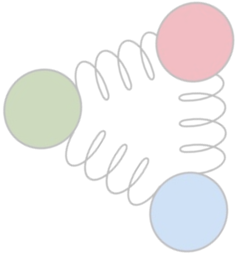
What carries the baryon number?
Simulations of baryon and electric charge stopping in isobar collisions at RHIC



-QGP France 2023-

Grégoire Pihan, Chun Shen, Akihiko Monnai, Bjoern Schenke

WAYNE STATE UNIVERSITY

Outline of the presentation

- Introduction:
  - What carries the baryon number?
  - Baryon stopping and the junction picture
  - Insight from isobar collisions at RHIC
- The iEBE-MUSIC Framework:
  - Initial conditions from the gluon junction
  - MUSIC with 4D Equation of State
- Results:
  - Experimental measurements
  - Baryon to electric charge stopping

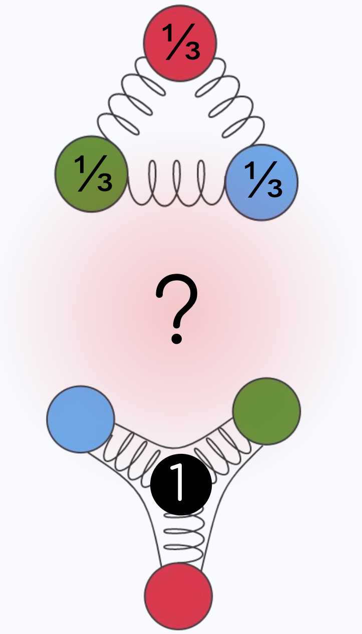
What carries the baryon number?

- The baryon number B:
  A conserved charge of the QCD matter
- Assumed to be carried by the valence quarks

What is actually known	
Mesons	B = 0
Baryons	B = 1
anti-Baryons	B = -1

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

➢ This is an assumption



Associating +-⅓ to each quarks cannot be inferred from QCD first principles!

Alternative model: The gluon junction

➢ Non-perturbative configuration of gluons represented by a locally gauge-invariant state vector: The gluon junction

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

➢ The gluon junction carries the baryon number

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

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

Baryon stopping

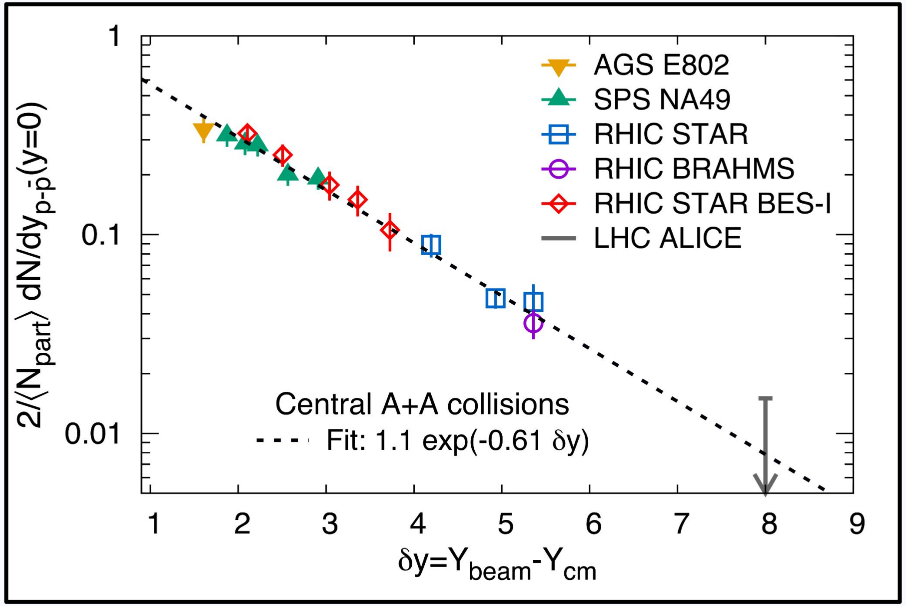
An excess baryon to anti-baryon number at mid-rapidity: the baryon stopping

- Connected to net-proton yield: experimentally accessible ✓

- Show a clear **exponential decrease** a as a function of the rapidity loss δy

$$\frac{dN_{p-\bar{p}}/dy}{2N_{\text{part}}} = N_B e^{-\alpha\delta y} \quad \longrightarrow \quad N_B = 1.1,\ \alpha = 0.61$$

