

高能与低能核物理交叉学术研讨会

重子输运与重子结实验探索

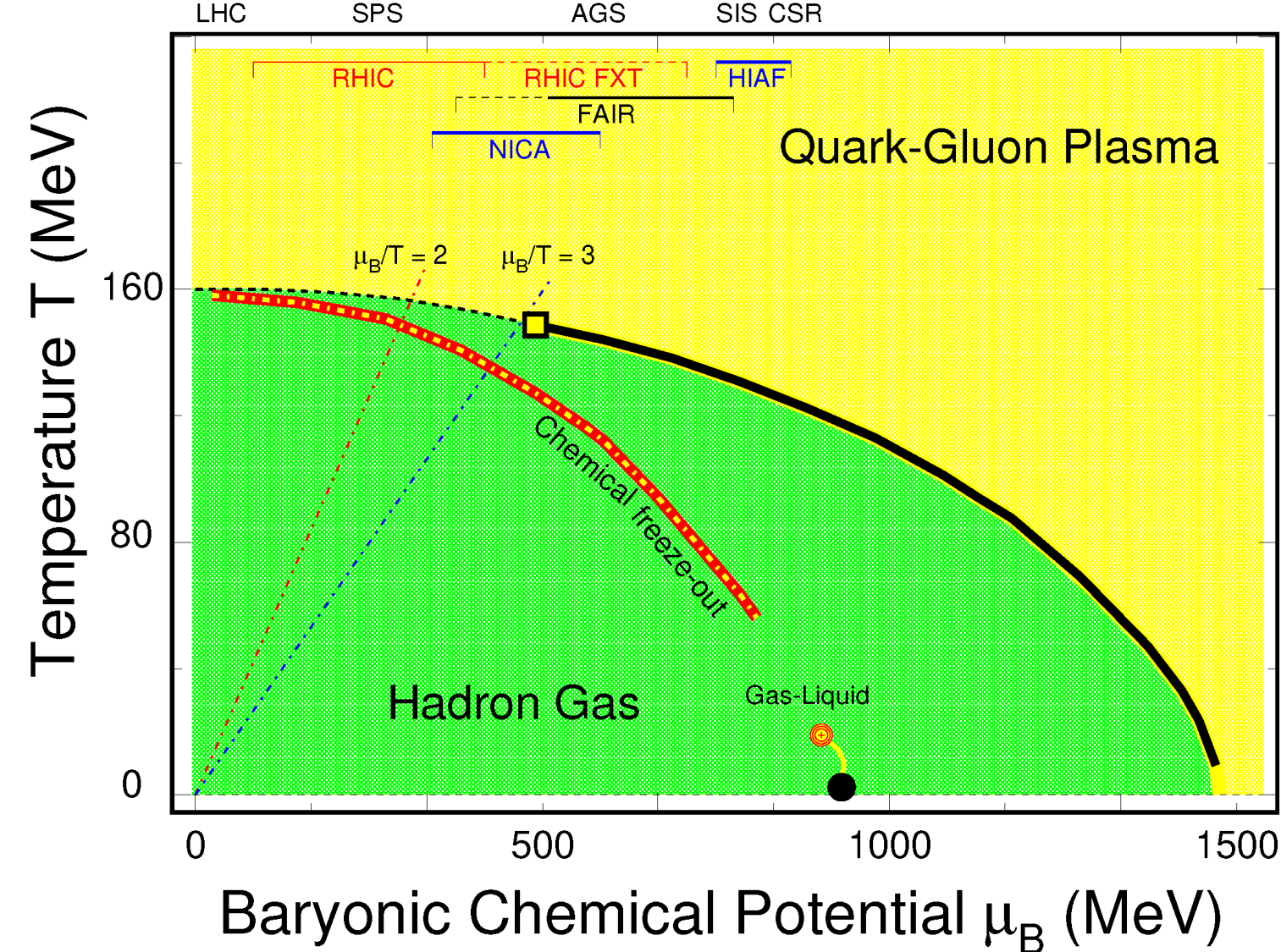
STAR, arXiv:2408.15441,
submitted to *Science*



Yang Li, PhD thesis, USTC (2023)



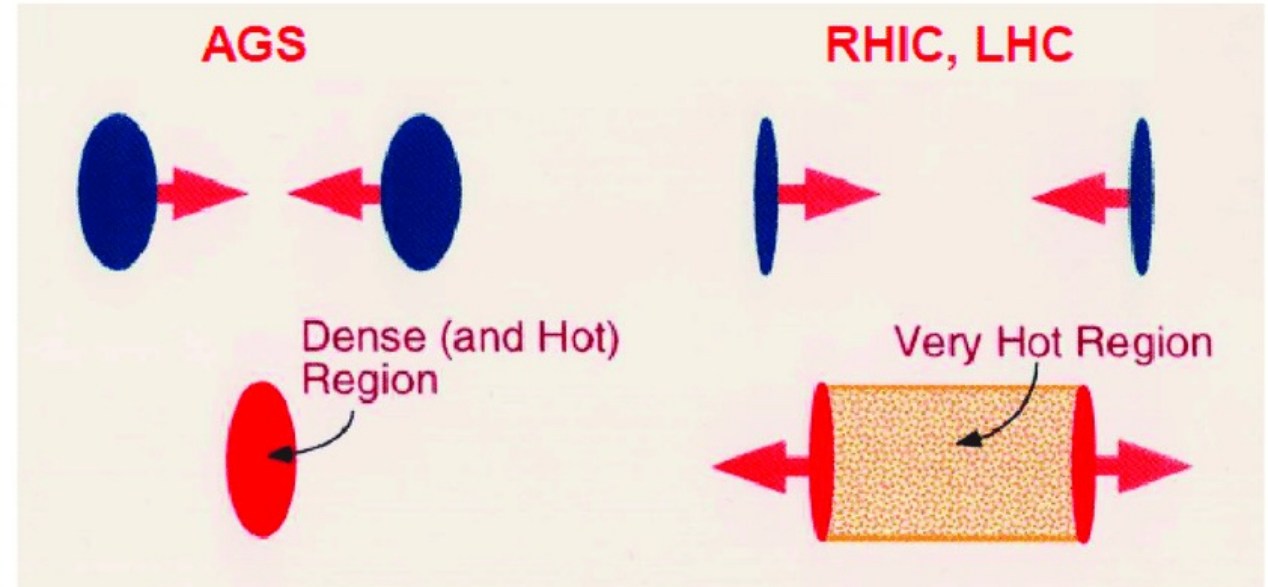
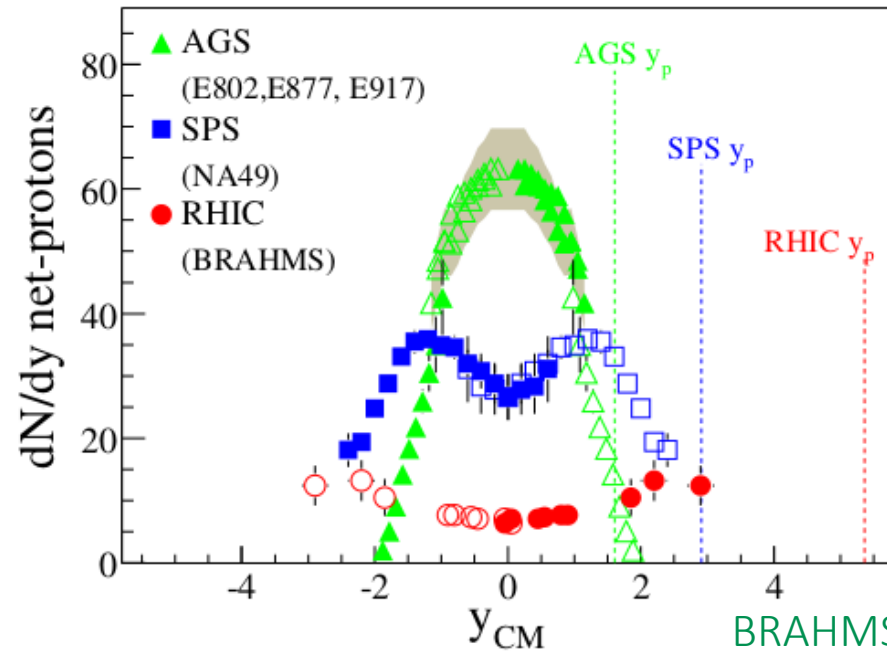
QCD Phase Diagram



“NuXu plot”-2

The baryonic chemical potential in heavy ion collisions determined by “Baryon Stopping” or “Baryon Transport”

Baryon Transport in Heavy Ion Collisions



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

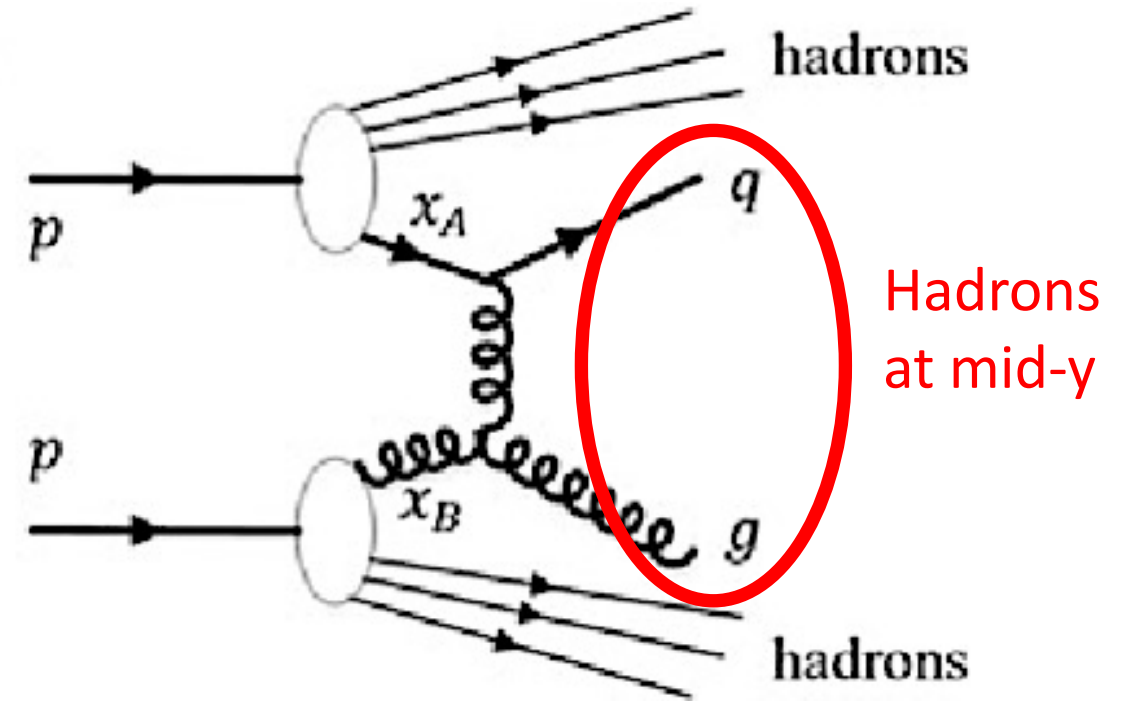
RHIC (Au+Au @ $\sqrt{s_{NN}}=200$ GeV):

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

Baryon Transport in High Energy Heavy Ion Collisions

Baryon numbers are strictly conserved

- The baryons have to come from the colliding nucleus
- The **baryon transport** reflects:
 - The constituent content (**internal structure**) of nucleons
 - The first interactions of the constituents of colliding nucleons
- Insensitive to subsequential processes such as quark-gluon plasma formation



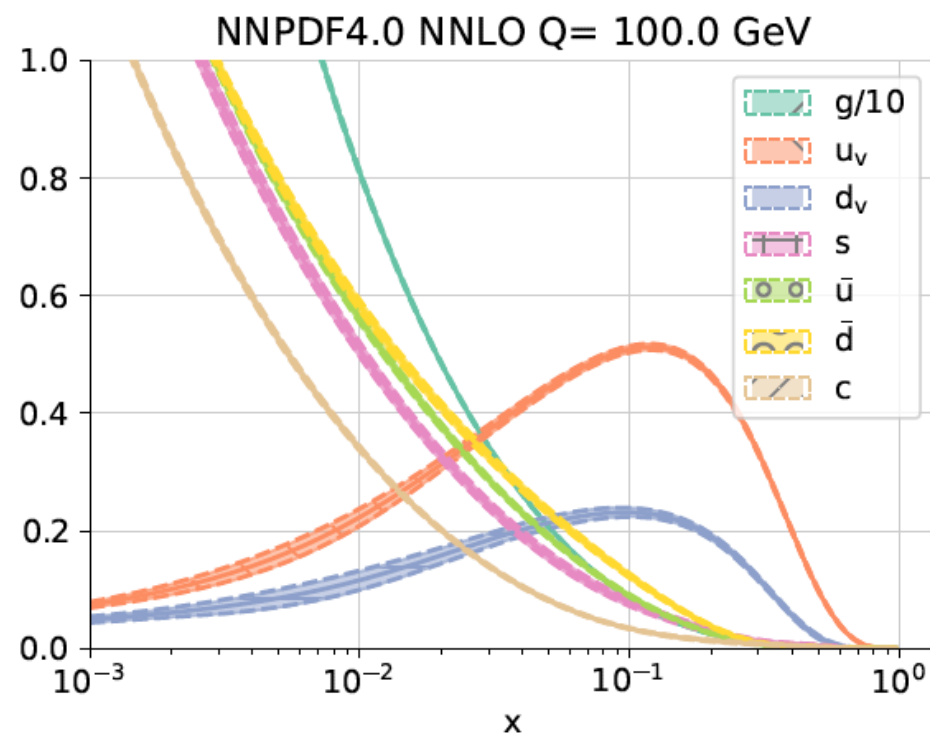
QCD factorization theorem:

