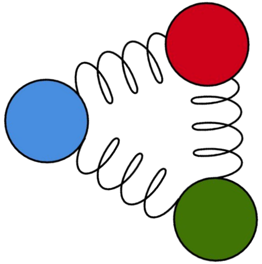
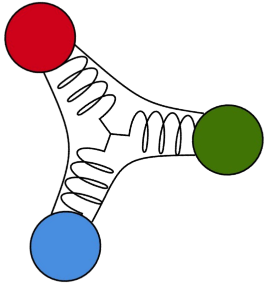
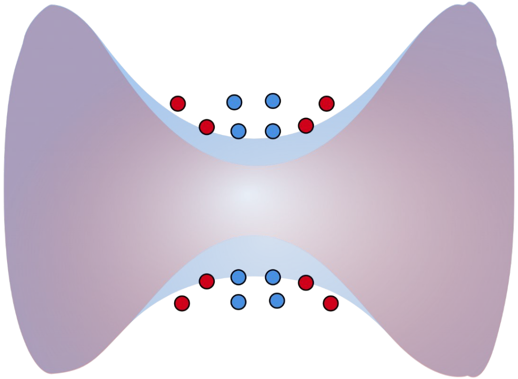
Tracing the conserved charges in high energy collisions







Hydrodynamics and related observables in heavy-ion collisions
Oct. 31, 2024, Nantes, France

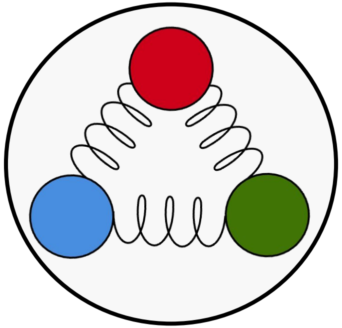
Grégoire **Pihan**[1], Akihiko **Monnai**[2], Bjoern **Schenke**[3], Chun **Shen**[1,3]

[1]*Wayne state University*, Detroit, USA,
[2]*Osaka Institute of technology*, Osaka, Japan,
[3]*Brookhaven National Lab*, Upton, USA

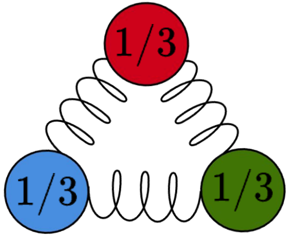
What carries the baryon number?

How do we build a baryon from quarks?

$$B = 1$$



$$B = \frac{1}{3}(n_q - n_{\bar{q}})$$

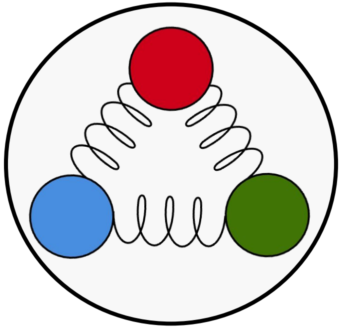


This is an assumption!

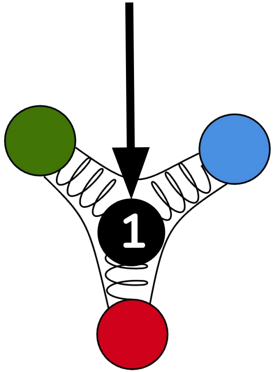
What carries the baryon number?

String junction?

$$B = 1$$

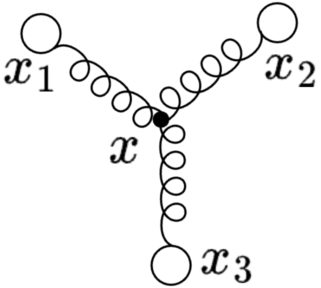


$$B = 1$$



What carries the baryon number?

String junction: The most simple way to build a baryon from quarks



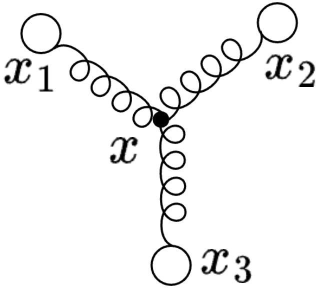
Non-perturbative configuration of gluons represented by a locally **gauge-invariant** state vector.

G.C Rossi and G.Veneziano PHYSICS REPORTS 63, No. 3 (1980)

$$B = \epsilon^{ijk}\Big[P\exp\big(ig\int_{x_1}^{x} A_\mu \mathrm{d}x^\mu\big)q(x_1)\Big]_i\Big[P\exp\big(ig\int_{x_2}^{x} A_\mu \mathrm{d}x^\mu\big)q(x_2)\Big]_j\Big[P\exp\big(ig\int_{x_3}^{x} A_\mu \mathrm{d}x^\mu\big)q(x_3)\Big]_k$$

What carries the baryon number?

String junction: The most simple way to build a baryon from quarks



Non-perturbative configuration of gluons represented by a locally **gauge-invariant** state vector.

G.C Rossi and G.Veneziano PHYSICS REPORTS 63, No. 3 (1980)

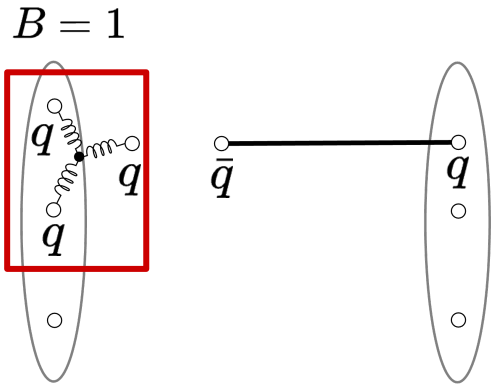
$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu \mathrm{d}x^\mu\right)q(x_1)\right]_i \left[P\exp\left(ig\int_{x_2}^{x} A_\mu \mathrm{d}x^\mu\right)q(x_2)\right]_j \left[P\exp\left(ig\int_{x_3}^{x} A_\mu \mathrm{d}x^\mu\right)q(x_3)\right]_k$$

The string junction x carries the baryon number inside the baryon

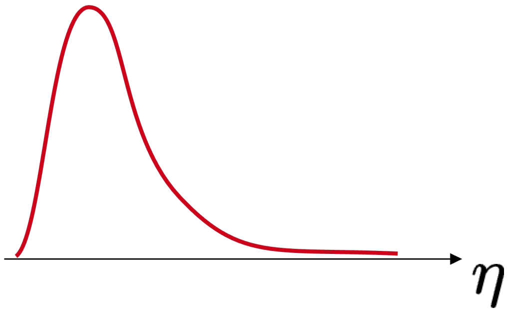
Baryon stopping in central pp and AA collisions

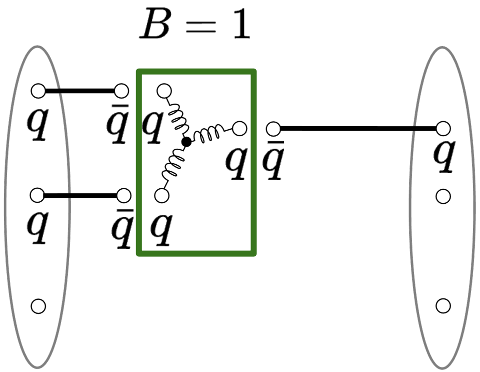
D. Kharzeev, Physics Letters B **378**, 238 (1996)

Baryon stopping and the junction

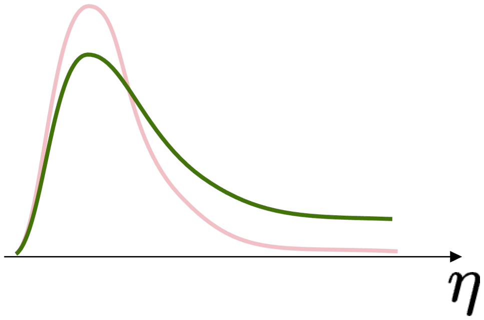


The baryon number remain attached to the nucleon

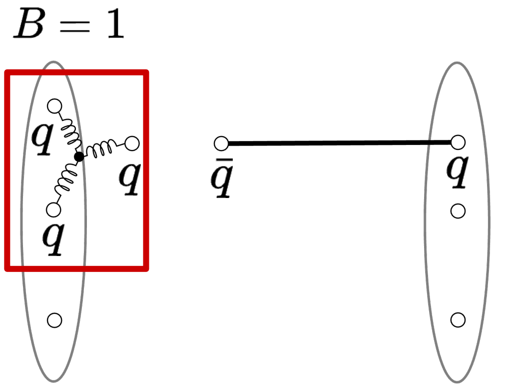




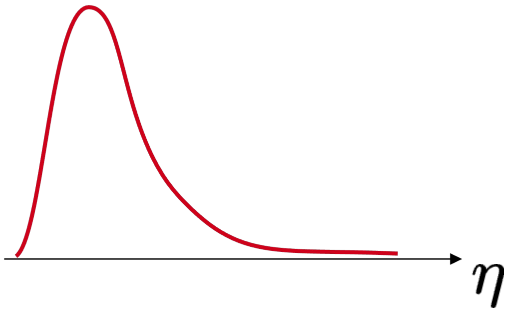
The baryon number to fluctuate towards mid-rapidity

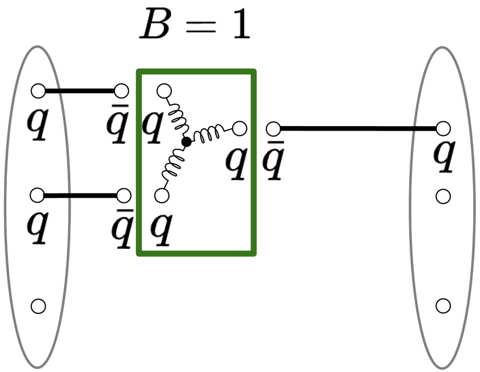


Baryon stopping and the junction

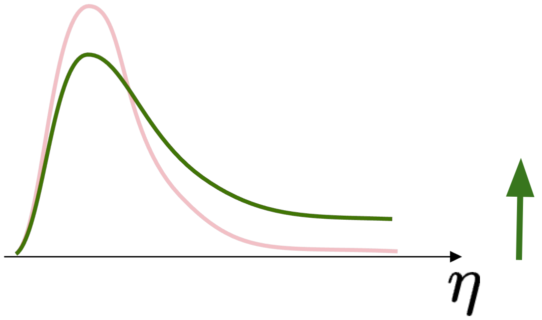


The baryon number remain attached to the nucleon

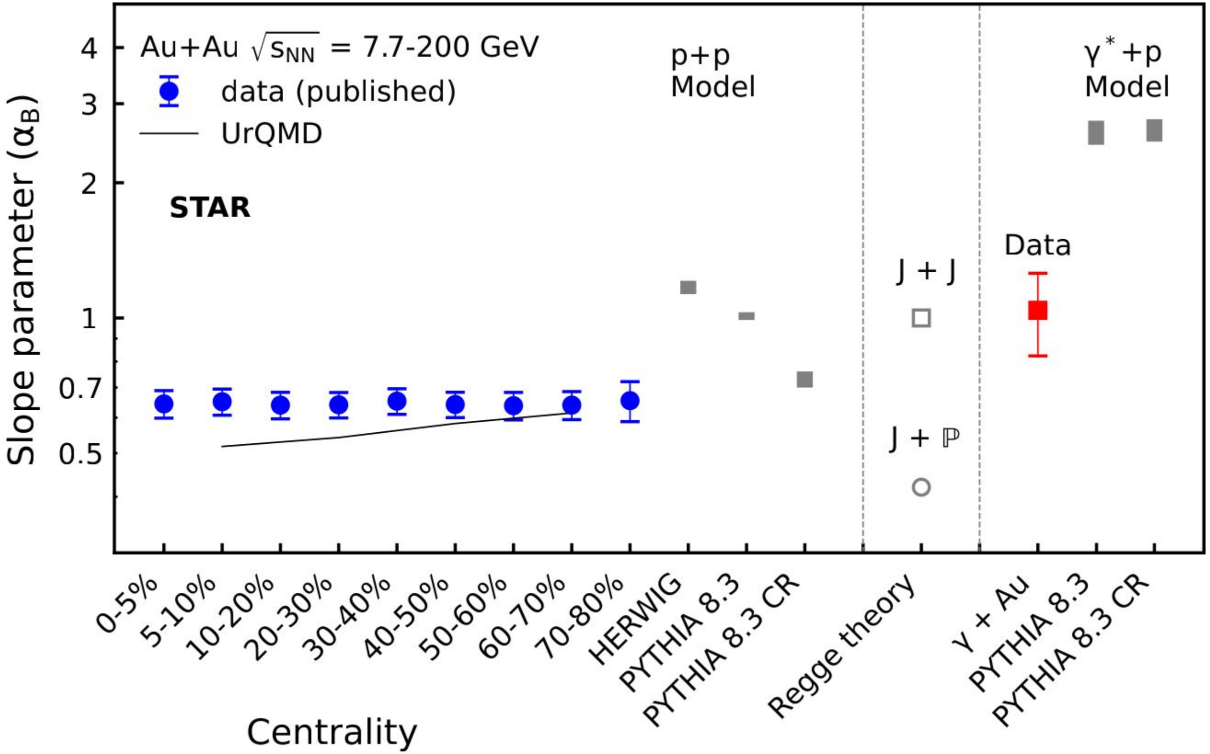




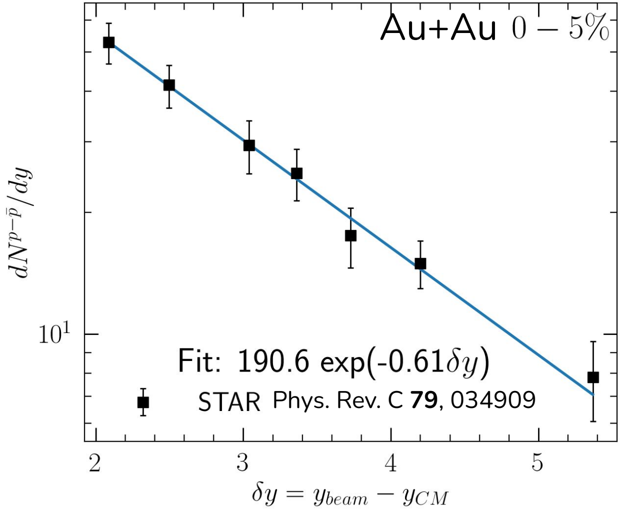
The baryon number to fluctuate towards mid-rapidity



