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Brookhaven National Laboratory

NEUTRON SKIN MEASUREMENTS USING CONSERVED CHARGES AT COLLIDER EXPERIMENTS

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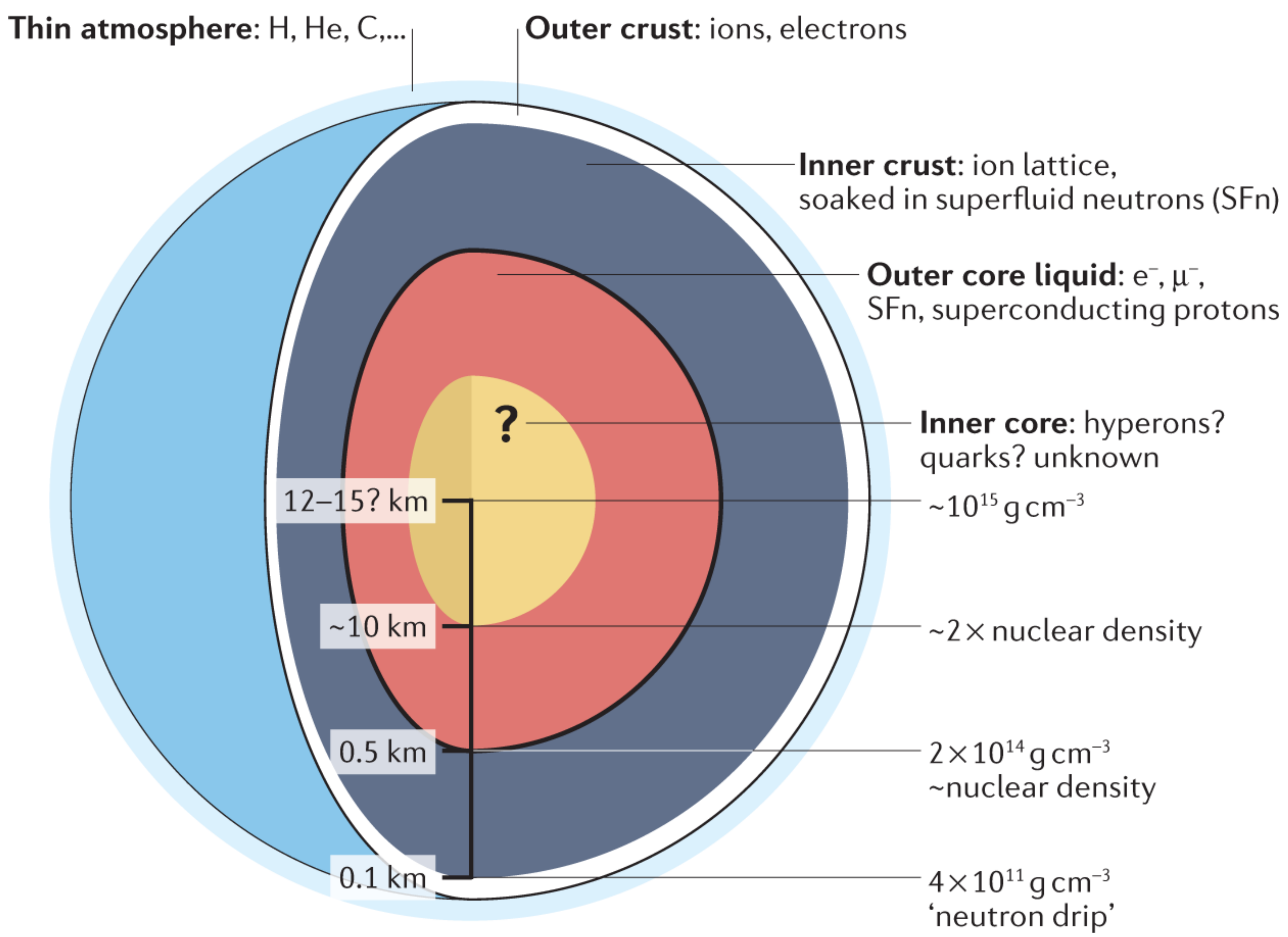
INTERSECTIONS OF NUCLEAR STRUCTURE AND HIGH-ENERGY NUCLEAR COLLISIONS 2026
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS, KYOTO UNIVERSITY

NEUTRON SKIN OF HEAVY NUCLEI

Measuring neutron skin constrains symmetry energy:

stiffer symmetry energy
→ larger cost for asymmetry in dense regions
→ excess neutrons prefer lower-density surface
→ neutron density profile extends farther out than proton profile
→ thicker neutron skin

also see Xavier Roca-Maza's talk, Monday



Precise measurements of the EOS at saturation density can also constrain properties of neutron stars, like mass radius relationship and the cooling mechanism, as well as core-crust transition density and pressure

N. Yunes, M. C. Miller, K. Yagi, Nature Reviews Physics 4, 237-246 (2022)

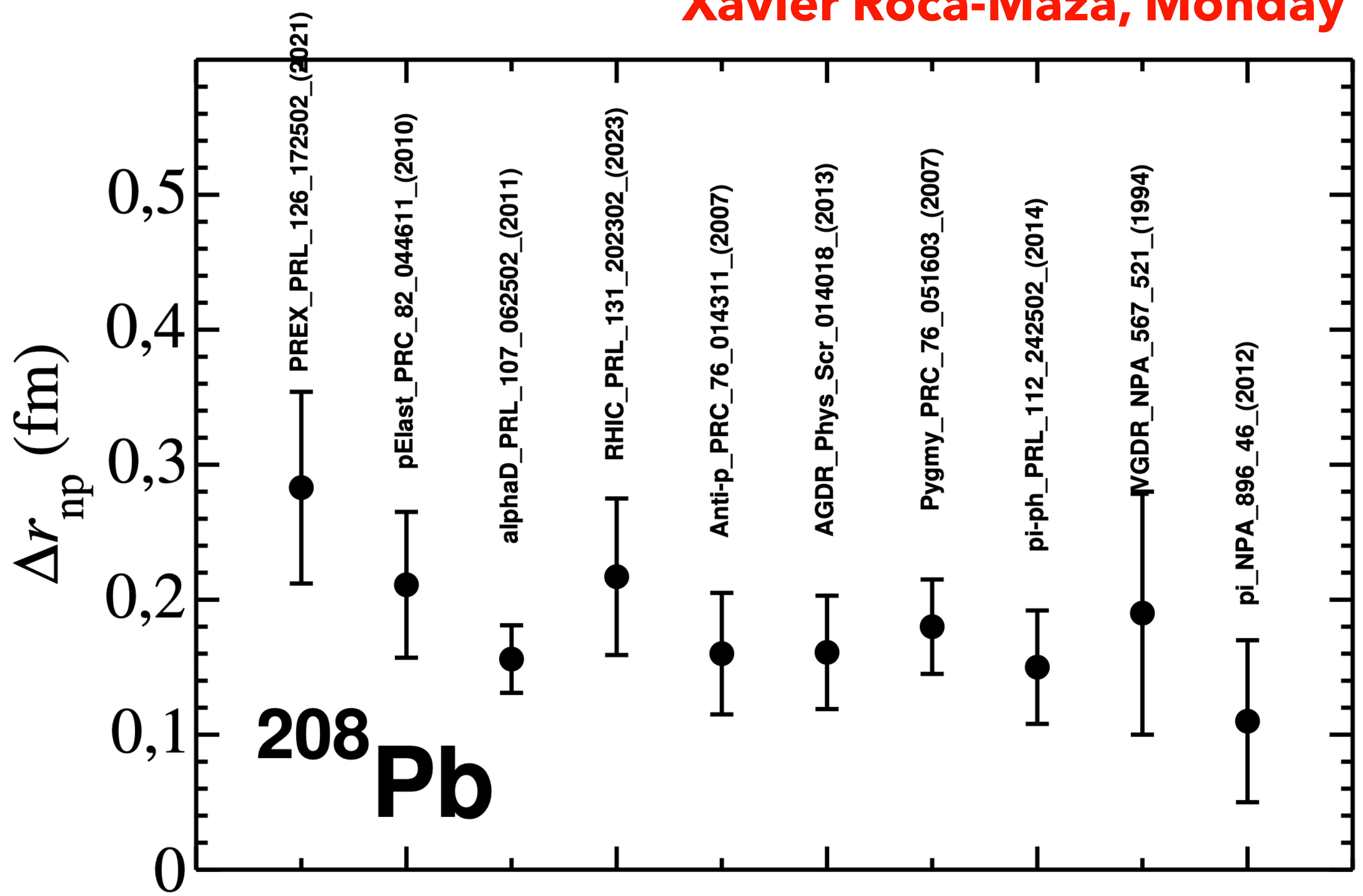
MEASUREMENTS

The neutron skin of Pb has been measured with many different methods.

Even heavy-ion experiments have been used to constrain the neutron skin of Pb using flow measurements and a Bayesian analysis

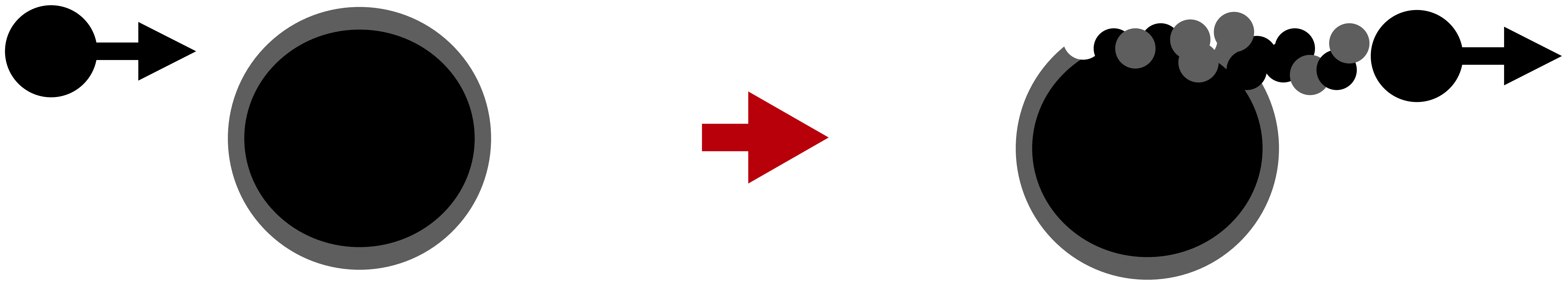
G. Giacalone, G. Nijs, W. van der Schee, Phys. Rev. Lett. 131, 202302

Xavier Roca-Maza, Monday

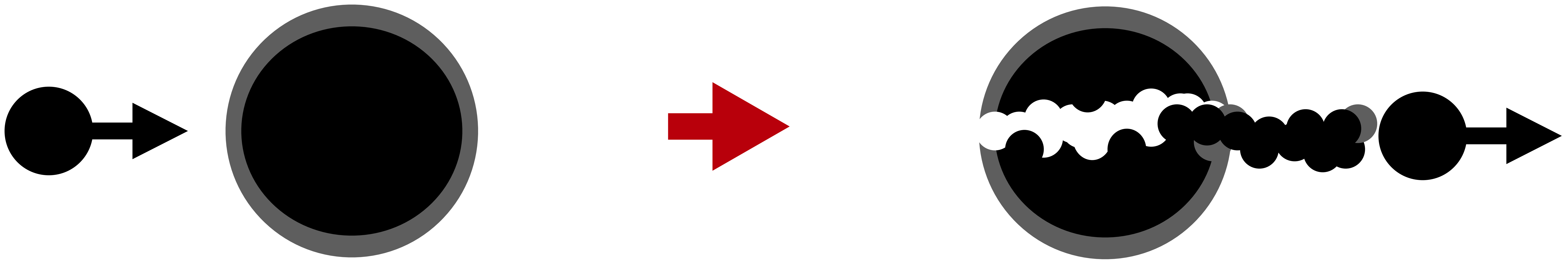


PROPOSAL: MOST SIMPLE MINDED MEASUREMENT

Hit the neutron skin and see how much charge is dragged out

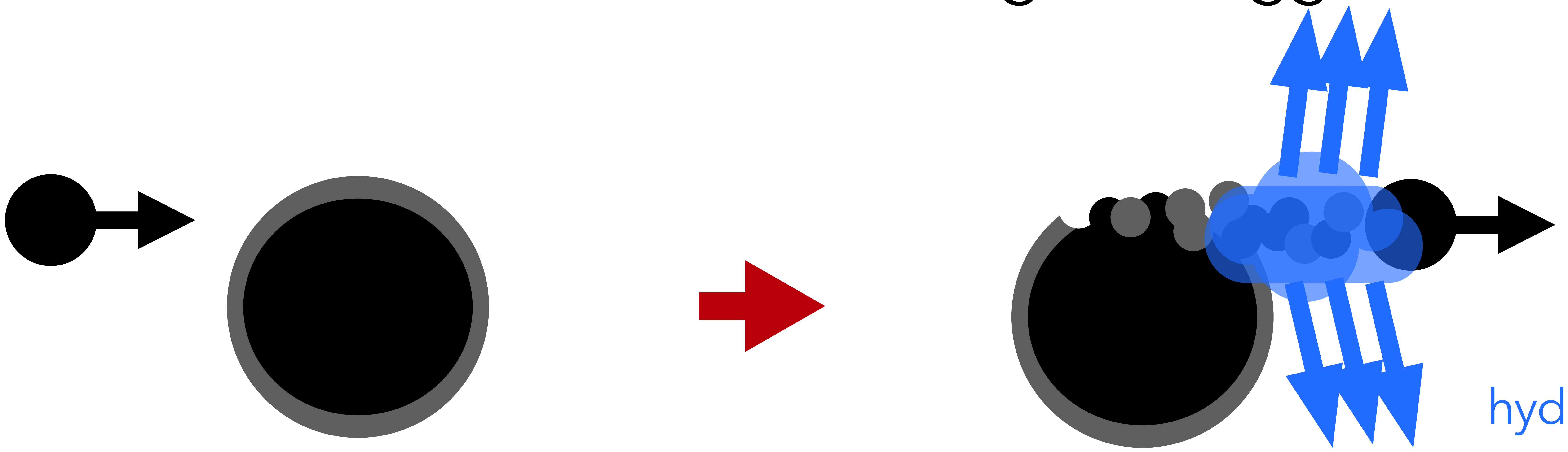


Compare to hitting the center

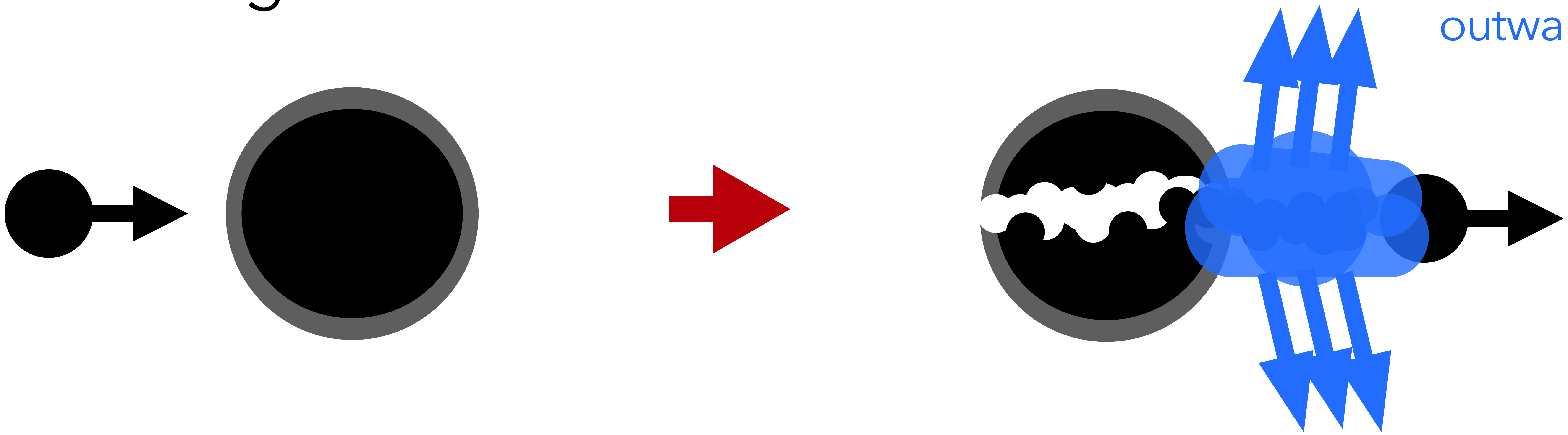


WE ARE ABLE TO DETECT THESE CHARGES

Hit the neutron skin and see how much charge is dragged out

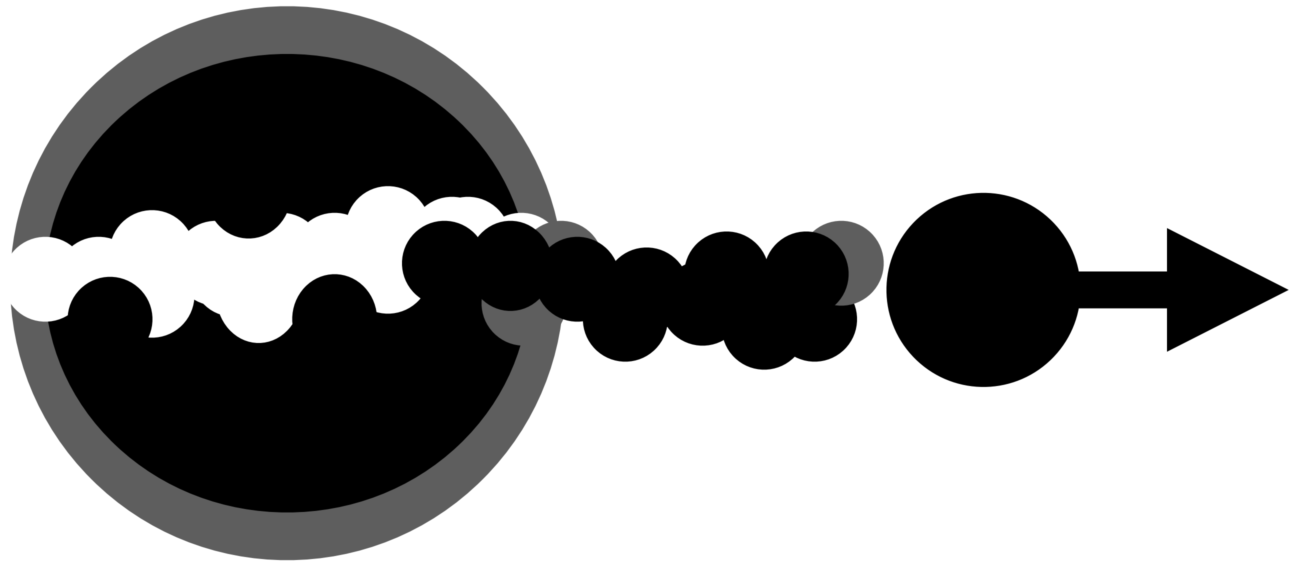


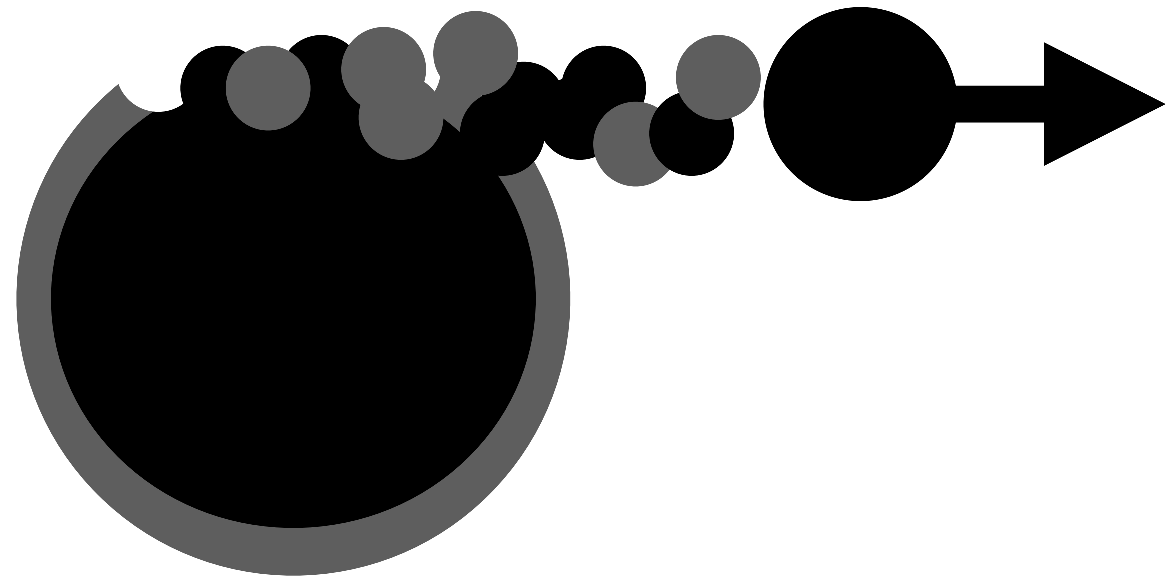
Compare to hitting the center



MEASURE TRANSPORTED CHARGES

Measure the ratio of net electric charge Q and net baryon number B across two geometries in p+Pb collisions to reveal the neutron skin of Pb





Central collisions: 0-20%

Baseline: High event activity correlates with small impact parameter. Proton interacts with a balanced mix of protons and neutrons.

Peripheral collisions: 80-100%

Grazing the halo: Low event activity correlates with large impact parameters. Proton strikes the neutron rich edge, altering ratio of proton to neutron participants and transported charges

OBSERVABLE G. Pihan, A. Monnai, B. Schenke, C. Shen, e-Print: 2509.21644 [nucl-th]

Measure charges transported to forward rapidity (Pb-going direction)

$$R = \frac{(Q/B)_{\text{peripheral}}}{(Q/B)_{\text{central}}}$$

Peripheral: 80-100% central, where neutron skin depletes net electric charge

Central: 0-20% central, skin insensitive baseline geometry

OBSERVABLE G. Pihan, A. Monnai, B. Schenke, C. Shen, e-Print: 2509.21644 [nucl-th]

⚠ Neutron yields are challenging to measure. So change to:

$$R = \frac{(Q/p)_{\text{peripheral}}}{(Q/p)_{\text{central}}}$$

with p the net proton number, which is much more accessible.

We will show that p is a very good proxy for B for the observable R.

MODEL OVERVIEW

3D-Glauber Model

Dynamic 3D initial state. Applies isospin-dependent Woods-Saxon distributions. Initializes electric and baryon charges and $T^{\mu\nu}$

(3+1)D iEBE-MUSIC + neos-4D EOS

Solves DNMR viscous hydro equations ($\tau_{\text{hydro}} = 0.5\text{fm}/c$) Tracks conserved charge currents.