- The baryon stopping mechanism is still not fully understood

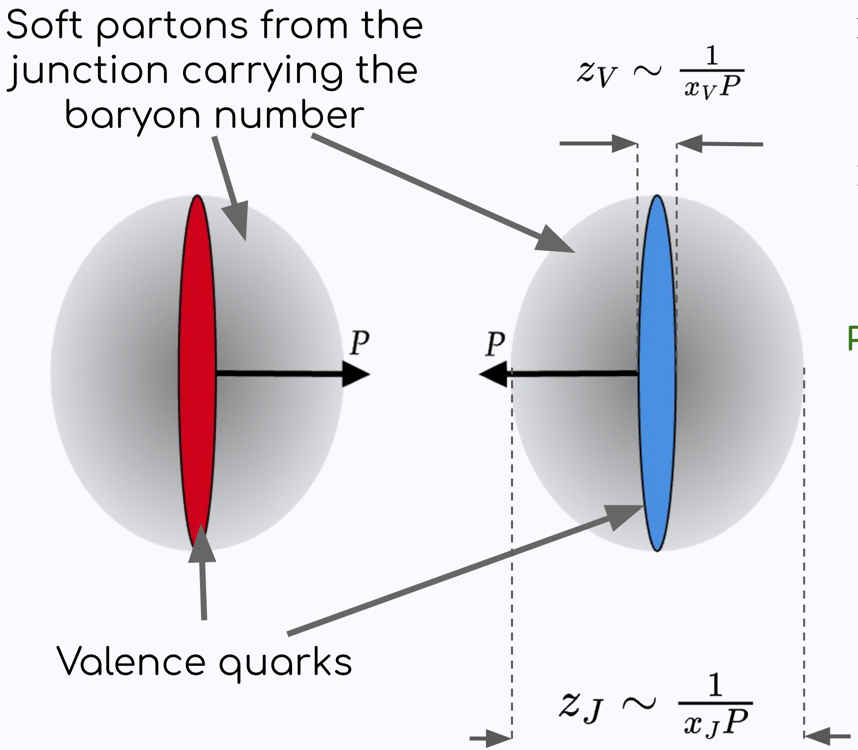


J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Recent insight: The string junction model is essential to reproduce the small but finite net-proton numbers around mid-rapidity at 200 GeV collisions at RHIC

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

Baryon stopping in the gluon junction

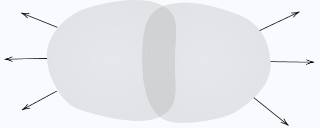


D. Kharzeev, Physics Letters B **378**, 238 (1996)

- ➢ Quarks have x_V~⅓ of nucleon momentum P: interaction time is short ~6.10^{-3} fm
- ➢ Soft gluons in the junction have $x_J P \ll x_V P$ Interaction time is large ~1 fm Baryon number is stopped!

Prediction of particle yields at mid-rapidity from the gluon junction is exponentially decreasing with rapidity loss!

$$dN/dy \propto e^{-\alpha_j \delta y} + e^{\alpha_j \delta y}$$

single	double
	
$\alpha_j = 0.42$	$\alpha_j = 1$

$< 0.61 <$ ✔

Insight from the isobar collisions at RHIC

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

- ➢ Due to charge conservation: $N_Q/N_B \sim Z/A \longrightarrow \Delta Q \sim N_B \Delta Z/A$

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

- ➢ True only if electric charge and baryon number stop the same way

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

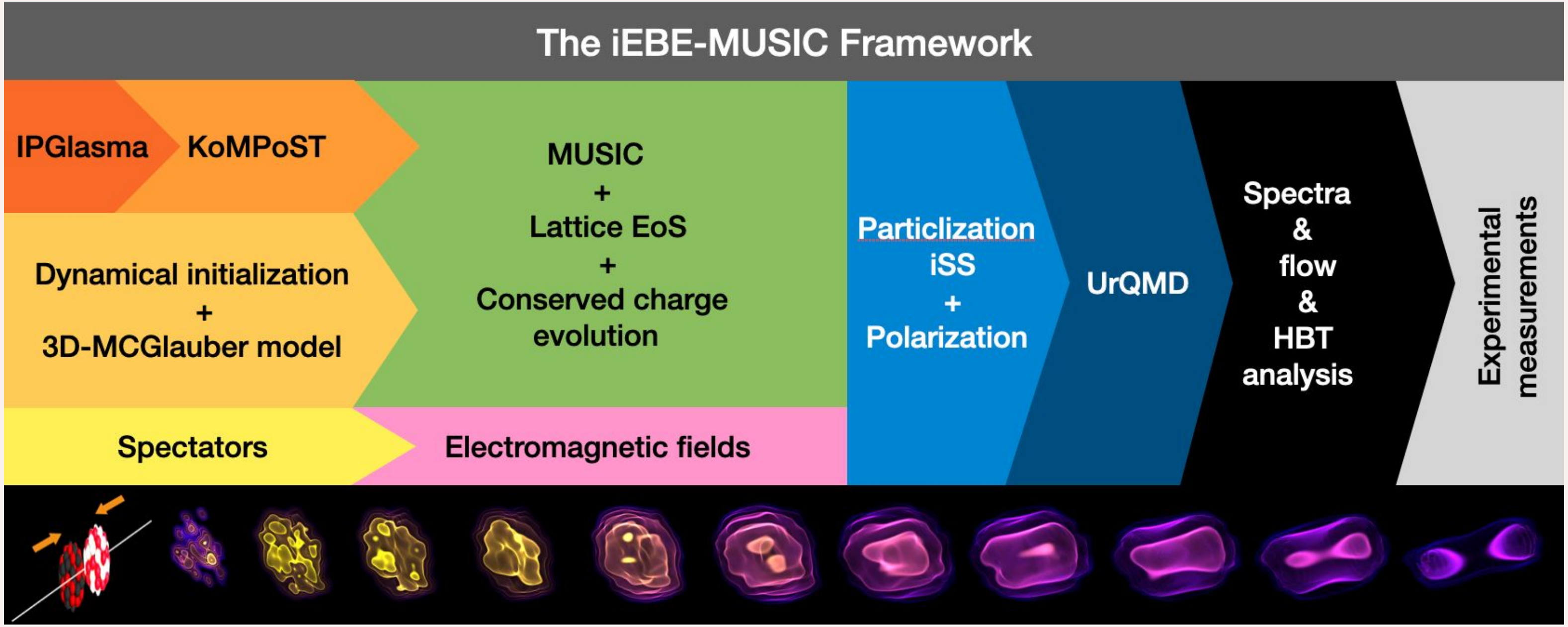
- ➢ Considering that the electric charge is carried by the valence quarks

If ΔQ is correlated to N_B ΔZ/A at mid-rapidity, the baryon number is carried by the valence quarks

and conversely!

