

The 255th seminar of  HENPIC

Tracking the Baryon Number with Heavy Ion Collisions

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University of Science and Technology of China

STAR, Science 393, 6812 (2026)

Yang Li, PhD thesis, USTC (2023)

N. Lewis et al., EPJC 84, 590 (2024)

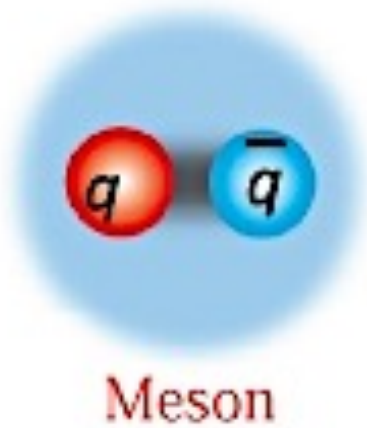
W. Lv et al., CPC 48, 044001 (2024)

C. Tsang et al., PLB 860, 139205 (2025)

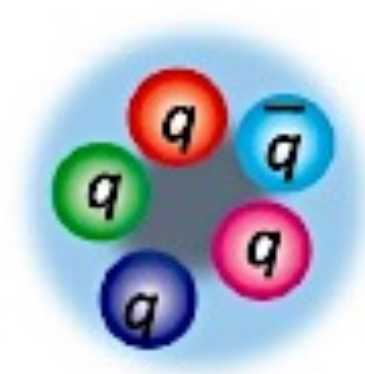
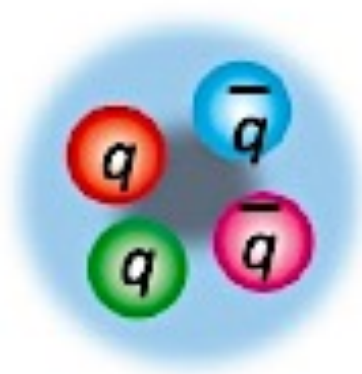


What is Baryon Number

Standard Hadrons



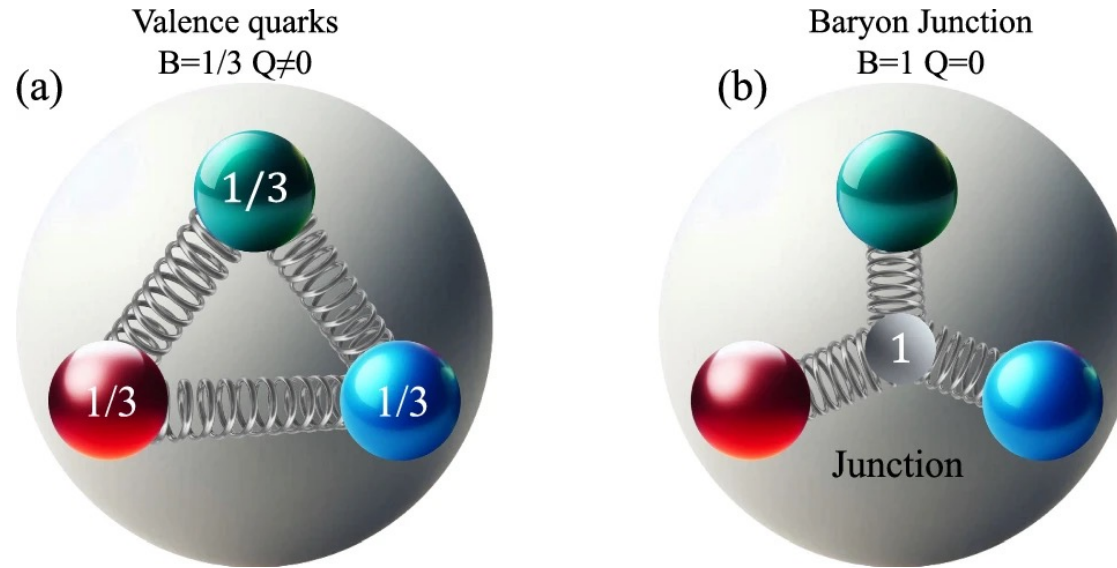
Exotic Hadrons



DeepSeek says:

Baryon number is a way to keep **track** of the number of "quark-based" particles (matter) versus anti-particles, and it remains constant in every interaction we have ever observed—even if we suspect it might not have been constant in the universe's first fraction of a second.

What Tracks Baryon Number



Conventional quark model:

Baryon number is carried (tracked) by quarks

$$B(q) = 1/3, B(q\text{bar}) = -1/3, \text{ and } B(g) = 0$$

Alternative picture:

Baryon number is carried (tracked) by gluon junction

$$B(q) = B(q\text{bar}) = 0, \text{ and } B(J) = 1$$

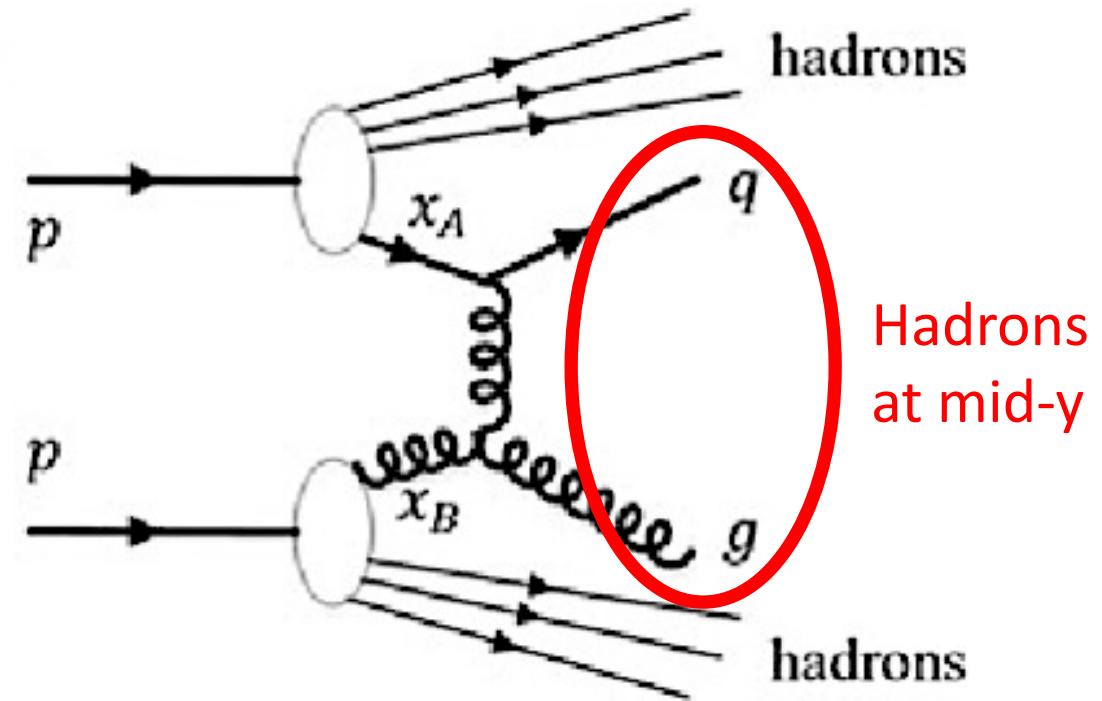
Not only baryon number carrier
But also baryon internal structure

How to Probe Experimentally

Baryon transport measurements in high-energy baryon collisions

D. Kharzeev, PLB378, 238 (1996)

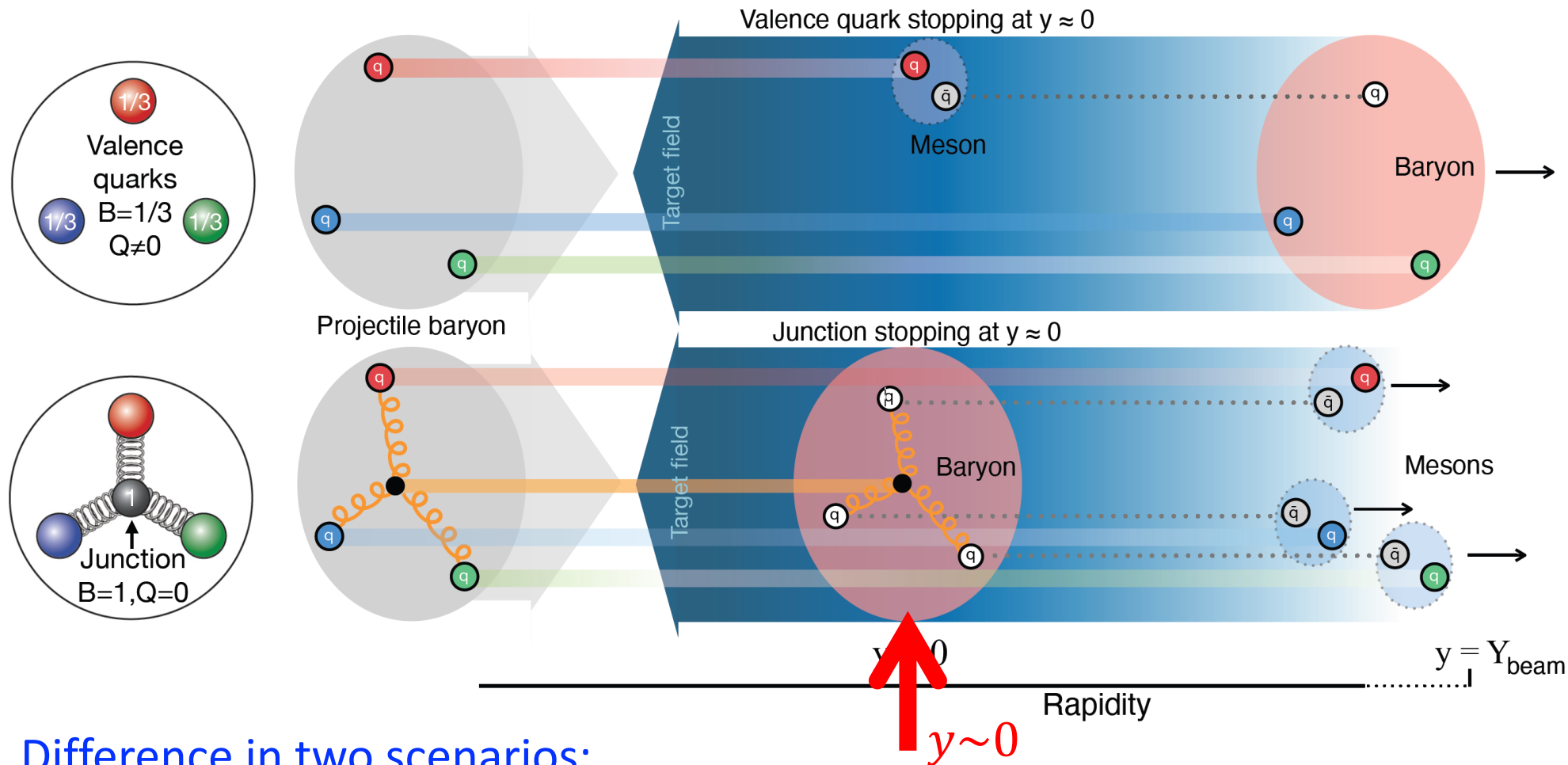
- Only part of the colliding baryons is stopped at mid-rapidity and yields net-baryons
- The measured net baryons have to come from the colliding baryons (conservation law)
- The baryon transport reflects:
 - The constituent content (internal structure) of baryons
 - The first interactions of the constituents of colliding baryons
- Insensitive to subsequential processes such as quark-gluon plasma formation



QCD factorization theorem:

$$PDF_A \otimes PDF_B \otimes \hat{\sigma}_{A+B \rightarrow C+D} \otimes H_C \otimes H_D$$

Observables

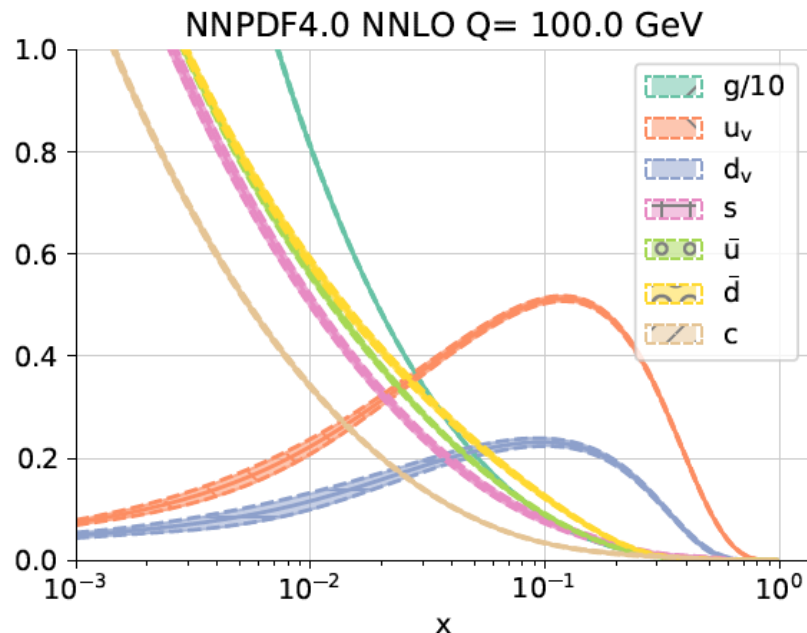


Difference in two scenarios:

- **Rapidity loss** of net-baryons
- Quark **flavor composition** of transported baryons

STAR, Science 393, 6812 (2026)

Conventional quark model:



