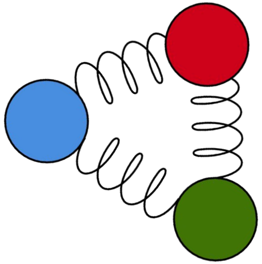
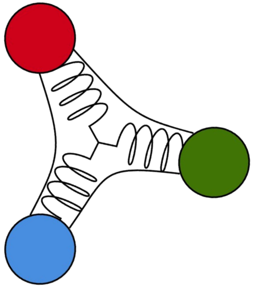
Tracing the baryon number in relativistic isobar collisions at RHIC



Brookhaven National Laboratory,
25th of Jan 2024



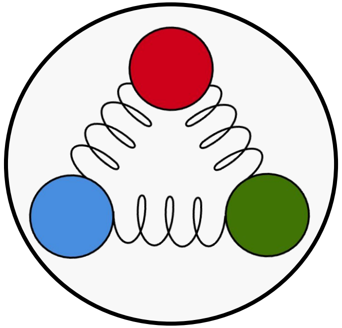
Grégoire **Pihan**[1], Akihiko **Monnai**[2], Bjoern **Schenke**[3], Chun **Shen**[1,3]

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

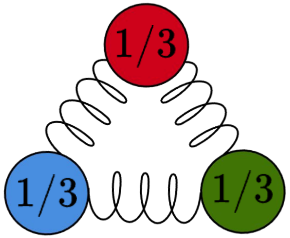
What carries the baryon number?

Baryon number: a conserved charge of strongly interacting matter

$$B = 1$$



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



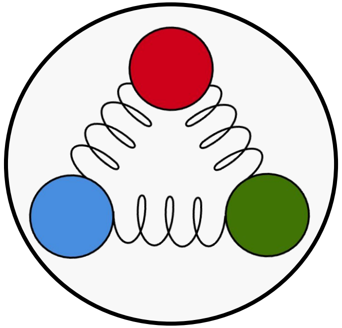
This is an assumption!

±⅓B to each quarks and antiquarks cannot be inferred from QCD first principles for baryons!

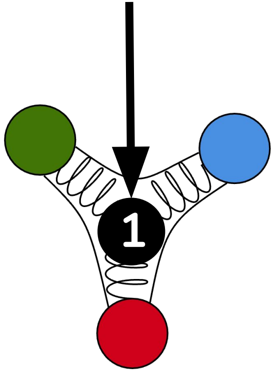
What carries the baryon number?

String junction?

$$B = 1$$

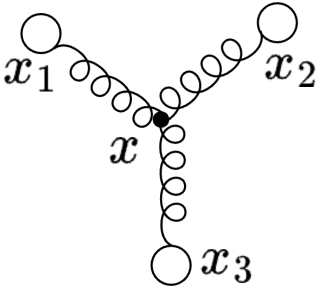


$$B = 1$$



What carries the baryon number?

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



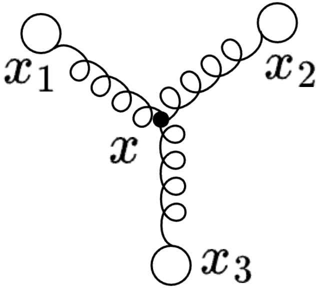
Non-perturbative configuration of gluons represented by a locally gauge-invariant state vector.

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

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

What carries the baryon number?

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



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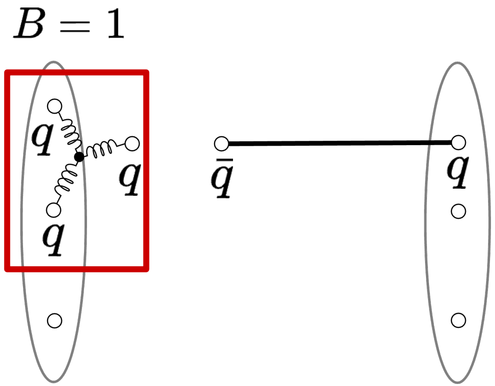
The string junction x carries the baryon number inside the baryon

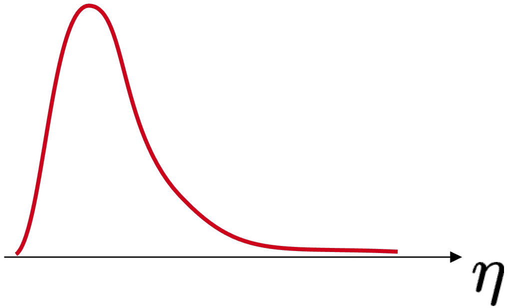
Can be verified experimentally: **Baryon stopping in central pp and AA collisions**

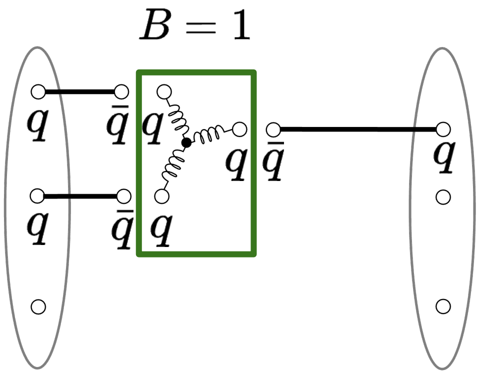
D. Kharzeev, Physics Letters B **378**, 238 (1996)

