

BARYON JUNCTIONS



U.S. DEPARTMENT OF
ENERGY

Office of
Science

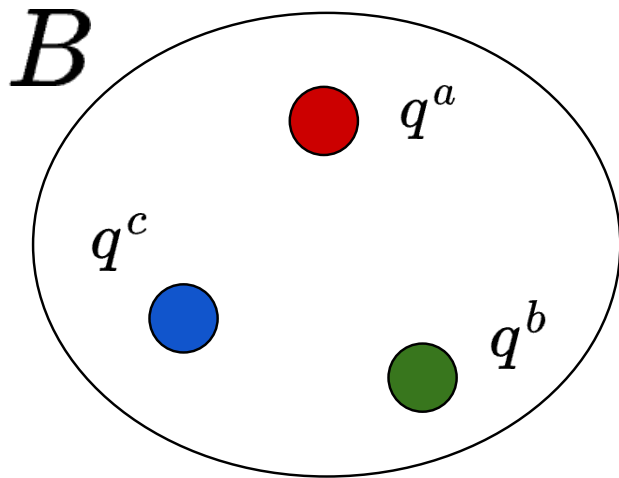
Grégoire Pihan
CPOD 2026
CERN



UNIVERSITY OF
HOUSTON

What is a baryon?

The quark model: a collection of 3 quarks



Baryons in QCD

$$\Psi = \underline{\Psi_{\text{color}}} \Psi_{\text{spin,flavor}} \Psi_{\text{space}}$$

$\text{SU}(3)_c$

Gauge invariance

$$\Psi_{\text{color}} \sim \epsilon_{abc} q^a q^b q^c$$

$$3 \otimes 3 \otimes 3 = \textcircled{1} \oplus 8 \oplus 8 \oplus 10$$

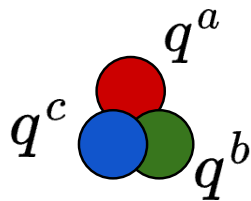
Color singlet

The baryon number has to be associated with the unique totally antisymmetric color-singlet three-quark state!

What is a baryon?

The quark model: a collection of 3 quarks

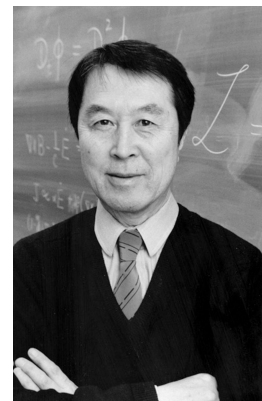
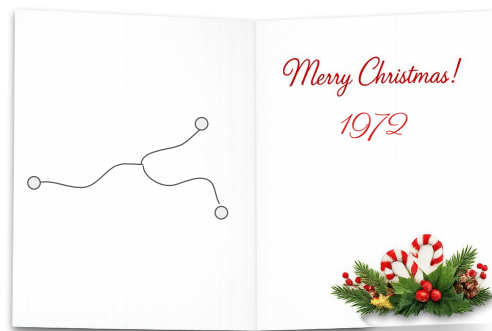
B



$$B \sim \epsilon_{abc} q^a q^b q^c$$

References

- 1) M. Imachi, S. Otsuki and F. Toyoda, Prog. Theor. Phys. **54** (1975), 280.
- 2) M. Imachi, S. Otsuki and F. Toyoda, Prog. Theor. Phys. **55** (1976), 551; Prog. Theor. Phys. **57** (1977), 517.
- 3) According to B. Sakita, baryon with junction was first written in the Christmas greeting card of Y. Nambu around 1972, Sakata Model 25th anniversary held in Nagoya University, Soryushiron Kenkyu **63** (1981), S50.
Y. Nambu, Butsuri **28** (1973), 452. [Imachi et al. Progress of Theoretical Physics, Volume 120, Issue 4, October 2008, Pages 723-739](#)



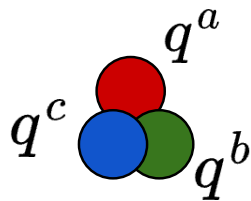
Pr. Yoichiro **Nambu**

[Michael S. Turner Nature 524, 416 \(2015\)](#)

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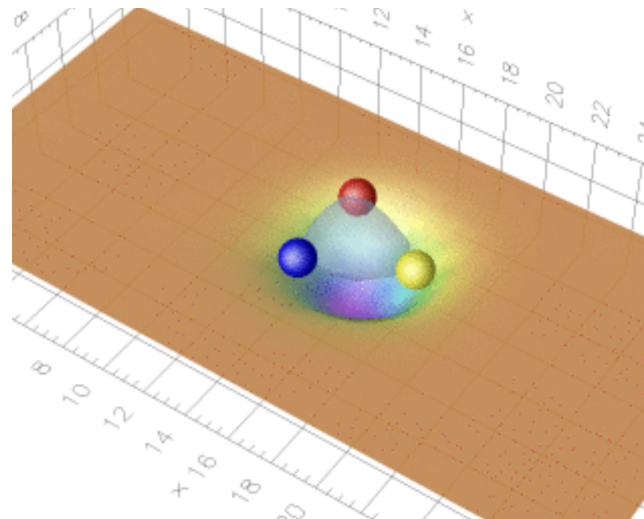
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- 1) M. Imachi, S. Otsuki and F. Toyoda, Prog. Theor. Phys. **54** (1975), 280.
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- 3) Color flux-tubes on the lattice

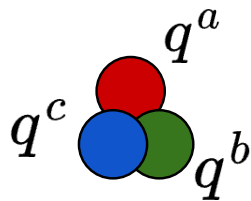


[F. Bissey et al, Phys. Rev. D 76, 114512](#)

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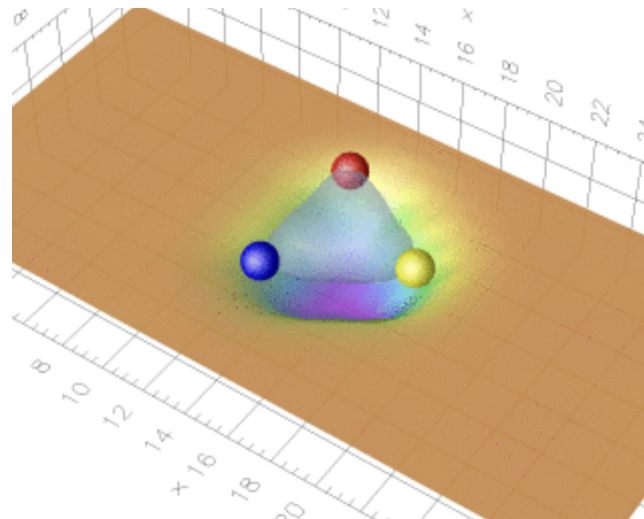
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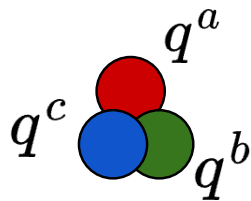


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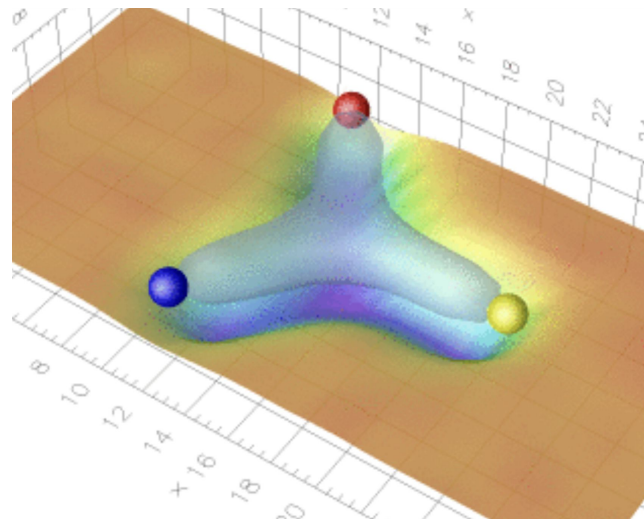


$$B \sim \epsilon_{abc} q^a q^b q^c$$

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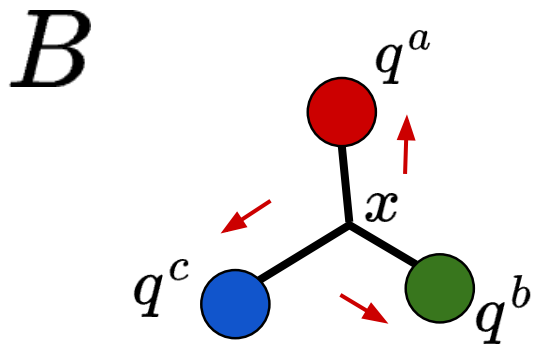
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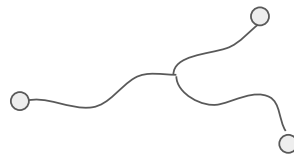
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What is a baryon junction?