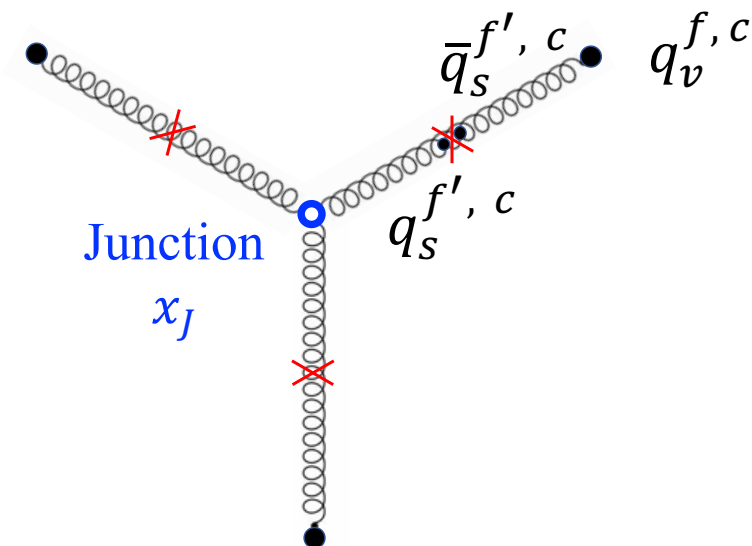
PDG, PRD 110, 030001 (2024)

Net-quarks predominantly at large-x

Very difficult to be stopped at mid-y

Small rapidity loss

Baryon junction:



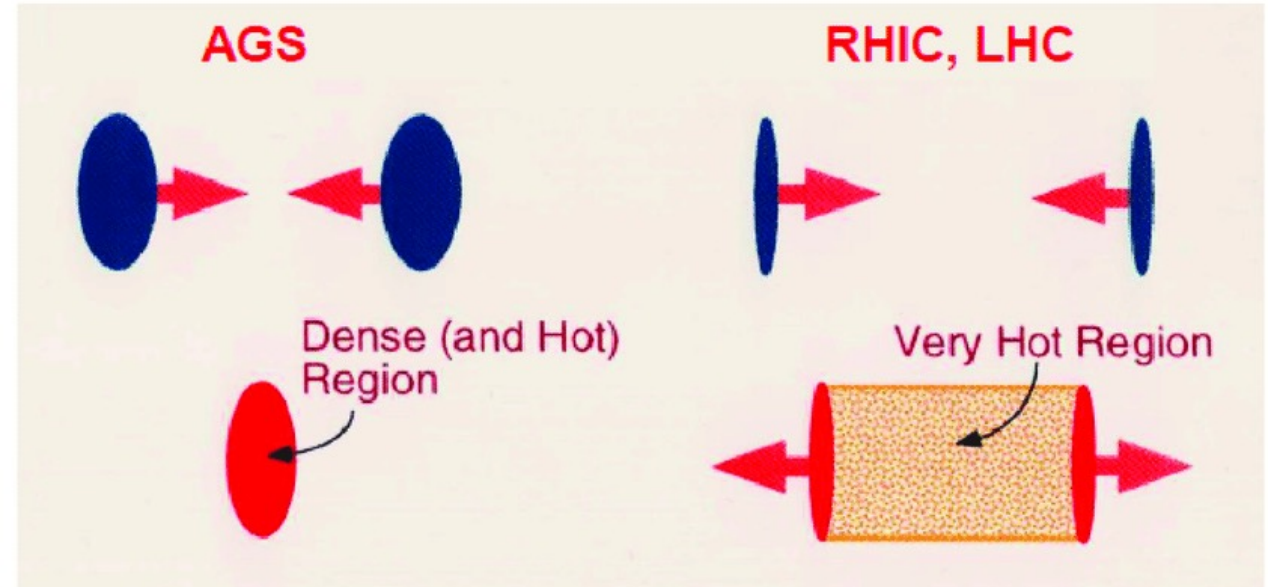
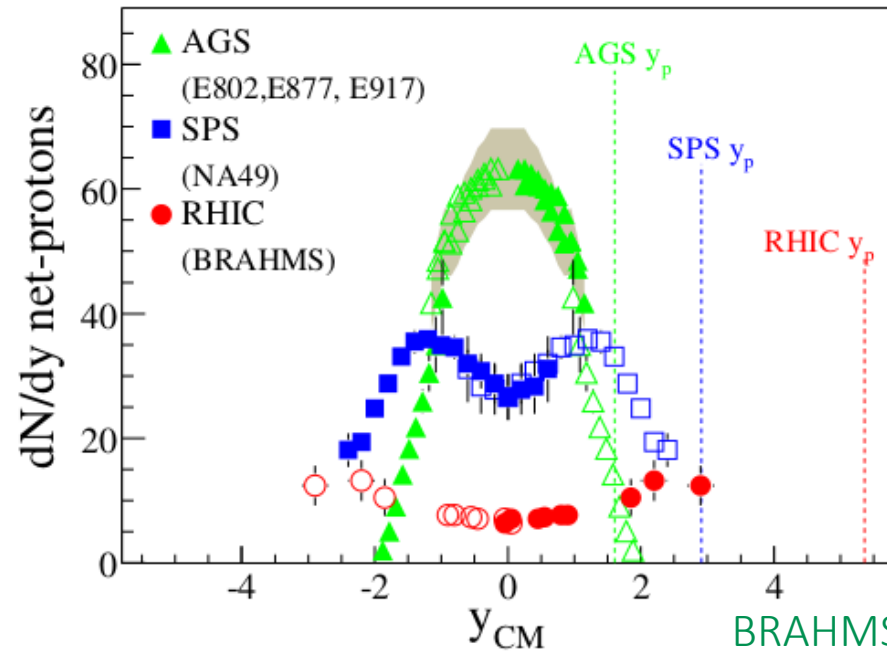
W. Lv et al., CPC 48, 044001 (2024)

Junctions are soft and easier be stopped

Stopped junction will be dressed up by sea quarks and form baryons

Large rapidity loss

Rapidity Distribution of Net-Proton



BRAHMS, PRL93, 102301 (2004) and references therein

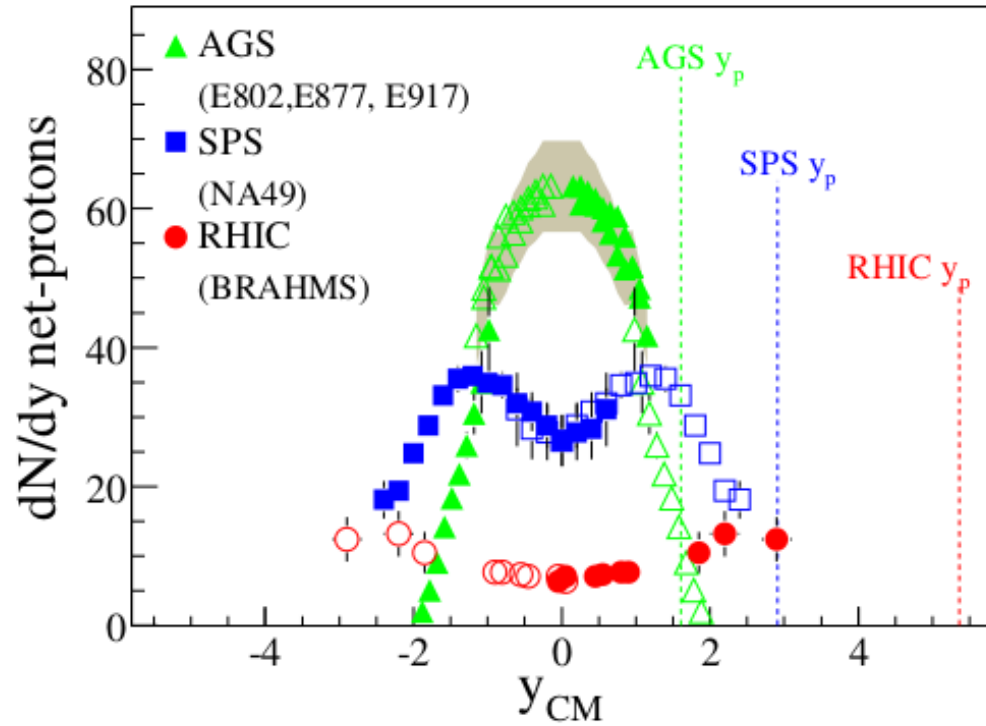
AGS (Au+Au @ $\sqrt{s_{NN}}=4.5$ GeV):

- Energy and baryons are stopped completely at mid-rapidity

RHIC (Au+Au @ $\sqrt{s_{NN}}=200$ GeV):

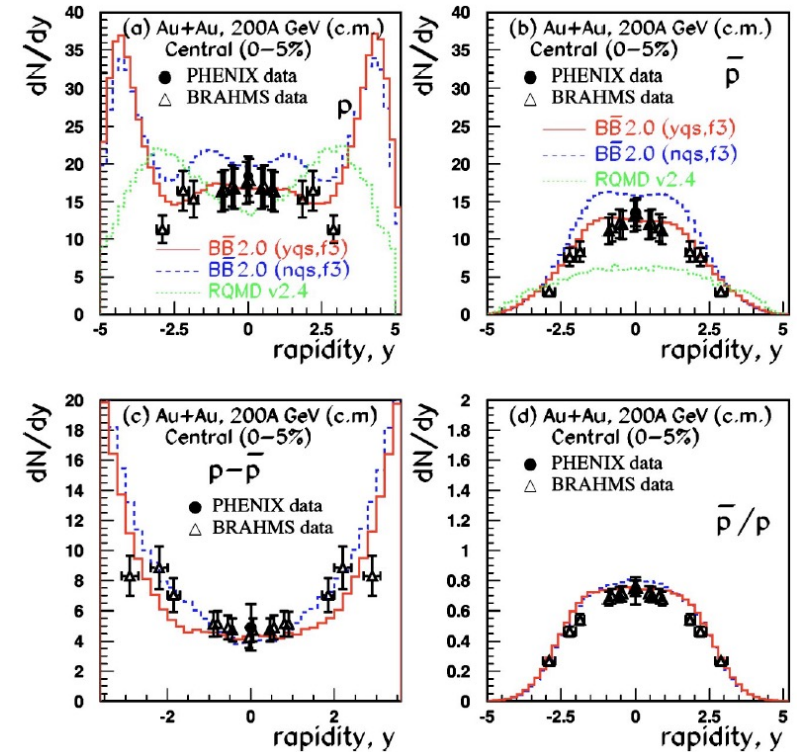
- Baryons pass through, deposit some fraction of energy at mid-rapidity
- But still large amount of net-baryons are measured at mid-rapidity

Rapidity Distribution of Net-Proton



BRAHMS, PRL 93, 102301 (2004)

The rapidity loss can be as large as more than 5 unit at RHIC

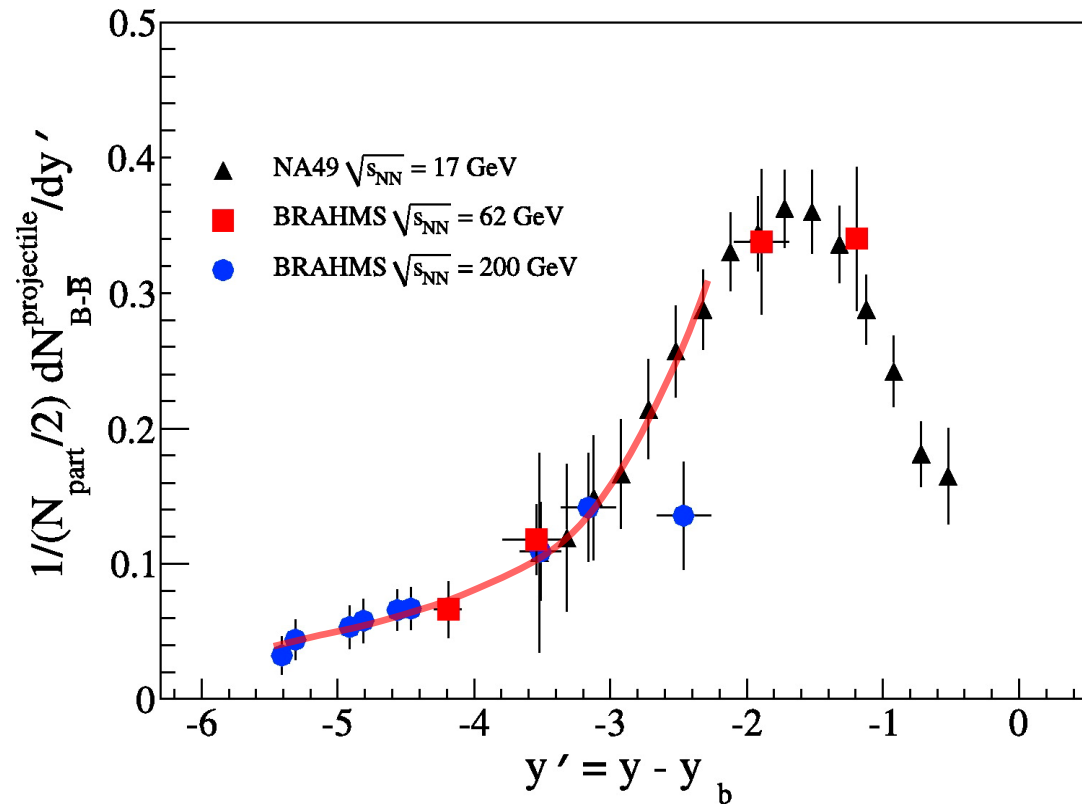


V. Pop, M. Gyulassy, J. Barrette, C. Gale, X. N. Wang and N. Xu, PRC 70, 064906 (2004)

HIJING/BBbar w/ baryon junction describes data
RQMD w/ mult. scattering reasonable description



Quantifying Baryon Number Transport



BRAHMS, PLB 677, 267 (2009)

Regge theory:

$$\frac{dN}{dy} \propto e^{-\alpha_B(y_{\text{beam}}-y)} + e^{-\alpha_B(y+y_{\text{beam}})}$$