Baryon stopping and string junction



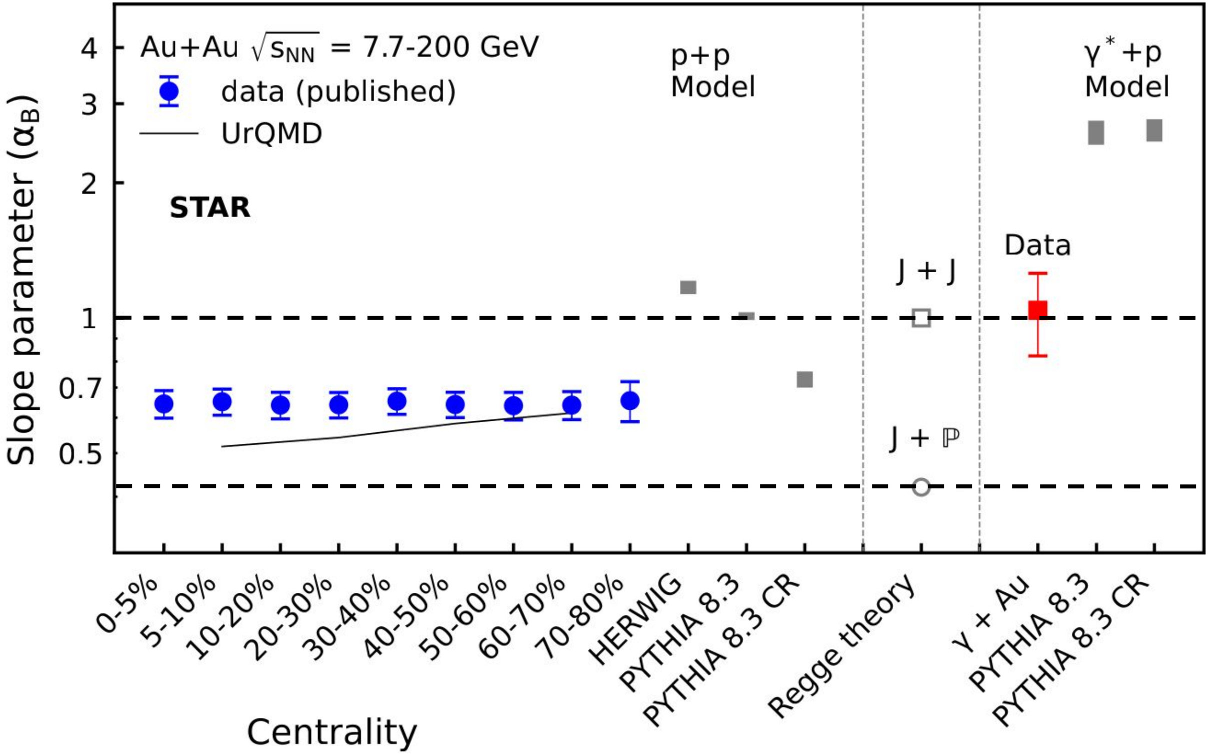
STAR Collab, arxiv:2408.15441



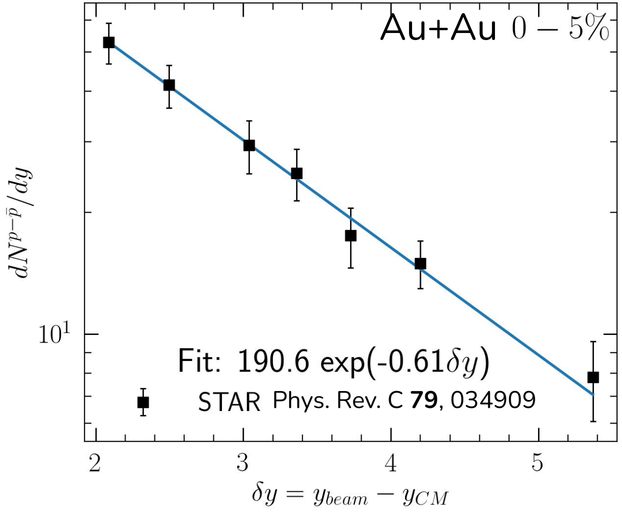
$$\frac{dN^{p-\bar{p}}}{d\delta y} \propto e^{-\alpha_B \delta y}$$

$$\alpha_B = 0.64 \pm 0.05$$

Baryon stopping and string junction



STAR Collab, arxiv:2408.15441



$$\frac{dN^{p-\bar{p}}}{d\delta y} \propto e^{-\alpha_B \delta y}$$

$$\alpha_B = 0.64 \pm 0.05$$

Compatible with
Baryon junction theory predictions!

Insight from the isobar collisions at RHIC

Baryon Junction: carries no electric charge! → **Decorrelation of B and Q!**
if B remains attached to the junction

Isobar Runs: Same number of nucleons A, different number of protons Z $^{96}_{44}\mathrm{Ru}$ $^{96}_{40}\mathrm{Zr}$

Baryon stopping compared to **electric charge stopping!**

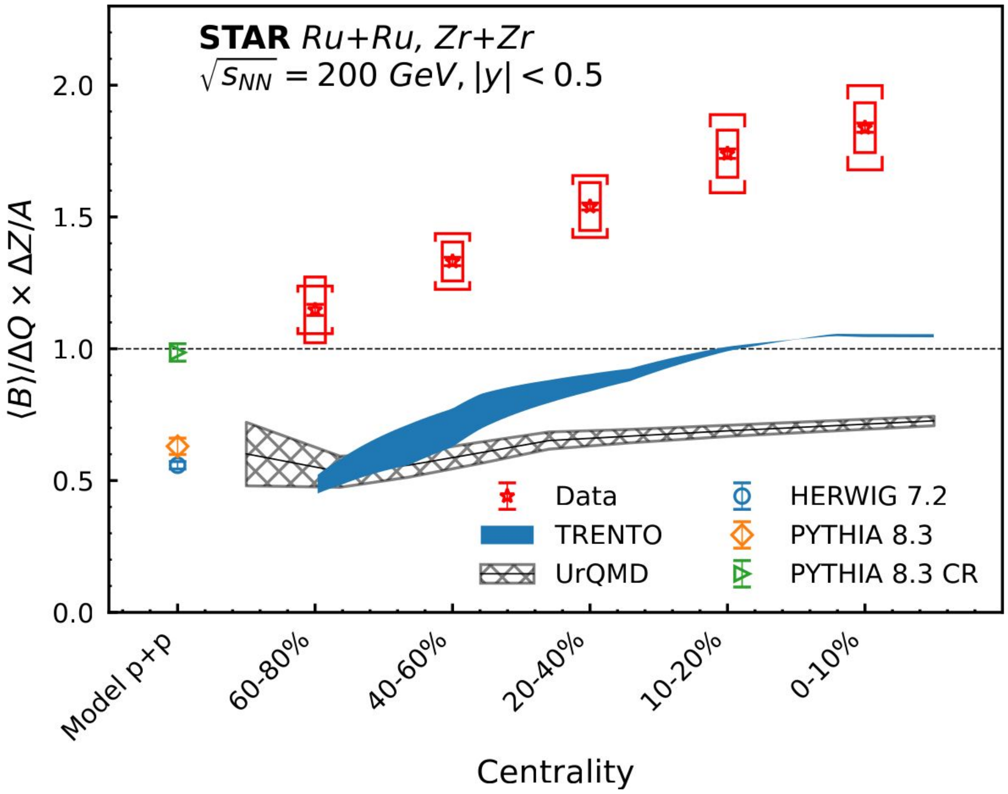
"Equal stoppings"

No longitudinal decorrelation from junction:
B and Q carried by valence quarks!

"Different stoppings"

B and Q are less correlated in the longitudinal direction:
B is carried by the junction!

Insight from the isobar collisions at RHIC



STAR collaboration, arxiv:2408.15441

STAR measurement of stopping ratio deviates from unity

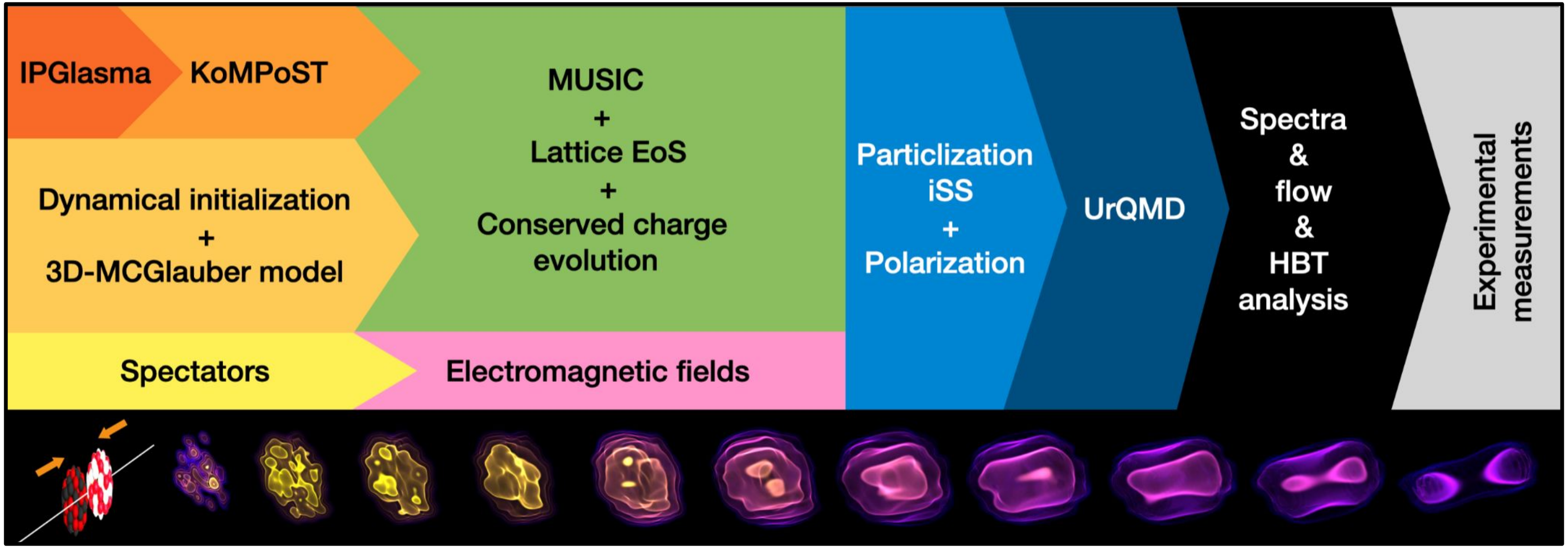
More baryon stopping than electric charge stopping:

Different stoppings!

Is this a sign of the existence of the baryon junction?

The iEBE-MUSIC framework

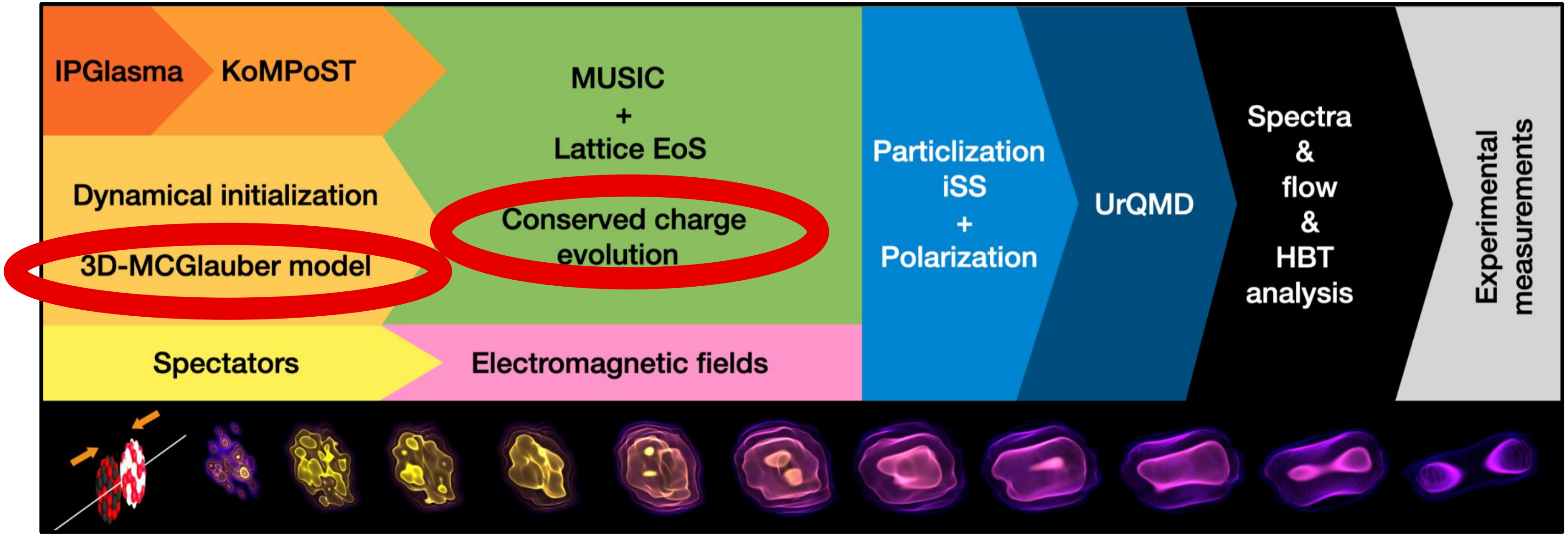
Open source hydrodynamics + hadronic transport hybrid framework