The iEBE-framework

Hydrodynamics + hadronic transport hybrid framework

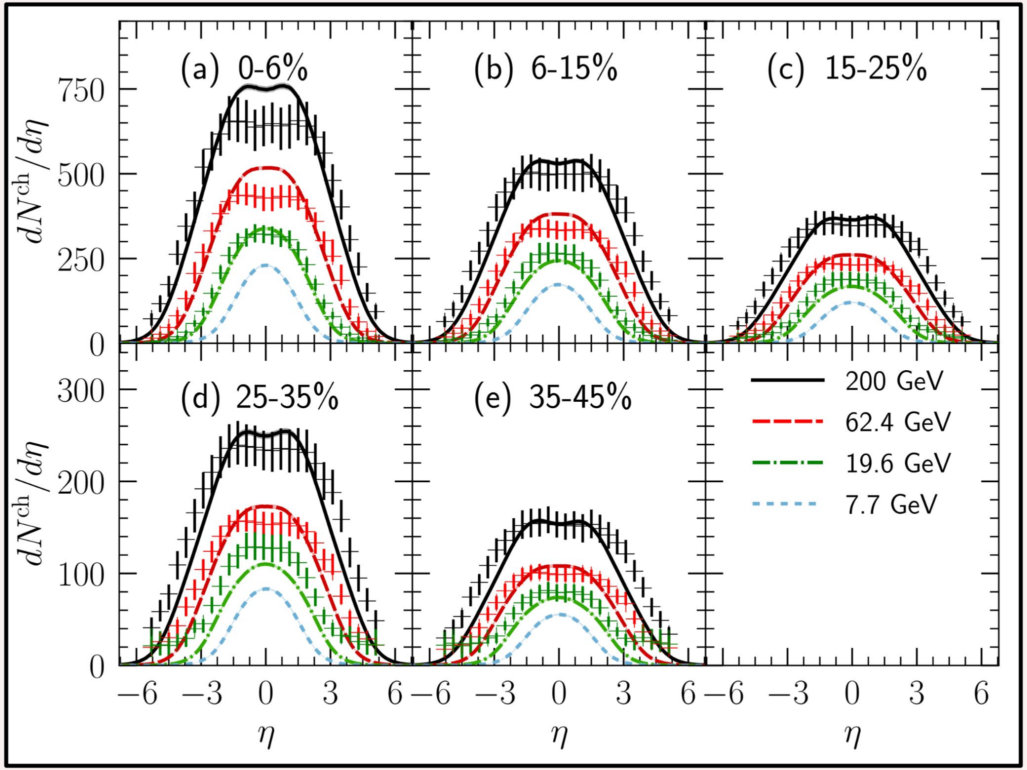


https://github.com/chunshen1987/iEBE-MUSIC

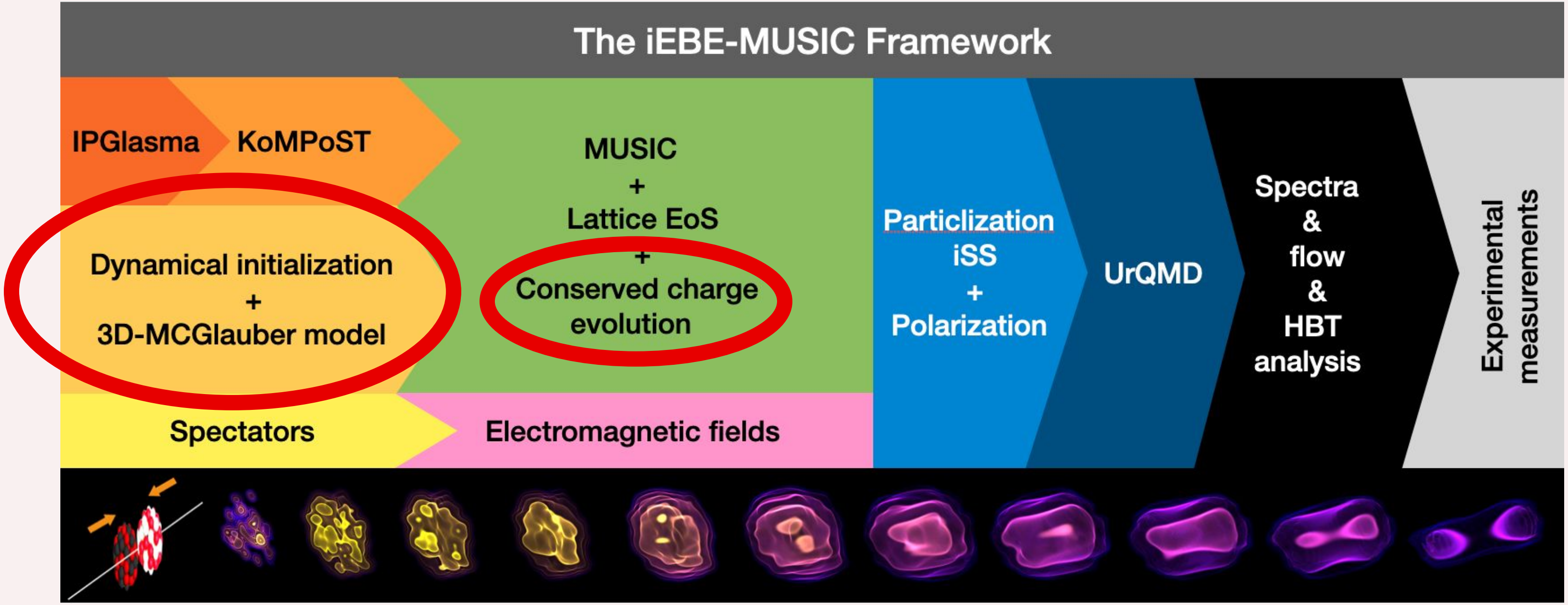
The iEBE-MUSIC framework: overall presentation