The net-proton rapidity loss of projectile is estimated by **subtracting contribution from target**

The distribution is **similar** in heavy ion collisions **at various energies**

$$\frac{dN}{dy} \propto e^{\alpha_B y'}$$

The parameter α_B reflects the power of **baryons stopping**



New Way to Quantify

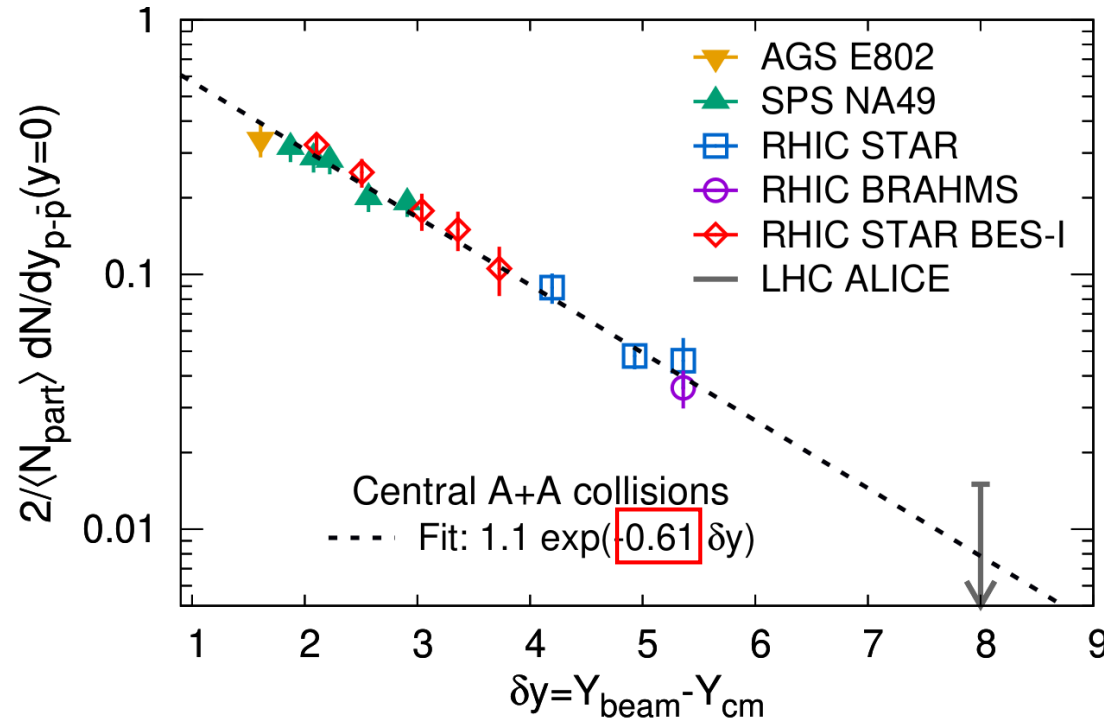
- The experiment need to cover a very large rapidity, especially at higher energy
- The subtraction of the contribution from the target is model dependent, introducing large systematic uncertainty

New way: Fix the acceptance of the experiment ($y \sim 0$) and scan beam rapidity

$$\frac{dN}{dy} \propto e^{-\alpha_B(y_{beam}-y)} + e^{-\alpha_B(y+y_{beam})} \xrightarrow{y=0} 2e^{-\alpha_B y_{beam}}$$



Net-Proton Yield at Various Energies



$$\left. \frac{dN}{dy} \right|_{y=0} \propto e^{-\alpha_B y_{beam}}$$

N. Lewis et al., EPJC 84, 590 (2024)

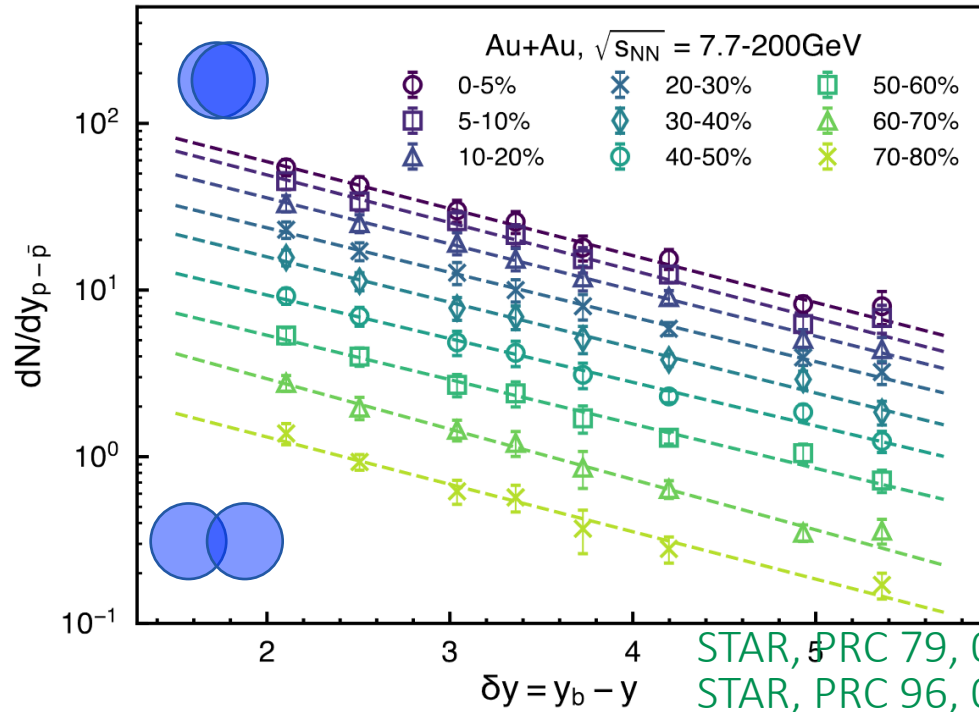
Net-proton yield at $y \sim 0$ scales nicely with exponential function of rapidity loss

$\alpha_B = 0.61 \pm 0.03$ in central A+A collisions

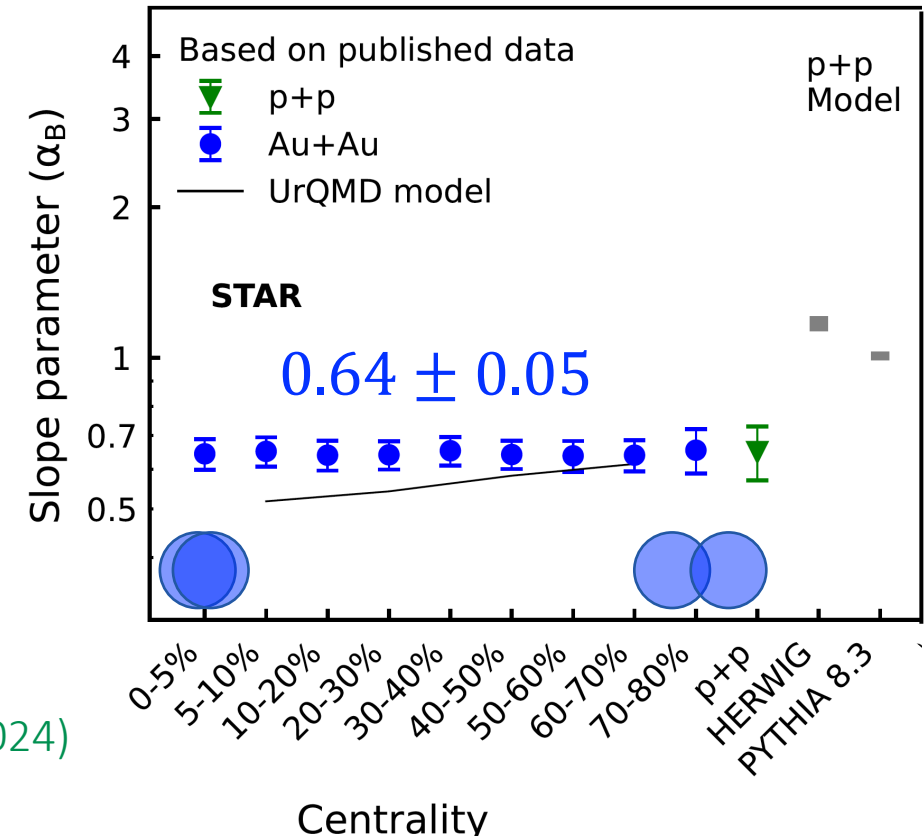
Significantly higher than predictions from PYTHIA8 and Herwig models (≥ 1)

Multiple scattering was proposed to explain large rapidity loss

Centrality Dependence of the Slope



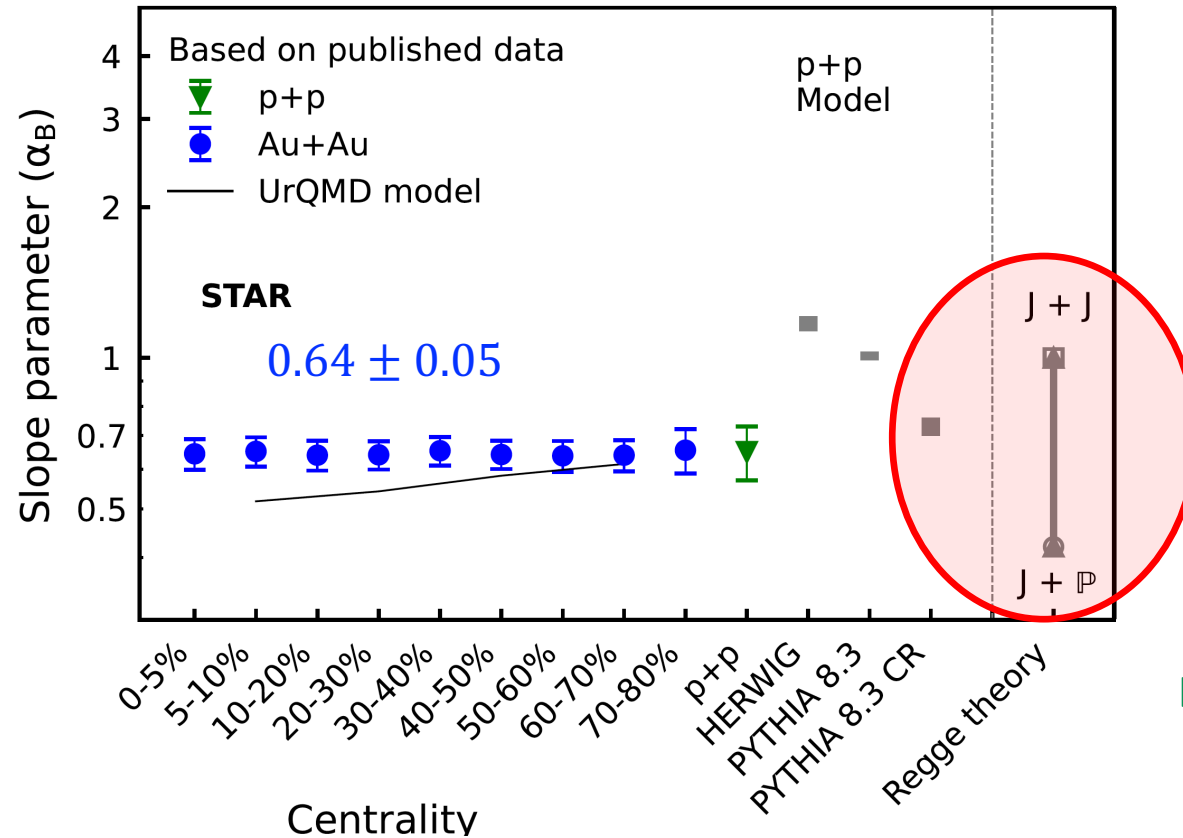
STAR, PRC 79, 034909 (2009)
 STAR, PRC 96, 044904 (2017)
 N. Lewis et al., EPJC 84, 590 (2024)



- Scaling in all centralities and collision energies
 - Slopes do not depend on centrality
 - Different from UrQMD model predictions with multiple scattering implemented
- ➔ Multiple scattering is not supported by data
- ➔ Baryon transport seems not tracked by valence quarks



Compare to Theories with Baryon Junction



STAR, Science 393, 6812 (2026)

Junction + Junction

Junction + Pomeron

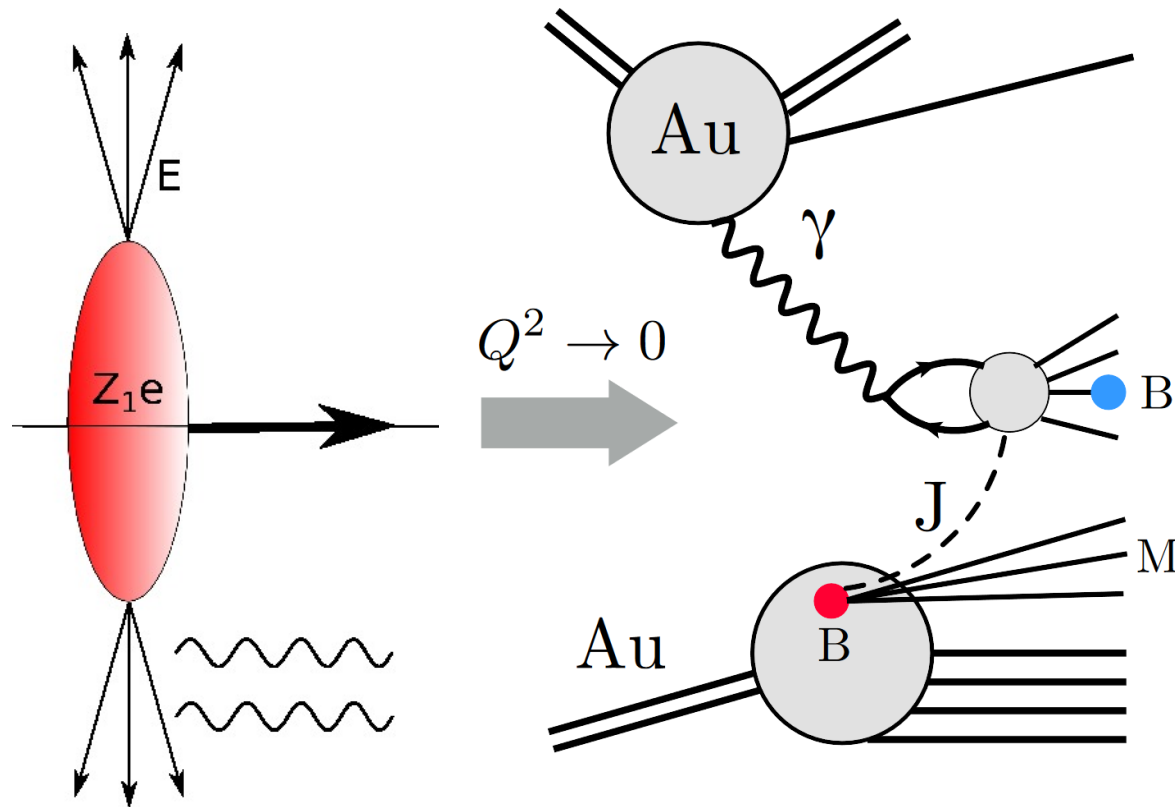
D. Kharzeev, PLB 378, 238 (1996)