The string junction allows for two possibilities

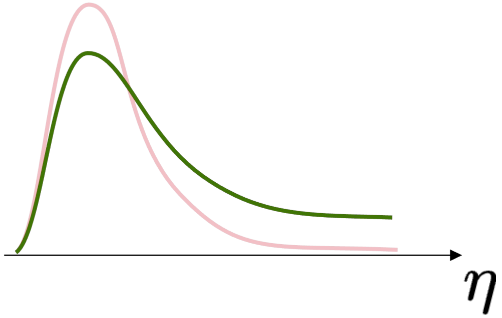


The baryon number remain attached to the nucleon





The baryon number to fluctuate towards mid-rapidity



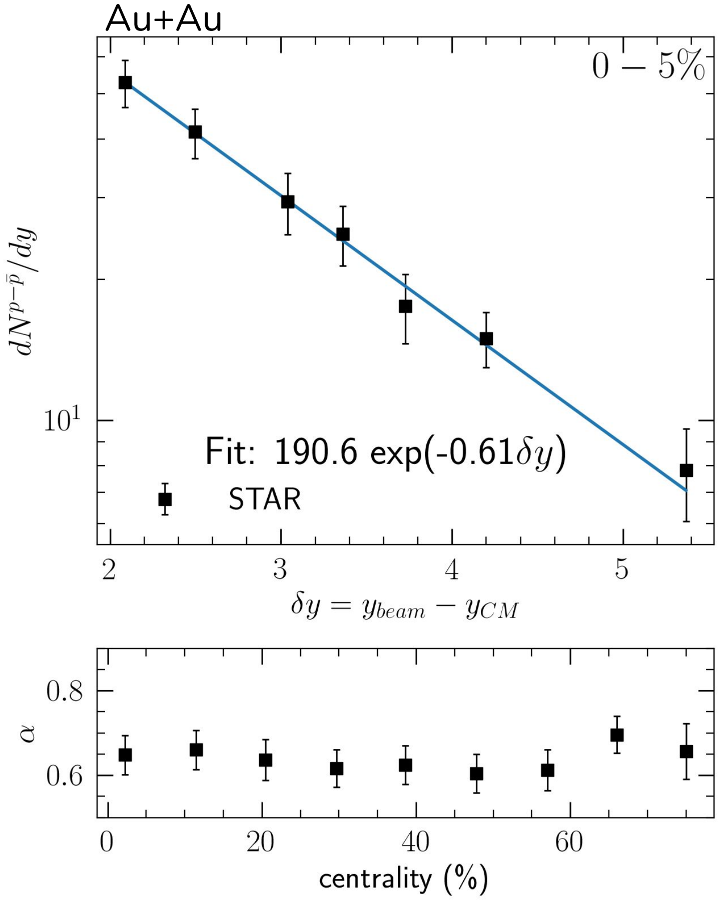
Baryon stopping and string junction

Exponential decrease as a function of the rapidity loss δy

$$\frac{dN^{p-\bar{p}}}{dy} = Ne^{-\alpha\delta y}$$

$$N = 190.6$$

$$\alpha = 0.61$$



Baryon stopping and string junction

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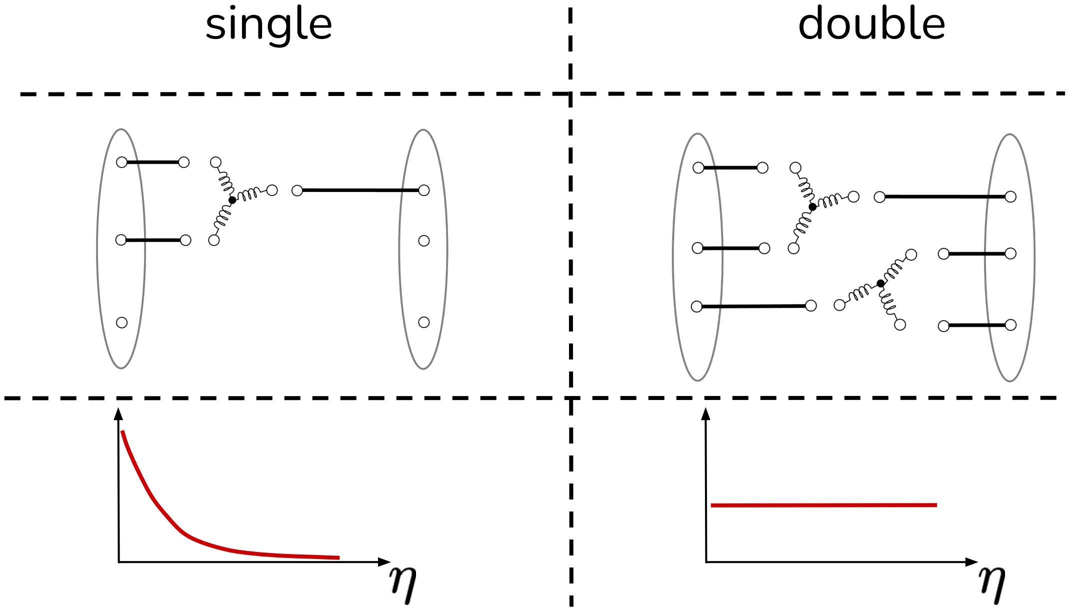
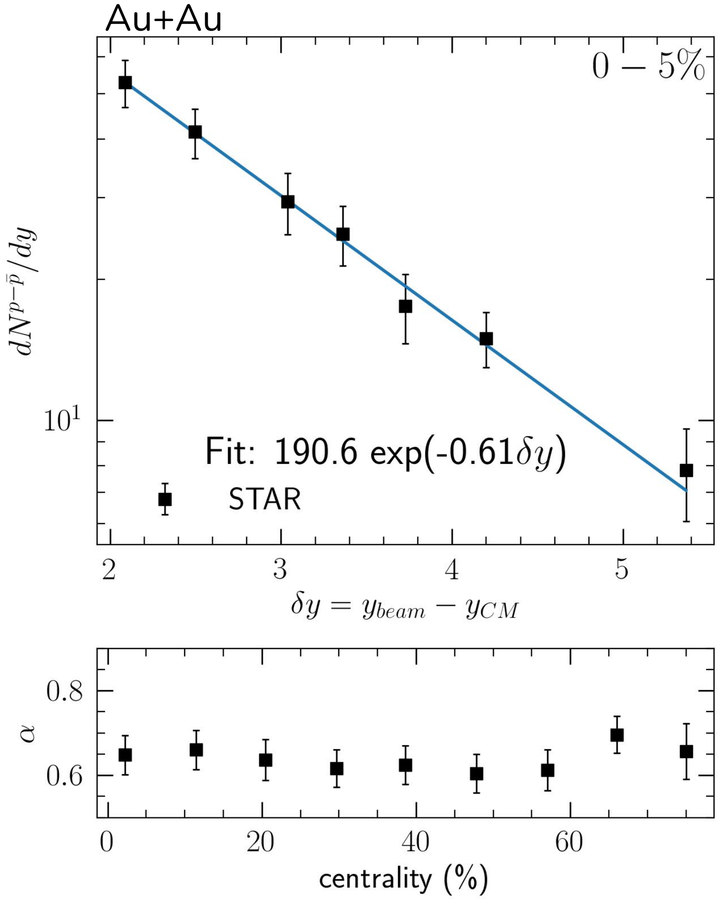


$$\alpha_j = 0.5$$



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

Insight from the isobar collisions at RHIC

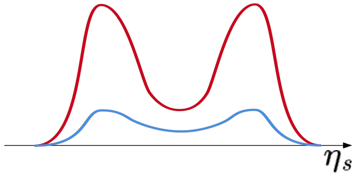
Isobar Runs: Same number of nucleons A, different number of protons Z

$^{96}_{44}\mathrm{Ru}$ $^{96}_{40}\mathrm{Zr}$

➢ **Allow for the measurement of the baryon stopping compared to electric charge stopping!**

Supposing that: **Valence quarks carry the electric charge**

net-Baryon number and net-electric charge stop in the same way

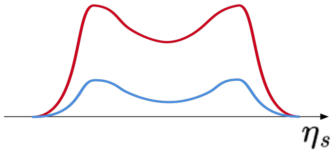


Valence quarks carry the baryon number

“Equal stoppings”

net-Baryon number and net-electric charge stop differently

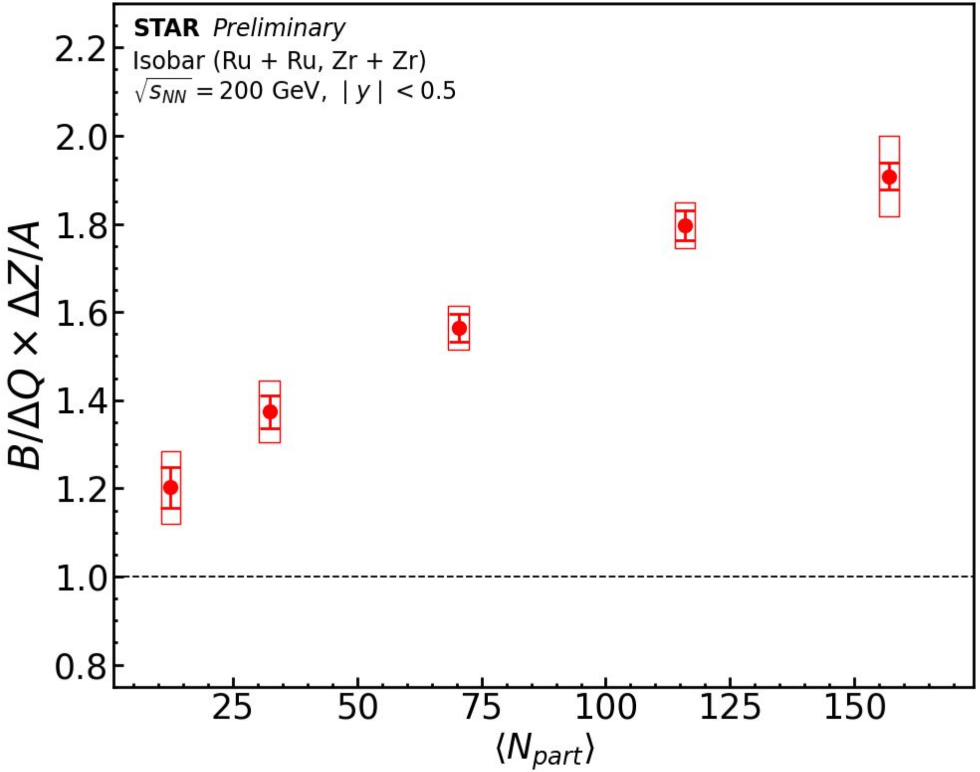
Baryon number is carried by something else. **Baryon junction?**



“Different stoppings”

Insight from the isobar collisions at RHIC

For isobars 200 GeV collisions at STAR, the ratio deviates from unity!



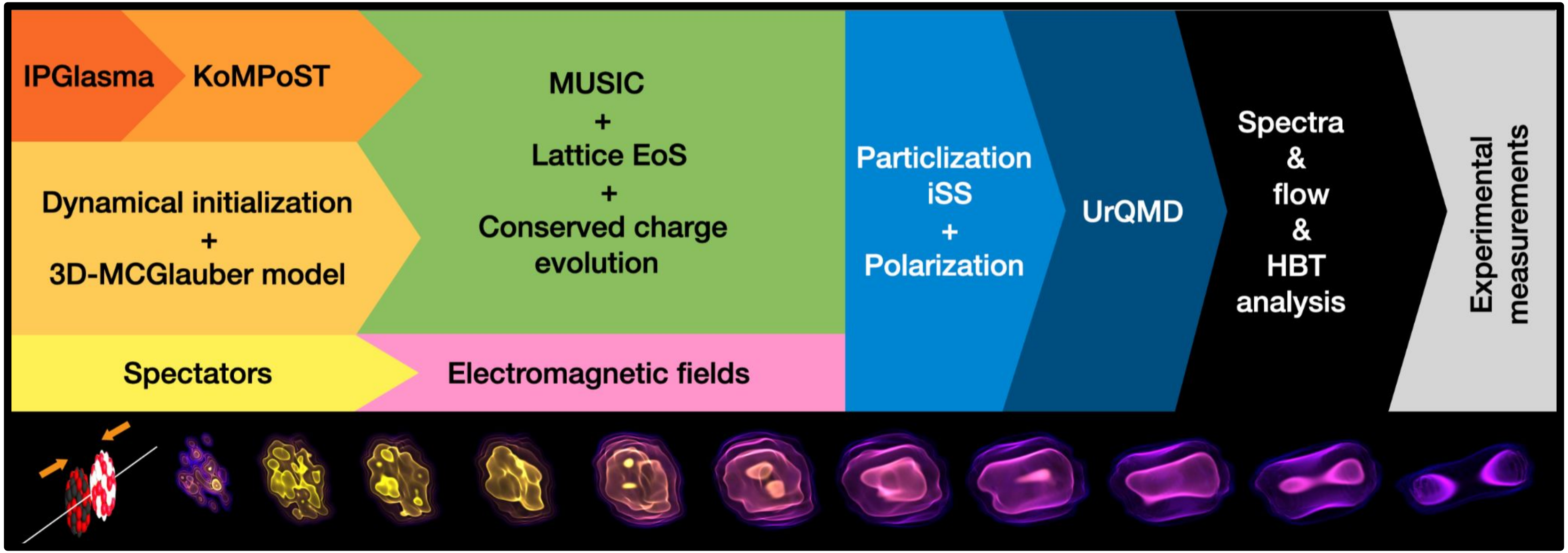
Is this a sign of the string junction?