Cornelius Algorithm

Identifies the constant energy density hyper surface ($e_{\text{sw}} = 0.2\,\text{GeV}/\text{fm}^3$)

Cooper-Frye Prescription

Converts the fluid to particles assuming thermal blackbody radiation + boost and viscous corrections for every freeze-out cell

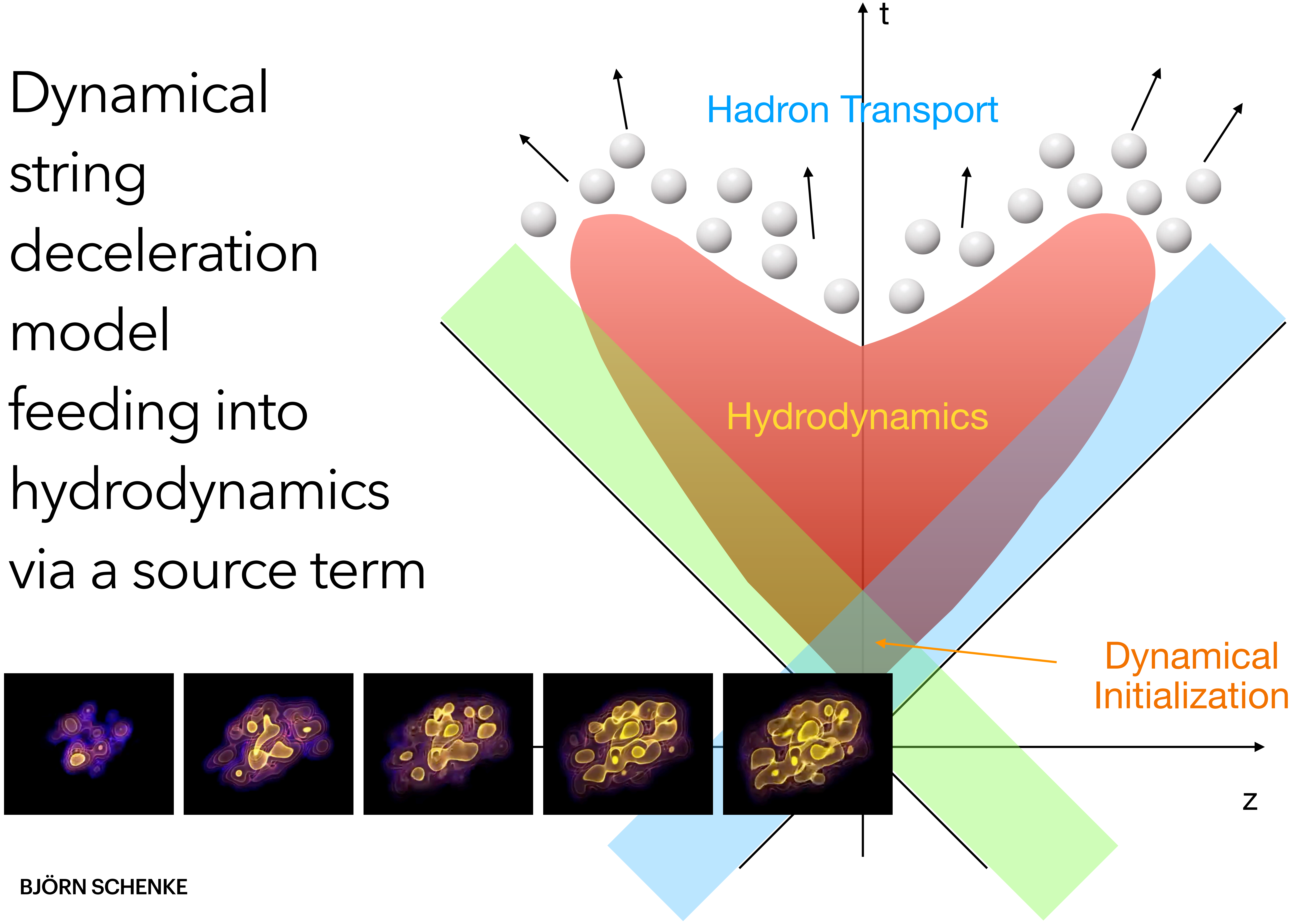
UrQMD

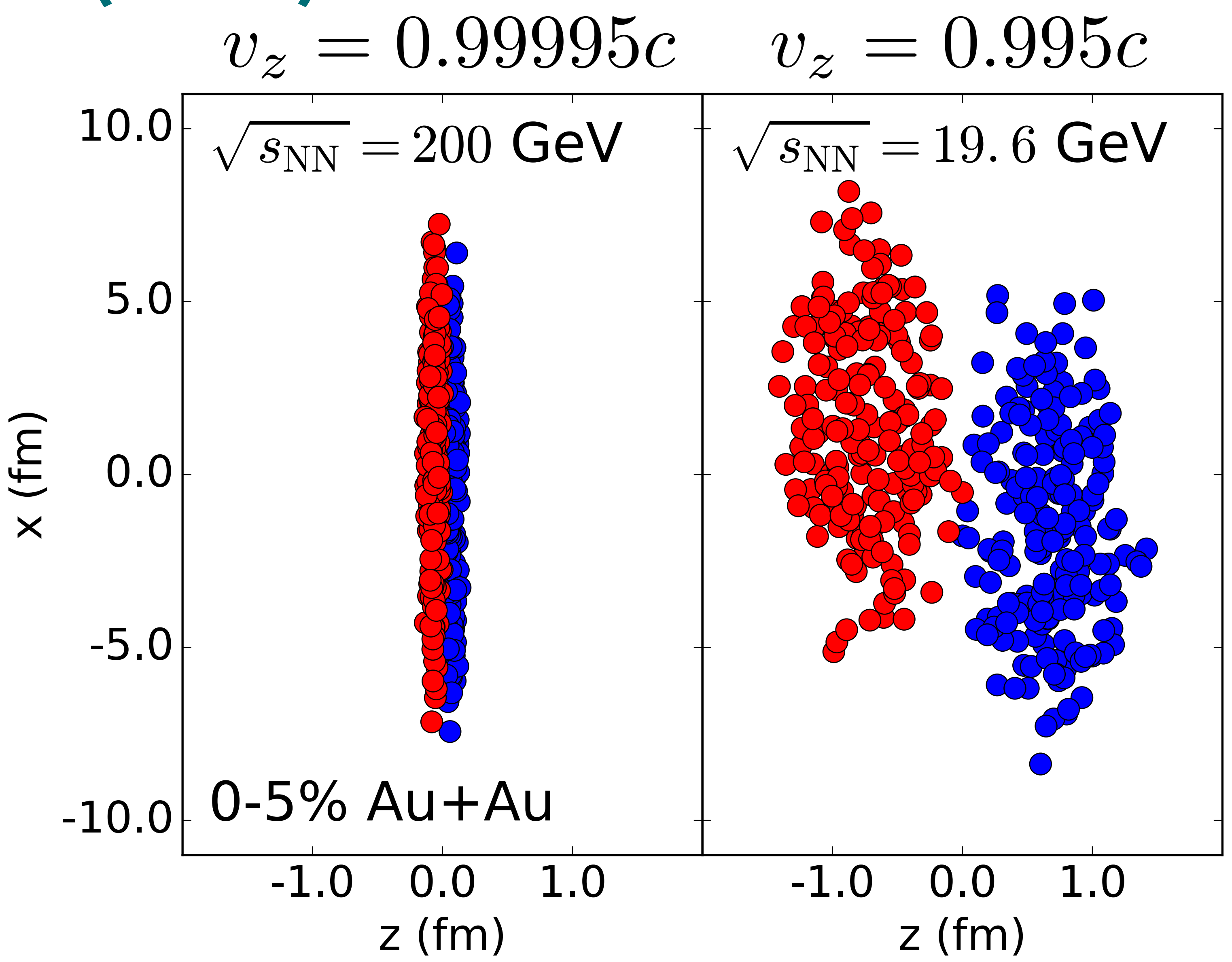
Simulates final-stage hadronic rescatterings and decays to yield observable hadrons.

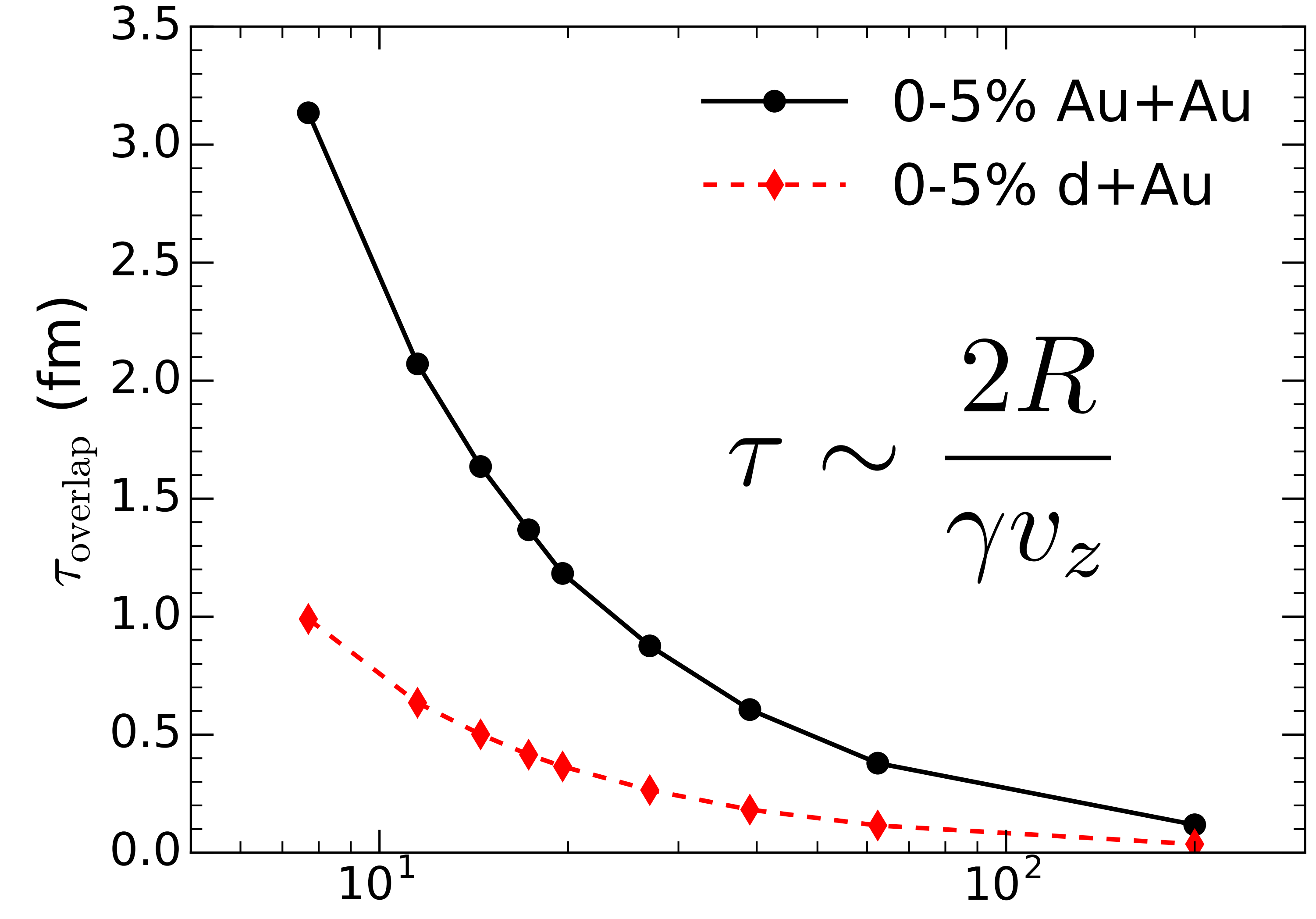
DYNAMIC 3+1D INITIAL STATE

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

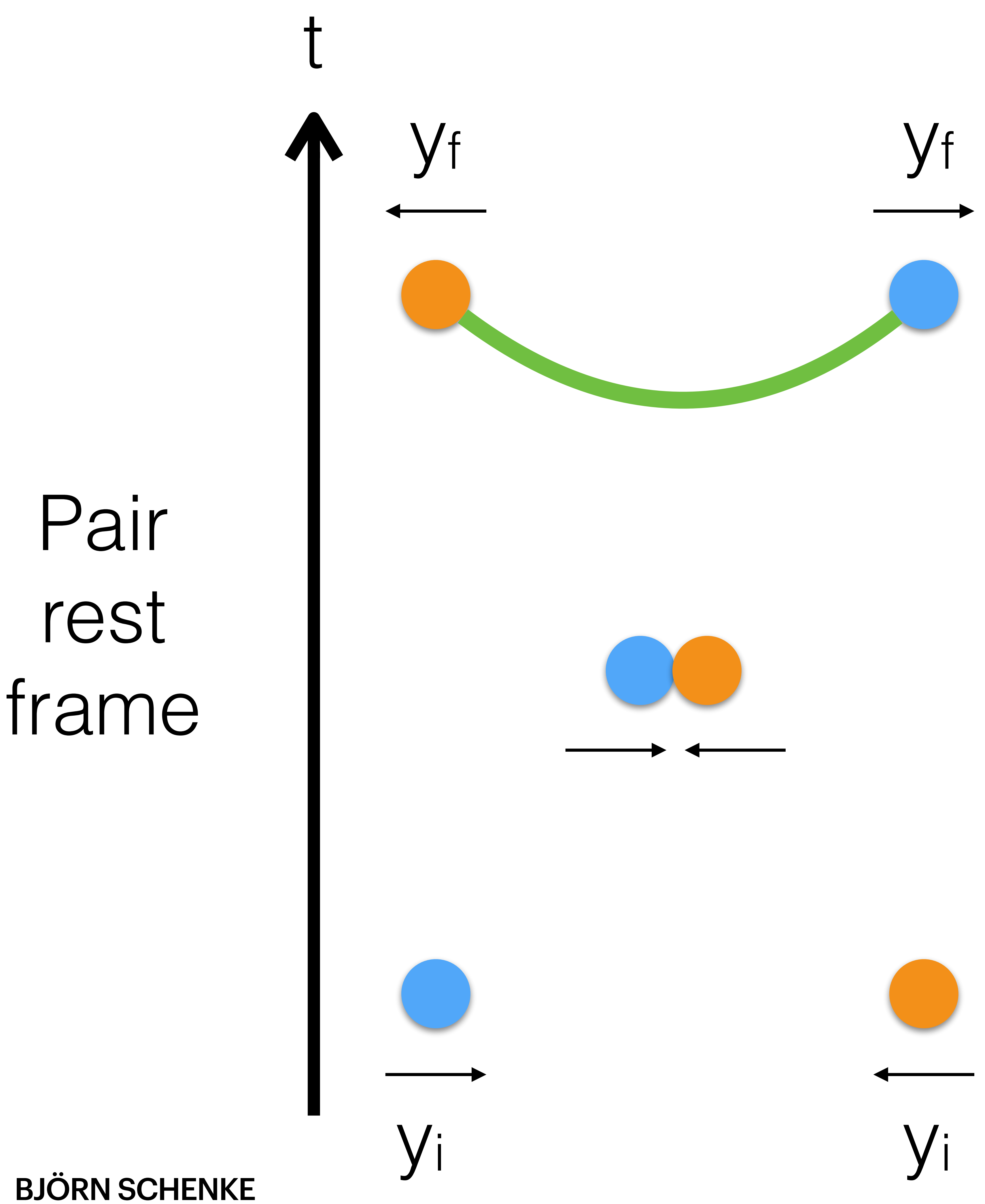






3D MC-GLAUBER + STRING MODEL

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



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

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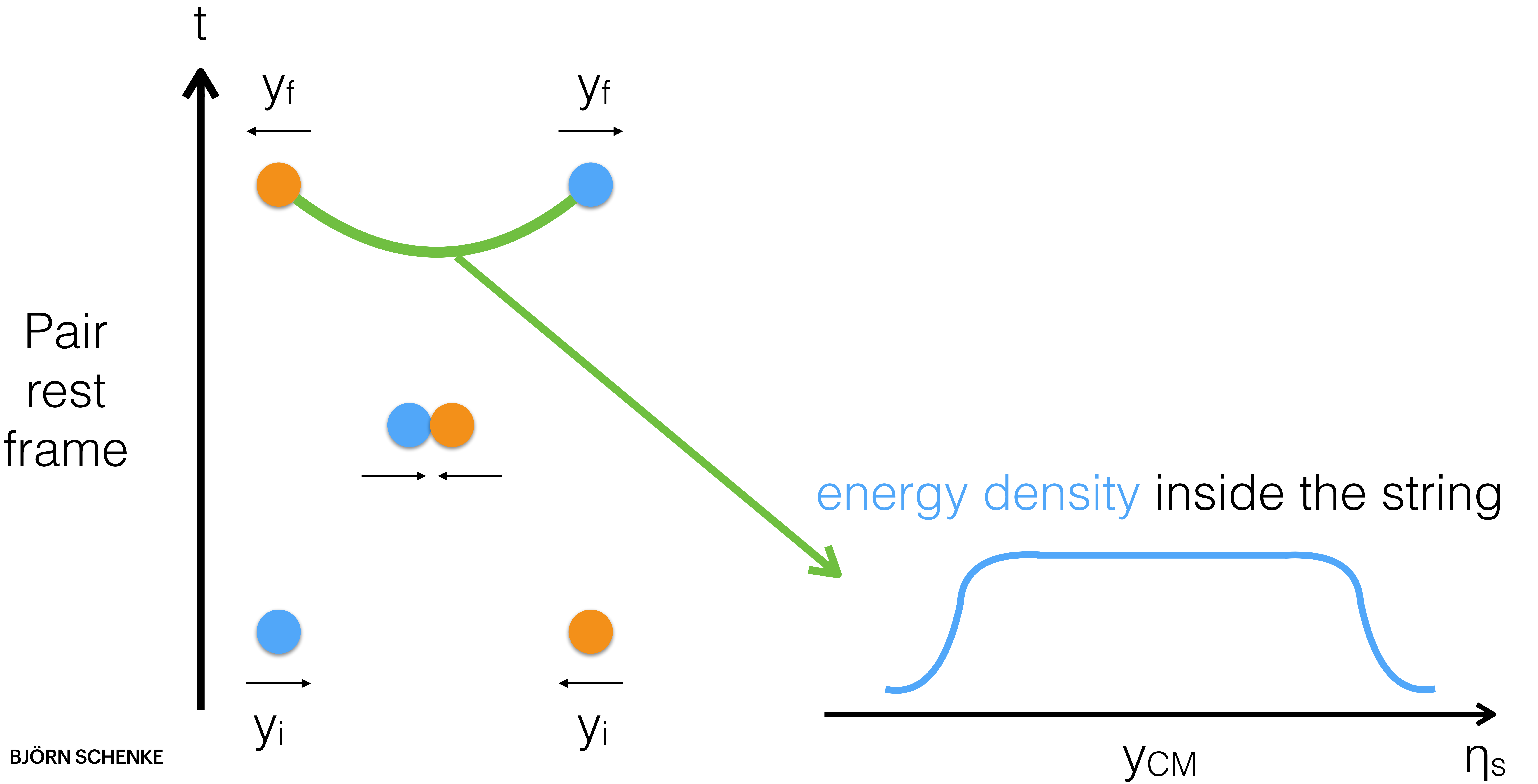

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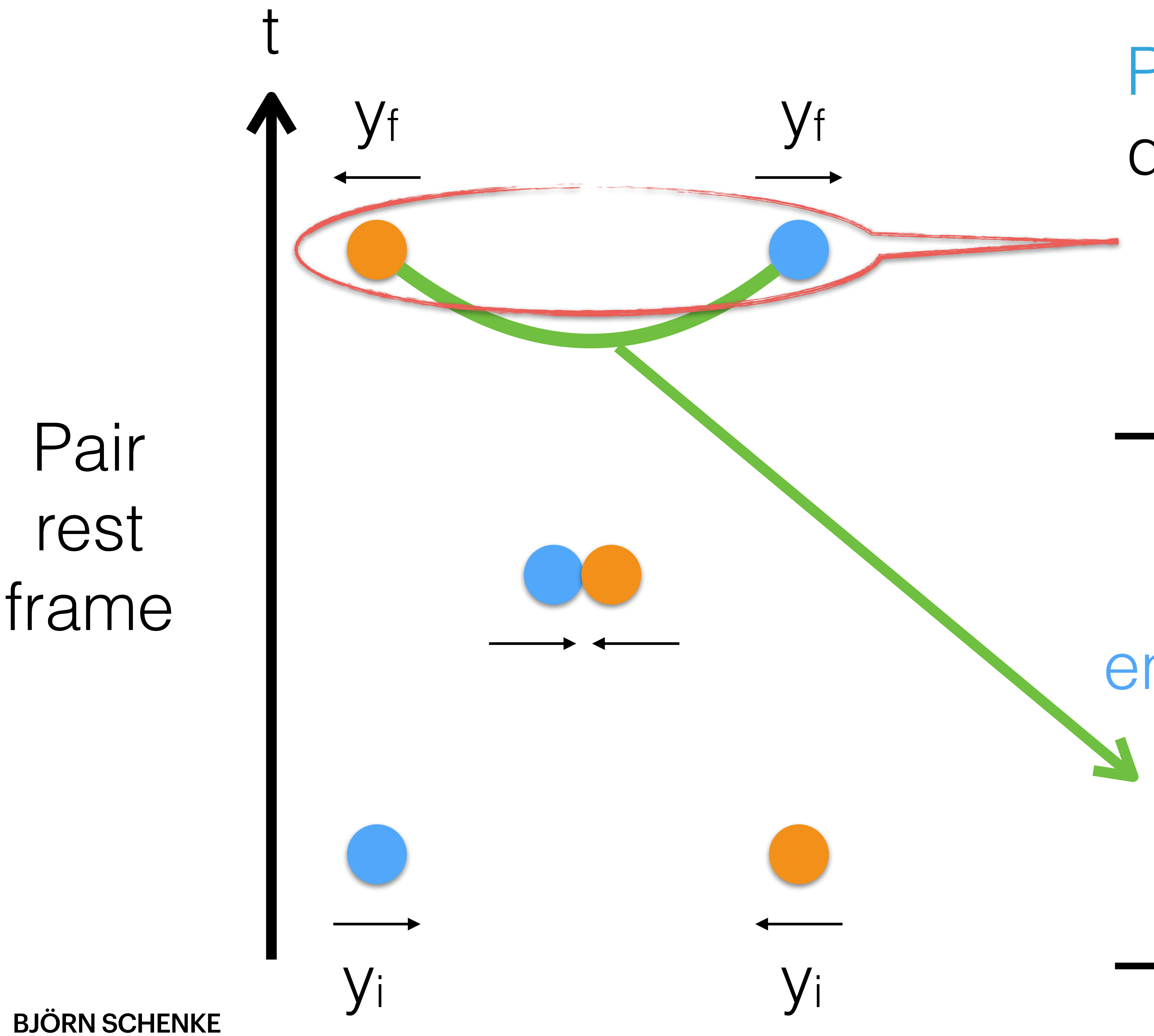
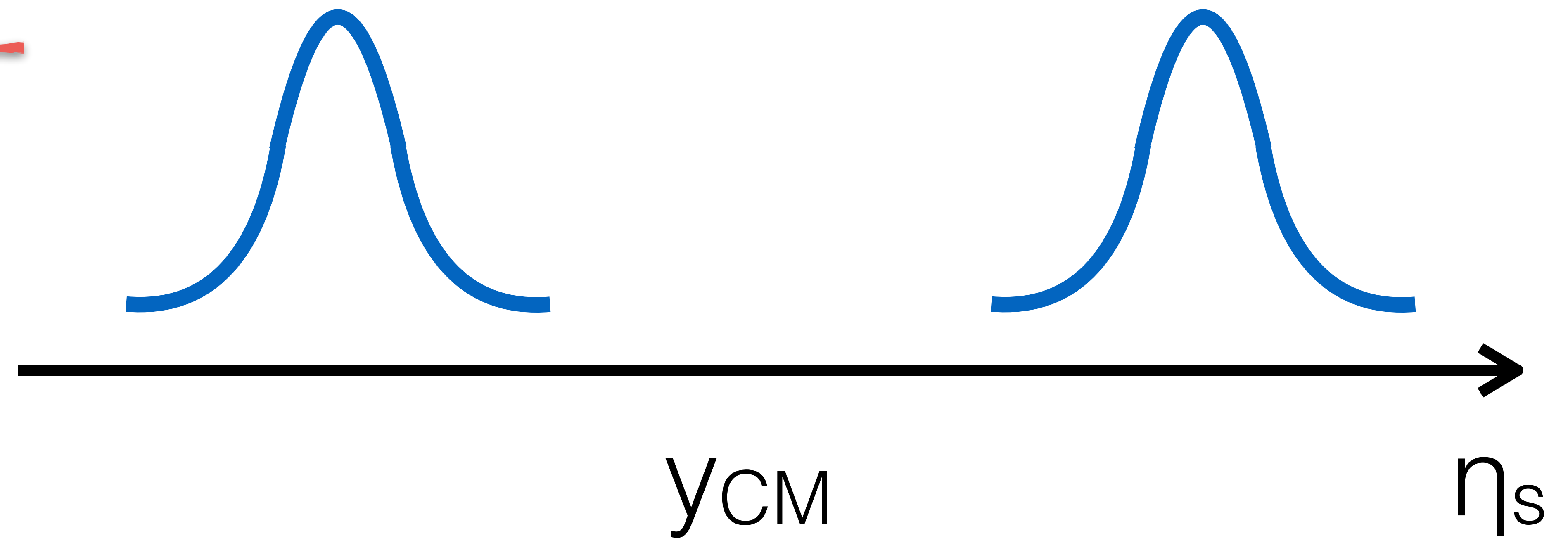
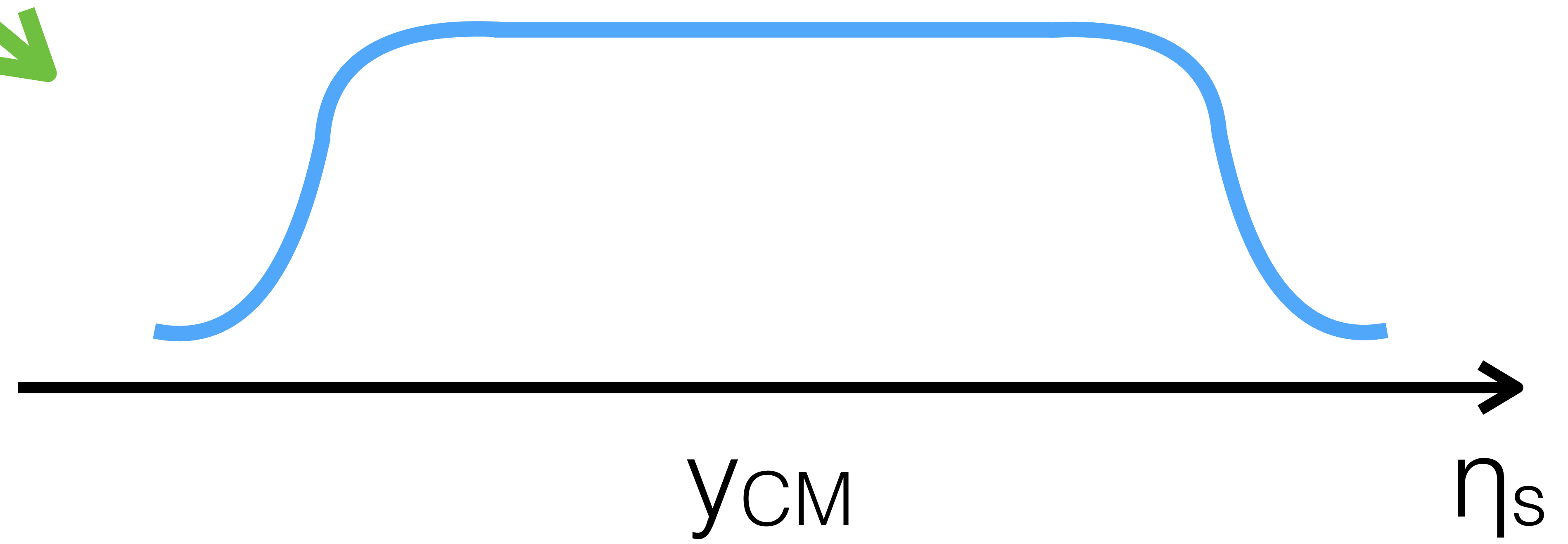


