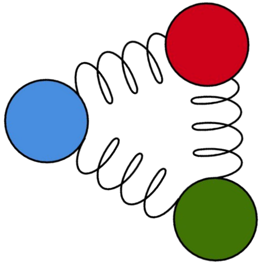
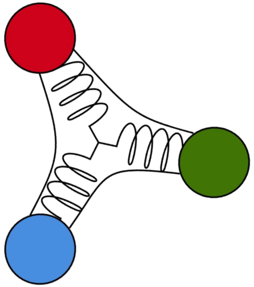
Tracing the baryon number in relativistic isobar collisions at RHIC



1st workshop on Baryon Dynamics from RHIC to EIC

Center for Frontiers in Nuclear Science
Stony Brook University, 24th of Jan 2024



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

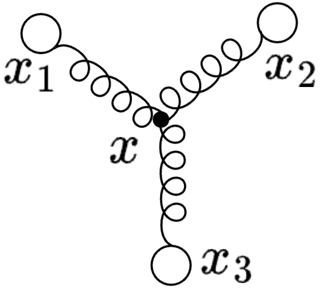
[1]***Wayne state University***, *Detroit, USA*, [2]***Osaka Institute of technology***, *Osaka, Japan*, [3]***Brookhaven National Lab***, *Upton, USA*

WAYNE STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY

What traces the baryon number?

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



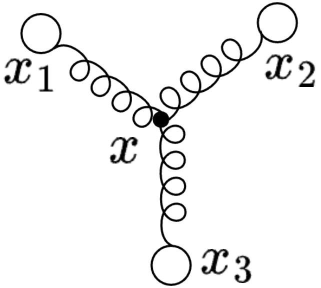
Non-perturbative configuration of gluons represented by a locally gauge-invariant state vector.

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 traces the baryon number?

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



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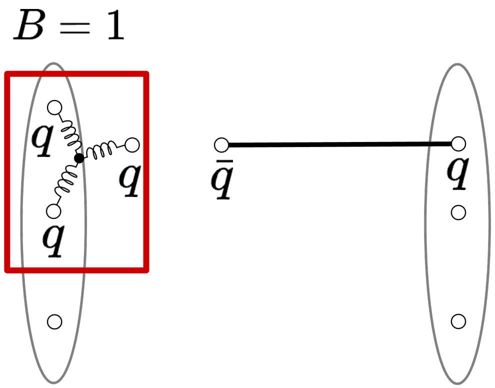
The string junction x carries the baryon number inside the baryon

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

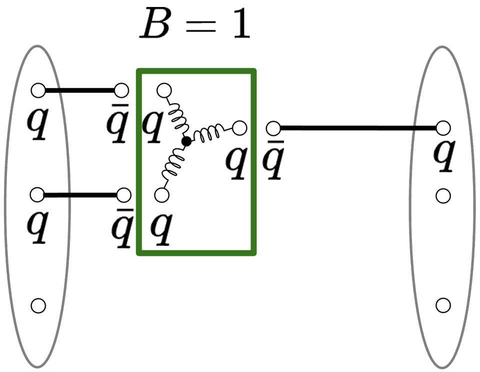
D. Kharzeev, Physics Letters B **378**, 238 (1996)

Baryon stopping and string junction

The string junction allows two possibilities

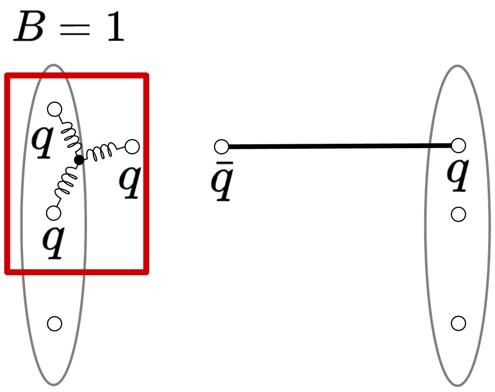


The baryon number remain
attached to the nucleon

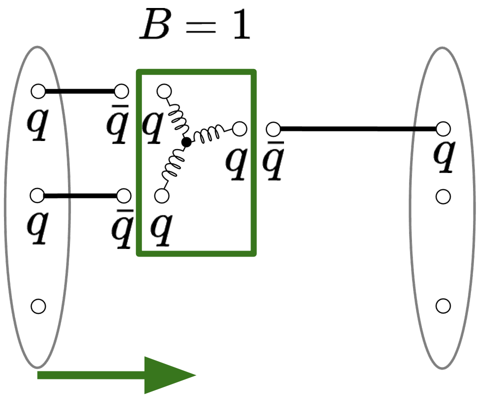


The baryon number to fluctuate
towards mid-rapidity

The string junction allows two possibilities



The baryon number remain attached to the nucleon



The baryon number is stopped!