Centrality independent slopes **consistent with** Regge theory with **junction stopping**

PYTHIA with partial implementation of baryon junction describes data better than default

Did not make HIJING/BBbar work

Baryon Transport in γ +A Collisions

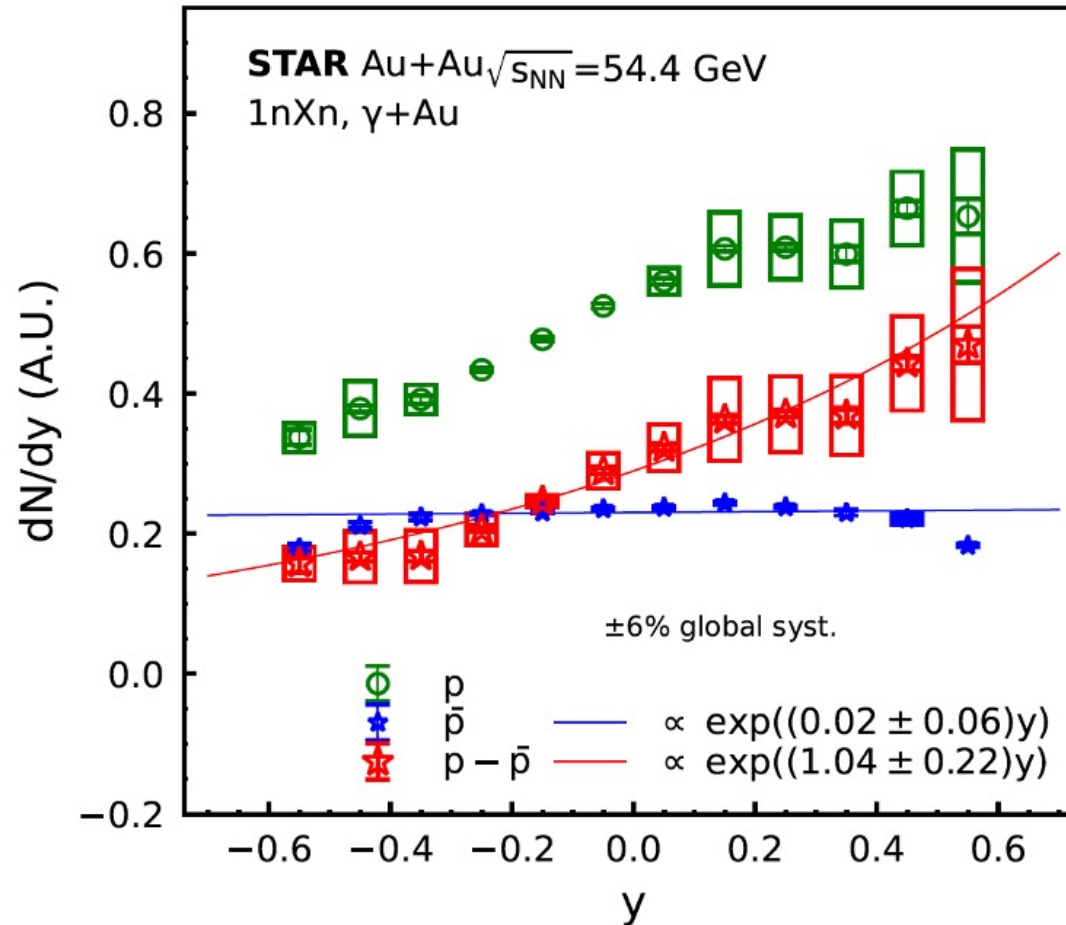


- Strong electromagnetic field accompanies the nuclei in relativistic heavy-ion collisions
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux
- Photon fluctuates into a quark pair and interact with the nucleus target
- Baryon transported from only **one side**

$$\frac{dN}{dy} \propto e^{-\alpha_B(Y_{beam}-y)} \propto e^{\alpha_B y}$$



Slope Parameter in γ +A Collisions

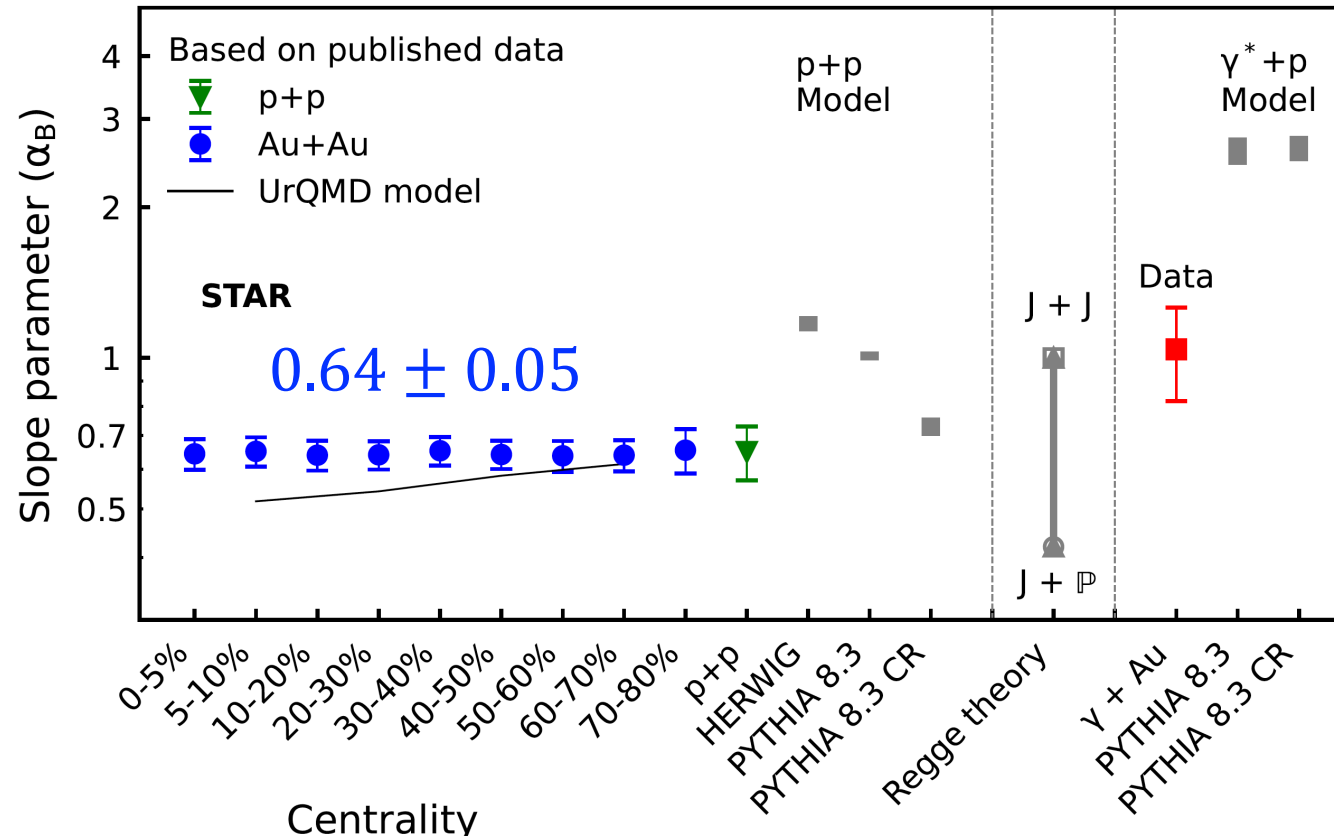


STAR, Science 393, 6812 (2026)

- Antiproton shows flat rapidity distribution
- Proton and net-proton show the characteristic exponential increase towards nucleus side

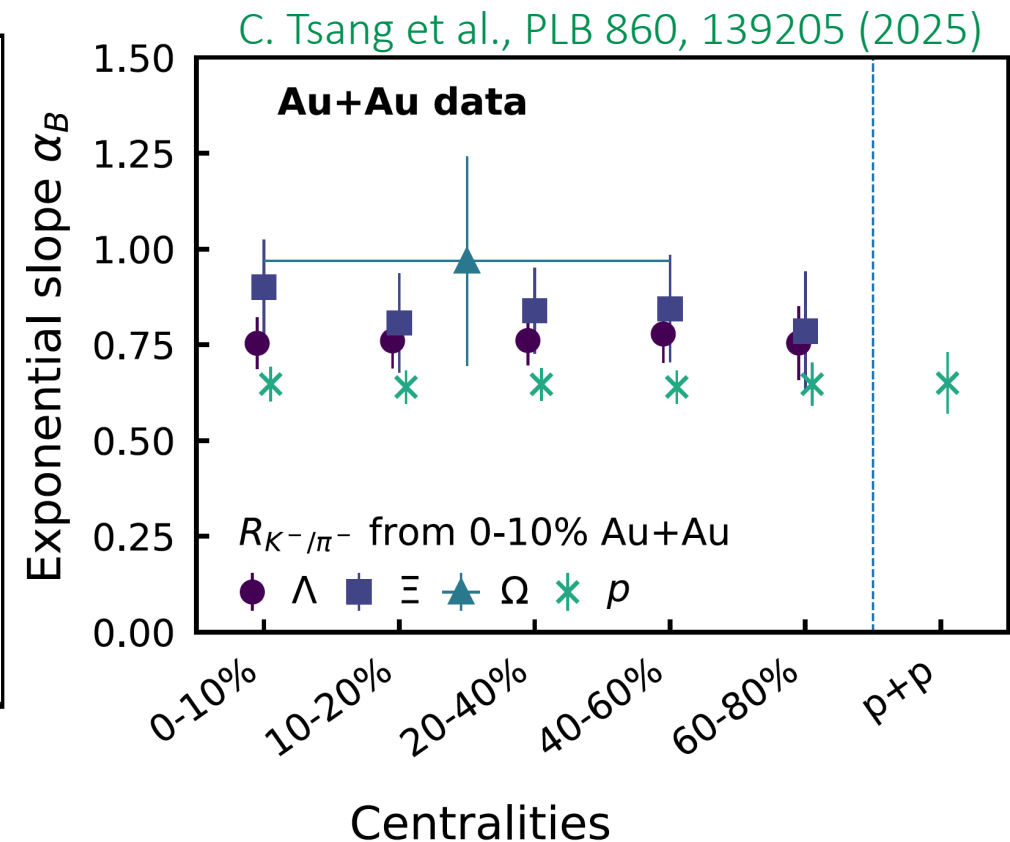
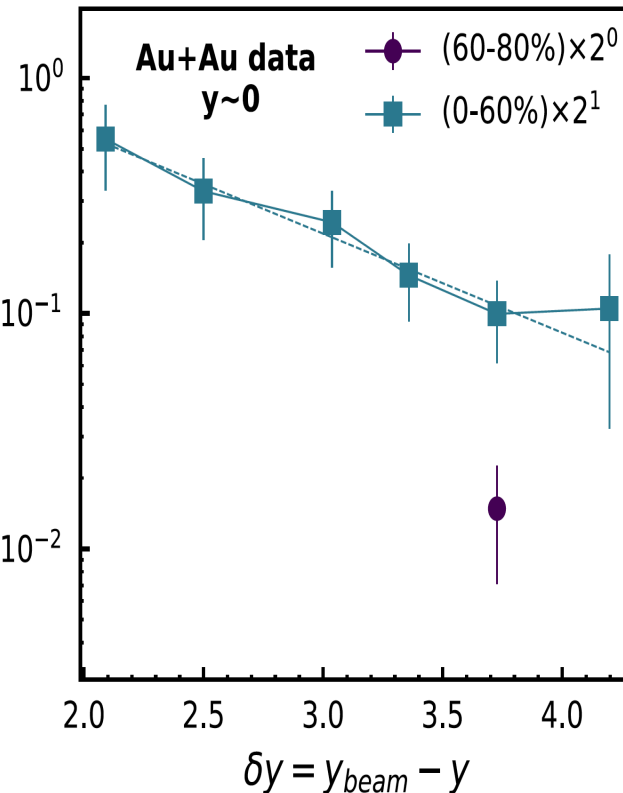
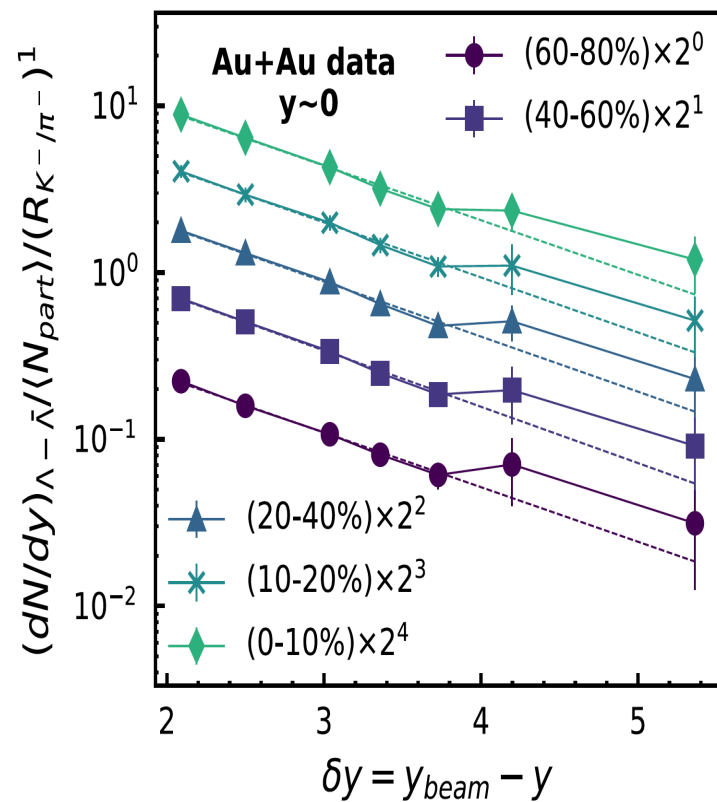
Slope Parameter in γ +A Collisions