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

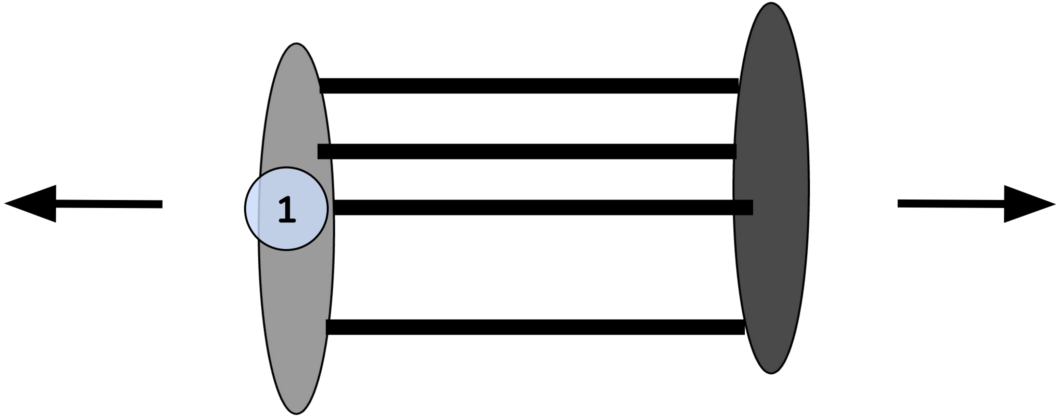
The iEBE-MUSIC framework

Open source hydrodynamics + hadronic transport hybrid framework

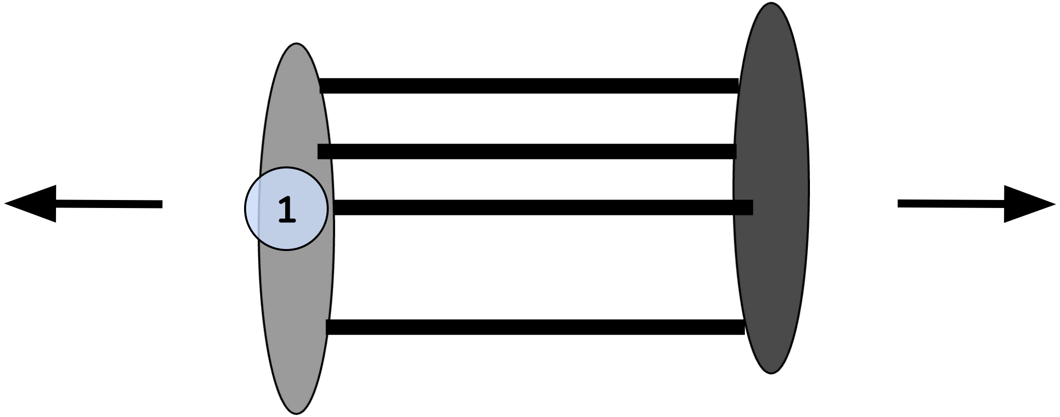


https://github.com/chunshen1987/iEBE-MUSIC

Initial conditions from the string junction 1/3

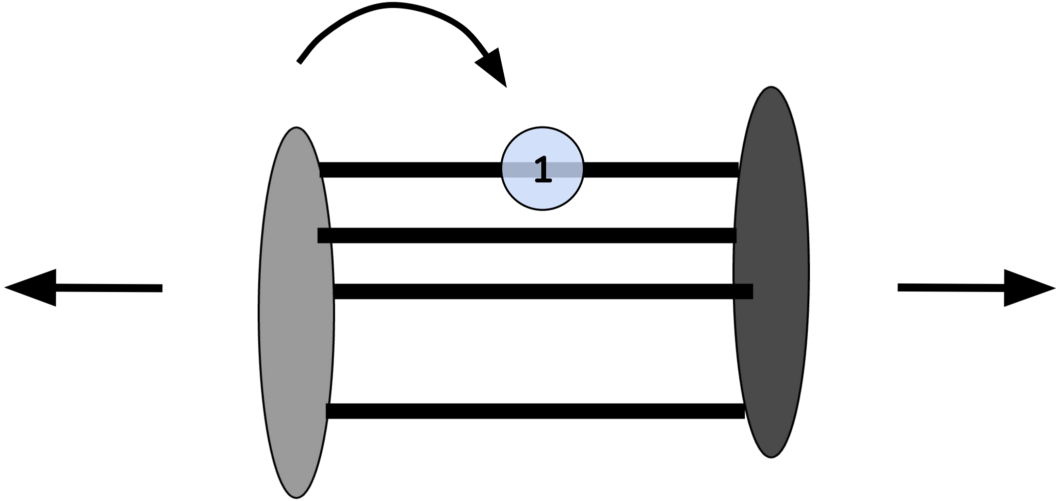


Initial conditions from the string junction 1/3



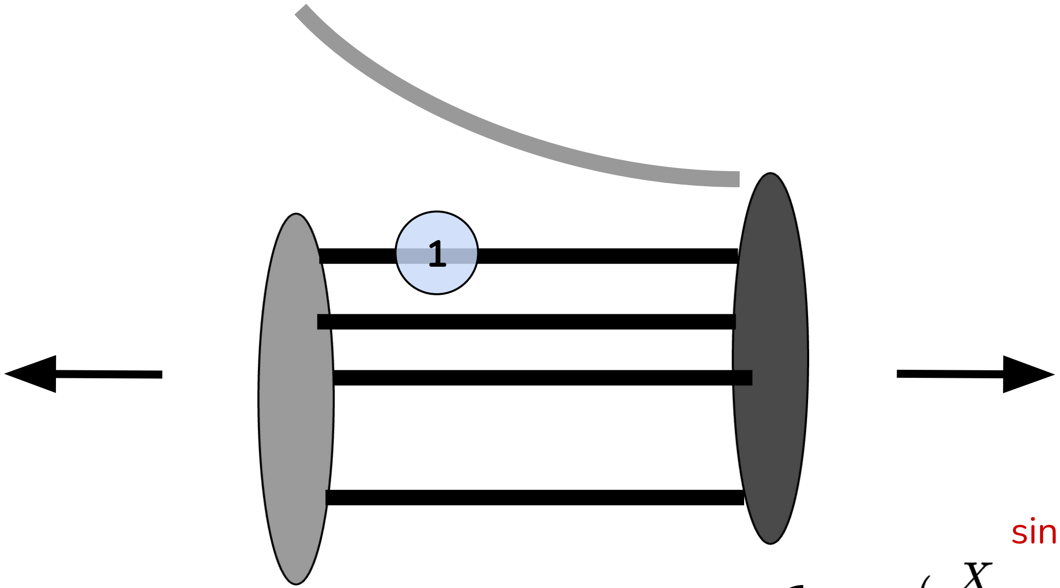
$$P(y^X_{P/T}) = (1 - \lambda_X) y_{P/T}$$

Initial conditions from the string junction 1/3



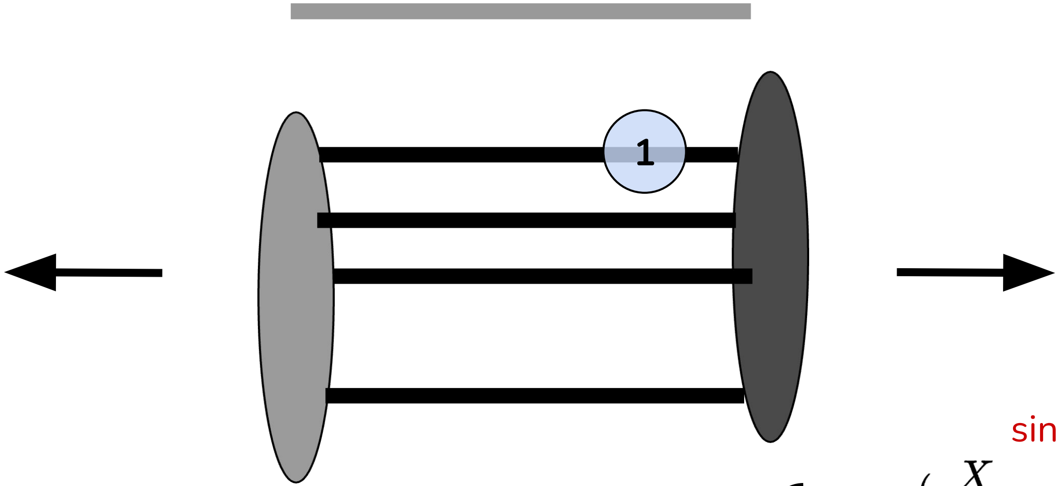
$$P(y^X_{P/T}) = (1-\lambda_X)y_{P/T} + \lambda_X$$

Initial conditions from the string junction 1/3



$$P(y^{X}_{P/T}) = (1-\lambda_X)\, y_{P/T} + \lambda_X \begin{cases} \dfrac{e^{(y^{X}_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)} & \text{single junction} \\ & \end{cases}$$

Initial conditions from the string junction 1/3



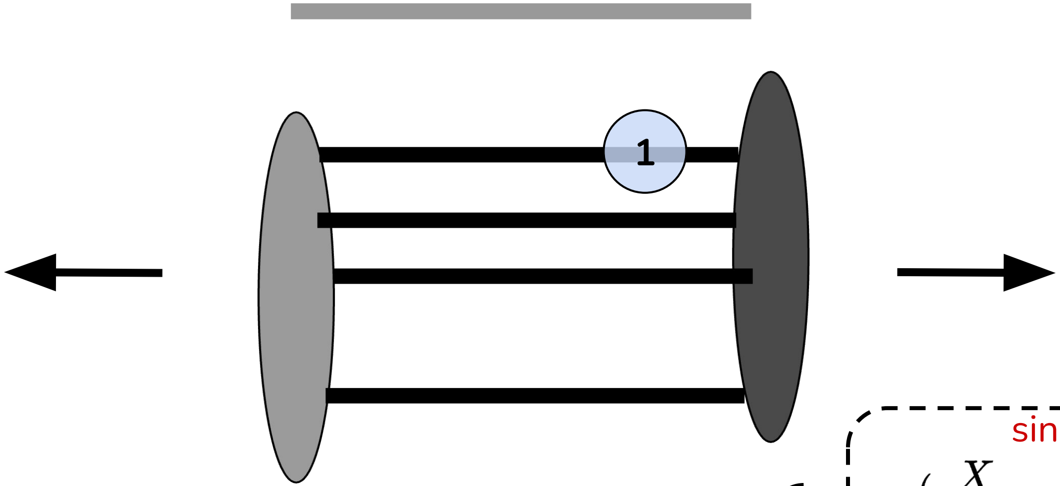
single junction

$$P(y^X_{P/T}) = (1-\lambda_X)y_{P/T} + \lambda_X \begin{cases} \dfrac{e^{(y^X_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)} \\ \text{constant} \end{cases}$$

double junction

constant

Initial conditions from the string junction 1/3



$$P(y^X_{P/T}) = (1-\lambda_X)\,y_{P/T} + \lambda_X \begin{cases} \dfrac{e^{(y^X_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)} & \text{single junction} \\ \cancel{\text{constant}} & \text{double junction} \end{cases}$$

Initial conditions from the string junction 1/3

$$P(y^X_{P/T}) = (1-\lambda_X)y_{P/T} + \lambda_X \frac{e^{(y^X_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)}$$

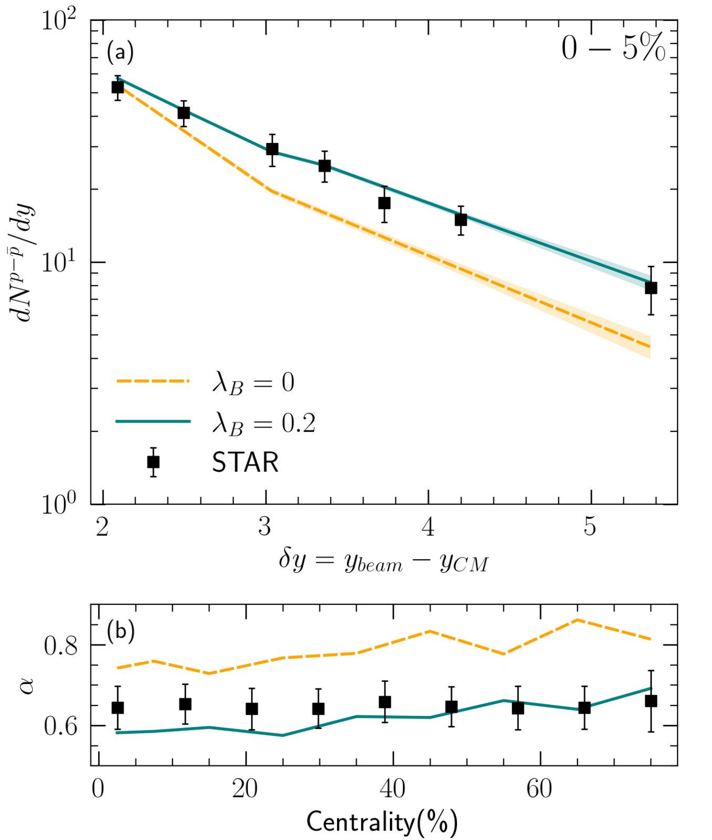
Net-baryon number: $\lambda_B = 0.2$

Net-electric charge: λ_Q

free parameter

$\lambda_Q = \lambda_B$ — Equal stoppings

$\lambda_Q \neq \lambda_B$ — Different stoppings



C. Shen and B. Schenke Phys. Rev. C **105**, 064905 (2022)
GP, A. Monnai, B. Schenke, C. Shen Phys. Rev. Lett. **133**, 182301
STAR collaboration, Phys. Rev. C **79**, 034909, arxiv:2408.15441