The string junction model

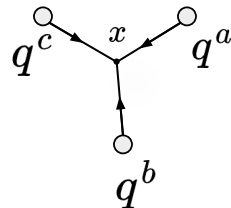


Pr. Nambu's
Christmas card



Pr. Giancarlo **Rossi**

Clear string formulation
(Wilson lines)

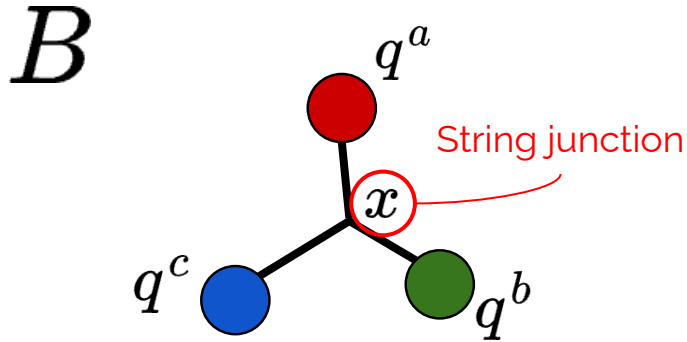


Pr. Gabriele **Veneziano**

[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

What is a baryon junction?

The string junction model



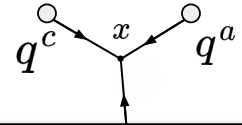
$$B = \epsilon_{ijk} (U_a q_a)^i (U_b q_b)^j (U_c q_c)^k$$

$$U_\theta = U(x, x_\theta) \quad q_\theta = q_\theta(x_\theta)$$

Pr. Nambu's
Christmas card



Clear string formulation
(Wilson lines)



3. A POSSIBLE DEFINITION OF DUAL BARYONS IN QCD

In order to find a definition of dual baryons in QCD which is not of the $1/N_c$ expansion type, we consider the two alternative definitions, b and c, of dual mesons in QCD, discussed in Section 2.1.

Definition b suggests that we look at gauge invariant operators with non-zero baryon numbers. The simplest one is, in $SU(N_c)$

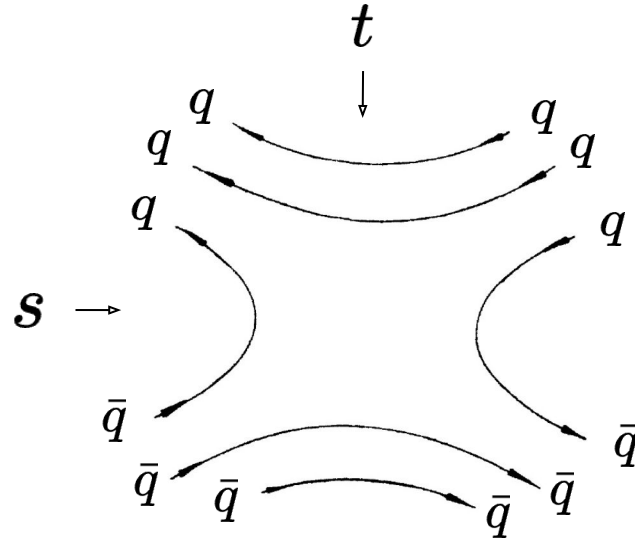
$$\begin{aligned} & \bigcirc_{q_1 \dots q_N} (P(x, x_1), P(x, x_2), \dots, P(x, x_N)) = \\ & = \epsilon^{i_1 i_2 \dots i_N} [G(P(x, x_1)) \psi(x_1)]_{i_1} [G(P(x, x_2)) \psi(x_2)]_{i_2} \dots [G(P(x, x_N)) \psi(x_N)]_{i_N} \end{aligned} \quad (3.1)$$

where $G(P(x, y))$ is given in Eq. (2.3b).

[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

Does the baryon junction exists?

$B - \bar{B}$ interactions? (in dual QCD)



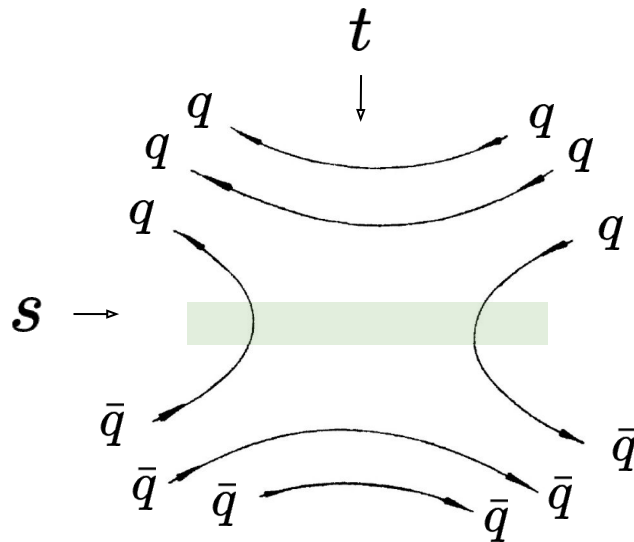
[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

Does the baryon junction exists?

$B - \bar{B}$ interactions? (in dual QCD)

No annihilation

t channel:
mesonic Reggeon



[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

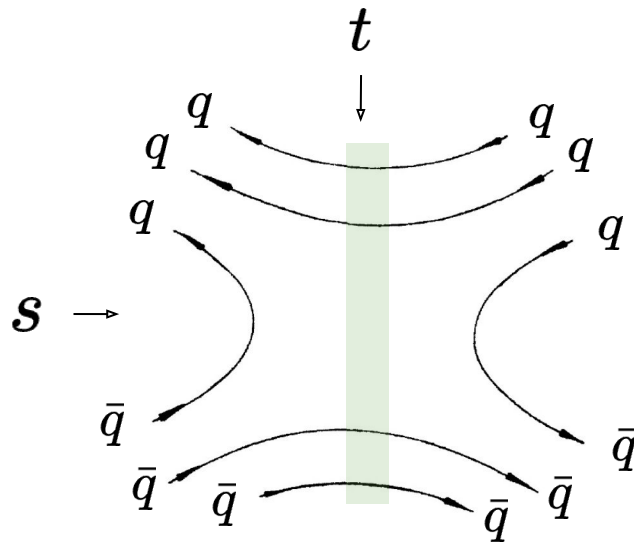
Does the baryon junction exists?

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No annihilation

t channel:
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s Channel:
Exotic $qq\bar{q}\bar{q}$ exchange



[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

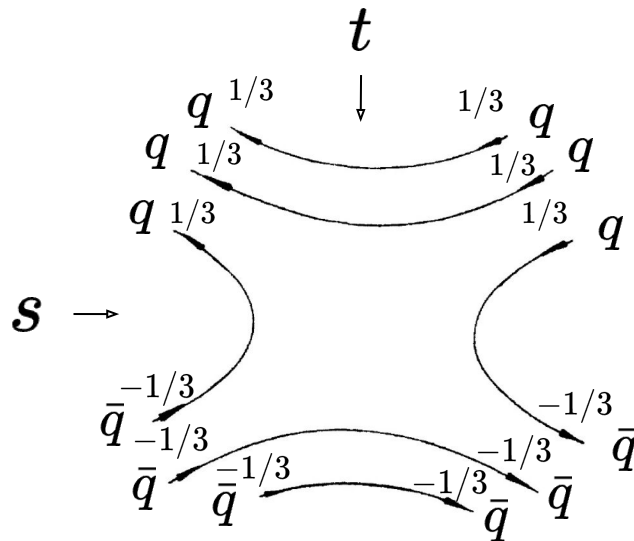
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Annihilation?

Where is the $B = 0$ object?

[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

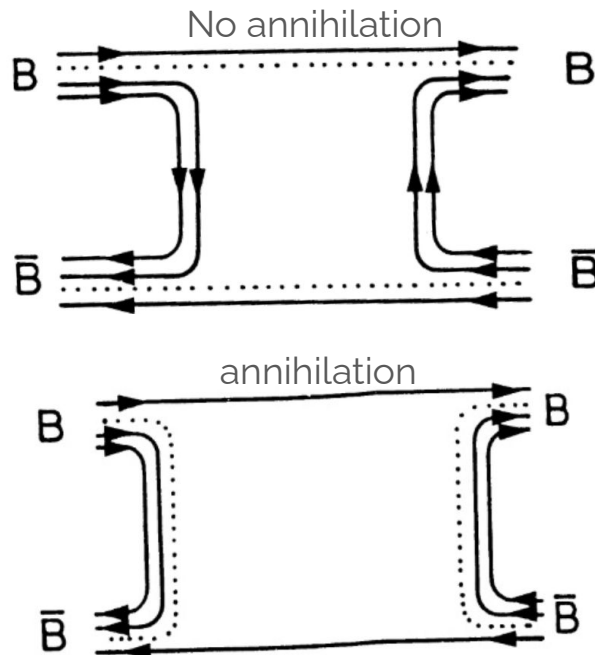
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Does the baryon junction exists?