STAR, Science 393, 6812 (2026)



- $\alpha_B = 1.04 \pm 0.22$
- Close to Regge theory with baryon junction, **significantly lower** than PYTHIA

Flavor Dependence of Baryon Transport



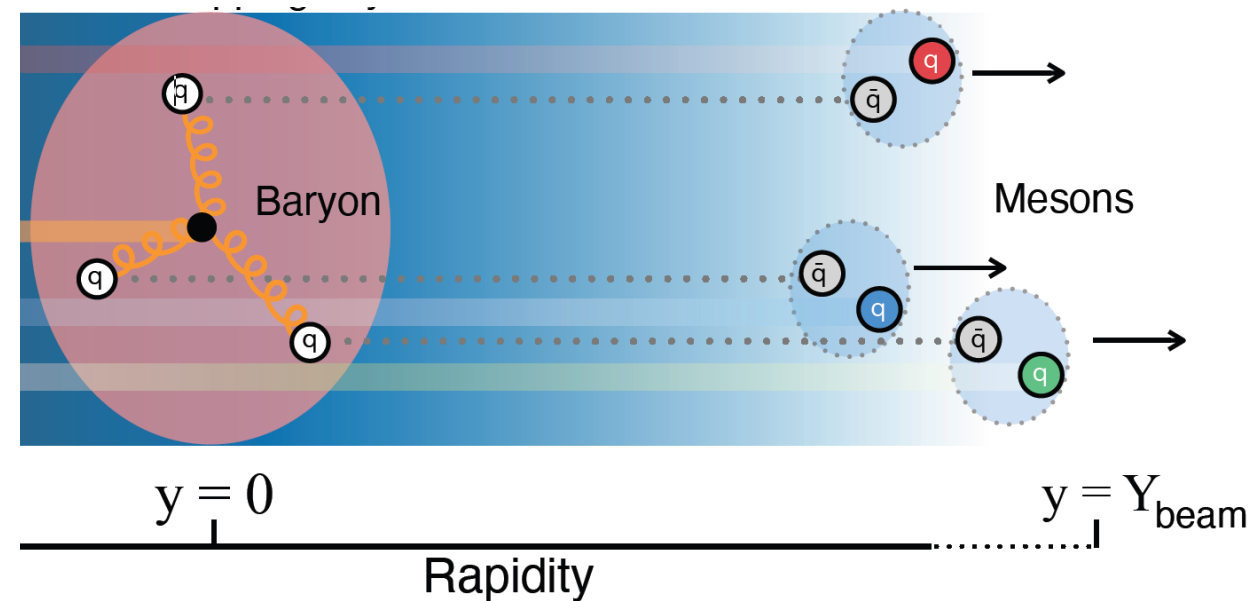
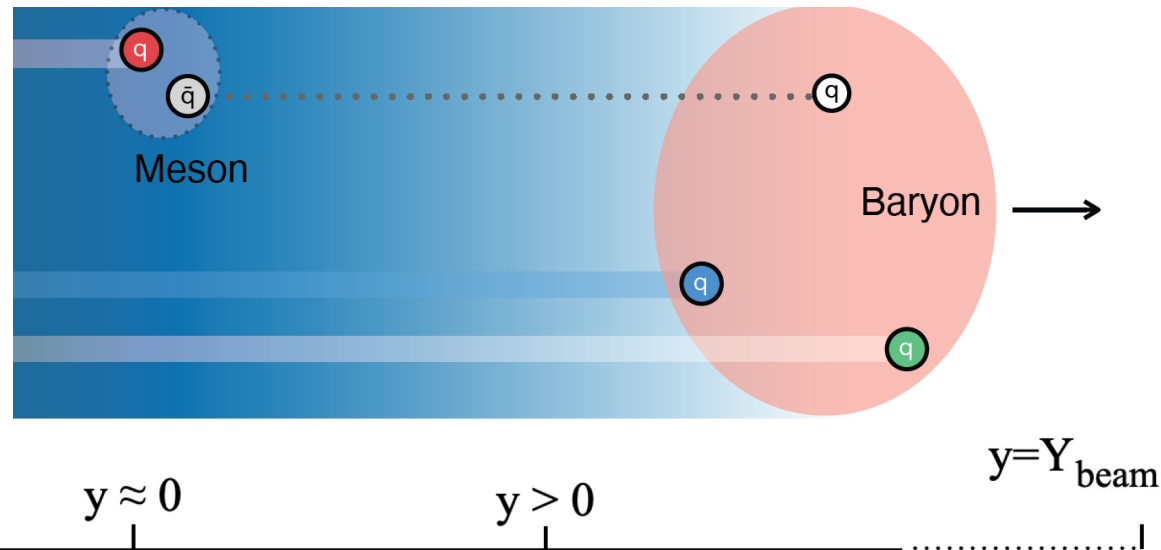
- Net-hyperons yield from RHIC Beam-Energy-Scan-I
- Suppression of strangeness taken out by $(K/\pi)^n$ factor
- Follows exponential nicely for Λ , Ξ and Ω
- No particle species dependence
- Flavor-blind baryon transport mechanism $\rightarrow$ **baryon junction**

Correlation of Baryon and Charge Transport

Valence quark stopping

VS

Baryon junction stopping



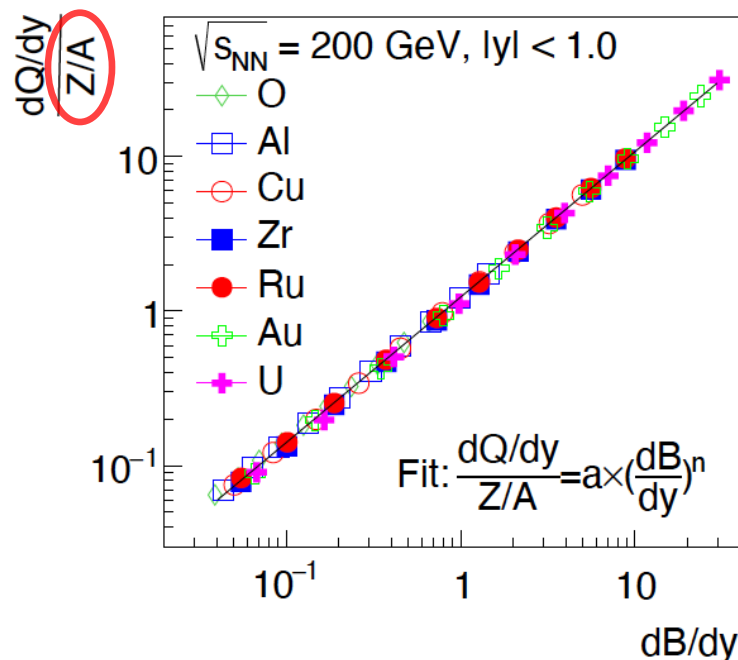
- Net quarks at mid-rapidity are mainly transported from initial nuclei
- Net-charge and net-baryon are **highly correlated**
- $B/Q \sim A/Z$

- Quarks connected to the stopped junction are sea quarks
- Quark flavors in the stopped baryon are **random**
- $B/Q \sim 2$, independent of A/Z



Net-Charges vs. Net-Baryons from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering



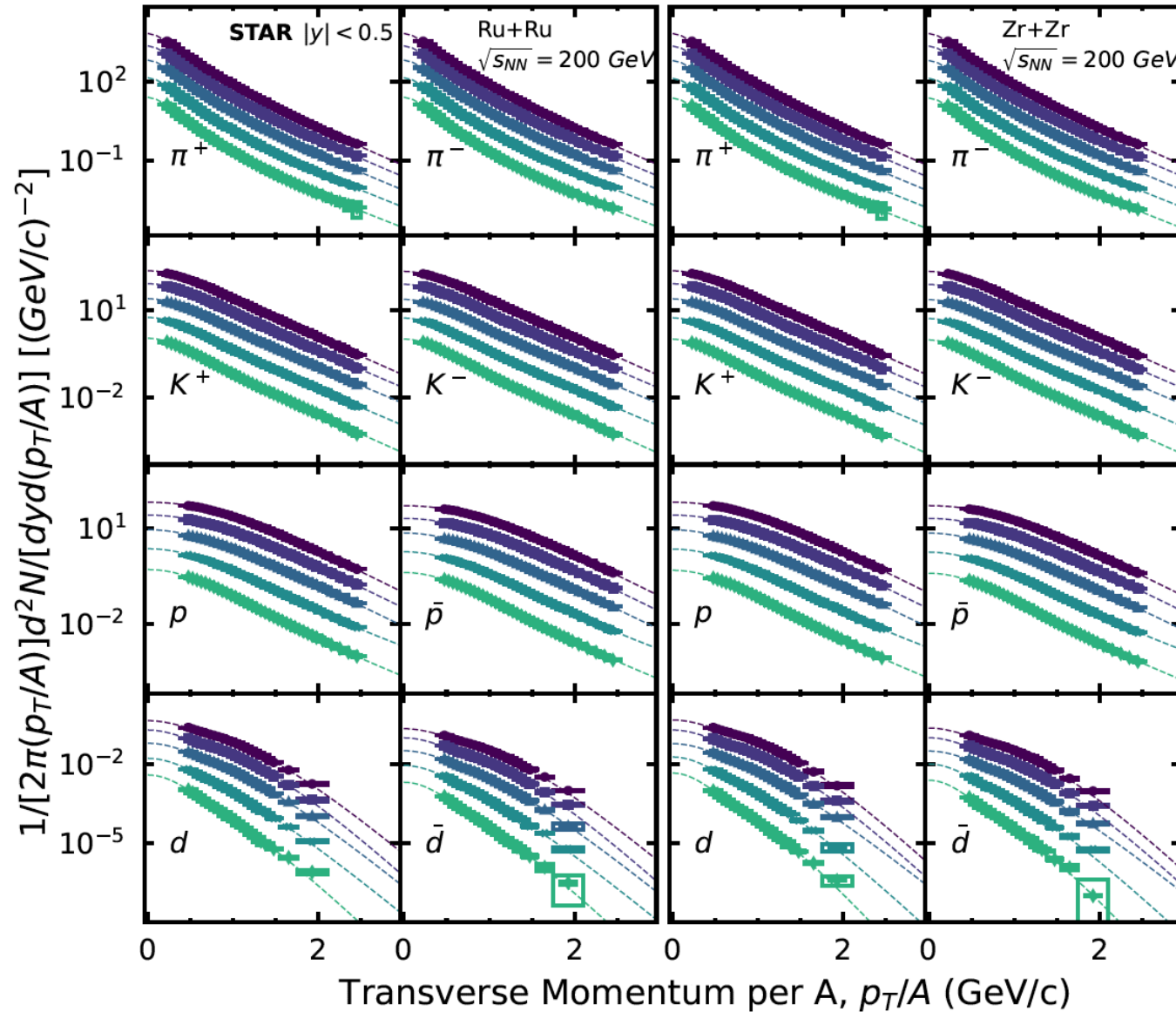
Nucleus	Z	A	Z/A
O	8	16	0.500
Al	13	27	0.481
Cu	29	64	0.453
Zr	40	96	0.417
Ru	44	96	0.458
Au	79	197	0.401
U	92	238	0.386

W. Lv et al., CPC 48, 044001 (2024)

- Net-charges vs. net-baryons scales with Z/A in UrQMD
- Isobar collisions (Ru+Ru vs. Zr+Zr) provide unique experimental opportunities
 - $A=96$ for both nuclei, very similar bulk properties
 - Data taken in the same year, same machine status
 - Z differ by 10%, produces difference in valence quark vs. junction stopping scenarios



Measurements of Charged Hadrons in Ru+Ru/Zr+Zr



Charged hadrons identified in broad p_T range by combining Time Projection Chamber and Time-of-Flight Detector

Blast-wave model used to extrapolate to unmeasured p_T range

Inclusive yields

--- Blast-wave

- 0-10% $\times 2^4$
- 10-20% $\times 2^3$
- 20-40% $\times 2^2$
- 40-60% $\times 2$
- 60-80% $\times 1$



Calculation of Net-Charge Difference

$$Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}}) = (N_{\pi^+} - N_{\pi^-}) + \dots$$