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 ✔



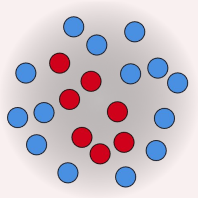
The iEBE-MUSIC framework: overall presentation



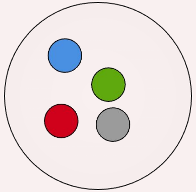
https://github.com/chunshen1987/iEBE-MUSIC

Initial conditions

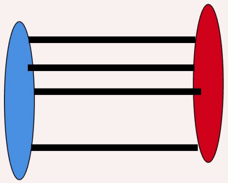
- **Nucleon distribution:** Wood-Saxon potential
  - Allow for neutron skin parameterization



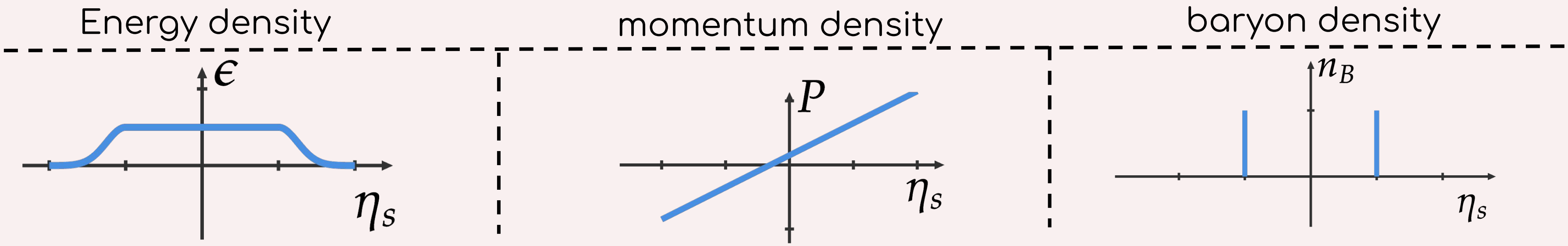
- **Parton distribution:** Gaussian profile in the nucleon
  - momentum fraction using NPDFs
  - consideration of wee partons from the see



- **Choice of binary collisions:** MC-Glauber



- **Energy-momentum and baryon number deposition:** Strings deceleration



Initial conditions from the gluon junction

Baryon density distribution on the string

$$P(y^B_{P/T}) = (1-\lambda_Q)\, y^B_{P/T} + \lambda_Q \frac{e^{(y^B_{P/T} - (y^B_P + y^B_T)/2)/2}}{4\sinh((y^B_P - y^B_T)/4)}$$

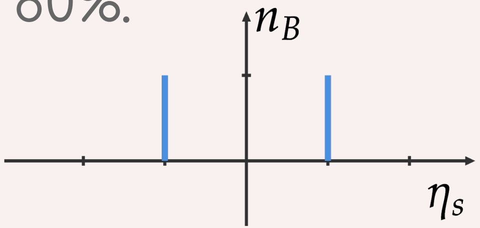
baryon density in valence quarks

baryon density in the junction

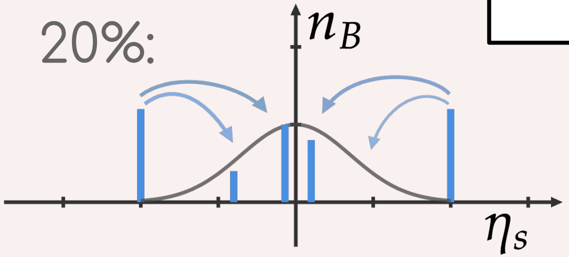
From STAR
Au-Au 200 GeV baryon stopping

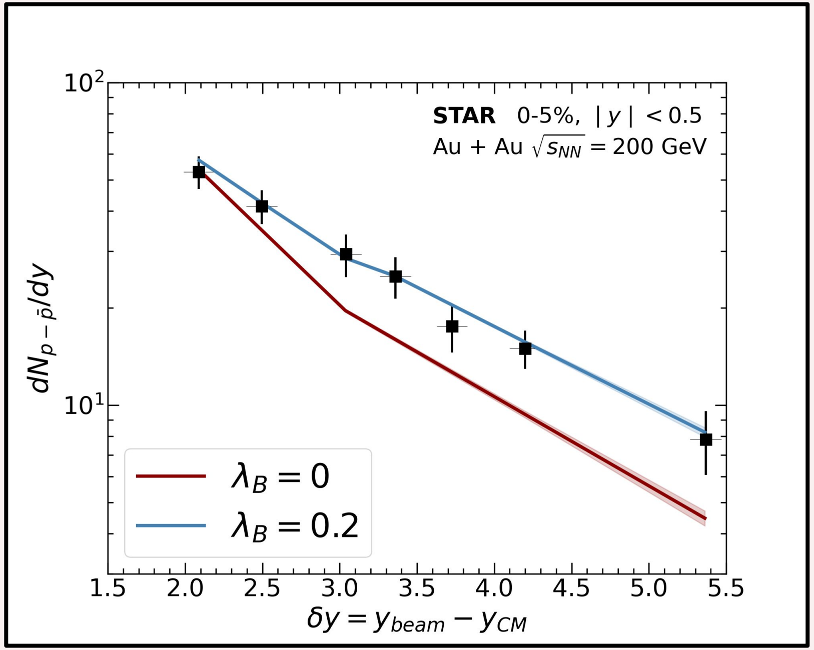
$$\lambda_B = 0.2$$

80%:



20%:





Tuning with PHOBOS Au+Au data includes the gluon junction!