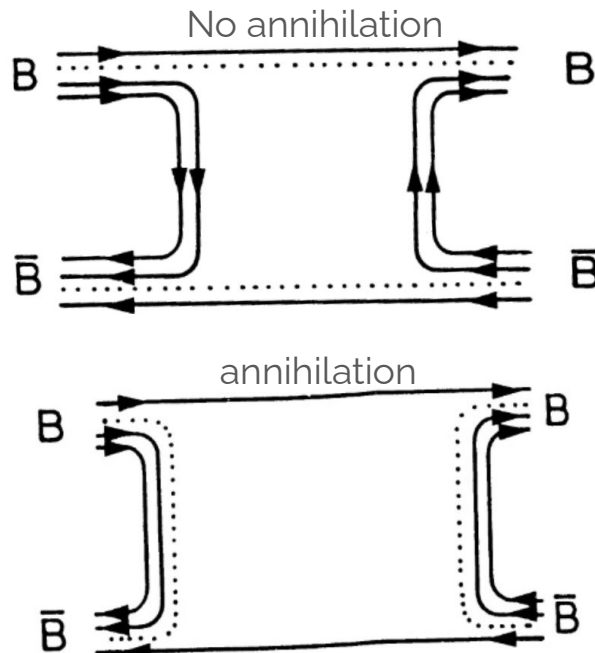
$B - \bar{B}$ interactions? (in dual QCD)

No annihilation

t channel:
mesonic Reggeon

s Channel:
Exotic $qq\bar{q}\bar{q}$ exchange

Now full baryon antibaryon
exchange + hidden JJbar in
the s channel



Annihilation?

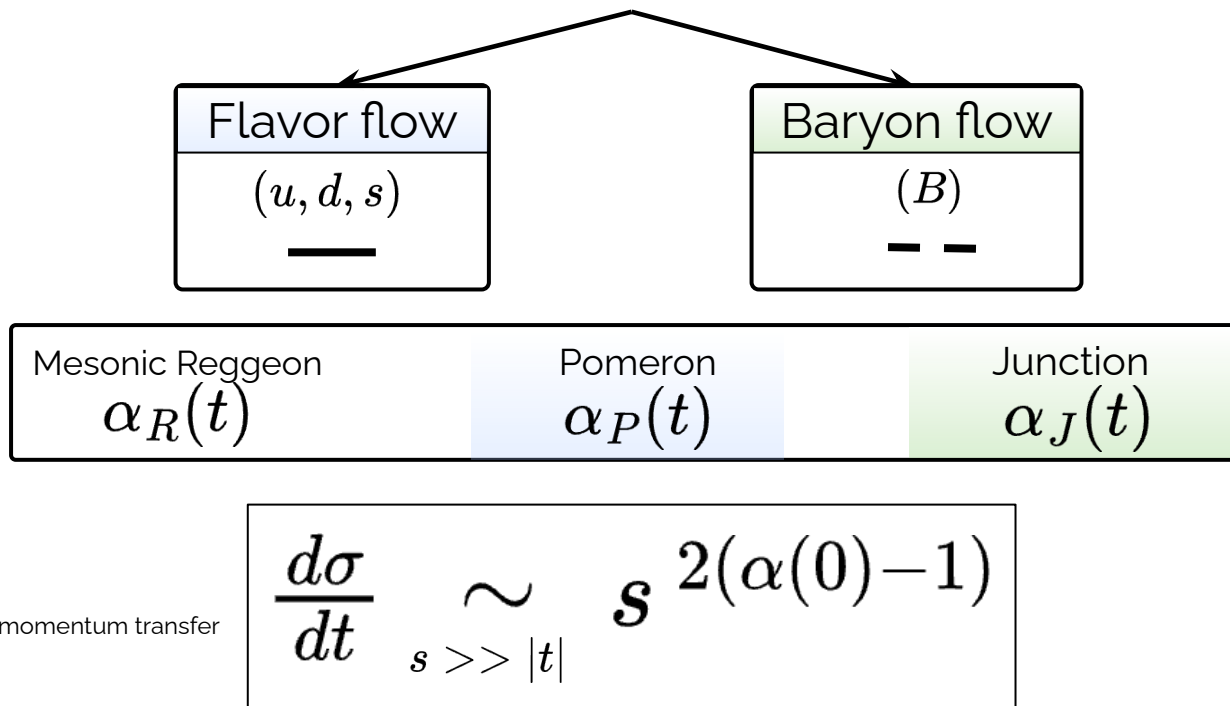
Where is the $B = 0$ object?

Natural in the
junction picture!

[G. C. Rossi and G. Veneziano, Nucl. Phys. B 123 \(1977\) 507-545.](#)

Does the baryon junction exists?

The junction is now part of interaction channels in hadronic interactions!



Does the baryon junction exists?

The junction is now part of interaction channels in hadronic interactions!

Flavor flow

Baryon flow

Experimental evidence for the
baryon number flavor separation

=

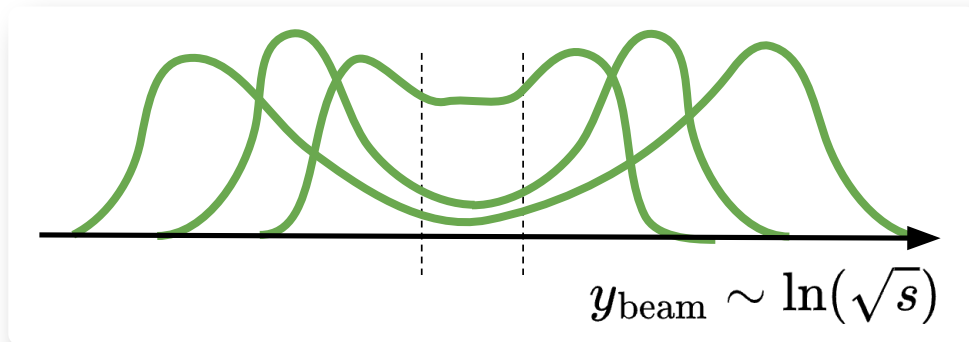
Existence of the junction!

t Square momentum transfer

$$\frac{d\sigma}{dt} \underset{s \gg |t|}{\sim} s^{2(\alpha(0)-1)}$$

Does the baryon junction exists?

Energy dependence => Rapidity dependence!



Pr. Dima Kharzeev

$$\frac{d\sigma}{dy} \propto s^{(\alpha_A + \alpha_B - 2)/2} e^{(\alpha_B - \alpha_A)y}$$

$A, B = R, P, J$

**The Regge intercepts are connected
to the **baryon stopping** in pp and AA collisions!**

[D. Kharzeev Phys.Lett.B 378 \(1996\) 238-246](#)

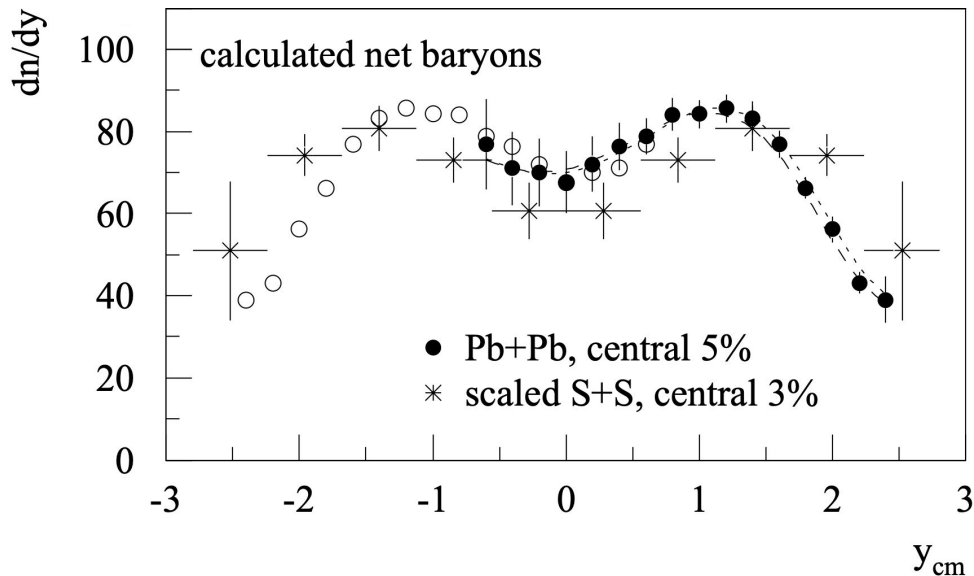
NA49

Baryon Stopping and Charged Particle Distributions in Central Pb+Pb Collisions at 158 GeV per Nucleon

1999

- Estimated net baryon
- Stopping measurement
- Pb+Pb and S+S
- System size dependence on the stopping

More interaction
=
More stopping?