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

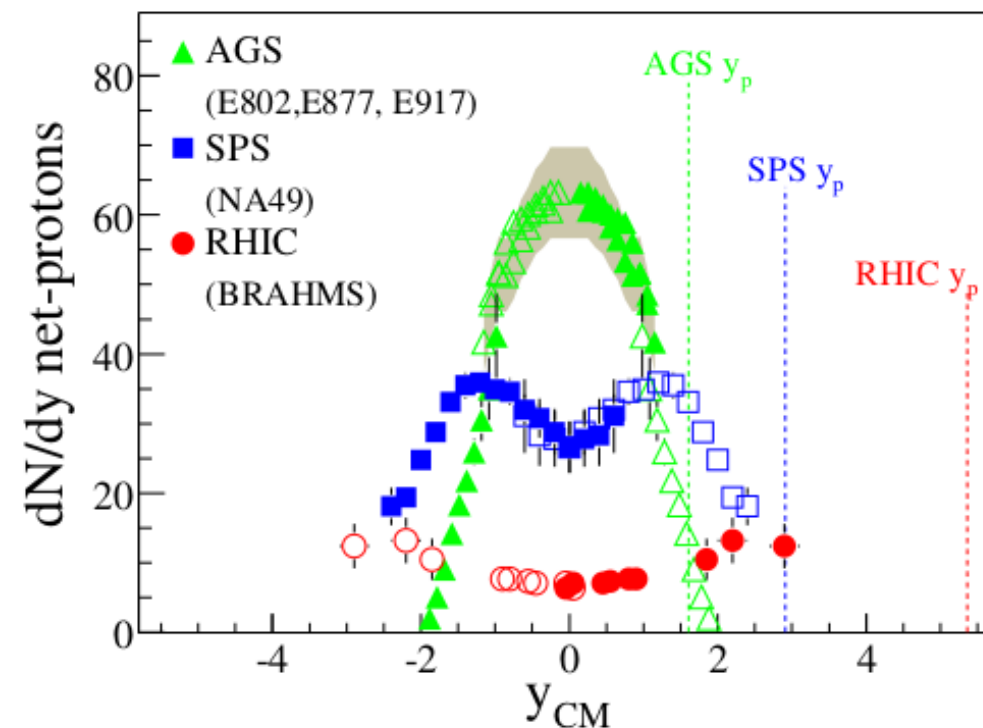
Baryon Transport at High Energy

Sea quarks and gluons are expected to have no contribution

Only valence quarks play a role



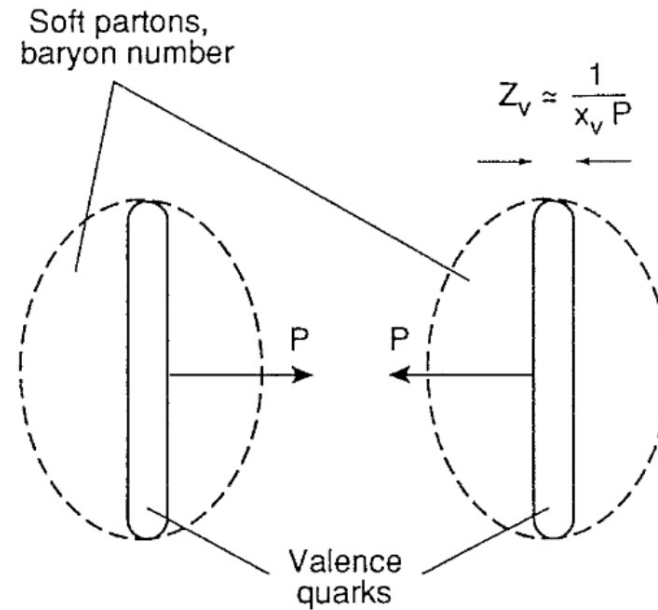
PDG, PRD 110, 030001 (2024)



BRAHMS, PRL93, 102301 (2004) and references therein

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

Difficulty to Explain Large Rapidity Loss

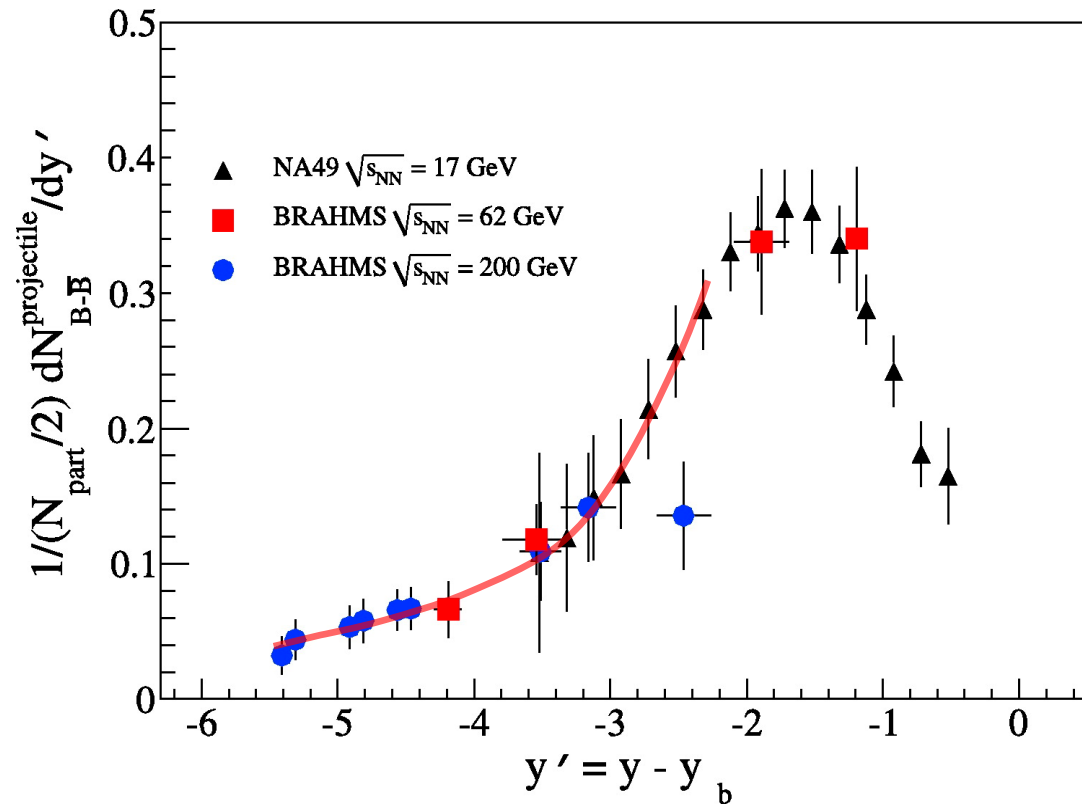


D. Kharzeev, PLB378, 238 (1996)

- Valence quarks typically have **large x**
- They have **short time** to interact due to Lorentz contraction
- It is **difficult** to have large rapidity loss thus be observed at mid-rapidity



Quantifying Baryon Number Transport



BRAHMS, PLB677, 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

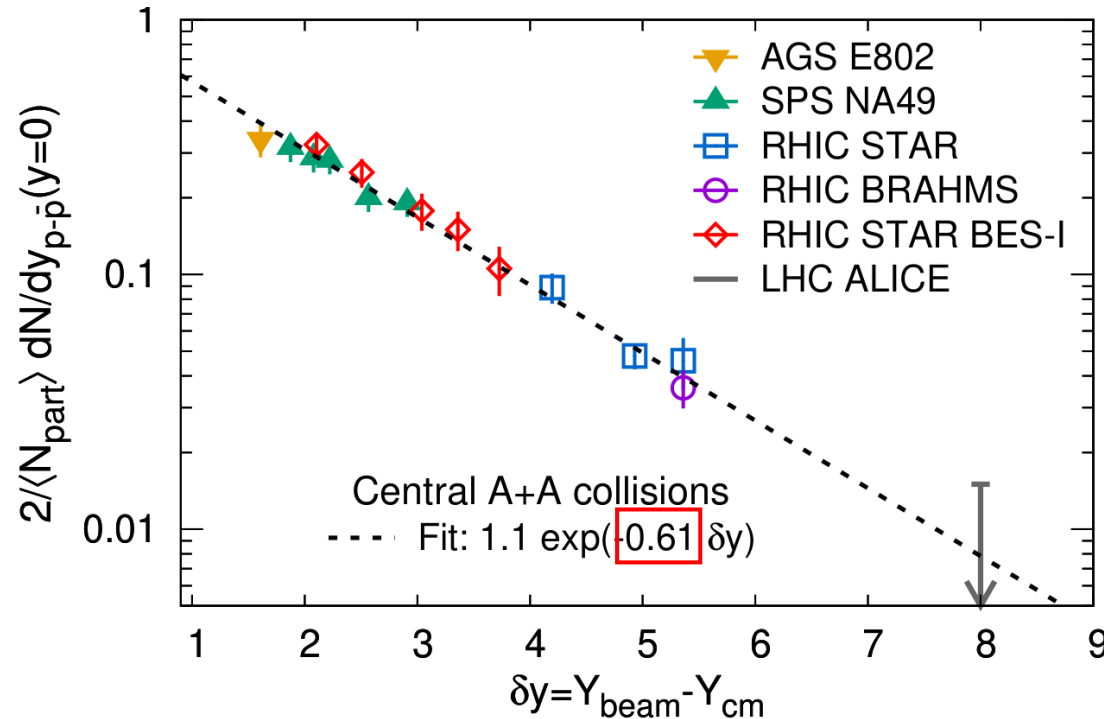
- The experiment need to cover a very large rapidity, especially at higher energy
- The subtraction of the contribution from the target is model dependent, introducing large systematic uncertainty

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



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

Nicole Lewis et al., EPJC84, 590 (2024)

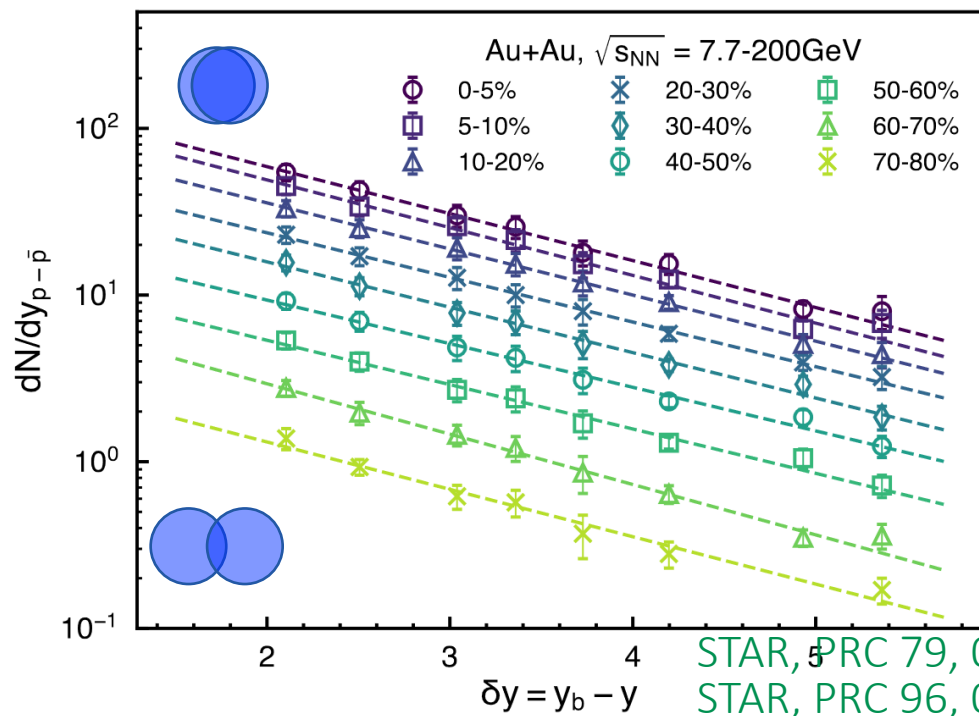
Net-proton yield at $y \sim 0$ scales nicely with exponential function of rapidity loss

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

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

Multiple scattering was proposed to explain large rapidity loss

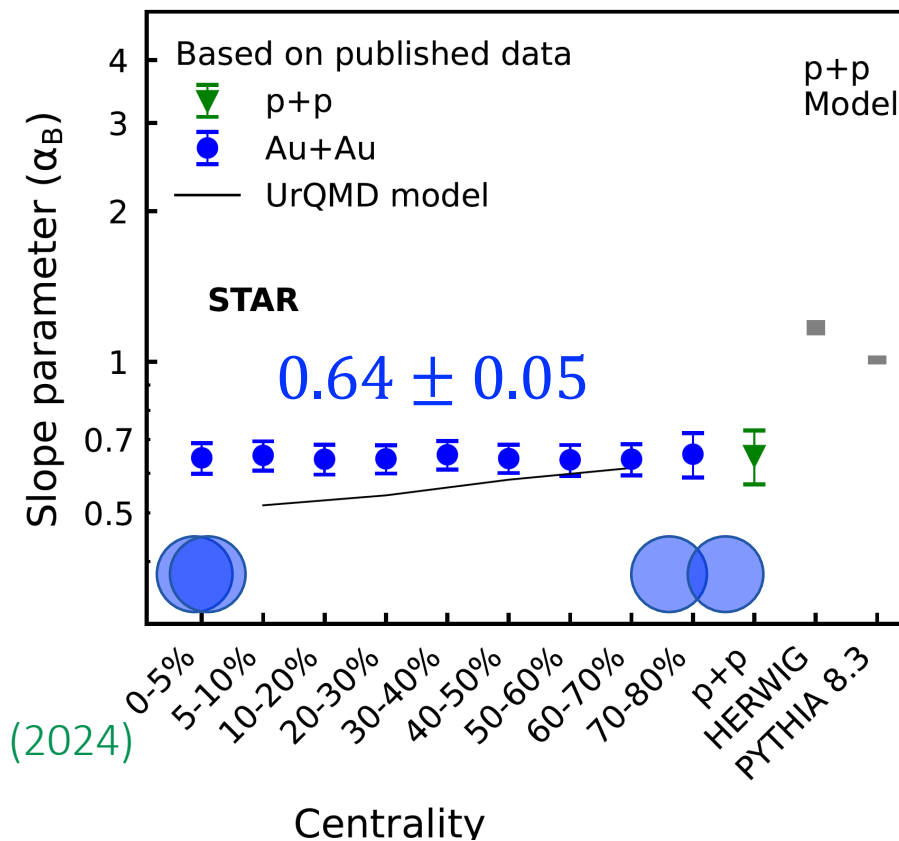
Centrality Dependence of the Slope



STAR, PRC 79, 034909 (2009)

STAR, PRC 96, 044904 (2017)

Nicole Lewis et al., EPJC84, 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 directly traced by valence quarks

