SIMULATING BARYON TRANSPORT

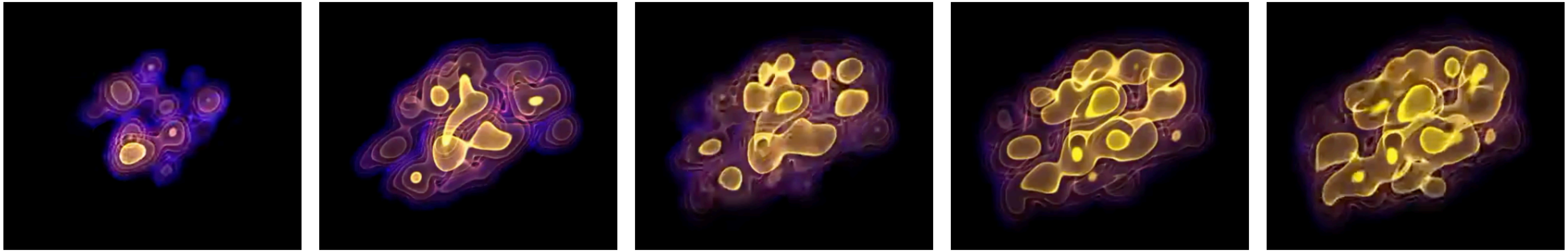
BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

JANUARY 22 2024

1ST WORKSHOP ON BARYON DYNAMICS FROM RHIC TO EIC
CFNS @ SBU

BARYON TRANSPORT IN NUCLEAR COLLISIONS

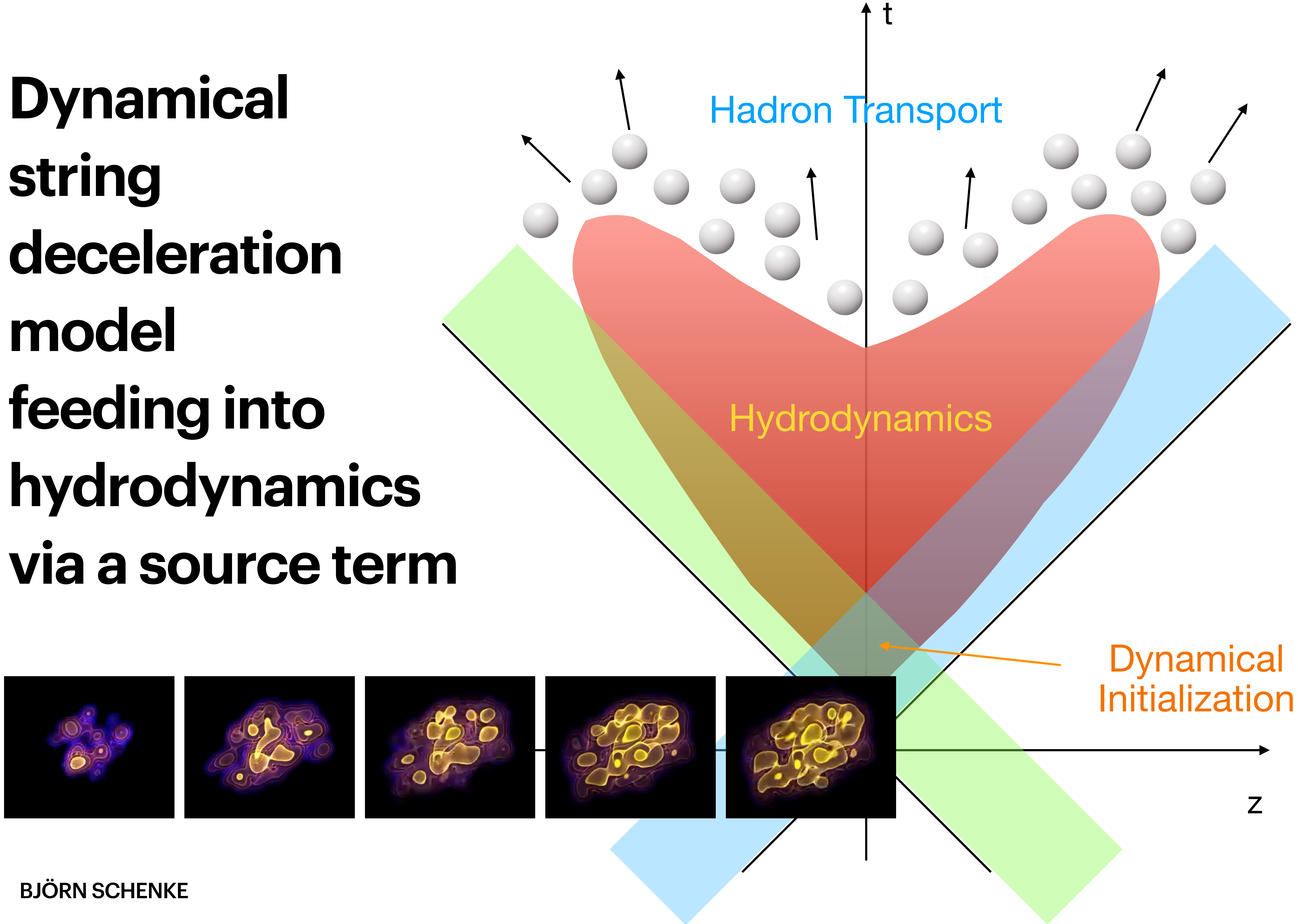
- Initial state baryon stopping
- Net-baryon transport in hydrodynamics
- Equation of state as function of baryon chemical potential
- Baryon diffusion
- Dependence of transport coefficients on baryon chemical potential
- Bayesian constraints

