## What carries the baryon number?

# Simulations of baryon and electric charge stopping in isobar collisions at RHIC

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#### Baryon number: carried by the valence quarks?

 $\pm \frac{1}{3}$ B to each quarks and antiquarks cannot be inferred from QCD first principles for baryons!

$$B=rac{1}{3}(n_q-n_{ar{q}})$$

This is an assumption

#### The string junction?



 $\succ$  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

q

 $\bigcirc$ 

0

Exponential decrease as a function of the rapidity loss  $\,\delta y$ 

$$rac{dN_{p-ar{p}}/dy}{2N_{ ext{part}}} = N_B e^{-lpha \delta y} \qquad \qquad N_B = 1.1 \ lpha = 0.61$$

String junction allows to two possibilities

The baryon number goes on one of the valence quark

The baryon number to fluctuate towards mid-rapidity

The baryon number is stopped!







 $\check{\overline{q}}$ 

mE

0

B=1

#### Baryon stopping and string junction

AGS E802 SPS NA49

RHIC STAR

LHC ALICE

7

double

8

9

RHIC BRAHMS RHIC STAR BES-I



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

#### Baryon stopping and string junction

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 $lpha_j=0.42 < 0.61 < lpha_j=1$  D. Kharzeev, Physics Letters B 378, 238 (1996)

## Insight from the isobar collisions at RHIC

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

Allow for precise measurement of electric charge at mid-rapidity via double ratios!

Charge conservation at mid-rapidity:





967r

## Insight from the isobar collisions at RHIC

 ${}^{96}{
m R}\upsilon$ 

**STAR** Preliminary

Isobar (Ru + Ru, Zr + Zr)

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

Allow for precise measurement of electric charge at mid-rapidity via double ratios!

Charge conservation at mid-rapidity:



2.2



96**7**.

## Insight from the isobar collisions at RHIC

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

Allow for precise measurement of electric charge at mid-rapidity via double ratios!

Charge conservation at mid-rapidity:



Is this a sign of the string junction ?





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J. D. Brandenburg, N. Lewis for STAR collaboration , in prep

#### The iEBE-MUSIC framework

Open source hydrodynamics + hadronic transport hybrid framework



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

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Open source hydrodynamics + hadronic transport hybrid framework



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## Initial conditions from the string junction 1/2

#### Initial distributions and choice of wounded nucleons:



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



**Parton distribution**: Gaussian profile in the nucleon momentum fraction using NPDFs

Choice of binary collisions: MC-Glauber

Energy, momentum and charge deposition:



Energy-momentum: string deceleration

Baryon/electric charge densities: valence quarks + string junction

$$P(y_{P/T}^X) = (1 - \lambda_X) y_{P/T} + \lambda_X rac{e^{(y_{P/T}^X - (y_P + y_T)/2)/2}}{4\sinh((y_P - y_T)/4)}$$
  
 $X = B, Q$ 
C. Shen and B. Schenke Phys. Rev. C **105**, 064905 (202  
GP, A. Monnai, B. Schencke, C. Shen in Pro-



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## Initial conditions from the string junction 2/2

Initial electric charge density rapidity distributions for different values of  $\lambda_Q$ 

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

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

 $ho_Q\simeq 0.4
ho_B$ 

#### MUSIC with 4D equation of state

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

 $ho_Q\simeq 0.4
ho_B$ 

Not possible with this fixed constraint!

## MUSIC with 4D equation of state

Impact of the hydrodynamic evolution on the initial B to Q stoppings :



Independent ideal evolution of conserved charges X = B, Q, S

$${j}^{\mu}_{X}=
ho_{X}u^{\mu}$$

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

B to Q stopping ratio can be studied!