[NA49 Collaboration, Phys. Rev. Lett. 82, 2471](#)

BRAHMS

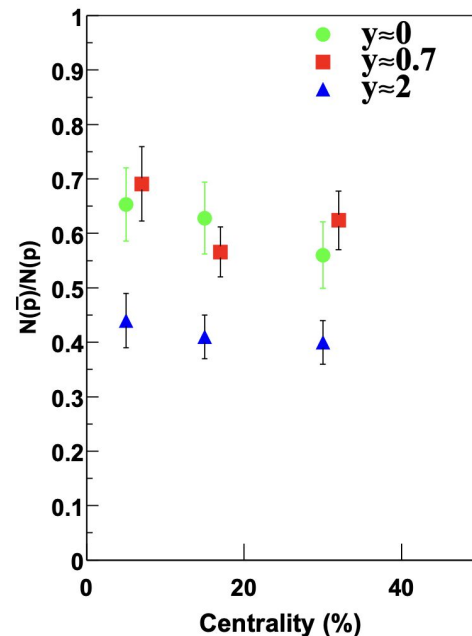
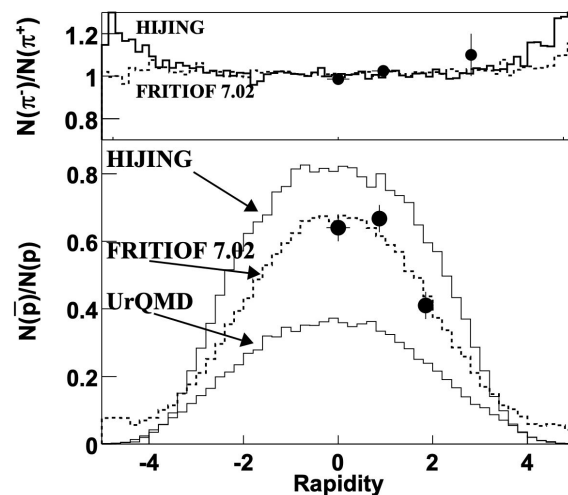
2001

Rapidity dependence of antiproton to proton ratios in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV

➤ $\bar{p}/p < 1$

➤ $\pi^-/\pi^+ \simeq 1$

➤ Mostly centrality independent



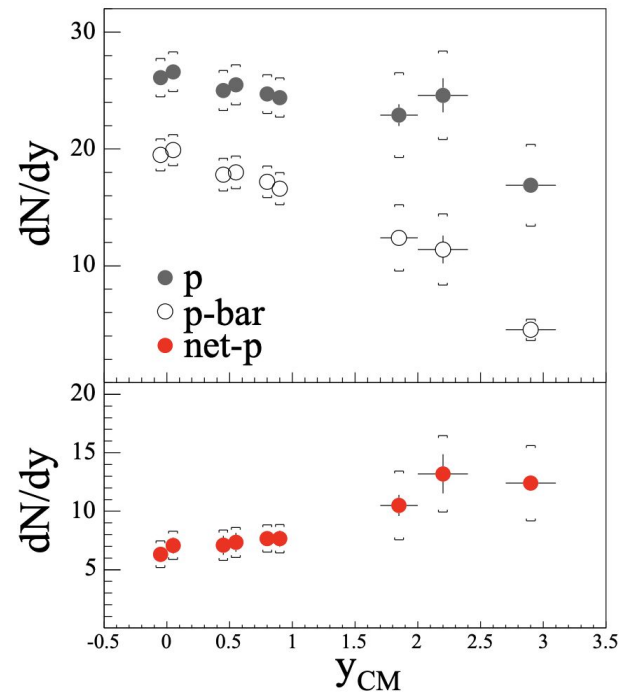
[BRAHMS Collaboration, Phys. Rev. Lett. 87, 112305](#)

BRAHMS

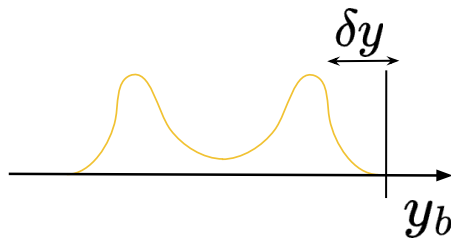
Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

2004

- Top RHIC energy:
Expected large transparency
- Excess proton stopping at midrapidity
- Over a large range of rapidities

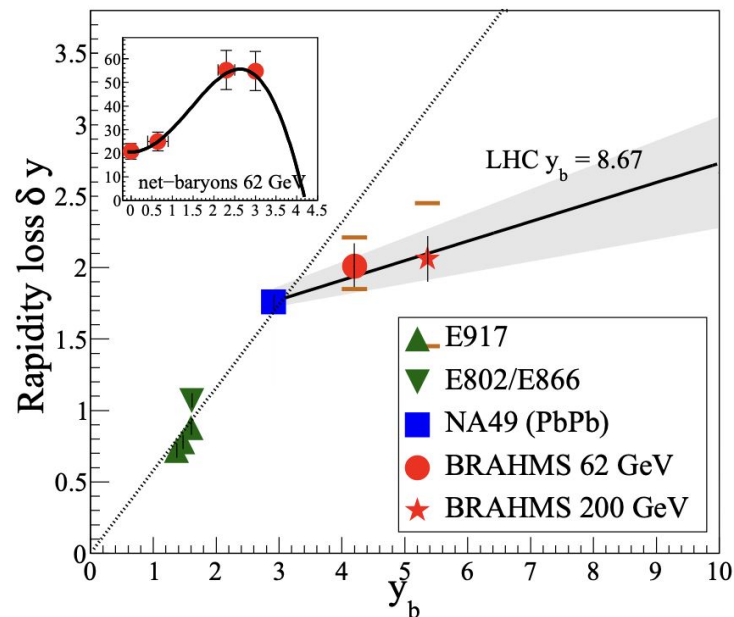


[BRAHMS Collaboration Phys. Rev. Lett. 93, 102301](#)



➤ Break of the y_b trend confirmed

What is going on?



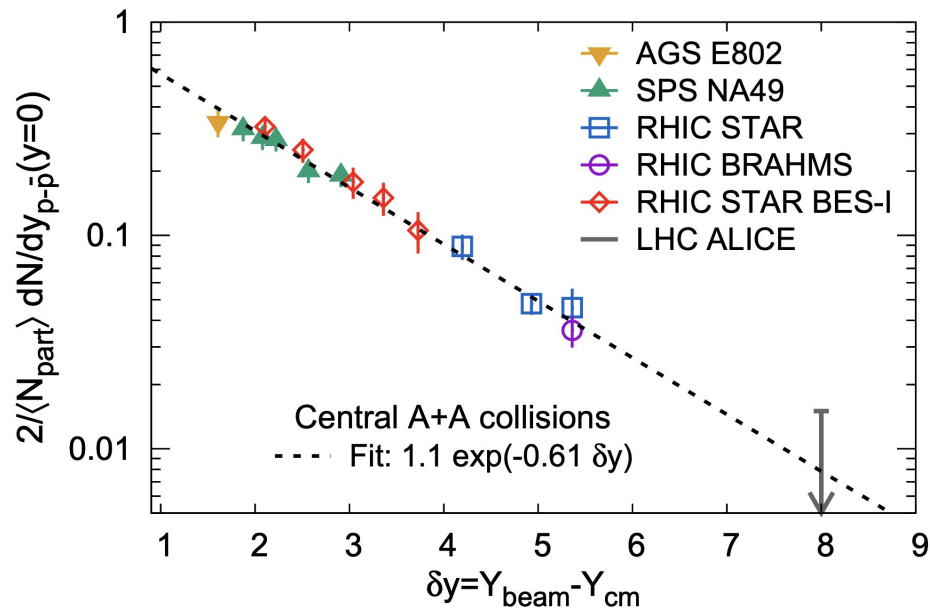
[BRAMHS Collaboration, Phys.Lett.B 677 \(2009\) 267-271](#)

$$\frac{d\sigma}{dy} \propto s^{(\alpha_A + \alpha_B - 2)/2} e^{(\alpha_B - \alpha_A)y}$$



$$\frac{dN_{p-\bar{p}}/dy}{N_{part}/2} = N_B \exp(-\alpha_B \delta y)$$

$$\alpha_B = 0.61 \pm 0.03$$



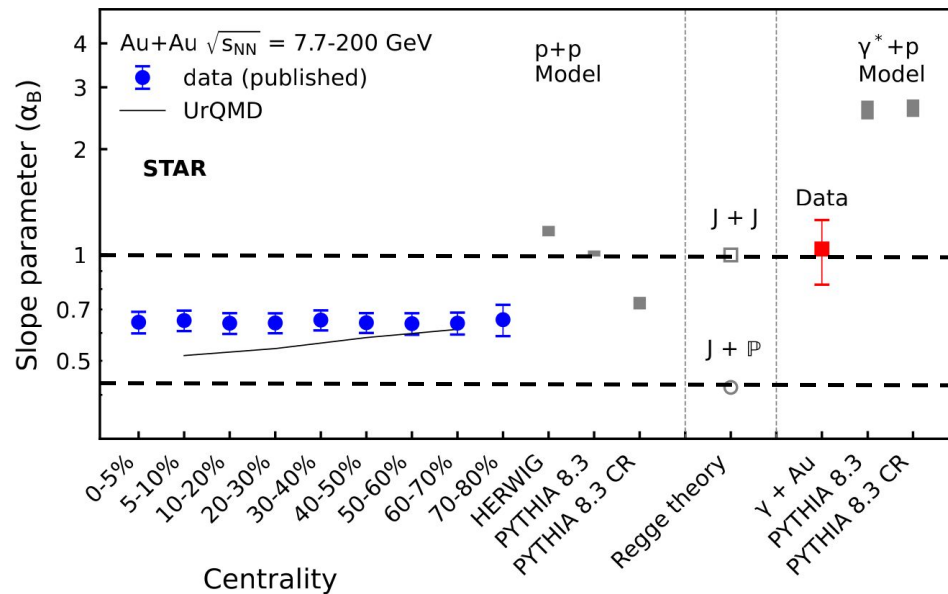
[STAR Collaboration, Eur.Phys.J.C 84 \(2024\) 6, 590](#)

STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

- Centrality independent
- Compatible with the Regge intercepts for single and double junction!