This result indicates that there is more baryon stopping than electric charge stopping

STAR collaboration , in prep

The iEBE-MUSIC framework

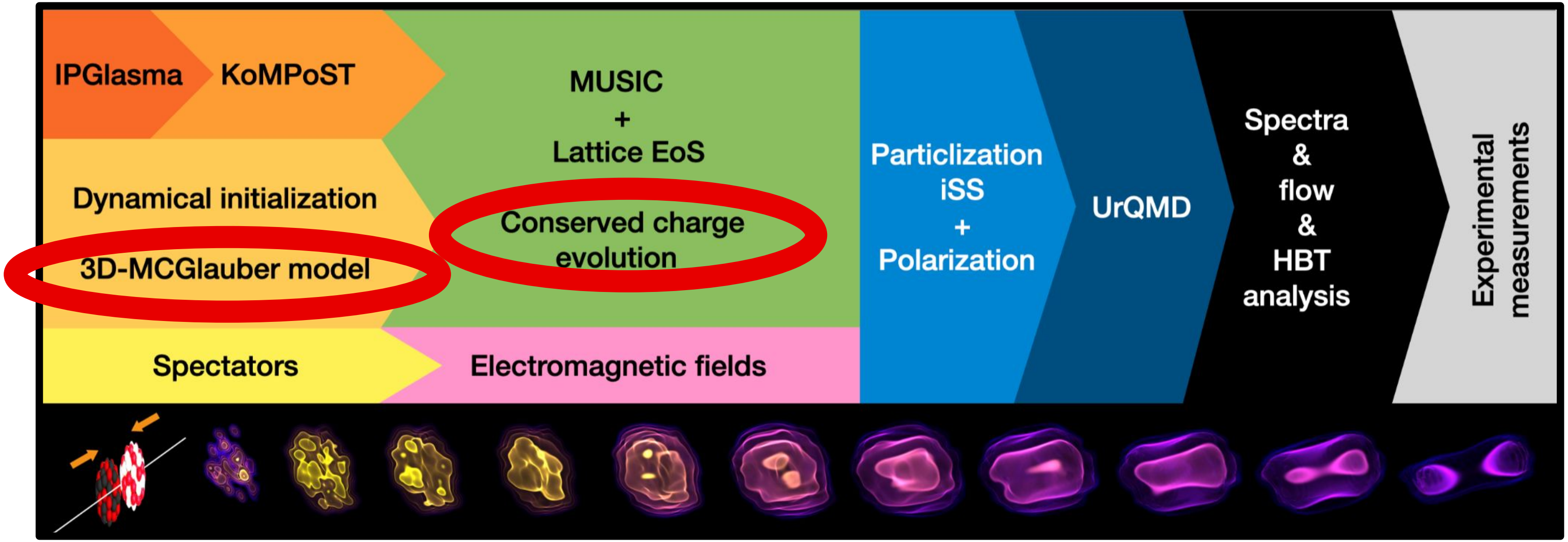
Open source hydrodynamics + hadronic transport hybrid framework



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

The iEBE-MUSIC framework

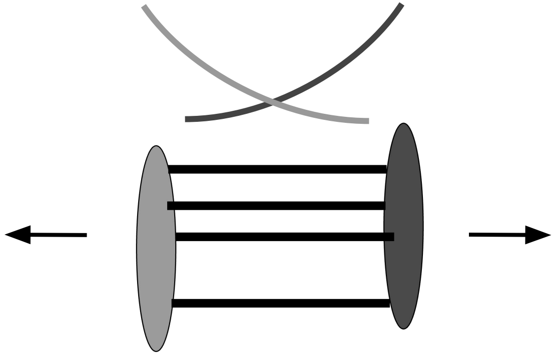
Open source hydrodynamics + hadronic transport hybrid framework



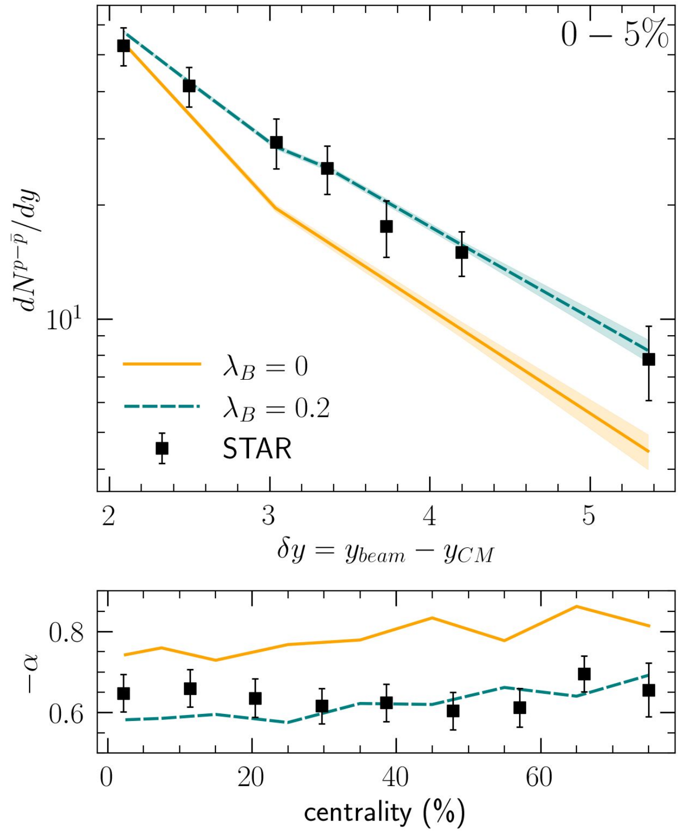
https://github.com/chunshen1987/iEBE-MUSIC

Initial conditions from the string junction 1/3

Energy, momentum and charge deposition:



Energy-momentum
string deceleration



Baryon/electric charge densities: nucleon + string junction

Probability for $X = B, Q$ to be at rapidity: $y^X_{P/T}$

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

$y_{P/T}$: projectile or target rapidity

we neglect double junction in this study

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

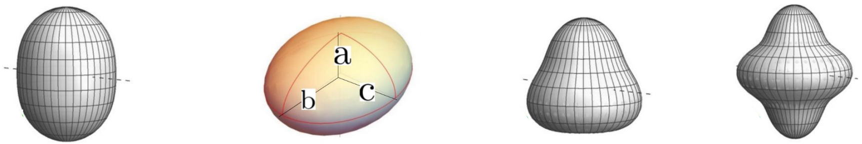
GP, A. Monnai, B. Schenke, C. Shen in Prep

Initial conditions from the string junction 2/3

Nucleon distribution: Wood-Saxon potential, **nuclear structure** and **neutron skin**

$$\rho(r,\theta) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)/a]}}$$

$$R(\theta,\phi) = R_0[1 + \beta_2(\cos(\gamma Y_{2,0}) + \sin(\gamma Y_{2,2})) + \beta_3 Y_{30} + \beta_4 Y_{40}]$$