Initial conditions from the string junction 2/3

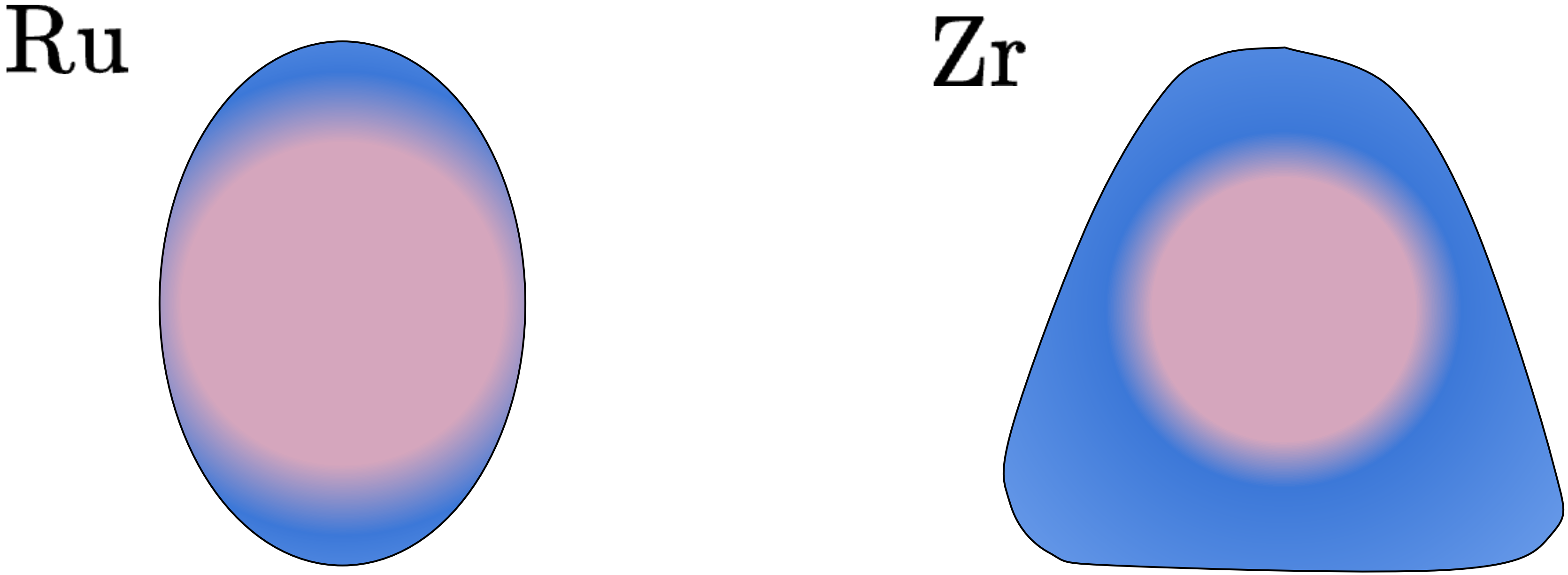
Wood-Saxon potential: nuclear structure and neutron skin

$$R_{p,n}(\theta,\phi) = R_{p,n}(1 + \beta_2 Y_2^0(\theta,\phi) + \beta_3 Y_3^0(\theta,\phi))$$

	R_p	a_p	R_n	a_n	β_2	β_3
Ru	5.09	0.46	5.105	0.47	0.16	0.0
Zr	5.02	0.52	5.12	0.57	0.06	0.2

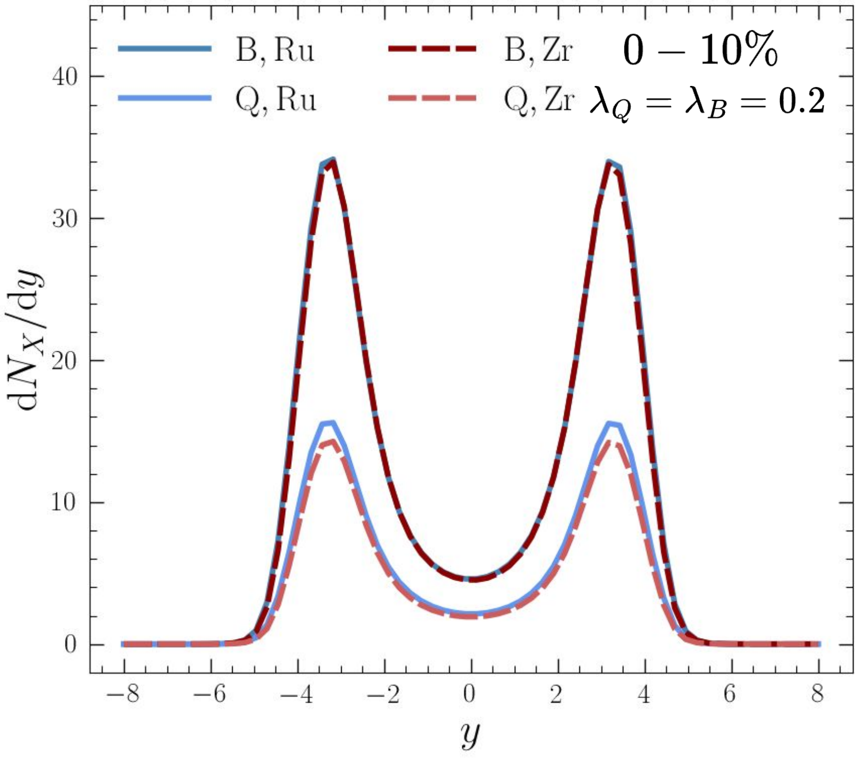
p: protons
n: neutrons

Initial conditions from the string junction 2/3

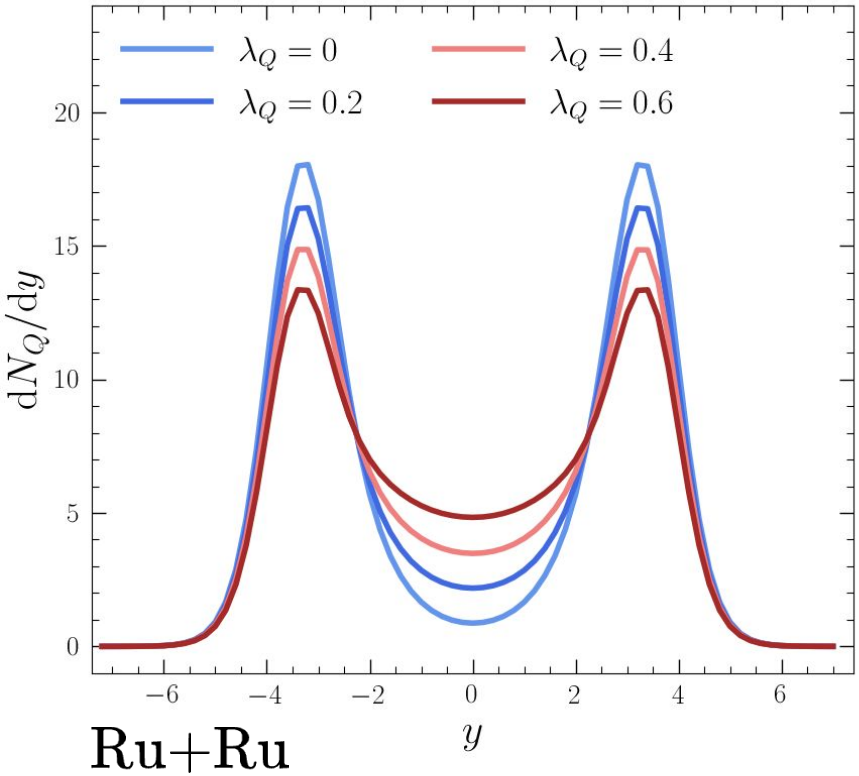


Initial conditions from the string junction 3/3

Initial baryon and electric charge density rapidity distributions for isobar runs at $\sqrt{s_{\rm NN}} = 200$ GeV



Initial electric charge density rapidity distributions for different values of λ_Q



MUSIC with 4D equation of state

NEOS 4D equation of state

Taylor expansion at finite chemical potentials

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

Hadron Resonance Gas

$$P_{\rm HRG} = \pm T \sum\nolimits_i \int \frac{g_i {\rm d}^3 k}{(2\pi)^3} \ln\left[1 \pm e^{(E_i(k)-\mu_i)/T}\right]$$

i : hadronic species $\quad \mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$

Matching

$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_X)]\frac{P_{HRG}}{T^4} + \frac{1}{2}[1 + f(T,\mu_X)]\frac{P_{\rm Latt}}{T^4}$$

No assumptions on the relation between conserved charge densities!

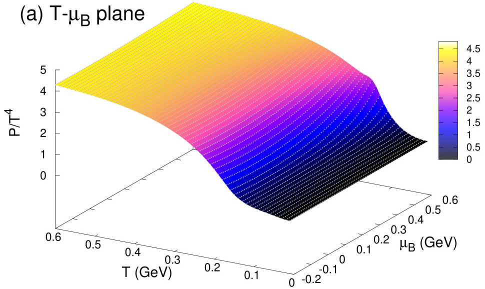
~~$\rho_Q \simeq 0.4\rho_B$~~

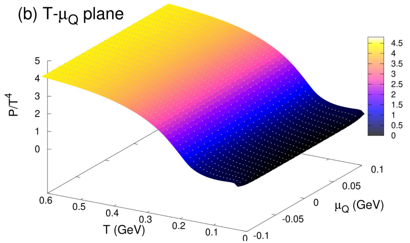
MUSIC with BQS conserved charges

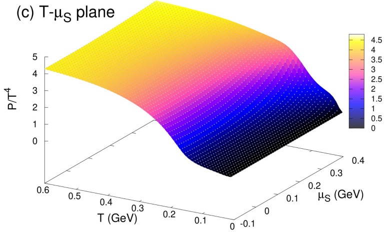
$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 \\ \partial_\mu N^\mu_X = 0 \end{cases} \qquad N^\mu_X = \rho_X u^\mu$$

B, Q and S currents evolve independently!