MUSIC with 4D Equation of State

Current MUSIC version: net-Q = Z/A net-B, net-S = 0 (fm^{-3})

Baryon to electric charge stopping directly from the input junction. No impact of hydrodynamics.

➢ New version: net-Q and net-S evolve separately according to ideal hydrodynamics

GP, C. Shen, A. Monnai and B. Schenke in prep

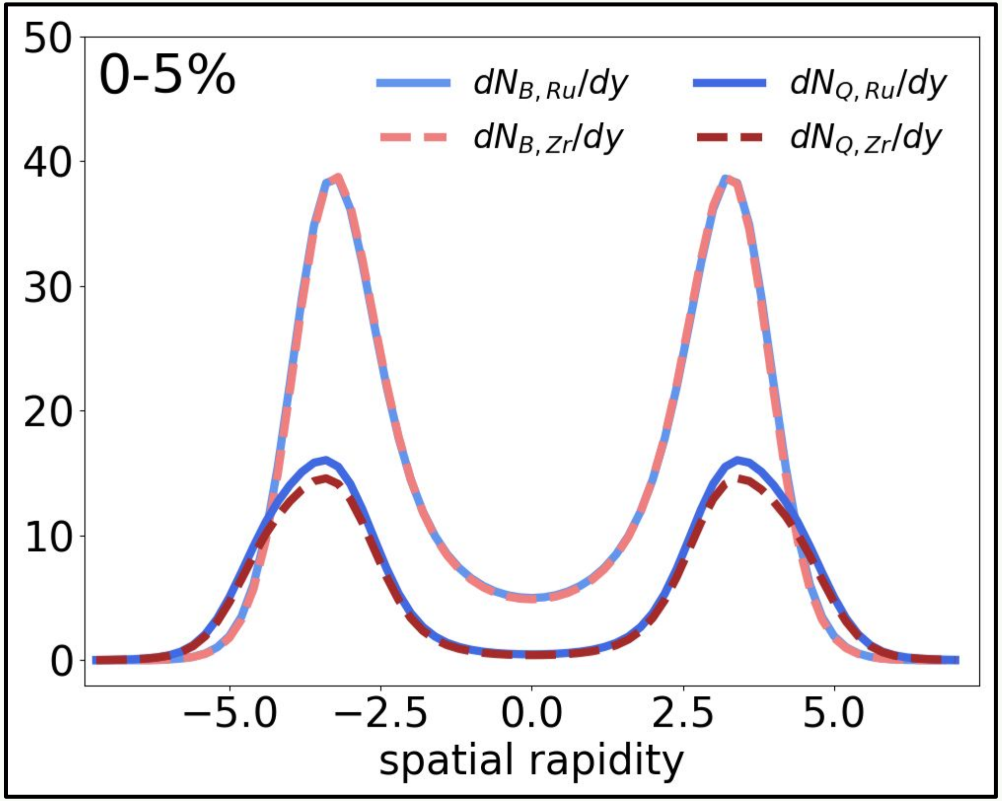
$$j^{\mu}_{B,Q,S} = n_{B,Q,S} u^{\mu}$$

The total charge is conserved and the detailed local balance can be studied!

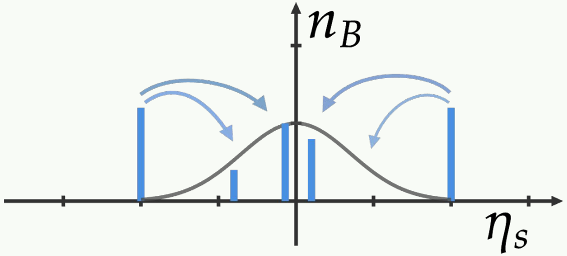
➢ In-line: NEOS equation of state
- Based on Lattice Taylor expansion at finite chemical potentials and matched to HRG at smaller temperature.
- No assumptions on the relation between conserved charge densities.

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

Initial conditions from gluon junction: yields



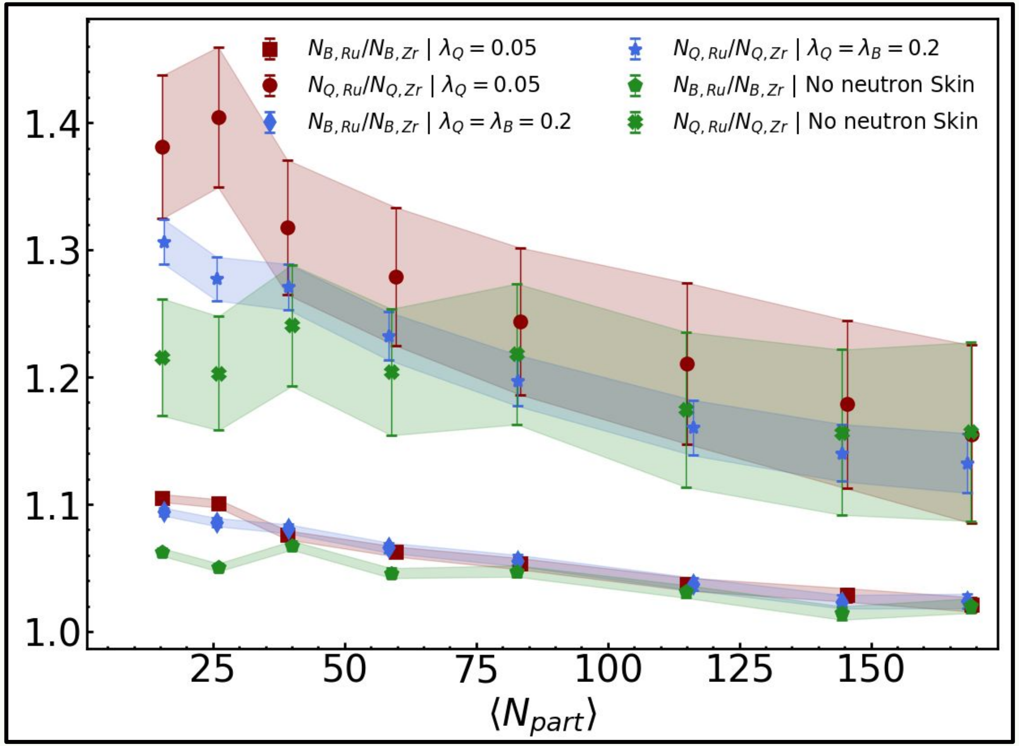
- Net-B yields at mid-rapidity: directly controlled by λ_B