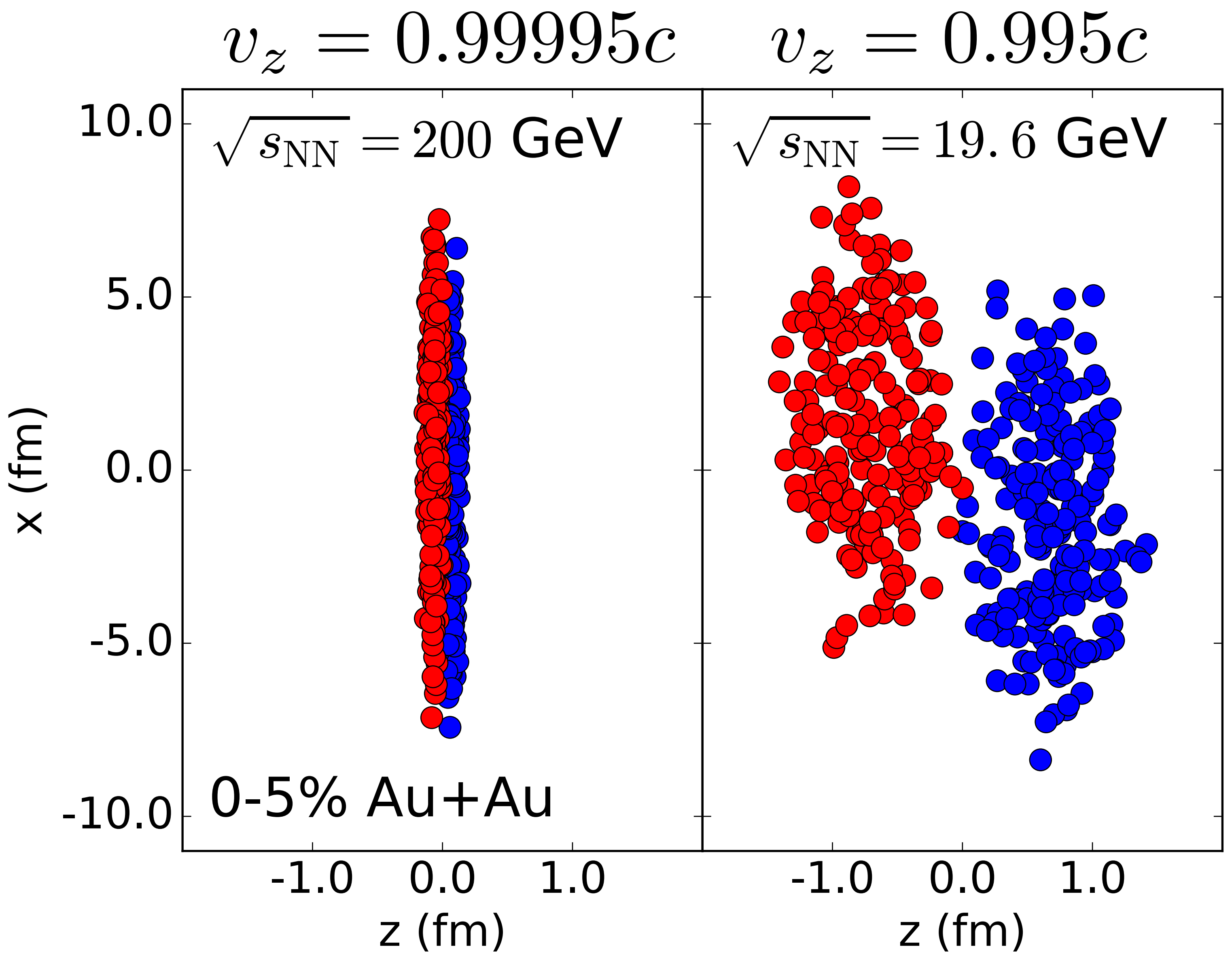


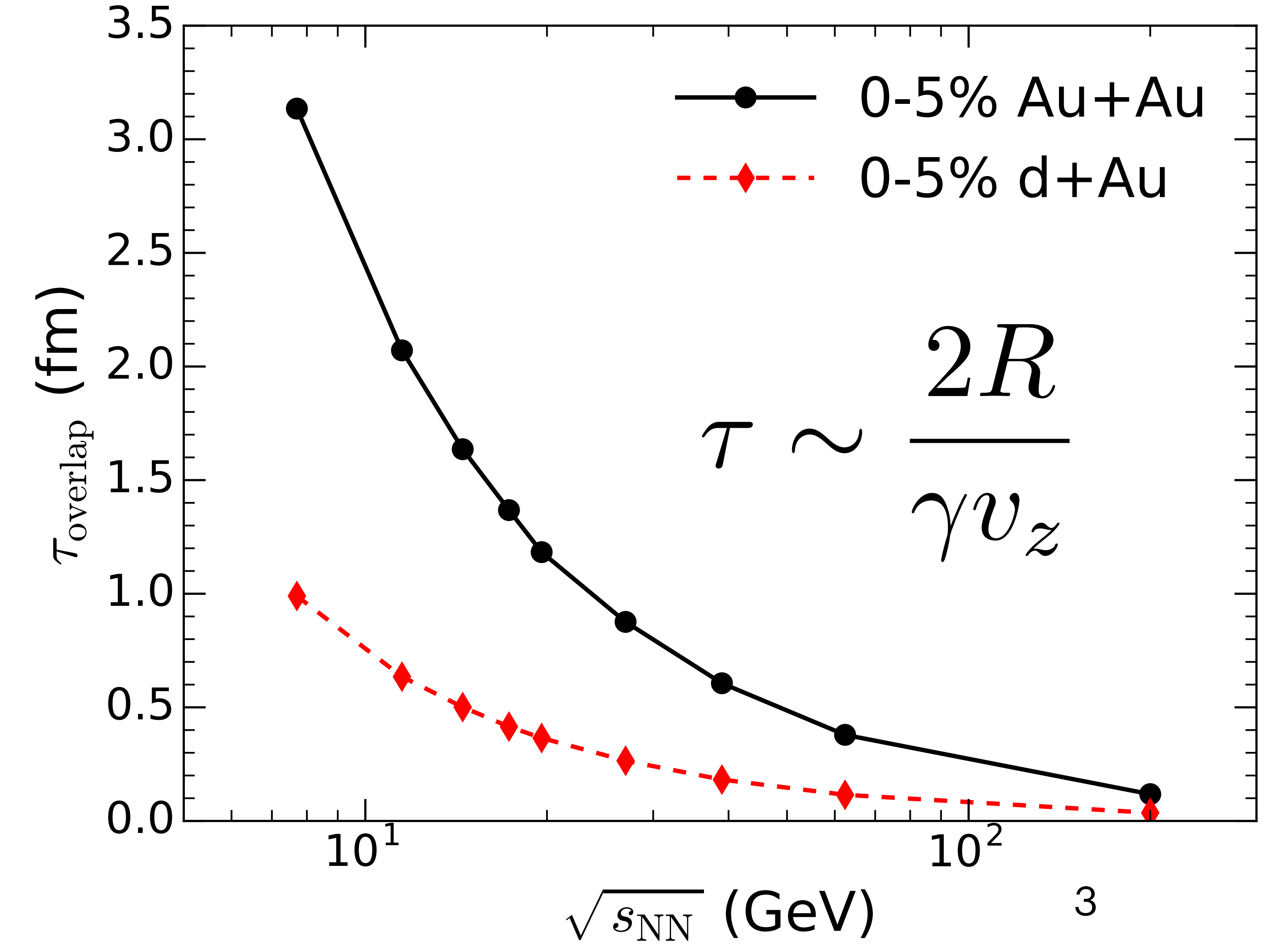
DYNAMIC 3+1D INITIAL STATE

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

Dynamical string deceleration model feeding into hydrodynamics via a source term



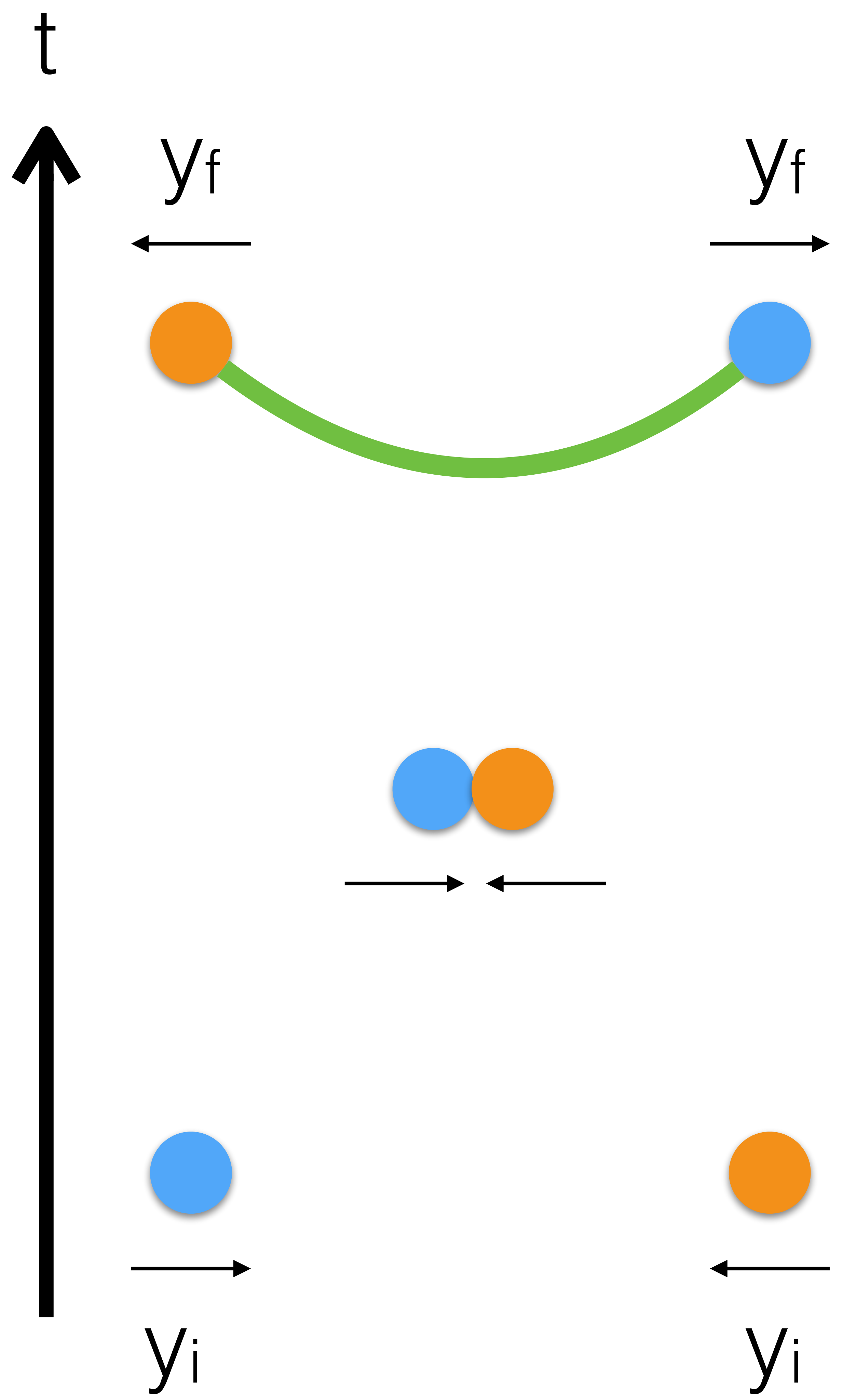




3D MC-GLAUBER + STRING MODEL

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

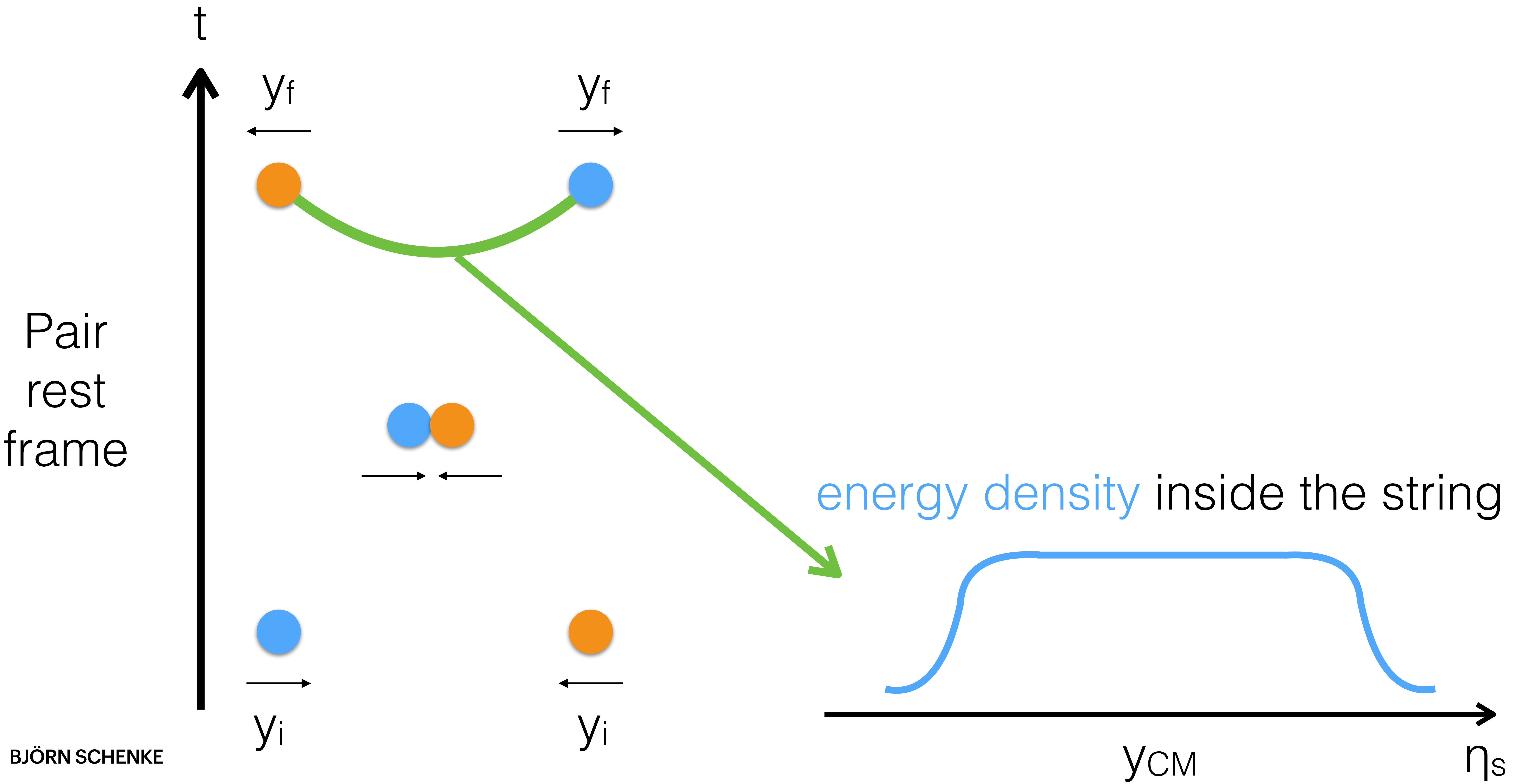
Pair rest frame



- Transverse collision geometry is determined by MC-Glauber model
- Hot spots associated with valence quarks are sampled from PDF + a soft partonic cloud carrying the rest (small *x* partons)
- Hot spots are randomly picked to lose energy during a collision, using a classical string tension $dp^z/dt = -\sigma$

3D MC-GLAUBER + STRING MODEL

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



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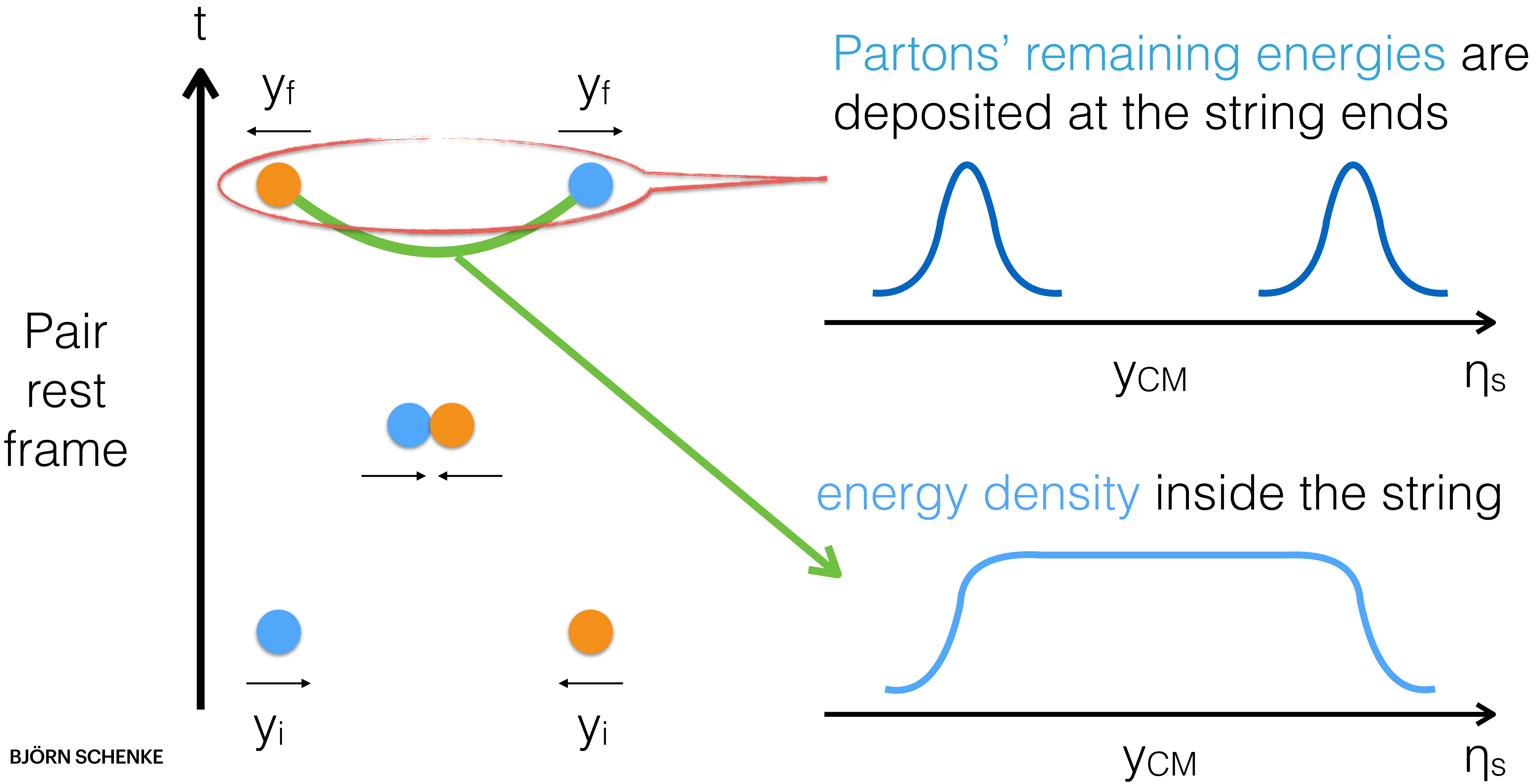

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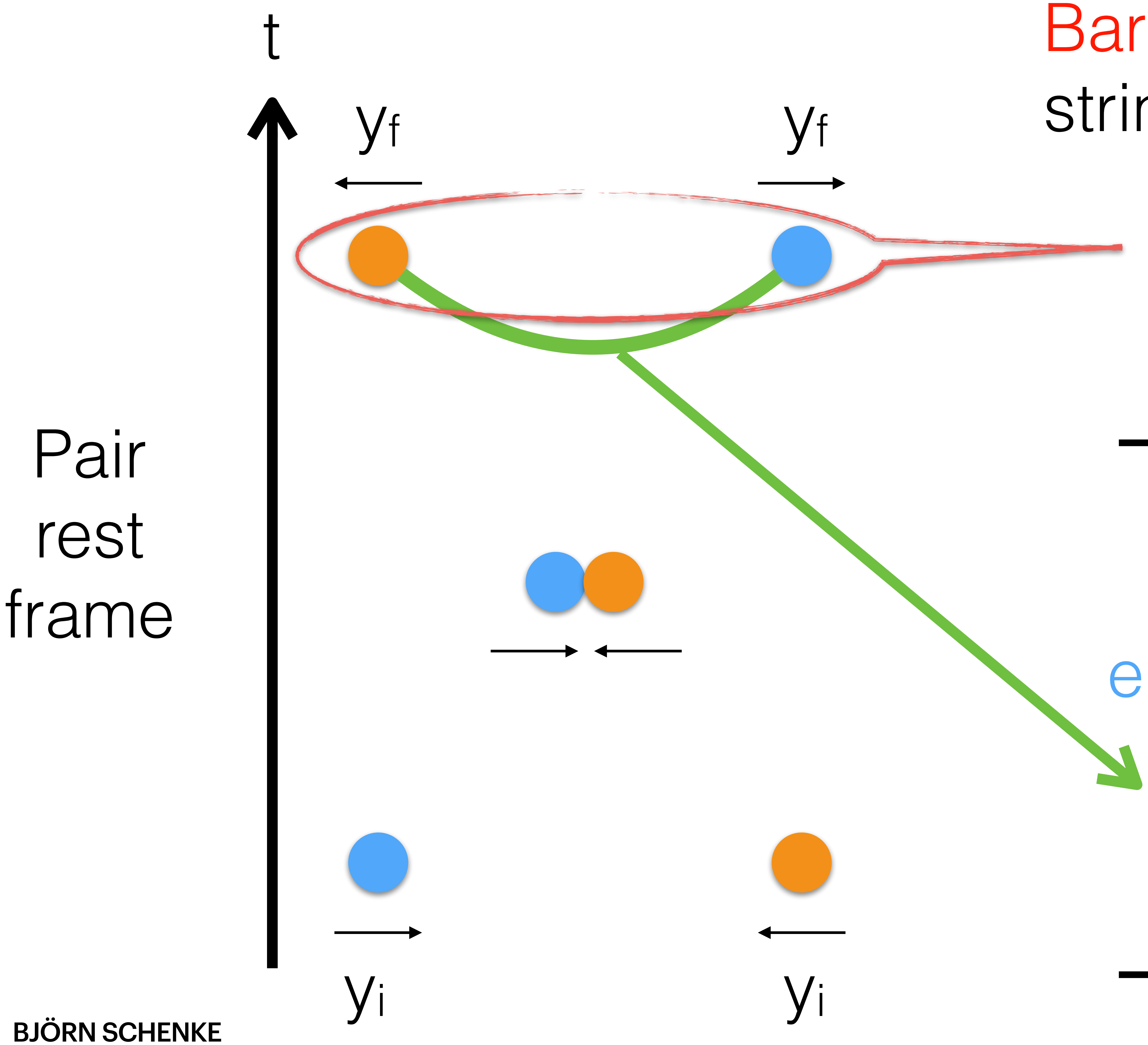
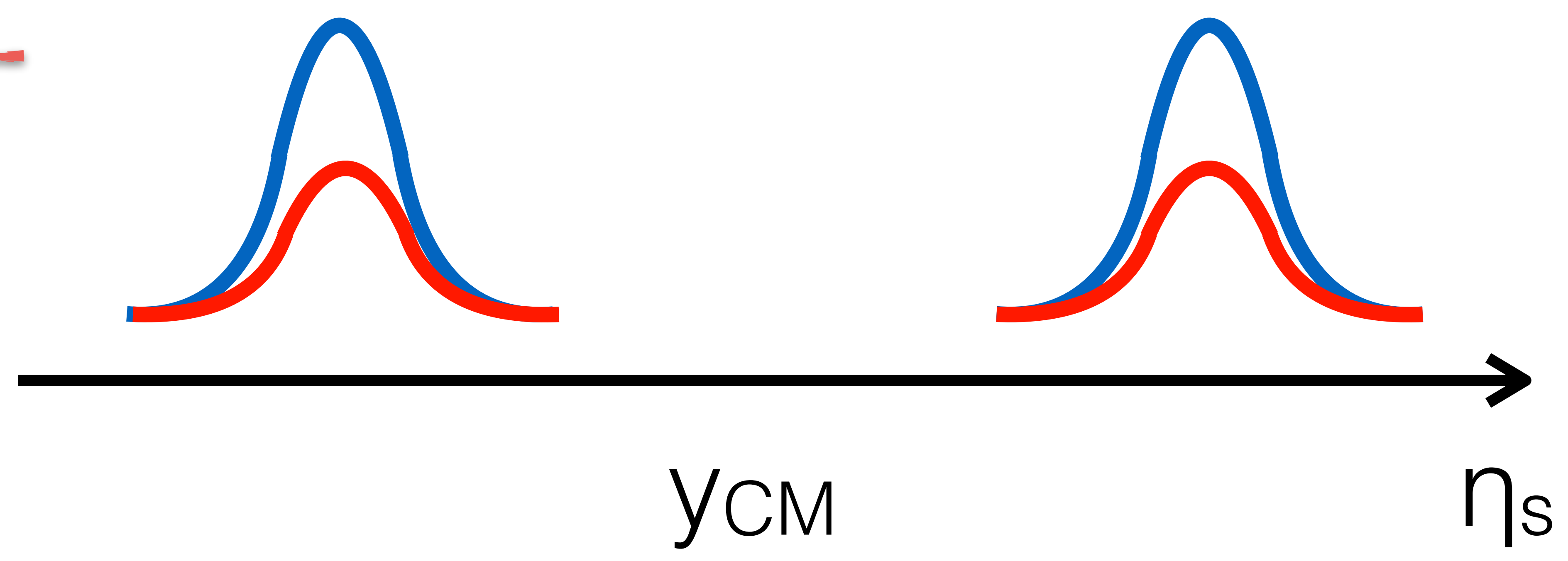
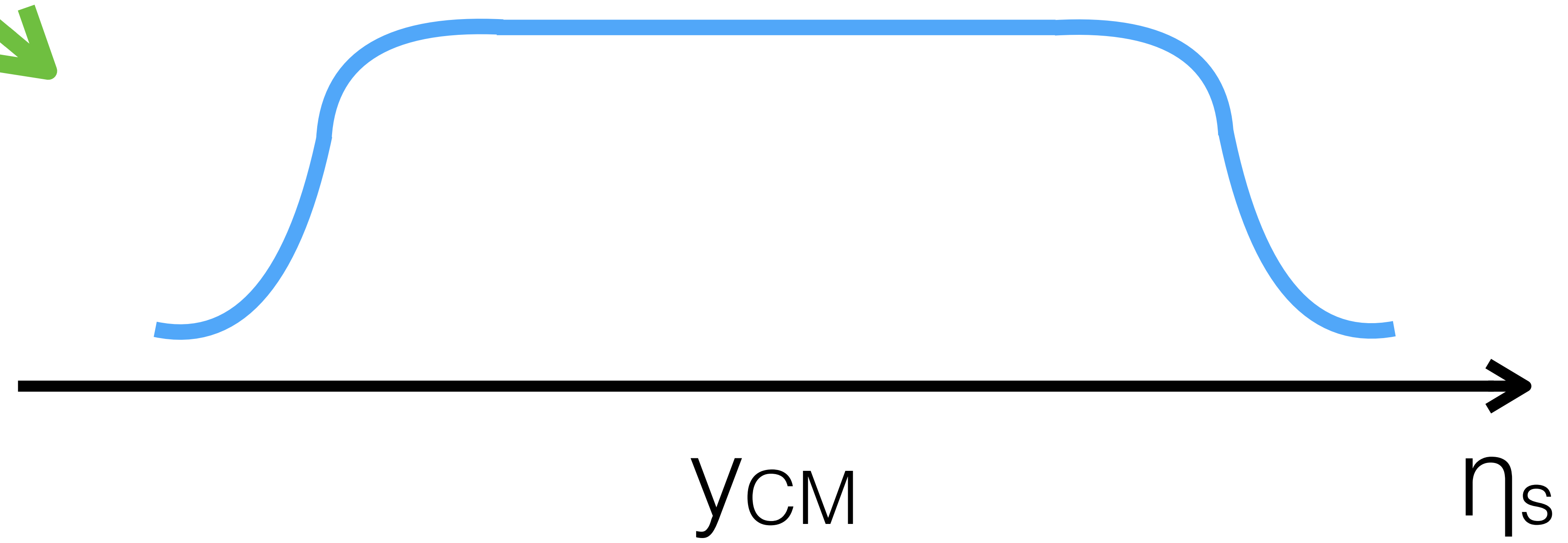