Partons' remaining energies are deposited at the string ends



energy density inside the string



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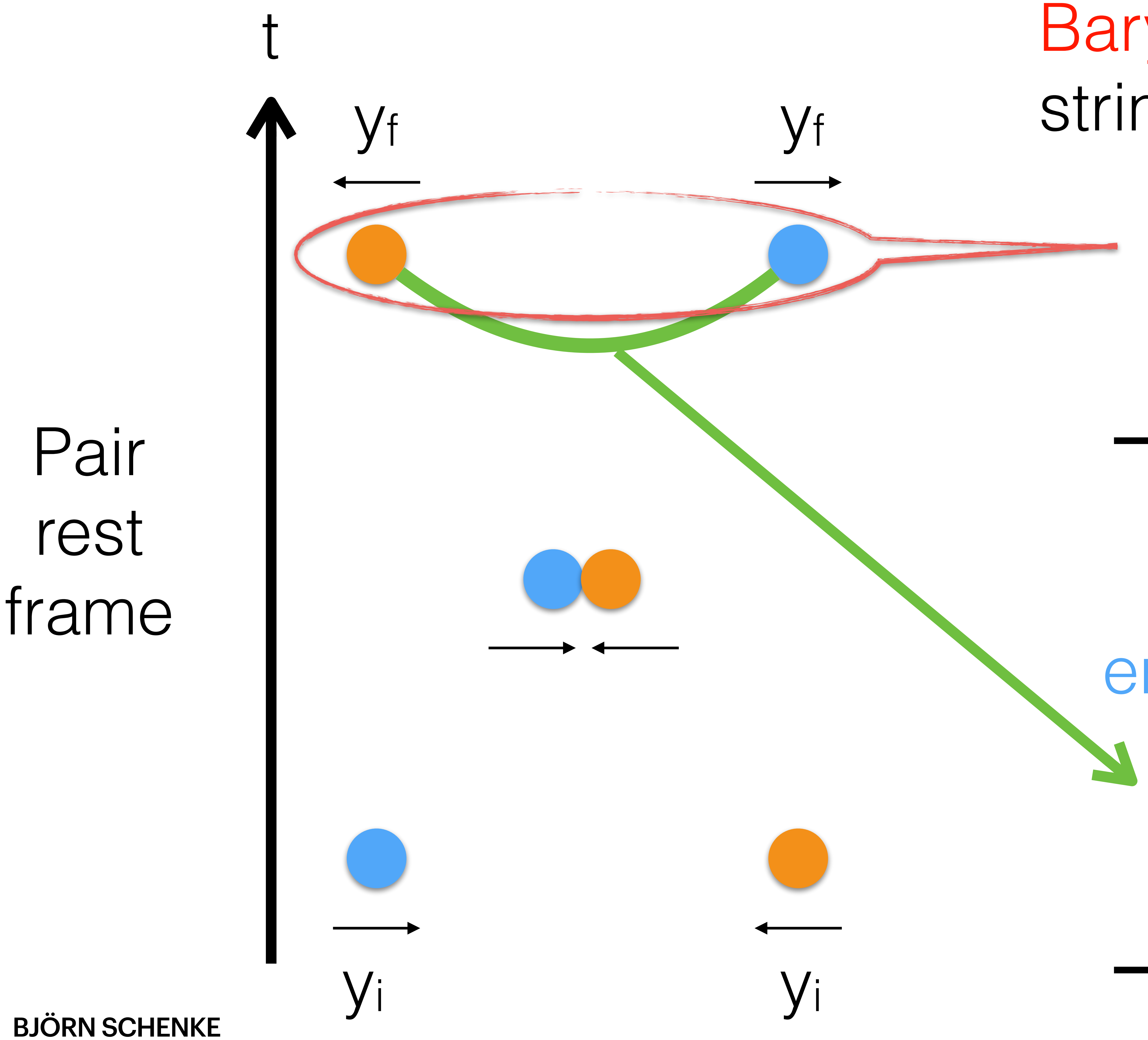
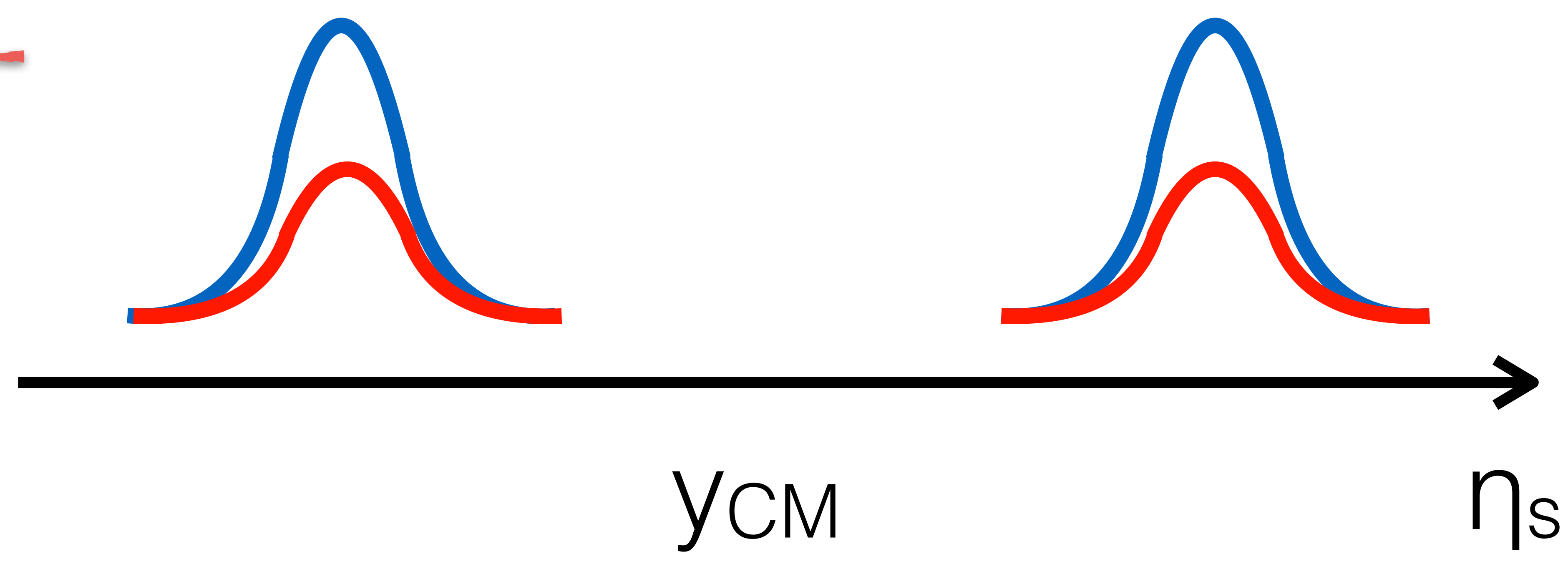
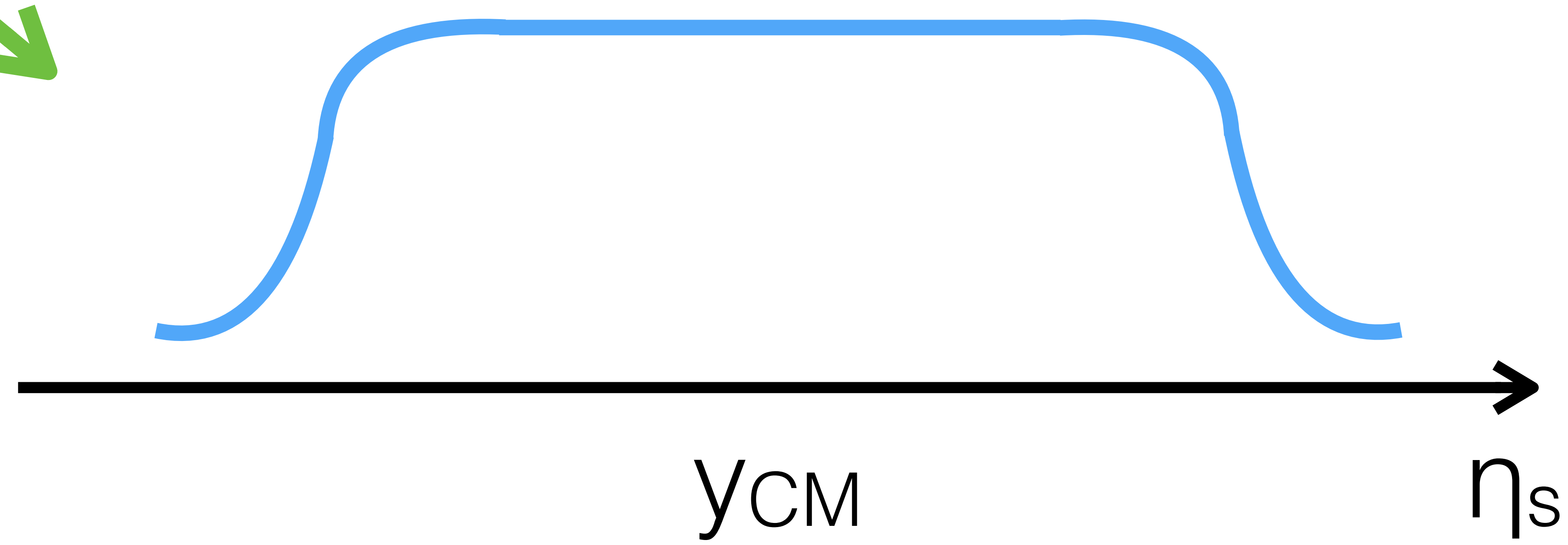


Baryon density is deposited at the string ends



energy density inside the string



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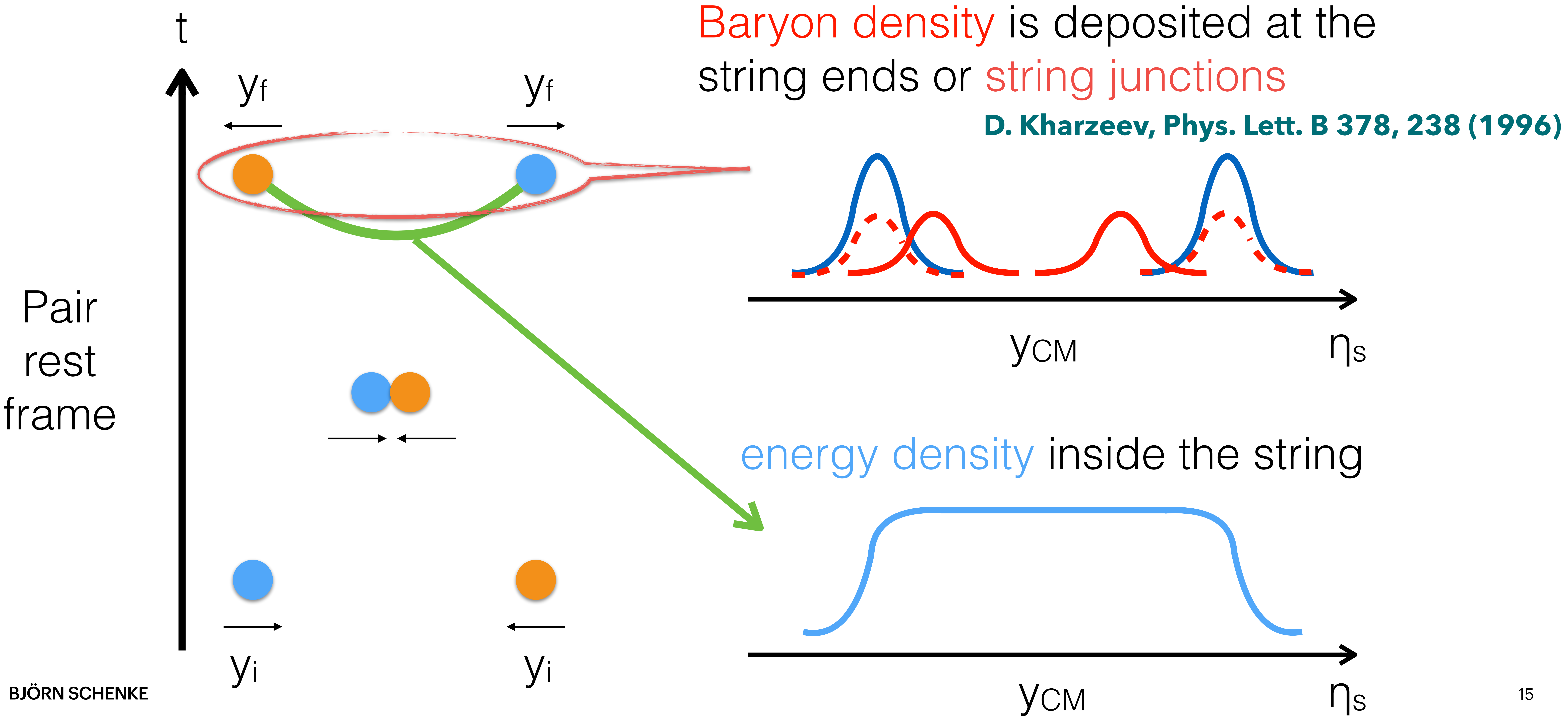
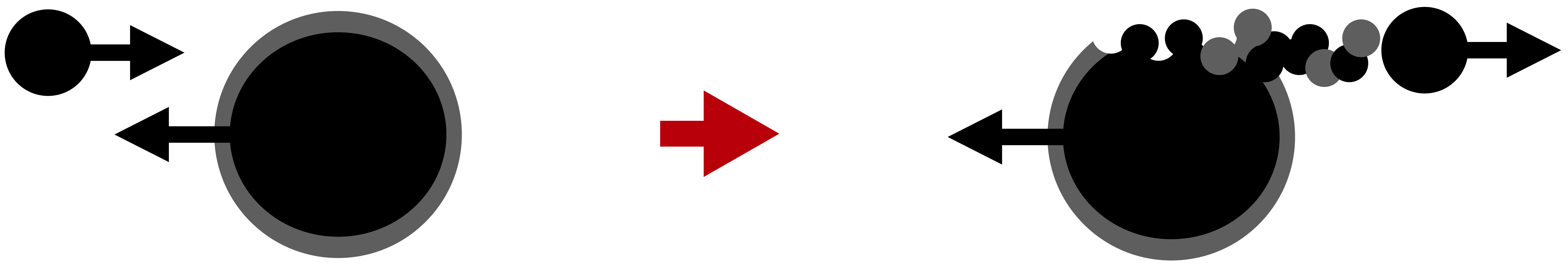


BARYON TRANSPORT

We are interested in baryon number and charge transport from the Pb nucleus in rapidity:



There is some uncertainty from how exactly baryon and electric charge is transported in rapidity.

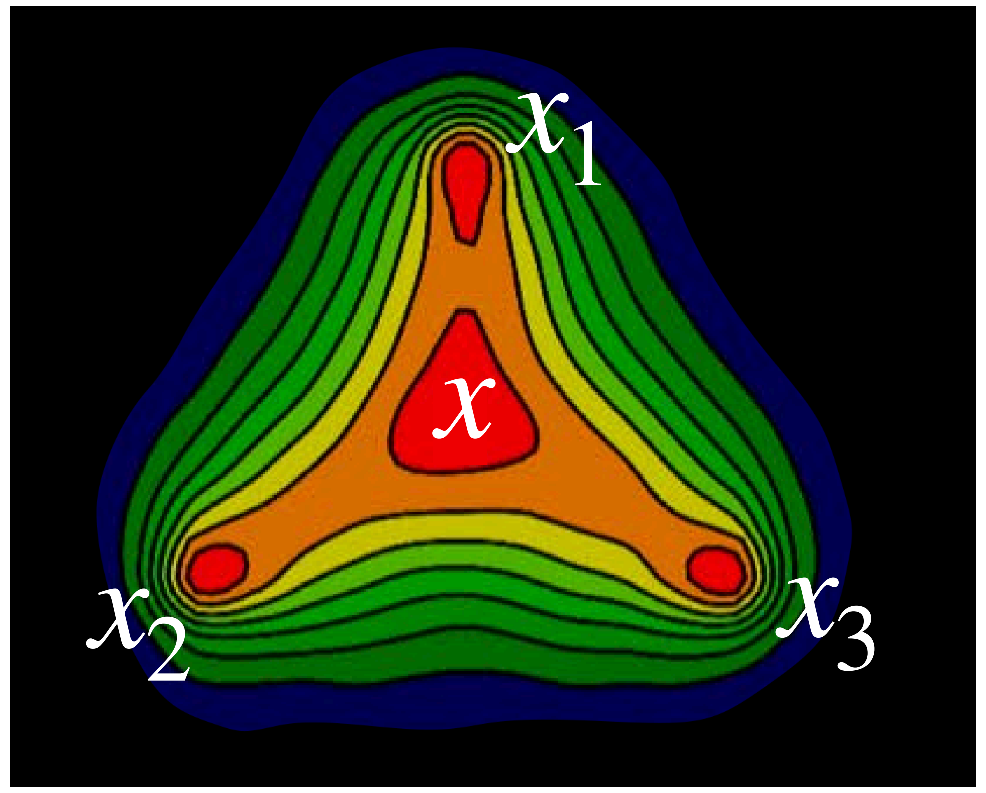
Baryon number could be located at the string ends or a transported baryon junction.