Alternative Picture

Sea quarks and **gluons** are expected to have no contribution

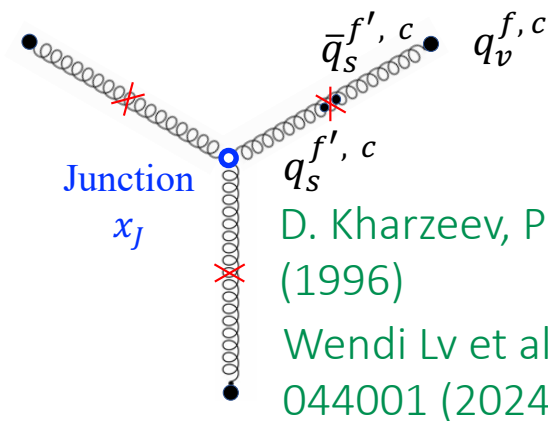
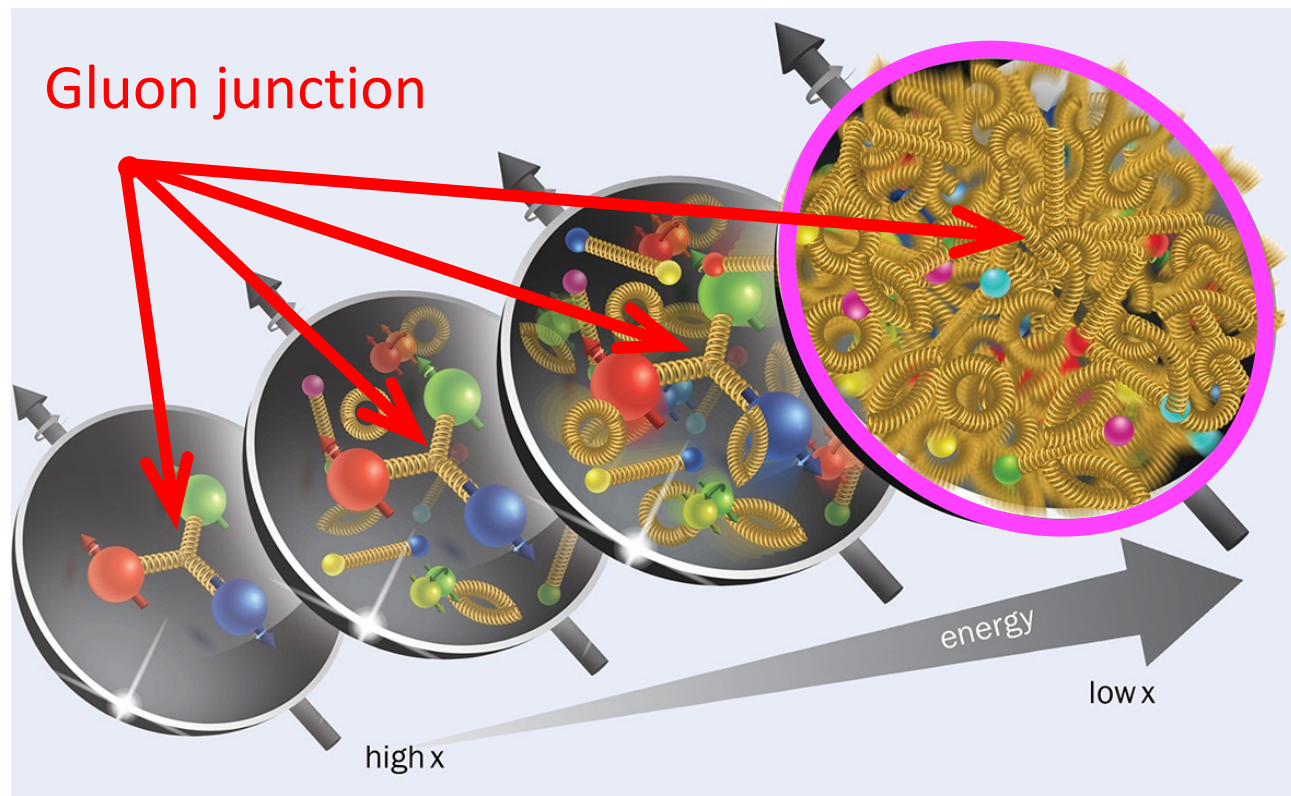
Only valence quarks play a role

???

A special configuration of gluons, **gluon junction** for instance, may carry/trace baryon number

X. Artru, NPB85, 442 (1975)

G. Rossi and G. Veneziano, NPB123, 507 (1977)

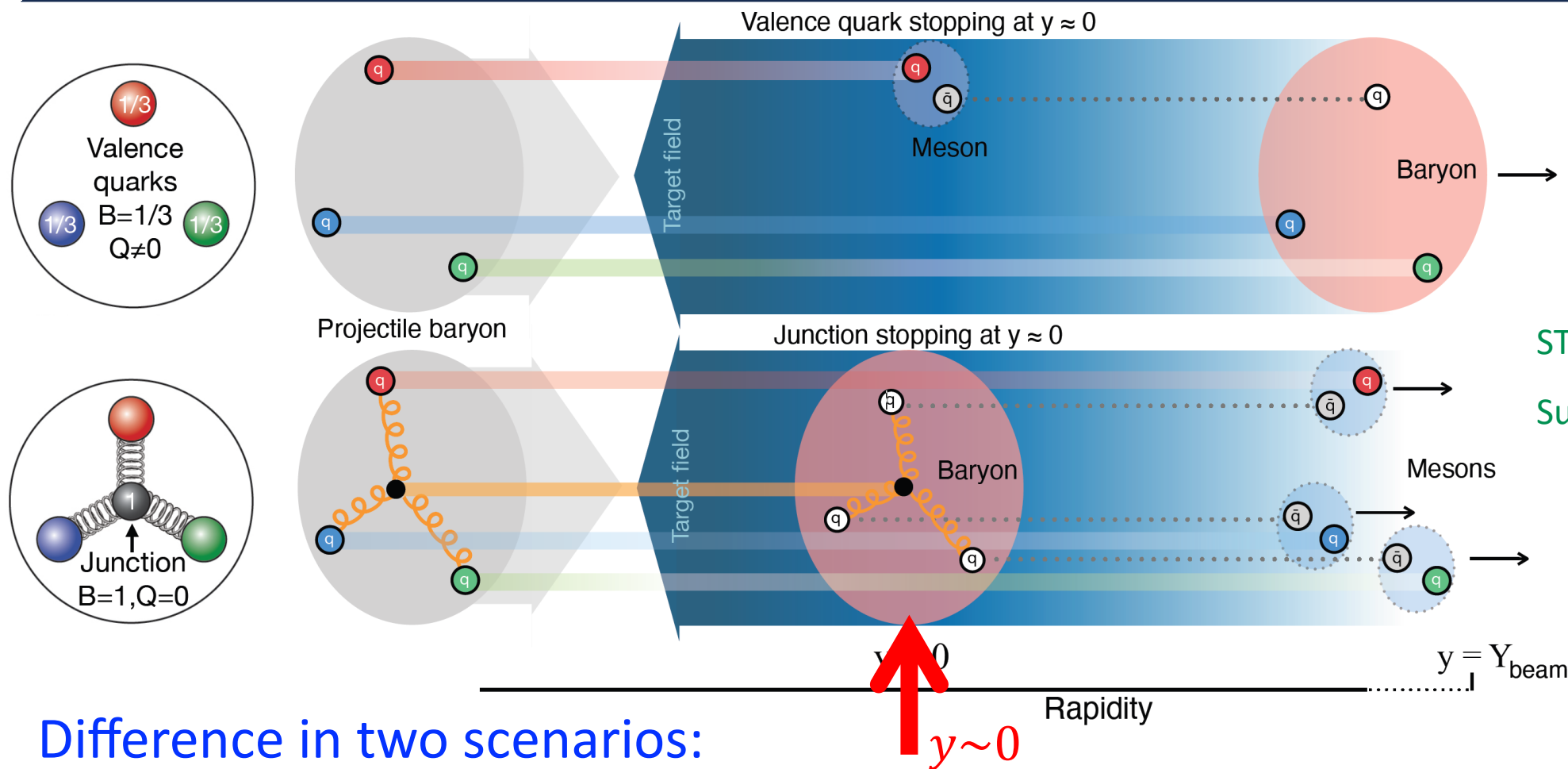


D. Kharzeev, PLB378, 238 (1996)

Wendi Lv et al., CPC48, 044001 (2024)

- Junctions are soft, have **enough time** to interact and **easier be stopped** at mid-y
- Stopped junction will be dressed up by **sea quarks** and form baryons

How to Test: Collision = Pull out from the Nucleus



STAR, arXiv: 2408.15441

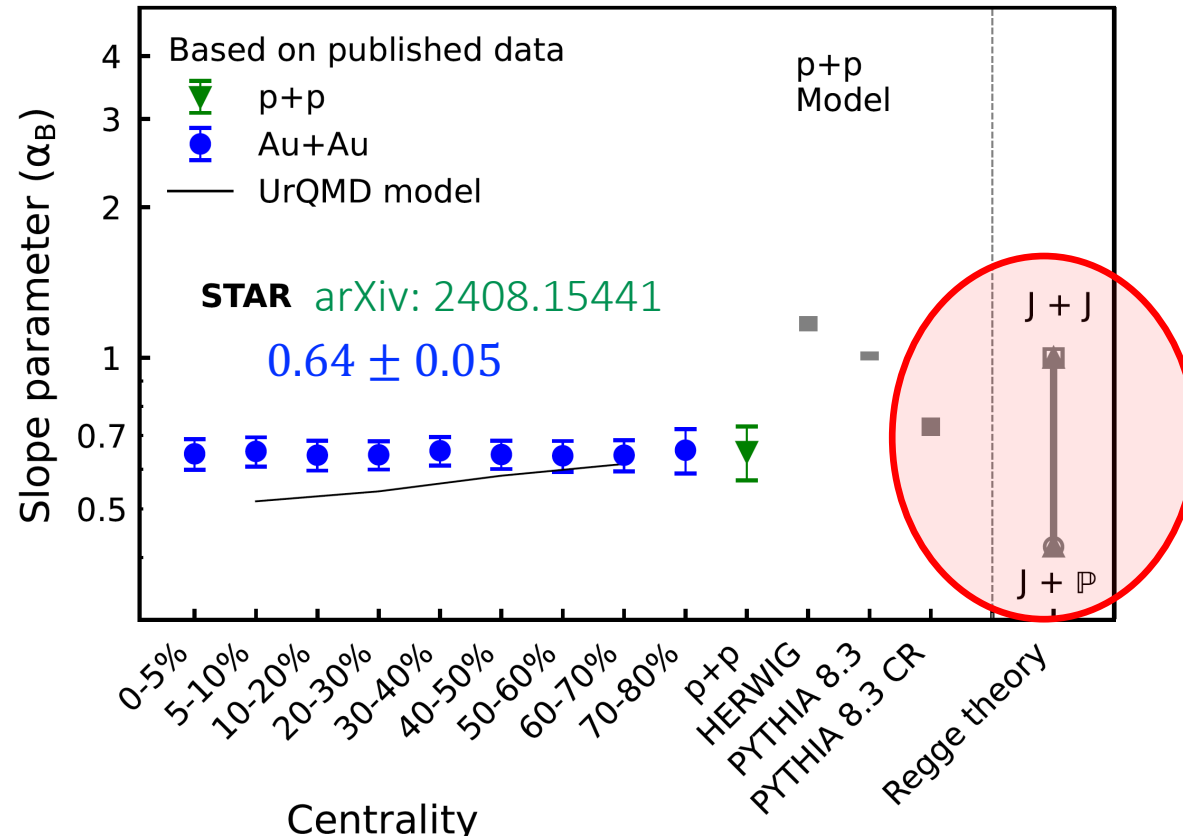
Submitted to Science

Difference in two scenarios:

- Rapidity loss of baryons
- Quark flavor composition of stopped baryons at mid-rapidity