Baryon density is deposited at the string ends

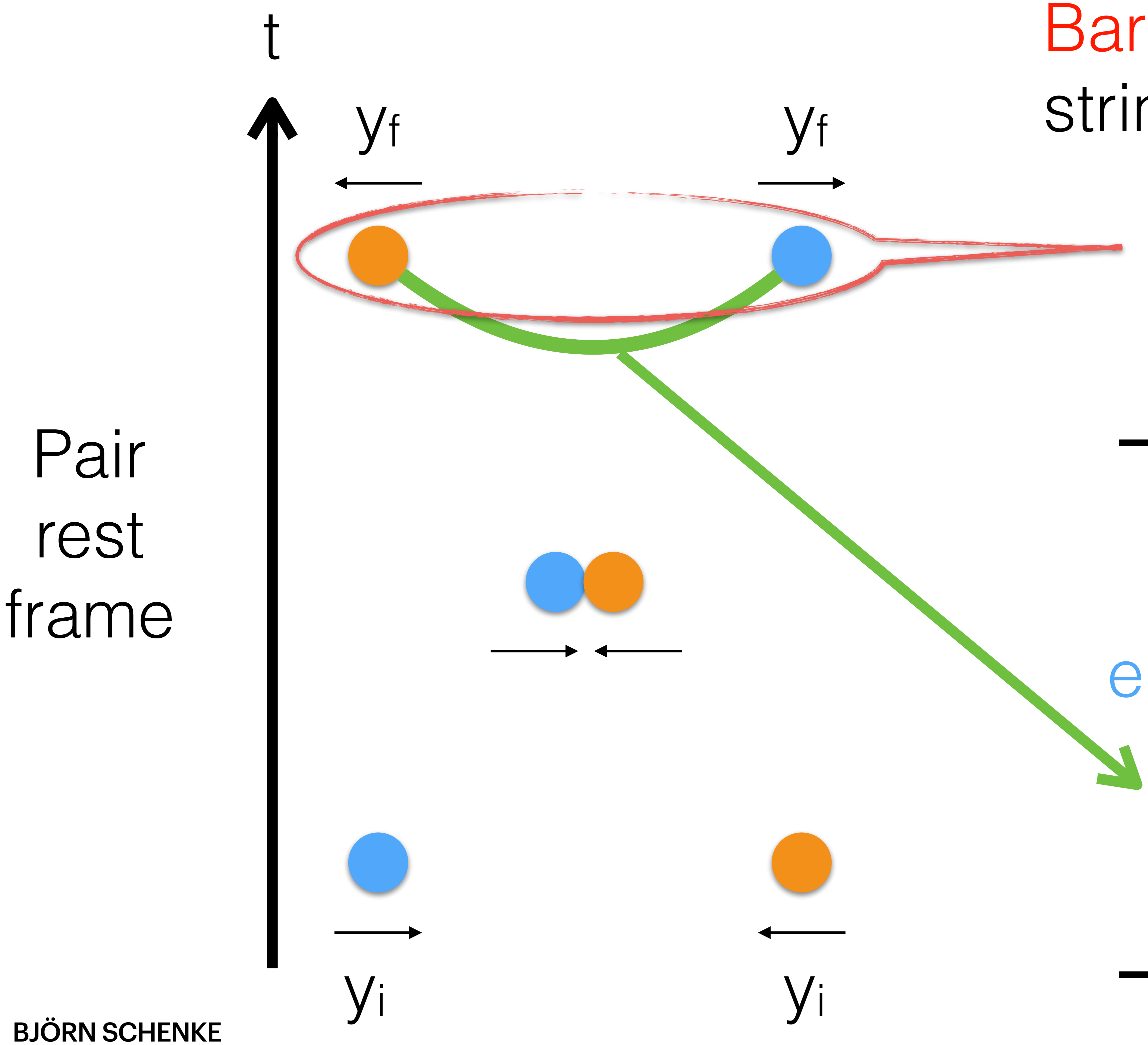


energy density inside the string



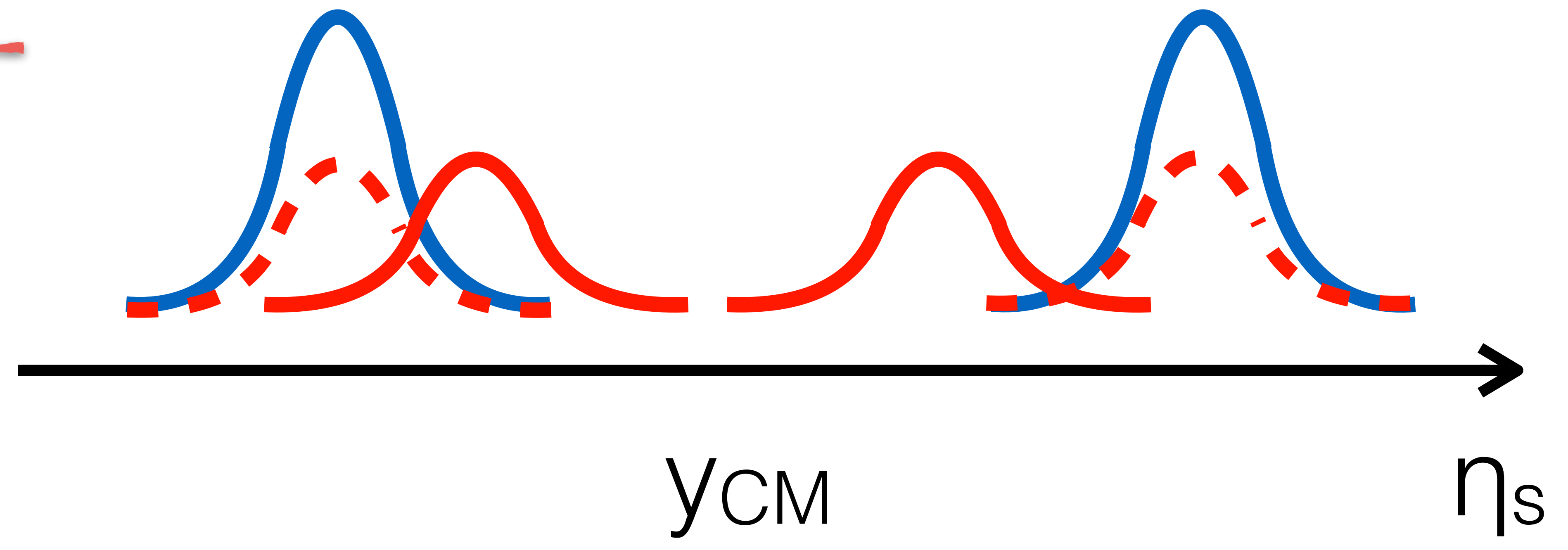
3D MC-GLAUBER + STRING MODEL

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

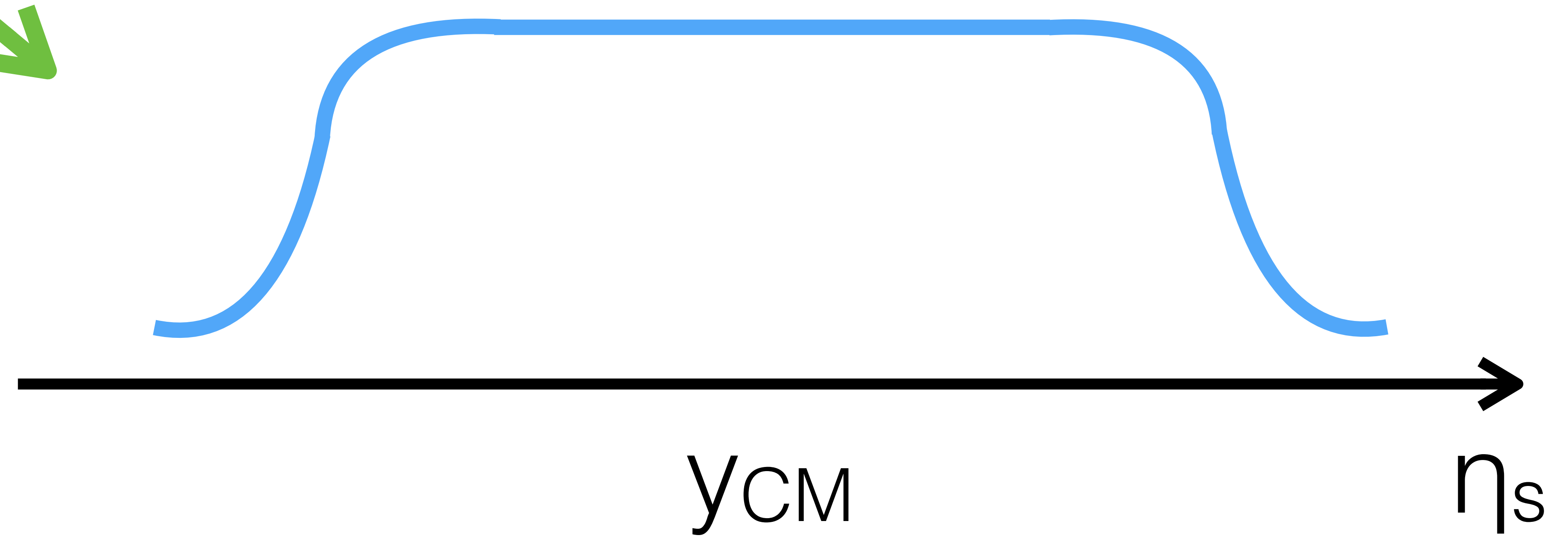


Baryon density is deposited at the string ends or string junctions

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



energy density inside the string



BARYON STOPPING

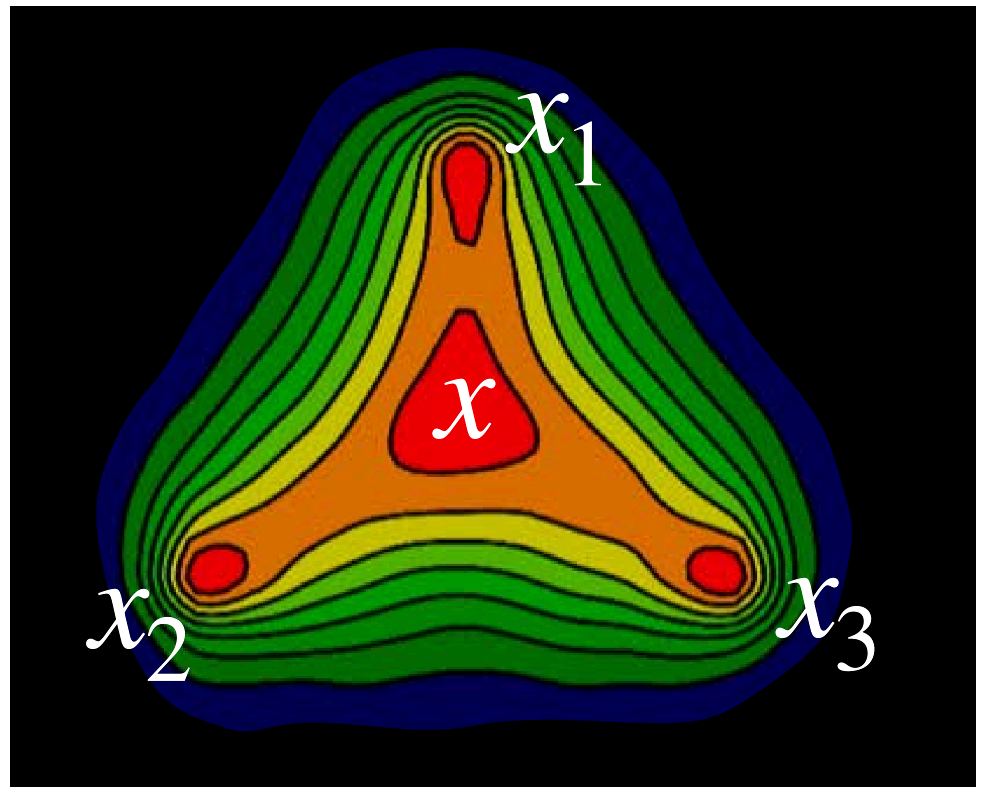
What carries baryon number? Valence quarks (1/3 each) or baryon junction?

Stopping valence quarks (large *x*) is hard (they have no time to interact)

What is a baryon junction?

"… there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons" **D. Kharzeev, Phys. Lett. B 378, 238 (1996)**

$$B = \epsilon^{ijk}\left[P exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right) q(x_1)\right]_i \left[P exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right) q(x_2)\right]_j \times \left[P exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right) q(x_3)\right]_k .$$

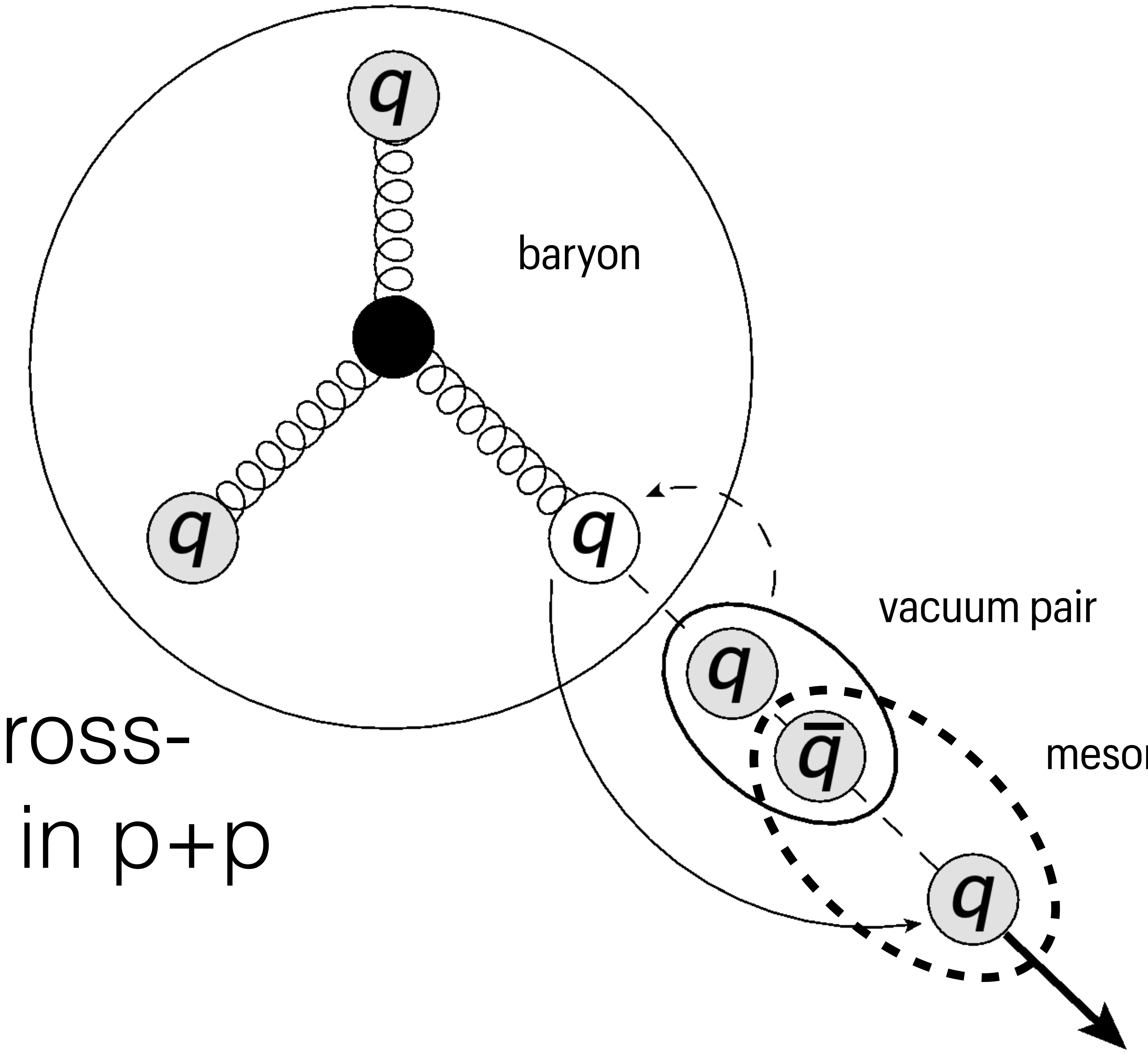


G.C. Rossi and G. Veneziano, Nucl. Phys.B123 (1977) 507; Phys. Rep.63 (1980) 149
D. Kharzeev, Phys. Lett. B 378, 238 (1996)

BARYON STOPPING

Baryon number should be associated with the junction:

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



If one pulls away quarks, strings will break and $q\bar{q}$ pairs will be produced

But the baryon will always restore itself around the string junction

In **D. Kharzeev, Phys. Lett. B 378, 238 (1996)** the differential cross-sections for single and double junction stopping in p+p collisions are computed using Regge theory

Single stopping dominates at high energy, has a characteristic rapidity dependence - double stopping is rapidity independent

RAPIDITY DEPENDENCE

Given the rapidity dependence of the single junction stopping cross section

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

we define the probability for where along the string the baryon number will be located as **C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)**

$$P(y^B_{P/T}) = (1-\lambda_B) y_{P/T} + \lambda_B \frac{e^{0.5[y^B_{P/T} - (y_P + y_T)/2]}}{4\sinh((y_p - y_T)/4)}$$

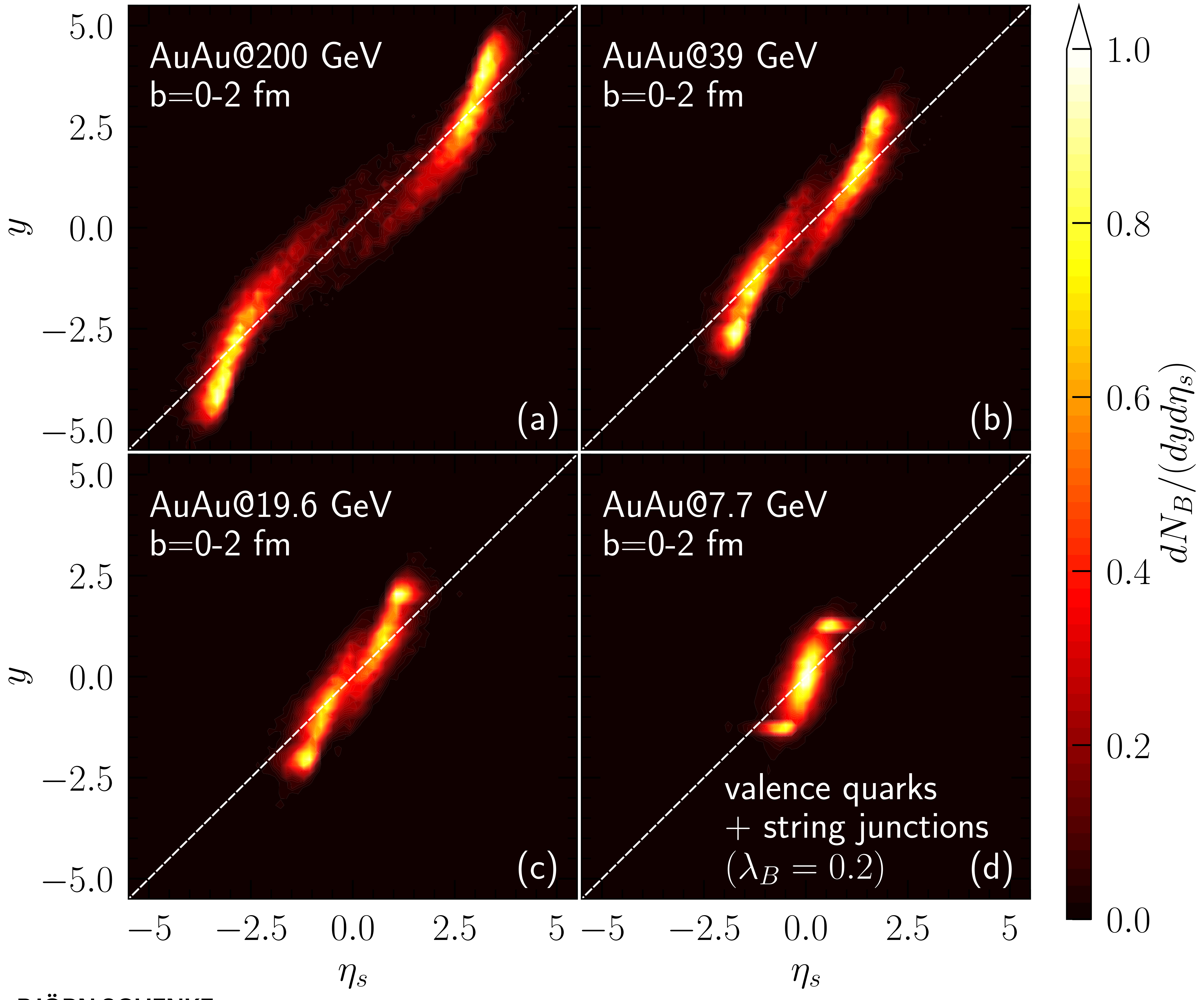
y_P and y_T are the rapidities of the string ends

