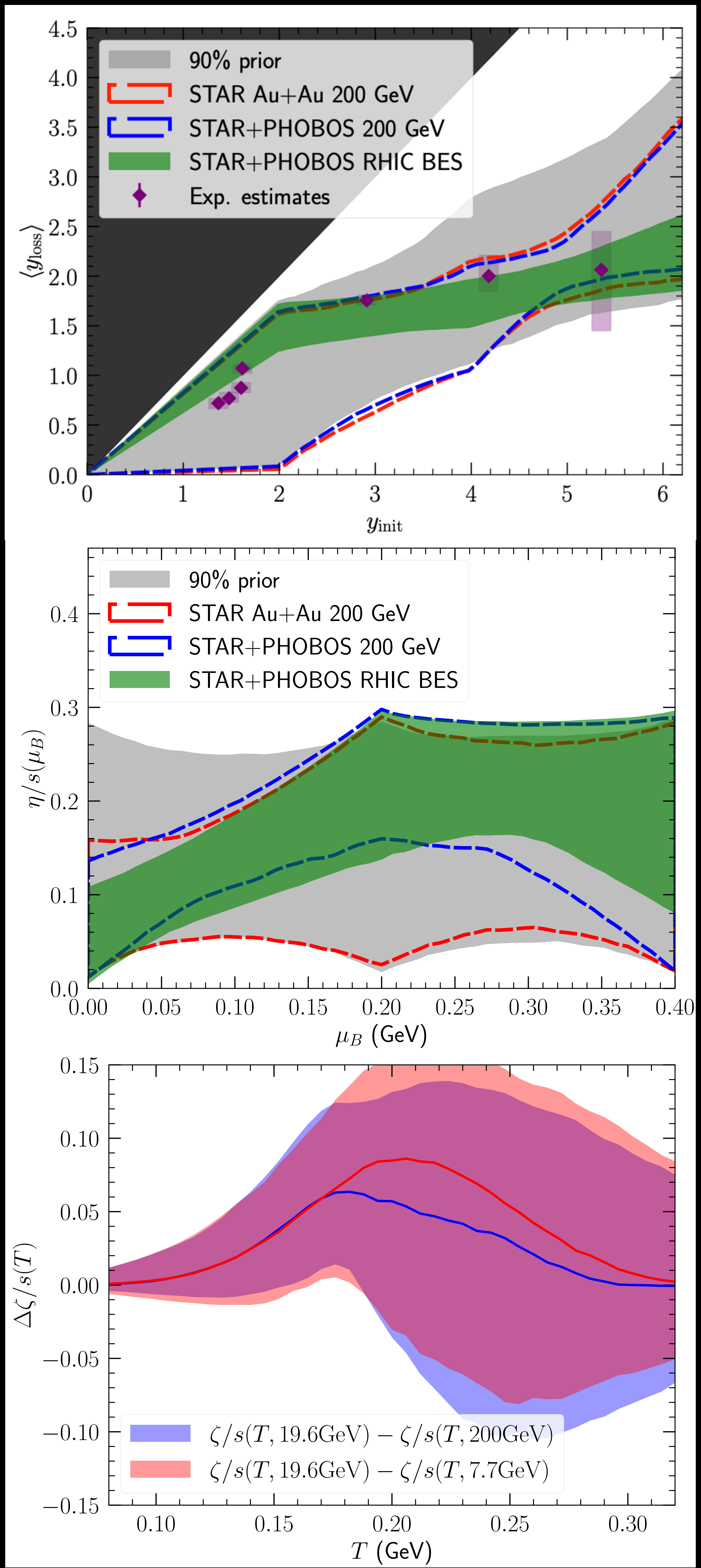
color bands indicate 90% credible interval in the posterior

- Allowing $\zeta/s(T)$ to be an independent function for the three collision energies, our calibration suggests a larger $\zeta/s(T)$ at 19.6 GeV than those at 200 and 7.7 GeV for $T \in [0.15, 0.2]$ GeV

Hint for softening(hardening) EoS at $\mu_B = 0.2(0.4)$ GeV?

CONCLUSIONS

- We performed a comprehensive Bayesian Inference study at multiple RHIC BES energies with a state-of-the-art event-by-event (3+1)D hybrid framework
- With the RHIC BES phase I data, robust constraints are obtained for initial state nuclear stopping, QGP $\eta/s(\mu_B)$, and $\zeta/s(T, \sqrt{s})$ for the first time
- The QGP effective η/s is larger at finite μ_B, while $\zeta/s(T)$ shows a hint for non-monotonic energy dependence around $\sqrt{s} = 19.6$ GeV
- Our work marks an important step towards quantitative characterization of the QCD phase structure with the RHIC BES and future FAIR programs



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OUTLOOK

- Confront with the RHIC BES phase II data
  - ➡ Constrain the speed of sound $c_s^2(T, \mu_B)$
  - ➡ Extend to multiple conserved charge currents $P(e, n_B, n_Q, n_S)$
  - ➡ Critical fluctuations/first-order phase transition
- (3+1)D dynamics at the LHC
  - ➡ Rapidity (small-x) evolution
  - ➡ The role of nuclear structure
- Open data
  - ➡ Engage more collaboration on developing robust and efficient statistical analyses