Comparison of Rapidity Loss Slope with Theories



Junction + Junction

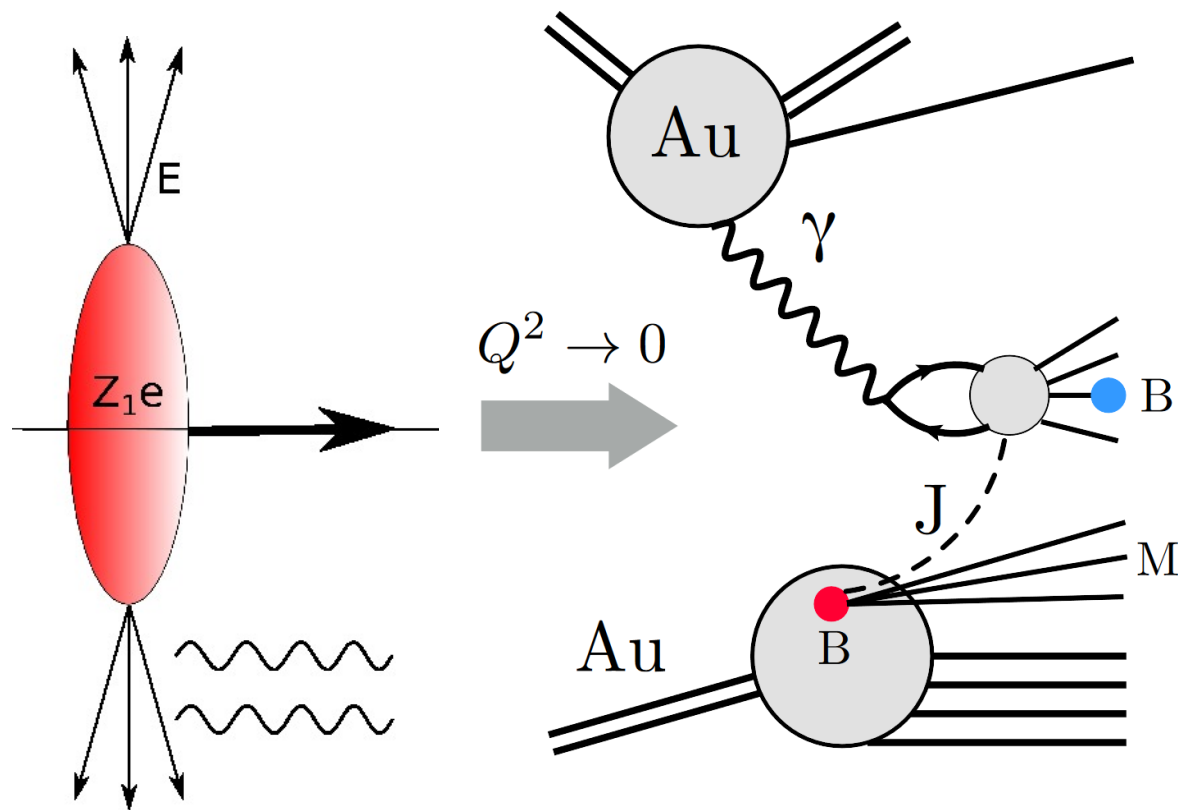
Junction + Pomeron

D. Kharzeev, PLB378, 238 (1996)

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

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

Baryon Transport in γ +A Collisions

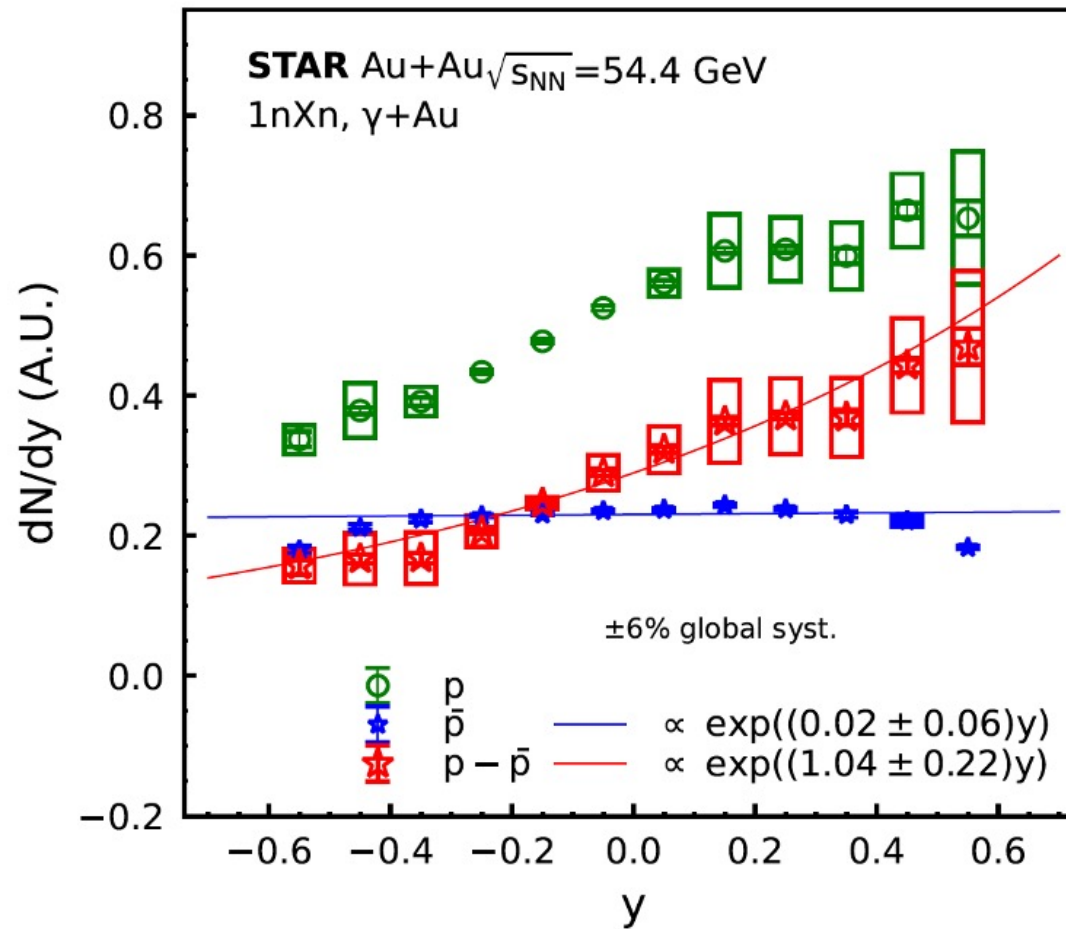


- Strong electromagnetic field accompanies the nuclei in relativistic heavy-ion collisions
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux
- Photon fluctuates into a quark pair and interact with the nucleus target
- Baryon transported from only **one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

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



Slope Parameter in γ +A Collisions



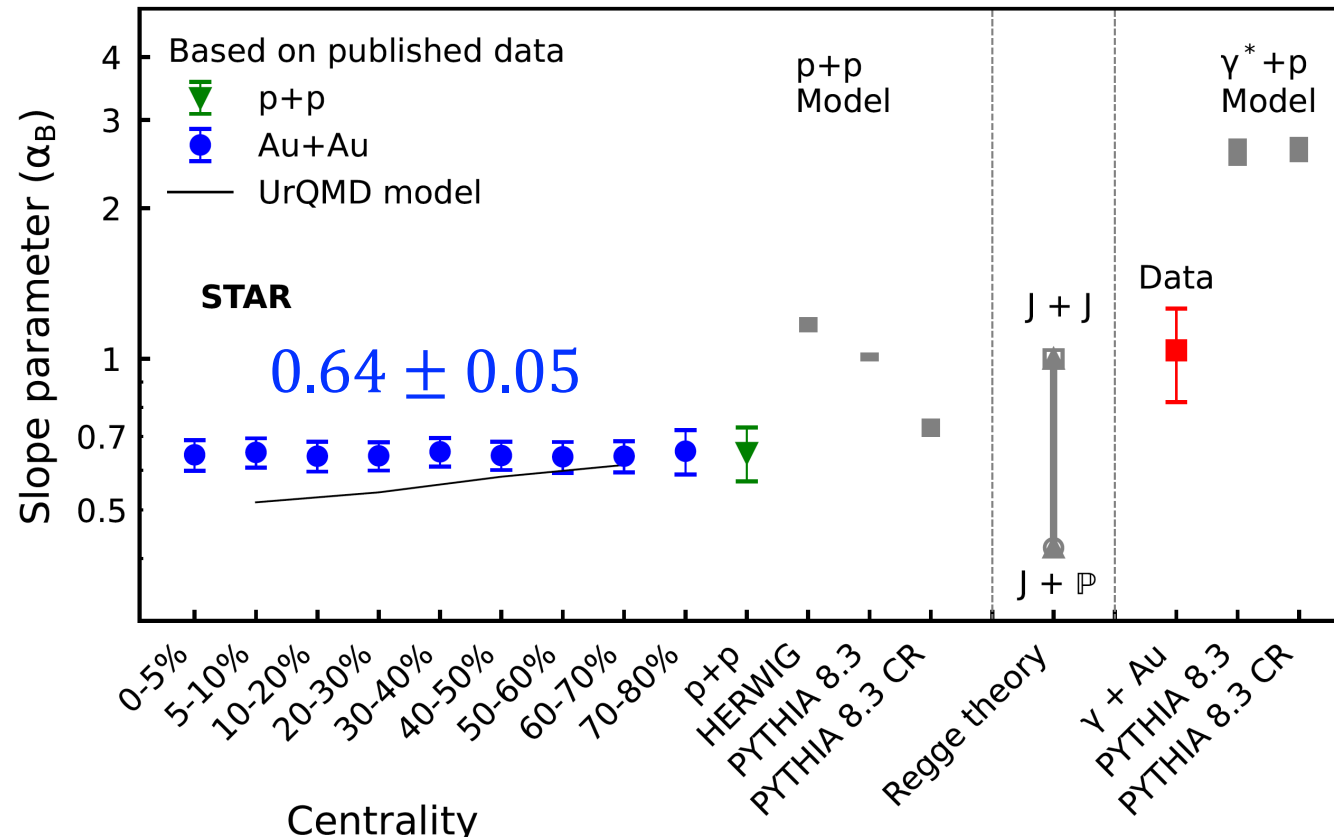
STAR, arXiv: 2408.15441

Submitted to **Science**

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



Slope Parameter in γ +A Collisions

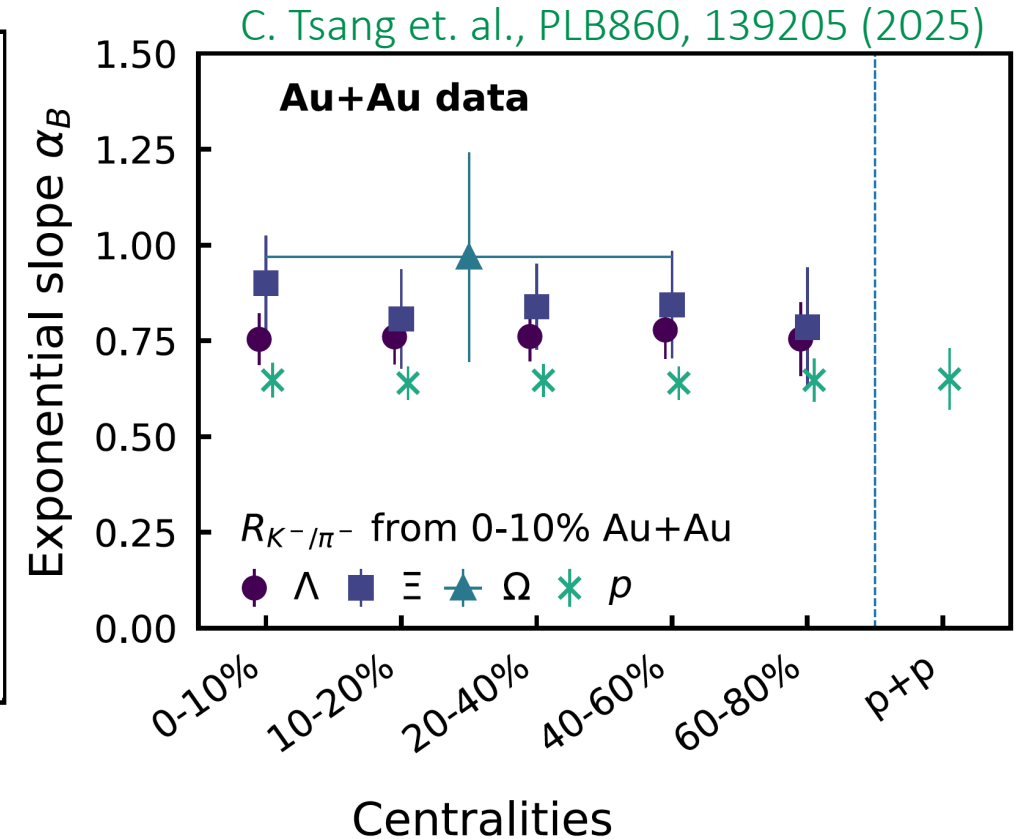
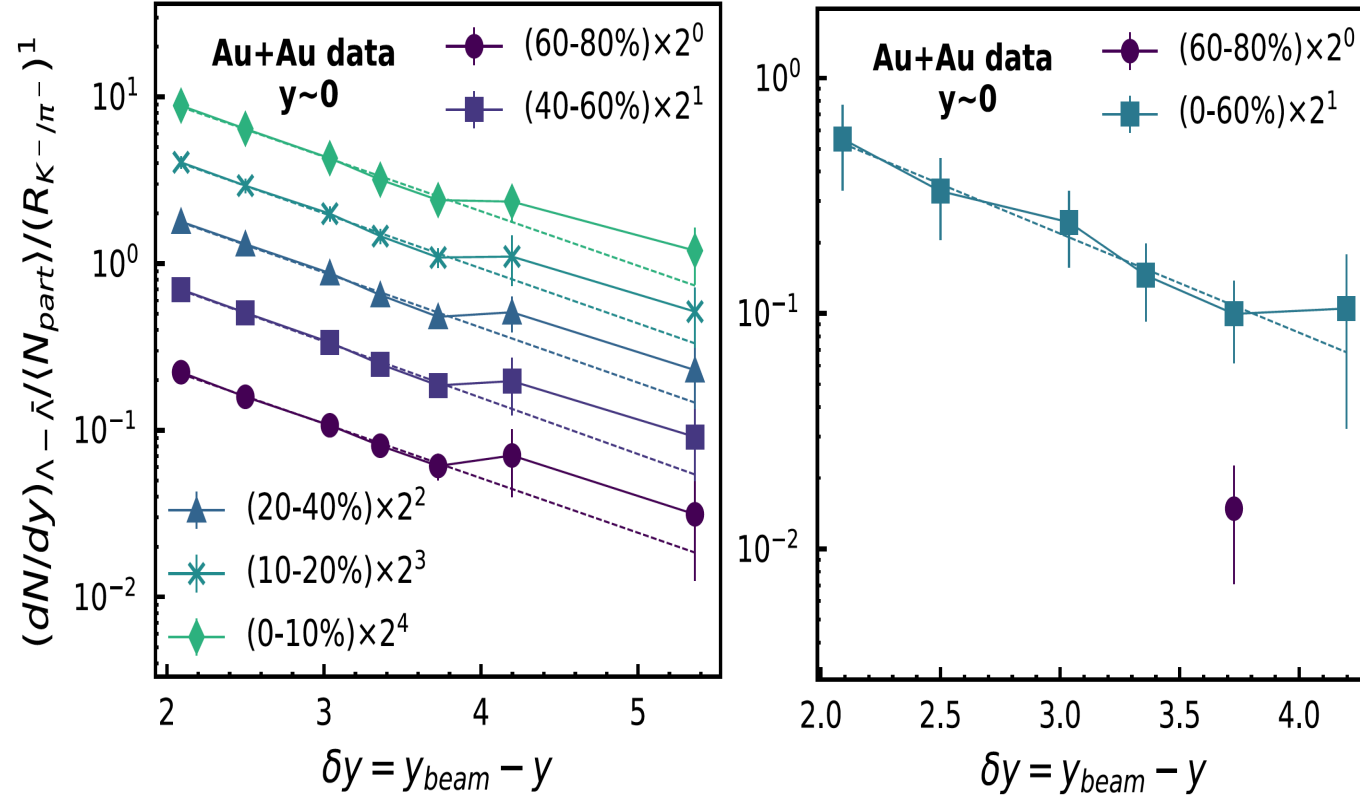