- Introduction of “electric junction” λ_Q: As a tool to understand the input yields

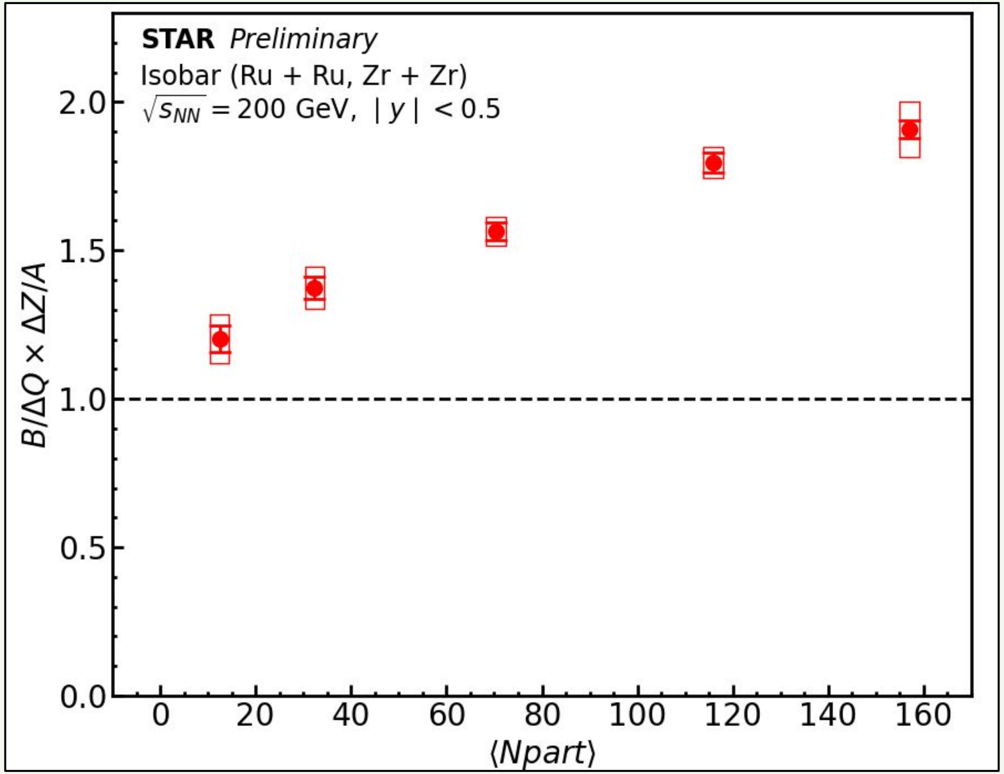
$$P(y^Q_{P/T}) = (1-\lambda_Q)y_{P/T} + \lambda_Q \frac{e^{(y^Q_{P/T}-(y^Q_P+y^Q_T)/2)/2)}}{4\sinh((y^Q_P-y^Q_T)/4)}$$

Initial conditions from gluon junction: Ratios



- ➢ Compatible for both Ru+Ru and Zr+Zr
- ➢ Difference between Net-B and Net-Q is mainly driven by Δz = 4
- ➢ The deviation from 1 is due to nuclear structure
  - ○ especially neutron skin