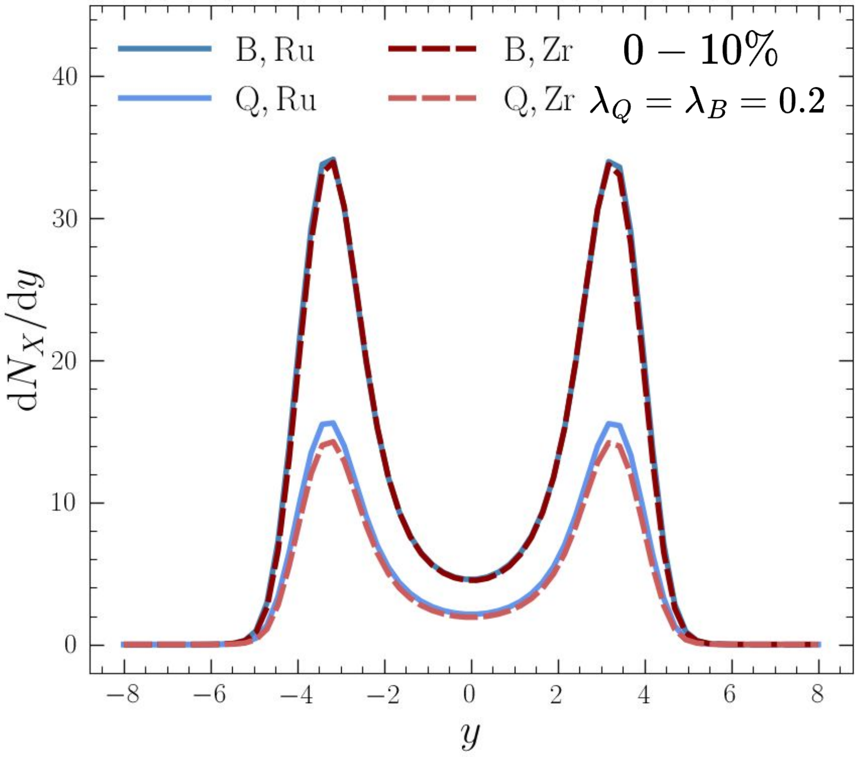


	R	a	γ	β_2	β_3	β_4	da	dR
Ru	5.09	0.46	0.0	0.16	0.0	0.0	0.01	0.015
Zr	5.02	0.52	0.0	0.06	0.2	0.0	0.05	0.1

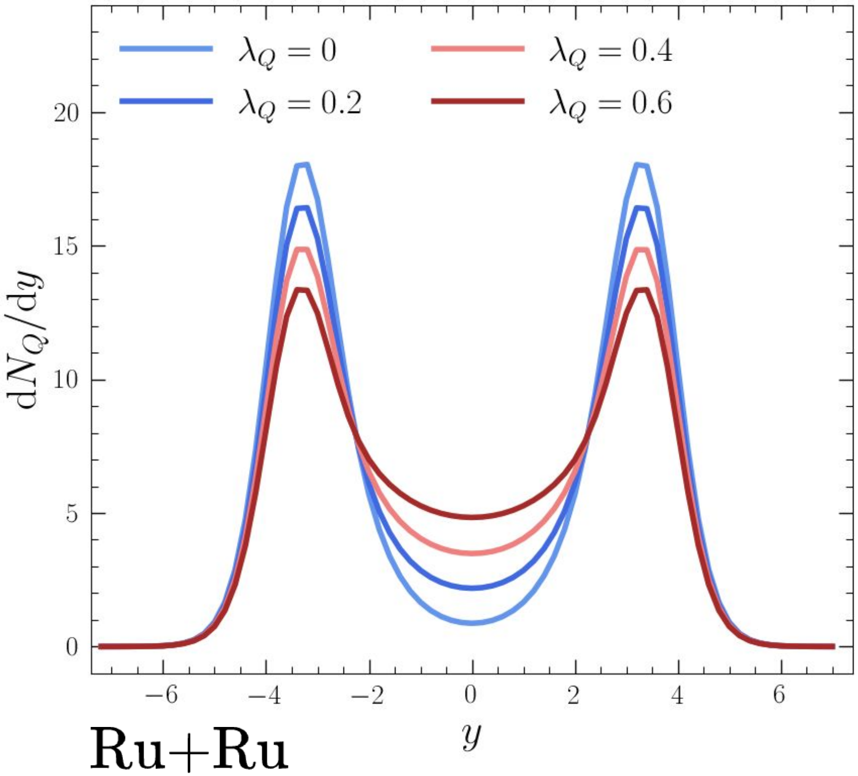
Neutron skin parameters: $\mathrm{d}a = a_n - a_p$ $\mathrm{d}R = R_n - R_p$

Initial conditions from the string junction 3/3

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



Initial electric charge density rapidity distributions for different values of λ_Q



MUSIC with 4D equation of state

Impact of the hydrodynamic evolution on the initial B to Q stoppings ratio?

$$\rho_Q \simeq 0.4\rho_B$$

MUSIC with 4D equation of state

Impact of the hydrodynamic evolution on the initial B to Q stoppings ratio?

$$\rho_Q \simeq 0.4 \rho_B$$

Not possible with this fixed constraint!

MUSIC with 4D equation of state

Impact of the hydrodynamic evolution on the initial B to Q stoppings ratio? ~~$\rho_Q \simeq 0.4\rho_B$~~

Ideal evolution of conserved charge**s**

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

$$N^\mu_X = \rho_X u^\mu$$

$X = B, Q, S$

B, Q and S current evolve independently!

MUSIC with 4D equation of state

NEOS 4D equation of state

Lattice Taylor expansion at finite chemical potentials: $$\frac{P_{\mathrm{Latt}}}{T^4} = \frac{P_0}{T^4} + \sum_{l,n,m} \frac{\chi_{l,n,m}^{B,Q,S}}{l!n!m!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^n \left(\frac{\mu_S}{T}\right)^m$$

Hadron Resonance Gas: $$P_{\mathrm{HRG}} = \pm T \sum_i \int \frac{g_i \mathrm{d}^3 k}{(2\pi)^3} \ln\left[1 \pm e^{(E_i(k)-\mu_i)/T}\right]$$

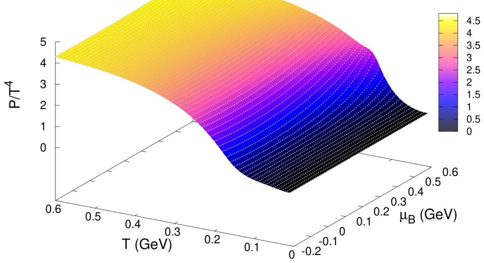
i : hadronic species $\quad \mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$

Matching: $$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_X)]\frac{P_{HRG}}{T^4} + \frac{1}{2}[1 + f(T,\mu_X)]\frac{P_{\mathrm{Latt}}}{T^4} \qquad X = B, Q, S$$

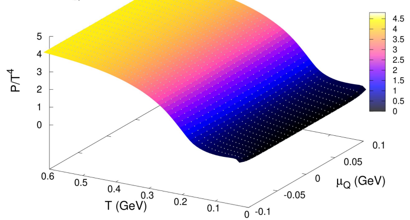
No assumptions on the relation between conserved charge densities.

B to Q stopping ratio can be studied!