STAR, arXiv: 2408.15441

Submitted to Science

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

Flavor Dependence of Baryon Transport



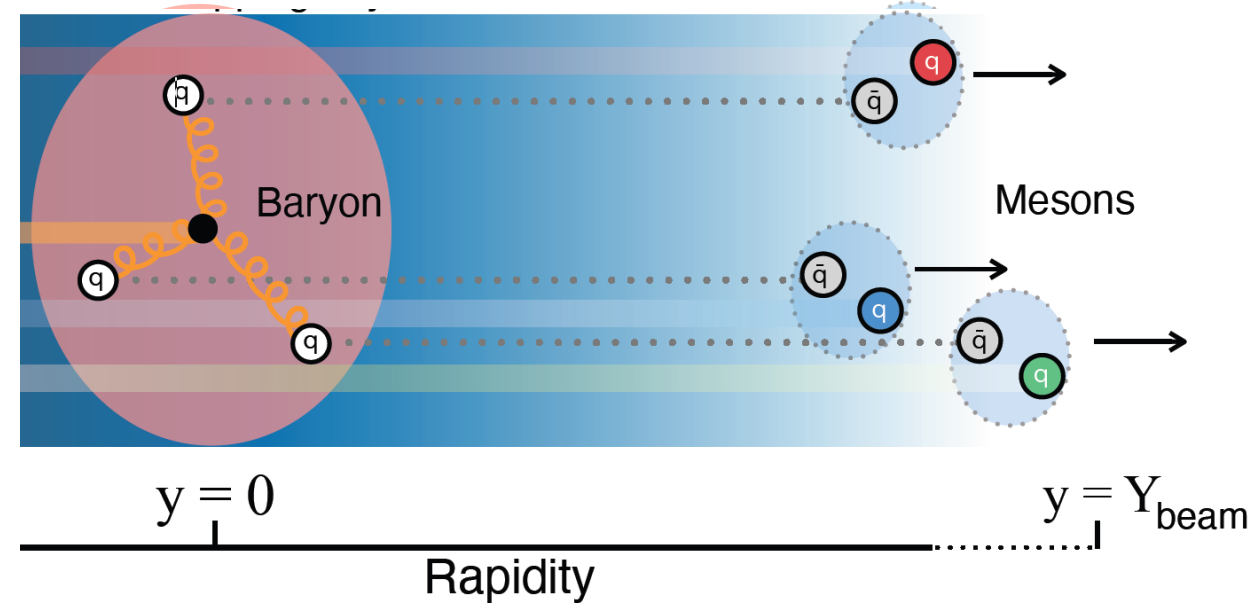
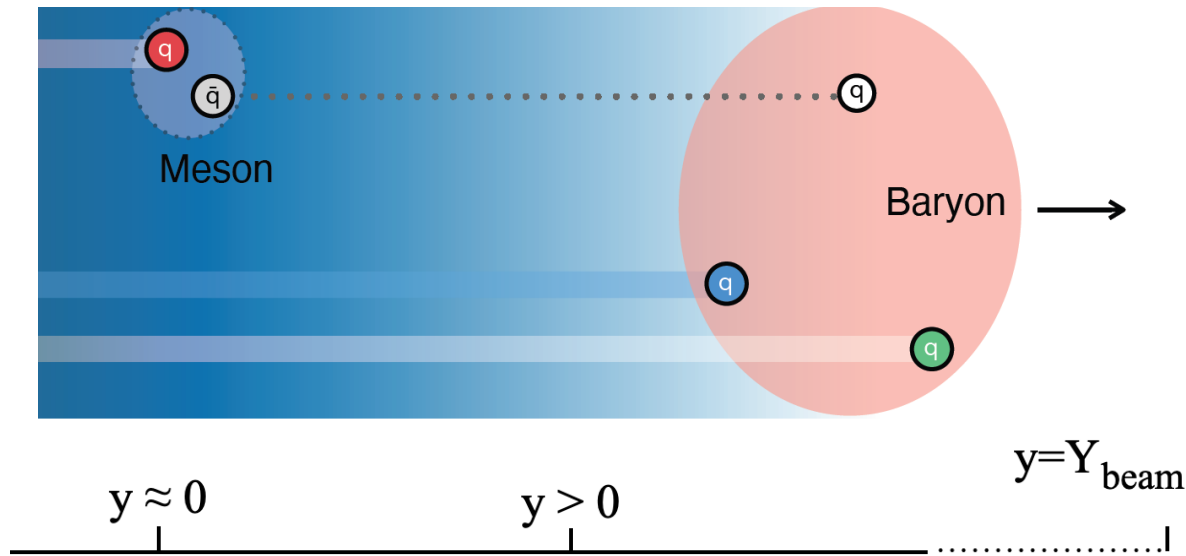
- Net-hyperons yield from RHIC Beam-Energy-Scan-I
- Suppression of strangeness taken out by $(K/\pi)^n$ factor
- Follows exponential nicely for Λ , Ξ and Ω
- No particle species dependence
- Flavor-blind baryon transport mechanism $\rightarrow$ **baryon junction**

Correlation of Baryon and Charge Transport

Valence quark stopping

VS

Baryon junction stopping



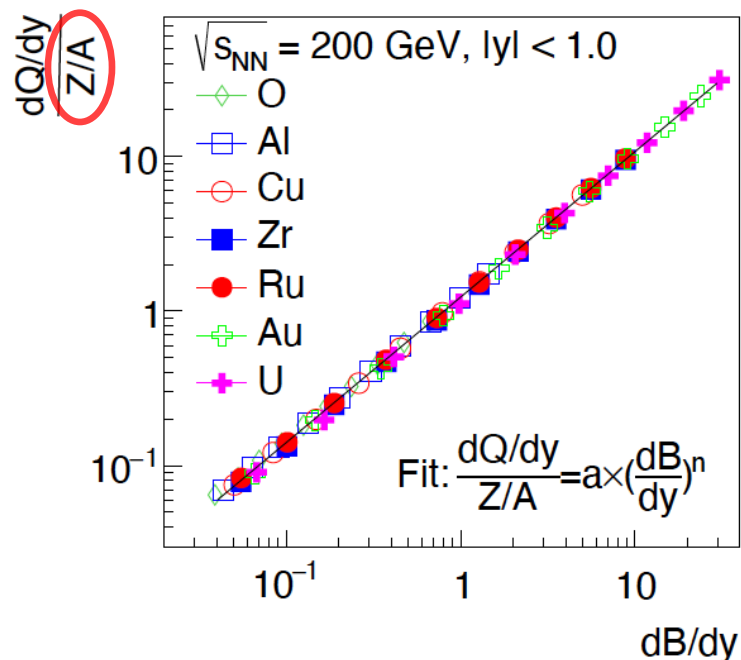
- Net quarks at mid-rapidity are mainly transported from initial nuclei
- Net-charge and net-baryon are **highly correlated**
- $B/Q \sim A/Z$

- 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

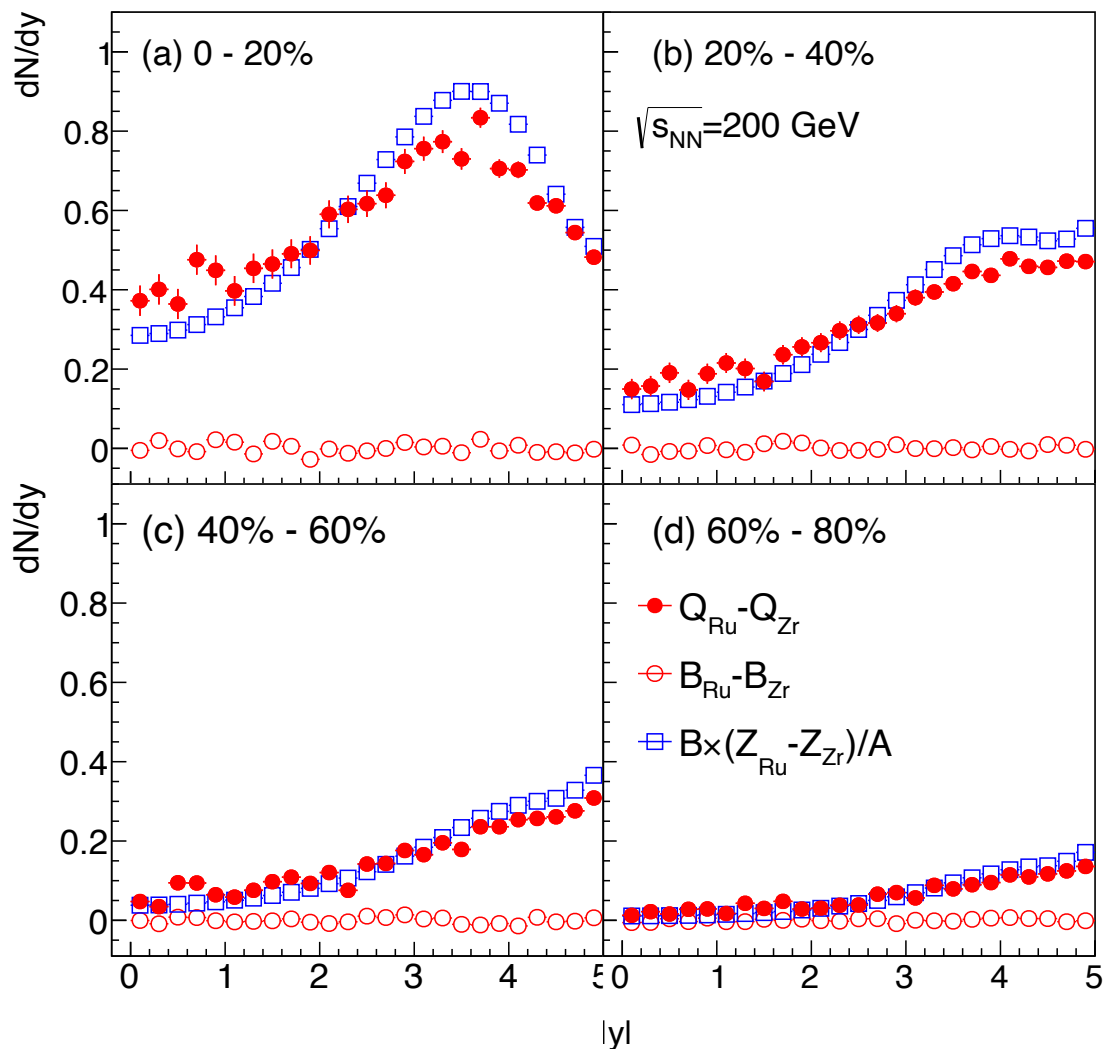
Wendi Lv et al., CPC48,
044001 (2024)

- 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

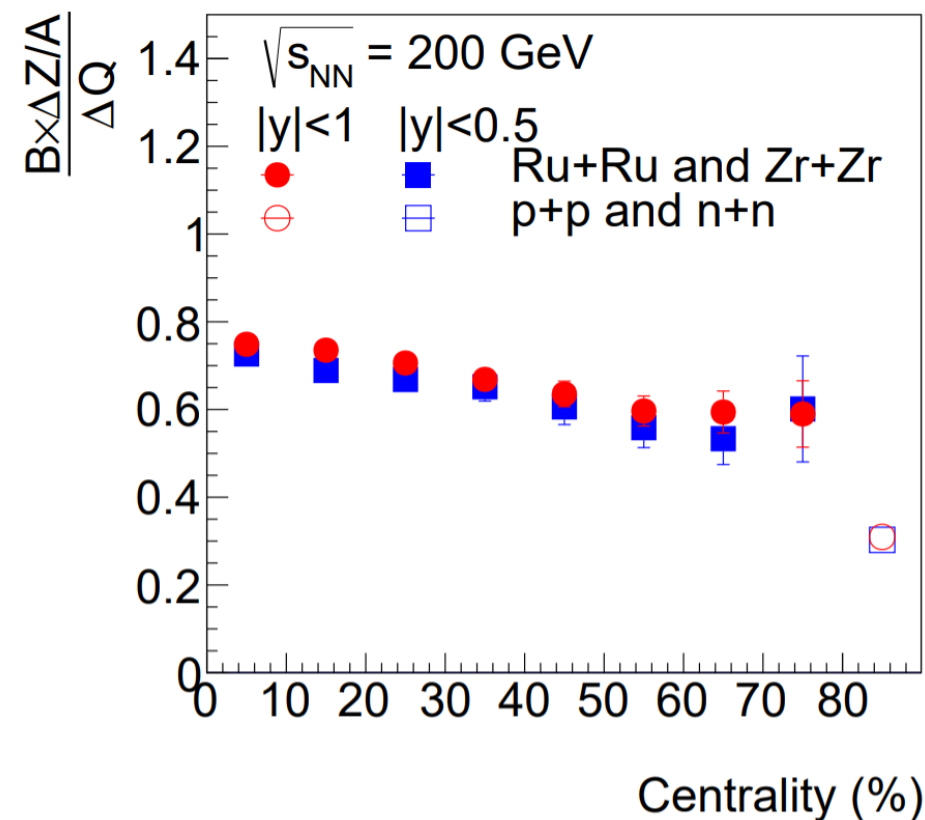


Expectation from Valence Quark Stopping

Ru+Ru and Zr+Zr collisions at 200 GeV from UrQMD

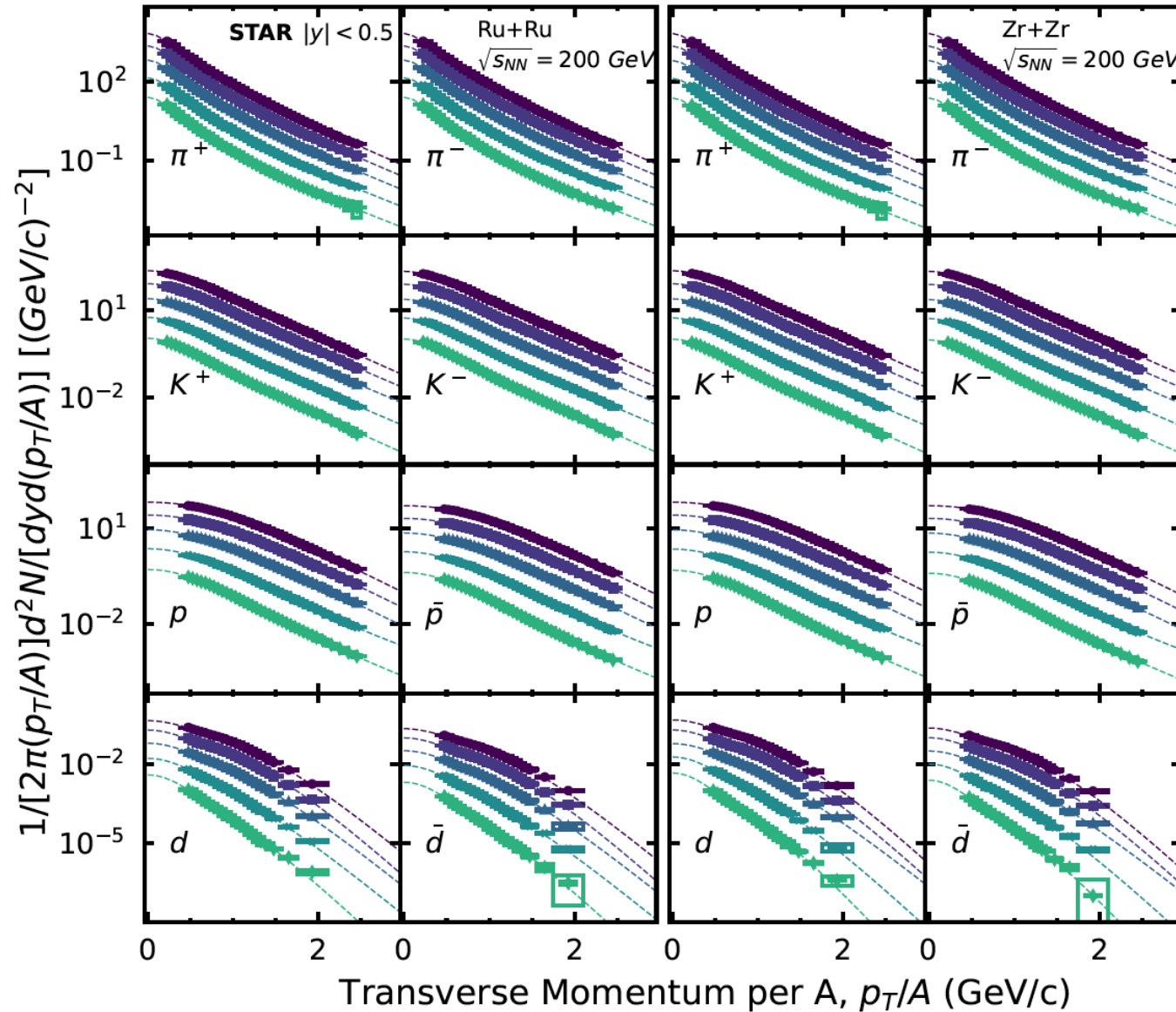


- Difference of B is almost zero
- Difference of Q is close to $B \times \Delta Z / A$





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



Calculation of Net-Charge Difference

Nicole Lewis et al.,
EPJC84, 590 (2024)