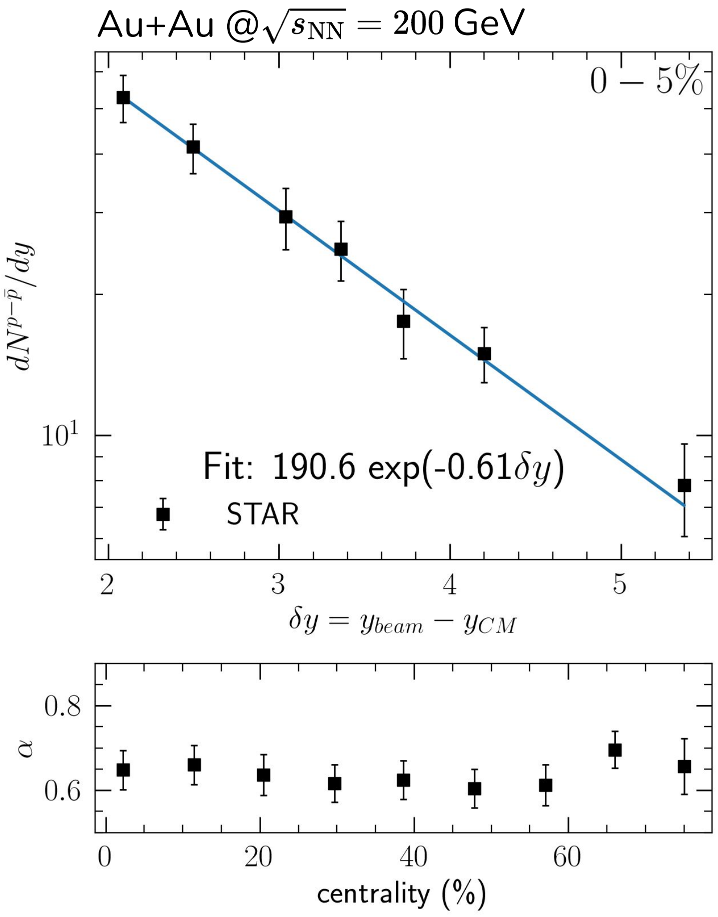
Baryon stopping and string junction

Exponential decrease as a function of the rapidity loss δy

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

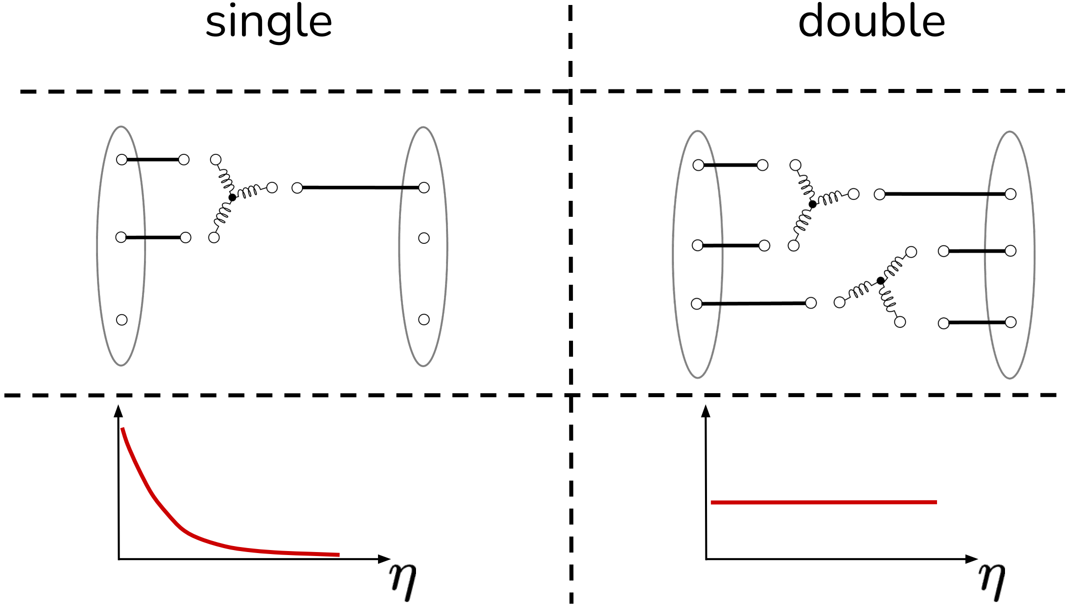
$$N = 190.6$$

$$\alpha = 0.61$$



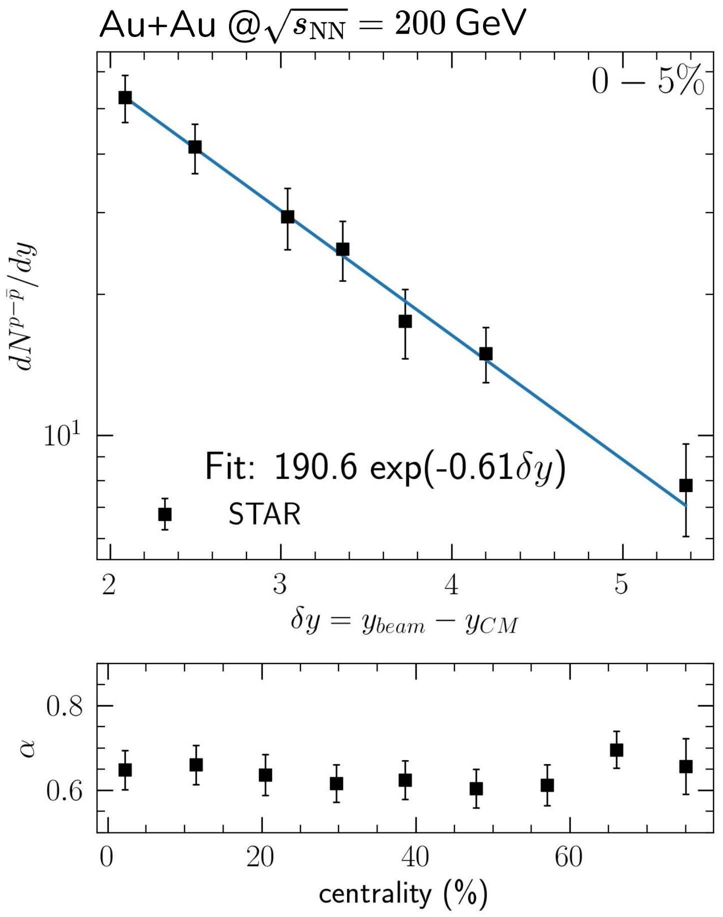
Baryon stopping and string junction

Exponential decrease as a function of the rapidity loss δy



$$\alpha_j = 0.5$$

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



Insight from the isobar collisions at RHIC

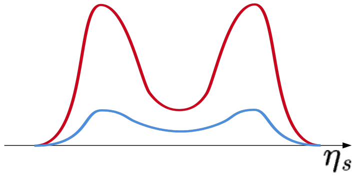
Isobar Runs: Same number of nucleons A, different number of protons Z

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

➢ **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

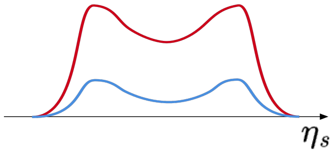


Valence quarks carry the baryon number

“Equal stoppings”

net-Baryon number and net-electric charge stop differently

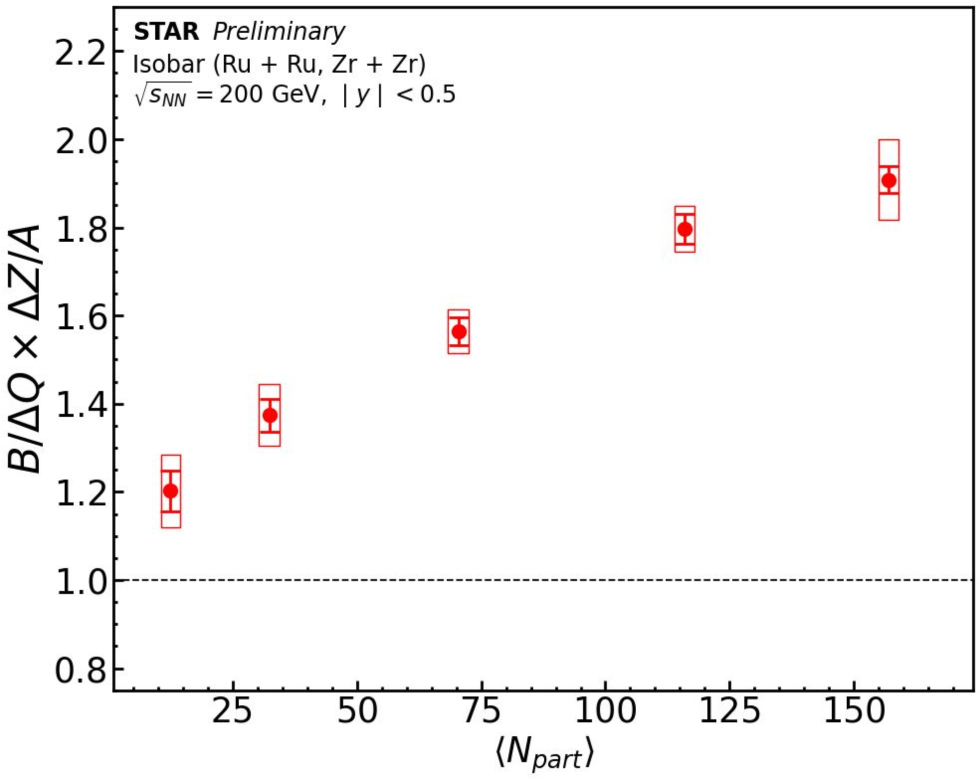
Baryon number is carried by something else. **Baryon junction?**



“Different stoppings”

Insight from the isobar collisions at RHIC

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



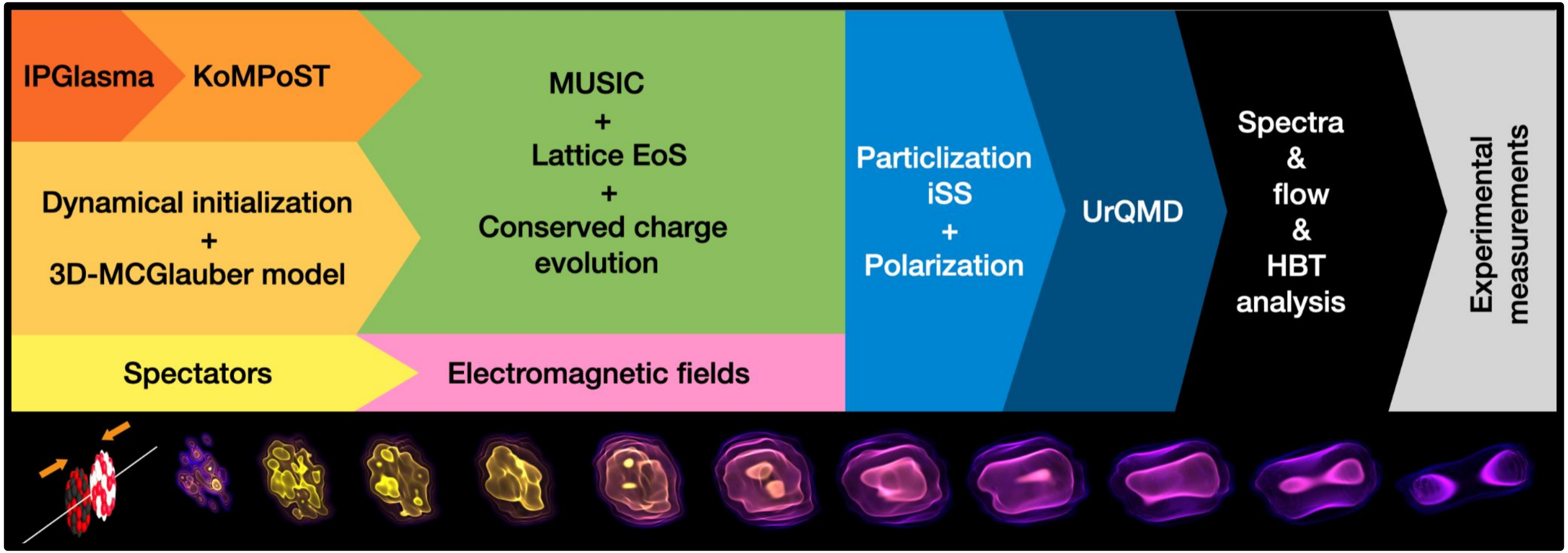
This result indicates that there is more baryon stopping than electric charge stopping