ASIDE: 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)**

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



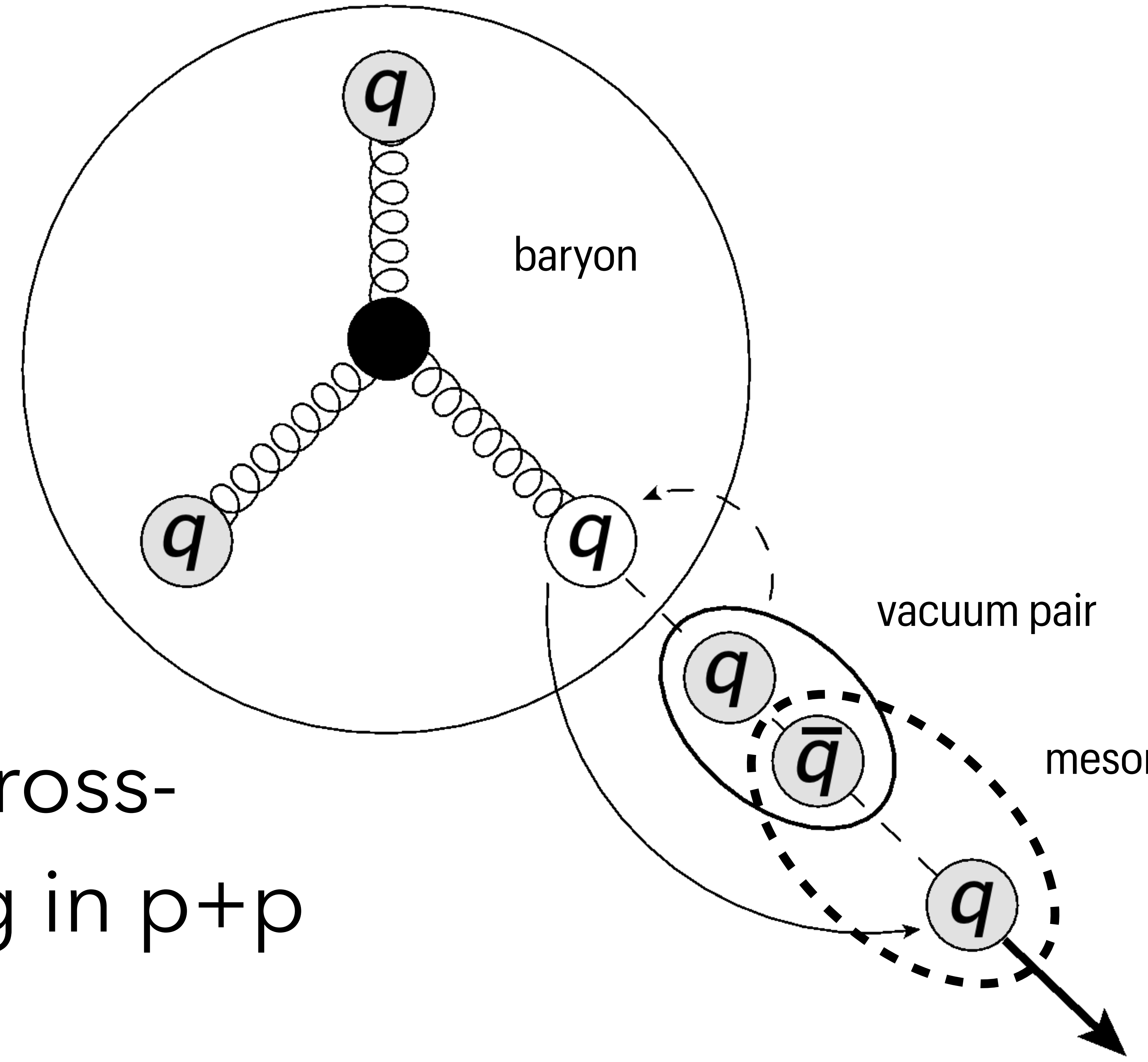
G.C. Rossi and G. Veneziano, Nucl. Phys.B123 (1977) 507; Phys. Rep.63 (1980) 149
D. Kharzeev, Phys. Lett. B 378, 238 (1996)

ASIDE: 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

ASIDE: BARYON STOPPING

Given the rapidity dependence of the single junction stopping cross section we define the probability density for where along the string the baryon number will be located as **C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)**

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

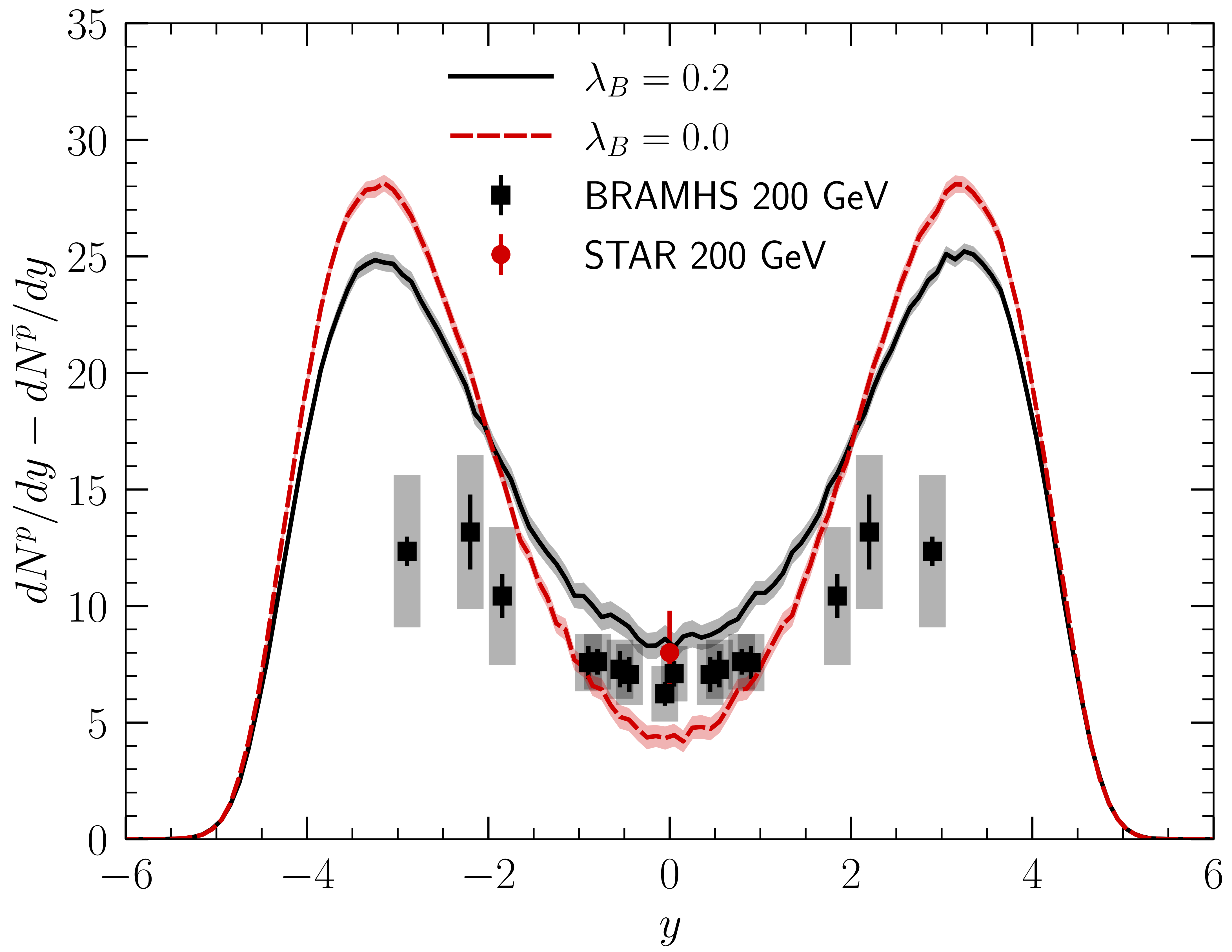
y_P and y_T are the rapidities of the string ends

A parameter $P(B_s)$ sets 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)

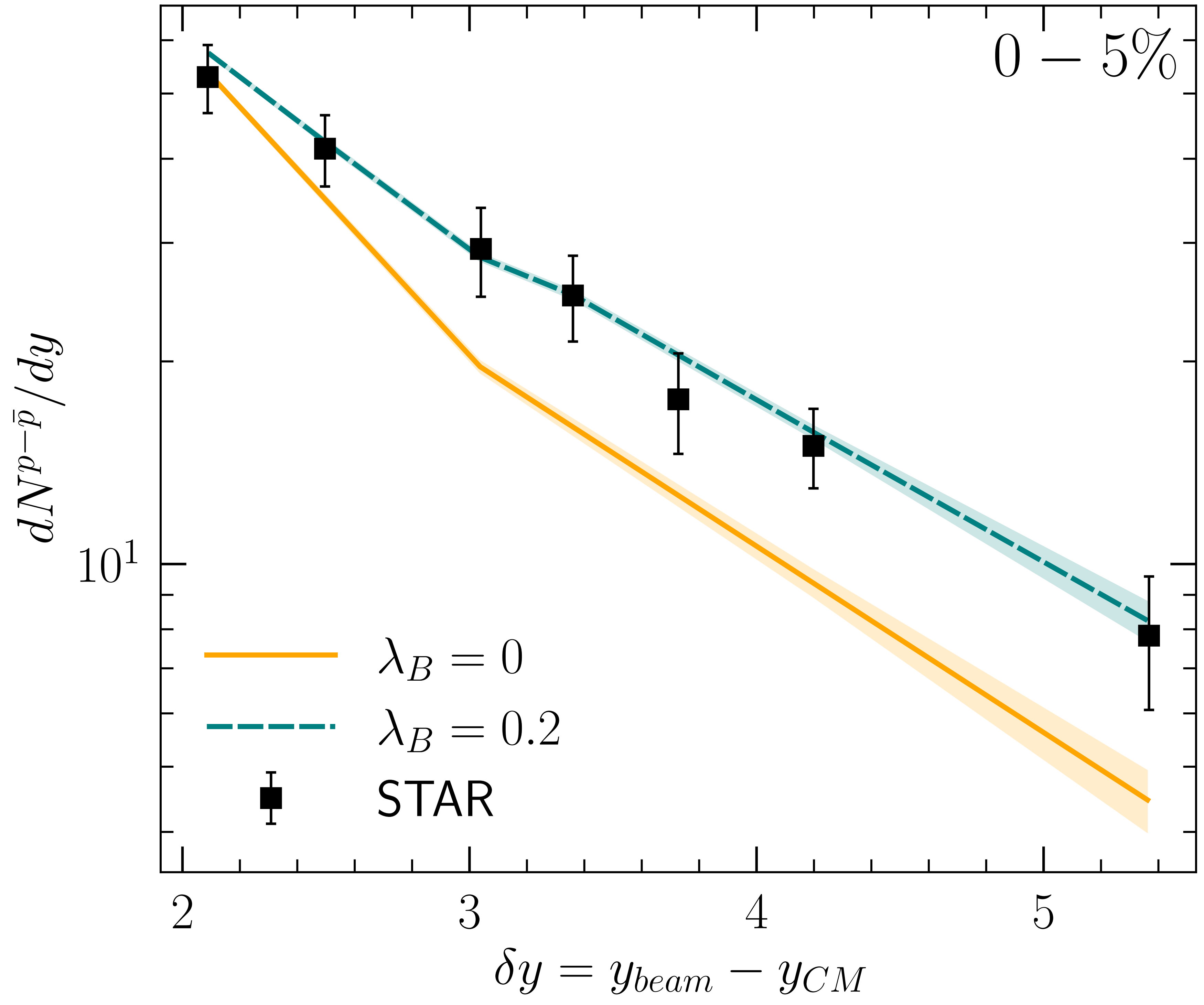
EFFECT OF JUNCTIONS

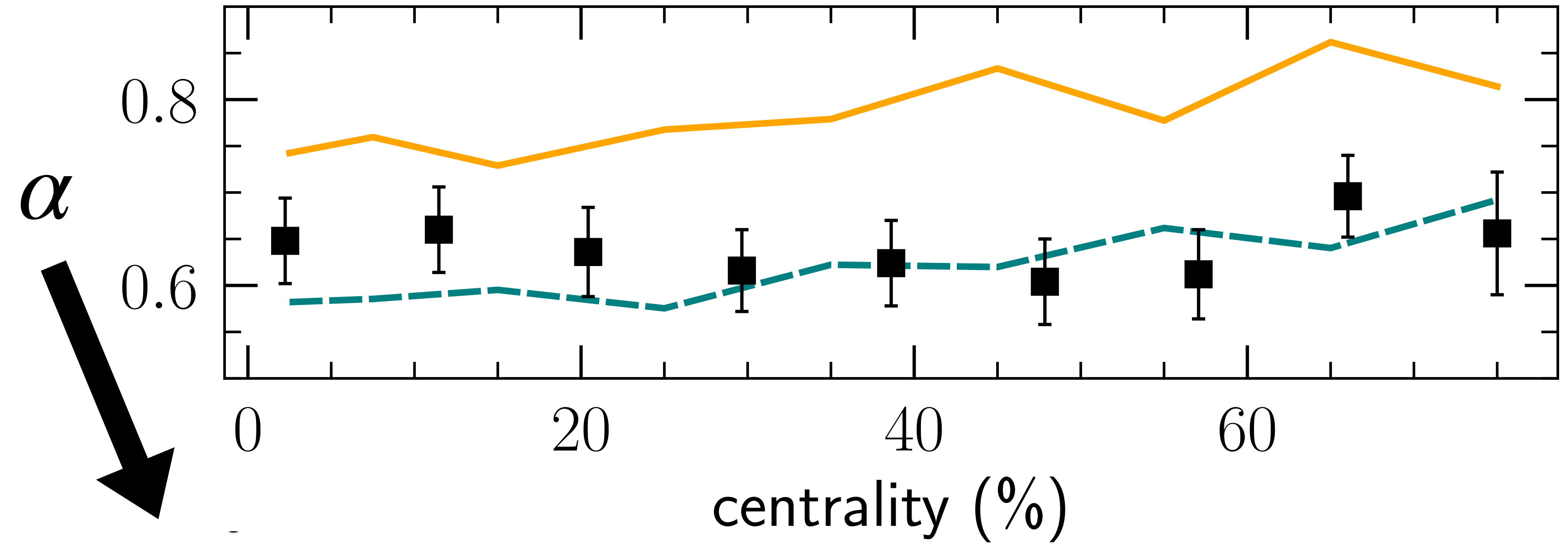
G. Pihan, A. Monnai, B. Schenke, C. Shen, Phys.Rev.Lett. 133 (2024) 18, 182301



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

$\lambda_B \equiv 2\,P(B_s)$

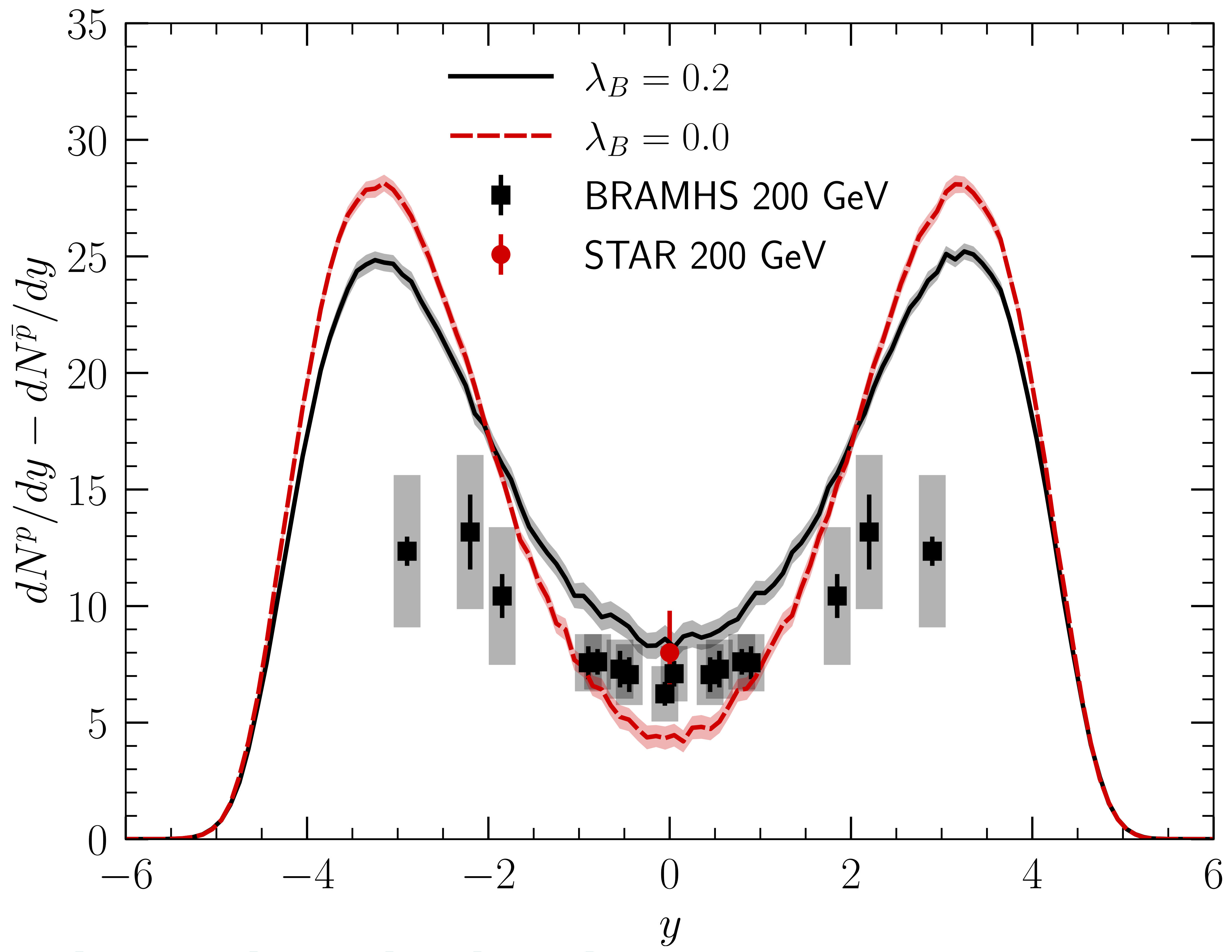




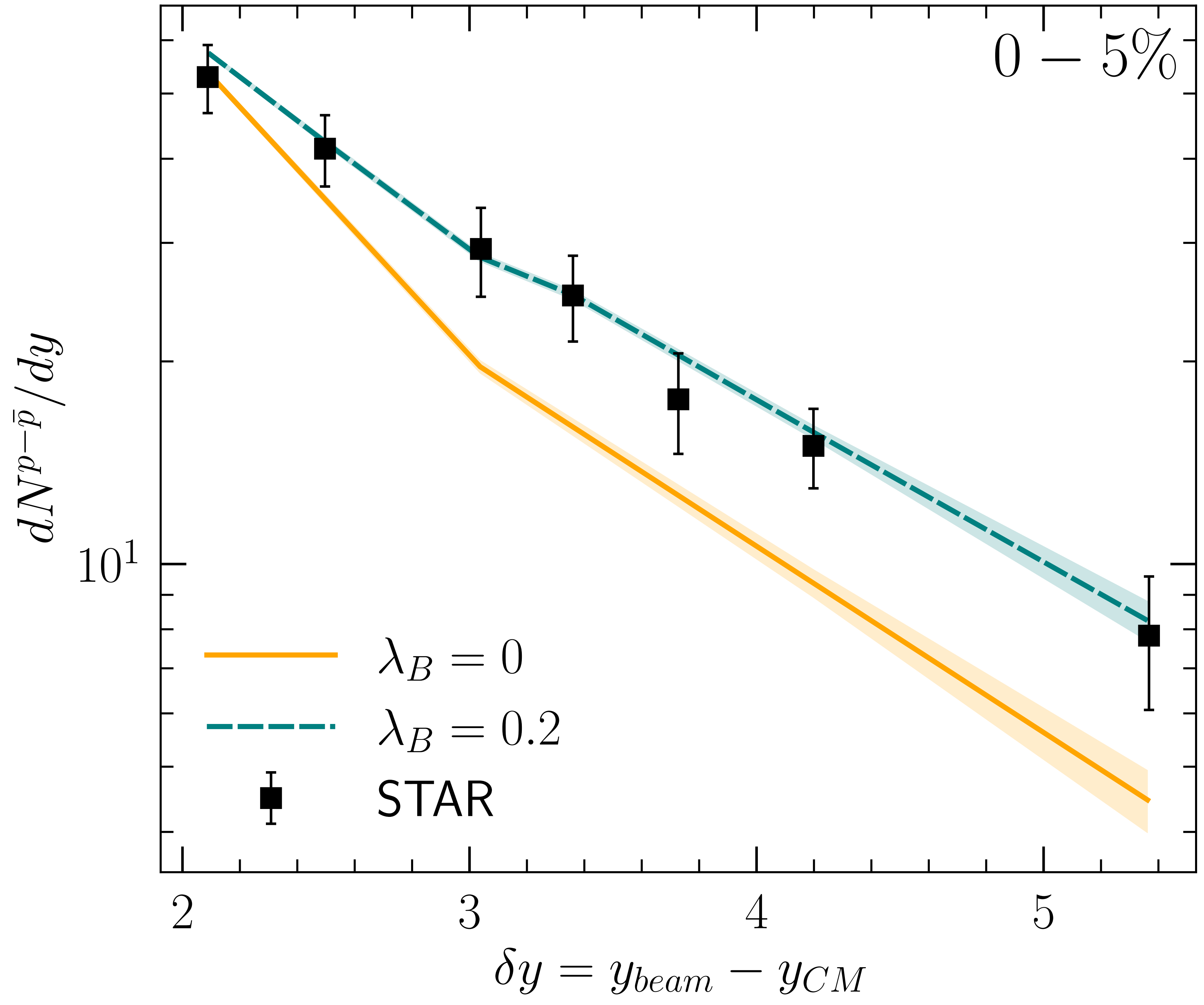
$dN^{p-\bar{p}}/dy \propto \exp(-\alpha\delta y)$

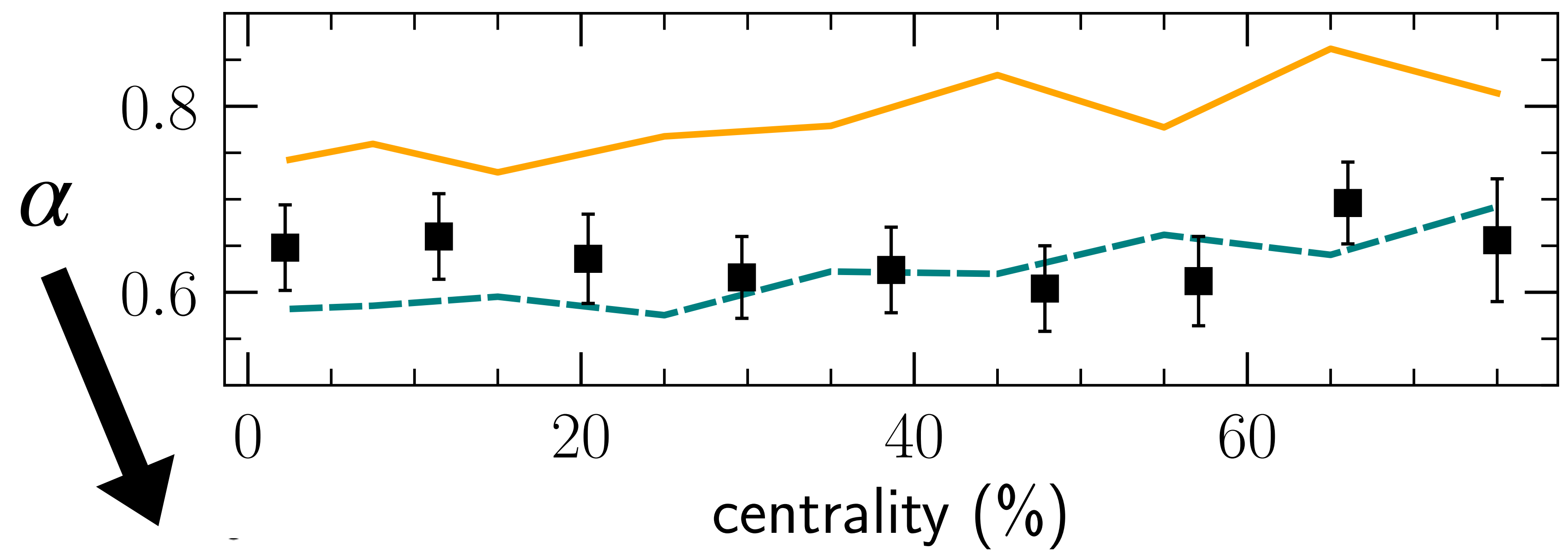
EFFECT OF JUNCTIONS

G. Pihan, A. Monnai, B. Schenke, C. Shen, Phys.Rev.Lett. 133 (2024) 18, 182301



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





Use $P(B_s) = 0.1$ and compare to $P(B_s) = 0$

$dN^{p-\bar{p}}/dy \propto \exp(-\alpha\delta y)$

BACK TO THE NEUTRON SKIN

G. Pihan, A. Monnai, B. Schenke, C. Shen, e-Print: 2509.21644 [nucl-th]

Modeling the neutron skin of Pb:

Woods–Saxon parametrization:

$$\rho_{p,n}(r) = \frac{1}{1 + e^{(r - R_{p,n}^{\mathrm{WS}})/a_{p,n}}}$$

Half-density radii of the proton and neutron distributions:

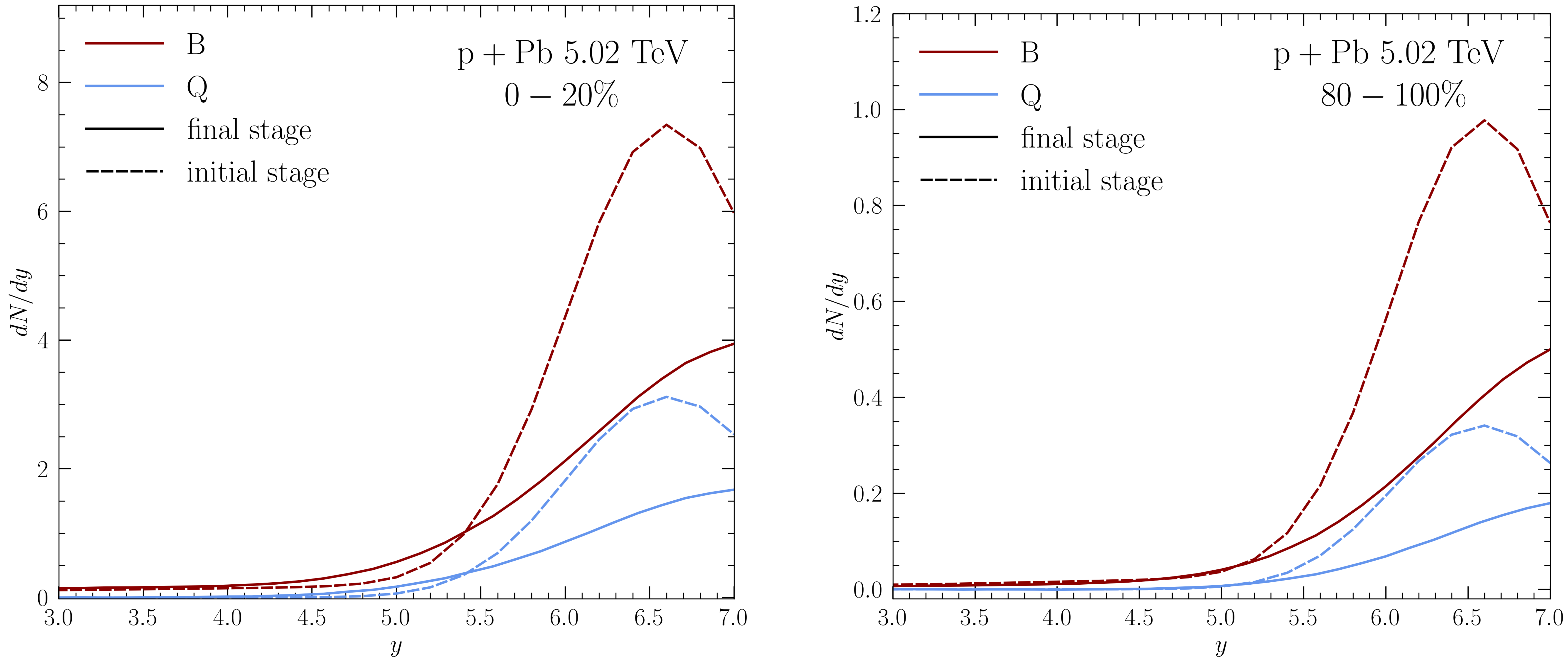
$R_p^{\mathrm{WS}} = 6.68\,\mathrm{fm}$ and $R_n^{\mathrm{WS}} = 6.69\,\mathrm{fm}$ (use $R_{p,n}^{\mathrm{WS}} = 6.68\,\mathrm{fm}$ in case of $\Delta R_{\mathrm{np}} = 0$)