N. Lewis et al., EPJC
84, 590 (2024)

$$\Delta Q = Q^{Ru} - Q^{Zr} = (N_{\pi^+} - N_{\pi^-})^{Ru} - (N_{\pi^+} - N_{\pi^-})^{Zr} + \dots$$

$$(N_{\pi^+} - N_{\pi^-})^{Ru} - (N_{\pi^+} - N_{\pi^-})^{Zr} = 2N_{\pi}^{Ru} \times \left(\frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}} \right)^{Ru} - 2N_{\pi}^{Zr} \times \left(\frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}} \right)^{Zr}$$

$$N_{\pi}^{Ru} \approx N_{\pi}^{Zr}, \quad \frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}} \ll 1$$

$$(N_{\pi^+} - N_{\pi^-})^{Ru} - (N_{\pi^+} - N_{\pi^-})^{Zr} \approx 2N_{\pi} \left(\frac{R_{\pi}^{Ru} - 1}{R_{\pi}^{Ru} + 1} - \frac{R_{\pi}^{Zr} - 1}{R_{\pi}^{Zr} + 1} \right)$$

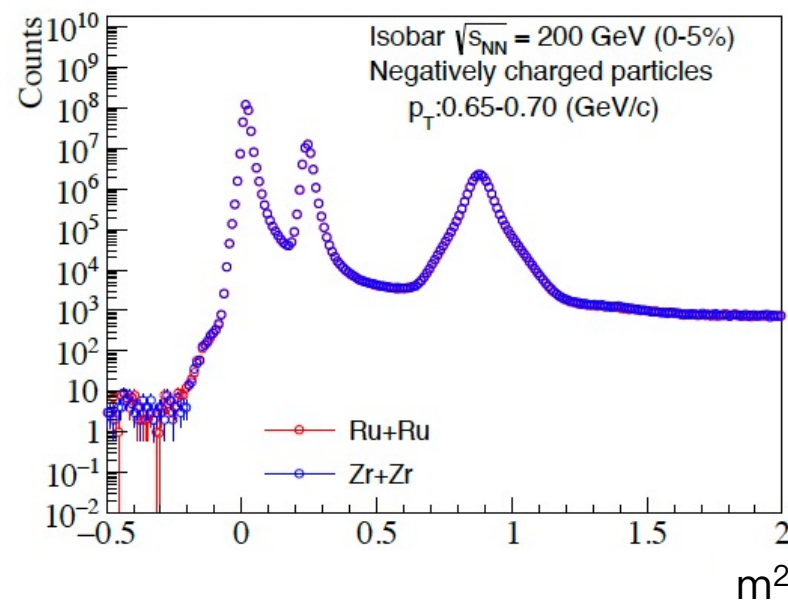
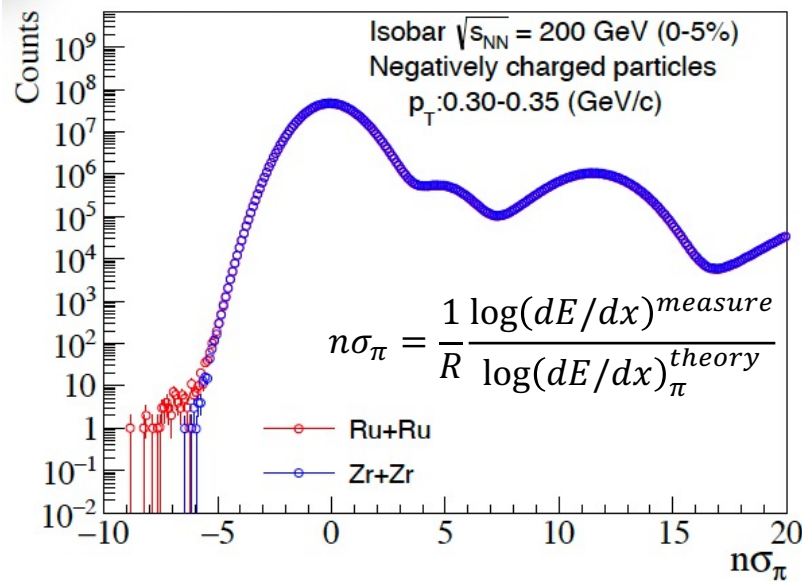
$$= 4N_{\pi} \frac{R_{\pi}^{Ru} - R_{\pi}^{Zr}}{(R_{\pi}^{Ru} + 1)(R_{\pi}^{Zr} + 1)} \approx N_{\pi} (R_{\pi}^{Ru} / R_{\pi}^{Zr} - 1) \quad R_{\pi} = \frac{\pi^+}{\pi^-}$$

$$\Delta Q = Q^{Ru} - Q^{Zr} \approx N_{\pi} (R_{\pi}^{Ru} / R_{\pi}^{Zr} - 1) + N_K (R_K^{Ru} / R_K^{Zr} - 1) + N_p (R_p^{Ru} / R_p^{Zr} - 1)$$

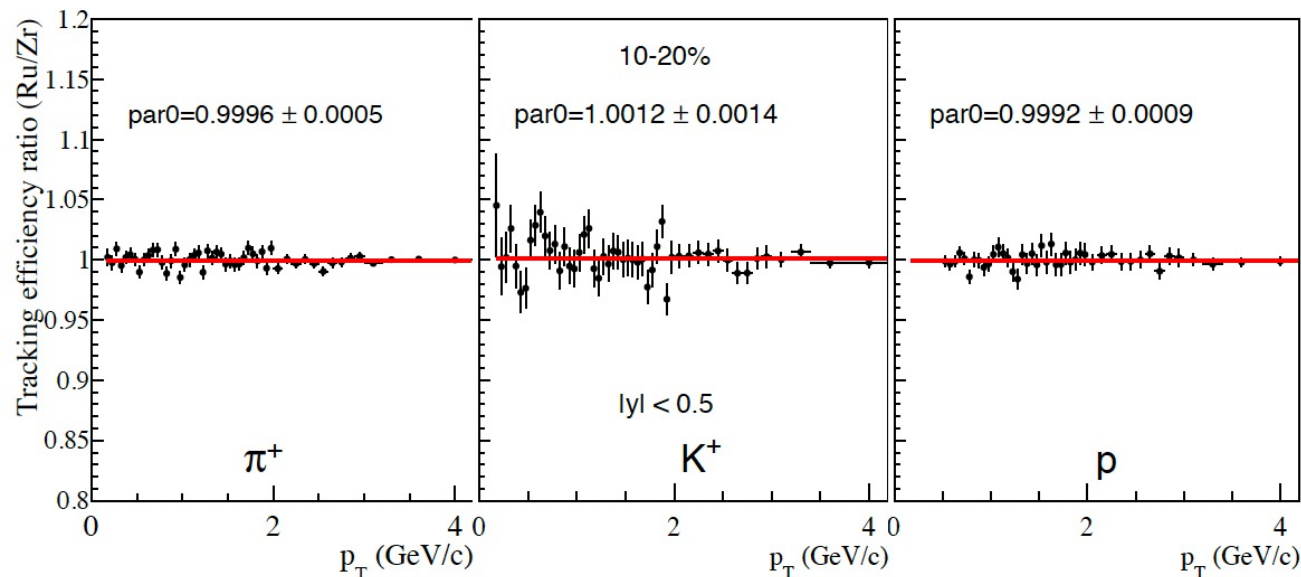
Double ratio method to preserve **high precision** measurements of net-charge difference in isobar collisions



Exactly Same Behaviors in Different Systems

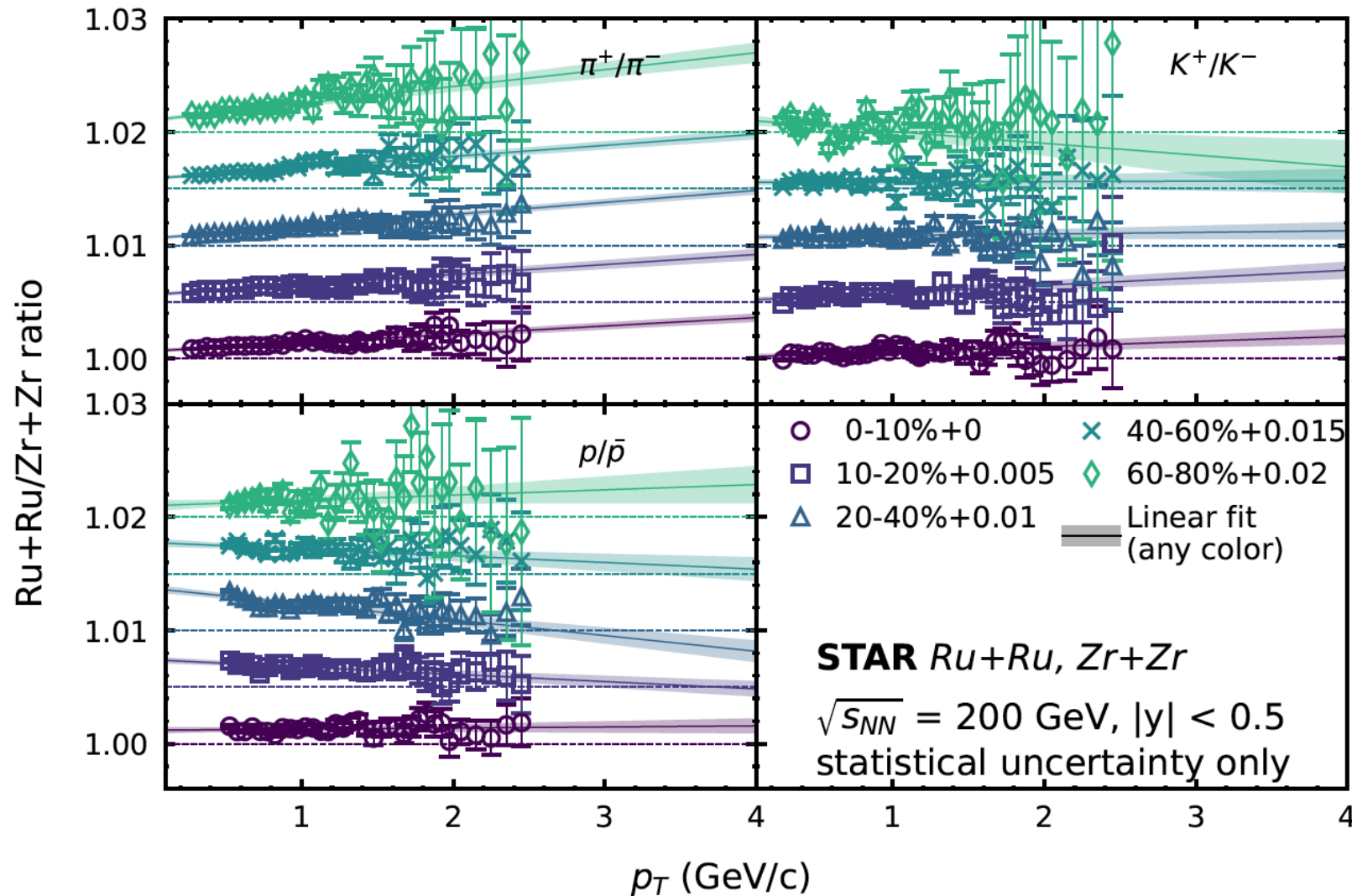


Same distributions of dE/dx and m^2



Same efficiency

Measurement of Double Ratios



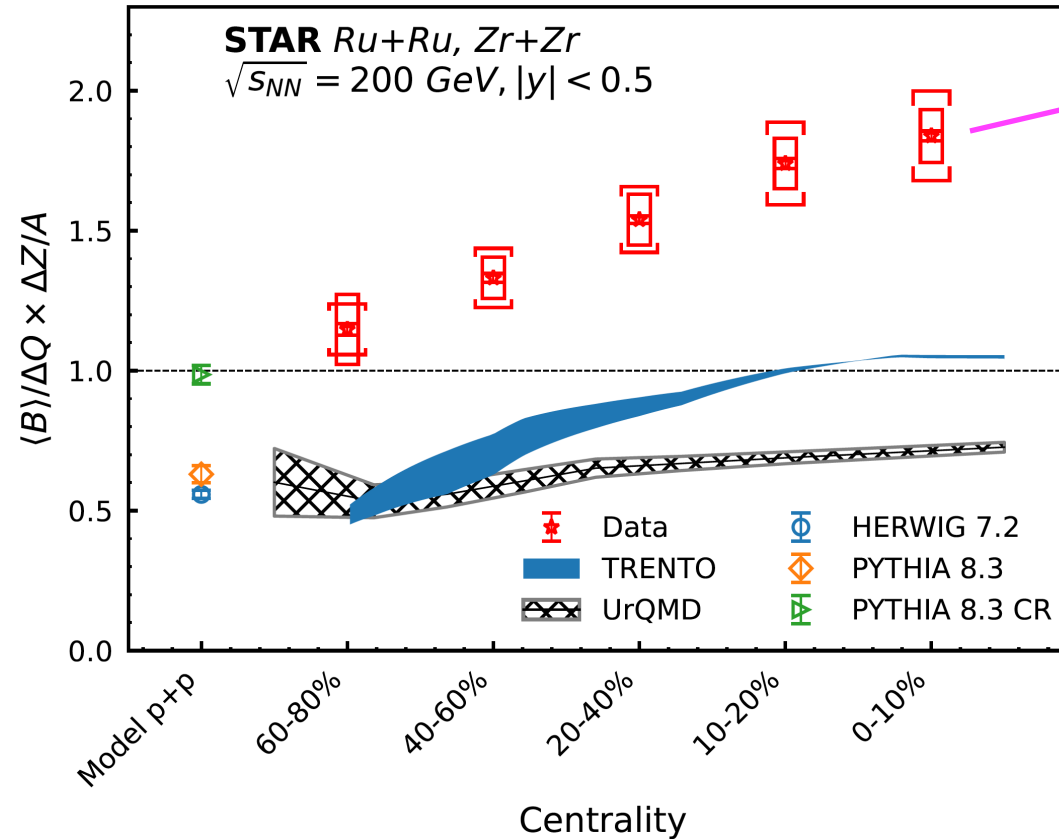
- Precise measurement of double ratios of identified charged particles
- Systematic uncertainties largely cancel out
- The double ratios of both π^+/π^- and $p/\bar{p}$ are larger than 1