Is this a sign of the string junction?

STAR collaboration , in prep

The iEBE-MUSIC framework

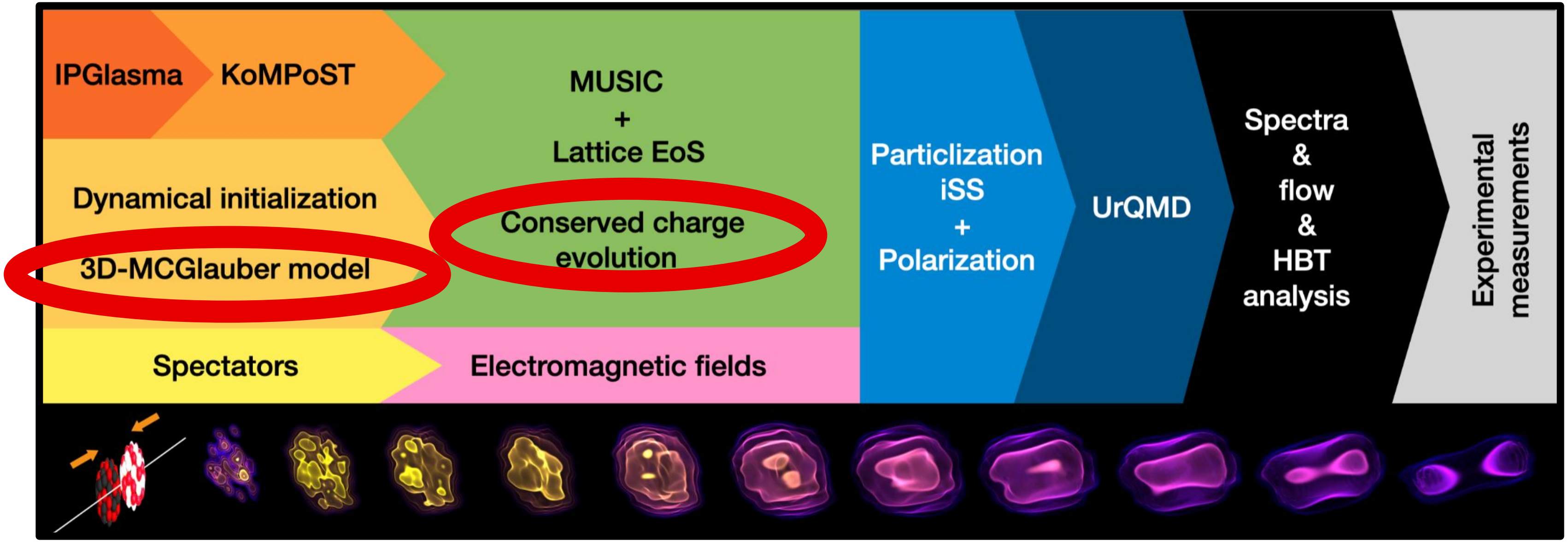
Open source hydrodynamics + hadronic transport hybrid framework



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

The iEBE-MUSIC framework

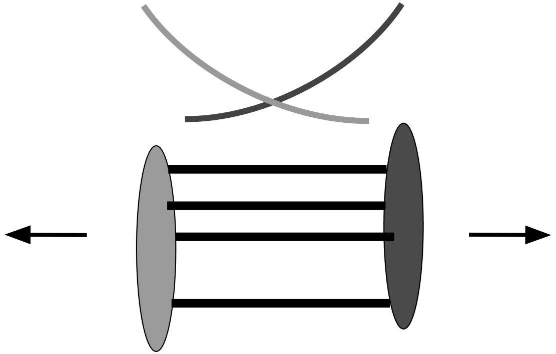
Open source hydrodynamics + hadronic transport hybrid framework



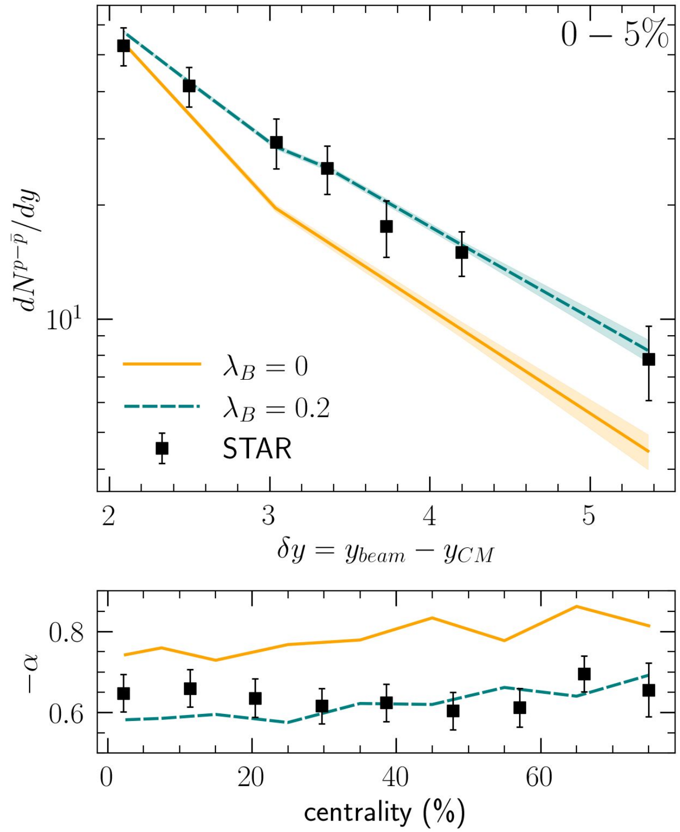
https://github.com/chunshen1987/iEBE-MUSIC

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)

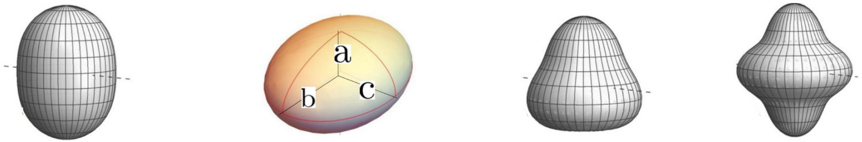
GP, A. Monnai, B. Schenke, C. Shen in Prep