[STAR Collaboration, Eur.Phys.J.C 84 \(2024\) 6, 590](#)

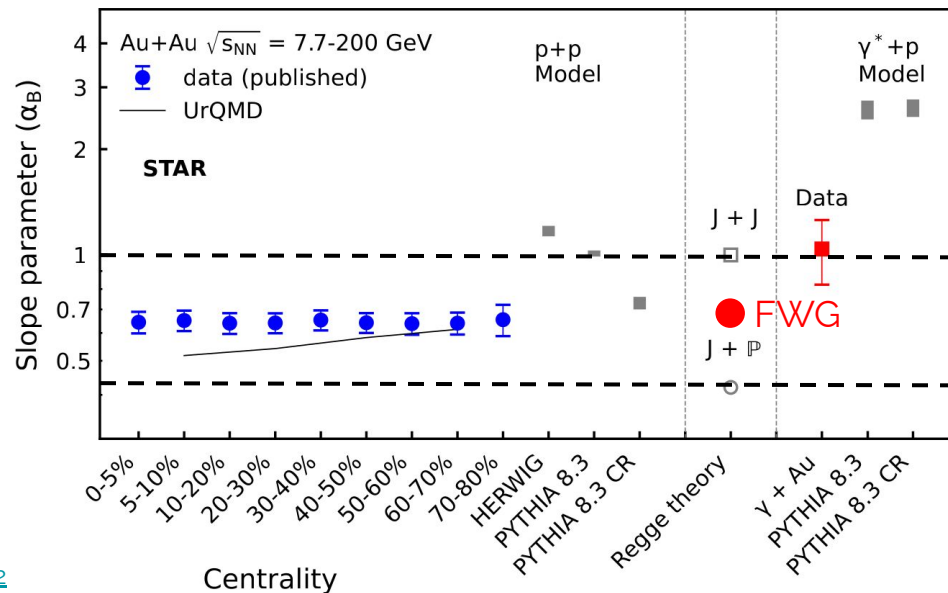
STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

- Centrality independent
- Compatible with the Regge intercepts for single and double junction!
- Taking three string correlation in the calculation: **excellent compatibility**

[D.Franklah, D. Kharzeev, G. Rossi, G. Veneziano JHEP 2407 \(2024\) 262](#)



[STAR Collaboration, Eur.Phys.J.C 84 \(2024\) 6, 590](#)

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Search for baryon junctions in photonuclear
processes and isobar collisions at RHIC

2024

The baryon stopping is well understood...

But, we can't really say if it follows the flavor
flow or the junction flow!

STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

The baryon stopping is well understood...

But, we can't really say if it follows the flavor
flow or the junction flow!

What if...

we measure the baryon stopping
relative
to the electric charge stopping?

The electric charge is attached to the flavor flow!
(No three photon vertex = no "electric charge junction")



Dr. Nicole **Lewis**



Dr. Daniel **Brandenburg**

Pr. Zhangbu **Xu**

STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

Isobar Runs: $^{96}_{44}\text{Ru}$ $^{96}_{40}\text{Zr}$

$$r^{\text{RuZr}} = B/\Delta Q \times \Delta Z/A$$

$$B = (B_{\text{Ru}} + B_{\text{Zr}})$$

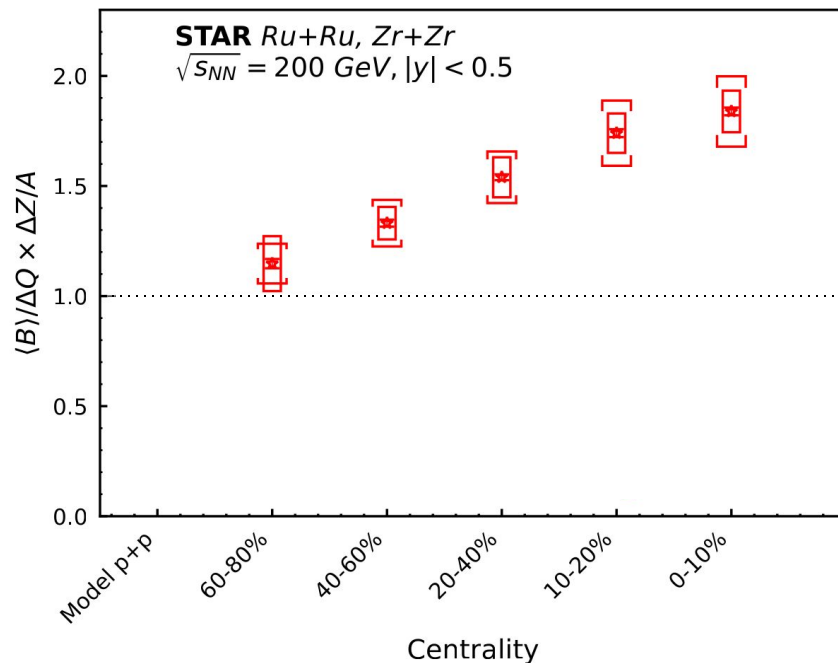
$$\Delta Q \equiv Q_{\text{Ru}} - Q_{\text{Zr}}$$

Flavor flow

Baryon flow

$$r^{\text{RuZr}} \sim 1$$

$$r^{\text{RuZr}} \neq 1$$



[STAR collaboration](#)

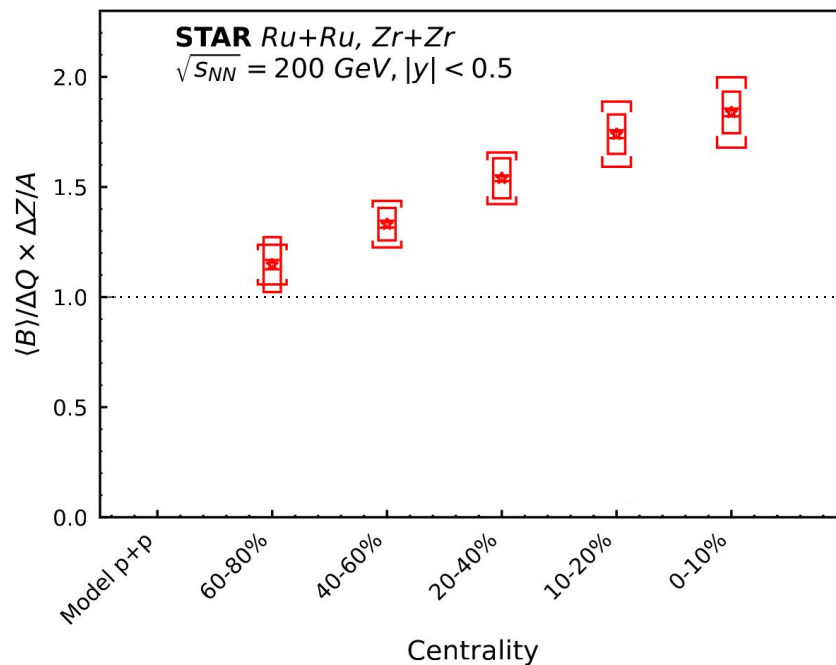
STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

$$r^{\text{RuZr}} \neq 1$$

Baryon flow?