Parameter λ_B determines the probability for the baryon number to move away from the string ends at all

Baryon density is Gaussian in 3D and located around η_s corresponding to $y^B_{P/T}$
(following the defined string's linear momentum rapidity profile as function of η_s)

BARYON CHARGE RAPIDITY y VS η_s

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- Diagonal: Free streaming limit
- Forward: $y > \eta_s$ because of finite overlap region: baryon charges produced at later times have reduced η_s
- Diagonal is crossed because of deceleration dynamics: Even baryons that get stopped ($y = 0$) will have moved to finite η_s
- At lower energy the two separate regions are joined and baryon charge in the beam remnants is visible

PHASE DIAGRAM

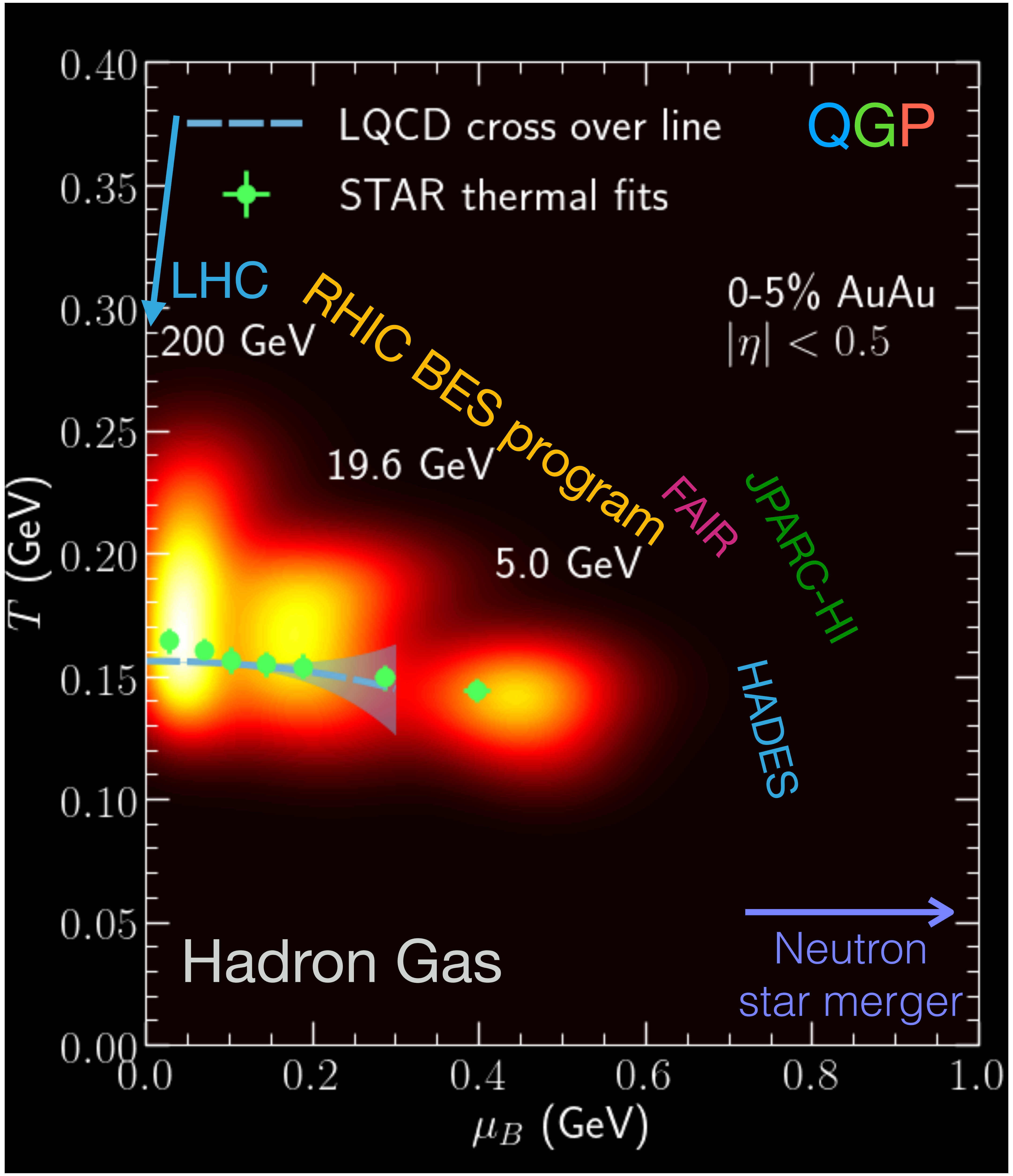
Energy-momentum current and net baryon density are fed into hydrodynamic simulations as source terms

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

Depending on collision energy the hydrodynamic evolution of the fireball covers different regions of the $T - \mu_B$ plane

For the equation of state we use NEOS with finite μ_B, μ_S, μ_Q and choose $n_S = 0$ and $n_Q = 0.4 n_B$ for Au+Au collisions

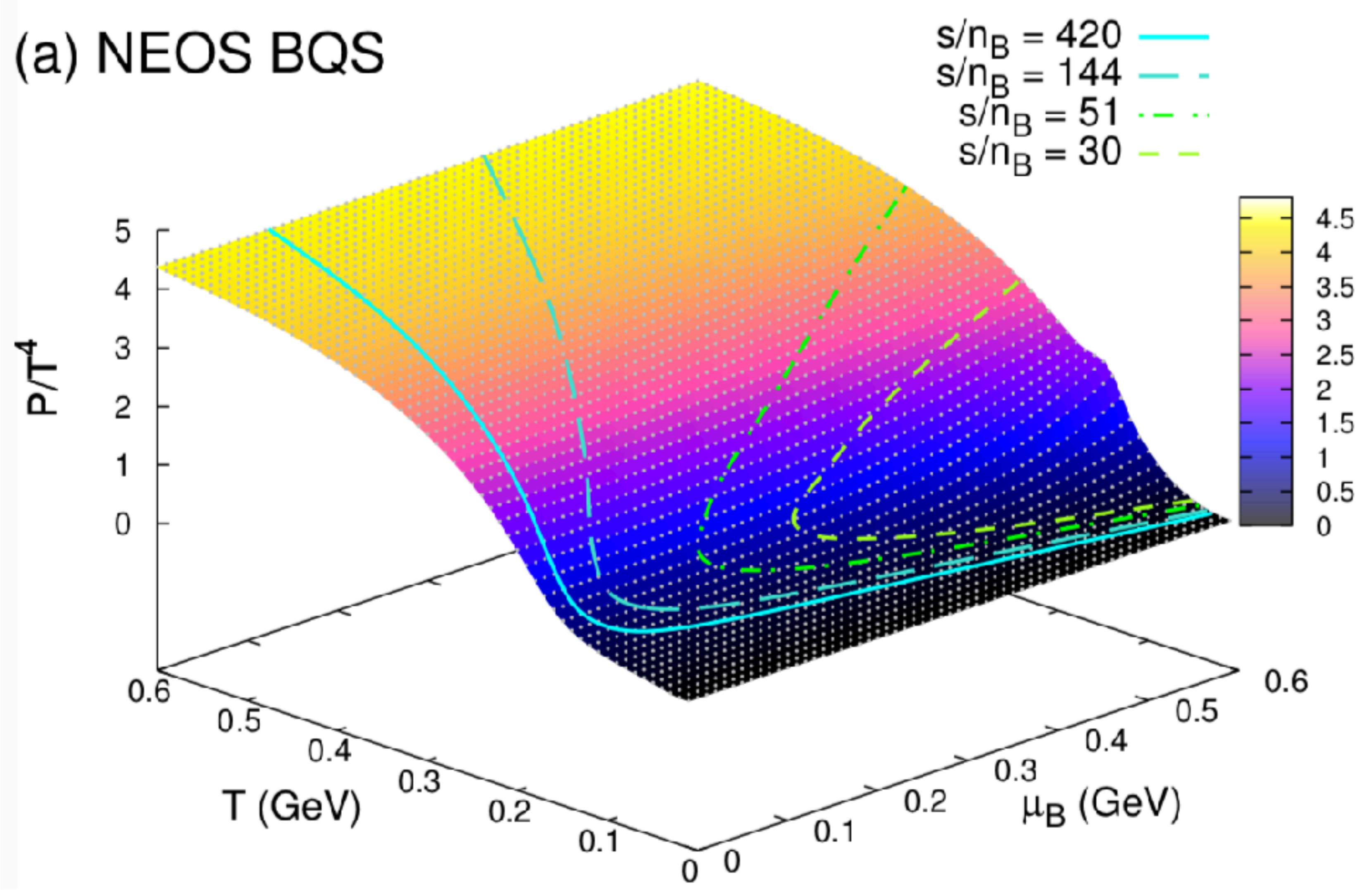
A. Monnai, B. Schenke, C. Shen, Phys. Rev. C 100, 024907 (2019)
A. Monnai, B. Schenke, C. Shen, Int.J.Mod.Phys.A 36 (2021) 07, 2130007



EQUATION OF STATE AT FINITE CONSERVED CHARGES

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. Karthein et. al, Eur. Phys. J. Plus 136 (2021) 6, 621

$n_s = 0 \quad n_Q = 0.4 n_B$



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

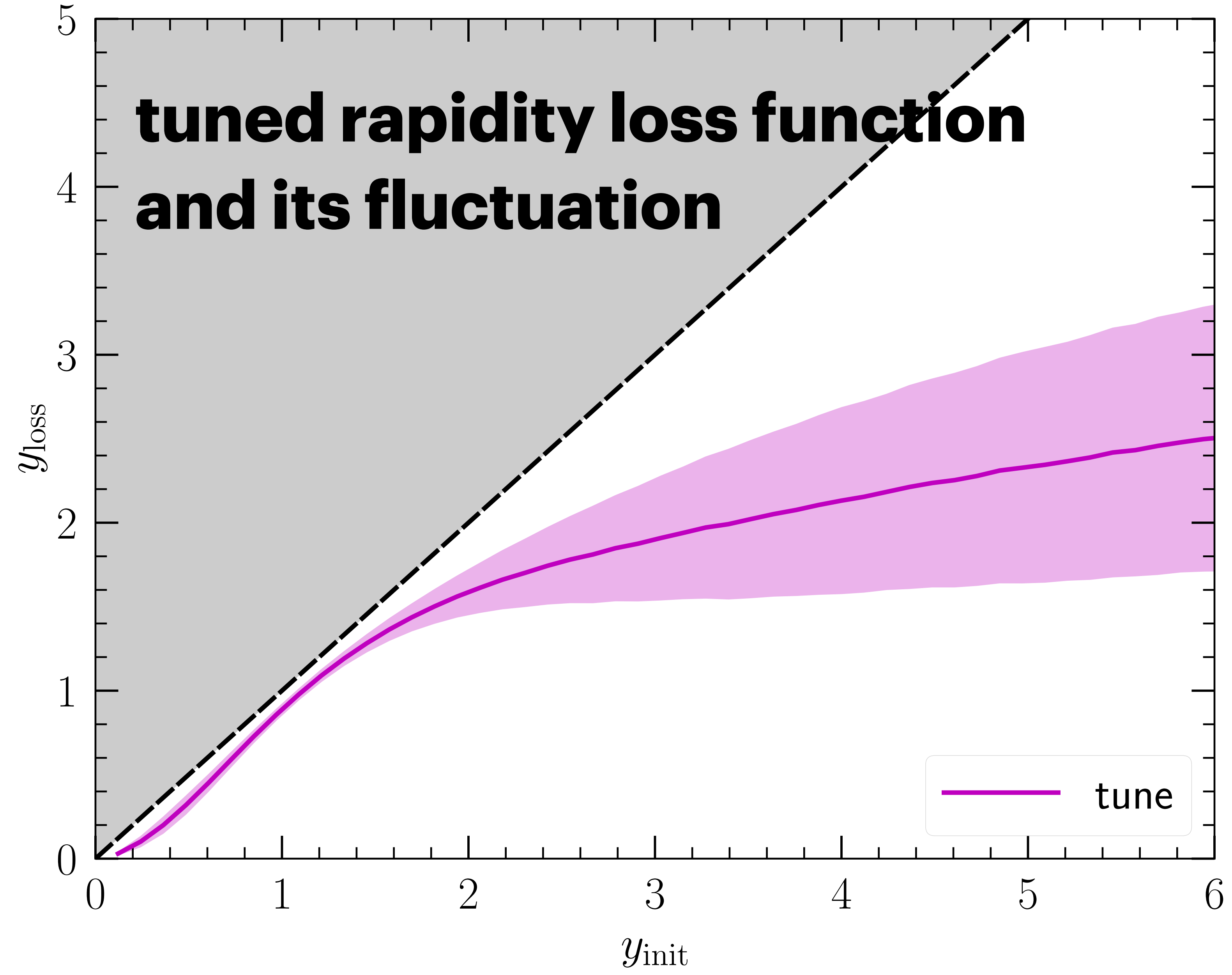
$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_J)]\frac{P_{\rm had}(T,\mu_J)}{T^4} + \frac{1}{2}[1 + f(T,\mu_J)]\frac{P_{\rm lat}(T,\mu_J)}{T^4}$$

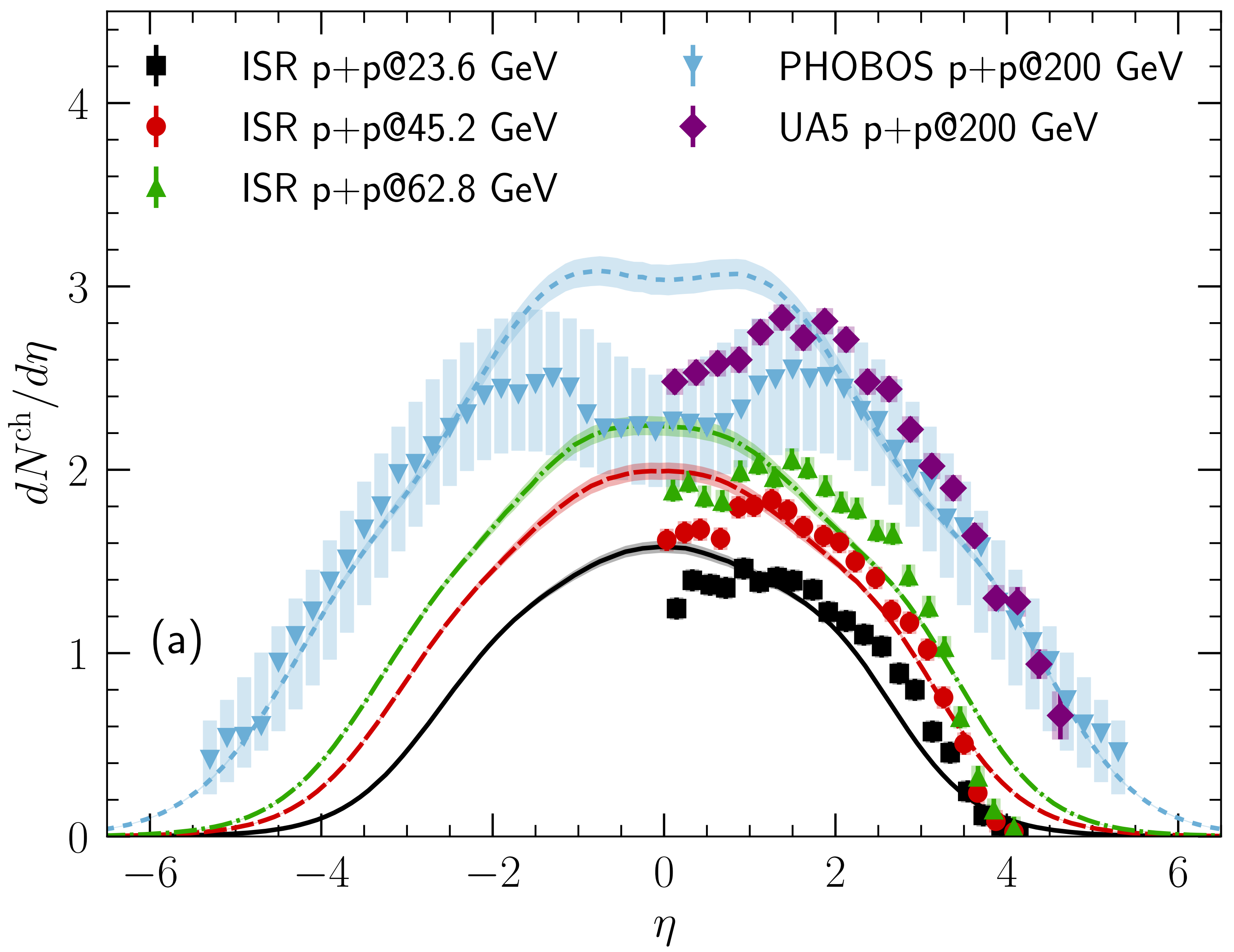
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