Diffuseness of the proton distribution $a_p = 0.448\,\mathrm{fm}$ kept constant

Vary the neutron diffuseness a_n to adjust neutron skin thickness ΔR_{np}

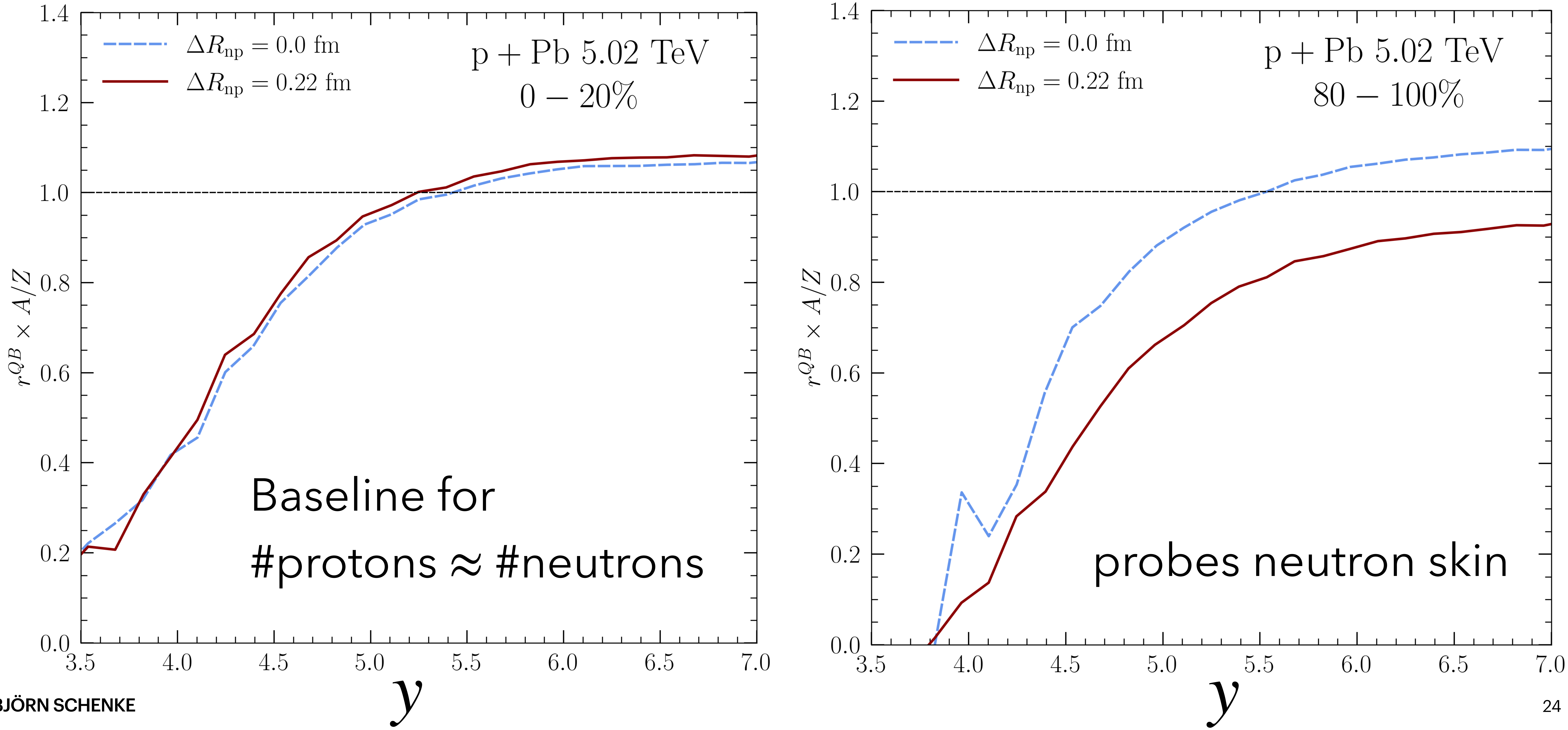
RAPIDITY DISTRIBUTIONS

Initial state (vs. η_s) and final state $dN_{B/Q}/dy$ distributions in Pb going direction



RATIO Q/B

$r^{QB} \times A/Z$ in central and peripheral collisions. Effect of neutron skin.



DOUBLE RATIO OBSERVABLE

Let's compute the double ratio

$$\mathscr{R}^{Q,B}_{c_1,c_2}(y_1, y_2) \equiv \frac{N_Q(y_1, y_2, c_1)\big/N_B(y_1, y_2, c_1)}{N_Q(y_1, y_2, c_2)\big/N_B(y_1, y_2, c_2)}$$

for $c_1 = 80 - 100\,\%$ and $c_2 = 0 - 20\,\%$

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DOUBLE RATIO OBSERVABLE

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for $c_1 = 80 - 100\,\%$ and $c_2 = 0 - 20\,\%$

Note: Centrality should be determined in a rapidity bin far from the rapidity bin in which we measure Q and B to avoid auto-correlations.

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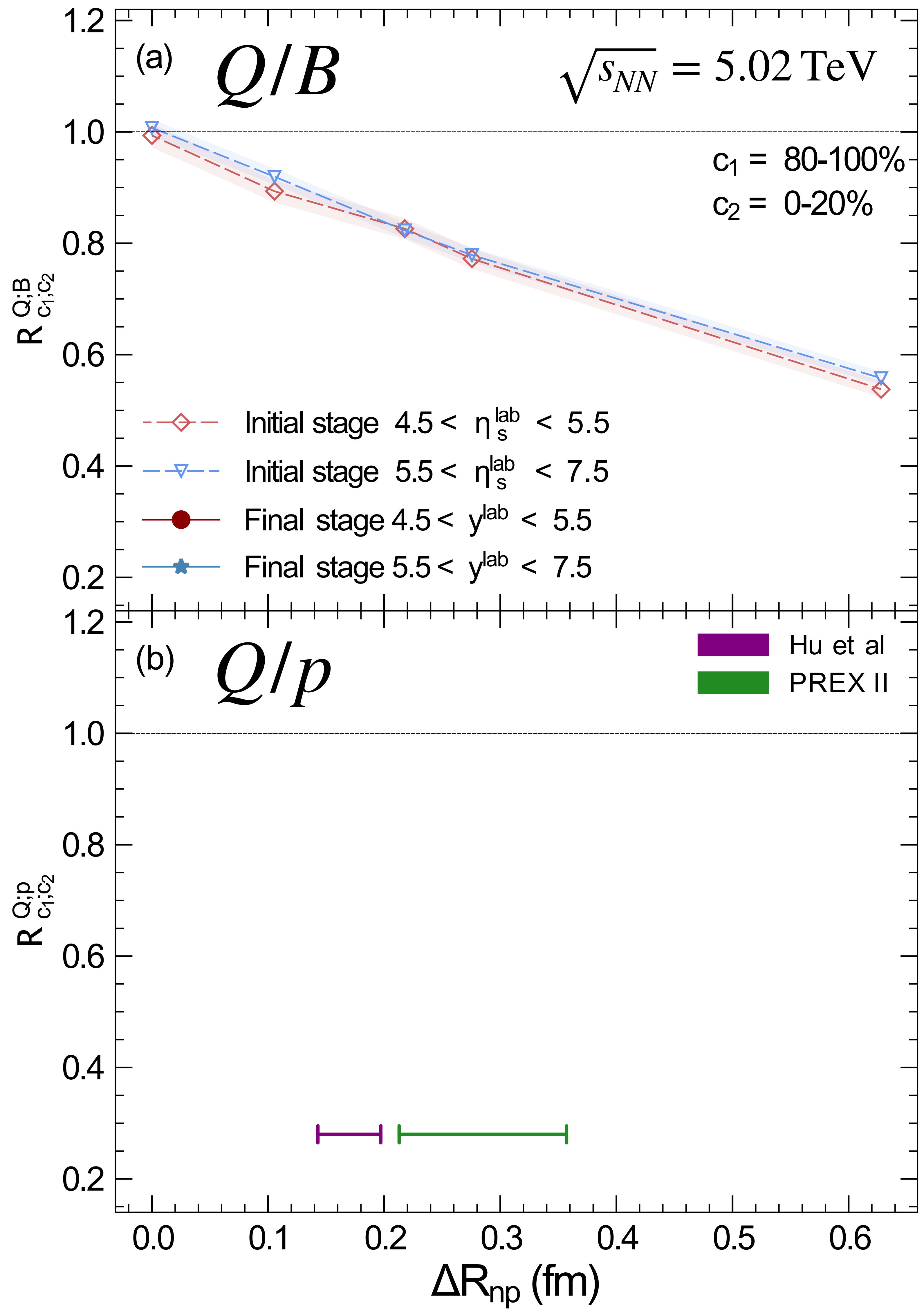
INITIAL STATE RESULT

Let's compute the double ratio

$$\mathscr{R}^{Q,B}_{c_1,c_2}(y_1, y_2) \equiv \frac{N_Q(y_1, y_2, c_1)/N_B(y_1, y_2, c_1)}{N_Q(y_1, y_2, c_2)/N_B(y_1, y_2, c_2)}$$

for $c_1 = 80 - 100\,\%$ and $c_2 = 0 - 20\,\%$

Dashed lines: Initial stage result



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FINAL STATE OBSERVABLE

Let’s compute the double ratio

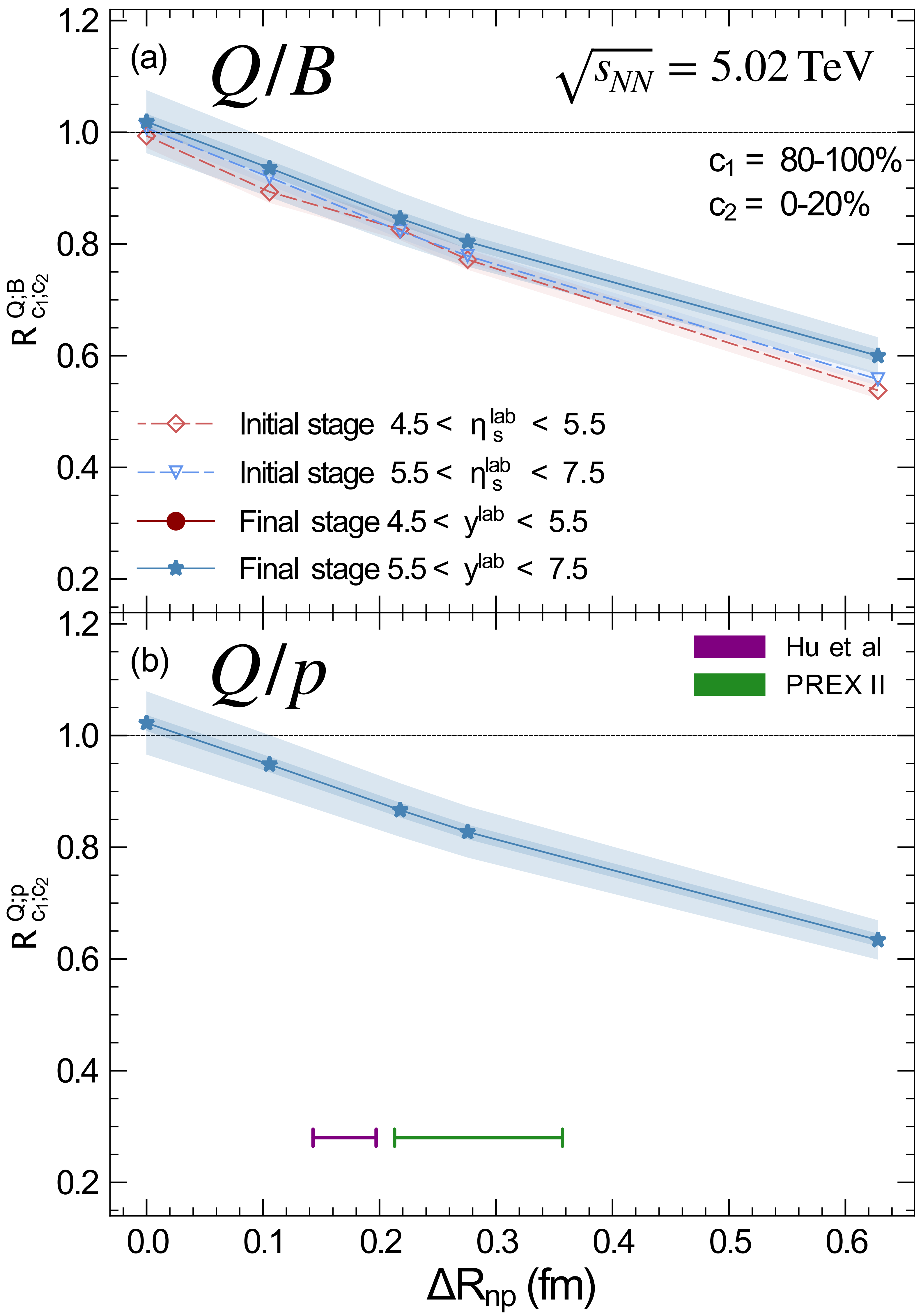
$$\mathscr{R}^{Q,B}_{c_1,c_2}(y_1,y_2) \equiv \frac{N_Q(y_1,y_2,c_1)/N_B(y_1,y_2,c_1)}{N_Q(y_1,y_2,c_2)/N_B(y_1,y_2,c_2)}$$

for $c_1 = 80 - 100\,\%$ and $c_2 = 0 - 20\,\%$

Dashed lines: Initial stage result

Blue solid lines: Large Pb-going rapidity

$5.5 < y_{\mathrm{lab}} < 7.5$



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FINAL STATE OBSERVABLE

Let's compute the double ratio

$$\mathscr{R}^{Q,B}_{c_1,c_2}(y_1,y_2) \equiv \frac{N_Q(y_1,y_2,c_1)/N_B(y_1,y_2,c_1)}{N_Q(y_1,y_2,c_2)/N_B(y_1,y_2,c_2)}$$

for $c_1 = 80 - 100\,\%$ and $c_2 = 0 - 20\,\%$

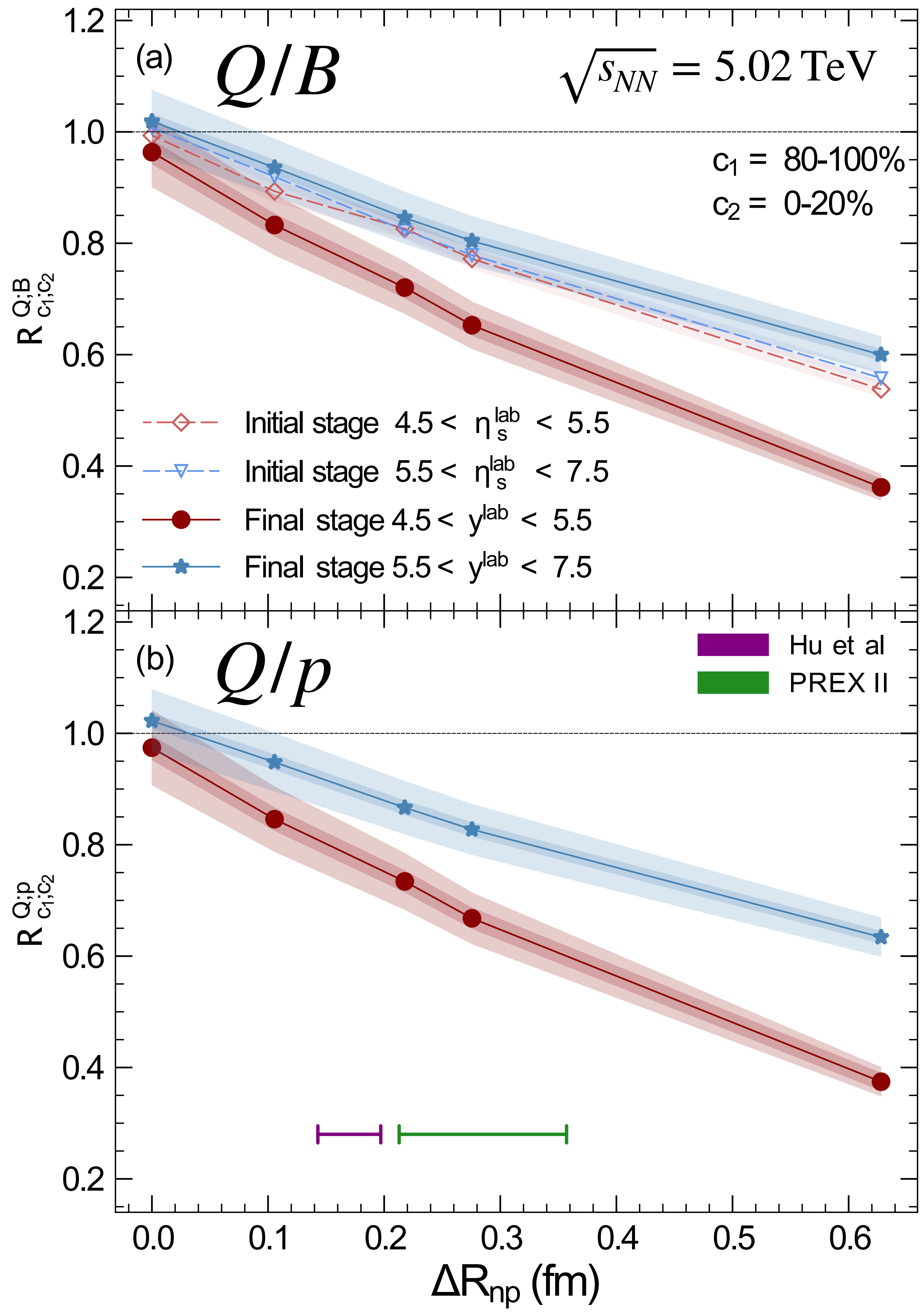
Dashed lines: Initial stage result

Blue solid lines: Large Pb-going rapidity

$5.5 < y_{\rm lab} < 7.5$

Red solid lines: Accessible Pb-going rapidity

$4.5 < y_{\rm lab} < 5.5$



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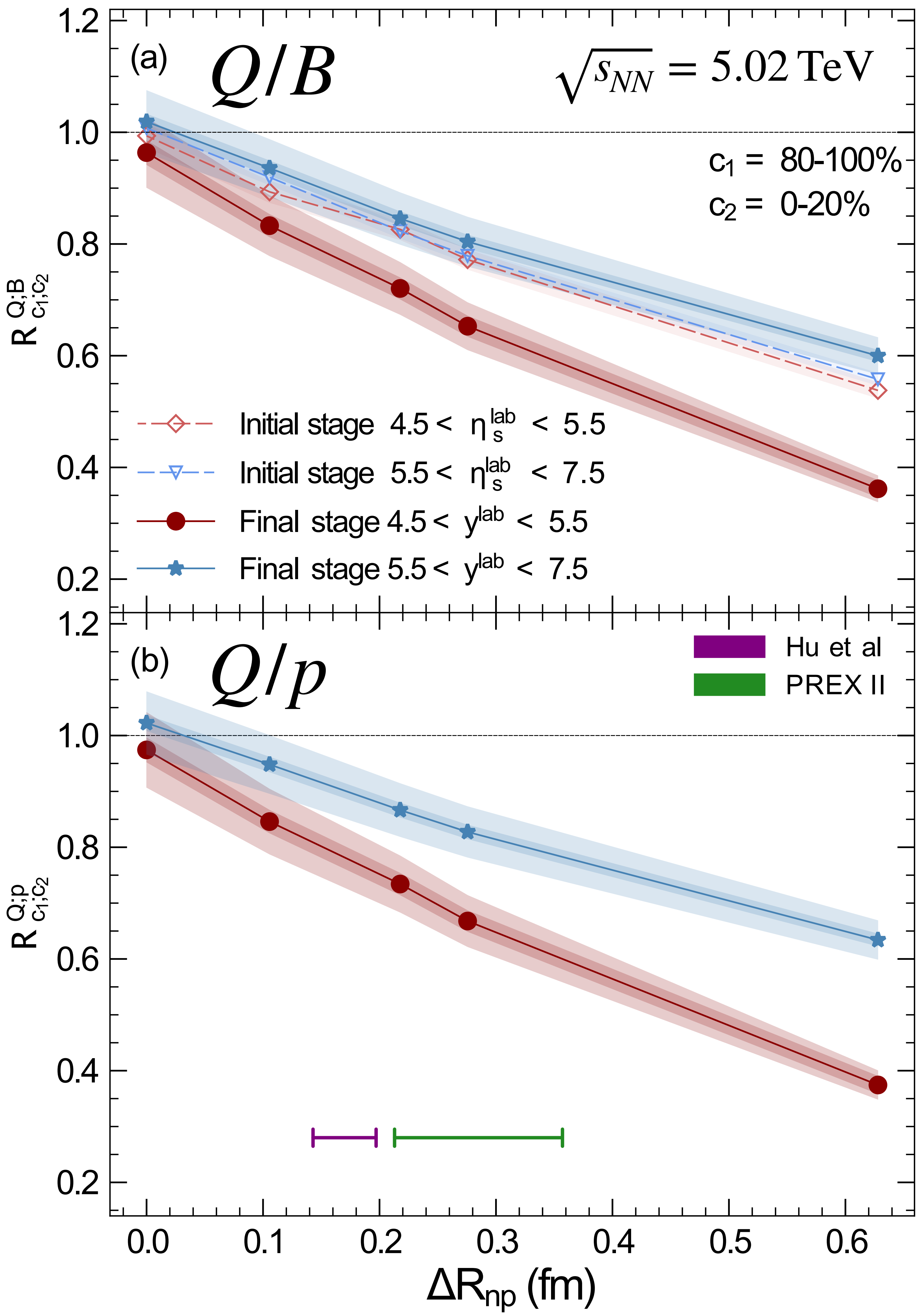
SYSTEMATIC ERRORS

Darker colored error bands: statistical errors

Lighter colored error bands include 3 sources of systematic errors:

- Diffusion effects
  - *-Estimate using 1+1D diffusive hydro*
- Uncertainty in baryon stopping
  - *-Turn on and off the baryon junction effect*
- Modeling of the neutron skin
  - *-Vary WS neutron radius instead of diffuseness*