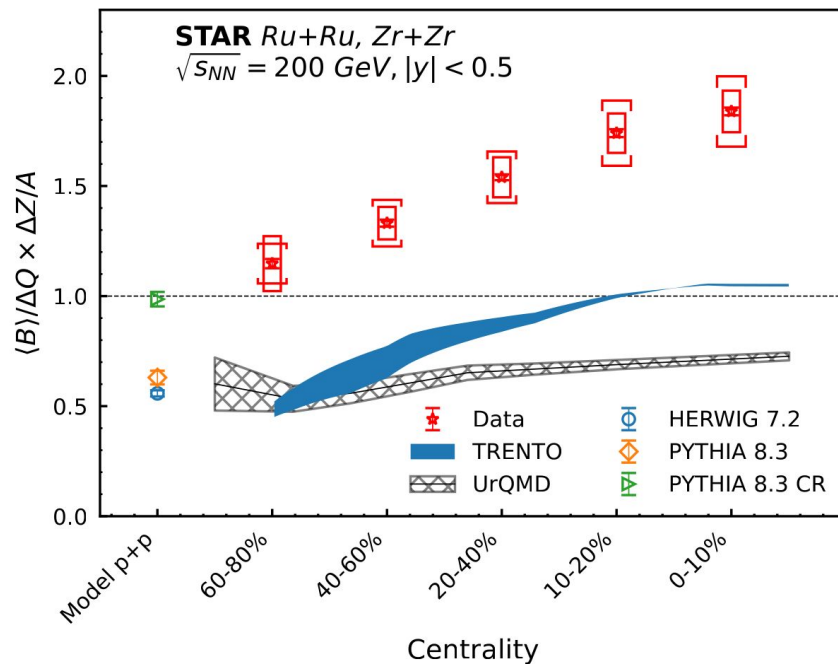
[STAR collaboration](#)

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Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

- Trento and UrQMD: below the data
- p+p Herwig / Pythia : CR ~ 1



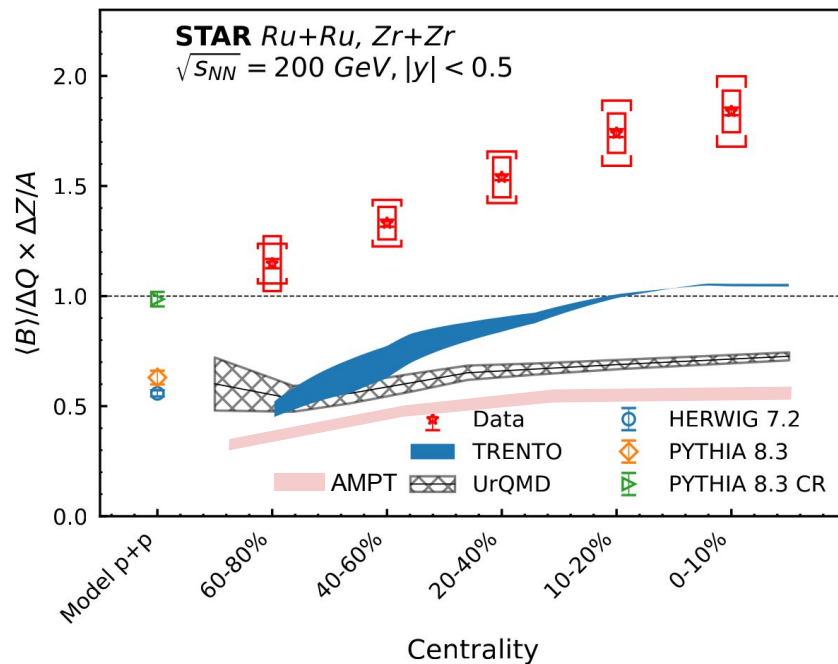
[STAR collaboration](#)

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Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

- Trento and UrQMD: below the data
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- AMPT: strangeness drives the ratio



[STAR collaboration](#)

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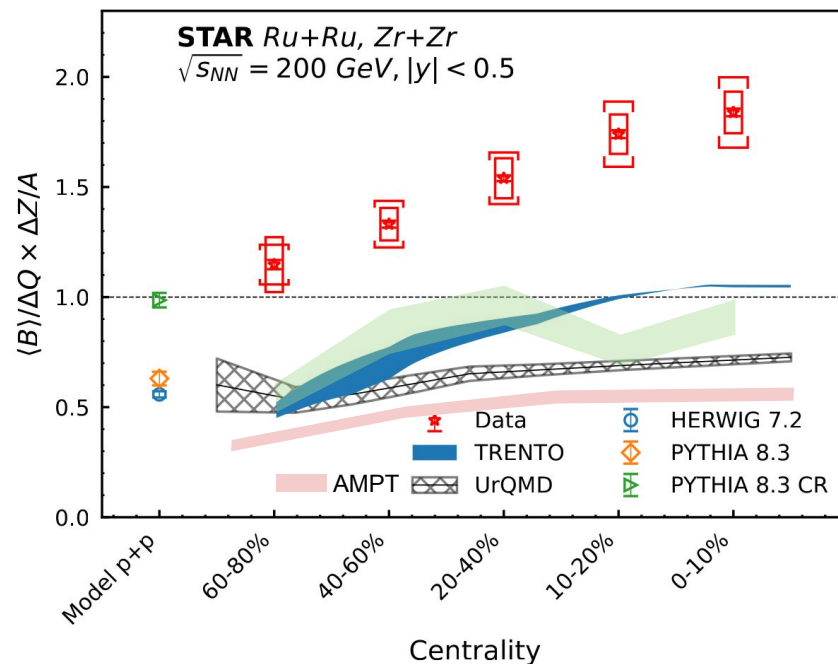
Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

2024

- Trento and UrQMD: below the data
- p+p Herwig / Pythia : CR ~ 1
- AMPT: strangeness drives the ratio
- iEBE-MUSIC framework: Equal stopping

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

$$\lambda_B = 0.2 \quad \lambda_Q = 0.2$$



[STAR collaboration](#)

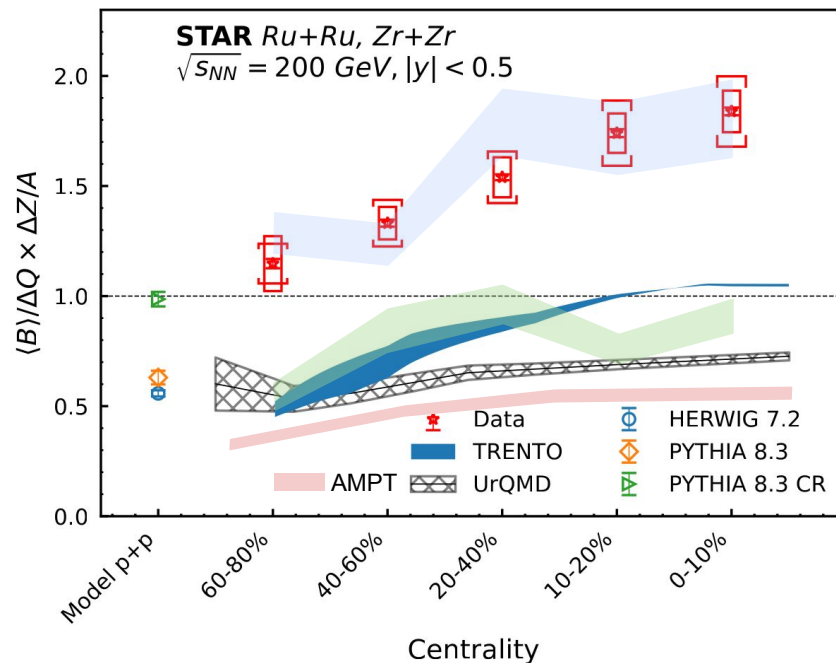
[GP, A. Monnai, B. Schenke, C. Shen, Phys.Rev.Lett. 133 \(2024\) 18, 182301](#)

- Trento and UrQMD: below the data
- p+p Herwig / Pythia : CR ~ 1
- AMPT: strangeness drives the ratio
- iEBE-MUSIC framework: Equal stopping
- iEBE-MUSIC framework: Different stopping

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

$$\lambda_B = 0.2$$

$$\lambda_Q = 0$$



[STAR collaboration](#)

[GP, A. Monnai, B. Schenke, C. Shen, Phys.Rev.Lett. 133 \(2024\) 18, 182301](#)

STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

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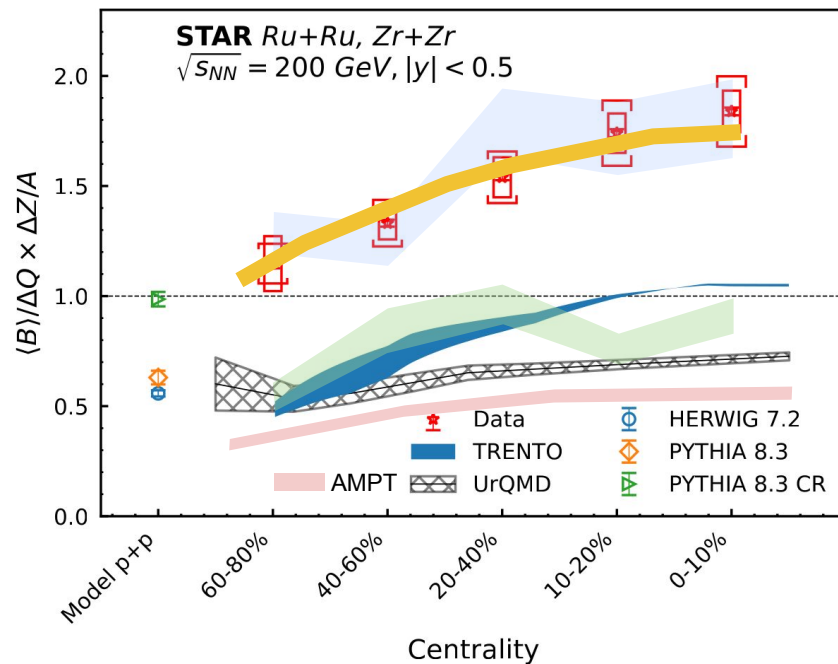
Extraction of the baryon stopping