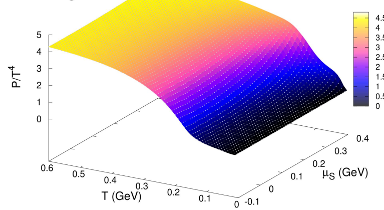
(a) T-μ_B plane



(b) T-μ_Q plane

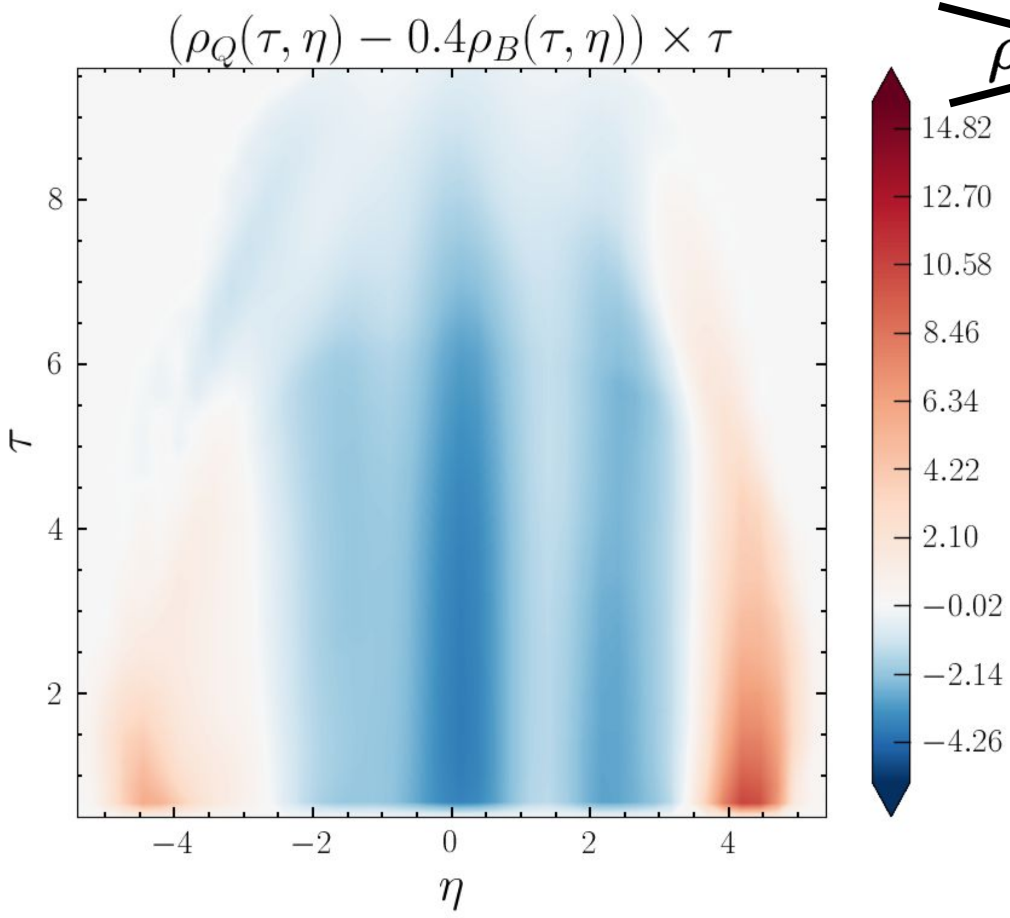


(c) T-μ_S plane



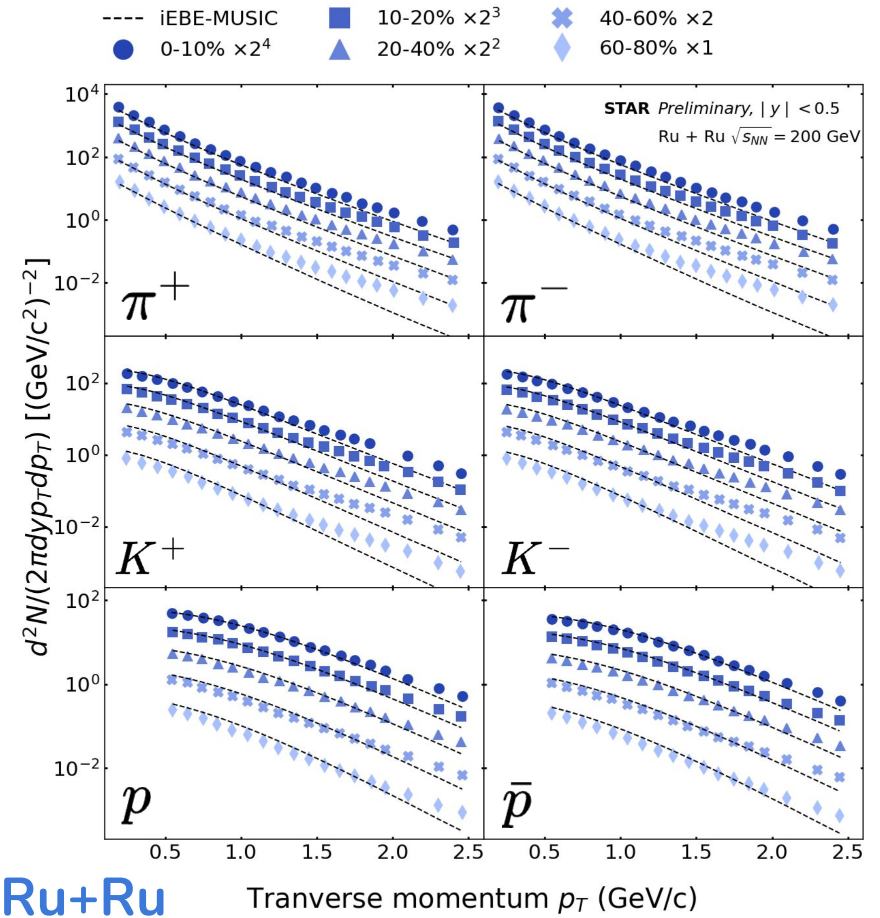
A. Monnai, B. Schenke and C.Shen Phys. Rev. C **100**, 024907

MUSIC with 4D equation of state

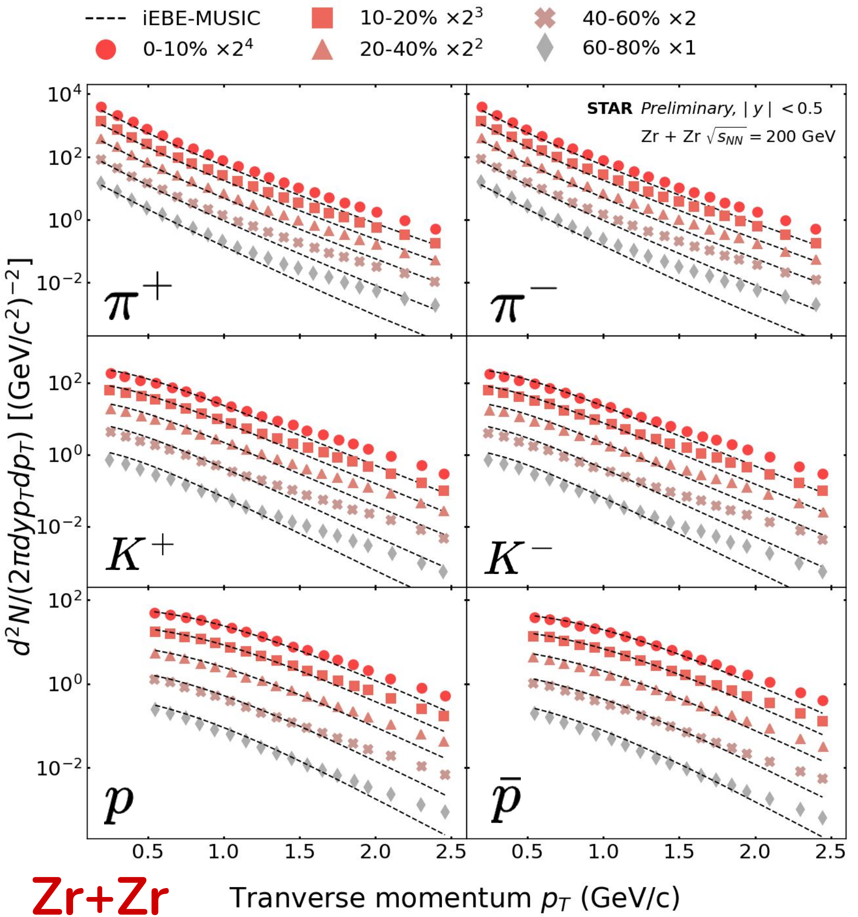


~~$\rho_Q \simeq 0.4\rho_B$~~

Identified particles pT



Ru+Ru



Zr+Zr

Equal stopping ratio definition

Charge conservation at mid-rapidity:

$$B_X = N_{B,X}[-0.5 < y < 0.5]$$
$$Q_X = N_{Q,X}[-0.5 < y < 0.5]$$
$$X = \mathrm{Ru}, \mathrm{Zr} \qquad A_X = A$$

$$\Rightarrow Q_X = B_X \times Z_X / A$$

Differentiation with respect to collision system:

$$\Delta Q = \Delta B Z_{\mathrm{Zr}}/A + B_{\mathrm{Ru}} \Delta Z / A$$

$$\Delta Q = Q_{\mathrm{Ru}} - Q_{\mathrm{Zr}} \quad \Delta B = B_{\mathrm{Ru}} - B_{\mathrm{Zr}} \quad \Delta Z = Z_{\mathrm{Ru}} - Z_{\mathrm{Zr}}$$

$$\boxed{r_2 = (\Delta B Z_{\mathrm{Zr}} + B_{\mathrm{Ru}} \Delta Z)/(A \Delta Q)}$$

$r_2 \sim 1$: charge conservation at mid-rapidity. Same stoppings.

$r_2 > 1$: extra baryon stopping!