$$X = B, Q, S$$



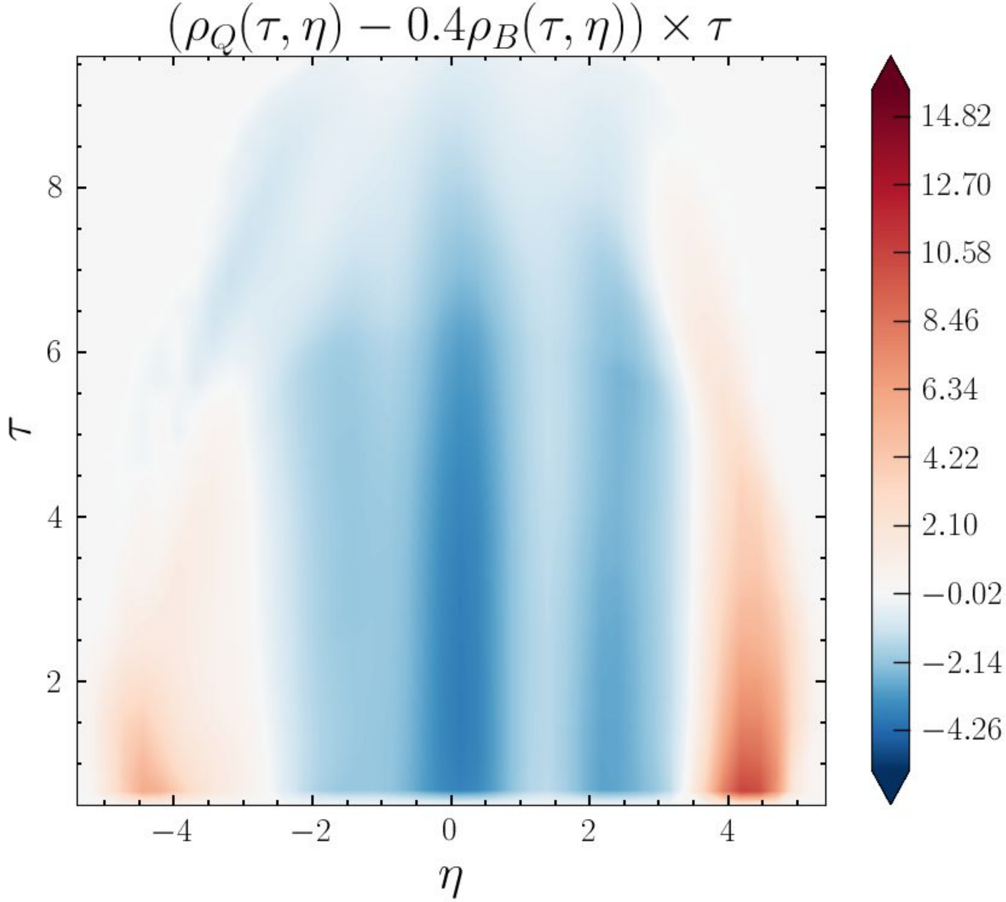




A. Monnai, B. Schenke and C.Shen Phys. Rev. C **100**, 024907

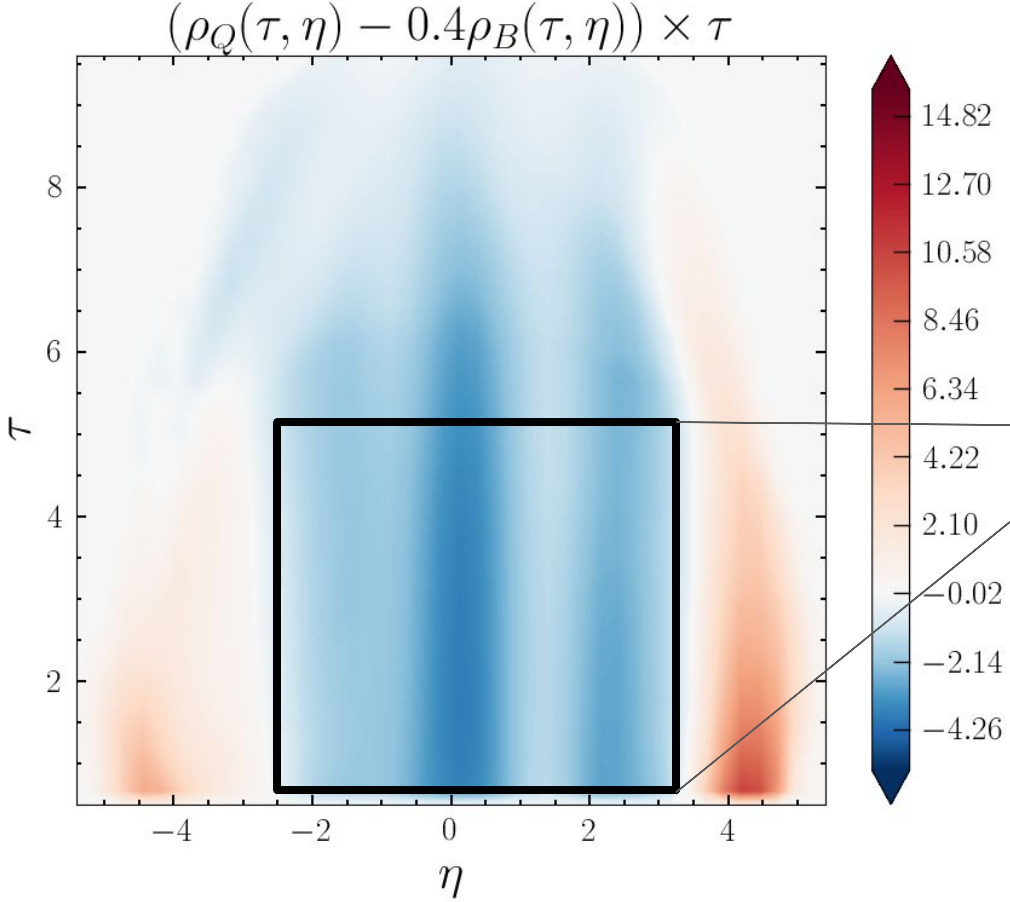
A.Monnai, GP, B. Schenke, C. Shen: arxiv:2406.11610

MUSIC with 4D equation of state



~~$\rho_Q \simeq 0.4\rho_B$~~

MUSIC with 4D equation of state



~~$\rho_Q \simeq 0.4\rho_B$~~

Local excess baryon density!

Study cases

Case 1
"Equal stopping"

$$\lambda_Q = \lambda_B = 0.2$$

Naive expectation from charge conservation

$$r \sim 1$$

Case 2
"No extra Q stopping"

$$\lambda_Q = 0, \lambda_B = 0.2$$

No extra stopping mechanism for electric charge:
Maximal difference between B and Q stopping at fixed λ_B

$$r > 1$$

Case 3
Case 1 + "No neutron skin"

$$\lambda_Q = 0, \lambda_B = 0.2$$
$$\mathrm{R}_p = \mathrm{R}_n, a_p = a_n$$

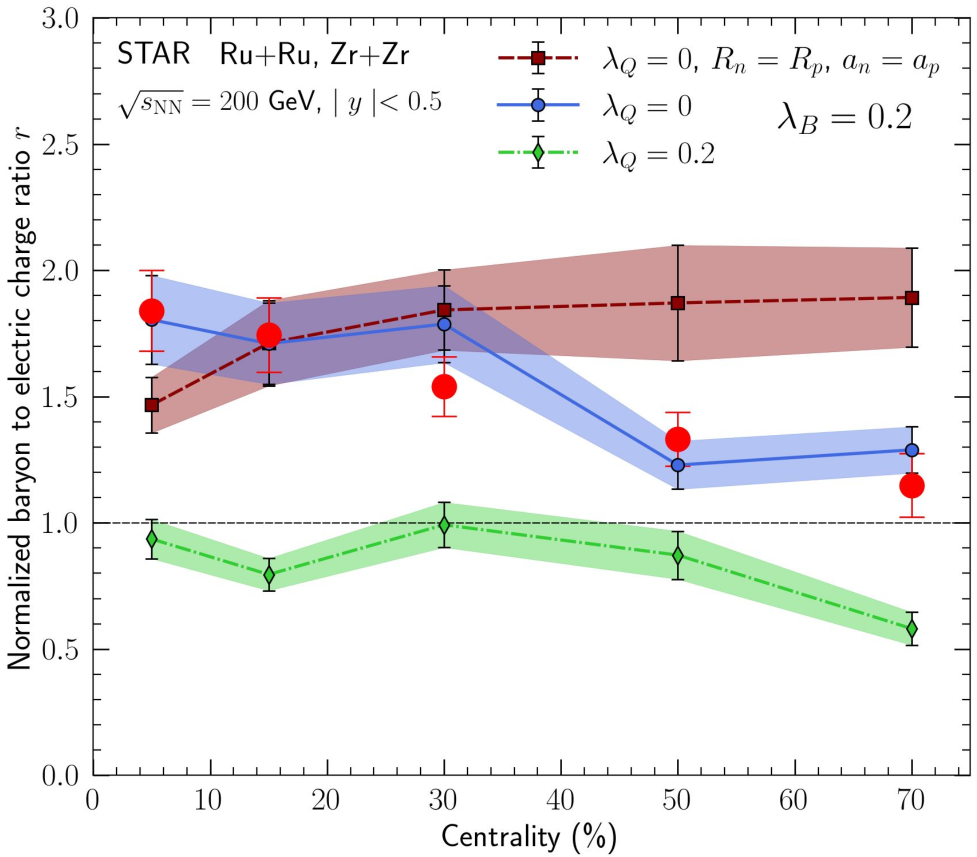
No extra stopping for electric charge and no structure as a function of centrality

$$r > 1 \quad \frac{dr}{dN_{\mathrm{part}}} \sim 0$$

Selection

In each centrality class

$$N_{\mathrm{ch,Ru}} = N_{\mathrm{ch,Zr}}$$



GP, A. Monnai, B. Schenke, C. Shen Phys. Rev. Lett. **133**, 182301

Case 2:

Unequivocally favored by experimental data!

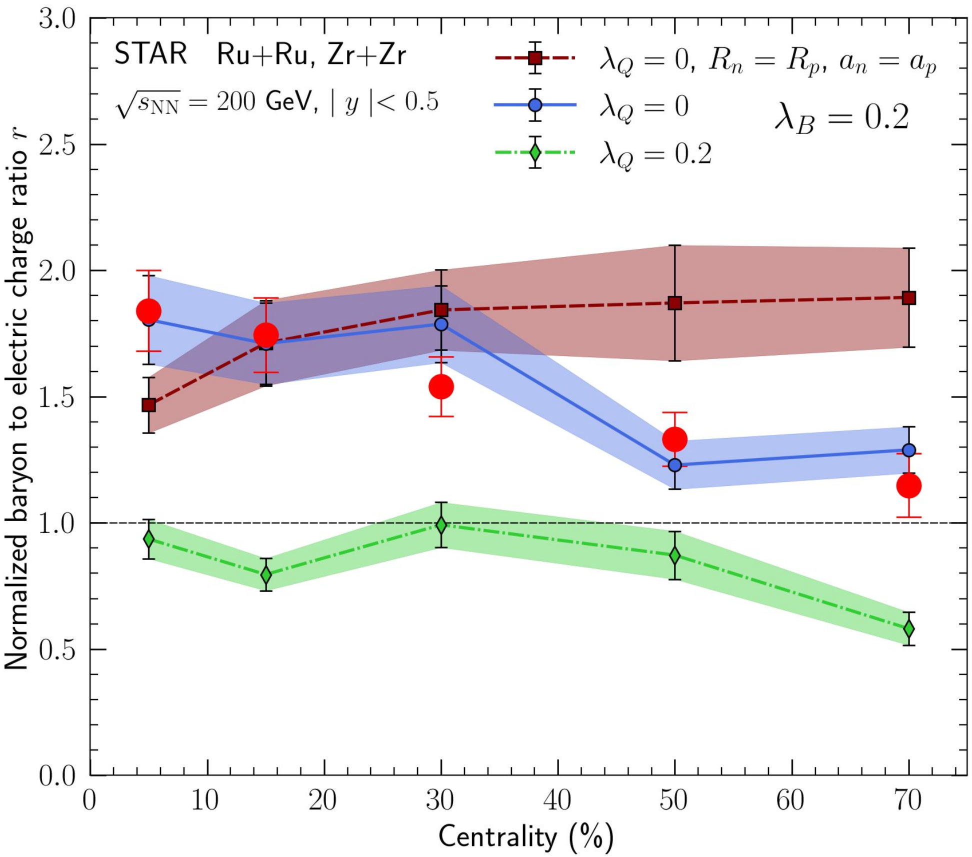
Case 1:

The naive expectation indeed falls to unity but has decreasing behavior at large centrality

Case 3:

The structure is due to the neutron skin of the Zirconium!

Ratio



GP, A. Monnai, B. Schenke, C. Shen Phys. Rev. Lett. **133**, 182301

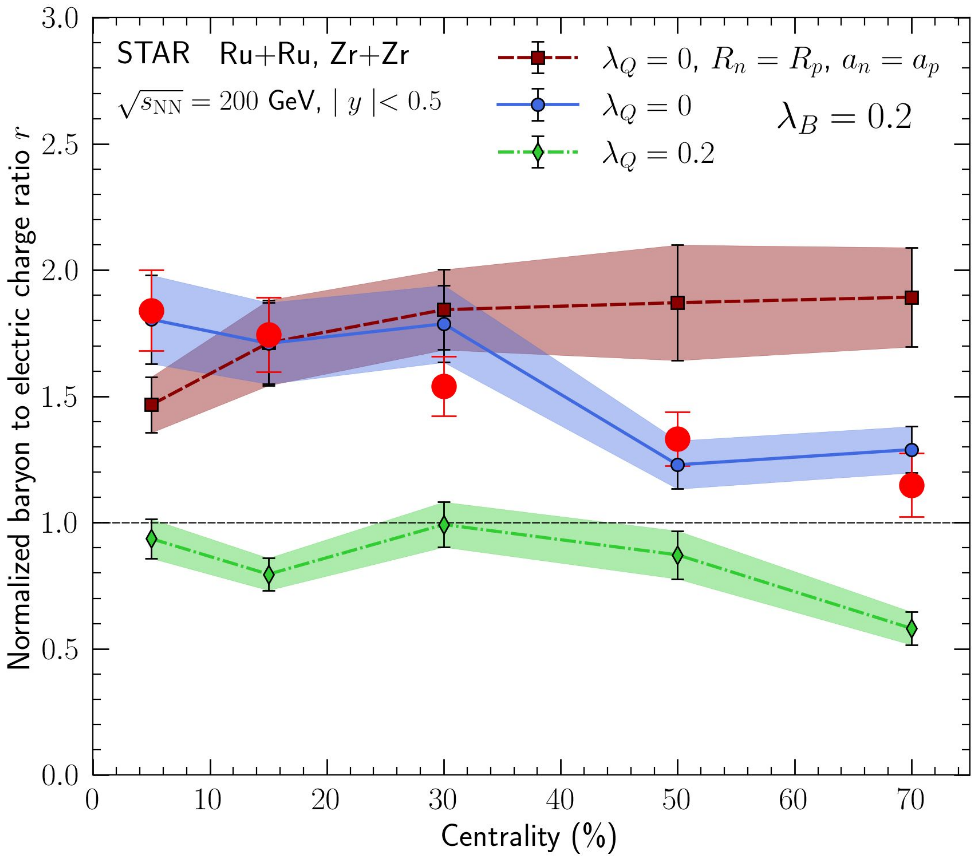
Case 2:

Unequivocally favored by experimental data!

This study:

Any stopping models that predicts an extra baryon stopping mechanism with the same longitudinal probability distribution as the single baryon junction is largely favored by the experimental measurement in the isobar runs at 200 GeV!

Ratio



GP, A. Monnai, B. Schenke, C. Shen Phys. Rev. Lett. **133**, 182301

Case 2:

Unequivocally favored by experimental data!

In all likelihood:

This is strongly in favor of the baryon junction picture!

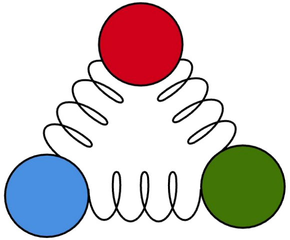
Baryon junction: take home

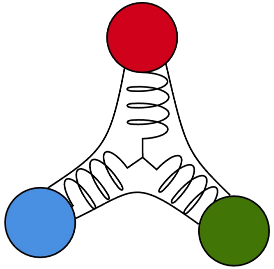
"Can gluon junction trace the baryon number?"