- In-line: NEOS 4D 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



#### PT spectra for isobar runs at RHIC



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#### Comparison to STAR yields: Baryon number



- From initial stage to final stage
  - Same shape
  - Net-baryon yield is increased
- Deviation from STAR yield
  - Net-baryon number in iEBE-MUSIC

$$N_B = N_p - N_{ar p} + N_n - N_{ar n}$$

• Net-baryon number at STAR

$$N_B\simeq N_p-N_{ar p}+ar p\sqrt{rac{d}{ar d}}-p\sqrt{rac{d}{ar d}}$$

Evaluation of net-neutron using deuterons STAR Collaboration, PhysRevC.99.064905

## Comparison to STAR yields: $\Delta Q$ at initial stage



➤ Cases:

- $\circ$  Equal stopping:  $\lambda_Q = \lambda_B = 0.2$
- Half stopping:

 $\lambda_Q = \lambda_B/2 = 0.1$ 

 $\circ$  No neutron skin  $\lambda_Q=0.1$ 

	А	Z	da	dR
Ru	96	44	0.01	0.015
Zr	96	40	0.05	0.1

- >  $\Delta Q$  needs many events!  $\circ$  Net electric charge definition  $N_Q = N_p - N_{ar p} + N_{K^+} - N_{K^-} + N_{\pi^+} - N_{\pi^-}$ 
  - Electric charge difference!

$$\Delta Q = N_{Q,\mathrm{Ru}} - N_{Q,\mathrm{Zr}}$$

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#### Ratio at initial stage



#### At initial stage

- $\succ$  Equal stopping  $\lambda_Q = \lambda_B = 0.2$
- Largely underestimate the experimental ratio
- ratio < 1 for smaller Npart.</li>
- Overall increase with Npart: Neutron skin
- $\succ$  Half stopping  $\lambda_Q = \lambda_B/2 = 0.1$
- Closer to experimental data
- Overall increase with Npart: Neutron skin
- $\succ$  No neutron skin  $\lambda_Q=0.1$
- Flat for a large range of Npart
- Cannot account for increasing behavior of the data

Comparison with STAR data at initial stage advocates for a difference in baryon to electric charge stopping ratio!

#### Ratio at final stage



#### At final stage

- $\succ$  Equal stopping  $\lambda_Q = \lambda_B = 0.2$
- Largely underestimate the experimental ratio
- ratio < 1.
- oscillatory behavior: remains to be understood
- $\succ$  Half stopping  $\lambda_Q = \lambda_B/2 = 0.1$ 
  - Compatible with experimental data
- slightly smaller  $\lambda_Q$  may match data!
- $\succ$  No neutron skin  $\lambda_Q=0.1$
- Flat for a large range of Npart
- Cannot account for increasing behavior of the data

Comparison with STAR data at final stage advocates for a difference in baryon to electric charge stopping ratio!

## Wrap up & outlook

- "Can gluon junction trace the baryon number?"
  - Clear difference in baryon and electric charge stopping at STAR
  - Results: compatible for half-stopping with STAR data!
  - The ratio observable is sensitive to the neutron skin: 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: tuning on isobars
- Long term: diffusion for conserved charge

## Thank you for your attention!

backup

#### Backup: B and $\Delta Q$ proxies at STAR

Net-baryon number:

Net-charge difference:

STAR does not measures neutrons, Evaluation of neutrons from deuterons yields via HRG model

$$N_B = (N_p - N_{ar p}) + (N_n - N_{ar n}) pprox (N_p - N_{ar p}) + ar p \sqrt{rac{d}{ar d}} - p \sqrt{rac{d}{ar d}}$$
STAR Collaboration, Phys Rev.99.064905

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.

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

$$R2_{\pi} = rac{(N_{\pi}^+/N_{\pi}^-)_{ ext{Ru}}}{(N_{\pi}^+/N_{\pi}^-)_{ ext{Zr}}} pprox 1 + (N_{\pi}^+ - N_{\pi}^-)_{ ext{Ru}} - (N_{\pi}^+ - N_{\pi}^-)_{ ext{Zr}}$$

$$\Delta Q = N_{\pi}(R2_{\pi}-1) + N_{K}(R2_{K}-1) + N_{p}(R2_{p}-1)$$

#### Backup: Wood-Saxon parameters

 $ho(r, heta)=rac{
ho_0}{1+e^{[r-R( heta,\phi)/a]}}$  $R( heta,\phi) = R_0 [1+eta_2(\cos(\gamma Y_{2,0})+\sin(\gamma Y_{2,2}))+eta_3 Y_{30}+eta_4 Y_{40}]$ b C R  $\beta_2$  $\beta_3$  $\beta_4$ dR da а V Ru 0.46 0.523 0.16 0.015 5.09 0.0 0.0 0.01 Zr 5.02 0.52 0.0 0.06 0.2 0.05 0.1 0.0

#### Backup: 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



Backup: Geometrical interpretation of ratio(Npart)