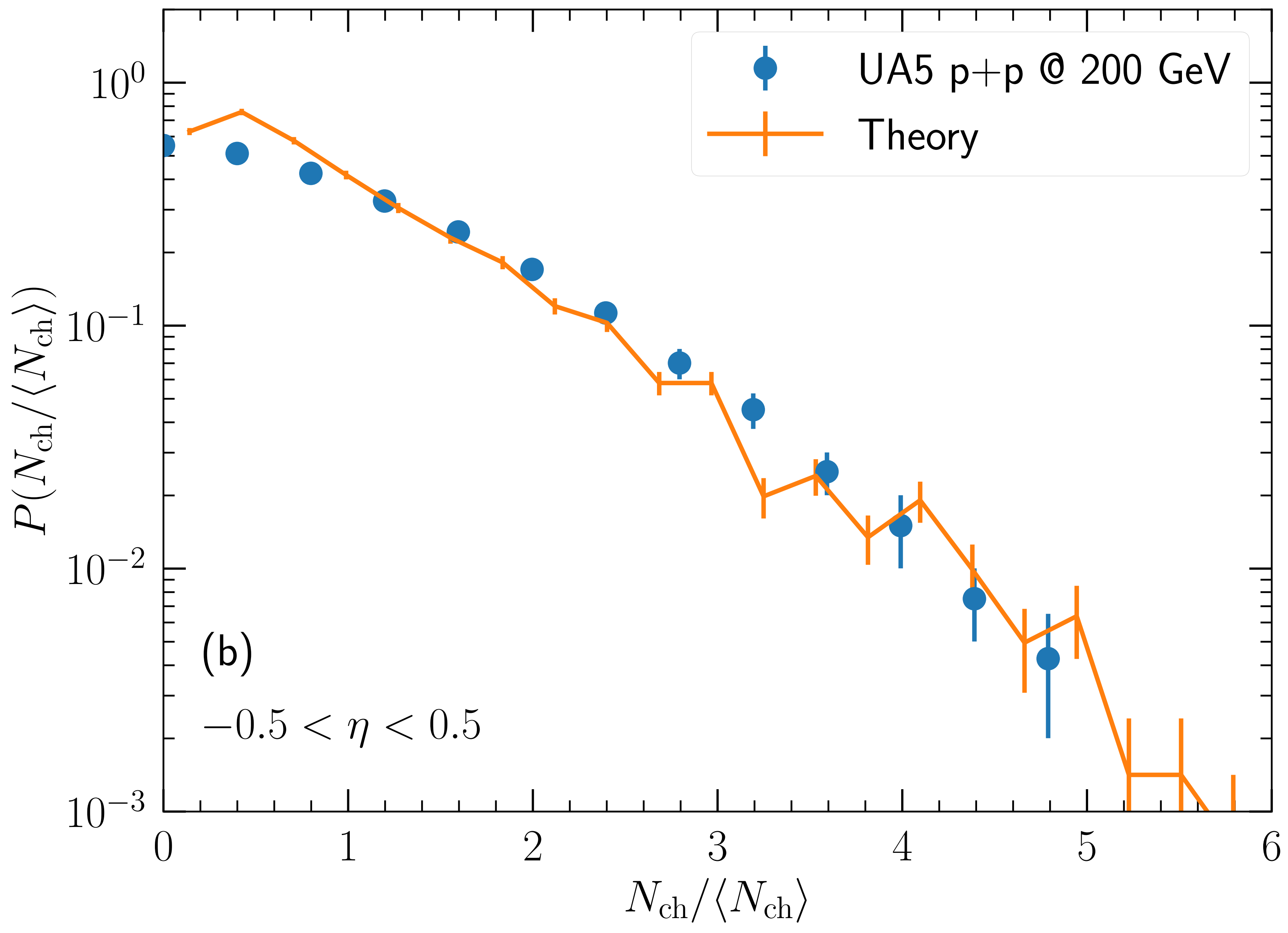
Being extended to fully 4D EOS $P(\varepsilon, n_B, n_Q, n_S)$ **see Gregoire Pihan's talk**

CALIBRATION IN p+p COLLISIONS

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



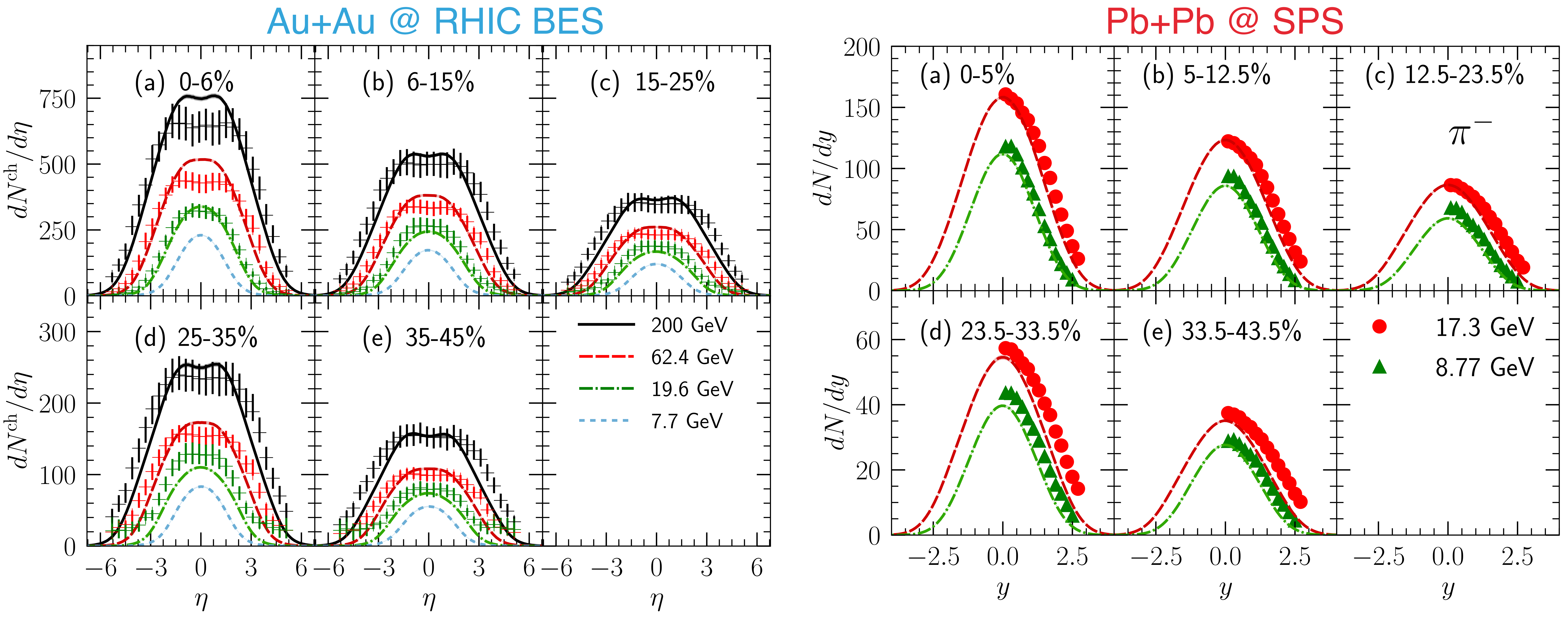




Calibrated with minimum bias p+p measurements at mid-rapidity and their multiplicity distributions

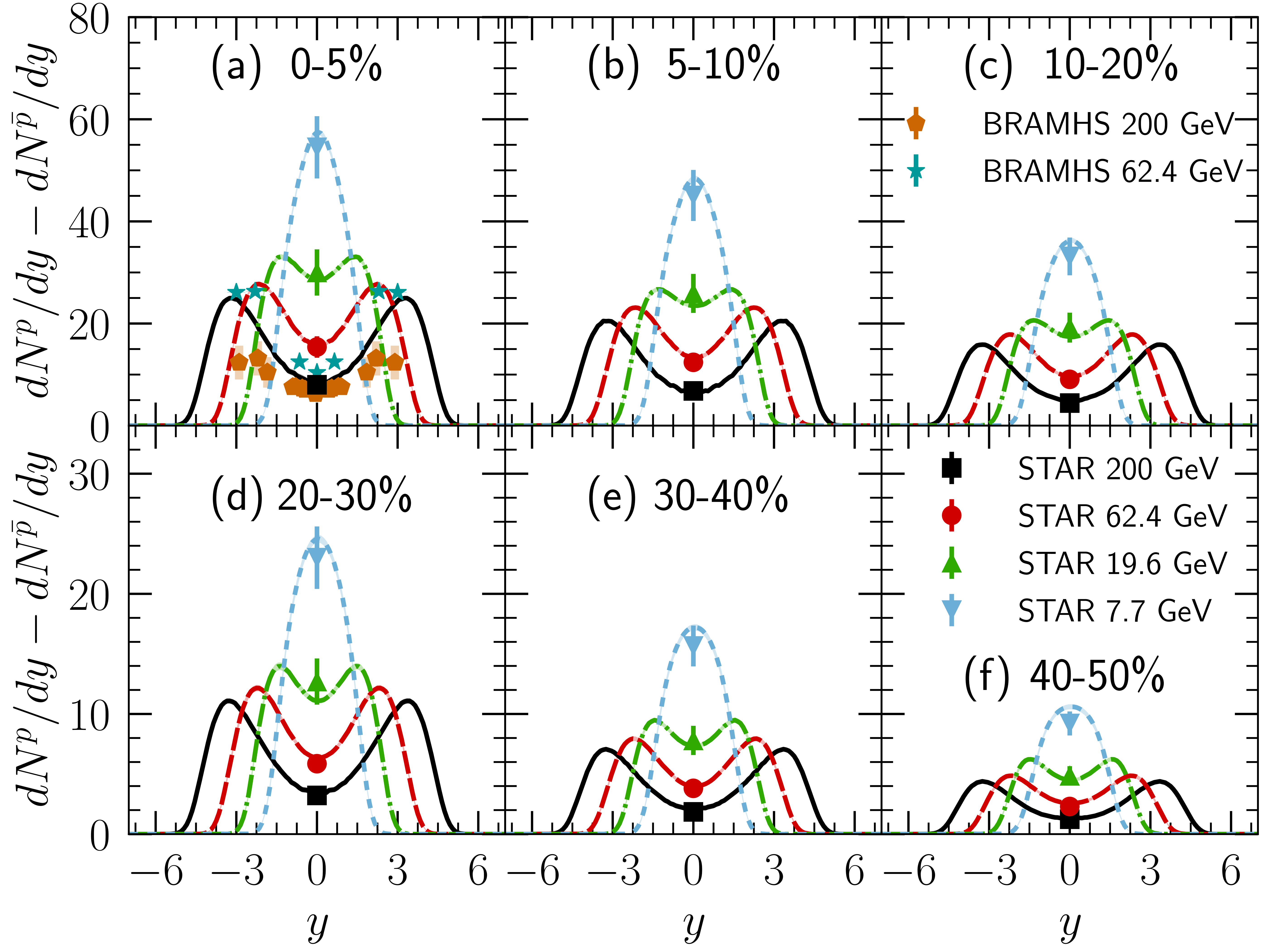
COMPARISON TO A+A DATA

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



NET-PROTON PRODUCTION

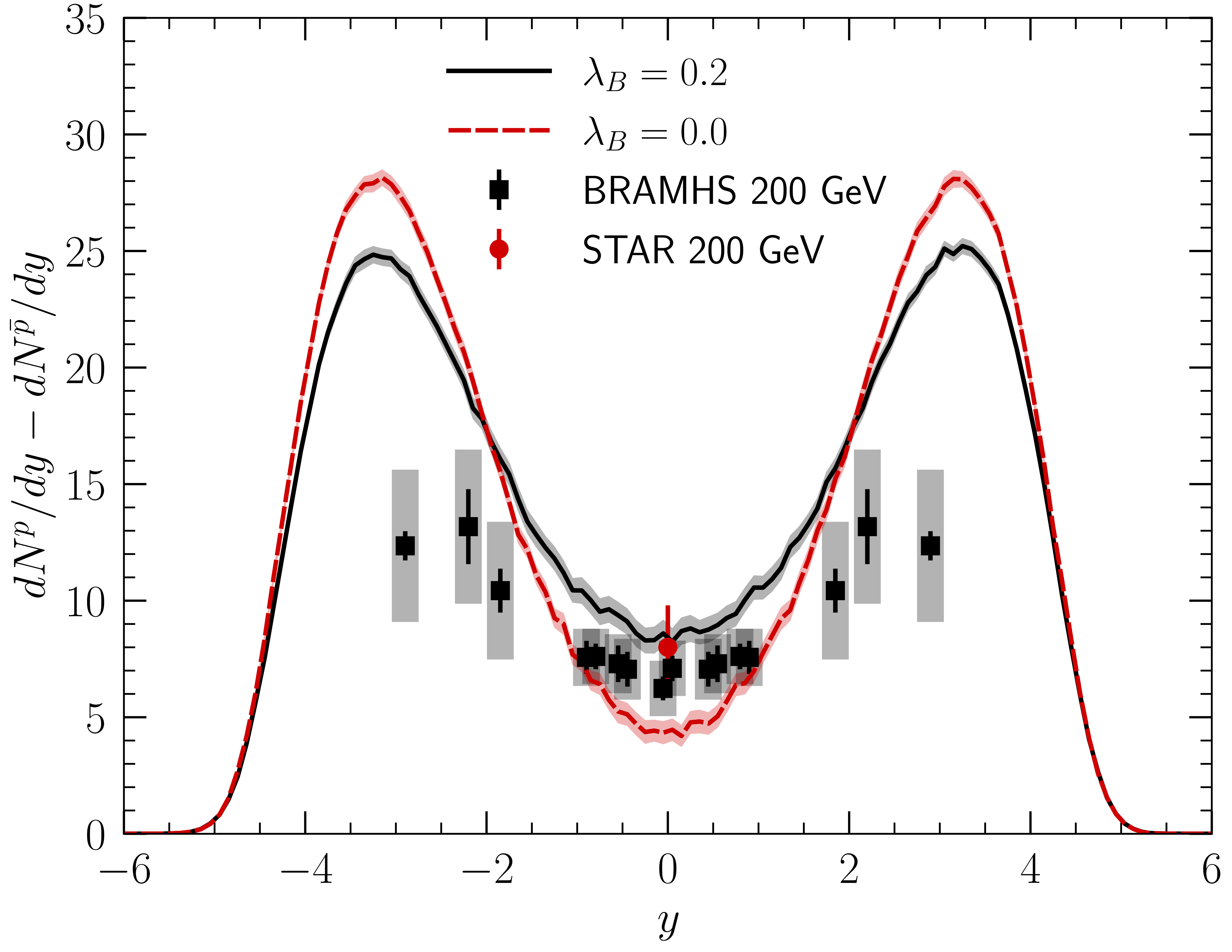
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

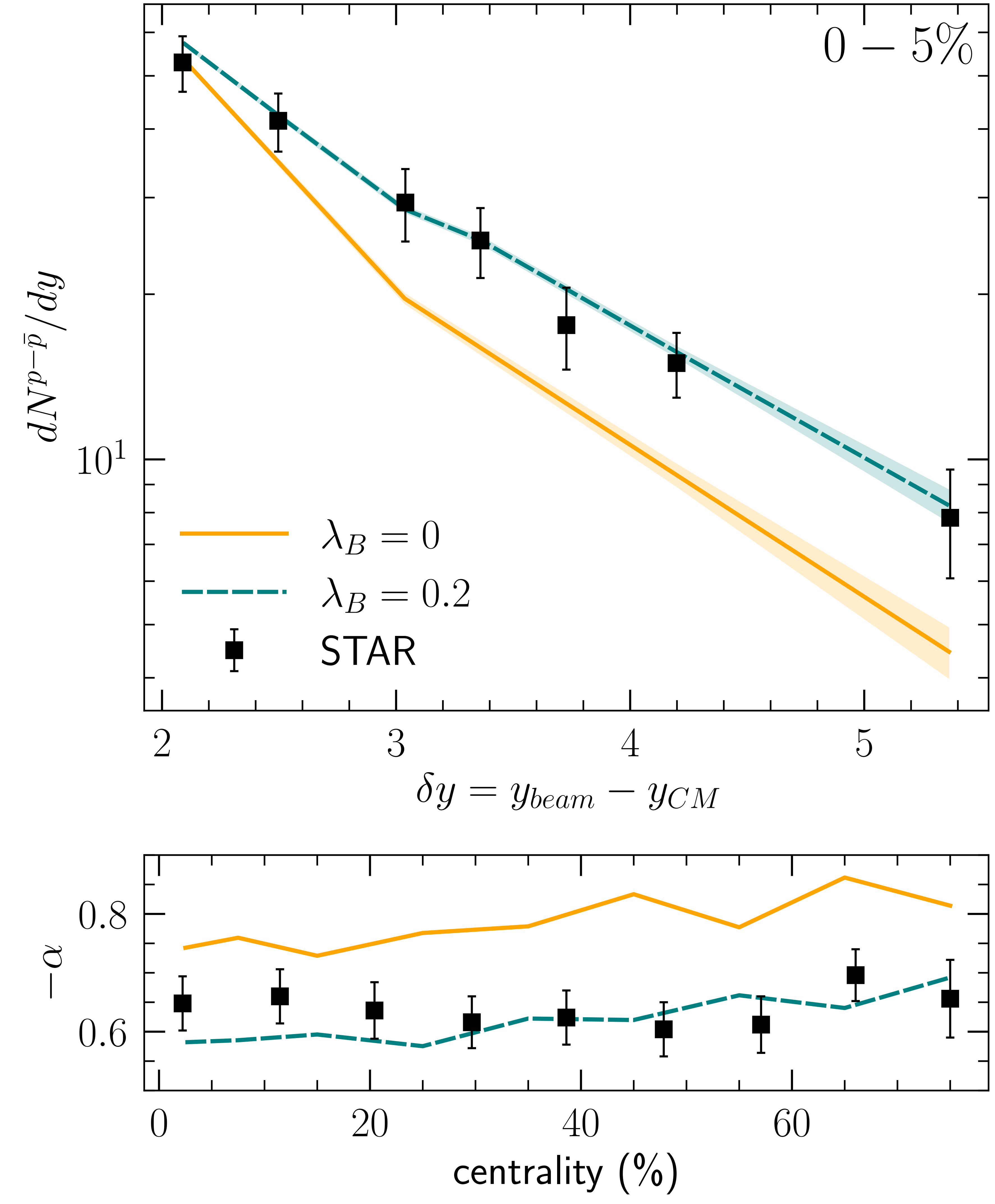


$\lambda_B = 0.2$

- Our results at mid-rapidity are consistent with the STAR measurements
- Measurements of the rapidity dependence can further constrain the distributions of initial baryon charges