The isobar simulations are in quantitative agreement with the STAR measurement.

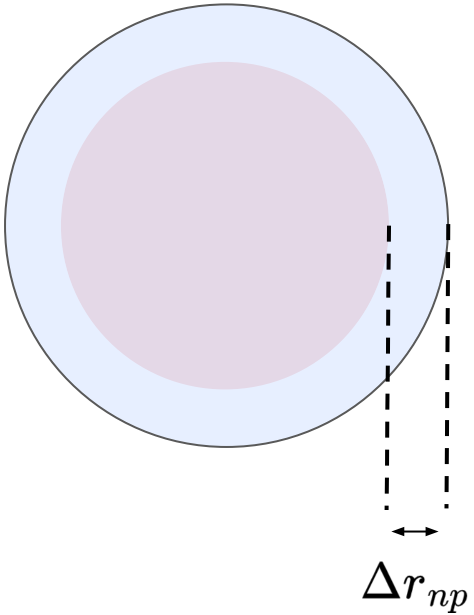
Strong evidence for the existence of the junction!

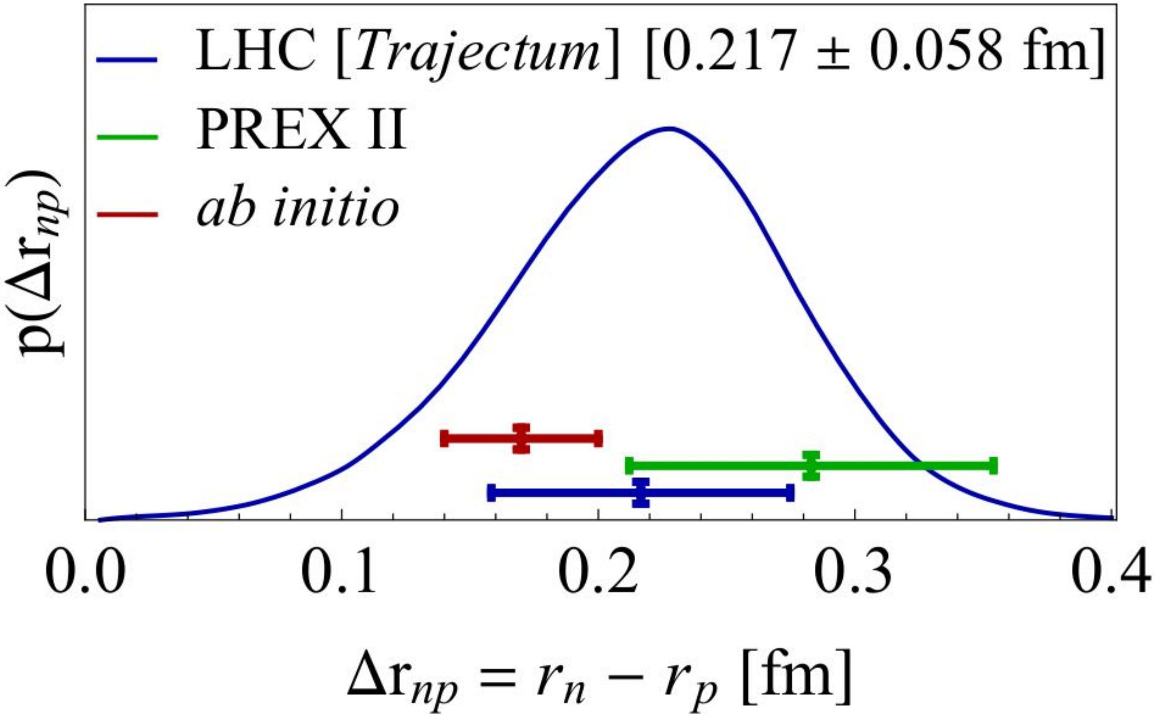
The ratio is sensitive to the Zr neutron skin
Study of the nuclear structure in Heavy-ion collisions?





Pb neutron skin

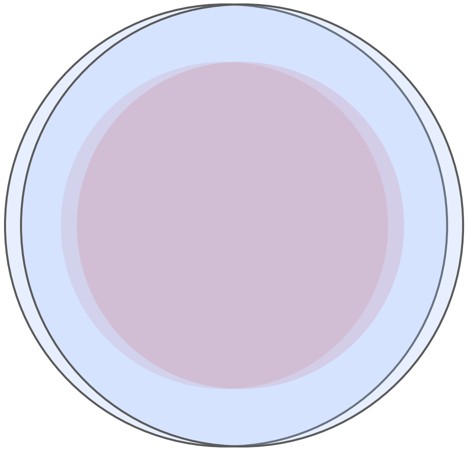




G. Giacalone Phys.Rev.Lett. 131 (2023) 20, 20

Pb neutron skin in Pb-Pb at LHC

Ultra-central collisions in ALICE Pb-Pb 5.02 TeV



A drop of $\langle n_p \rangle / \langle n_n \rangle$ in the ZDC!

Pb neutron skin in p-Pb at LHC

Isobars:

Ratios involving dN_B/dy and dN_Q/dy:

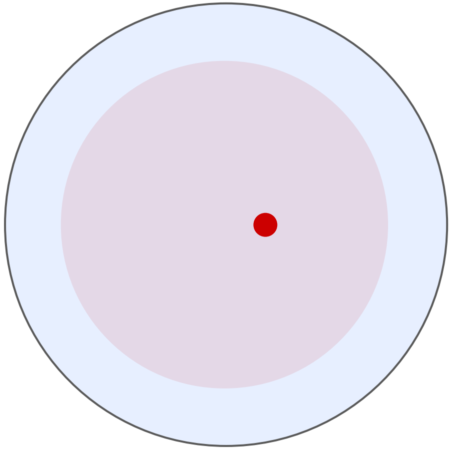
Sensitive to protons and neutron distribution

Nuclear structure and neutron skin!

Pb neutron skin in p-Pb at LHC

Pb neutron skin in p-Pb at LHC

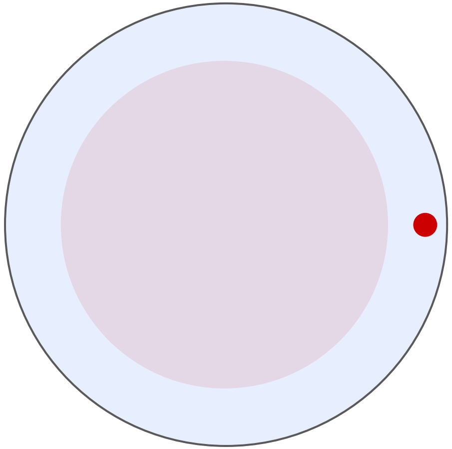
Central collisions



more p-p collisions

More Q/B than baseline

Peripheral collisions



more p-n collisions

Less Q/B than baseline

Pb neutron skin in p-Pb at LHC

$$R_{c_1,c_2}(y) = r_{c_1}(y)/r_{c_2}(y)$$

$$c_1 > c_2$$

$$r_{(\mathrm{C})}(y) = \frac{\mathrm{d}N_Q}{dy} / \frac{\mathrm{d}N_B}{\mathrm{d}y}(c) \times A/Z$$

$$R_{c_1,c_2}(y) \sim 1$$

No neutron skin Q depletion effect

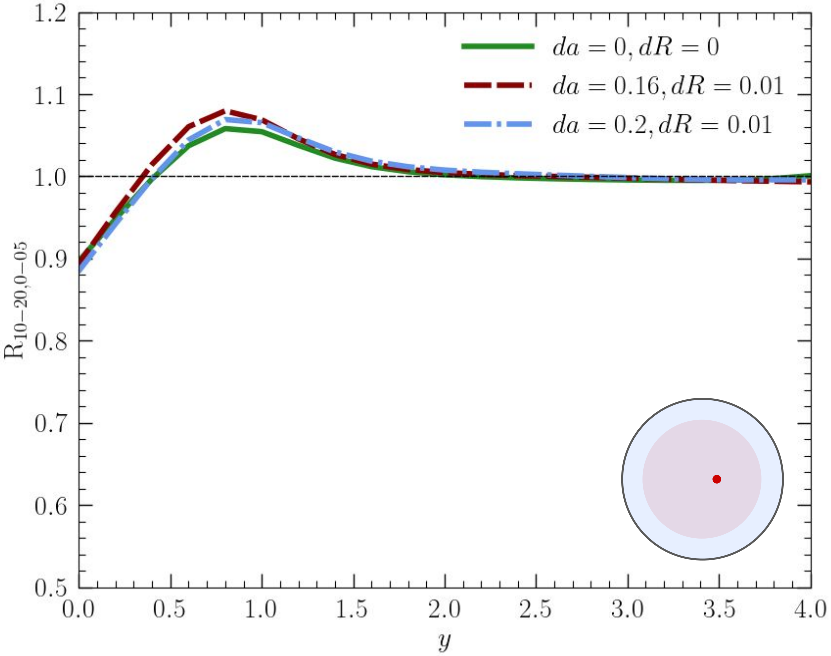
$$R_{c_1,c_2}(y) < 1$$

Neutron skin Q depletion effect!

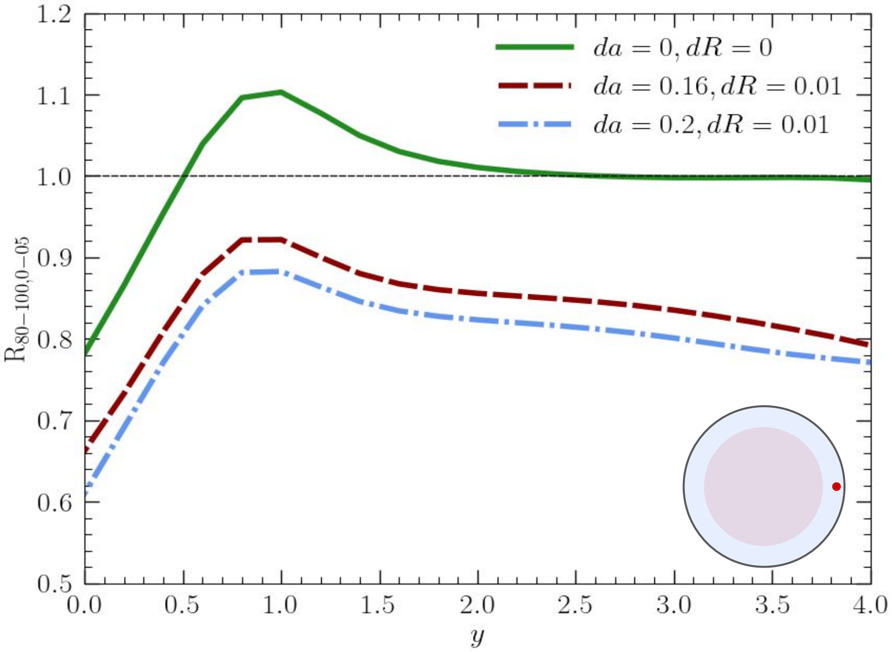
Pb neutron skin in p-Pb at LHC

Initial stage pPb 72 GeV

10-20%



80-100%



Pb neutron skin in p-Pb at LHC

Initial stage pPb 72 GeV

Constraining the Pb neutron skin

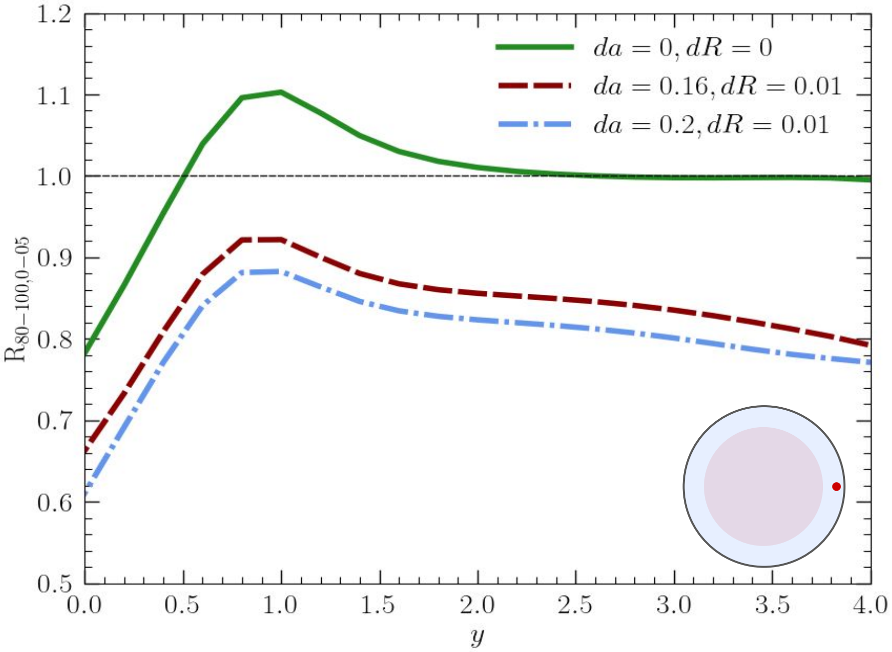
SMOG 2 at LHCb!

The ratio R_{c_1,c_2} could be defined from proxies

net-pion/net-proton

Weaker signal but easier access experimentally!