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

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

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

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

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

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

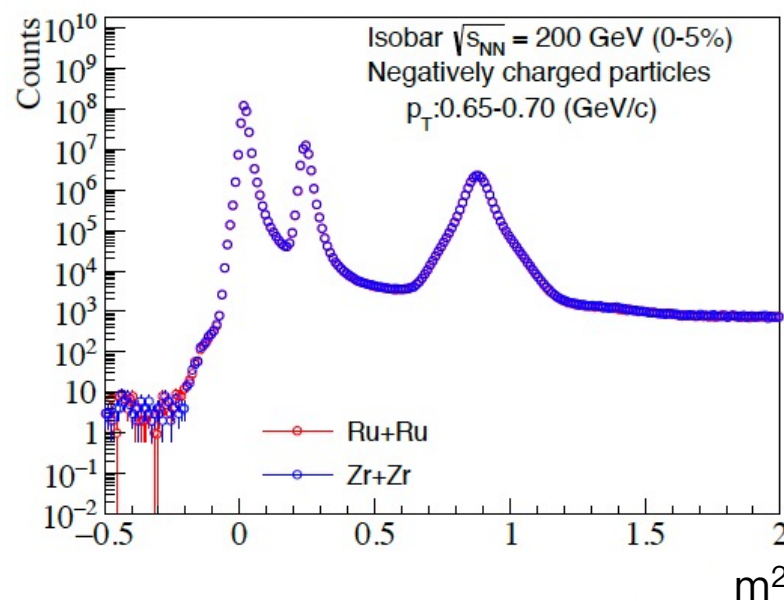
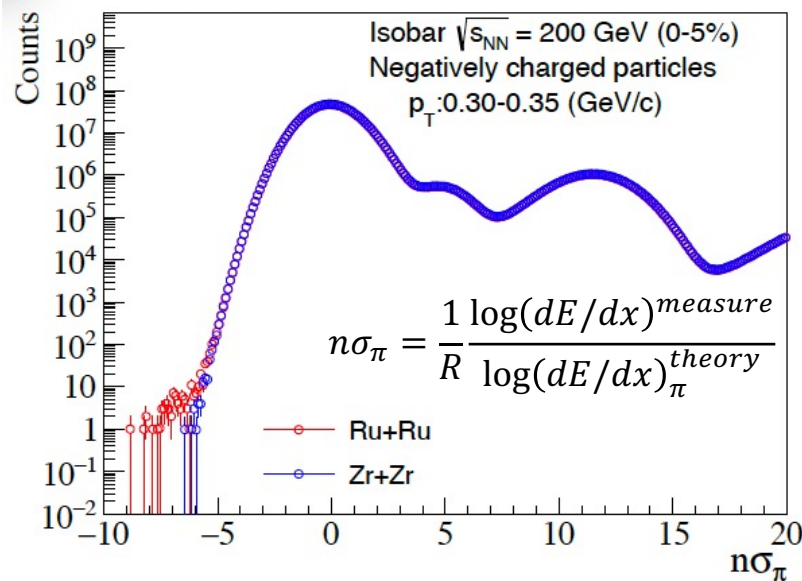
$$R_{\pi} = \frac{\pi^+}{\pi^-}$$

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

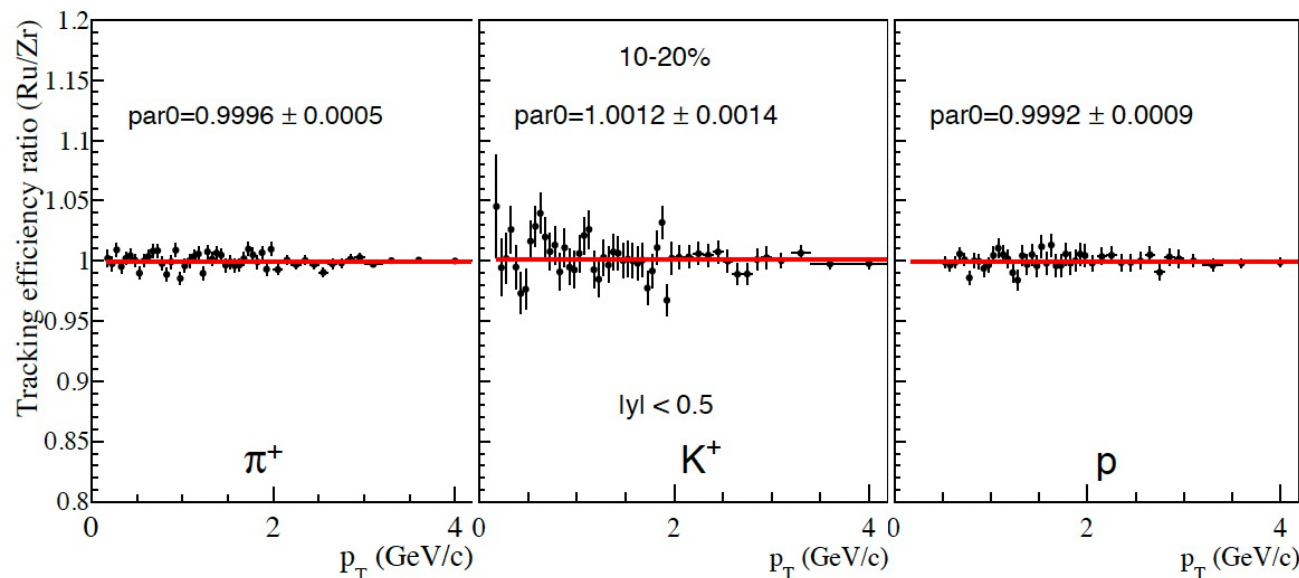
Double ratio method to preserve **high precision** measurements of net-charge difference in isobar collisions