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SYSTEMATIC ERRORS

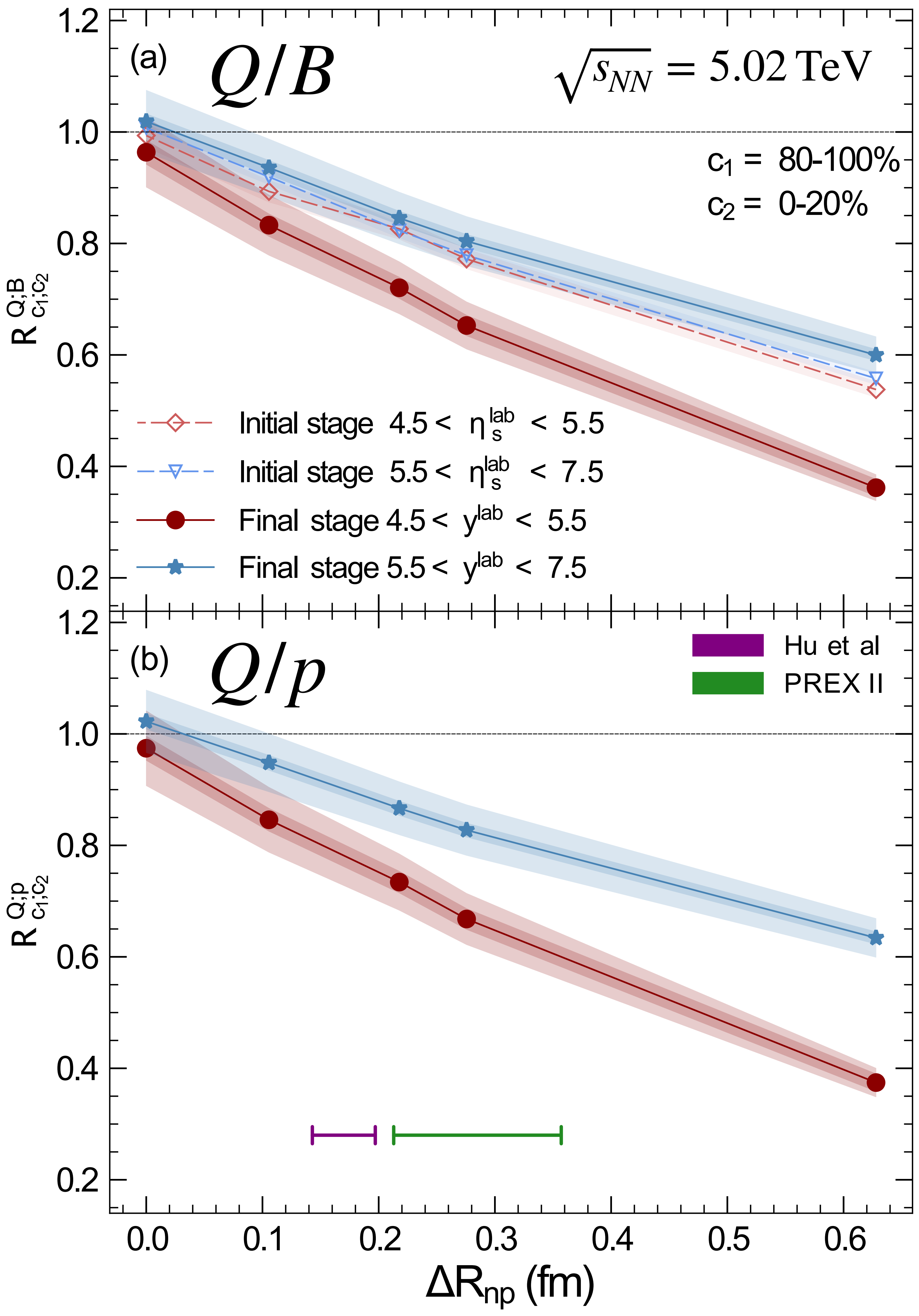
Darker colored error bands: statistical errors

Lighter colored error bands include 3 sources of systematic errors:

$4.5 < y^{\text{lab}} < 5.5$	Diffusion	Baryon stopping	R_n^{WS}	total
$\mathcal{R}^{Q,B}_{c_1,c_2}$	5.0	4.0	1.5	6.5
$\mathcal{R}^{Q,p}_{c_1,c_2}$	5.0	4.5	1.5	6.9

$5.5 < y^{\text{lab}} < 7.5$	Diffusion	Baryon stopping	R_n^{WS}	total
$\mathcal{R}^{Q,B}_{c_1,c_2}$	5.0	1.7	1.6	5.5
$\mathcal{R}^{Q,p}_{c_1,c_2}$	5.0	1.7	1.3	5.5

relative errors (%)



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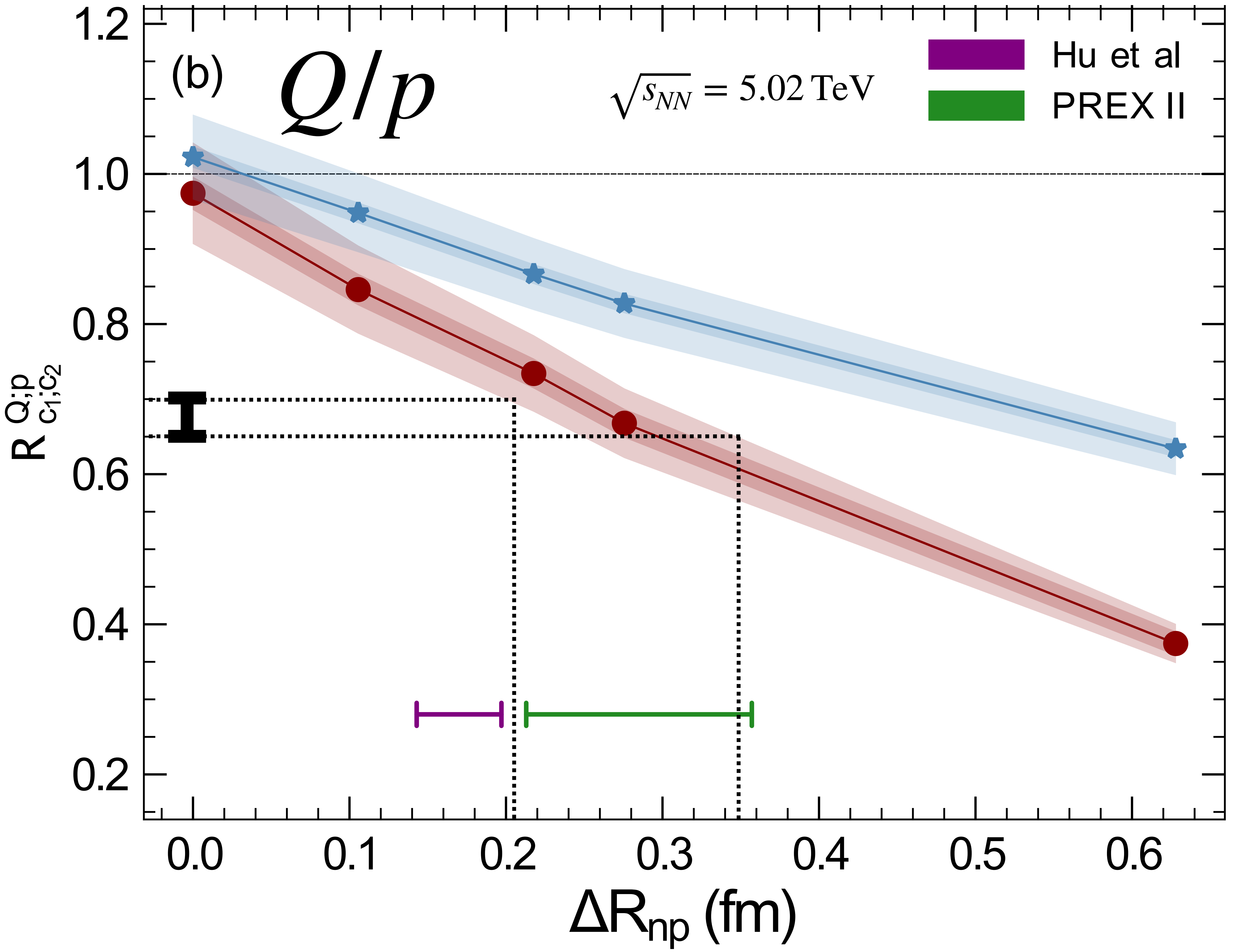
SYSTEMATIC ERRORS



If experiment can measure R with shown accuracy, e.g. $0.65 < R < 0.7$, then the error on the extracted neutron skin will be comparable to the PREX II error.

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SYSTEMATIC ERRORS: DIFFUSION

Estimate the effect of diffusion in 1+1D simulation of Au+Au collisions (we do not have all charge diffusion implemented in the 3+1D code yet)

$$\begin{pmatrix} V_B^\mu \\ V_Q^\mu \\ V_S^\mu \end{pmatrix} = \mathcal{K} \begin{pmatrix} \nabla^\mu \frac{\mu_B}{T} \\ \nabla^\mu \frac{\mu_Q}{T} \\ \nabla^\mu \frac{\mu_S}{T} \end{pmatrix} - \mathcal{T} \Delta^\mu{}_\nu \begin{pmatrix} DV_B^\nu \\ DV_Q^\nu \\ DV_S^\nu \end{pmatrix}$$

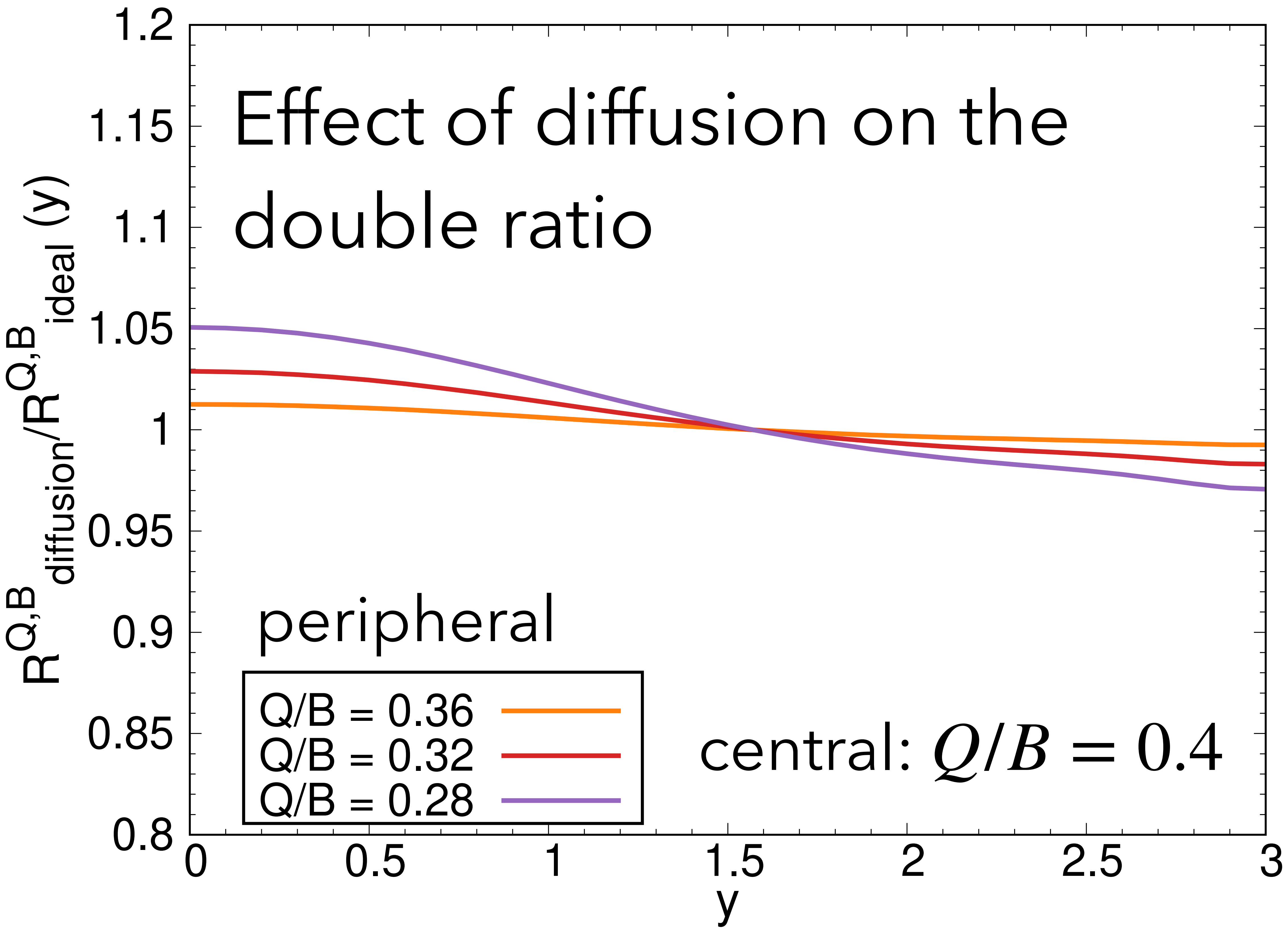
diffusion currents

$$\mathcal{K} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \qquad \mathcal{T} = \begin{pmatrix} \tau_{BB} & \tau_{BQ} & \tau_{BS} \\ \tau_{QB} & \tau_{QQ} & \tau_{QS} \\ \tau_{SB} & \tau_{SQ} & \tau_{SS} \end{pmatrix}$$

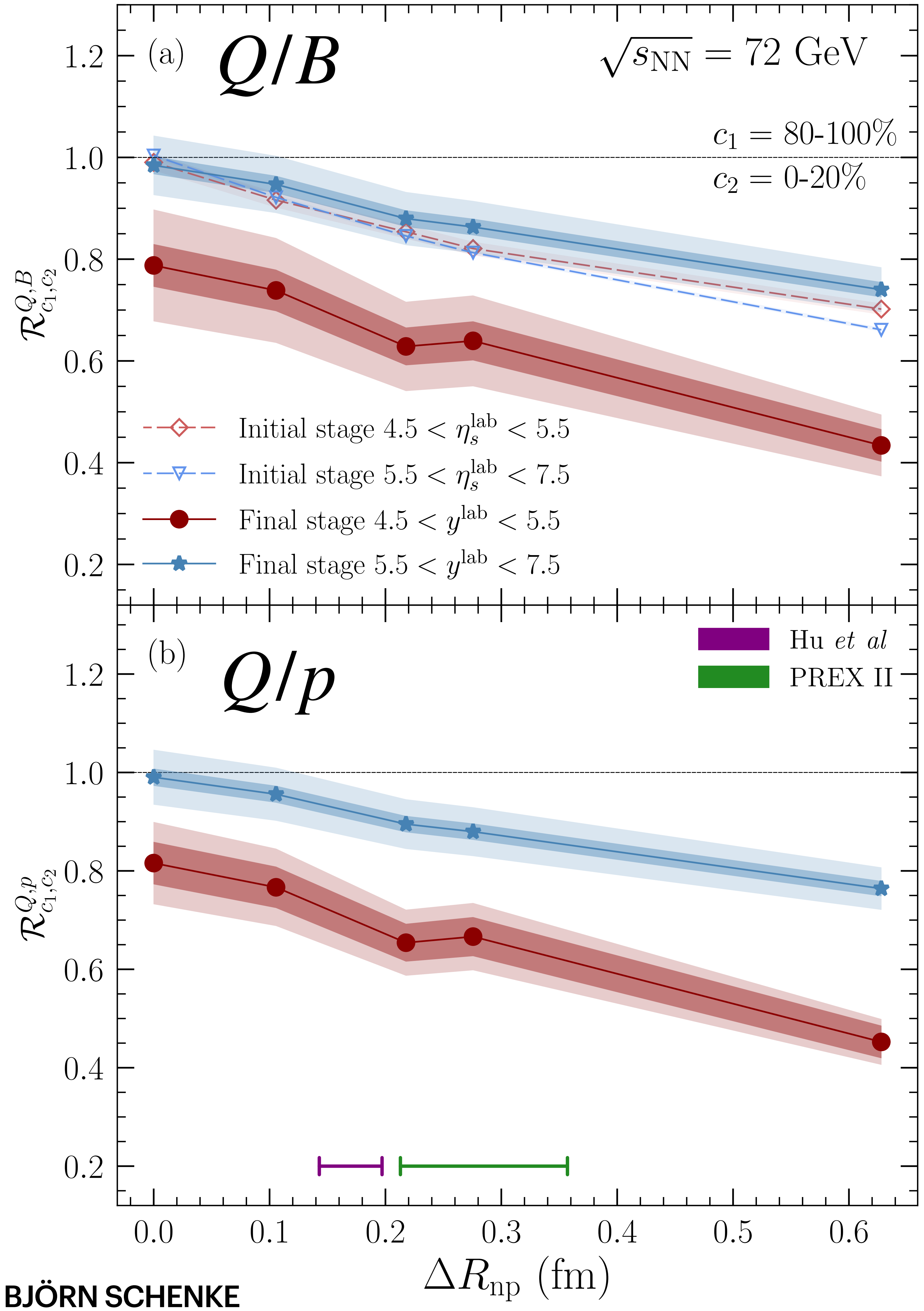
conductivity matrix relaxation time matrix

A. Monnai, G. Pihan, B. Schenke, C. Shen
arXiv:2601.12384, PRC, in print

Take the maximum effect of 5% as systematic error for our p+Pb result



FIXED TARGET MODE WITH LHCb



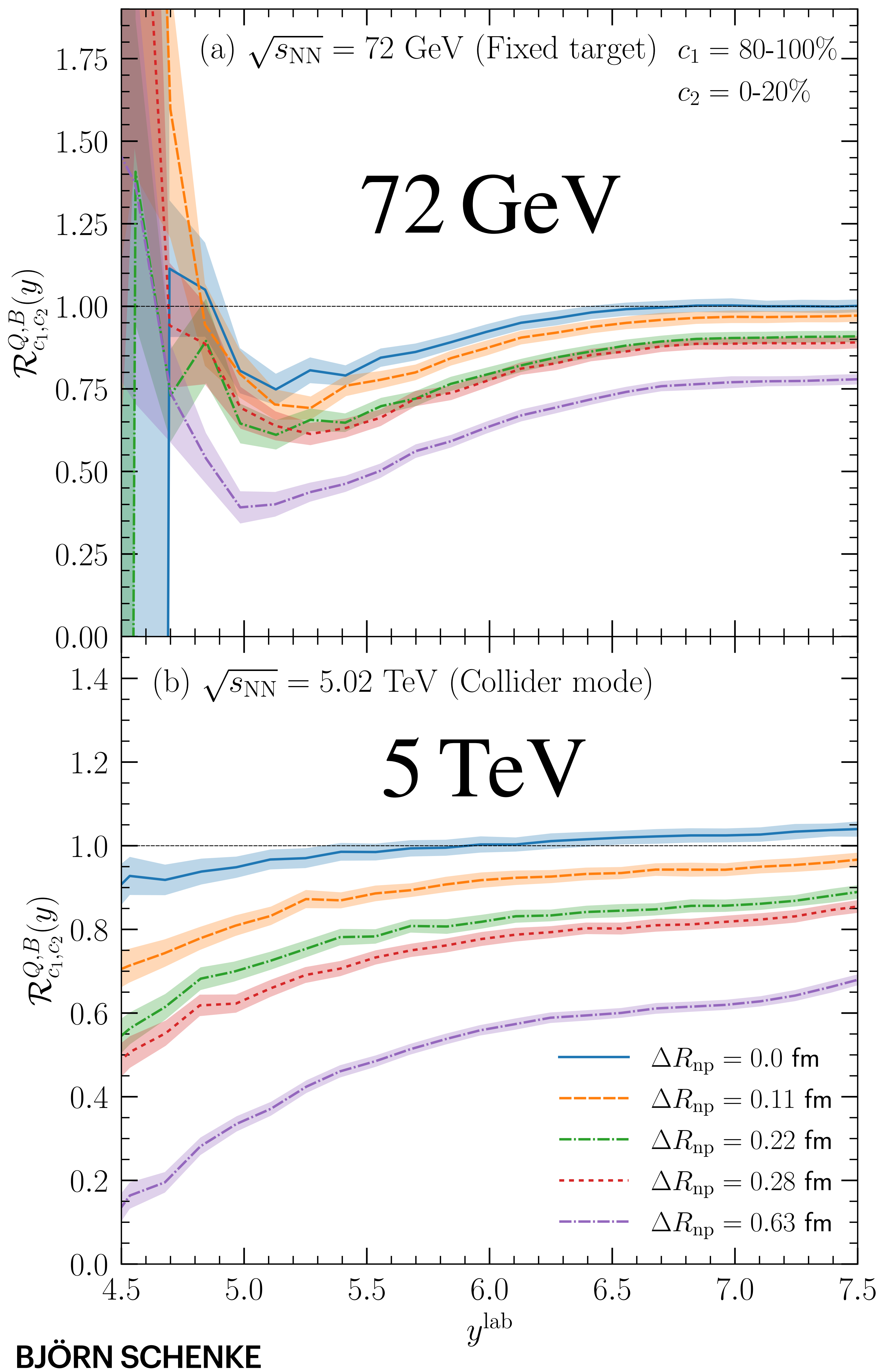
$4.5 < y^{lab} < 5.5$	Diffusion	Baryon stopping	R_n^{WS}	total
$\mathcal{R}^{Q,B}_{c_1,c_2}$	5.0	12.9	1.5	13.9
$\mathcal{R}^{Q,p}_{c_1,c_2}$	5.0	8.8	1.5	10.2

$5.5 < y^{lab} < 7.5$	Diffusion	Baryon stopping	R_n^{WS}	total
$\mathcal{R}^{Q,B}_{c_1,c_2}$	5.0	2.6	1.6	5.9
$\mathcal{R}^{Q,p}_{c_1,c_2}$	5.0	2.6	1.3	5.6

Weaker dependence on the neutron skin.
Collider mode seems referable.
But provides additional constraint.
For $4.5 < y_{lab} < 5.5$ $\mathscr{R} \neq 1$ for vanishing ΔR_{np}:
Possibly due to species dependent thermal smearing at participation and/or different B and Q stopping.