80-100%



Wrap and outlook

Tracing the conserved charge in heavy-ion collisions:

- ➢ Distributions of the conserved charges B and Q

  Give access to protons and neutrons difference in
  stopping mechanisms

  The baryon junction certainly carries the baryon number!

  spatial distribution

  The nuclear shape and neutron skin can be studied in heavy-ion collisions in this way

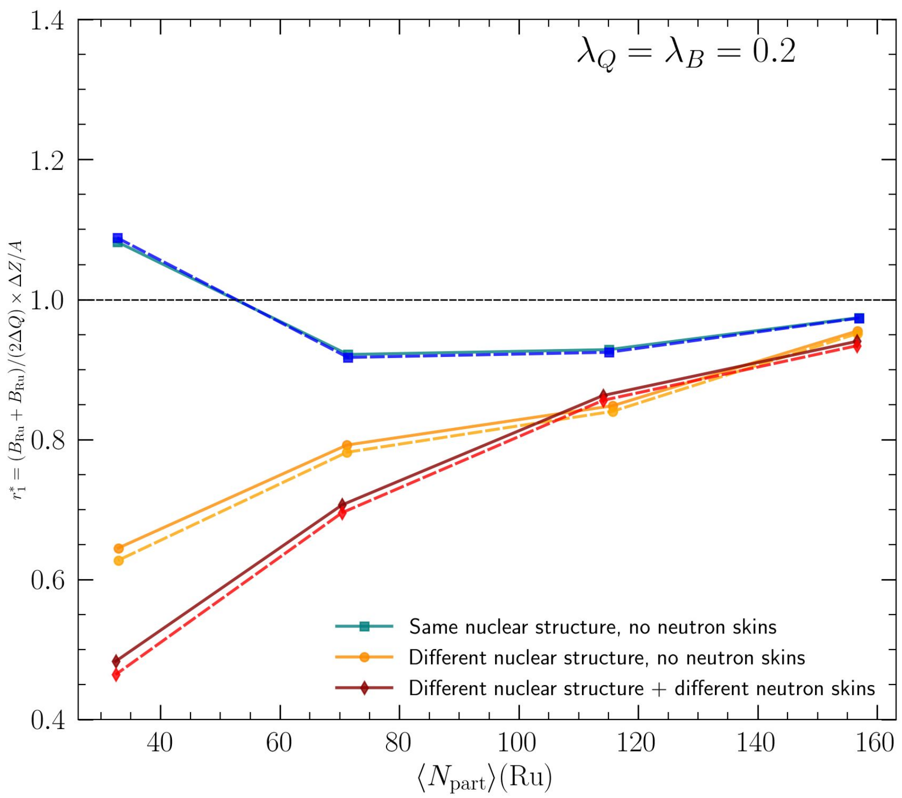
- ➢ Future related work:

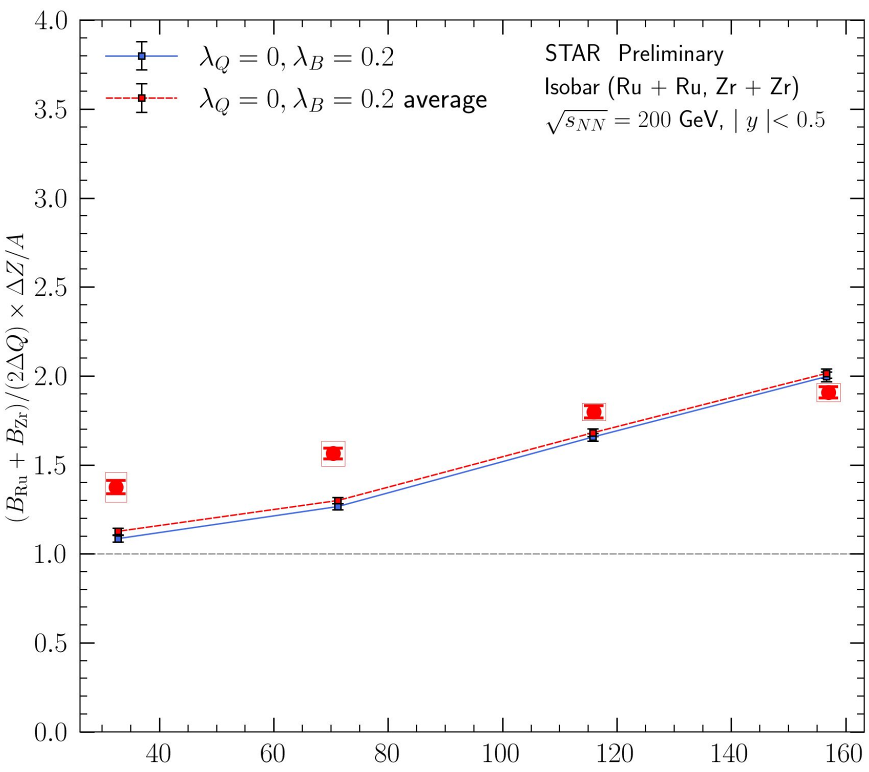
  Predict the pPb at final stage
  Enhance statistics via machine learning
  Study the baryon junction in pPb net-proton number slope!

backup

Comparison with STAR ratio

The ratio is defined as: $r_1^* = (B_{\rm Ru} + B_{\rm Zr})/(2\Delta Q) \times \Delta Z/A$





Experimental RuB ratio

$$B/\Delta Q \times \Delta Z/A$$

Net-baryon number:

STAR does not measures neutrons,

Evaluation of neutrons from deuterons yields via HRG model

$$N_B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}}) \approx (N_p - N_{\bar{p}}) + \bar{p}\sqrt{\frac{d}{\bar{d}}} - p\sqrt{\frac{\bar{d}}{d}}$$

STAR Collaboration, Phys Rev.99.064905

Net-charge difference:

The electric charge is a non-trivial measurement at mid-rapidity (small yields!).

Making use of the convenient double ratios to cancel uncertainties accessible in isobars collisions.

$$\Delta Q = [(N_\pi^+ + N_K^+ + N_p) - (N_\pi^- + N_K^- + N_{\bar{p}})]_{\mathrm{Ru}} - []_{\mathrm{Zr}}$$

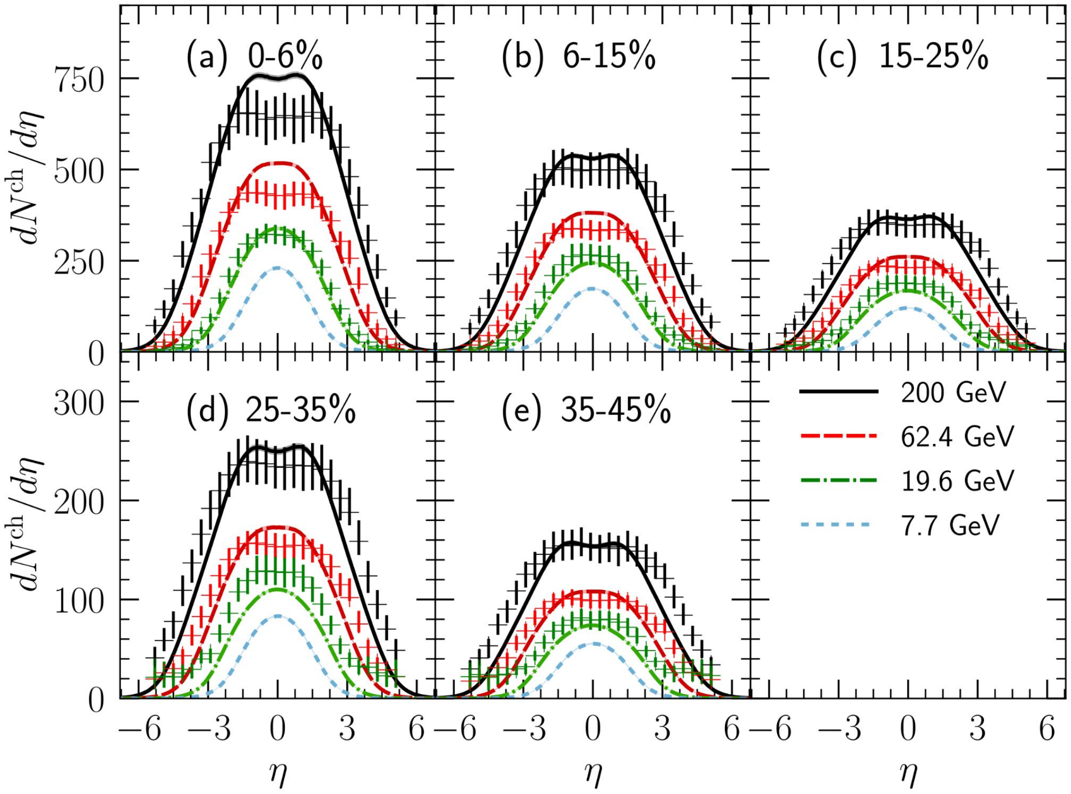
$$R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{\mathrm{Ru}}}{(N_\pi^+/N_\pi^-)_{\mathrm{Zr}}} \approx 1 + (N_\pi^+ - N_\pi^-)_{\mathrm{Ru}} - (N_\pi^+ - N_\pi^-)_{\mathrm{Zr}}$$

$$\Delta Q = N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$$

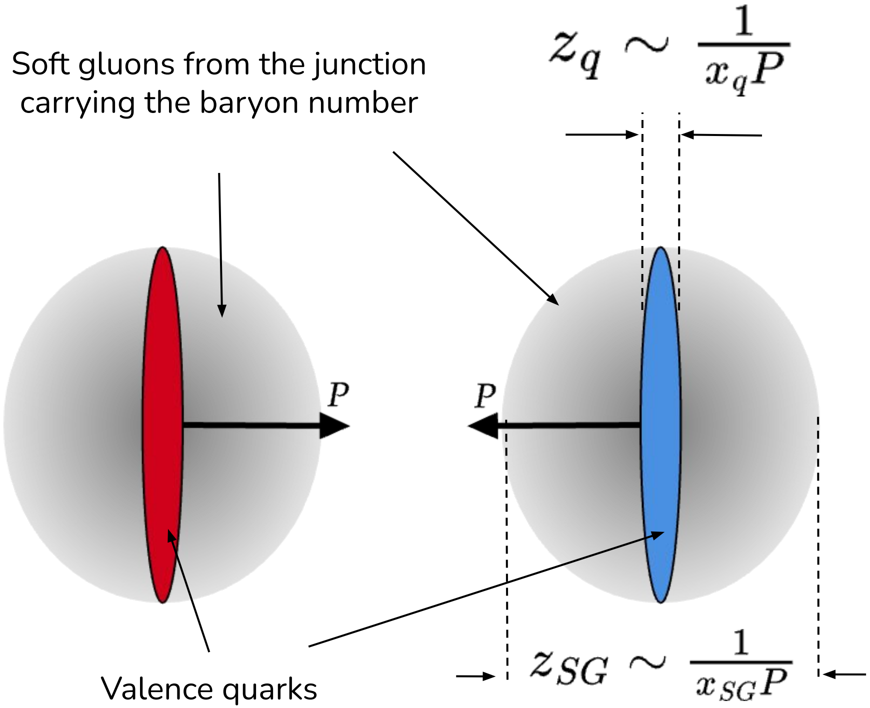
MUSIC tuning on PHOBOS Au+Au data

Current version:

- ➢ Tuned on charged particle rapidity distributions for Au+Au collisions at RHIC PHOBOS
- ➢ Overestimate yields at mid-rapidity for most central collision
- ➢ Overall good agreement ✔