EFFECT OF JUNCTIONS





C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

G. Pihan, A. Monnai, B. Schenke, C. Shen, in preparation

BARYON DIFFUSION

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C 98, 034916 (2018), arXiv:1804.10557

$$J_B^\mu = n_B u^\mu + q^\mu$$

Net-baryon diffusion current's evolution described by Israel-Stewart-like equation:

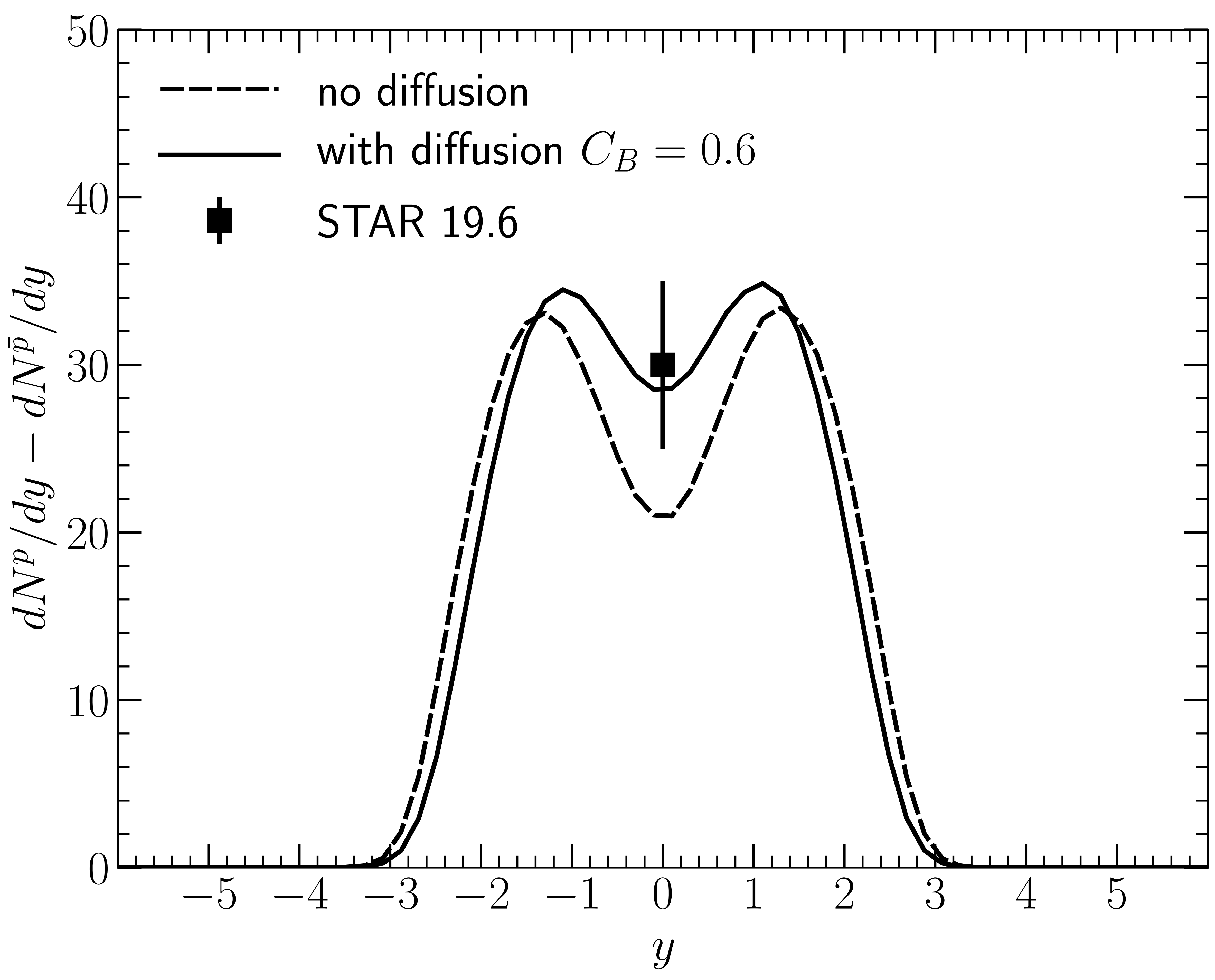
$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \boxed{\kappa_B \nabla^\mu \frac{\mu_B}{T}}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q} \Delta^{\mu\nu} \partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q} \pi^{\mu\nu} \nabla_\nu \frac{\mu_B}{T}$$

Transport coefficient from relaxation time approximation of the Boltzmann equation:

$$\kappa_B = \frac{C_B}{T} n_B \left(\frac{1}{3}\coth\left(\frac{\mu_B}{T}\right) - \frac{n_B T}{e + \mathcal{P}}\right)$$

C_B is a free parameter taken to be constant

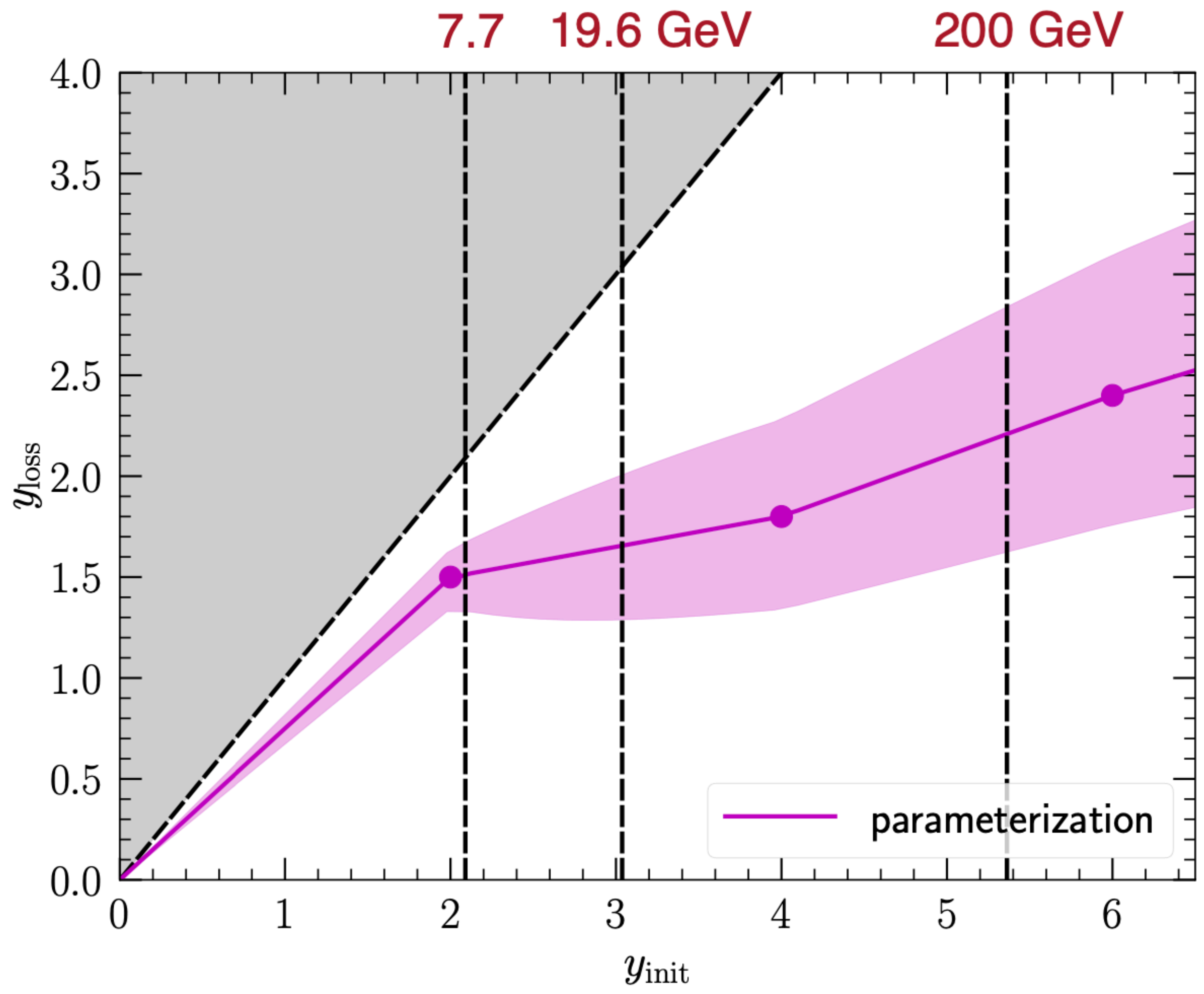
In the following slides we will **not** consider baryon diffusion



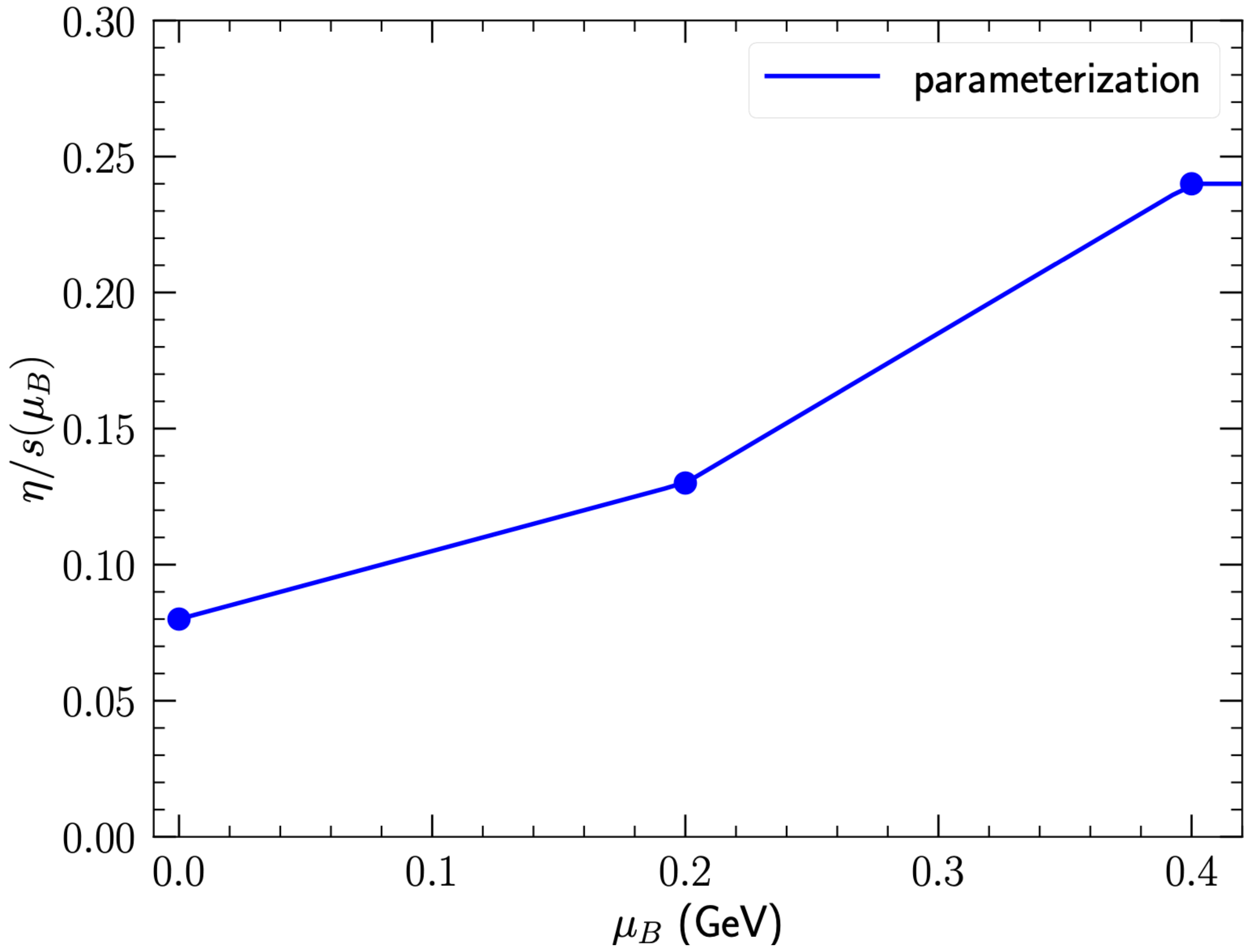
CONSTRAINING PARAMETERS

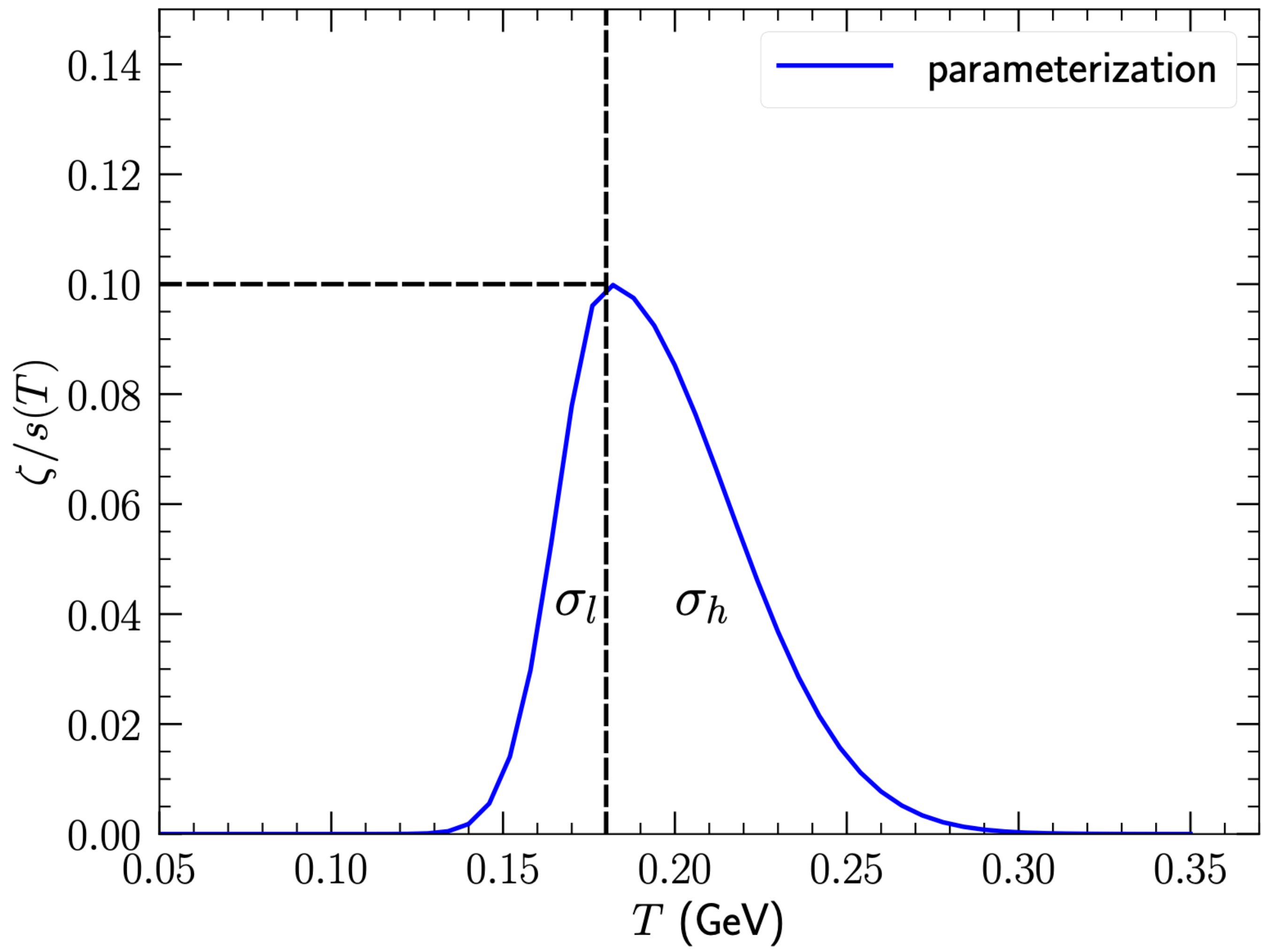
C. Shen, B. Schenke, W. Zhao, arXiv:2310.10787

Parameters for stopping and T and μ_B dependencies from Bayesian analysis



$y_{\rm loss}$: amount of rapidity that string end with initial $y_{\rm init}$ loses