G. Pihan, A. Monnai, B. Schenke, C. Shen, e-Print: 2509.21644

RAPIDITY DEPENDENCE



The differential Q/B double ratio in the laboratory frame as a function of rapidity for different values of the neutron skin thickness

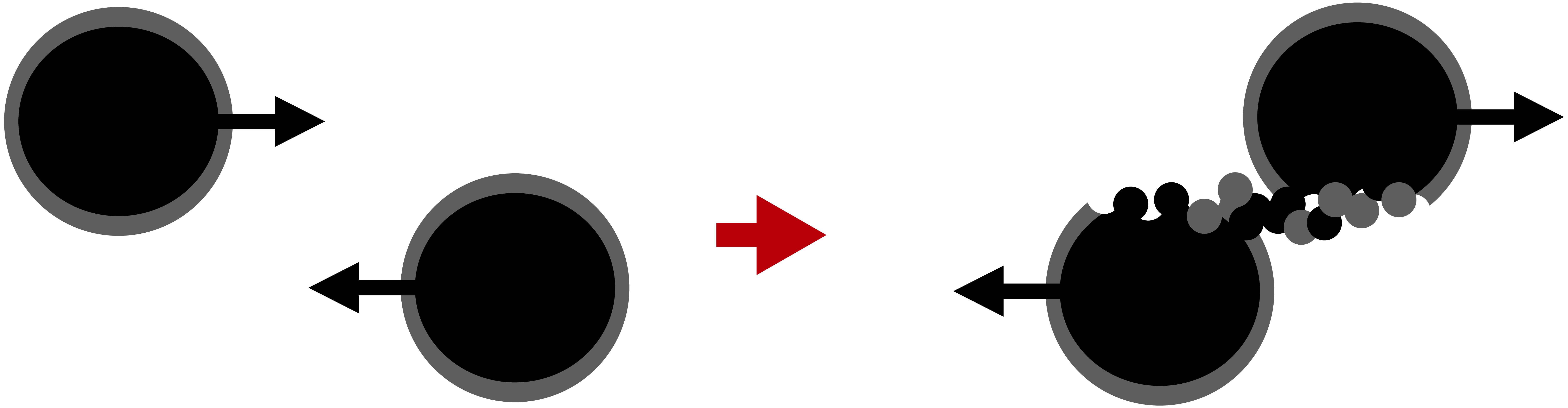
$$\mathscr{R}^{Q,B}_{c_1,c_2}(y) \equiv \frac{\langle dN_Q/dy\rangle_{\text{ev}}(y,c_1)}{\langle dN_B/dy\rangle_{\text{ev}}(y,c_1)} \Big/ \frac{\langle dN_Q/dy\rangle_{\text{ev}}(y,c_2)}{\langle dN_B/dy\rangle_{\text{ev}}(y,c_2)}$$

The signal is cleaner at more forward rapidity

G. Pihan, A. Monnai, B. Schenke, C. Shen, e-Print: 2509.21644

Pb+Pb COLLISIONS

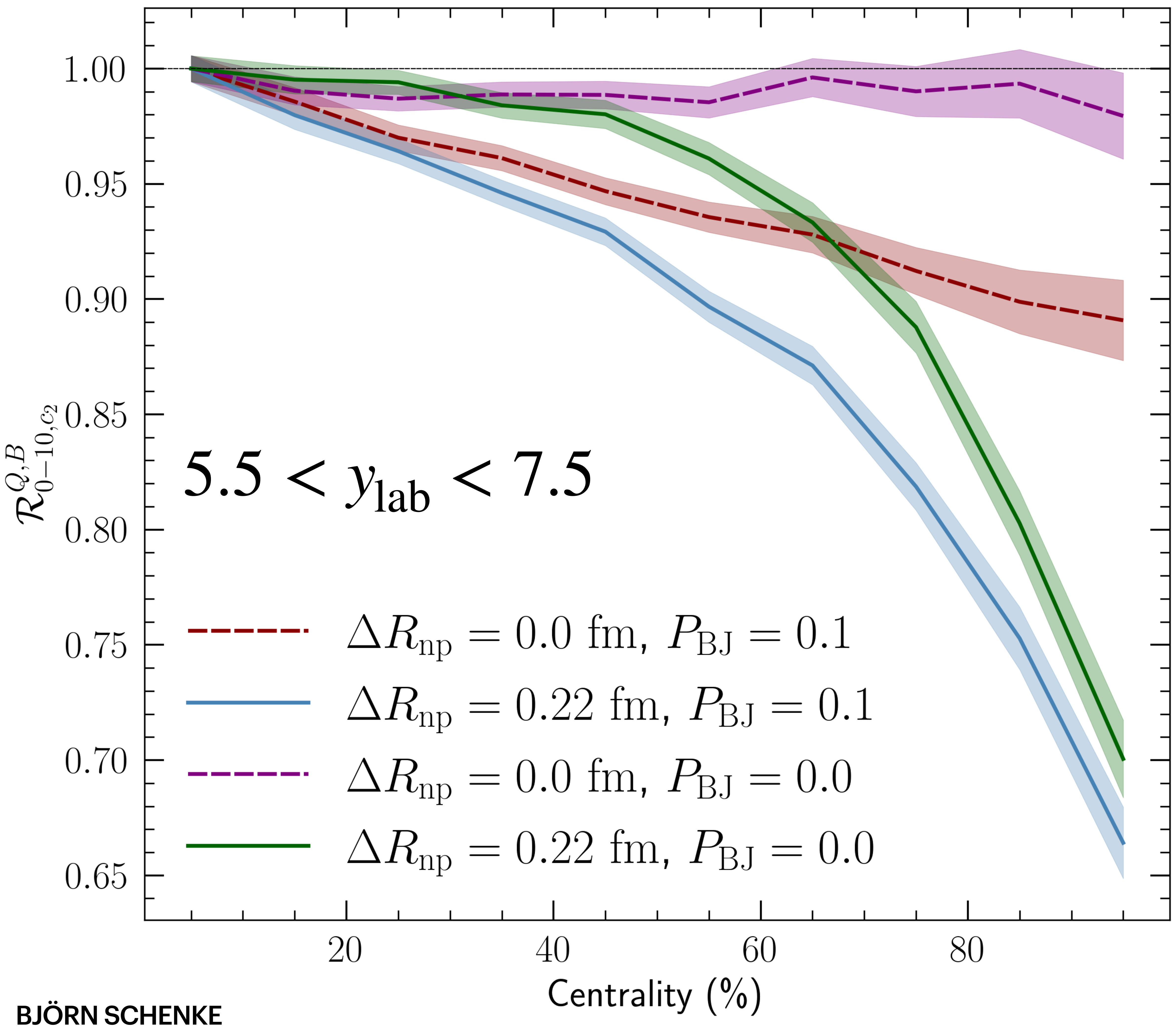
Measure the same observable in Pb+Pb collisions



Better correlation between event activity and geometry

Pb+Pb COLLISIONS

The same observable in Pb+Pb collisions

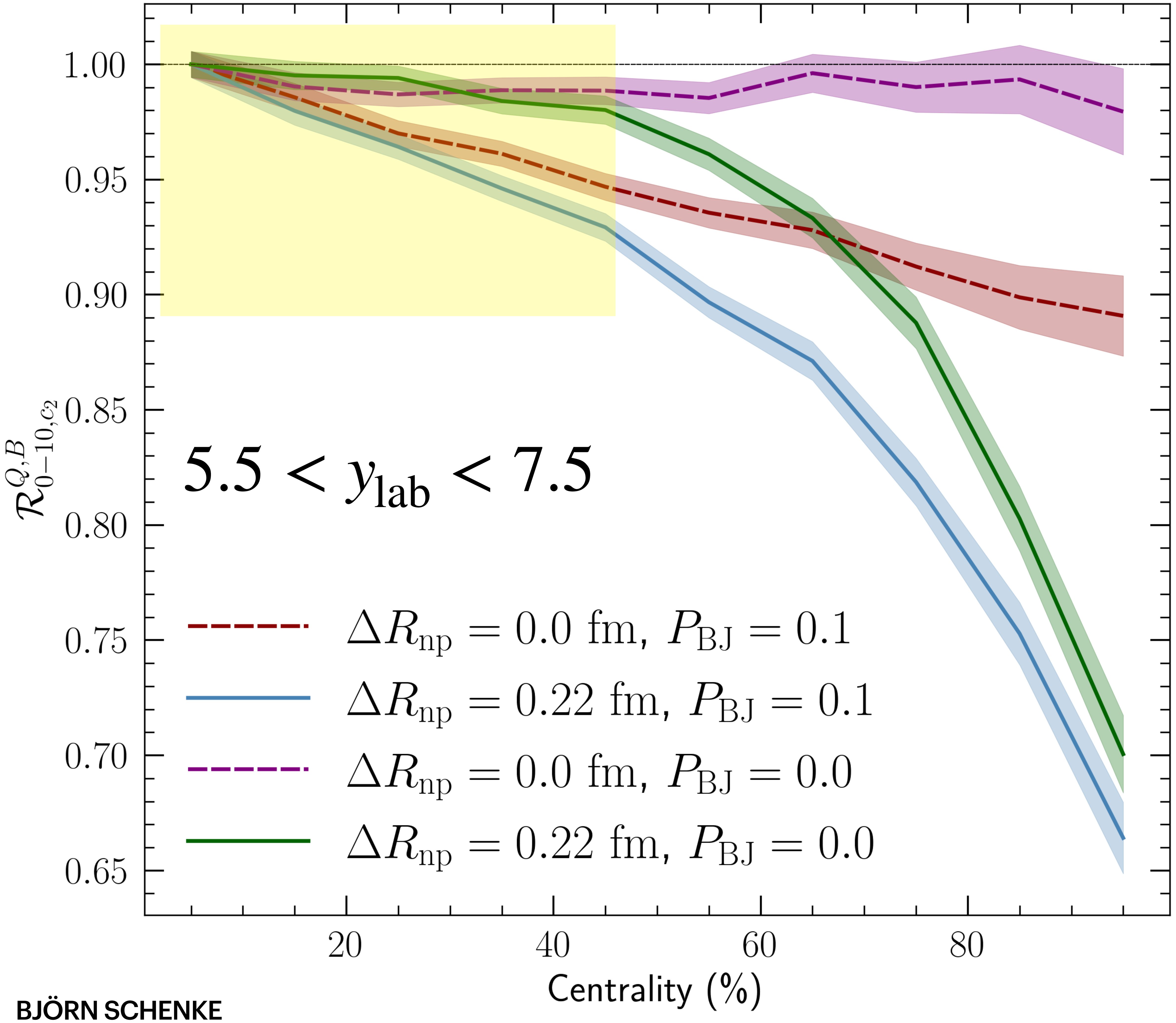


Problem:

Sensitive to baryon stopping and the neutron skin

Pb+Pb COLLISIONS

The same observable in Pb+Pb collisions

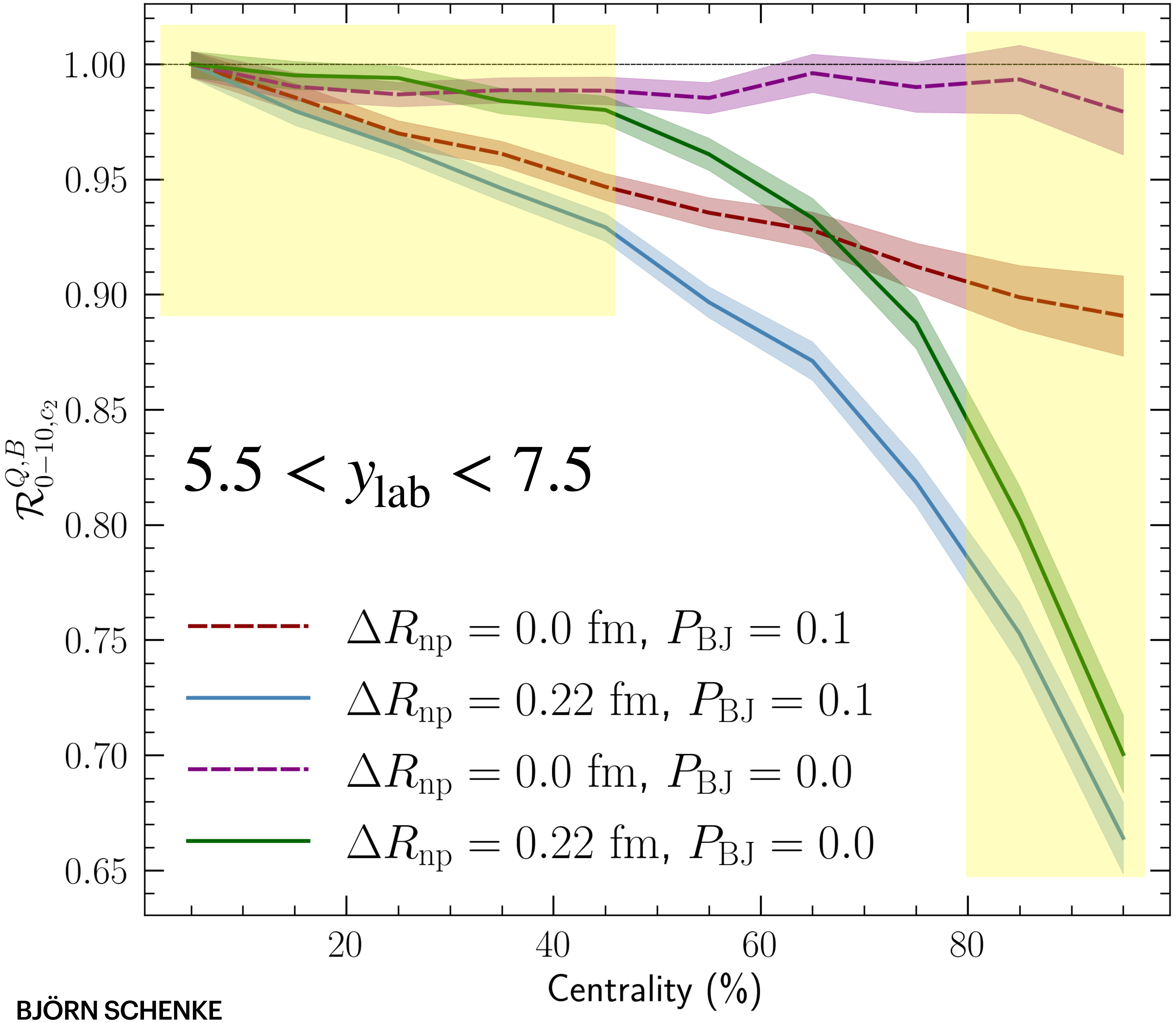


Problem:
Sensitive to baryon stopping and the neutron skin

More central events: Slope sensitive to the choice of baryon stopping

Pb+Pb COLLISIONS

The same observable in Pb+Pb collisions



Problem:
Sensitive to baryon stopping and the neutron skin

More central events: Slope sensitive to the choice of baryon stopping

Peripheral events: Sensitive to the neutron skin

SUMMARY

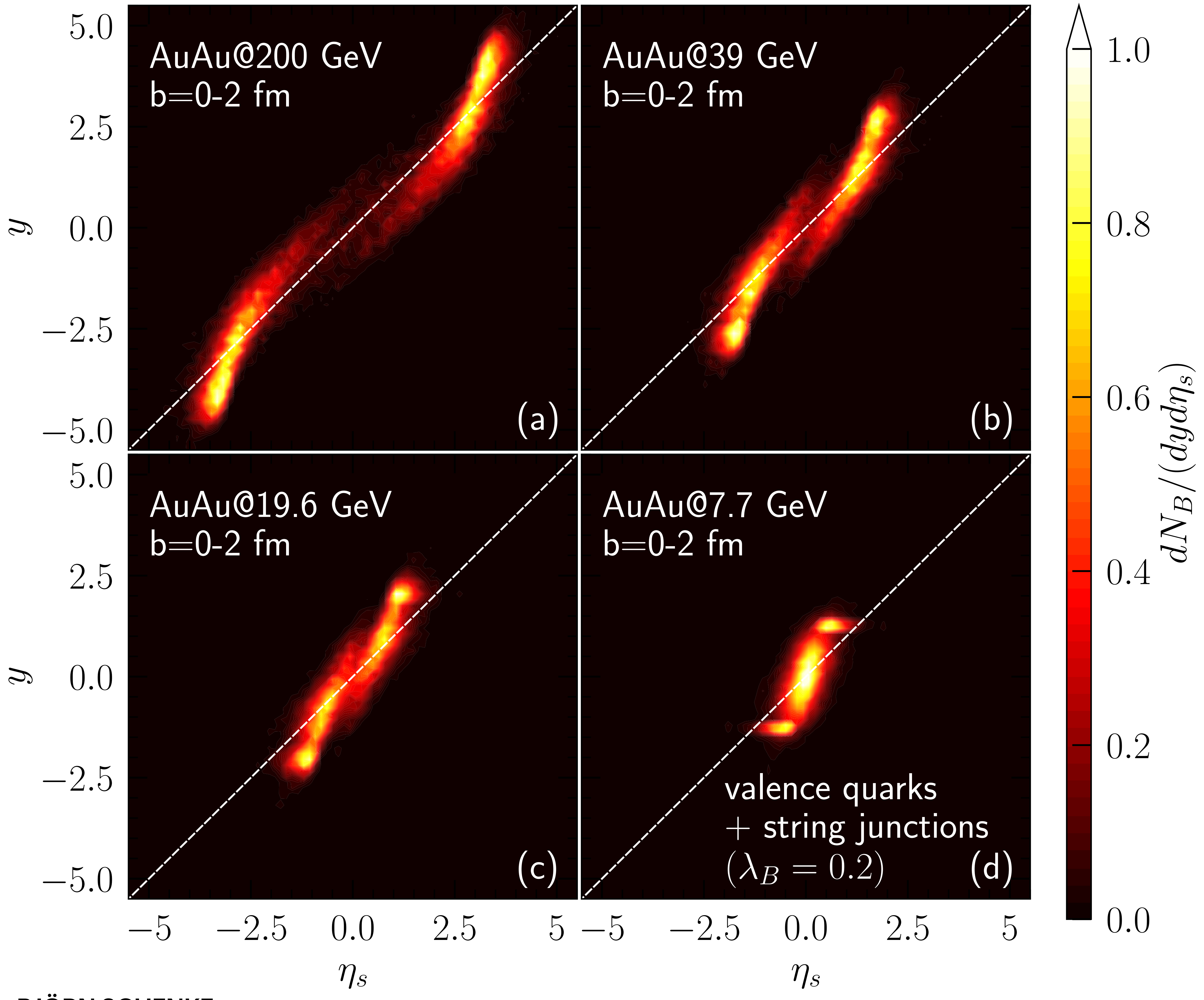
- High energy p+Pb and Pb+Pb collisions: Baryon and electric charge transported in rapidity
- How much charge vs. baryon number in peripheral collisions depends on the size of the Pb neutron skin
- **A double ratio of Q/B in peripheral vs. central collisions is sensitive to the neutron skin of Pb**
- Q/p is a good measurable proxy and e.g. LHCb has potential to perform this measurement
- Systematic uncertainties from baryon stopping, charge diffusion, modeling of neutron skin

- Can do this for other nuclei, e.g. $^{48}\mathrm{Ca}$ (although expensive)
- Experimental uncertainties, e.g. from centrality selection, acceptance, etc.

BACKUP

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

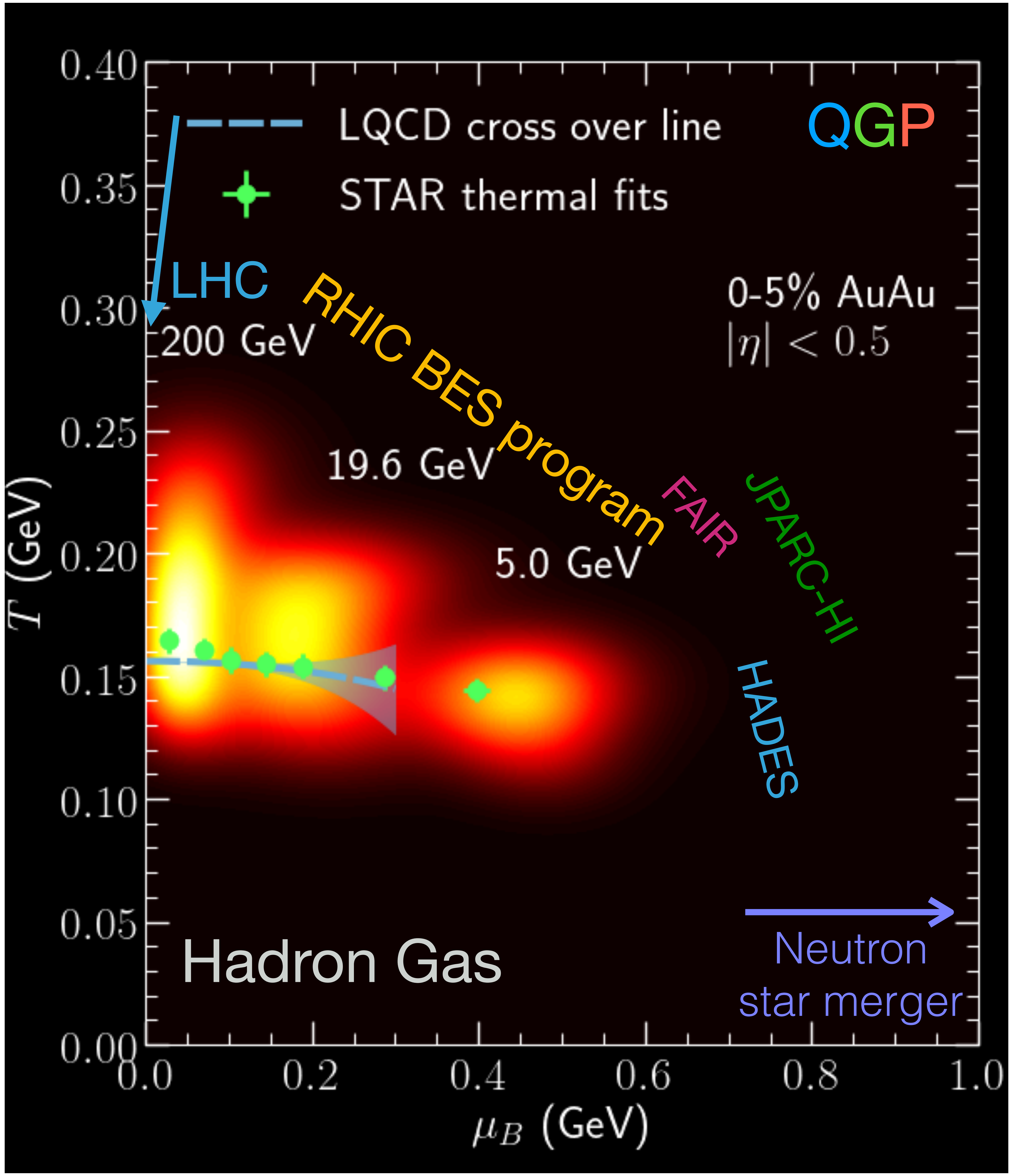
Energy-momentum current and net baryon density are fed into hydrodynamic simulations as source terms

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

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

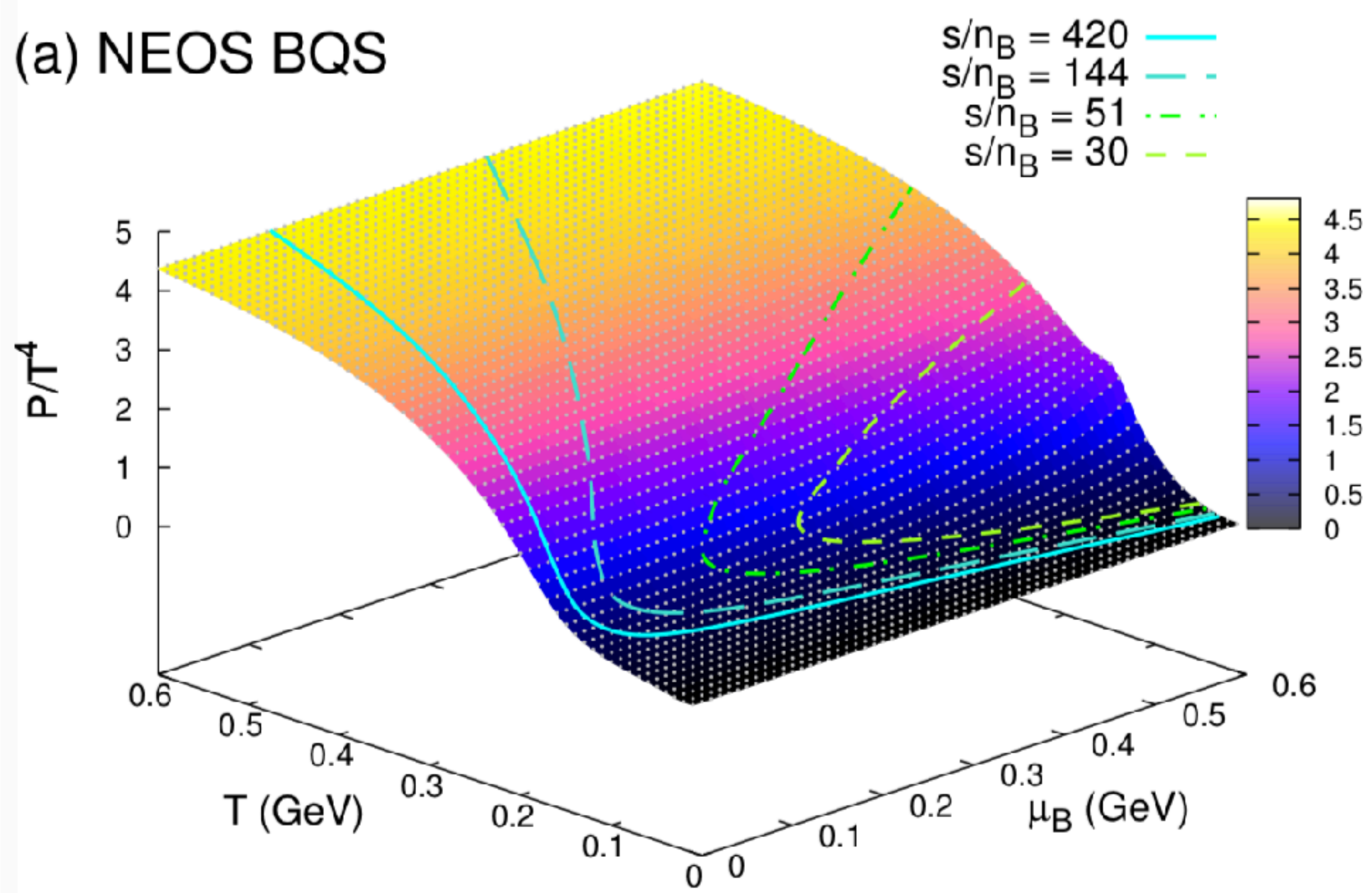
A. Monnai, B. Schenke, C. Shen, Phys. Rev. C 100, 024907 (2019)
A. Monnai, B. Schenke, C. Shen, Int.J.Mod.Phys.A 36 (2021) 07, 2130007