Thermal-FIST

$$\frac{n_Q^X}{n_B^X} = \frac{p_{\text{frac}}^X(c)}{\gamma_B}$$

$$\gamma_B = 1.61 \pm 0.06$$

[GP, V. Vovchenko, arxiv:2602.04079](#)



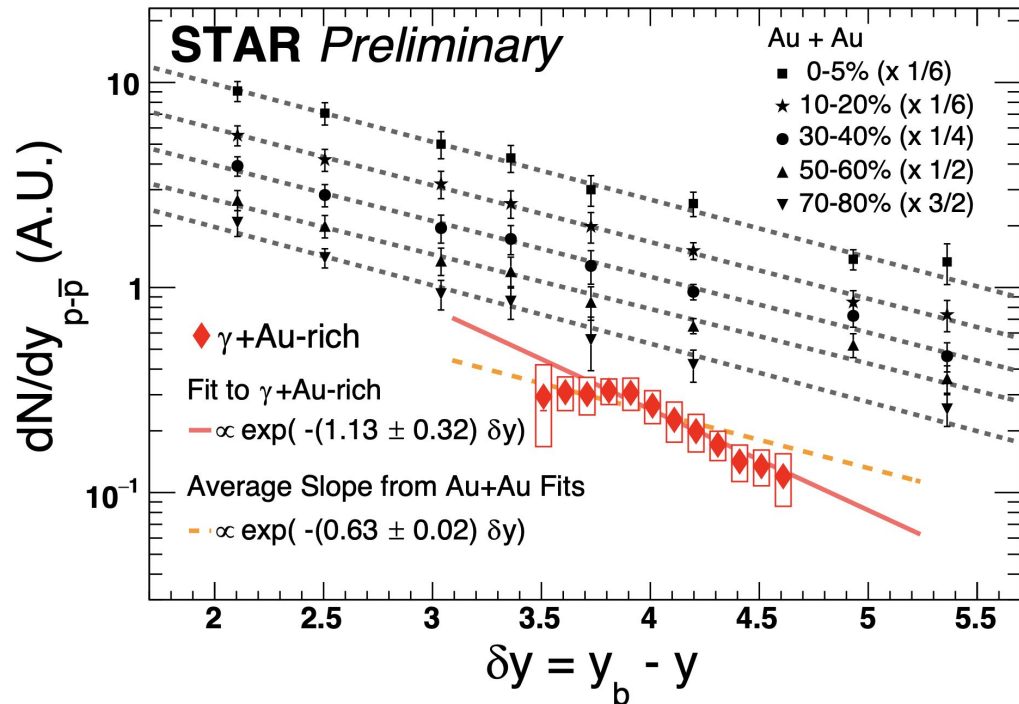
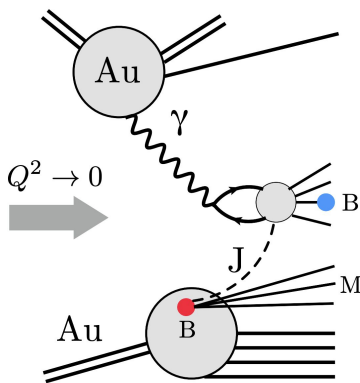
[STAR collaboration](#)

STAR

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

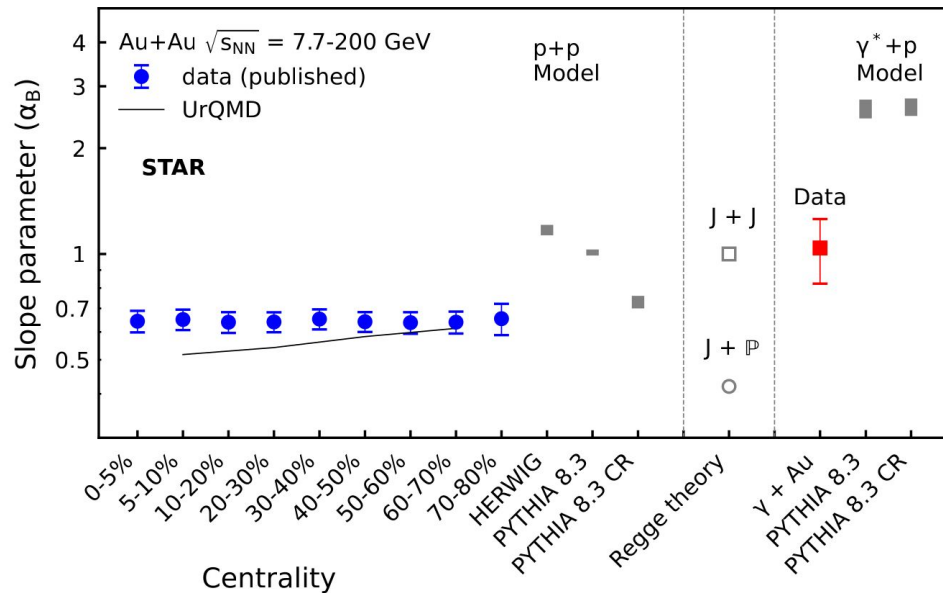
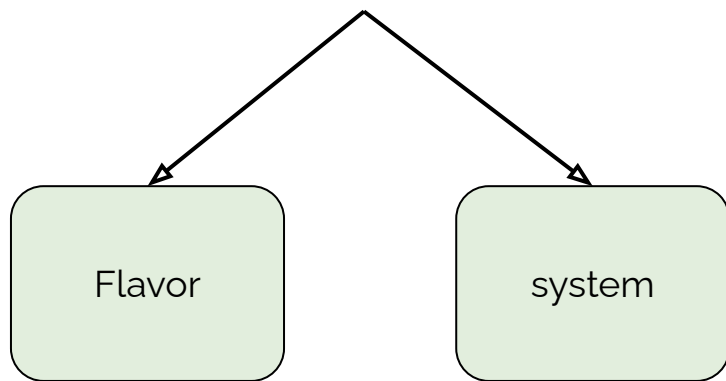
2024

- The cleaner signal for baryon stopping
- The slope is a bit larger than in A+A
- No clear Regge Intercept for this process



- No centrality dependence

Universality of the baryon
junction effects!



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Beam energy dependence of net-hyperon yield
and its implication on baryon transport mechanism

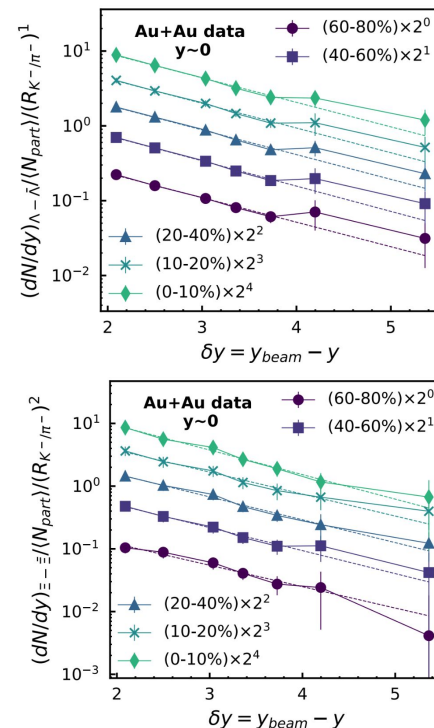
2024

Factor out s-quark effects $\rightarrow$ Normalize by production ratex

$$R_{K^-/\pi^-}$$

Measuring the s-quark production rate

[T. C. Yuen and M. Rongrong, P. Tribedy Z. Xu Phys.Lett.B 860 \(2025\) 139205](#)



Beyond the STAR measurement: universality - flavor independence

STAR

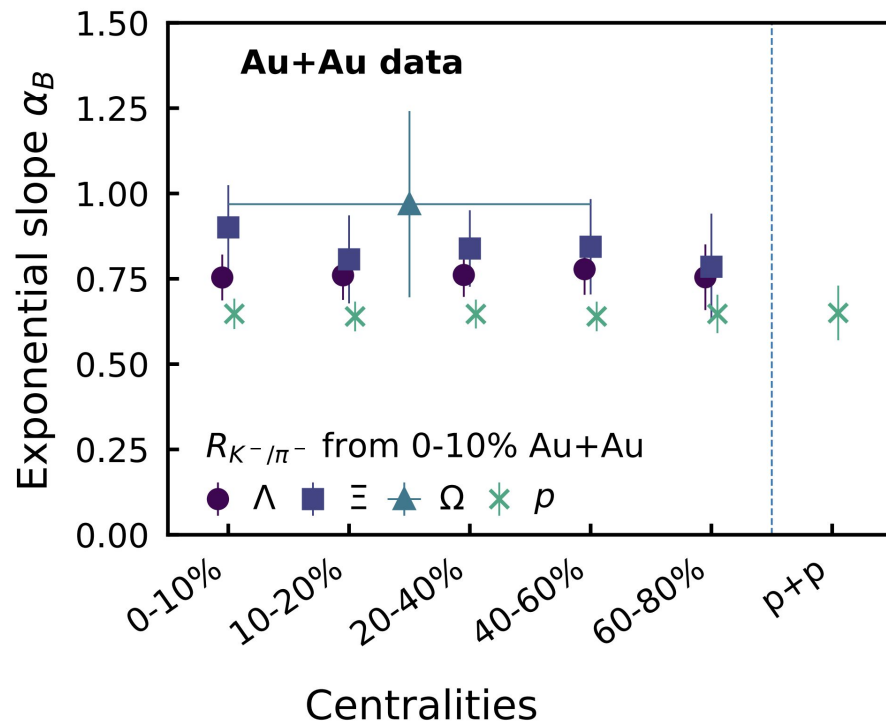
Beam energy dependence of net-hyperon yield
and its implication on baryon transport mechanism

2024

The slope for hyperon is compatible
with the junction picture!