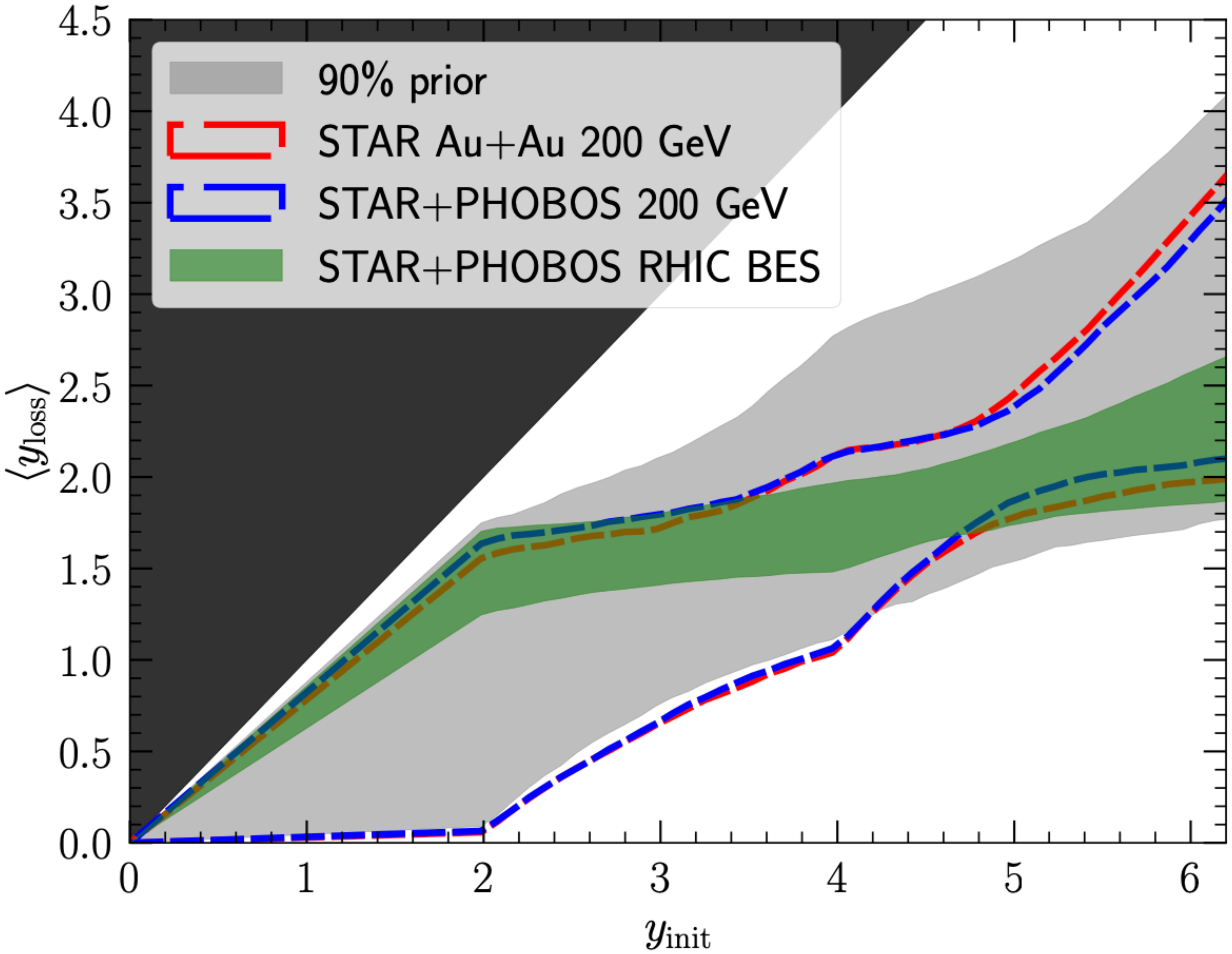


Assume η/s is constant in T, depends on μ_B

Construct ζ/s from 2 half-Gaussians

STOPPING PARAMETERS

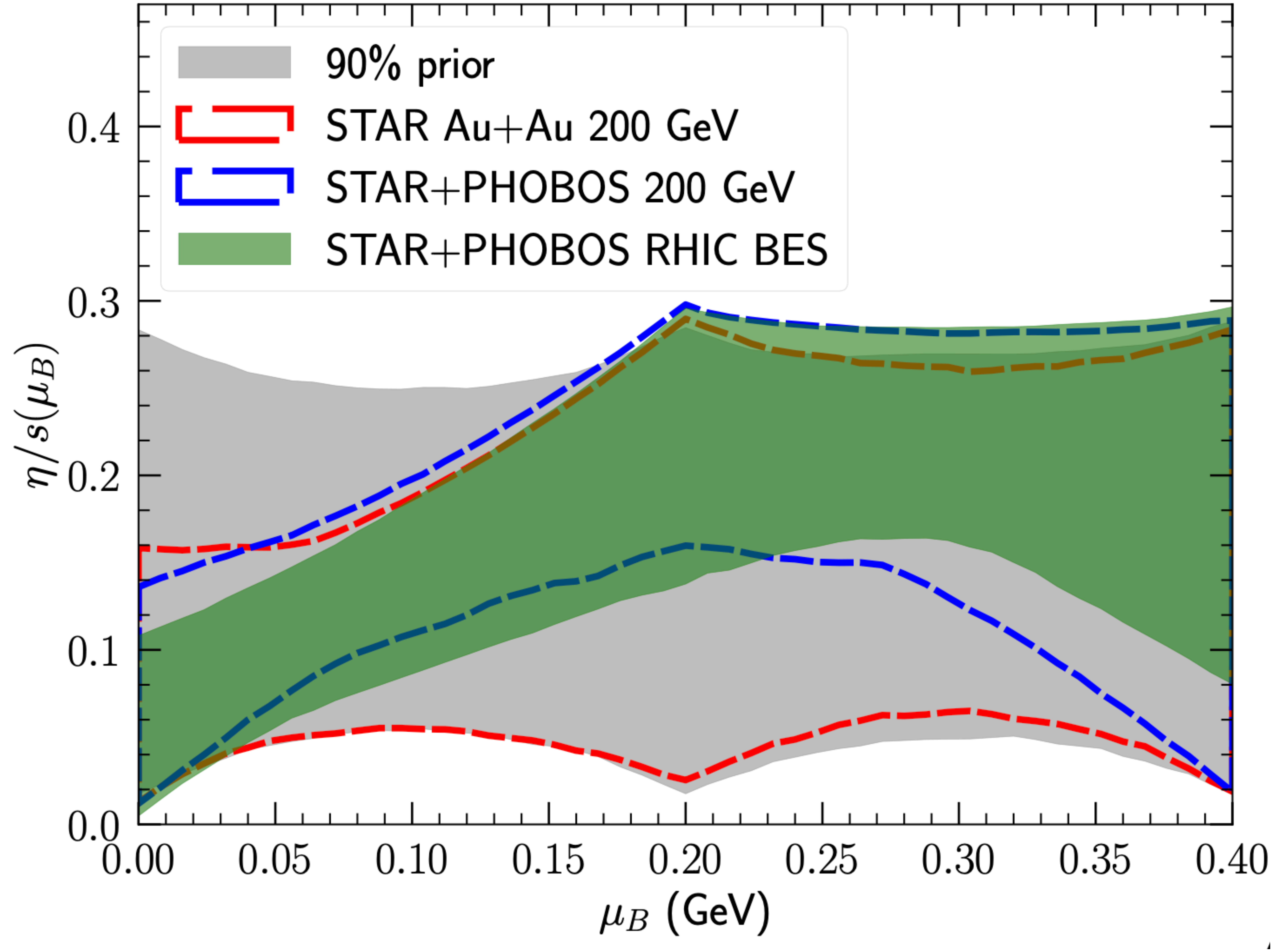
C. Shen, B. Schenke, W. Zhao, arXiv:2310.10787



- Mid-rapidity particle productions at 200 GeV yields $y_{\rm loss} \sim 2$ for $y_{\rm init} \sim 5$
- The rapidity distributions from PHOBOS yield only small improvements to the constraint
- Particle production from 7.7, 19.6, and 200 GeV set strong constraints on $y_{\rm loss}(y_{\rm init})$ for $y_{\rm init} \in [0,6]$

TRANSPORT COEFFICIENTS AT FINITE μ_B

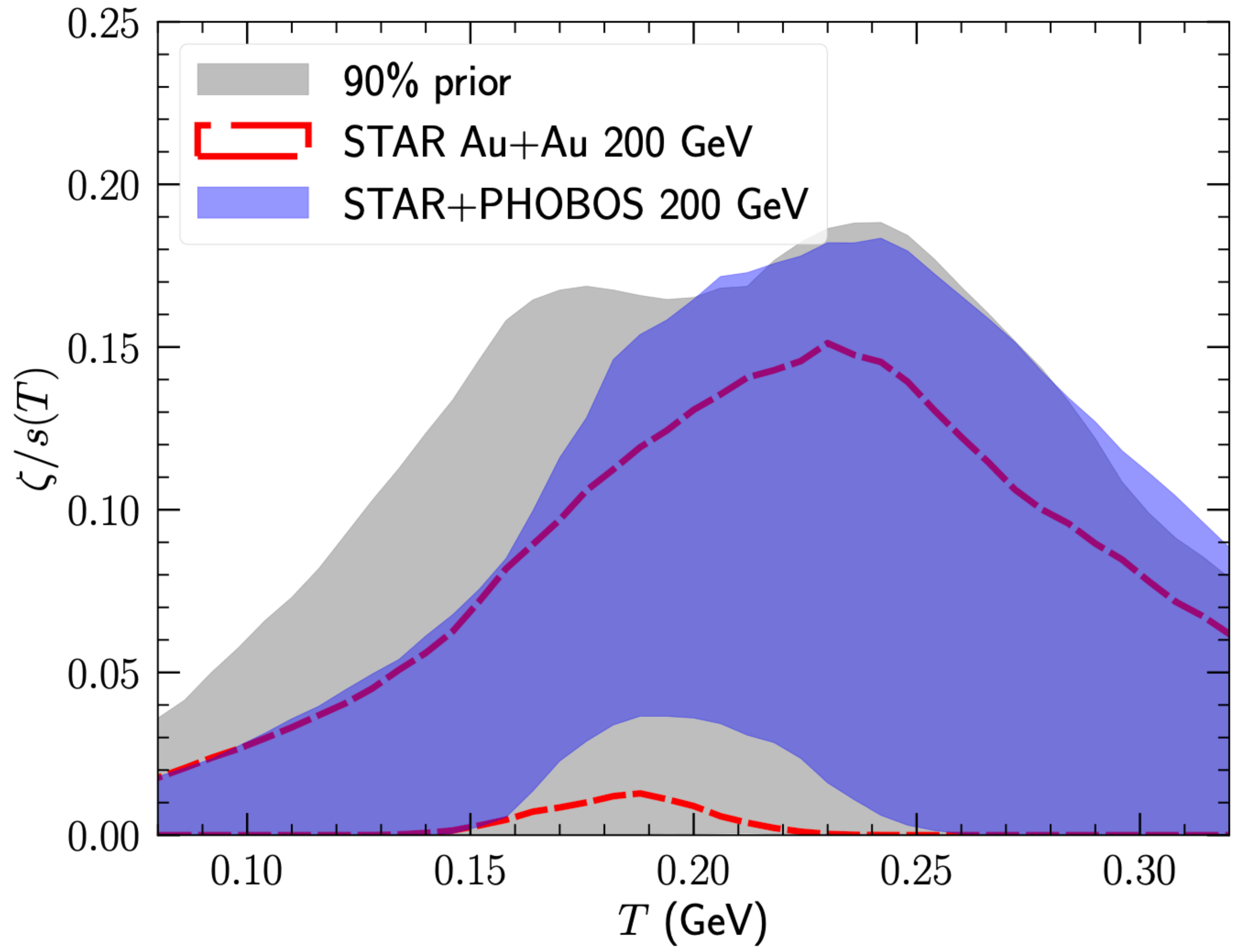
C. Shen, B. Schenke, W. Zhao, arXiv:2310.10787



- 200 GeV Midrapidity data constrains η/s around $\mu_B \approx 0$
- Rapidity dependent spectra and $v_2(\eta)$ improve constraint on η/s around $\mu_B \approx 0.2\,\mathrm{GeV}$
- BES data prefers η/s to be larger at finite μ_B compared to $\mu_B \approx 0$

BULK VISCOSITY

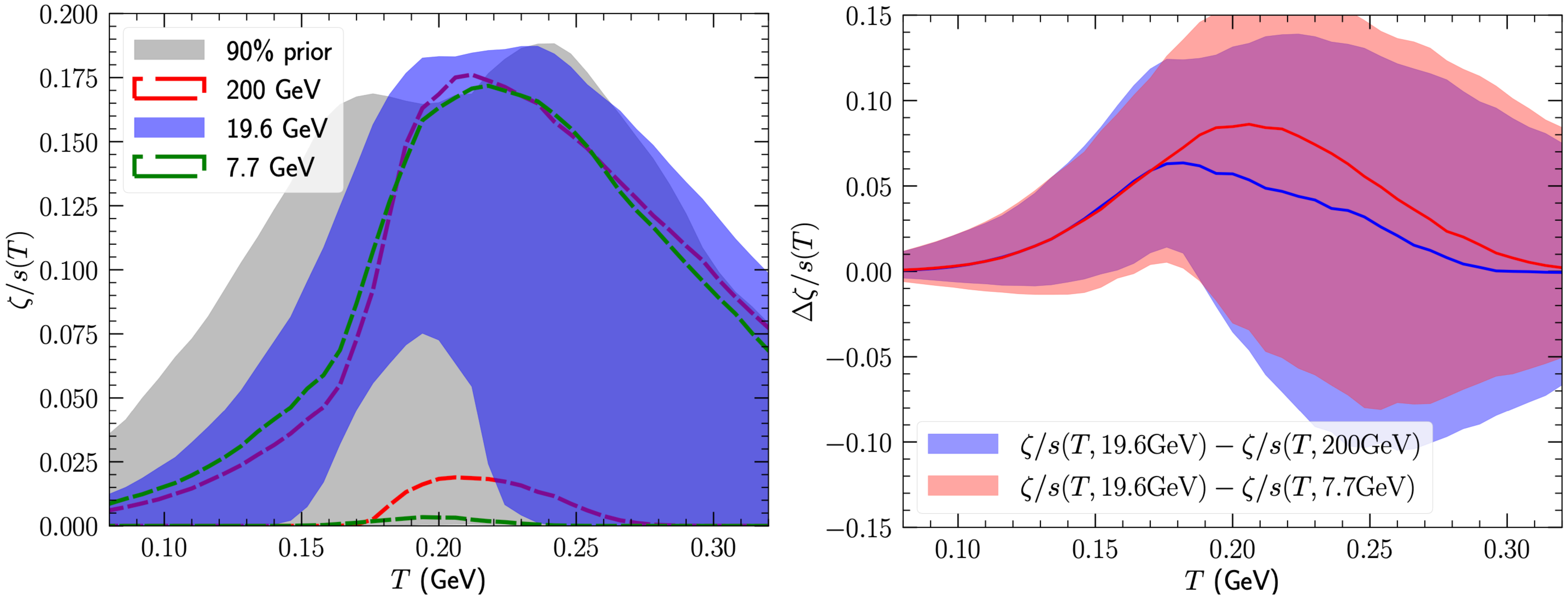
C. Shen, B. Schenke, W. Zhao, arXiv:2310.10787



- 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 slightly shifts the posterior $\zeta/s(T)$ to larger values

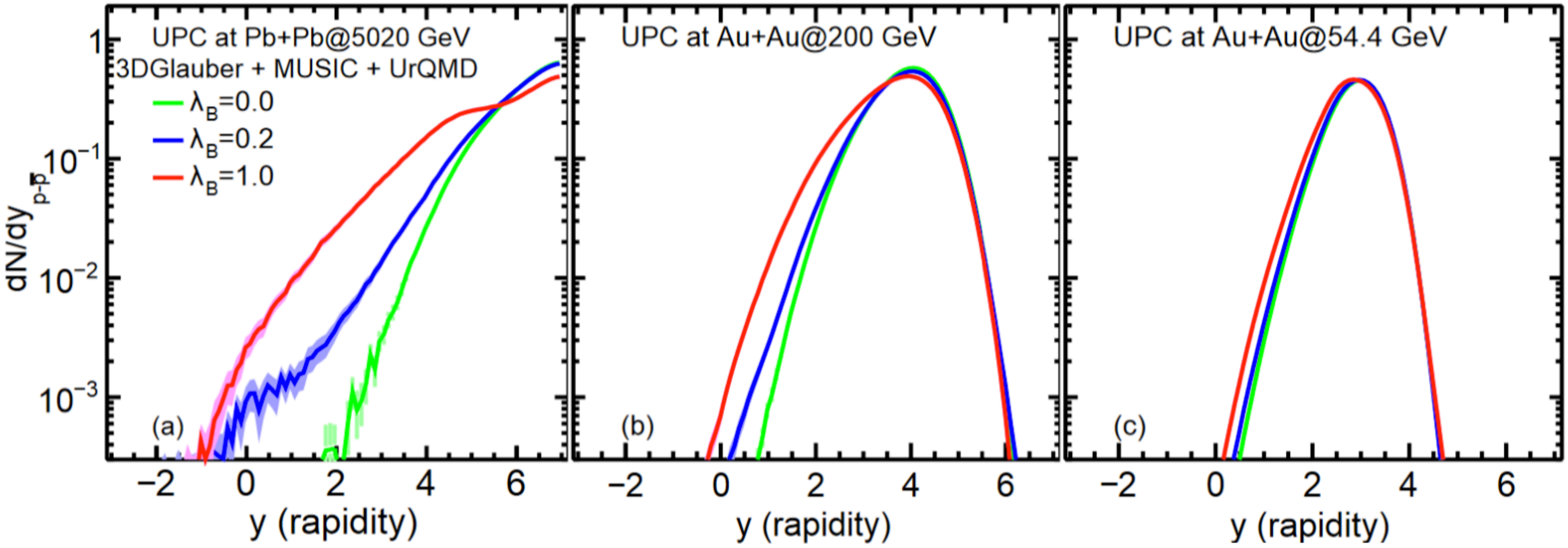
BULK VISCOSITY'S ENERGY DEPENDENCE

C. Shen, B. Schenke, W. Zhao, arXiv:2310.10787



Allowing $\zeta/s(T)$ to be an independent function for the three collision energies, our analysis suggests a larger $\zeta/s(T)$ at 19.6 GeV than at 200 and 7.7 GeV for $T \in [0.16, 0.2]\,\mathrm{GeV}$ - could also be a hint of softening EOS…