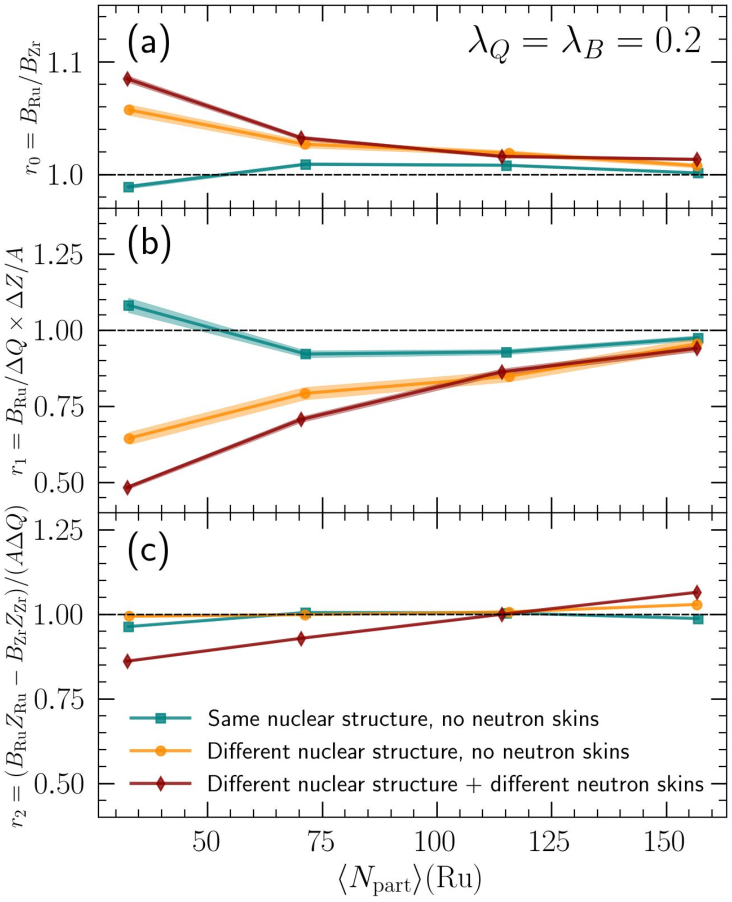
$$r_0 = B_{\mathrm{Ru}}/B_{\mathrm{Zr}}$$ net-baryon number ratio at mid-rapidity

$$r_1 = B_{\mathrm{Ru}} \Delta Z / A \qquad r_0 \sim 1$$ "RuB ratio"

$$r_2 = r_1[1 + Z_{\mathrm{Z_r}}/\Delta Z(1 - 1/r_0)]$$ corrections due to r_0

Disentangle contributions from stoppings, baryon number ratio and nuclear structure in RuB ratio "equal stopping" baseline!

Equal stopping and nuclear structure



- **Same nuclear structure, no neutron skins**

  r_0 : ~ 1 up to 1%.
  r_1 : deviates from unity and has a non-monotonic structure.
  r_2 : closer to 1.

  The baryon number ratio impacts r_1

- **Different nuclear structure, no neutron skins**

  r_0 : global increase due to nuclear structure selection bias
  r_1 : r_0 shape amplified by ΔQ^{-1}
  r_2 : closer to 1. Weakly related to r_0

  The nuclear structure impacts r_1

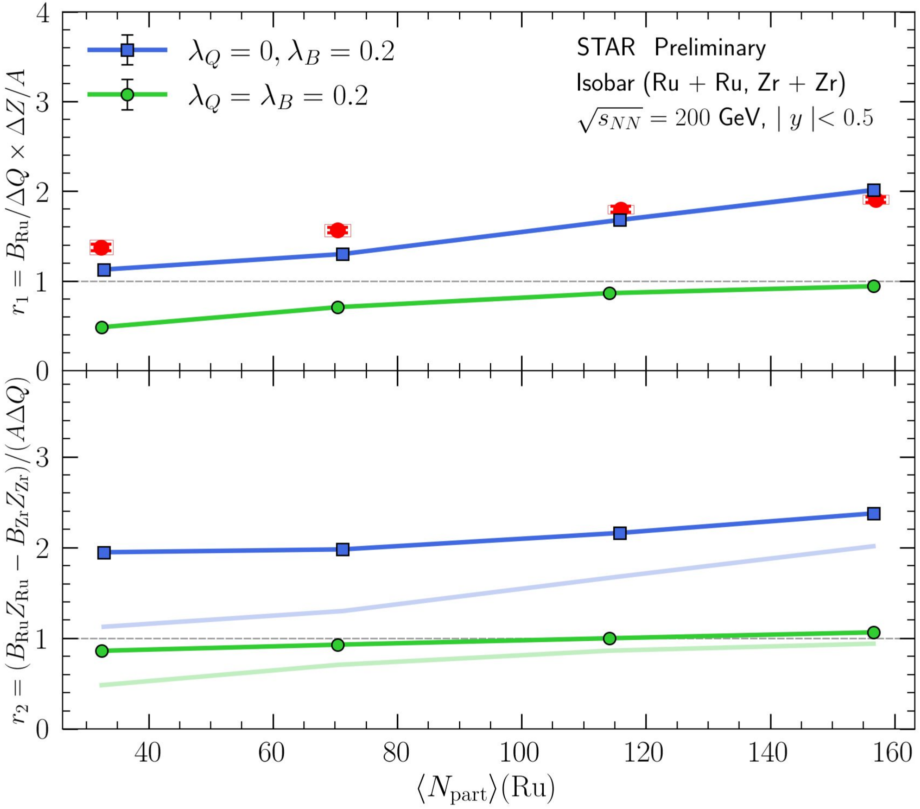
- **Different nuclear structure + neutron skins**

  r_2 : shows the net effect from neutron skin (~20%) on the increasing behavior of r_1.

The increasing behavior is mainly due to the net baryon charge difference between Ru and Zr caused by different nuclear shapes

The centrality dependence of the ratio r_2 shows strong sensitivity to the neutron skin difference between Ru and Zr.

Ratio at initial stage



➢ **"Equal stopping"** $\lambda_Q = \lambda_B = 0.2$

- Underestimate STAR data.
- $r_1 < 1$
- $r_2 \sim 1$

➢ **No Q stopping from junction** $\lambda_Q = 0$

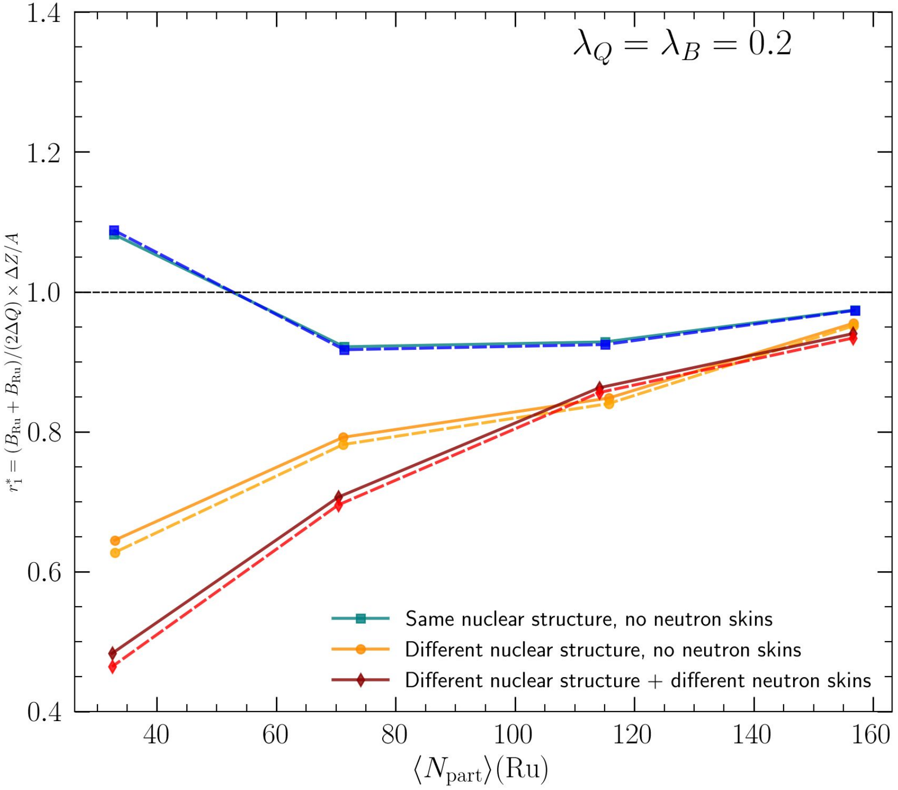
- Closer to STAR data.
- $r_1 > 1$
- $r_2 \sim 2$

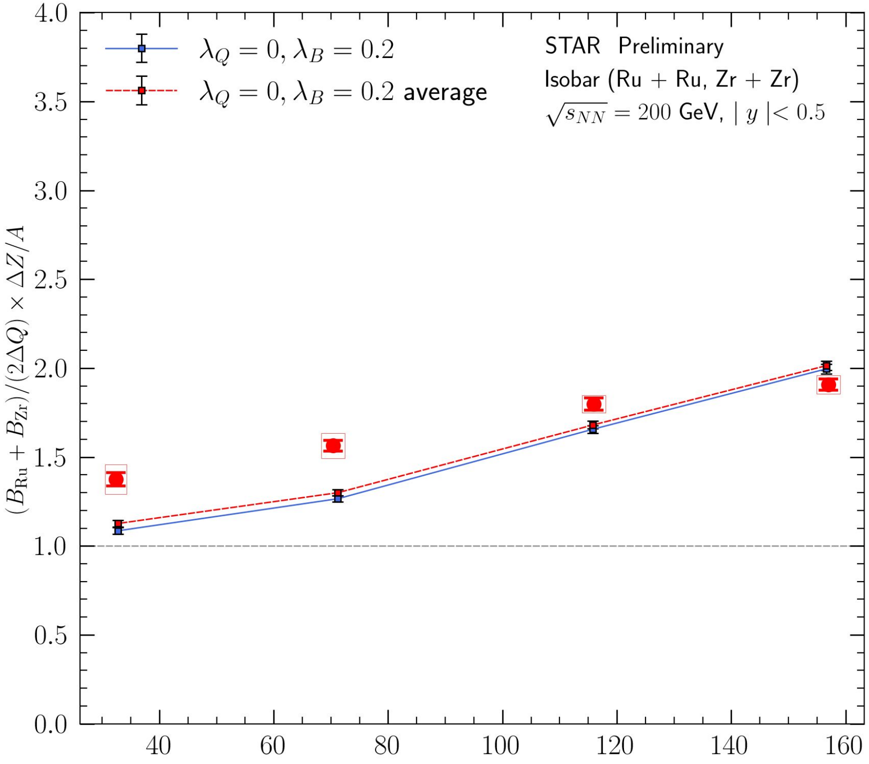
r_2 : Generally flatter. Npart behavior solely due the neutron skin.