Initial conditions from the string junction 2/3

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

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

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

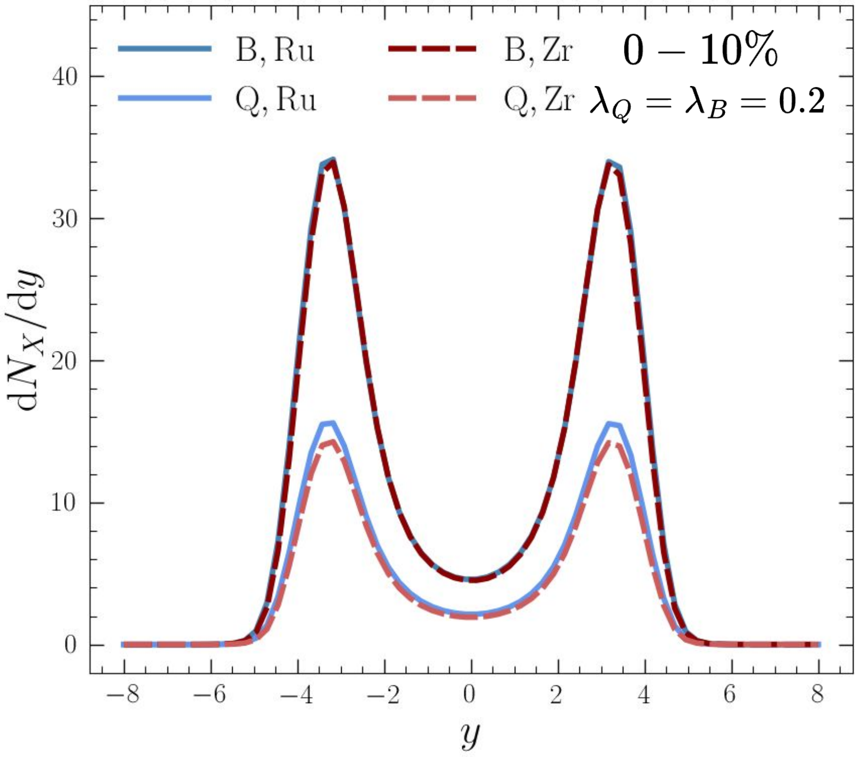


	R	a	γ	β_2	β_3	β_4	da	dR
Ru	5.09	0.46	0.0	0.16	0.0	0.0	0.01	0.015
Zr	5.02	0.52	0.0	0.06	0.2	0.0	0.05	0.1

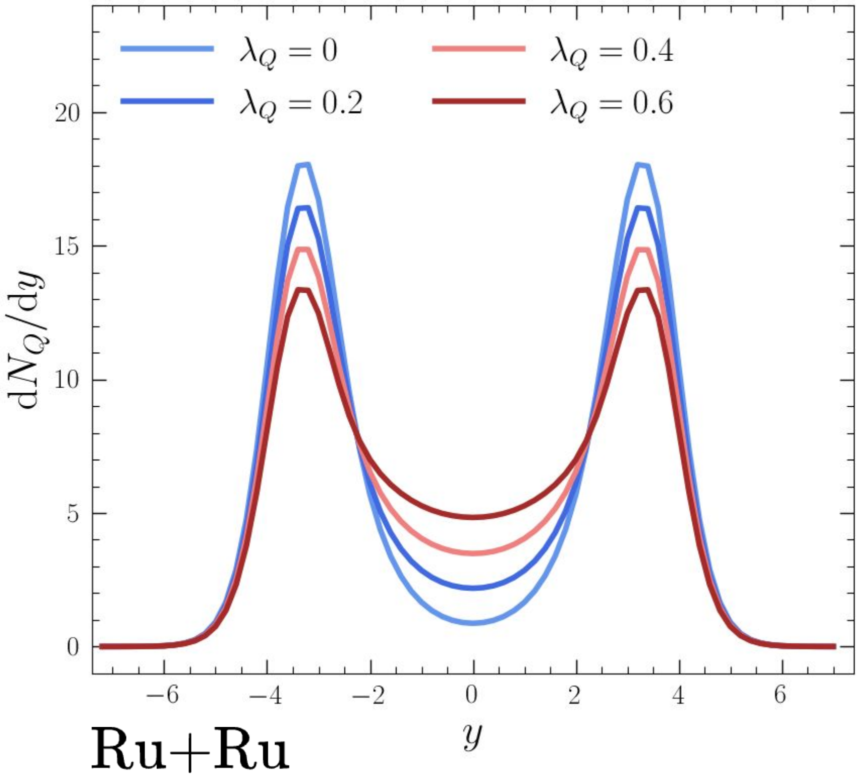
Neutron skin parameters: $\mathrm{d}a = a_n - a_p$ $\mathrm{d}R = R_n - R_p$

Initial conditions from the string junction 3/3

Initial baryon and electric charge density rapidity distributions for isobar runs at $\sqrt{s_{\rm NN}} = 200$ 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: $$\frac{P_{\rm Latt}}{T^4} = \frac{P_0}{T^4} + \sum_{l,n,m} \frac{\chi^{B,Q,S}_{l,n,m}}{l!n!m!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^n \left(\frac{\mu_S}{T}\right)^m$$

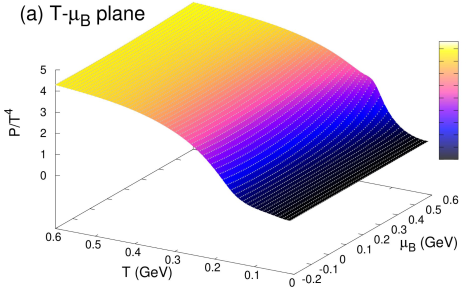
Hadron Resonance Gas: $$P_{\rm HRG} = \pm T \sum_i \int \frac{g_i d^3k}{(2\pi)^3} \ln\left[1 \pm e^{(E_i(k)-\mu_i)/T}\right]$$

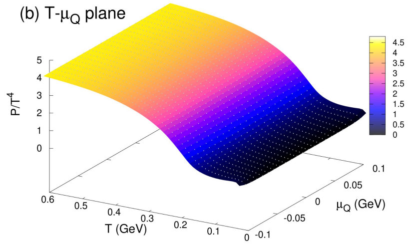
i : hadronic species $\quad \mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$

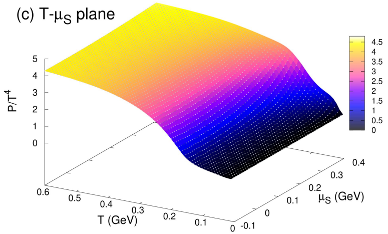
Matching: $$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_X)]\frac{P_{HRG}}{T^4} + \frac{1}{2}[1 + f(T,\mu_X)]\frac{P_{\rm Latt}}{T^4} \qquad X = B, Q, S$$

No assumptions on the relation between conserved charge densities.

B to Q stopping ratio can be studied!