Exactly Same Behaviors in Different Systems

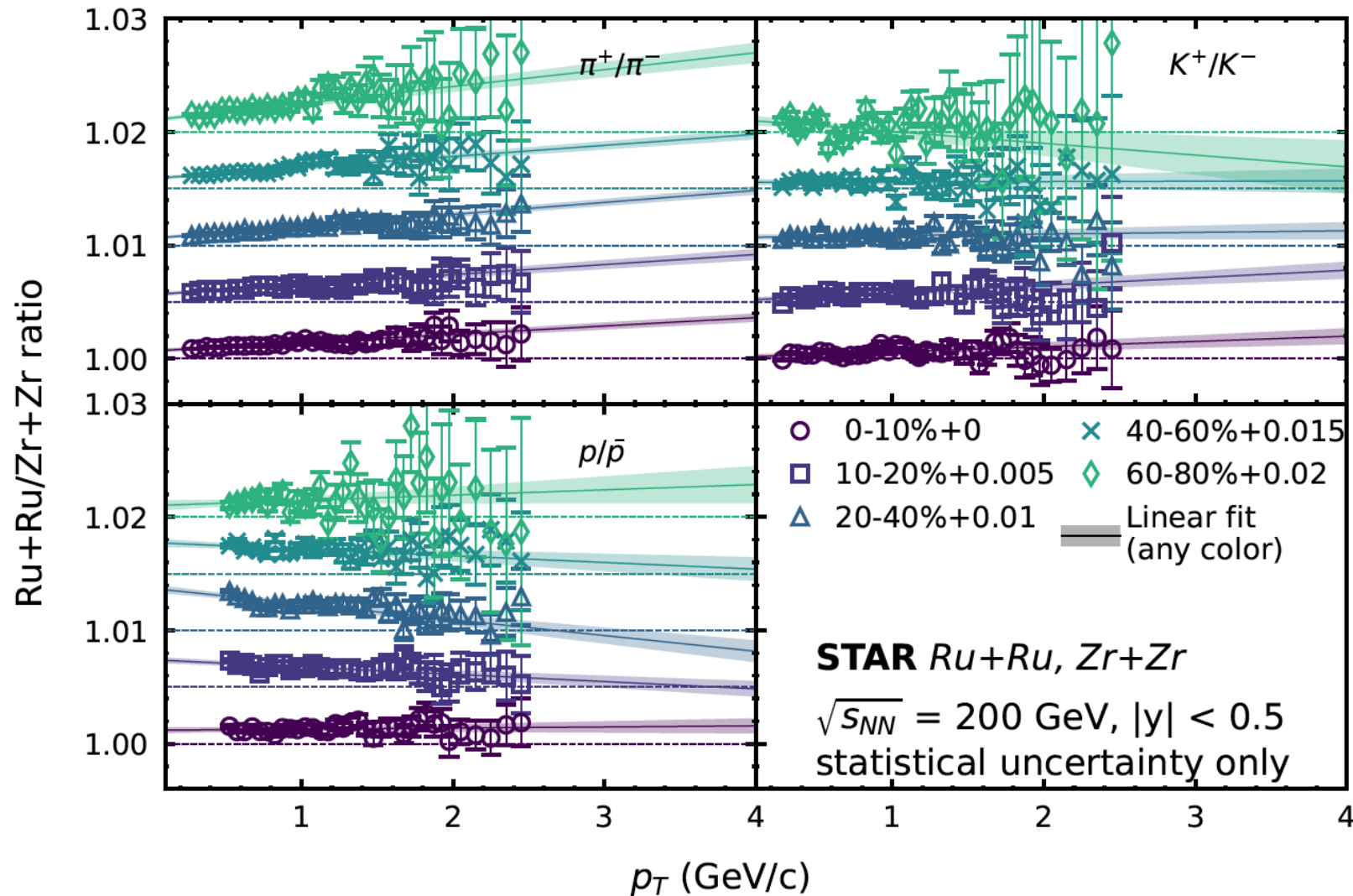


Same distributions of dE/dx and m^2



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

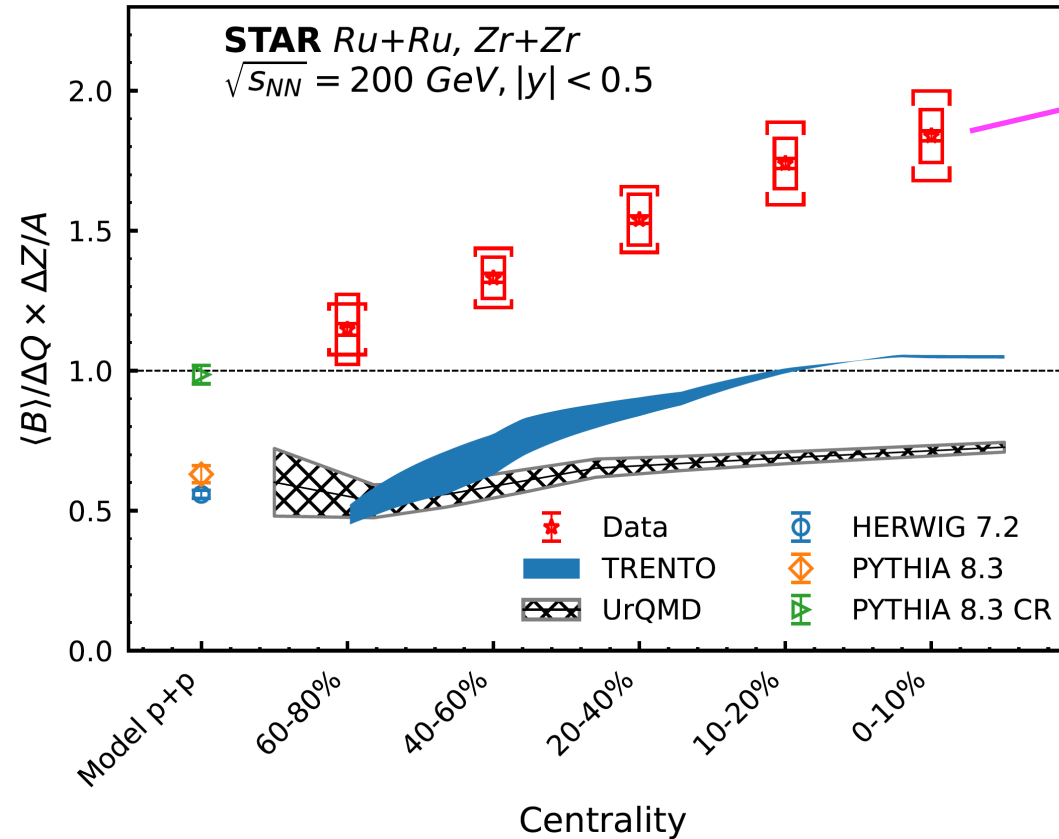


Measurement of $B/\Delta Q$ in Ru+Ru/Zr+Zr Collisions

STAR, arXiv: 2408.15441

Submitted to Science

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



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

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

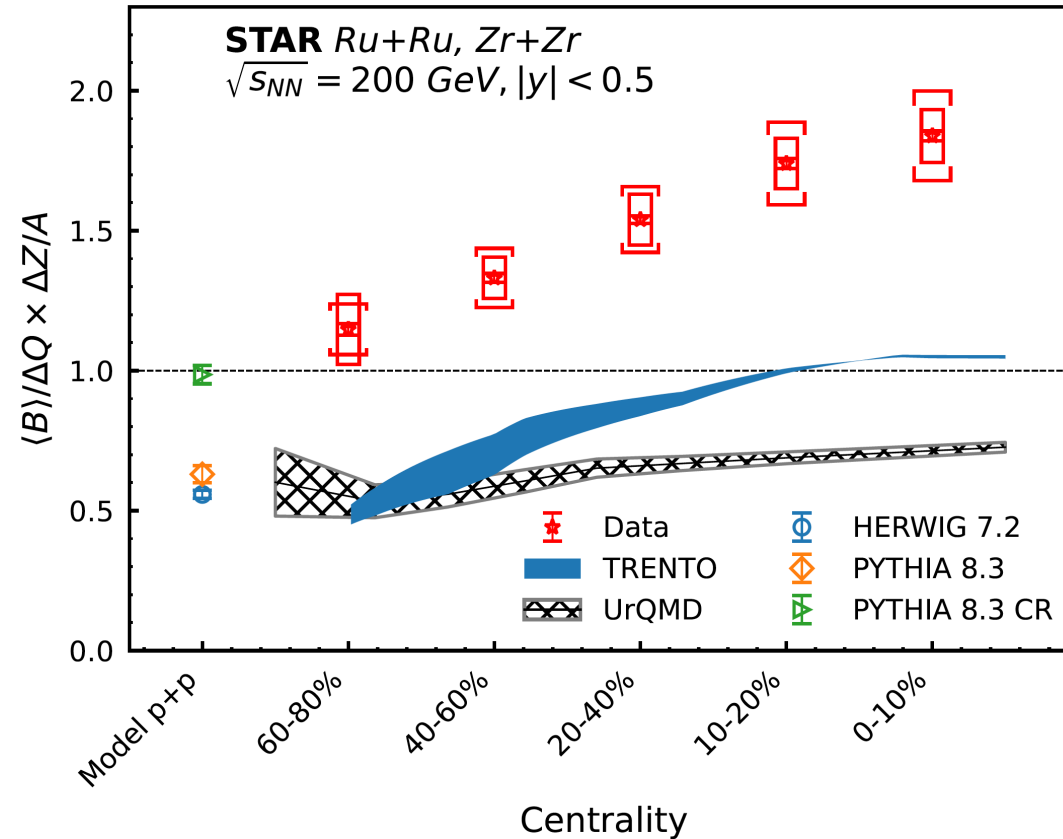


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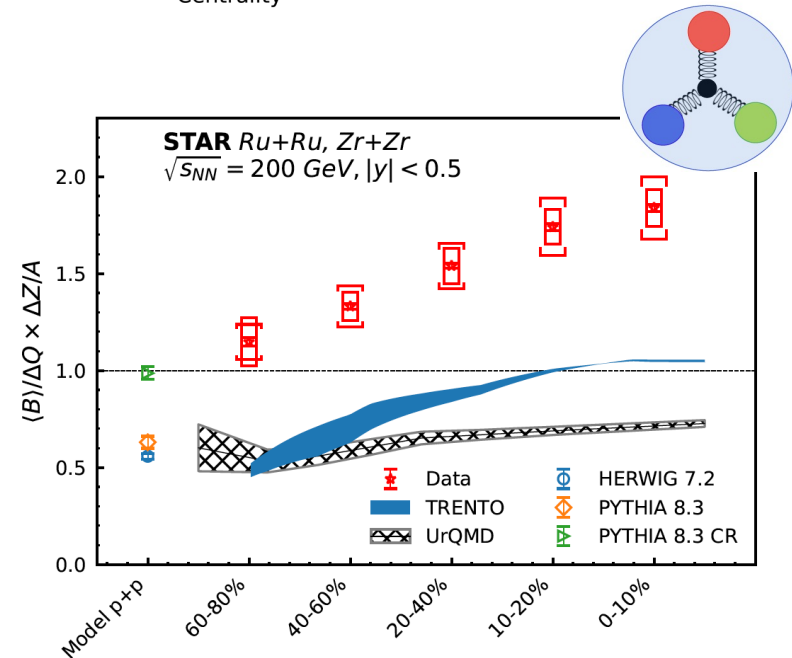
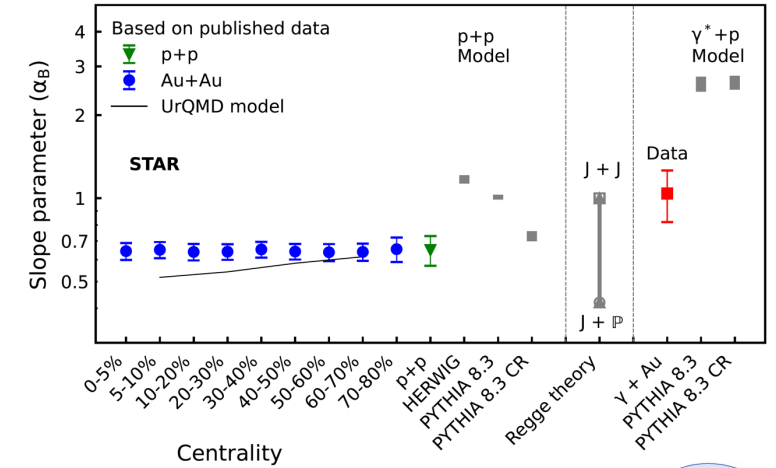
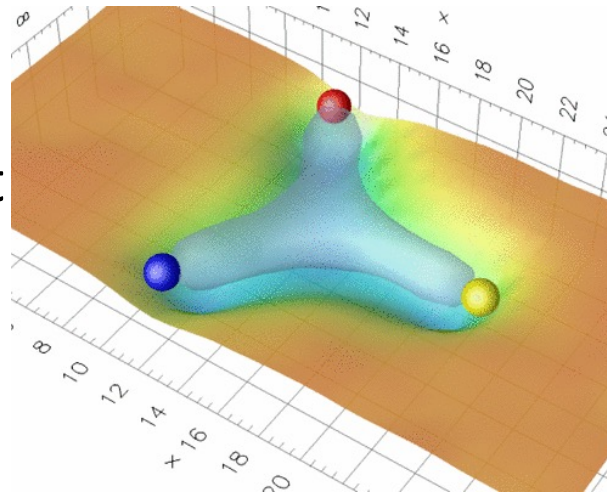
UrQMD: W. Lv, CPC48, 044001 (2024)

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 trace baryon number
- The picture is **different from** what we learnt from **textbooks**, however consistent with LQCD expectations





Roles of Baryon Junctions

- **Transport baryons** from colliding hadrons in the initial scatterings

← This work

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

One example is the color reconnection in PYTHIA

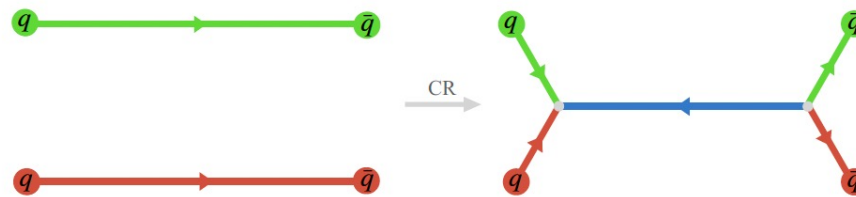
Impact of Baryon Junction

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

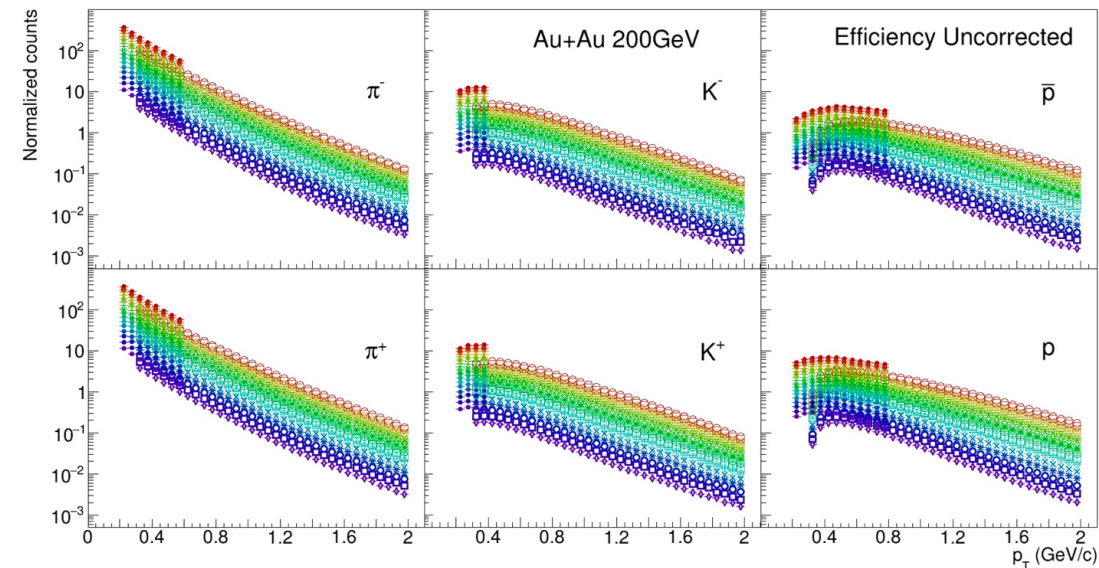
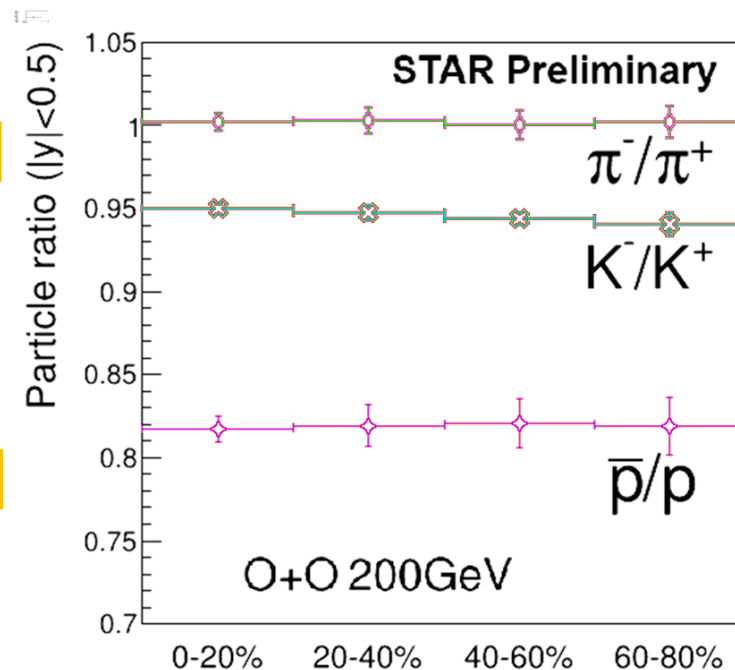
- Plays import role in probing QGP properties from experiments
 - Heavy flavor hadron production
 - QCD critical end point search with net-proton number higher moments
 - ...
- Exotic hadrons
- ...



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

O+O vs. Au+Au

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



Larger expected signal due to larger Z/A difference

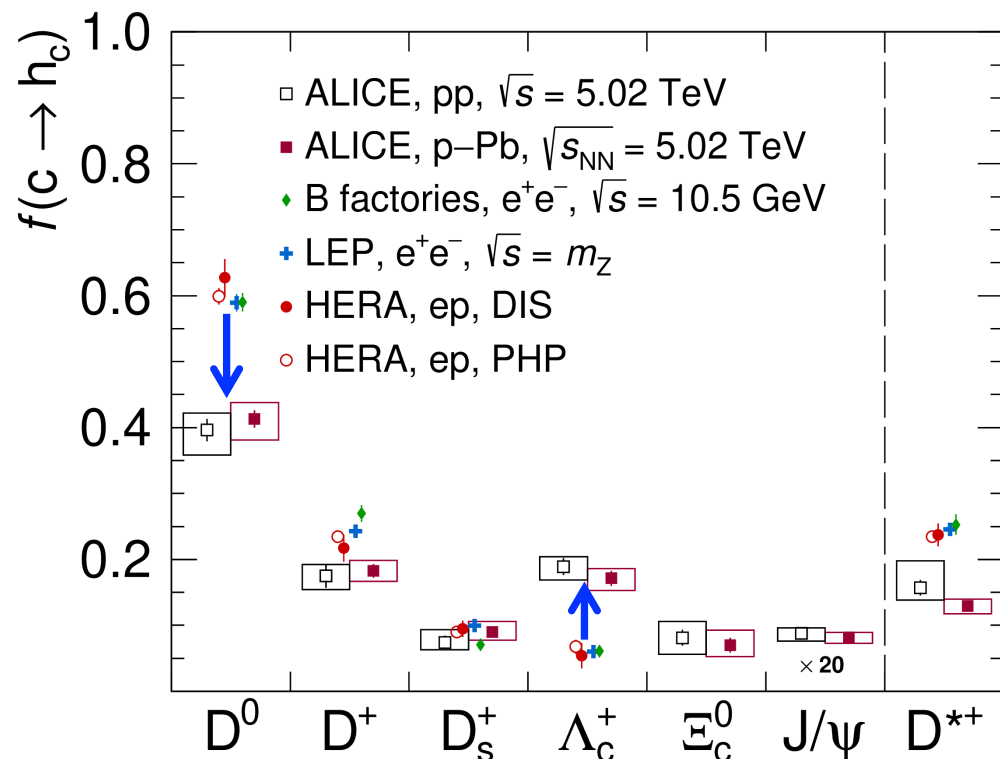
O+O premilitary results obtained

Au+Au analysis is ongoing

Stay tuned

Thanks for your attention!

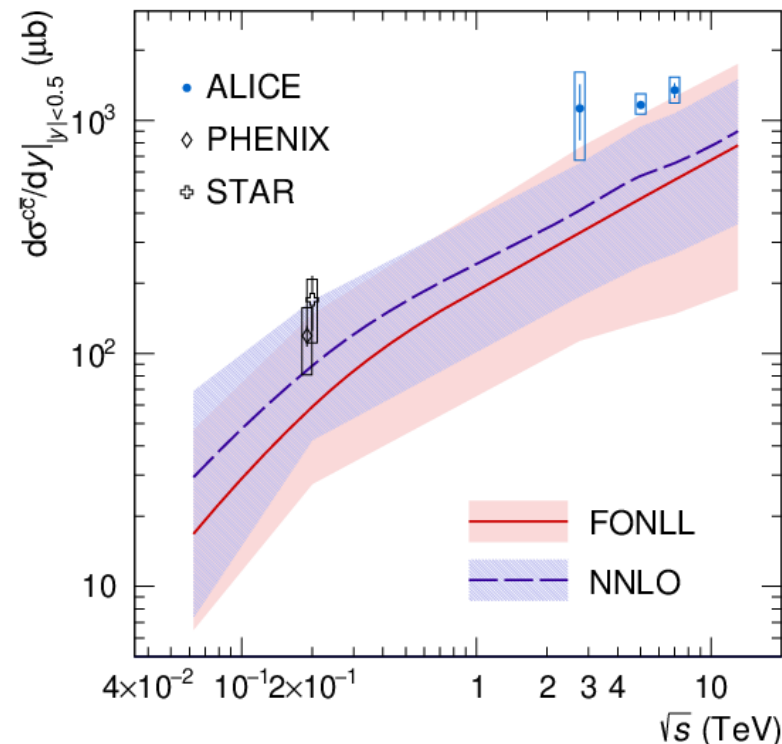
Enhancement of Charmed Baryon in Small System



ALI-PUB-570972

ALICE, EPJC84,12 (2024)