Measurement of $B/\Delta Q$ in Ru+Ru/Zr+Zr Collisions

STAR, Science 393,
6812 (2026)

$$\langle B \rangle / \Delta Q \div A / \Delta Z =$$



$1.84 \pm 0.02 \text{ (stat)} \pm 0.09 \text{ (sys)}$
 $\pm 0.16 \text{ (feeddown)}$

HERWIG: J. Bellm et al., EPJC80, 452 (2020)

PYTHIA: C. Bierlich et al., SciPost Phys.
Codebases 8 (2022)

UrQMD: W. Lv, CPC48, 044001 (2024)

Trento: H. Xu et al., PRC 105, L011901
(2022)

- Experimental observation:
More baryon transported to mid-y than charge by a factor of **up to 2**
- Model with valence quark stopping:
Less baryon transported to mid-y than charge

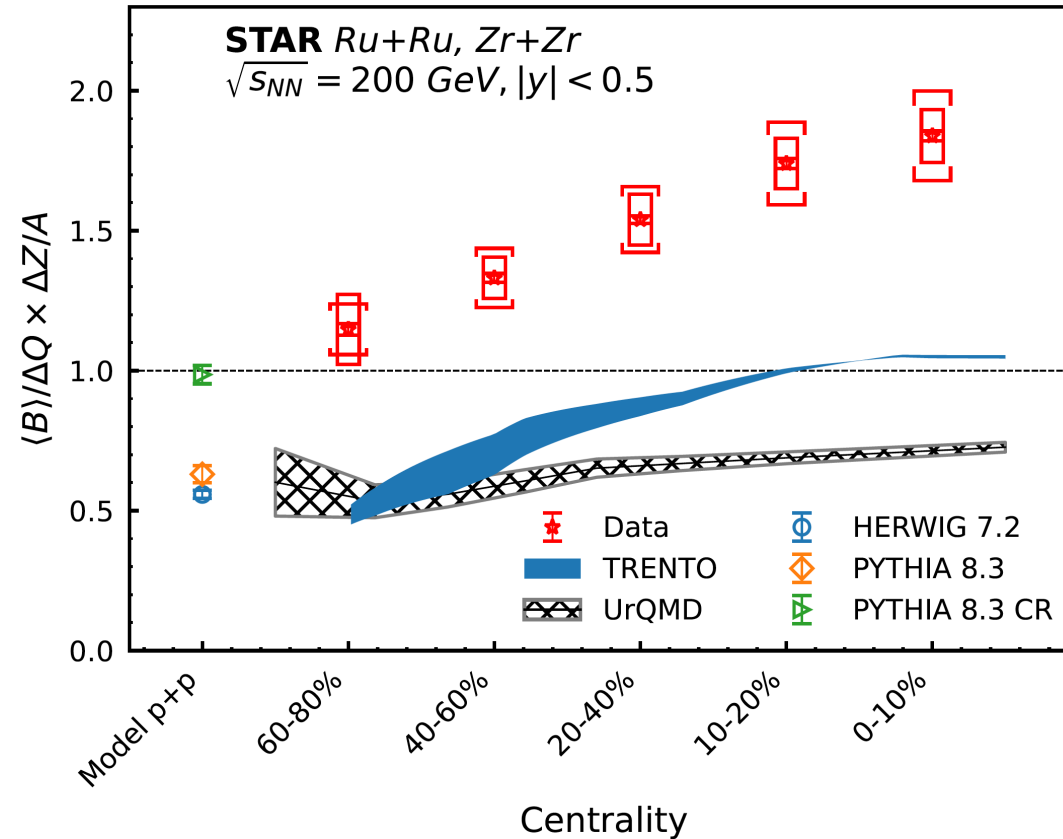


Measurement of $B/\Delta Q$ in Ru+Ru/Zr+Zr Collisions

STAR, arXiv: 2408.15441

Submitted to Science

$$\langle B \rangle / \Delta Q \div A / \Delta Z =$$



HERWIG: J. Bellm et al., EPJC80, 452 (2020)

PYTHIA: C. Bierlich et al., SciPost Phys. Codebases 8 (2022)

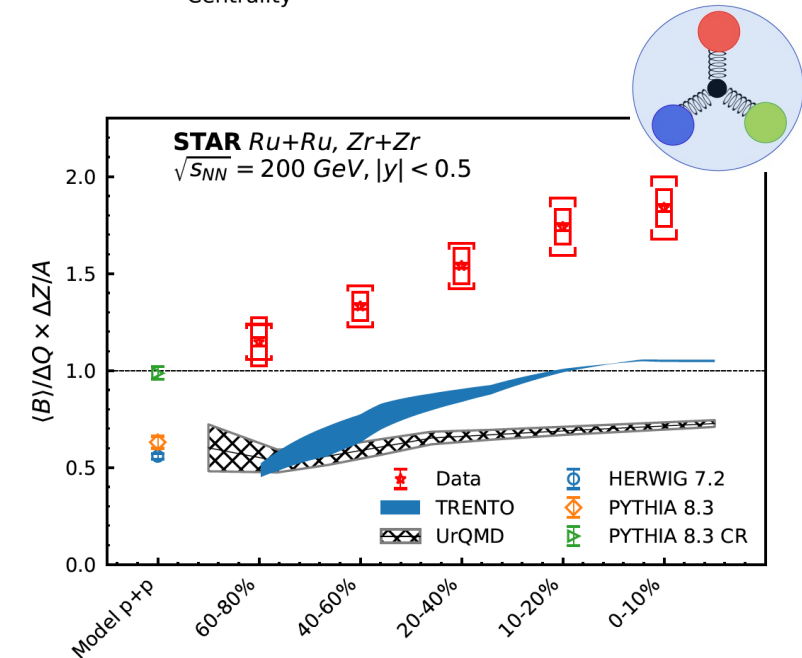
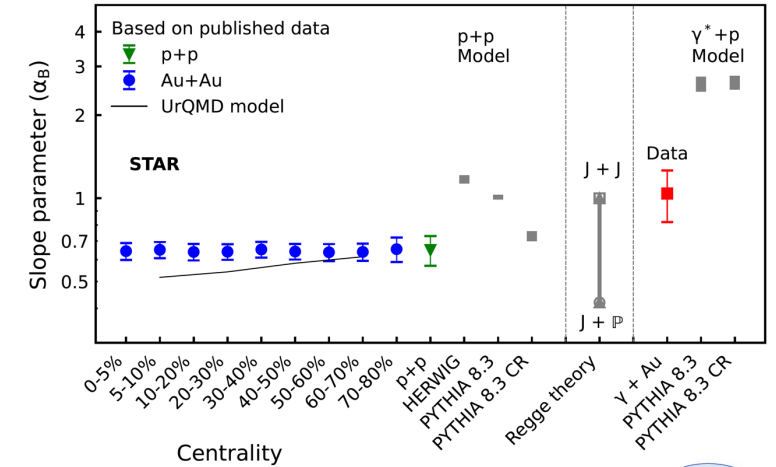
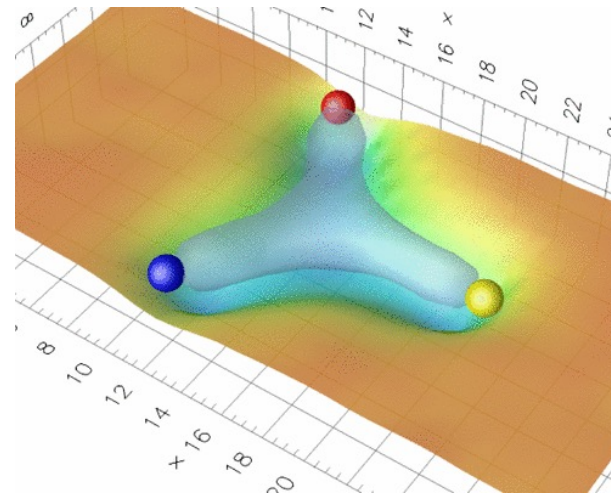
UrQMD: W. Lv, CPC48, 044001 (2024)

Trento: H. Xu et al., PRC 105, L011901 (2022)

- PYTHIA with color reconnection (**partial** implementation of baryon junction) describes better the data than the default PYTHIA
- Scenario of quark stopping is disfavored / **baryon junction is supported**

Summary & Conclusion

- **Three** experiments conducted, all **disfavor** the scenario that baryon transport is due to **quark stopping**
 - Slope of net-proton rapidity loss distribution in Au+Au
 - Slope of net-proton rapidity distribution in γ +Au
 - Net-baryon over net-charge ratio in isobar collisions
- There need **nontrivial object**, i. e. **gluon junction**, inside nucleon to track baryon number
- The picture is **different from** what we learnt from **textbooks**, however consistent with LQCD expectations





Roles of Baryon Junctions

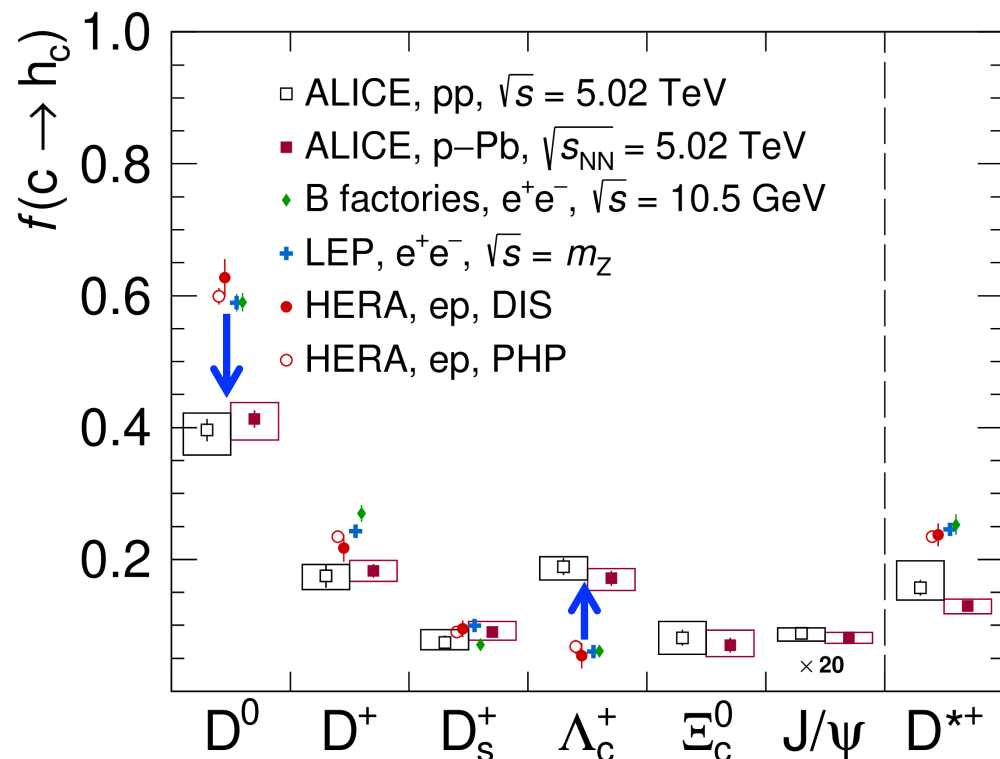
- **Transport baryons** (and energy flow) from colliding baryons in the initial scatterings

← This work

- **Hadronization** in the evolution of the system

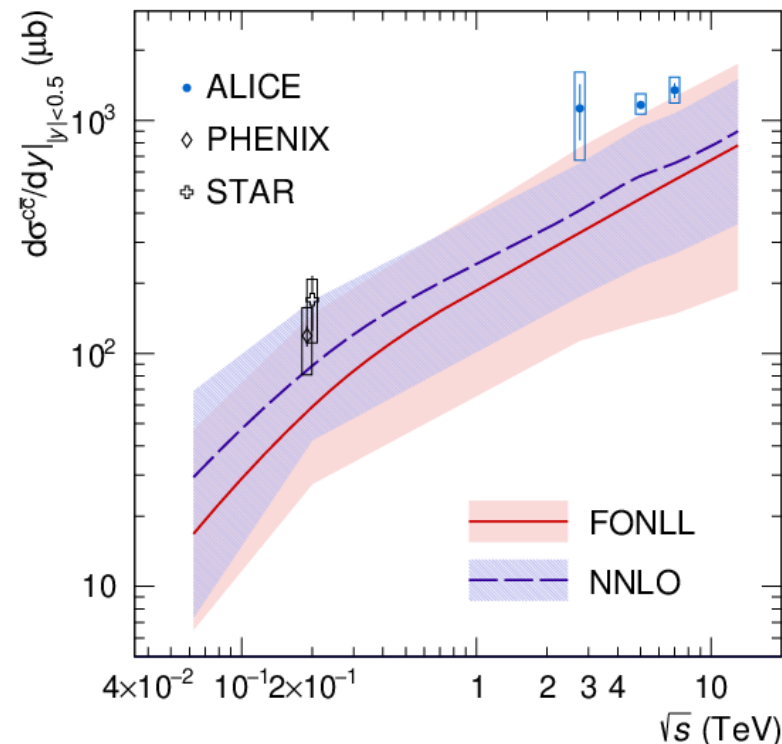
One example is the color reconnection in PYTHIA