Backup: Gluon cloud interpretation



Quarks: $x_q \sim 1/3$

interaction time is short

~6.10^-3^ fm

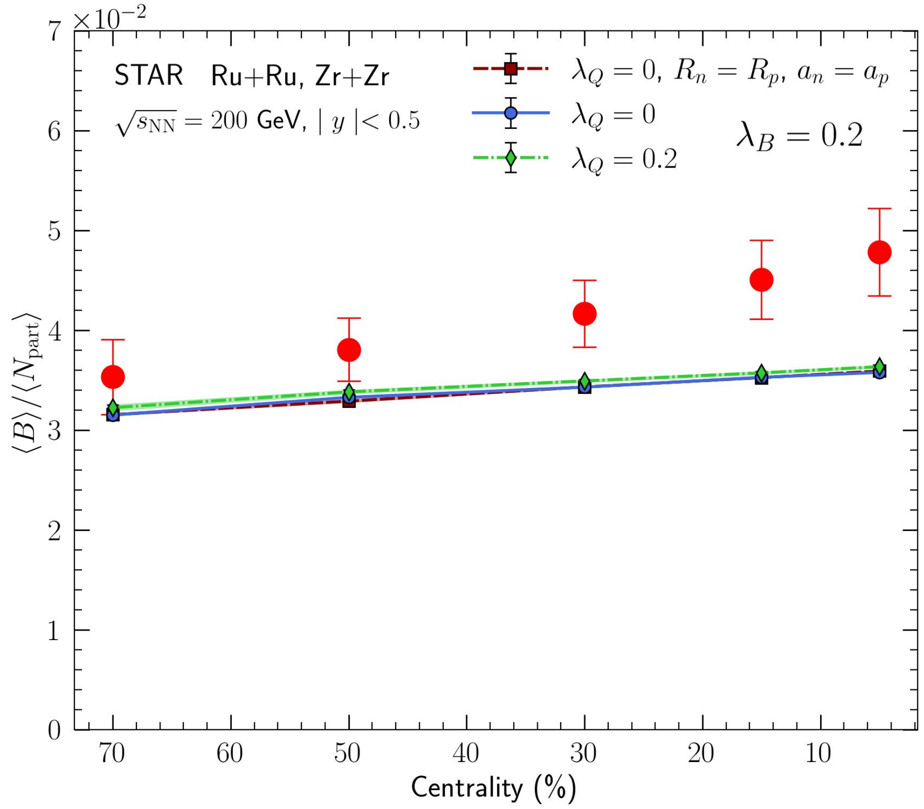
Soft gluons: $x_{SG} \ll x_q$

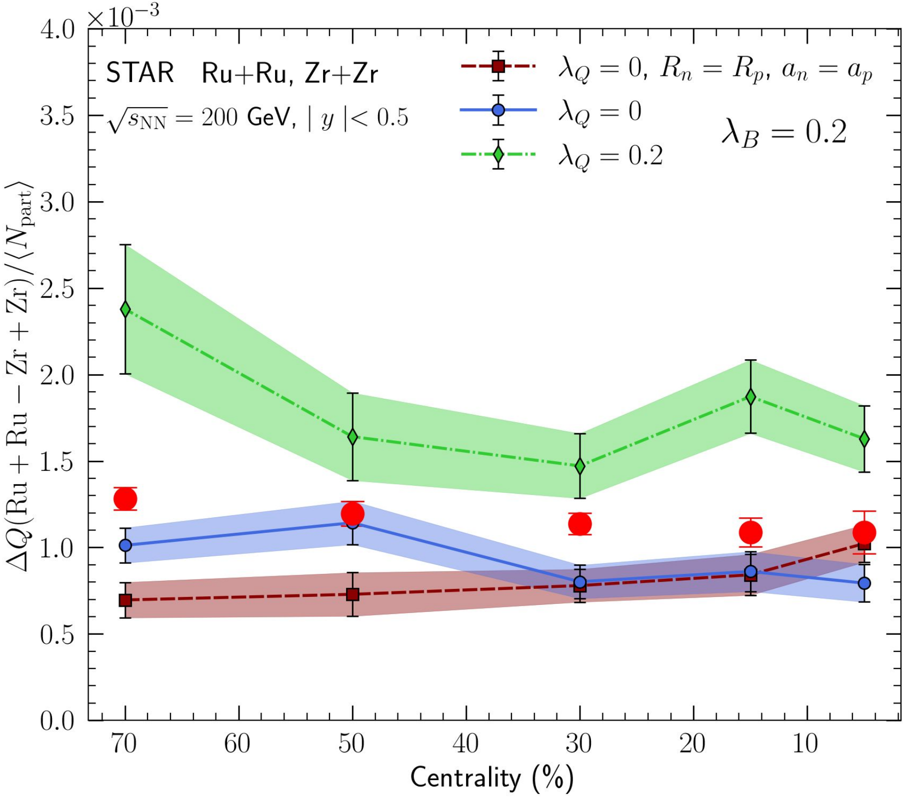
interaction time is large

~1 fm

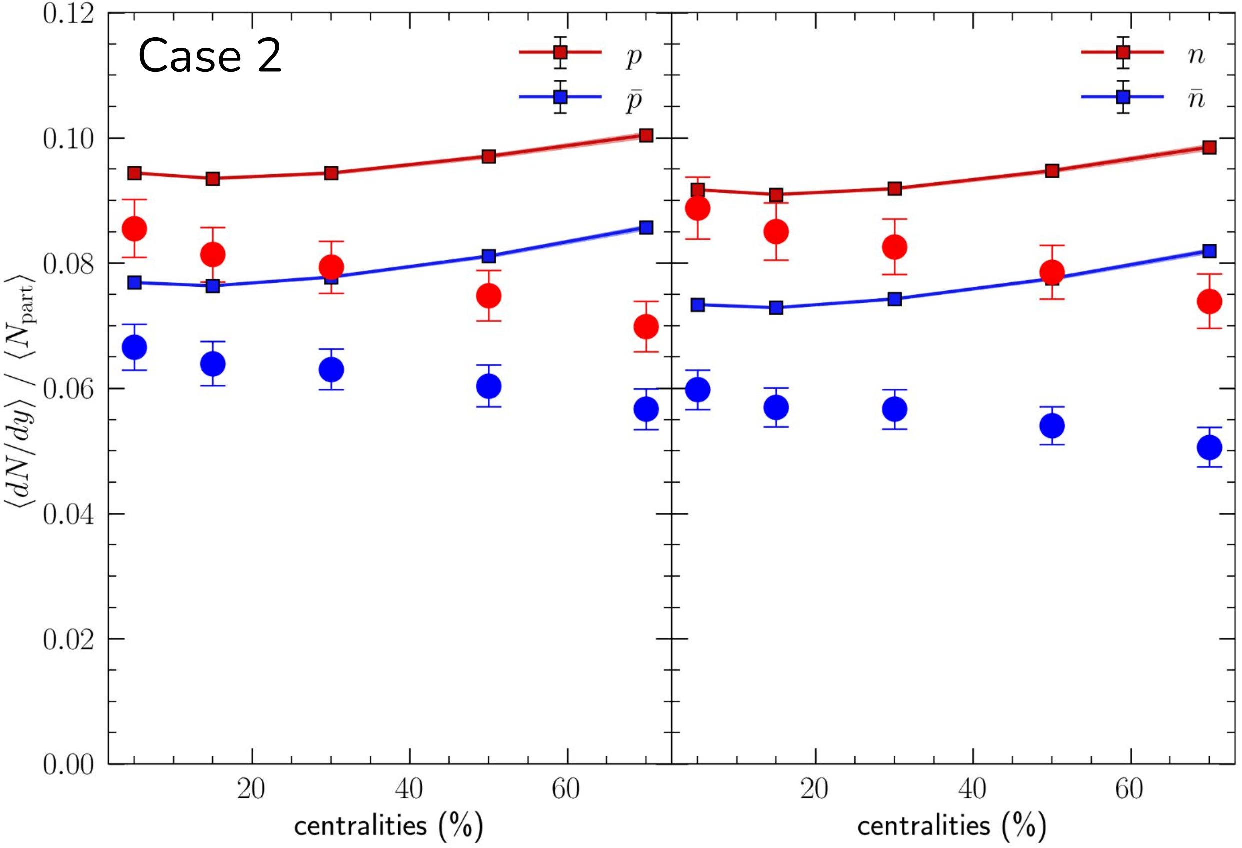
The baryon number is stopped!

Baryon number and ΔQ vs STAR measurement





Proton, neutron yield vs STAR measurement



A fine tuning of λ_B and λ_Q

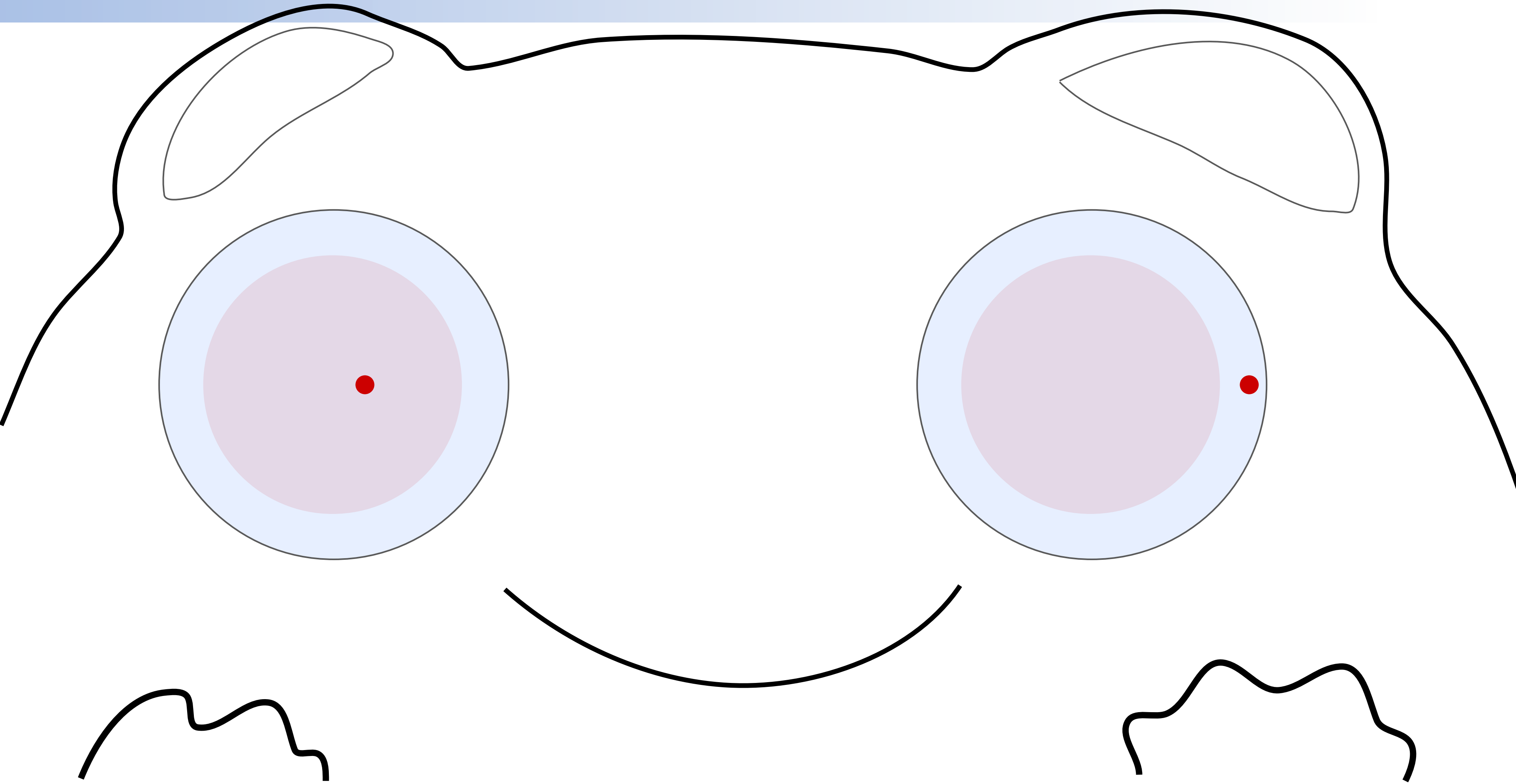
Overall amplitude can be reduced

A fine tuning of freeze out energy density

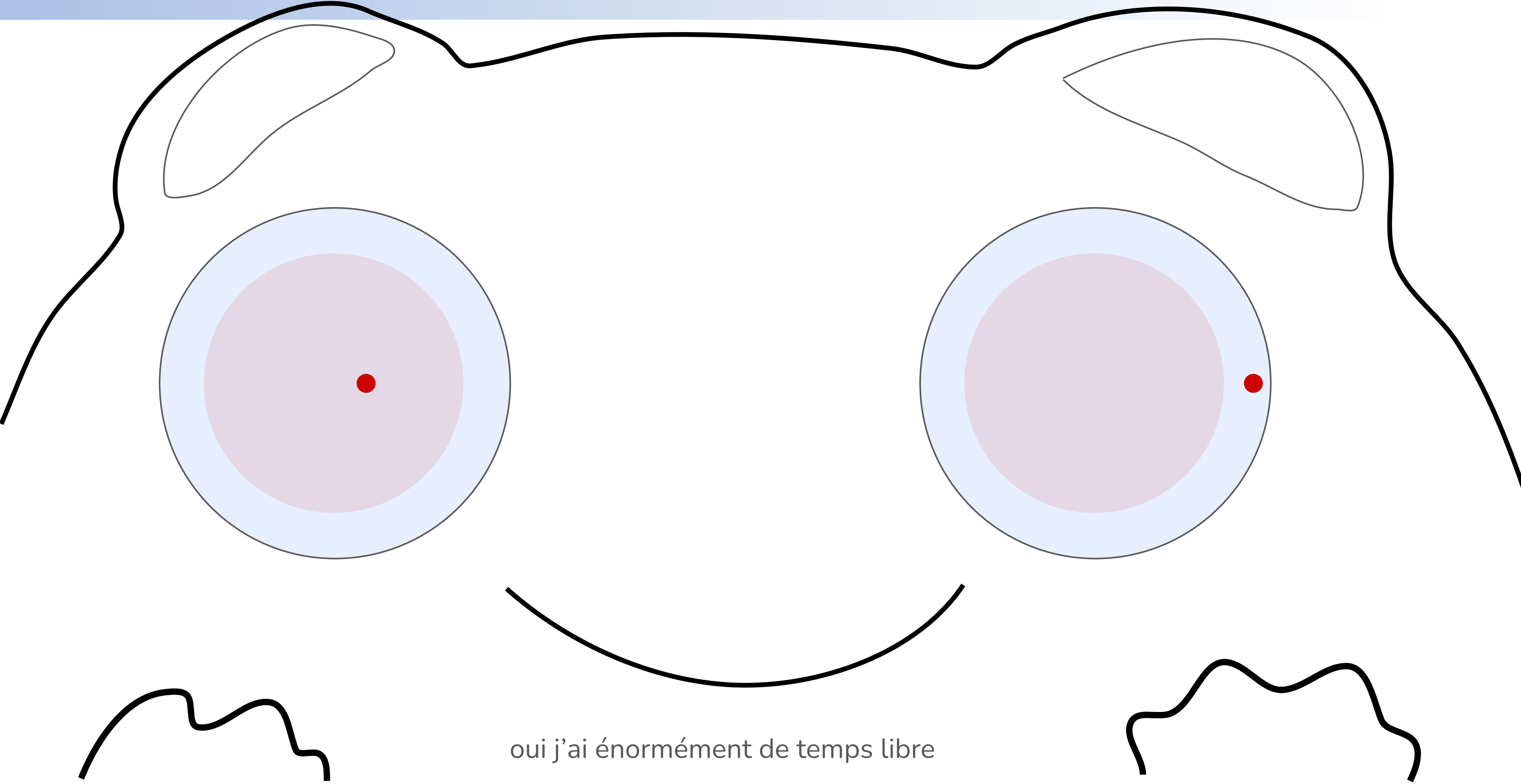
Difference in particles and antiparticles can fitted

Left for future study

Pilède the kind Monster



Pilède the kind Monster



oui j’ai énormément de temps libre