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

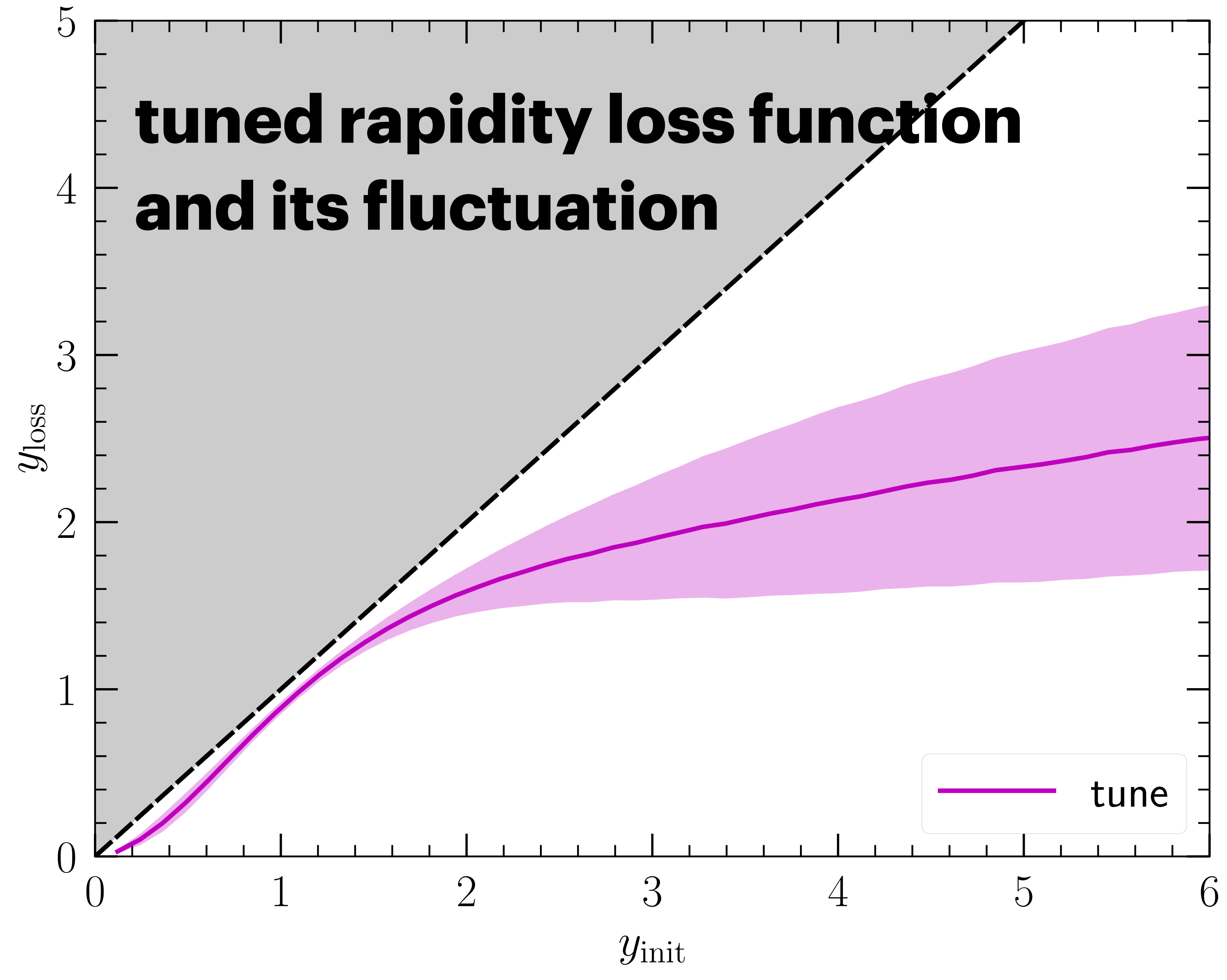
$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_J)]\frac{P_{\rm had}(T,\mu_J)}{T^4} + \frac{1}{2}[1 + f(T,\mu_J)]\frac{P_{\rm lat}(T,\mu_J)}{T^4}$$

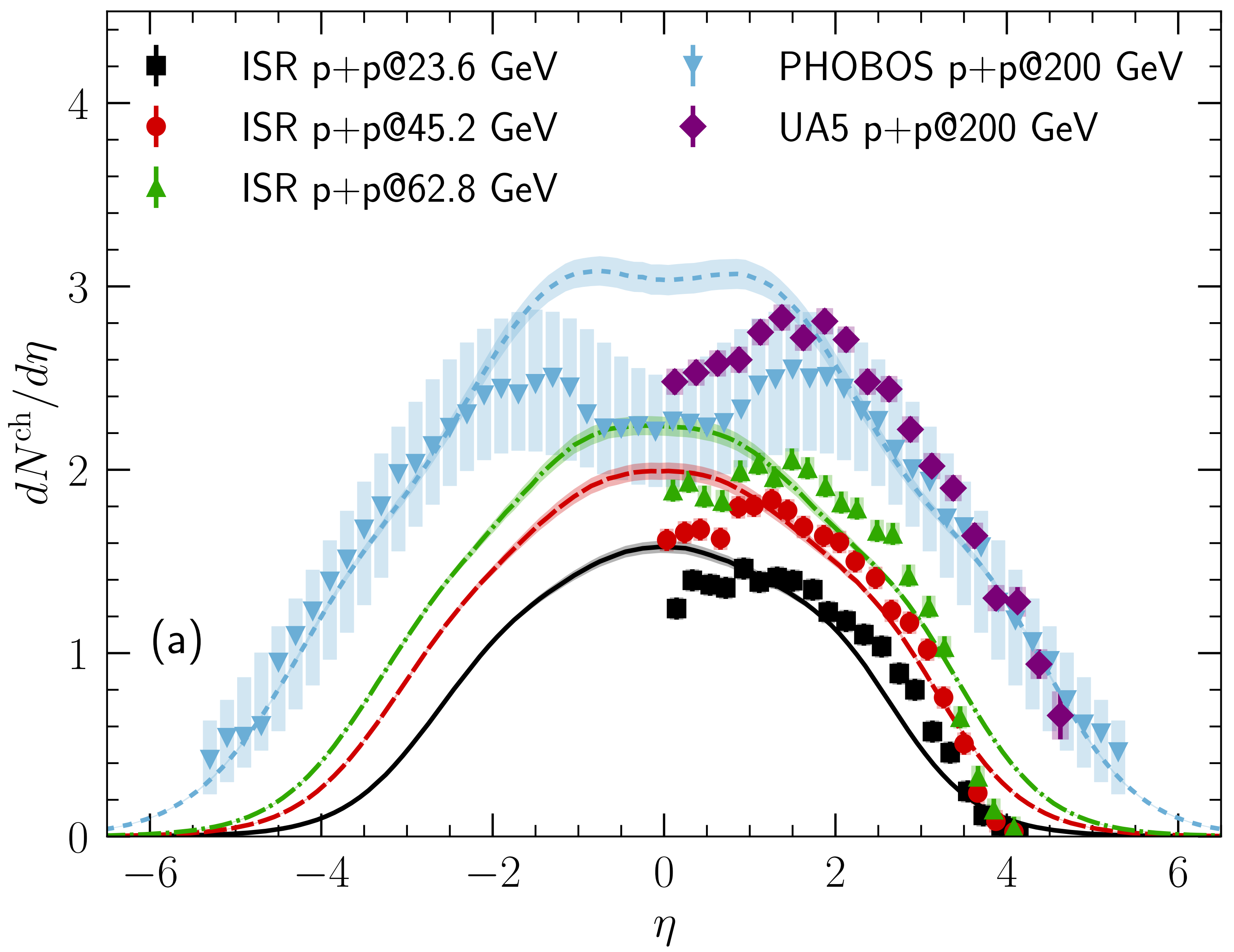
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

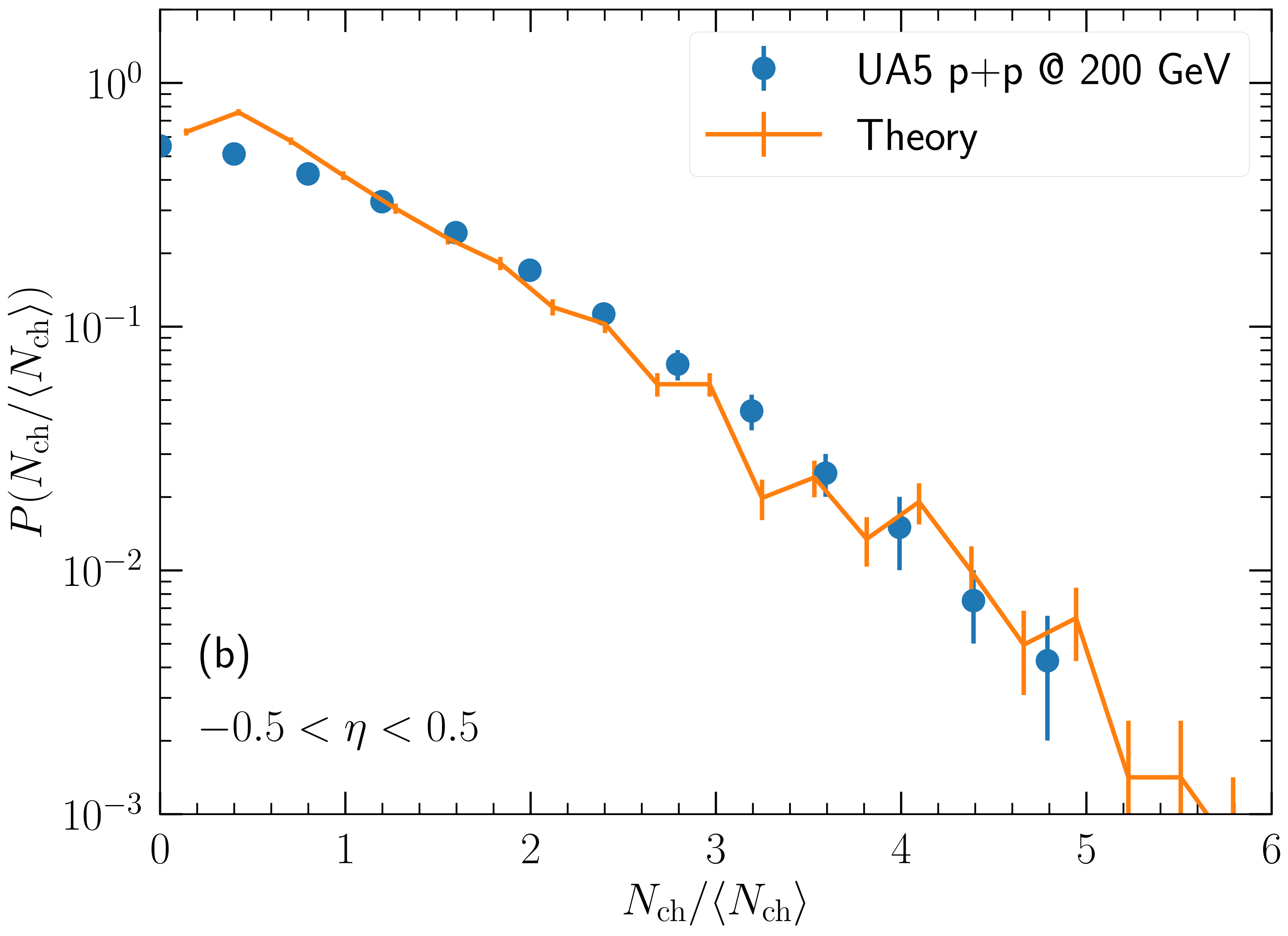
Being extended to fully 4D EOS $P(\varepsilon, n_B, n_Q, n_S)$ **see Gregoire Pihan's talk**

CALIBRATION IN p+p COLLISIONS

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



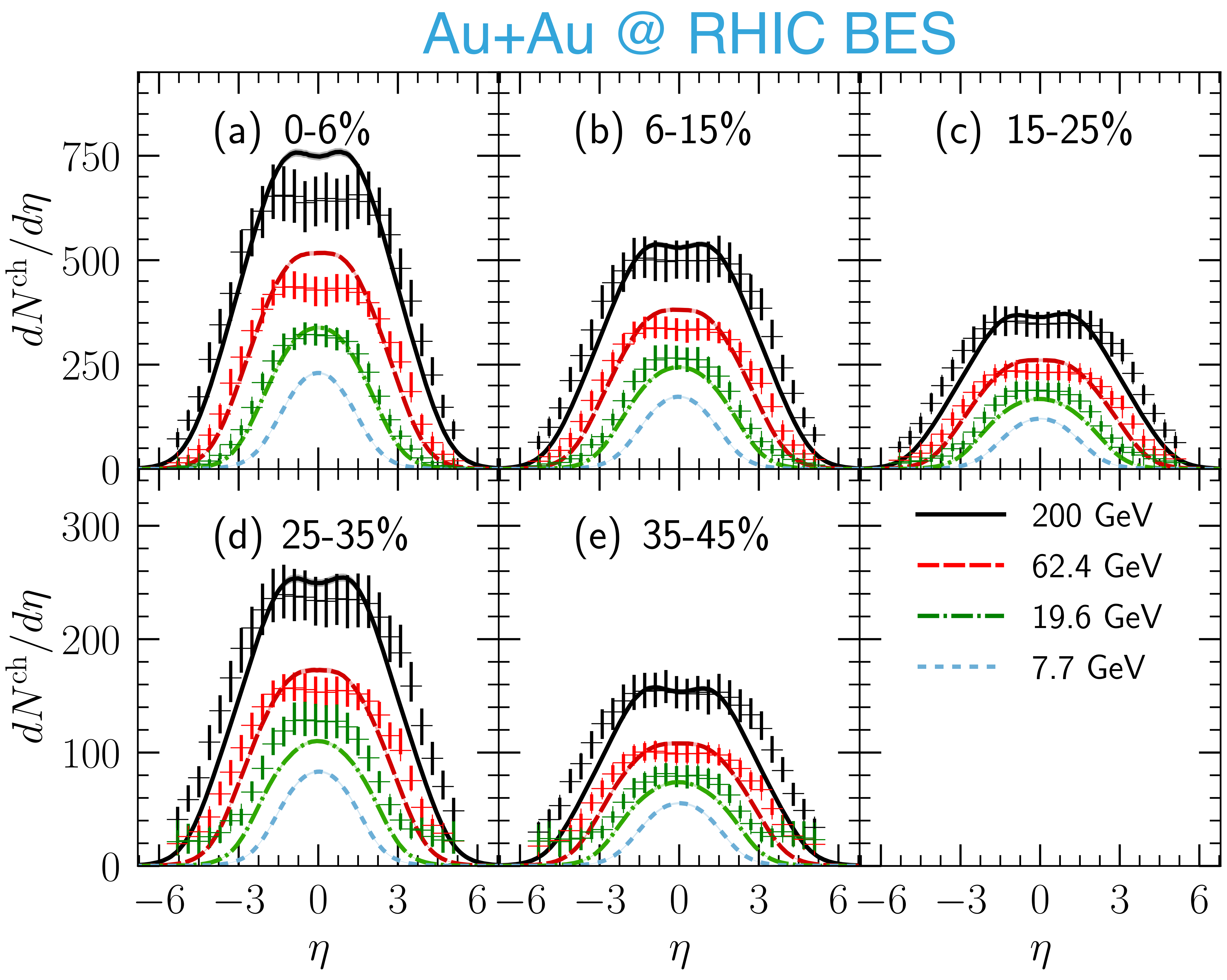


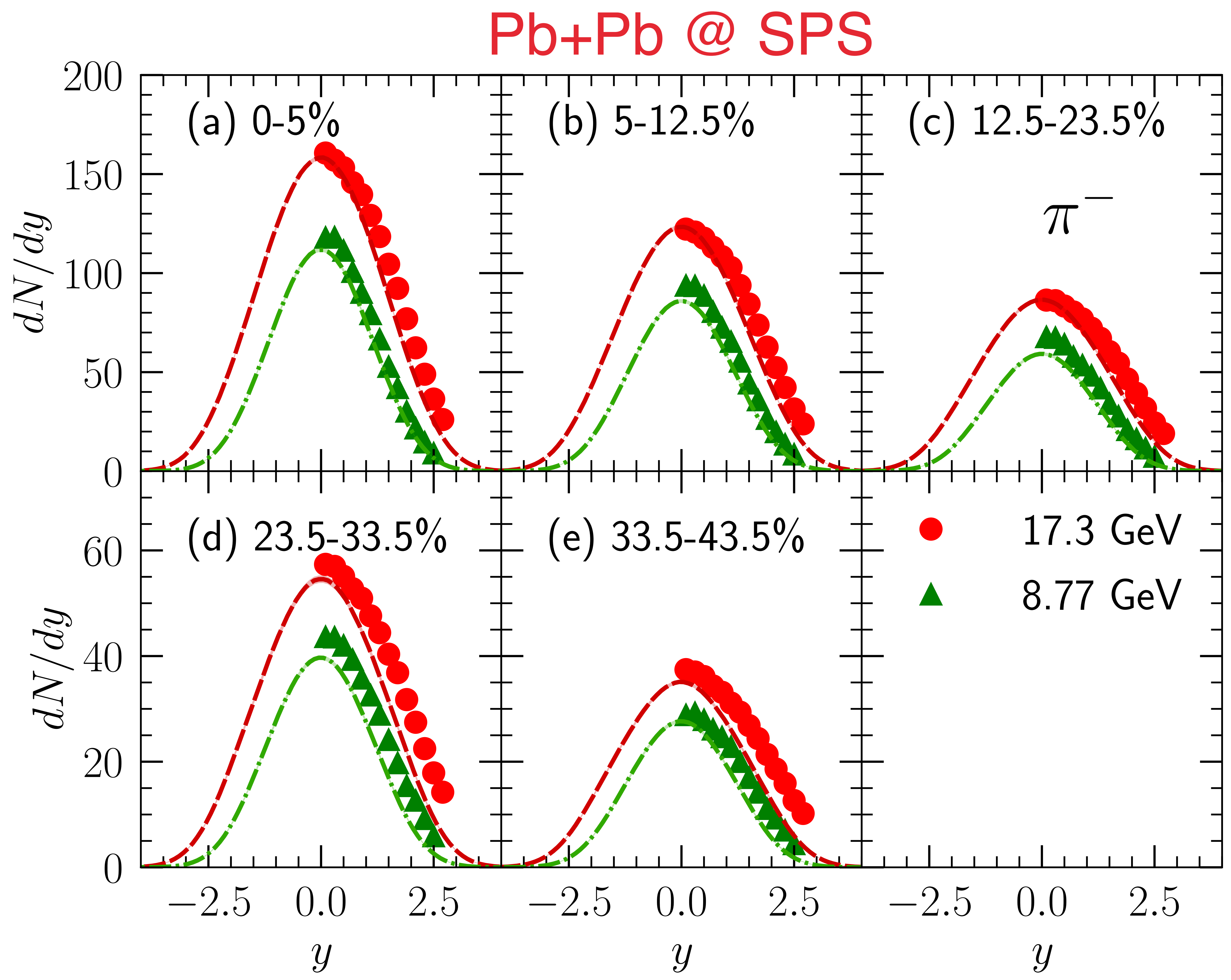


Calibrated with minimum bias p+p measurements at mid-rapidity and their multiplicity distributions

MODEL VALIDATION WITH A+A DATA

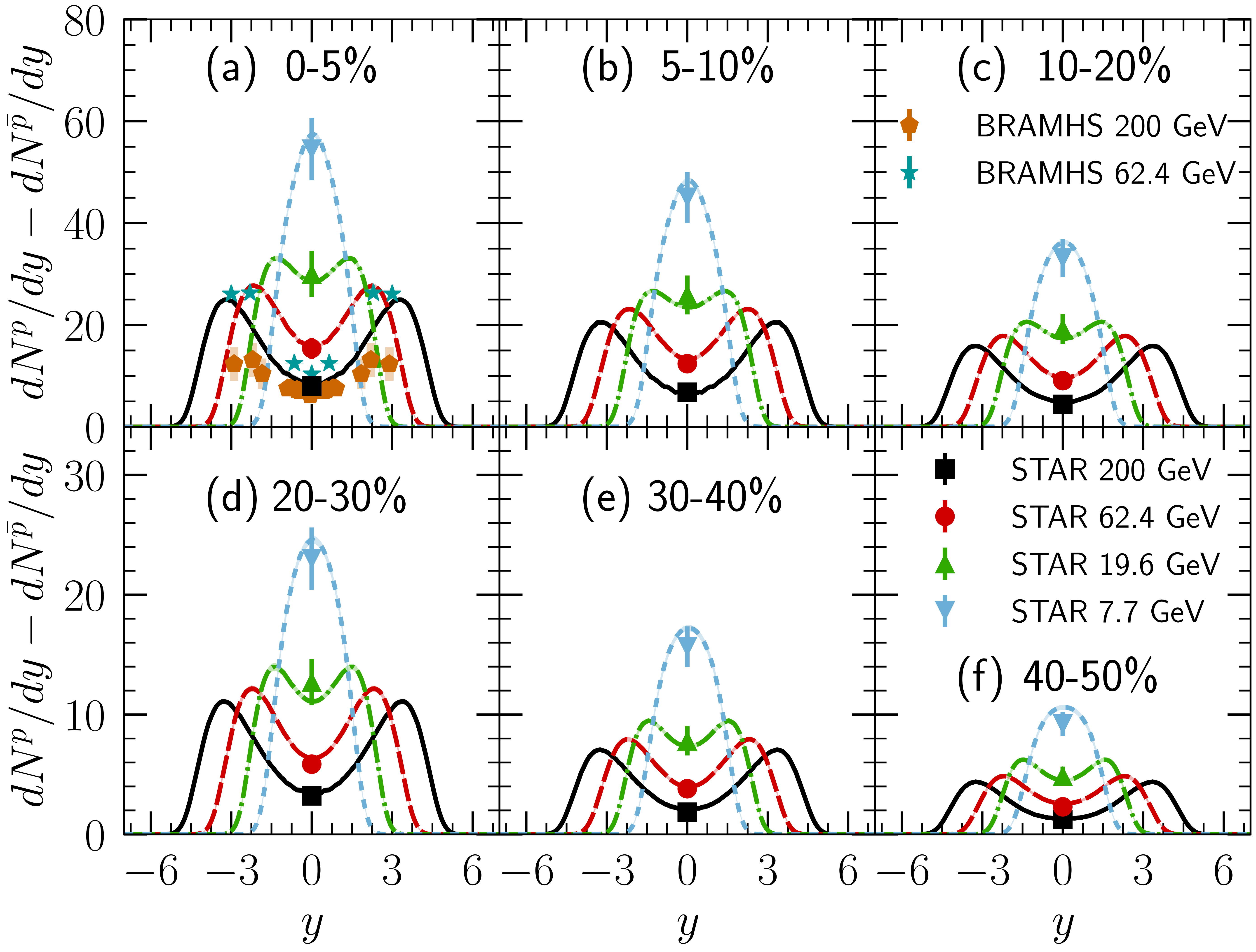
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)





NET-PROTON PRODUCTION

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



- 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

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:

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

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