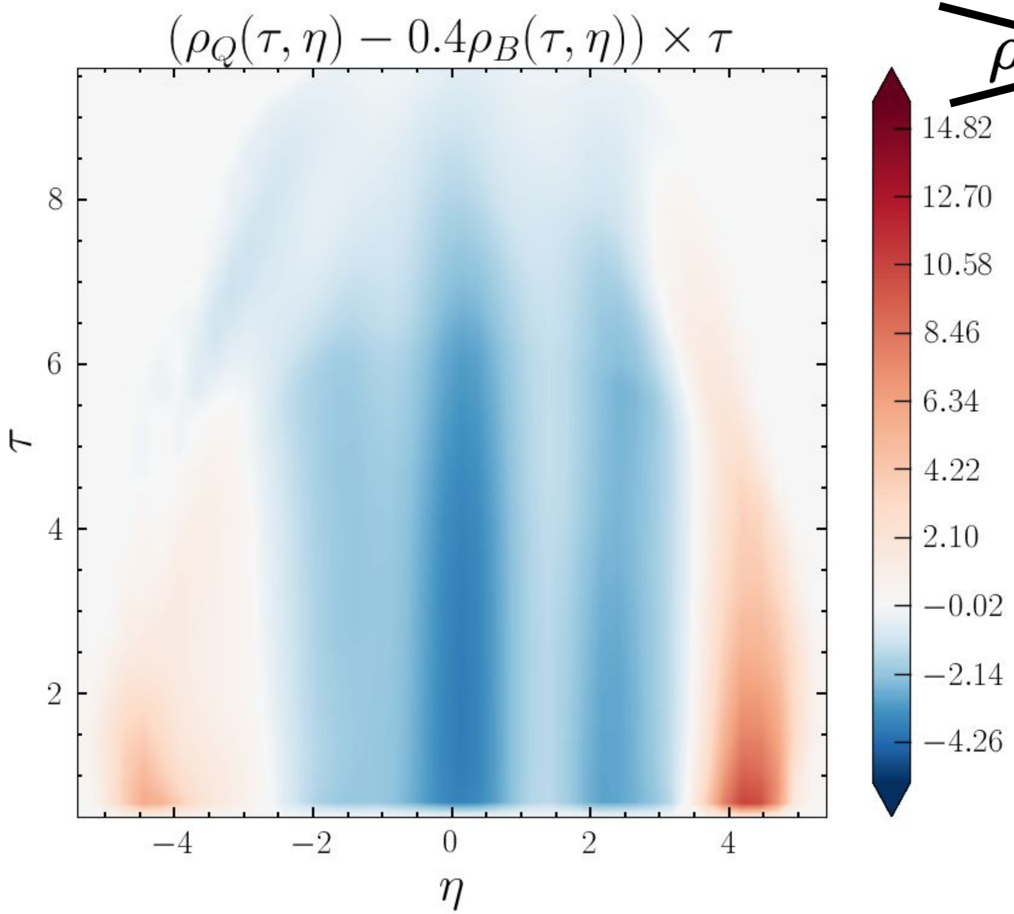






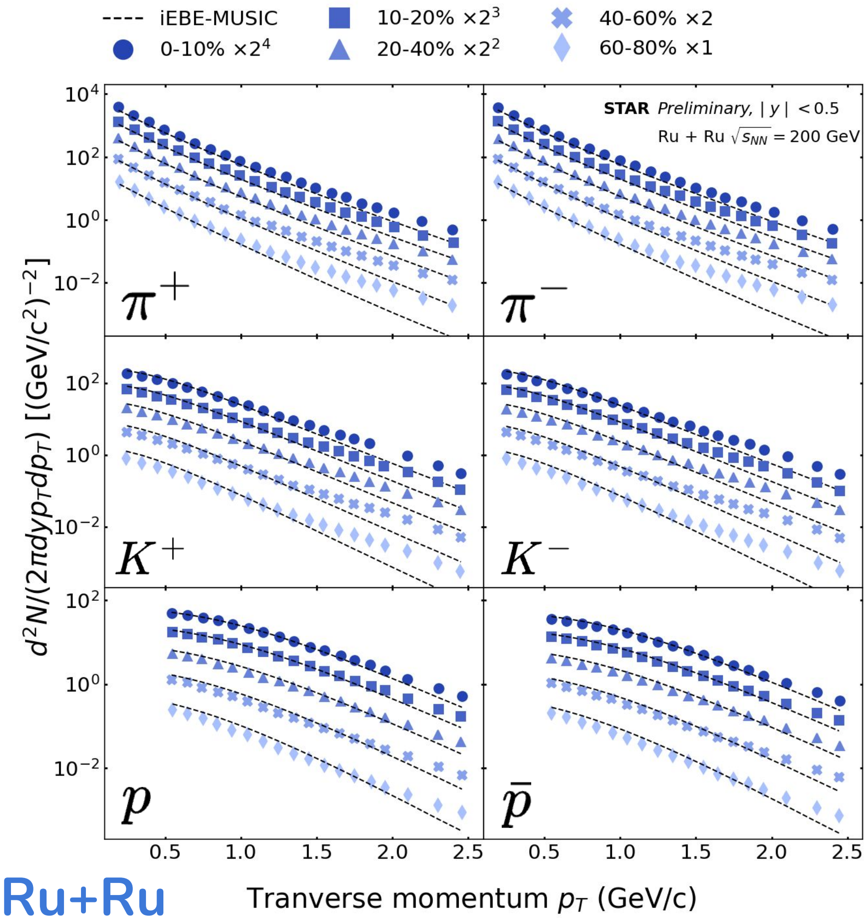
A. Monnai, B. Schenke and C.Shen Phys. Rev. C **100**, 024907

MUSIC with 4D equation of state

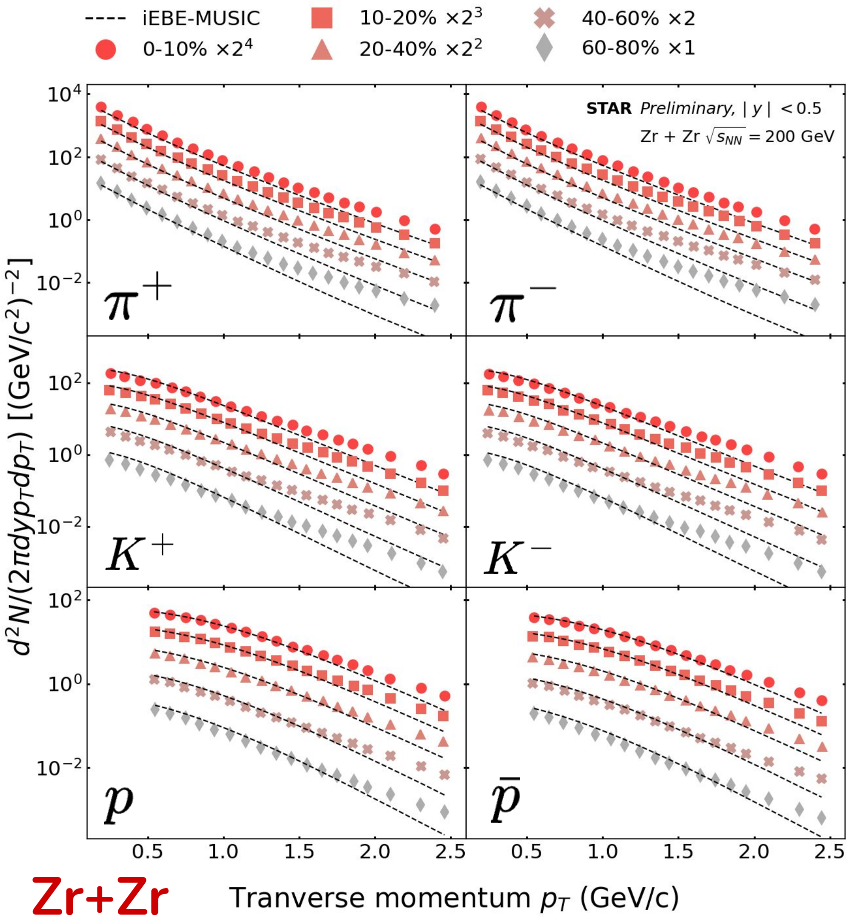


~~$\rho_Q \simeq 0.4\rho_B$~~

Identified particles pT



Ru+Ru



Zr+Zr

Equal stopping ratio definition

Charge conservation at mid-rapidity:

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

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!

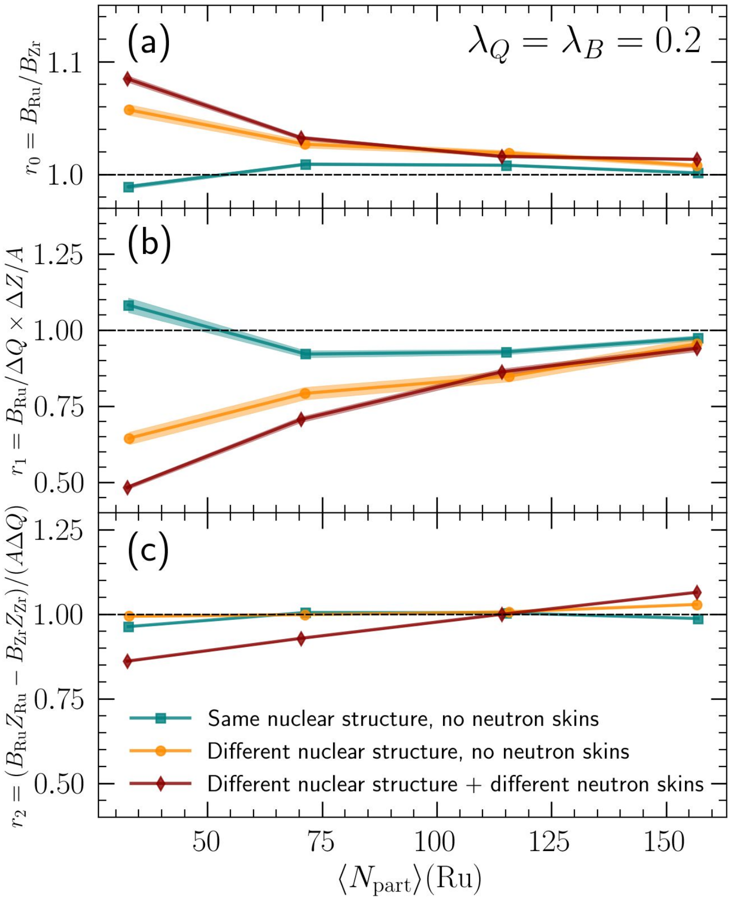
$r_0 = B_{\mathrm{Ru}} / B_{\mathrm{Zr}}$ — net-baryon number ratio at mid-rapidity