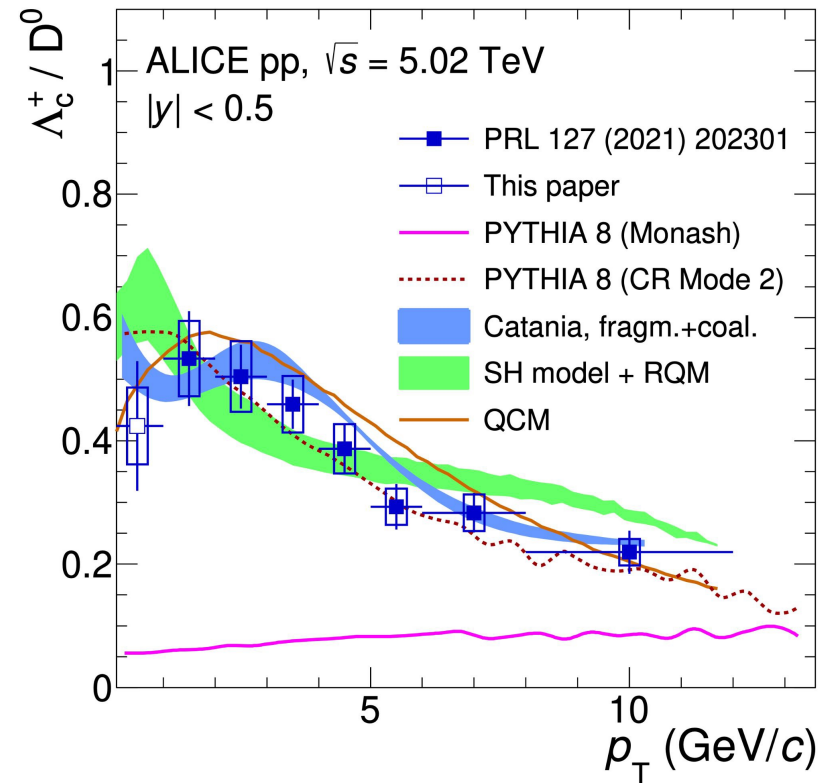
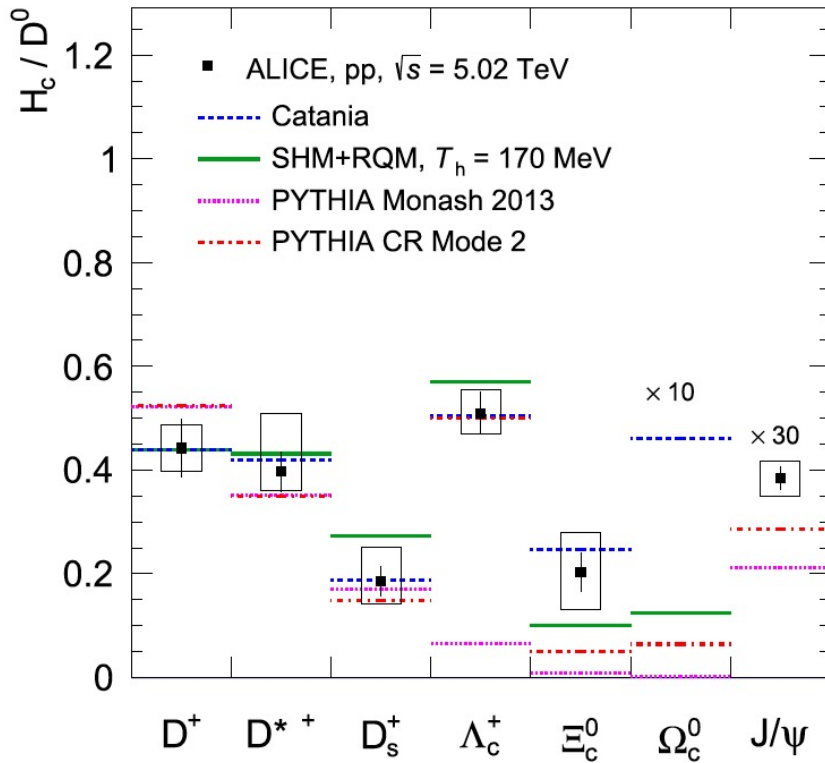
ALICE, PRD105, L011103 (2022)



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



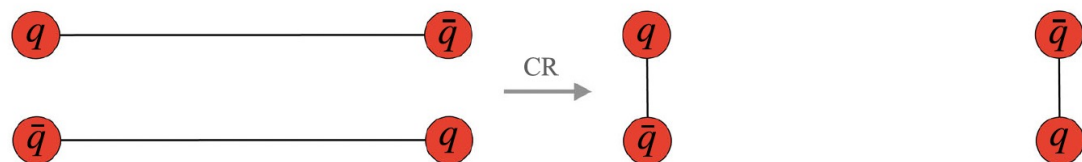
J. Altmann, A. Dubla, V. Greco et al., EPJC85, 16 (2025)

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

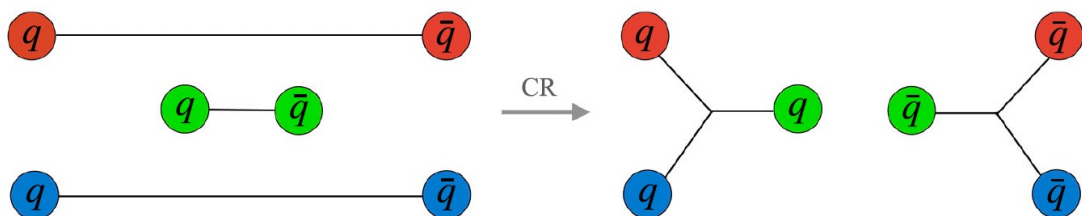
VS.

PYTHIA with color reconnection can describe the enhancement of charmed baryons

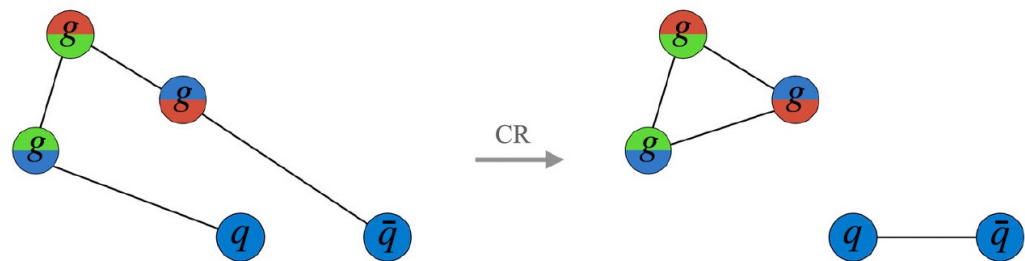
Hadronization in PYTHIA with Color Reconnection



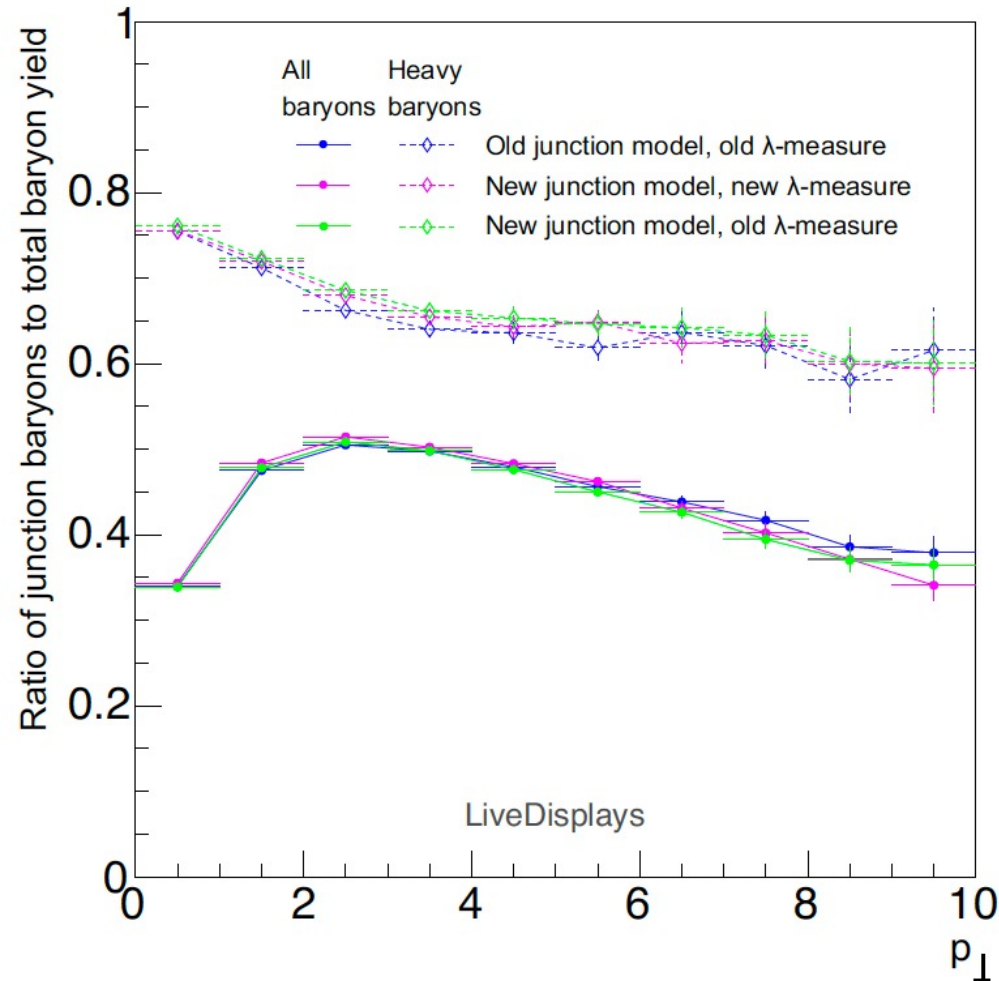
(a) Dipole-type reconnection.



(b) Junction reconnection.



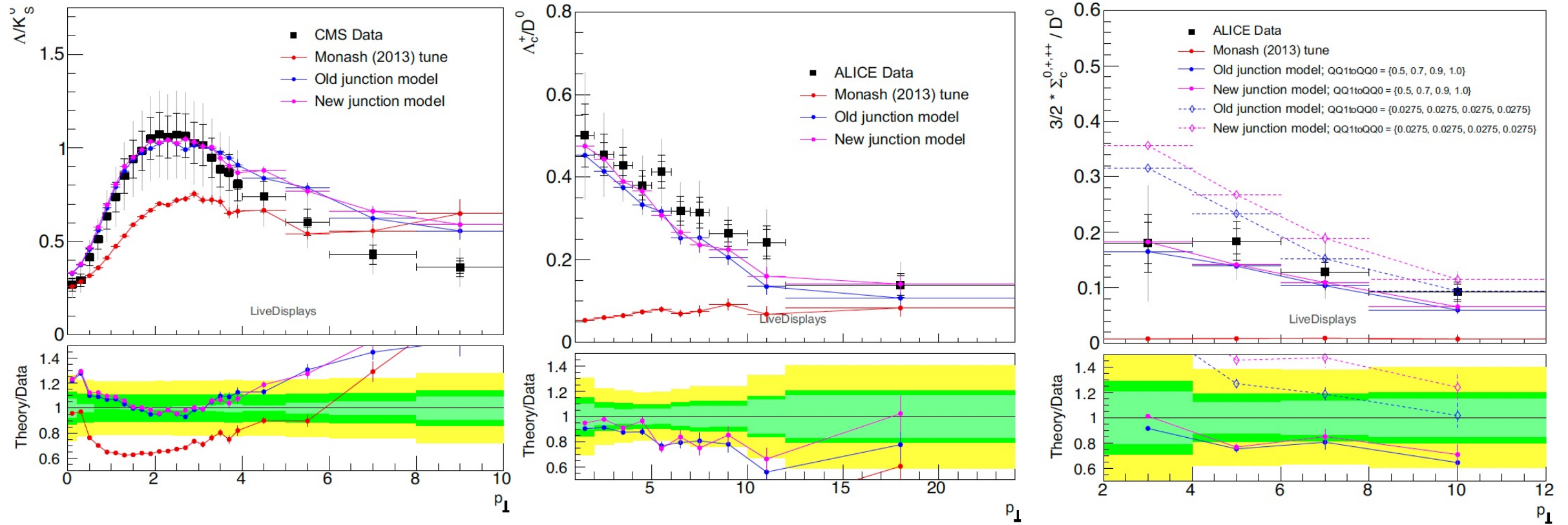
(c) Gluon-loop formation.



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

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

Baryon Production in PYTHIA

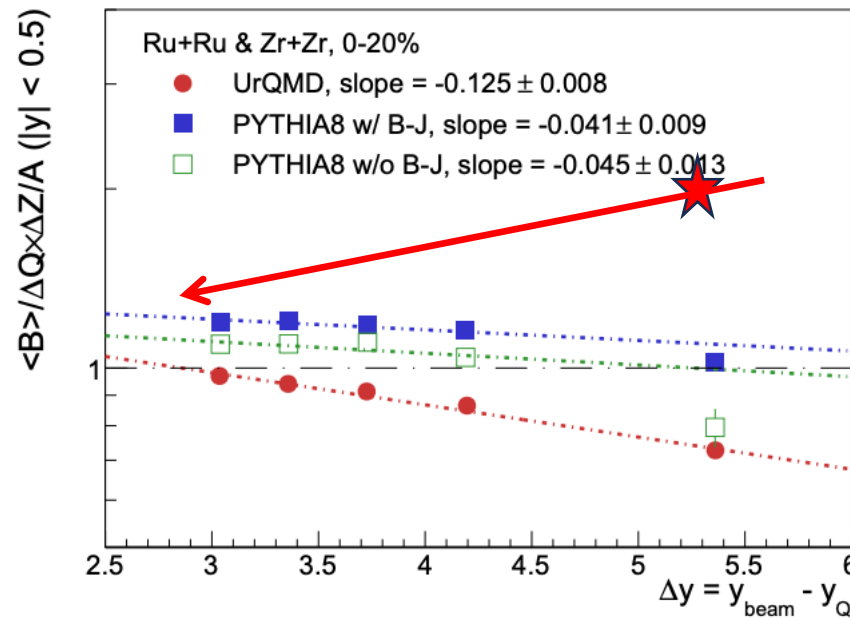


Strange and charm baryon-to-meson ratios described by junction in PYTHIA

Rapidity loss method

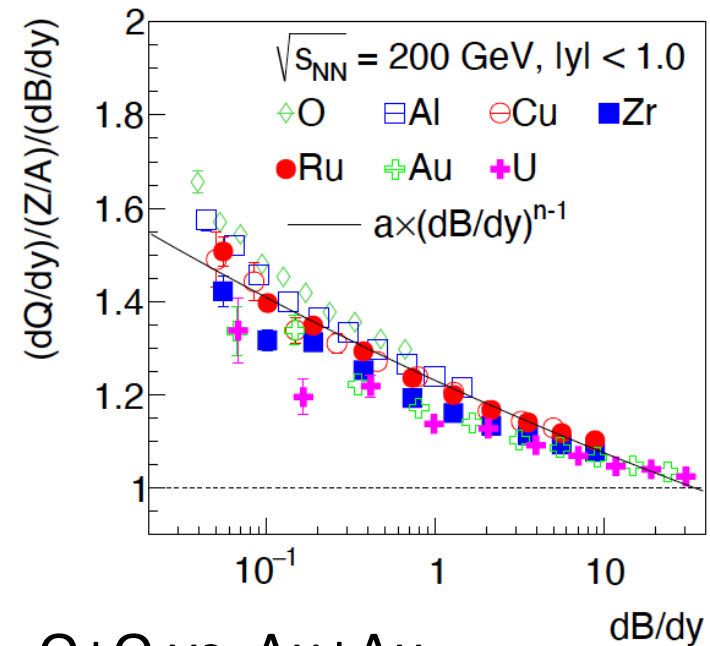
- Precision data from BES-II
- net-baryon rapidity distribution in γ +A collisions

W. Lv et al., arXiv:2604.02825



- Beam energy scan of isobar collisions

Baryon-flavor correlation method



- O+O vs. Au+Au
- p+Au vs. d+Au vs. $^3\text{He}+\text{Au}$
- Fancy correlation measurements
- ...