Baryon to electric stopping ratio at RHIC

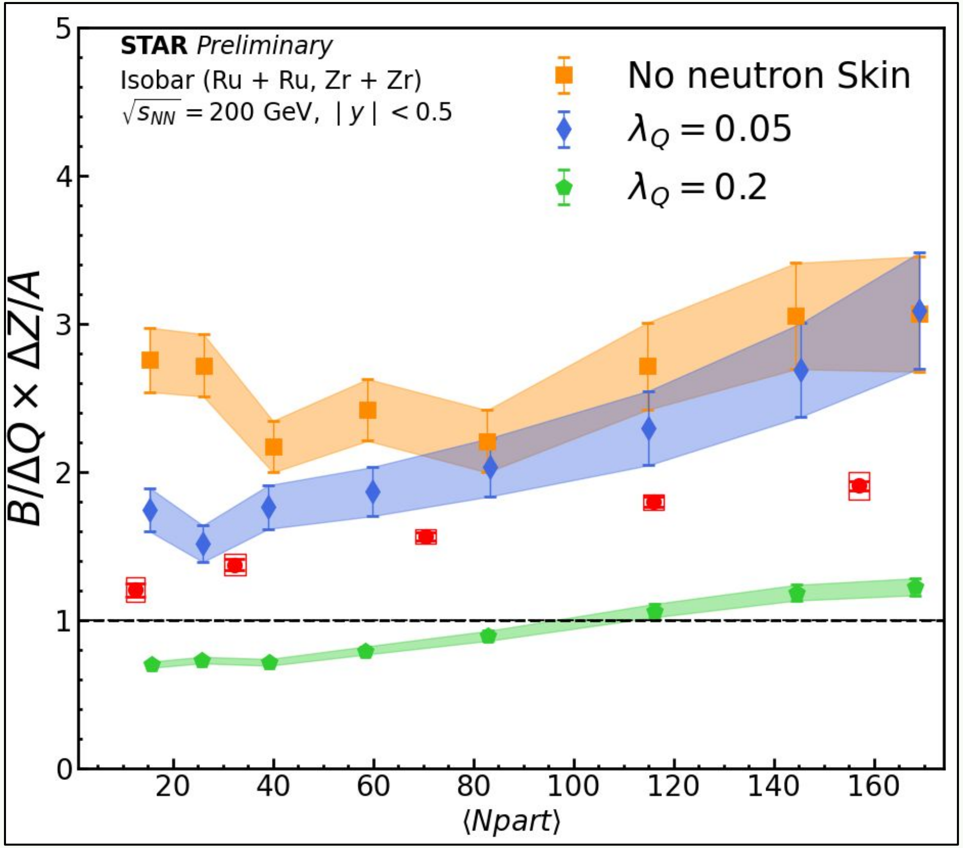


- Data show:

$$B/\Delta Q \times \Delta z/A > 1$$

Baryon stopping is larger than electric charge stopping

Initial conditions from gluon junction: BQ stoppings



- ➢ Data show:

$$B/\Delta Q \times \Delta z/A > 1$$

Baryon stopping is larger than electric charge stopping

- ➢ Considering $B_{Ru} = B_{Zr}$
  - Equal stopping: ratio close to 1
  - Neutron skin have a sizable impact

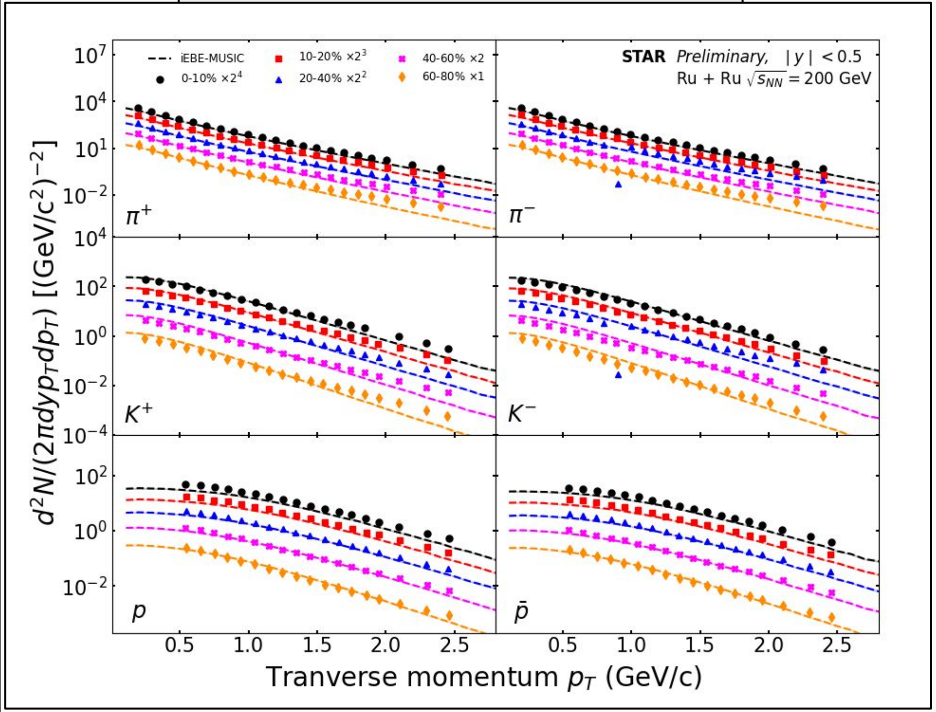
decrease toward smaller <Npart>
Possibility of studying nuclear structure

Larger B/Q stopping: Larger ratio

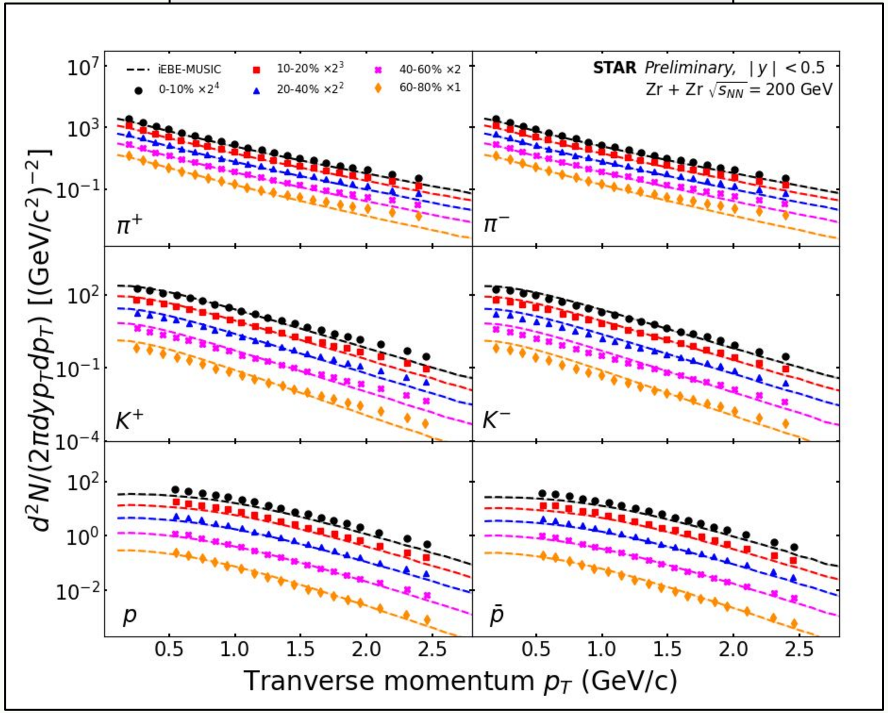
+monotonic behavior for larger $<N_{part}>$