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

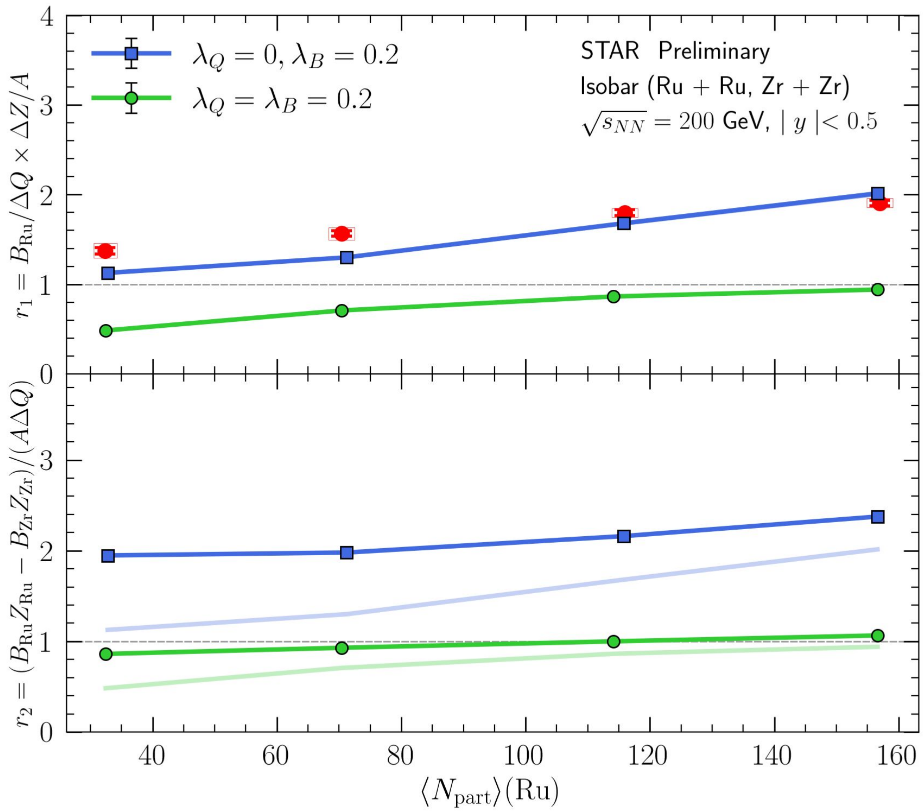
➢ **Different nuclear structure + neutron skins**

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.

Wrap up & outlook

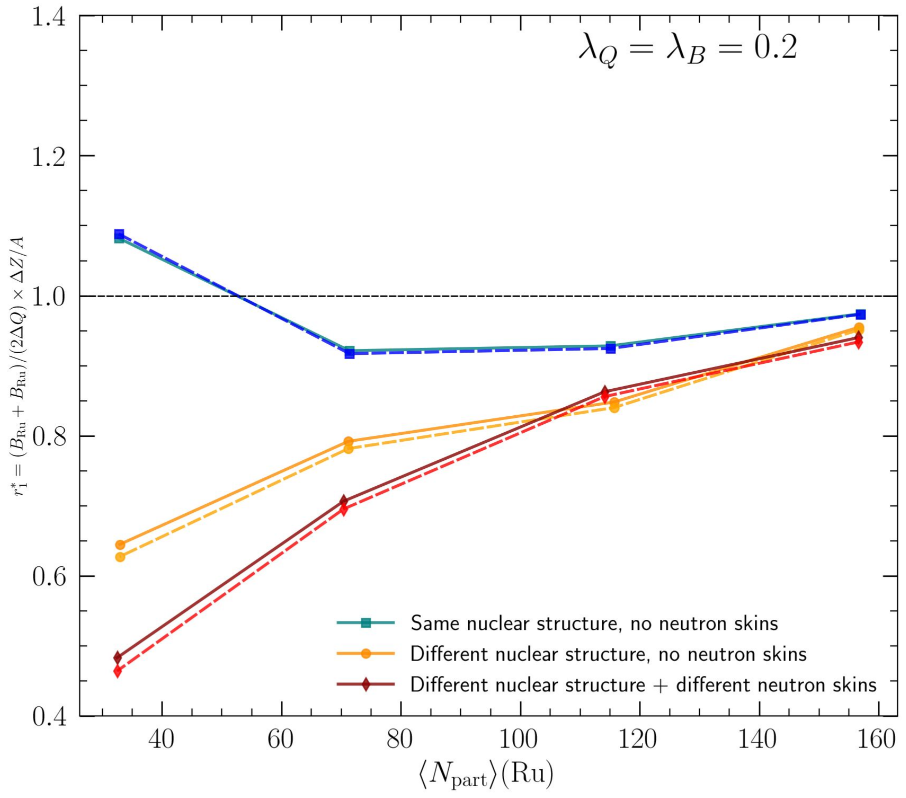
- “Can gluon junction trace the baryon number?”
  - Clear difference in baryon and electric charge stopping at STAR
  - Results: **compatible with STAR data for the baryon junction picture.**
  - The ratios is sensitive to the neutron skin: **study of the nuclear structure?**

- 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

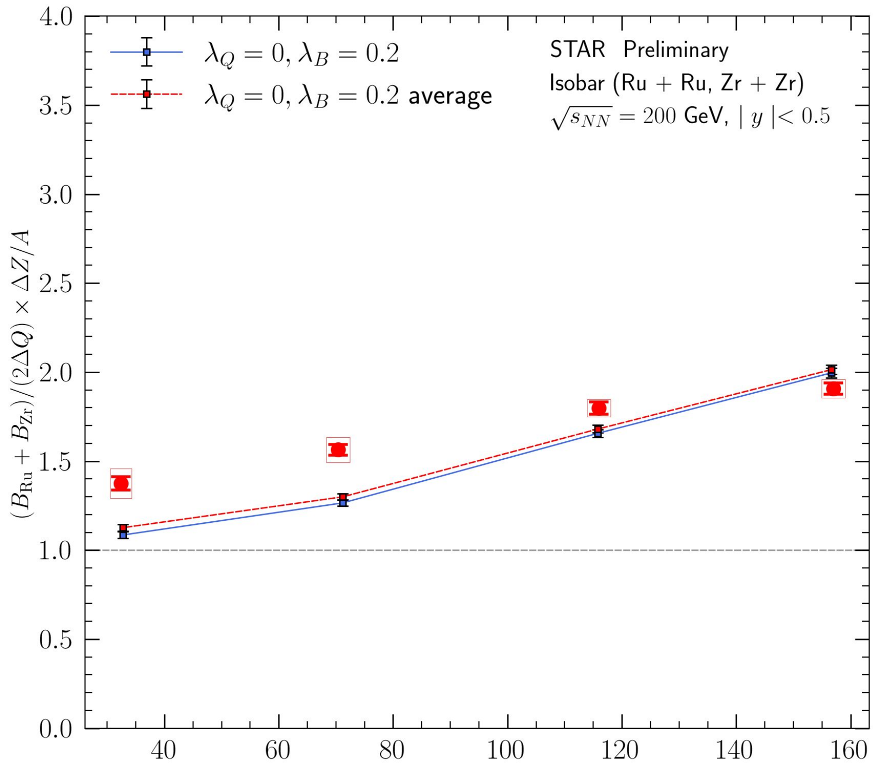
Thank you for your attention!

backup

(RuB + ZrB) / 2



$\lambda_Q = \lambda_B = 0.2$
$r_1^* = (B_{\rm Ru} + B_{\rm Ru})/(2\Delta Q) \times \Delta Z/A$
1.4
1.2
1.0
0.8
0.6
0.4
40
60
80
100
120
140
160
$\langle N_{\rm part} \rangle$(Ru)
Same nuclear structure, no neutron skins
Different nuclear structure, no neutron skins
Different nuclear structure + different neutron skins



$\lambda_Q = 0, \lambda_B = 0.2$
$\lambda_Q = 0, \lambda_B = 0.2$ average
STAR Preliminary
Isobar (Ru + Ru, Zr + Zr)
$\sqrt{s_{NN}} = 200$ GeV, $|y| < 0.5$
$(B_{\rm Ru} + B_{\rm Zr})/(2\Delta Q) \times \Delta Z/A$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
40
60
80
100
120
140
160

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!).