Confirmation of the universality?

[T. C. Yuen and M. Rongrong, P. Tribedy Z. Xu Phys.Lett.B 860 \(2025\) 139205](#)



Beyond the STAR measurement: universality - flavor independence?

Possibility at the EIC?

$$e + p$$

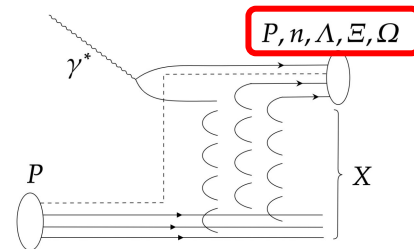
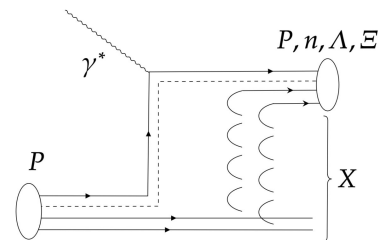
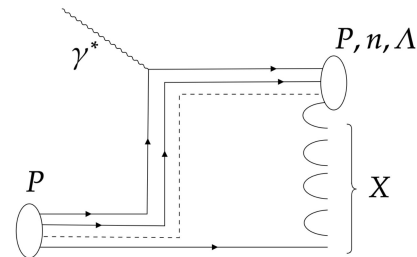
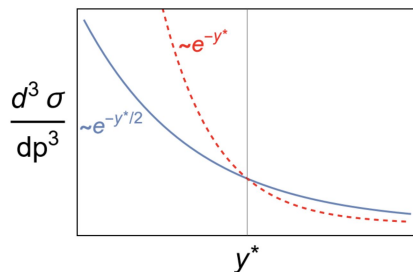
$$e + A$$

Dominant contribution

Gamma-junction

Increase of strange baryon production in DIS in the photon fragmentation region

Rapidity dependence of the baryon production in the photon direction



Adapted from D. Franklah QM2023

Beyond the STAR measurement: universality - system independence?

Possibility at LHC?

Thermal-FIST

$$\frac{n_Q^X}{n_B^X} = \frac{p_{\text{frac}}^X(c)}{\gamma_B}$$

$$\gamma_B = 1.61 \pm 0.06$$

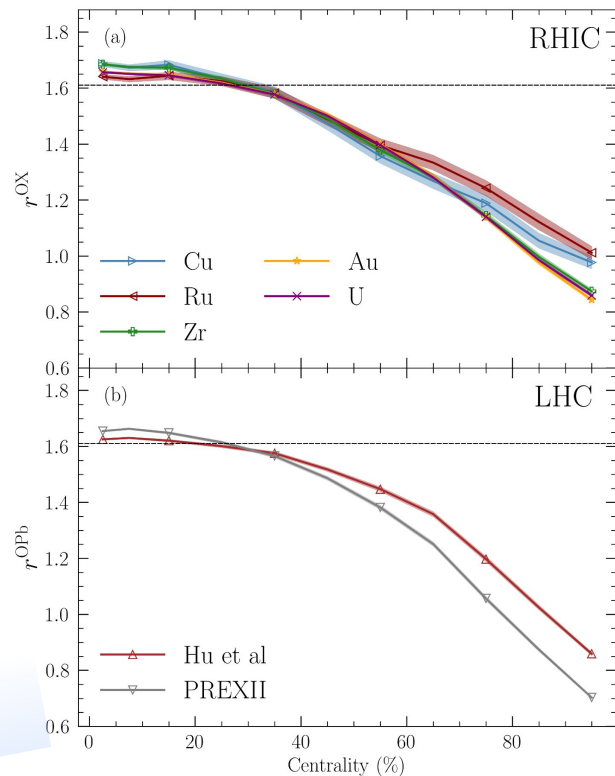
Can we extract this value for other systems?

New Ions @LHC Run 4 initiative

New Ions?

Second injector @ LHC?

See Talk from R.A. Fernandez
Wed. 04/15 4:50PM



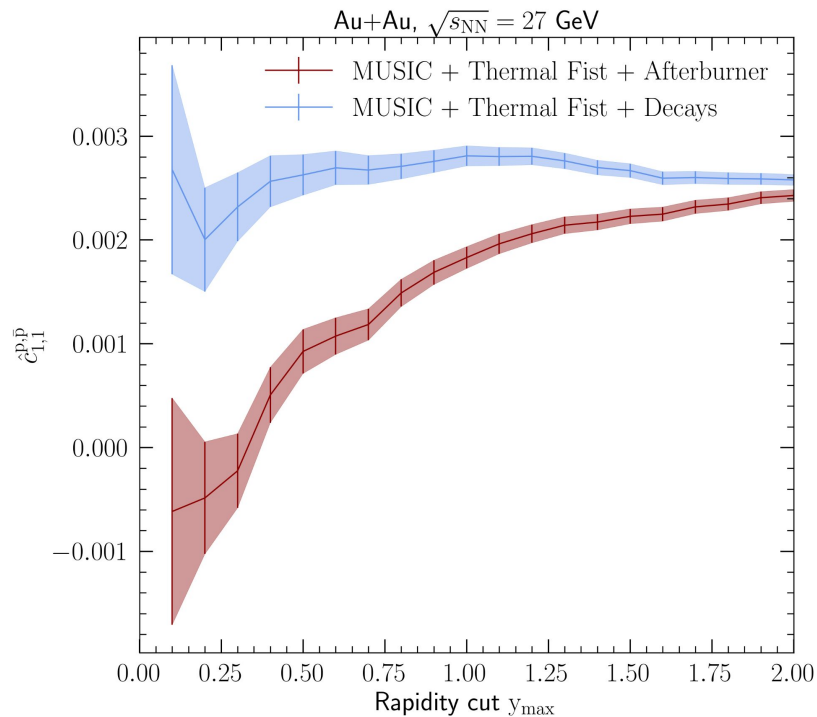
[GP, V. Vovchenko, arxiv:2602.04079](https://arxiv.org/abs/2602.04079)

Connection to net-baryon number fluctuations

$$\hat{c}_{1,1}^{p,\bar{p}} = \frac{\hat{C}_{11}^{p,\bar{p}}}{\langle N_p \rangle \langle N_{\bar{p}} \rangle}$$

Compatible with constant before
afterburner (annihilations)

Strong suppression of the long range
correlation for short range correlation due
to annihilations

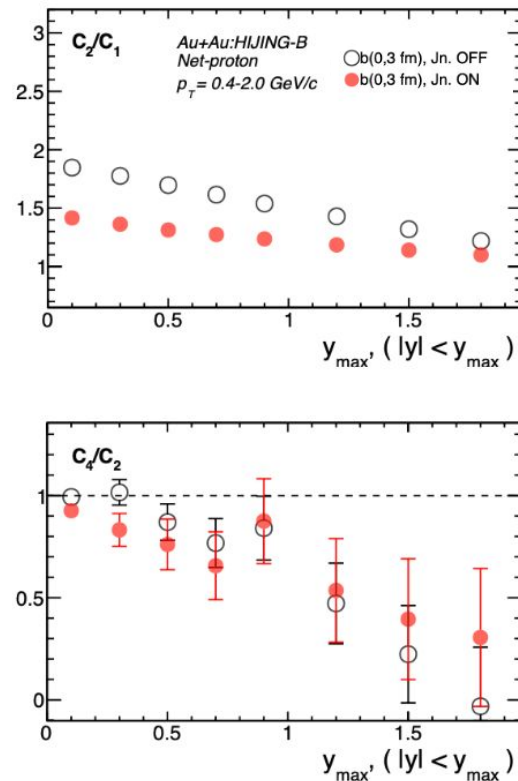


J. Parra, GP, V. Koch, V. Vovchenko in prep

Connection to net-baryon number fluctuations

Hijing B-Bbar calculations

- B-Bbar production from the junction
- Long range correlations
- Impact on the protons cumulants?



[Adapted from B. Mohanty, 1st Workshop on Baryon Dynamics from RHIC to EIC](#)

- The baryon junction is essential to construct baryons
- The baryon junction allows to understand B-Bbar interactions in a much more intuitive way
- It can be connected to the baryon stopping in p+p and A+A collisions
- Clear sign of extra baryon stopping at STAR - junction?
- New potential observables - universality of the junction
- Impact on the proton fluctuations?