PT spectra for isobar Runs at RHIC

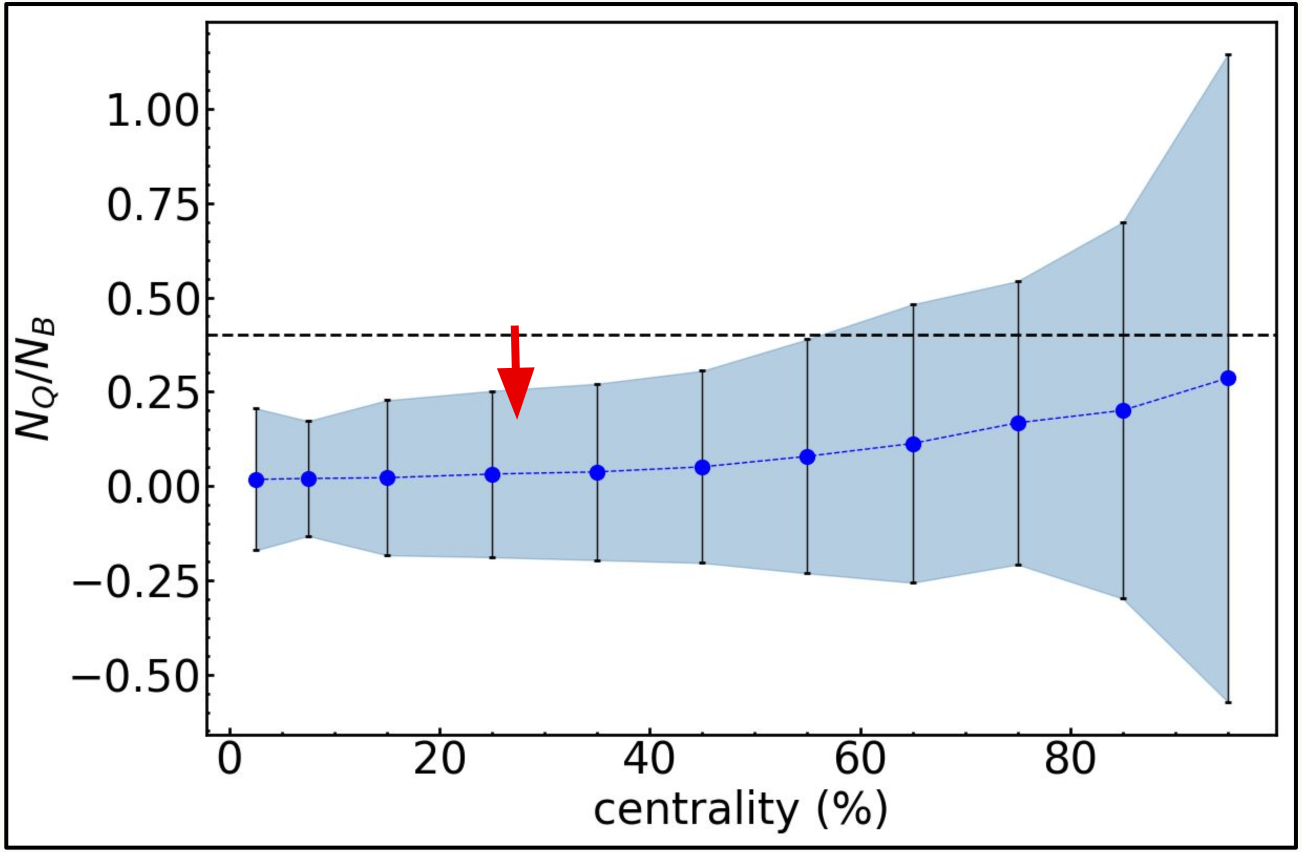
Ru+Ru



Zr+Zr



First result for full event: Yield ratio at mid-rapidity



Conclusion

- Testing gluon junction picture
  - Can gluon junction trace the baryon number
  - Baryon stopping vs electric charge stopping
  - Insight from isobar collisions at RHIC

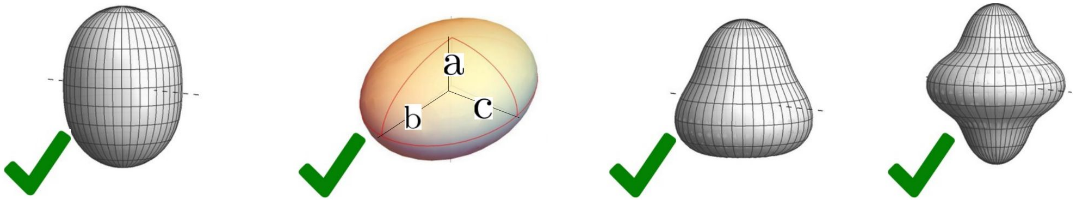
- The iEBE-MUSIC Framework:
  - Building initial conditions from the junction
  - Decoupled Net-B and Net-Q densitities
  - 4D Equation of State

- Results:
  - Isobar ratios at STAR shows deviation from 1
  - At initial stage, ratios are sensitive to stopping
  - Ratios are sensitive to nuclear structure
  - Need for full event simulations!

Backup: Wood-Saxon parameters

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

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



	R	a	γ	β_2	β_3	β_4	da	dR
Ru	5.09	0.46	0.523	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

Backup: B and ΔQ proxies at STAR

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, PhysRevC.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.

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

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

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