NET-PROTON dN/dy IN ULTRA PERIPHERAL COLLISIONS



- No net protons from the vector meson's fragmentation region
- The baryons at the string junctions lead to a flatter slope of net proton dN/dy near the mid-rapidity in UPC events at LHC and the top RHIC energies
- The shape of net proton dN/dy at 54.4 GeV is dominated by fragmentation

SUMMARY

- Baryon stopping and transport are of fundamental importance for understanding physics of heavy ion collisions
- Fundamental question in itself: What carries baryon number in a nucleon?
- HICs at varying energy require description of initial state, equation of state, and transport coefficients at finite baryon density (and other conserved charges)
- Net-proton rapidity distributions provide hints at what carries baryon number
  $\rightarrow$ *much more in Gregoire Pihan's talk on baryon vs. electric charge stopping*
- BES and rapidity dependent data can constrain charge stopping and transport coefficients at finite baryon chemical potential
- UPCs could provide additional constraints on baryon stopping

BACKUP

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

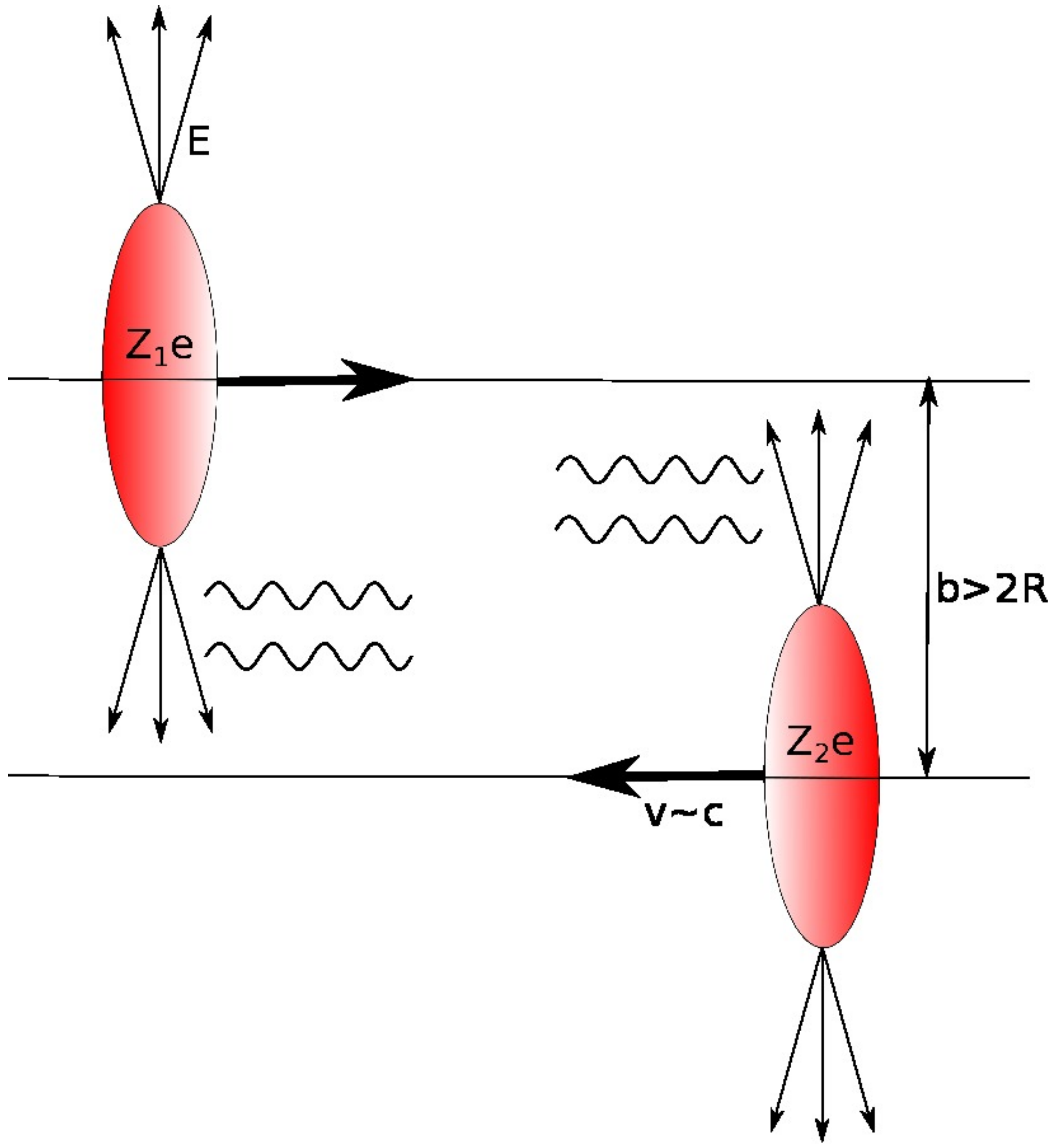
604 experimental data points

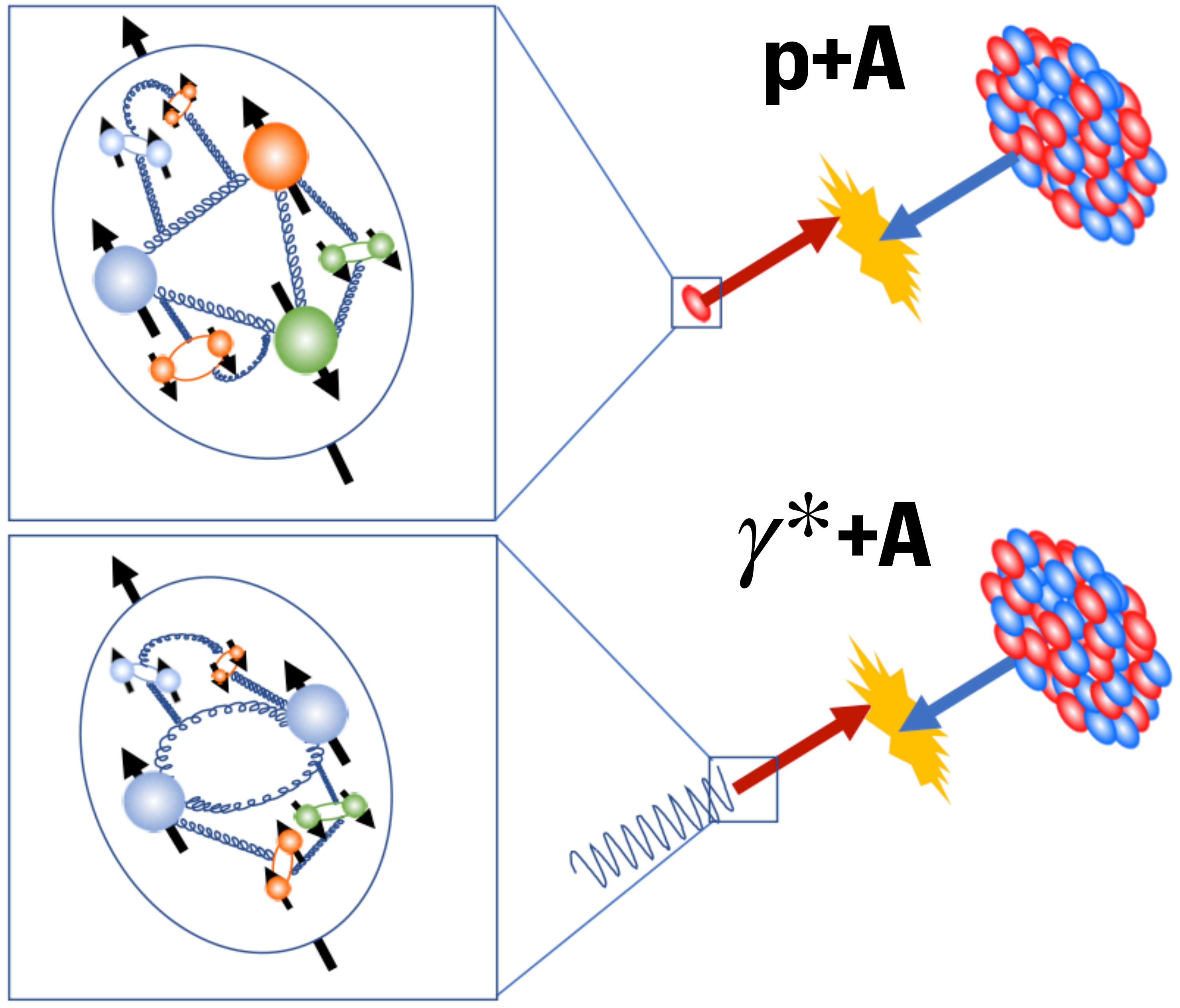
Au+Au	STAR midrapdity data vs. centrality	PHOBOS rapidity distribtion
200 GeV	$dN/dy(\pi^+, K^+, p, \bar{p})$ $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ $v_2^{\rm ch}\{2\}, v_3^{\rm ch}\{2\}$	$dN^{\rm ch}/d\eta$ $v_2(\eta)$
19.6 GeV	$dN/dy(\pi^+, K^+, p)$ $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$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

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

ULTRAPERIPHERAL COLLISIONS

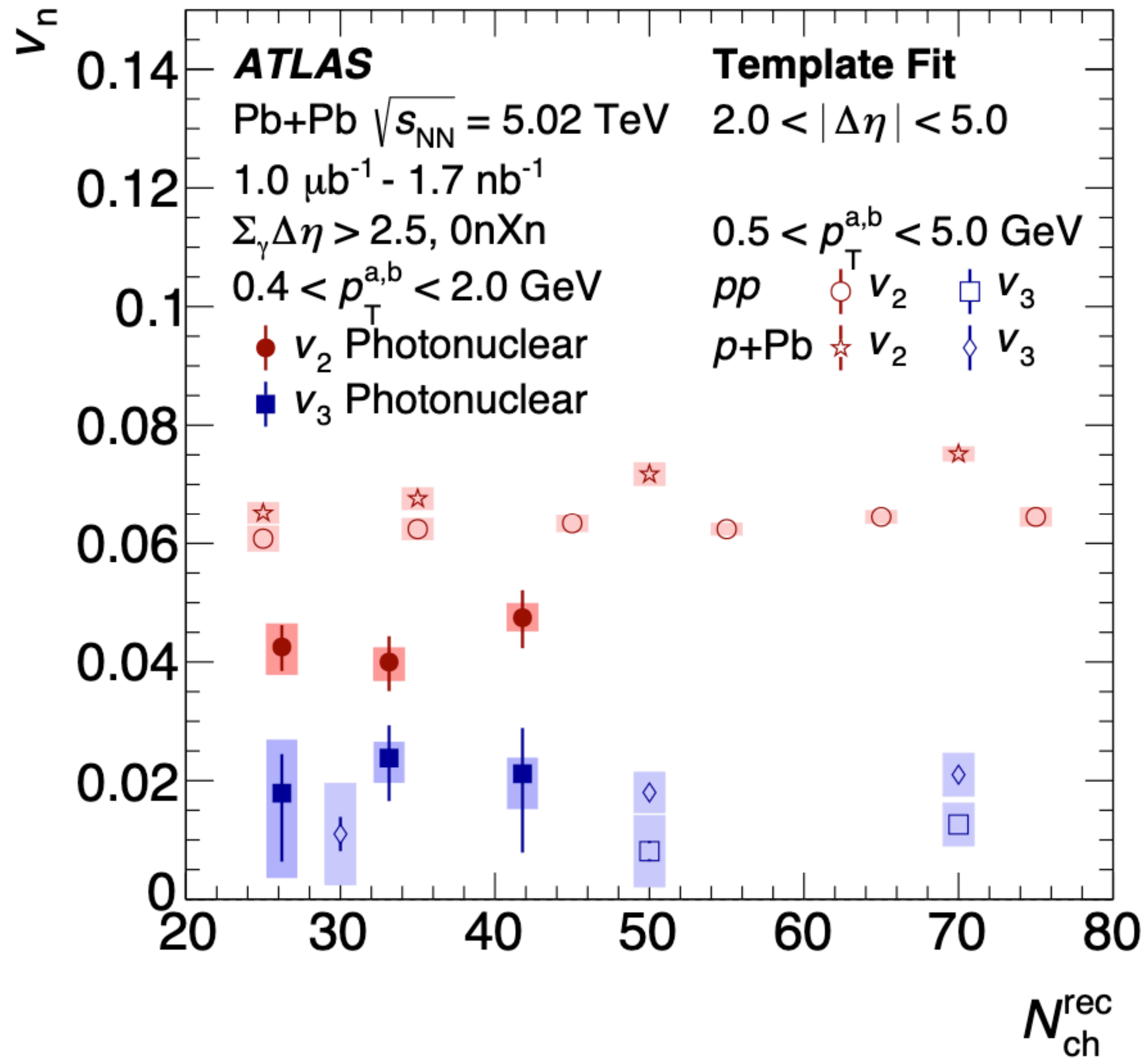
W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302





Phys. Rev. D 103, 054017 (2021)

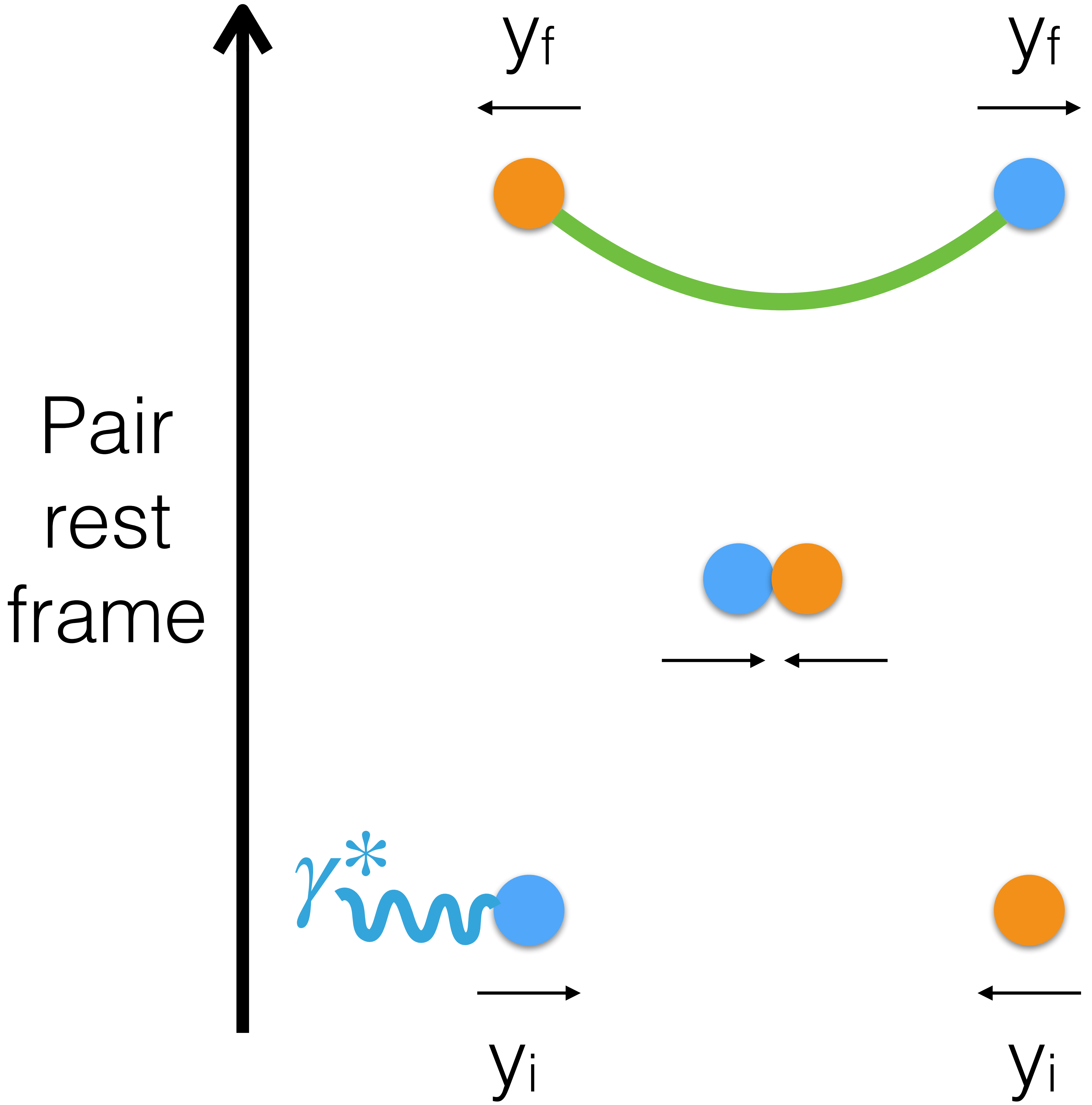
ATLAS Phys. Rev. C 104, 014903 (2021)



- Long range two-particle correlations were observed in photo-nuclear processes in ultra-peripheral Pb+Pb collisions (UPC) at the LHC
- The magnitudes of v_n in UPCs are comparable with those in p+Pb collisions

INITIAL STATE FOR $\gamma^* + \mathrm{Pb}$

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302



- Same model as used in collision systems discussed so far
- Virtual photon described as a vector meson: two quarks plus soft cloud