Enhancement of Charmed Baryon in Small System



ALI-PUB-570972

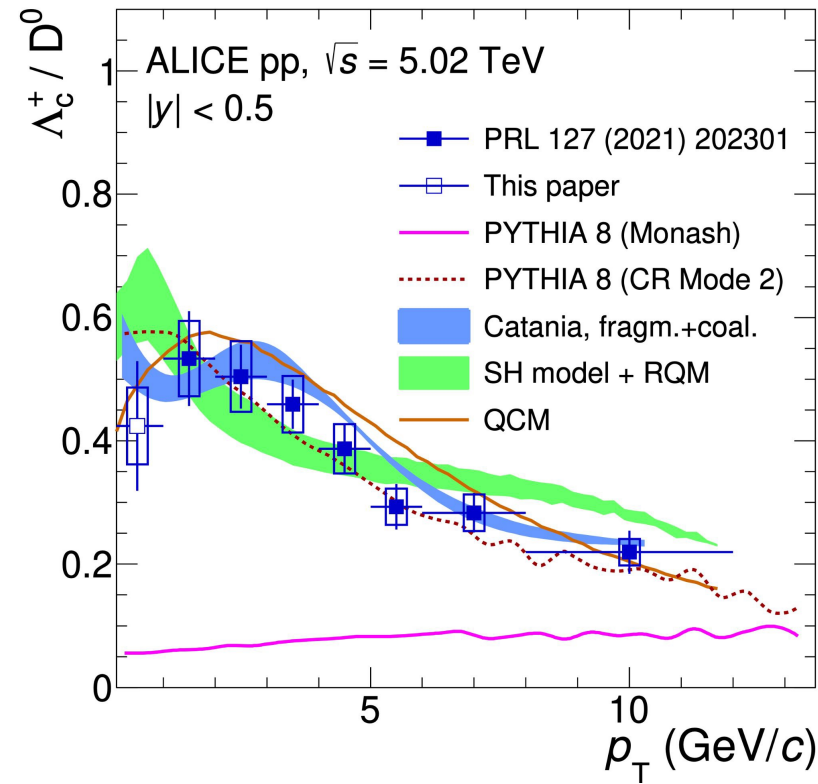
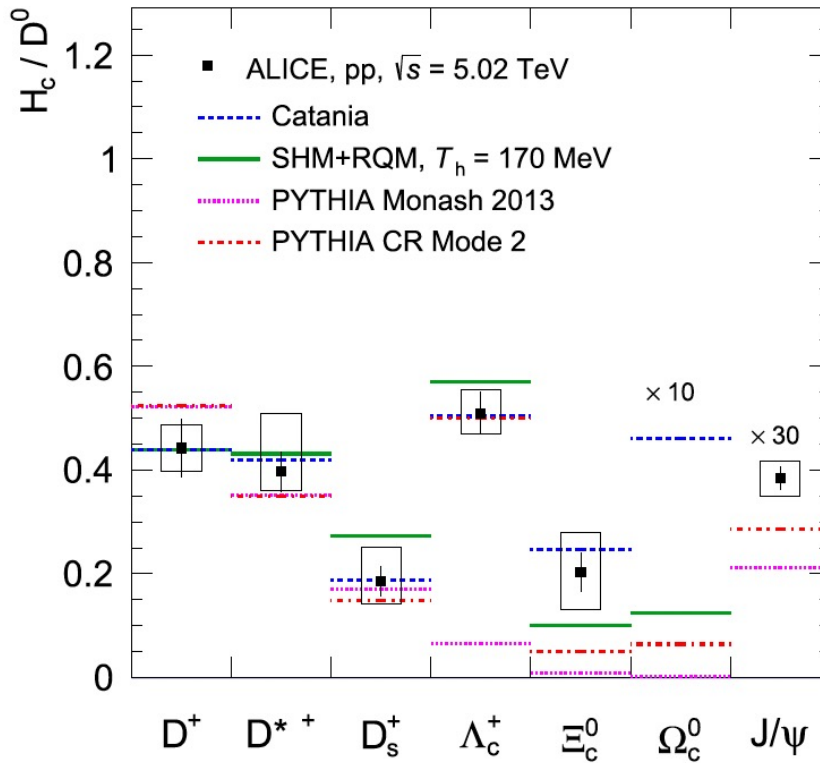
ALICE, EPJC 84,12 (2024)
ALICE, PRD 105, L011103 (2022)



ALI-PUB-500755

- Charmed hadron production different in pp/pA and ee
 - Suppression of mesons and enhancement of baryons
- Total cross-section consistent with FONLL
- Redistribution of charm quarks among hadrons

Comparison with Models



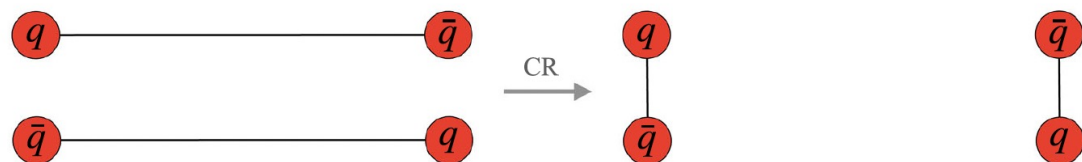
J. Altmann, A. Dubla, V. Greco et al., EPJC 85, 16 (2025)

Models with **coalescence** or statistical hadronization can describe the data

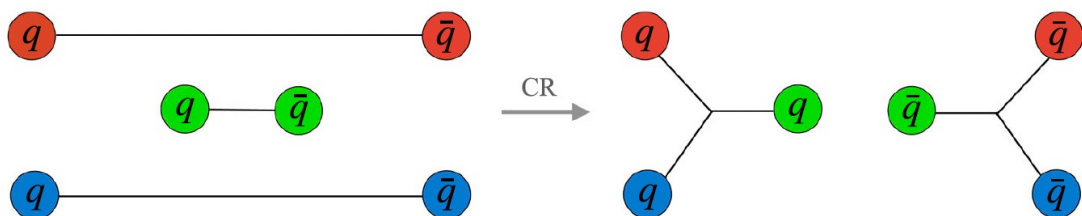
VS.

PYTHIA with color reconnection can describe the enhancement of charmed baryons

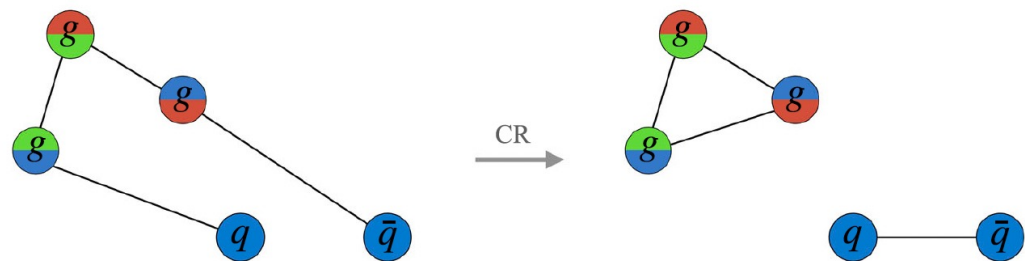
Hadronization in PYTHIA with Color Reconnection



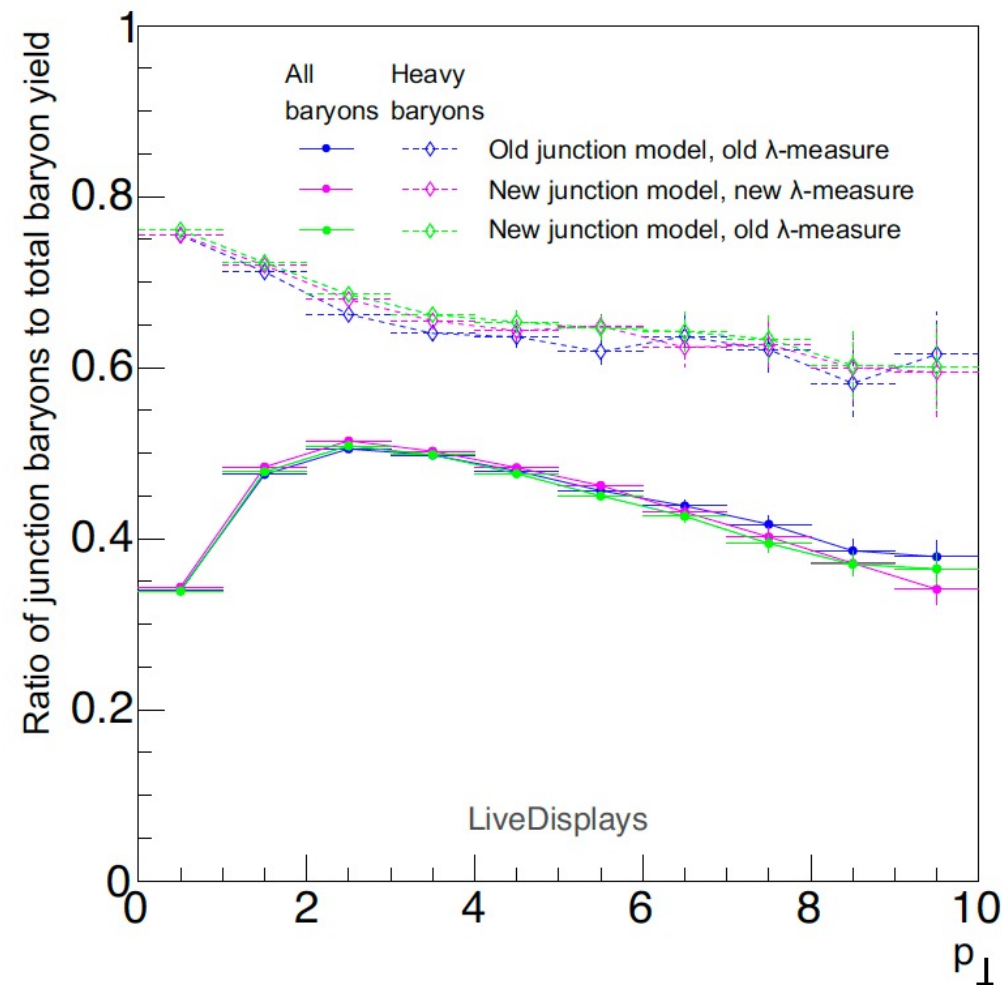
(a) Dipole-type reconnection.



(b) Junction reconnection.



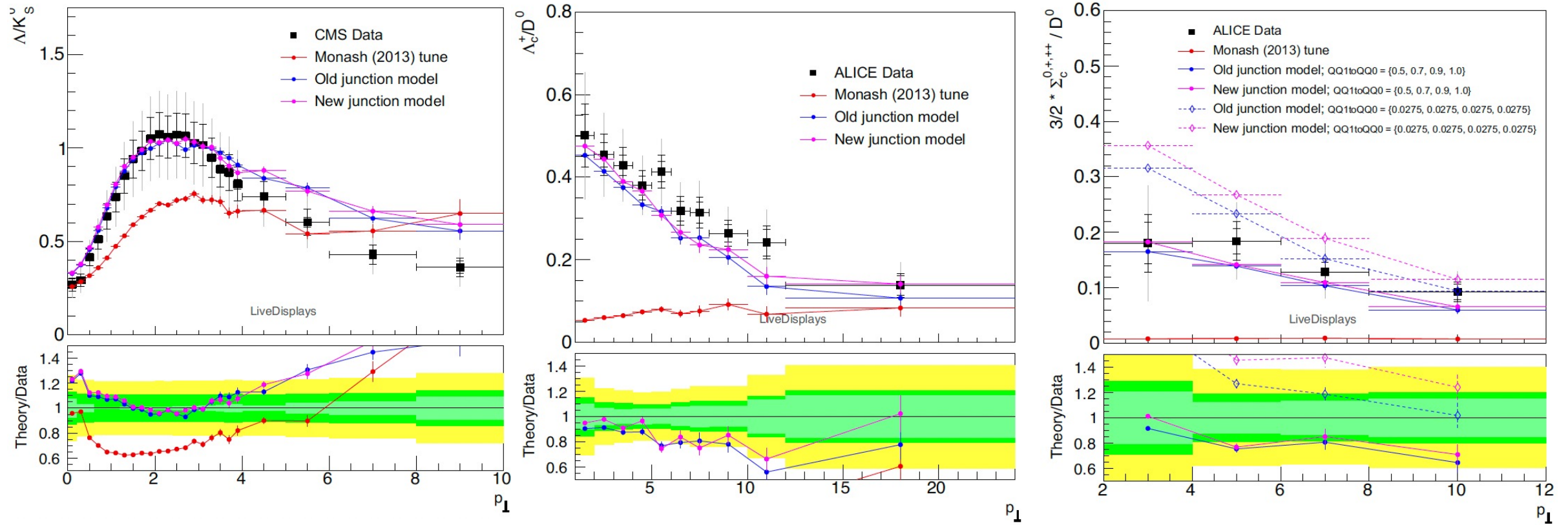
(c) Gluon-loop formation.



J. Altmann and P. Skands, JHEP07, 238 (2024)

String (baryon) junctions play an important role in baryon production

Baryon Production in PYTHIA



Strange and charm baryon-to-meson ratios described by junction in PYTHIA



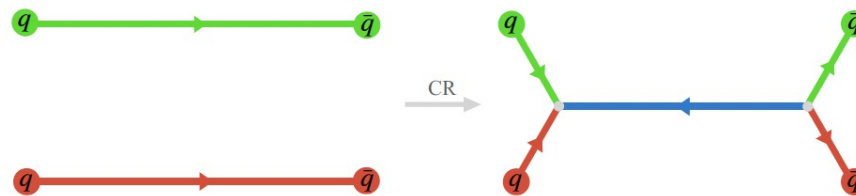
Impact of Baryon Junction

It changes our view of the internal structure of nucleon

Question the application of collinear factorization for particle production, especially baryon production in high energy collisions

Hadronization mechanism

- Plays import role in probing QGP properties from experiments
 - Heavy flavor hadron production
 - QCD critical end point search with net-proton number higher moments
 - ...
- Exotic hadrons
- ...



J. Altmann, A. Dubla, V. Greco et al., EPJC85, 16 (2025)

Thank you, teachers!!!