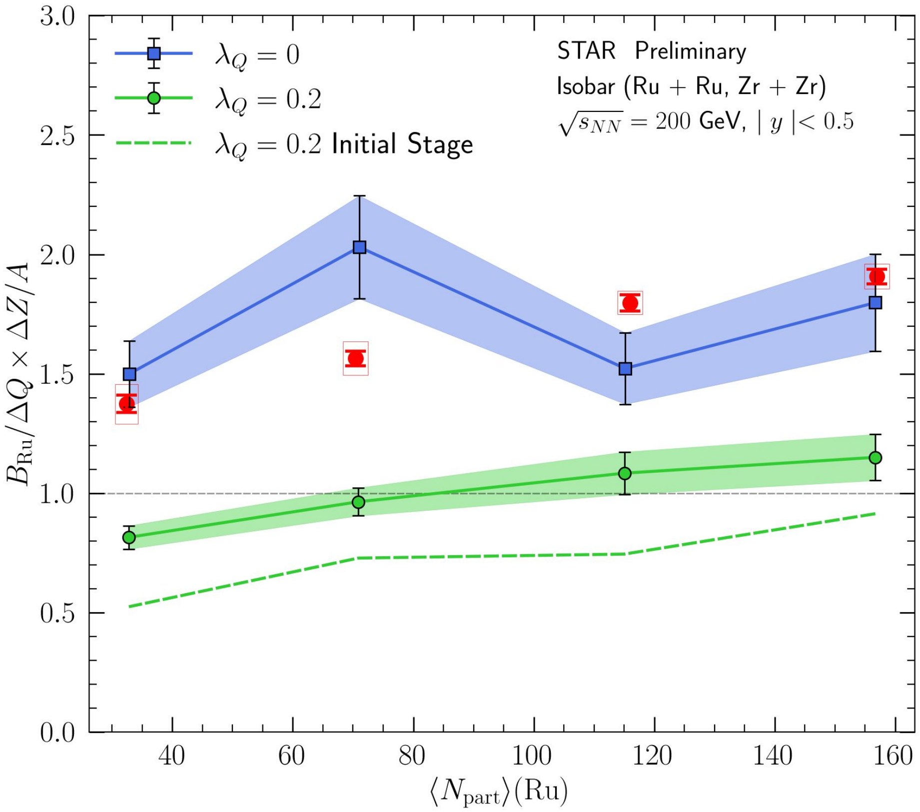
Making use of the convenient double ratios to cancel uncertainties accessible in isobars collisions.

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

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

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

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%

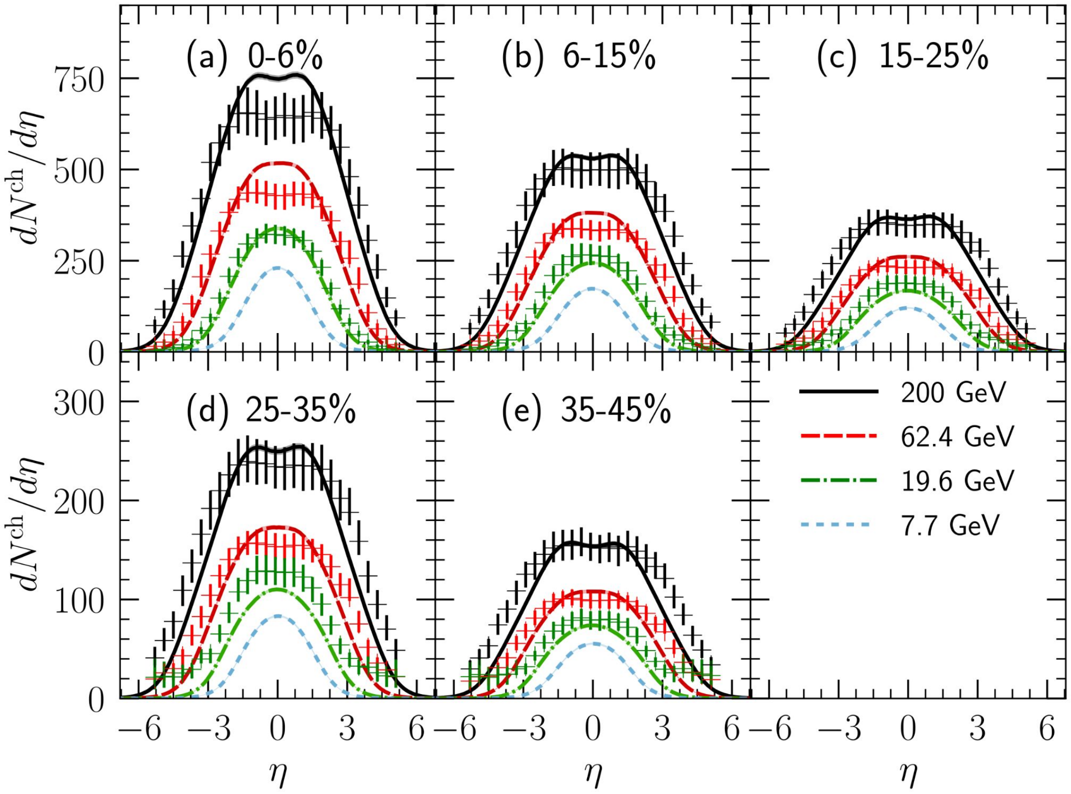
➢ Associated to a mismatch between HRG and urQMD particle list.

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

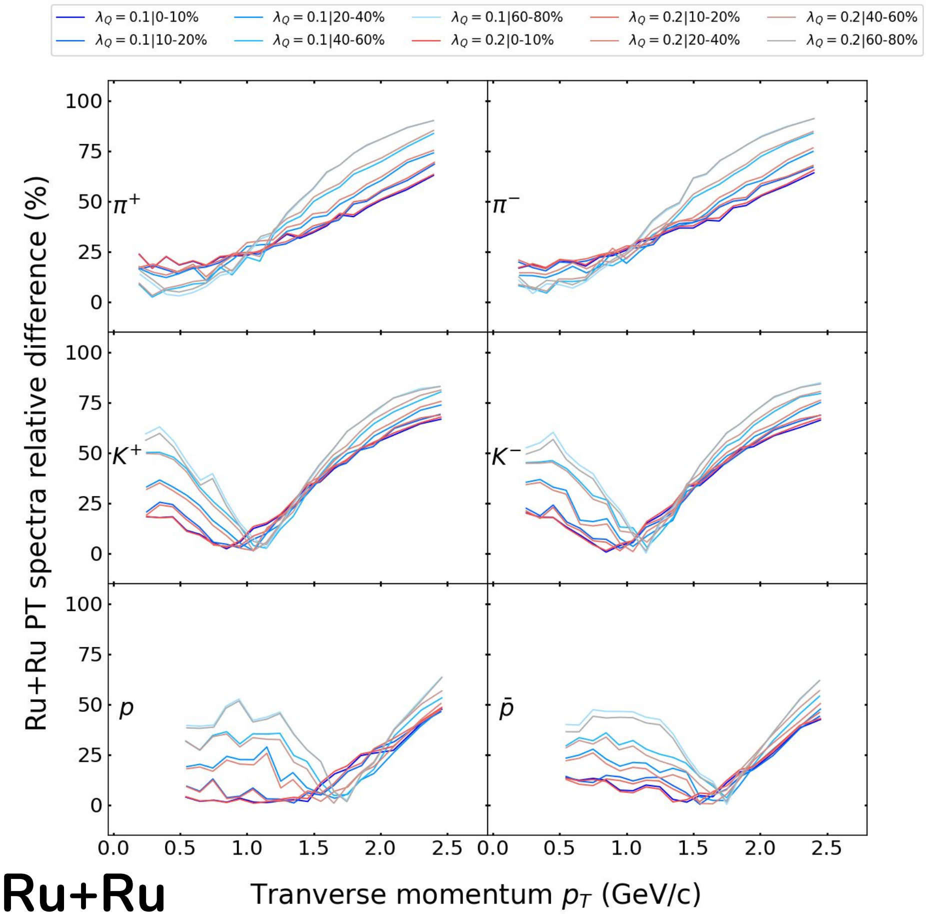
MUSIC tuning on PHOBOS Au+Au data

Current version:

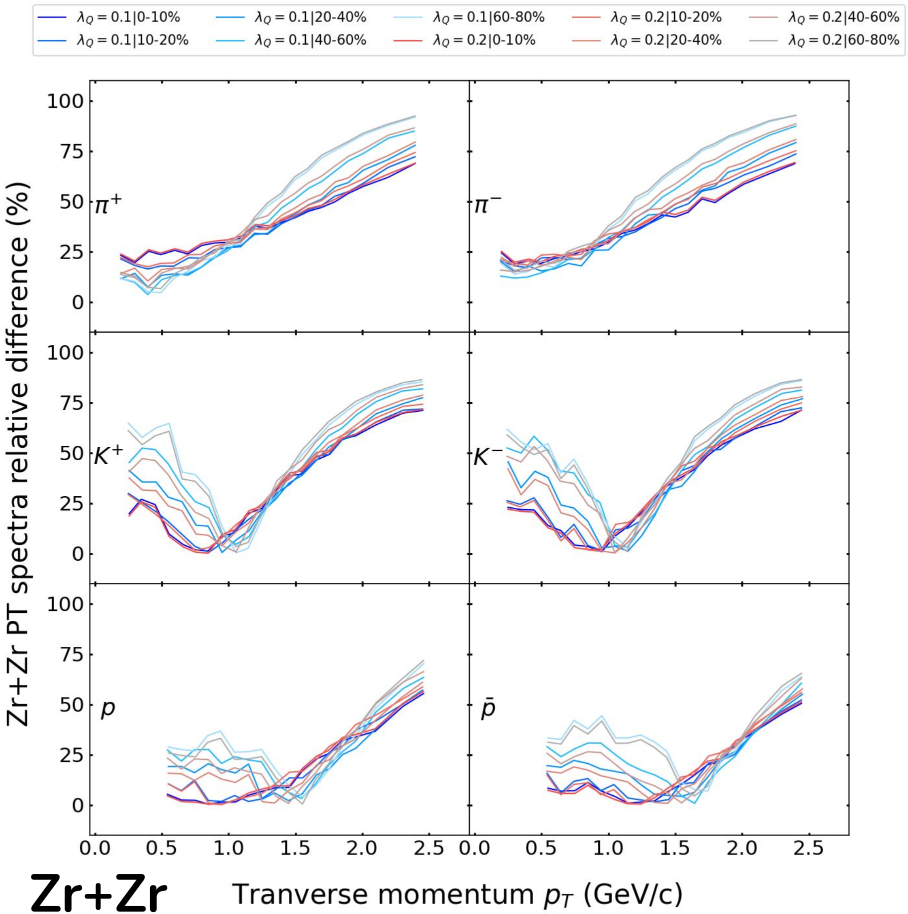
- ➢ Tuned on charged particle rapidity distributions for Au+Au collisions at RHIC PHOBOS
- ➢ Overestimate yields at mid-rapidity for most central collision
- ➢ Overall good agreement ✔



Backup: PT spectra relative difference

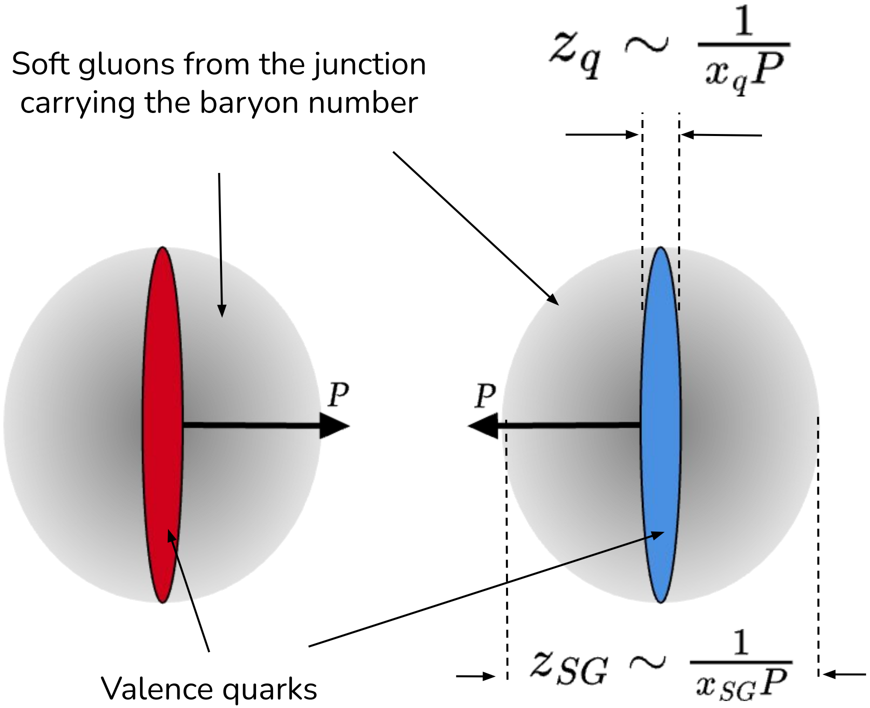


Ru+Ru



Zr+Zr

Backup: Gluon cloud interpretation

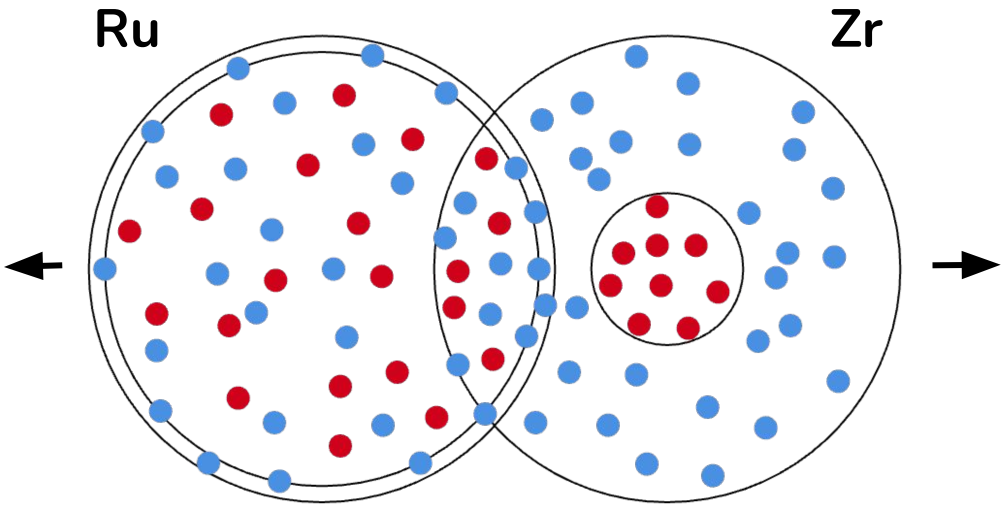


Quarks: $x_q \sim 1/3$
interaction time is short
~6.10^-3 fm

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

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

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

The baryon number escapes from both sides B ↘↘

The electric charge difference escapes only from Ru side ΔQ ↘

B decreases faster than ΔQ

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