Comparison to STAR measurement at initial stage advocates for
a finite baryon transport due to string junctions, but not for electric charges.

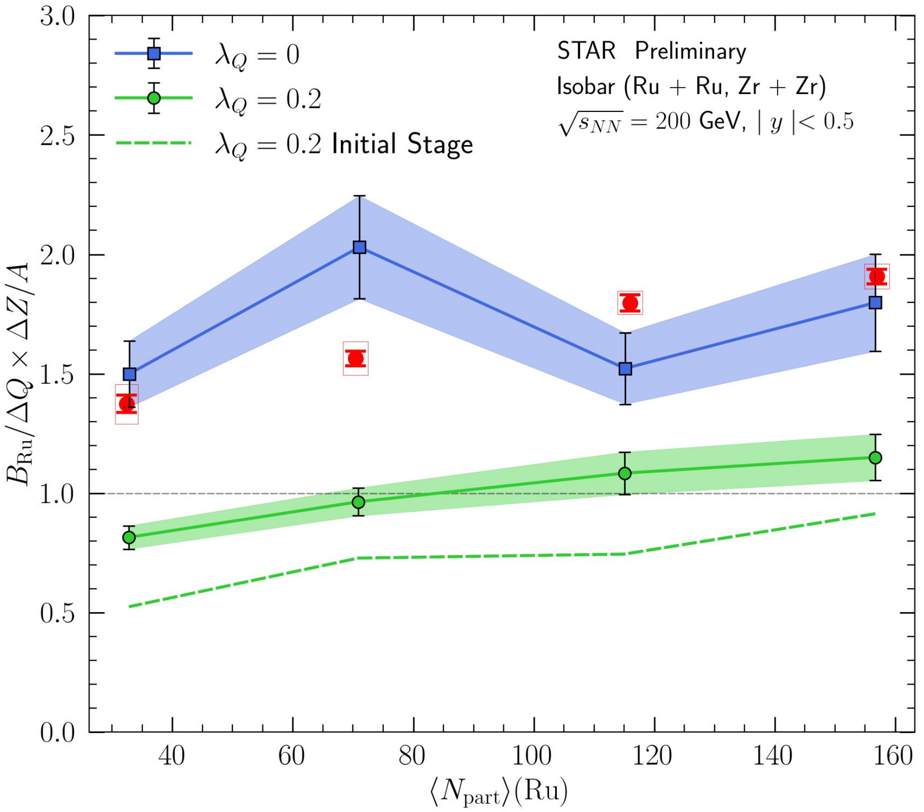
Comparison with STAR ratio

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





Ratio at final stage



➢ **"Equal stopping"** $\lambda_Q = \lambda_B = 0.2$

- Underestimate the experimental ratio
- ratio ~ 1.

➢ **Q stopping from junction** $\lambda_Q = 0$

- Close to experimental data

Initial to final stage: increase of 30%

➢ Associated to a mismatch between EoS HRG and urQMD particle list
-> New EoS Matching UrQMD available!!

Ideal hydrodynamics is not expected to have a strong impact on initial ratios.

Comparison to STAR measurement at final shows a significant increase of r_1 for a finite baryon transport and not for the electric charges.

Wrap up & outlook

- "Can gluon junction trace the baryon number?"
  - Clear difference in baryon and electric charge stopping at STAR
  - Results: **compatible with STAR data for the baryon junction picture.**
  - The ratios is sensitive to the neutron skin: **study of the nuclear structure?**

- The iEBE-MUSIC framework:
  - 4D EoS in MUSIC
  - Decoupled Net-B and Net-Q densitities evolution: study of **neutron rich nucleus collisions.**
  - Short term: ML techniques to have an idea of final result.
  - Long term: diffusion for conserved charge

Thank you for your attention!

backup

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.

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

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

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

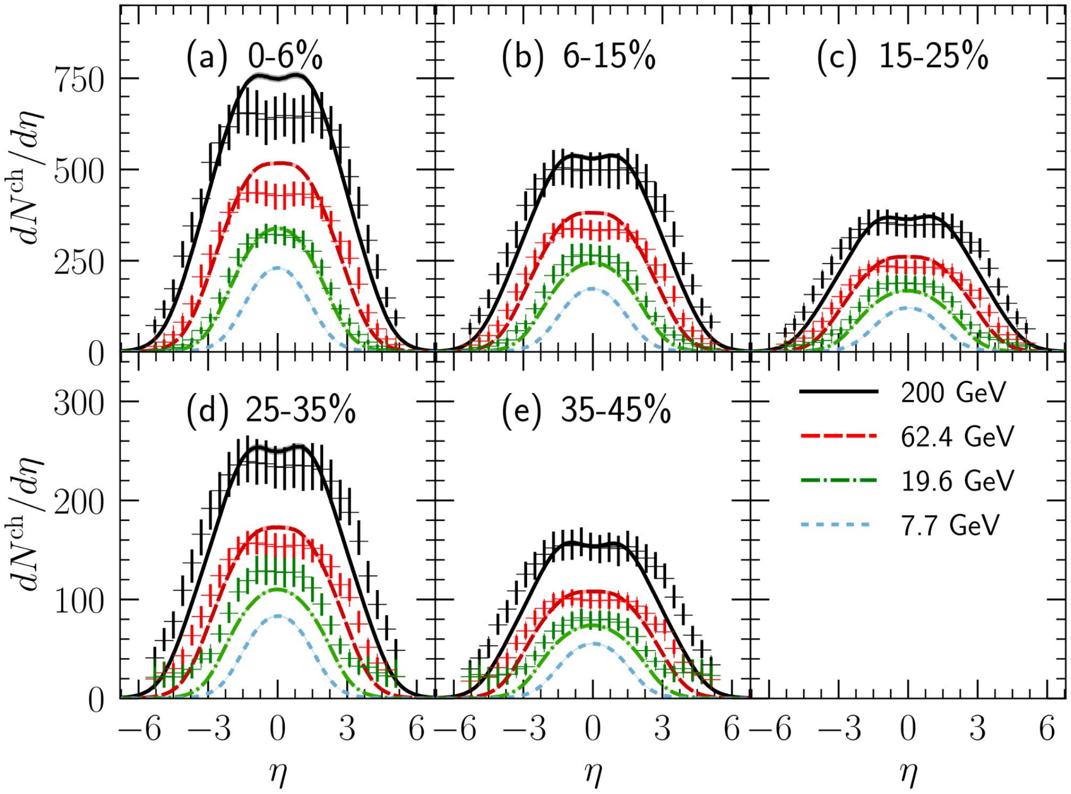
MUSIC tuning on PHOBOS Au+Au data

Current version:

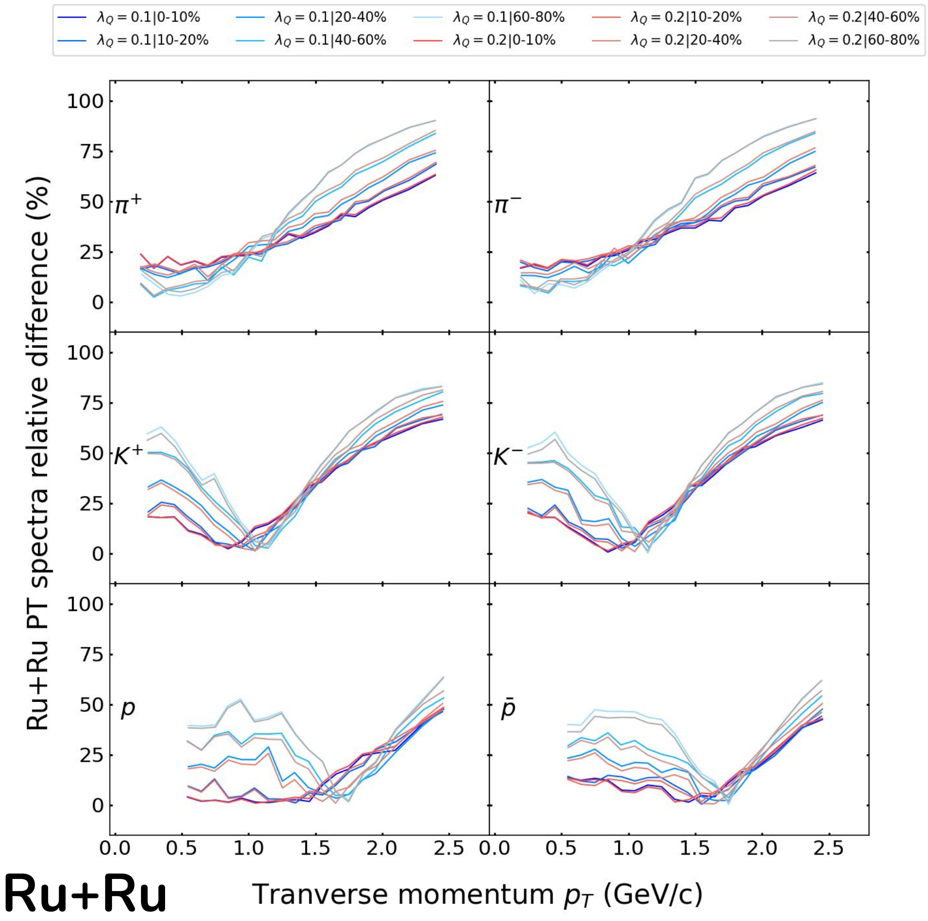
- ➢ Tuned on charged particle rapidity distributions for Au+Au collisions at RHIC PHOBOS

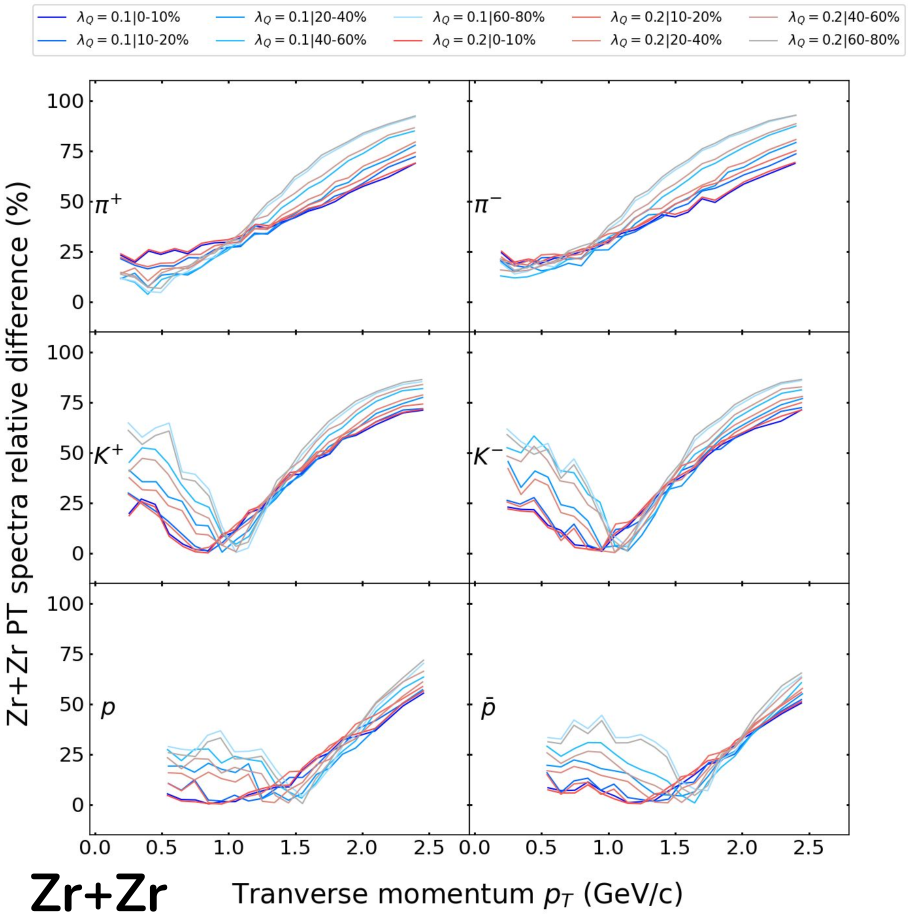
- ➢ Overestimate yields at mid-rapidity for most central collision

- ➢ Overall good agreement ✔

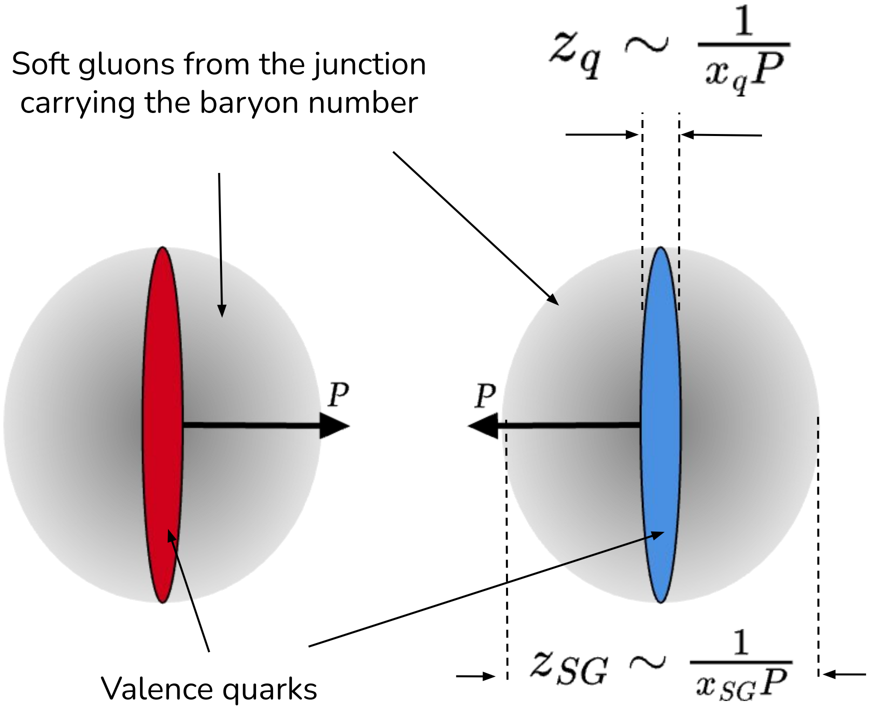


Backup: PT spectra relative difference





Backup: Gluon cloud interpretation



Quarks: $x_q \sim 1/3$

interaction time is short

~6.10^-3 fm

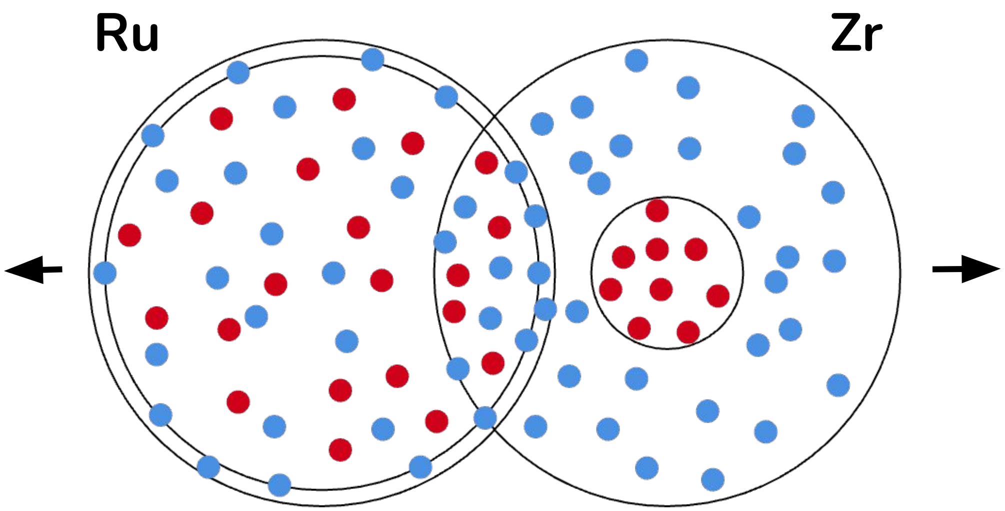
Soft gluons: $x_{SG} \ll x_q$

interaction time is large

~1 fm

The baryon number is stopped!

Backup: Geometrical interpretation of ratio(Npart)



The neutron skin is larger for Zirconium

The ruthenium nucleus controls the electric charge

- No protons from zirconium in the overlap region

$$\Delta Q \simeq Q_{\text{Ru}}$$

For decreasing Npart $\Delta N_{\text{part}} < 0$

The baryon number escapes from both sides B

The electric charge difference escapes only from Ru side ΔQ

B decreases faster than ΔQ

$$B/\Delta Q(N_{\text{part}} + \Delta N_{\text{part}}) < B/\Delta Q(N_{\text{part}})$$