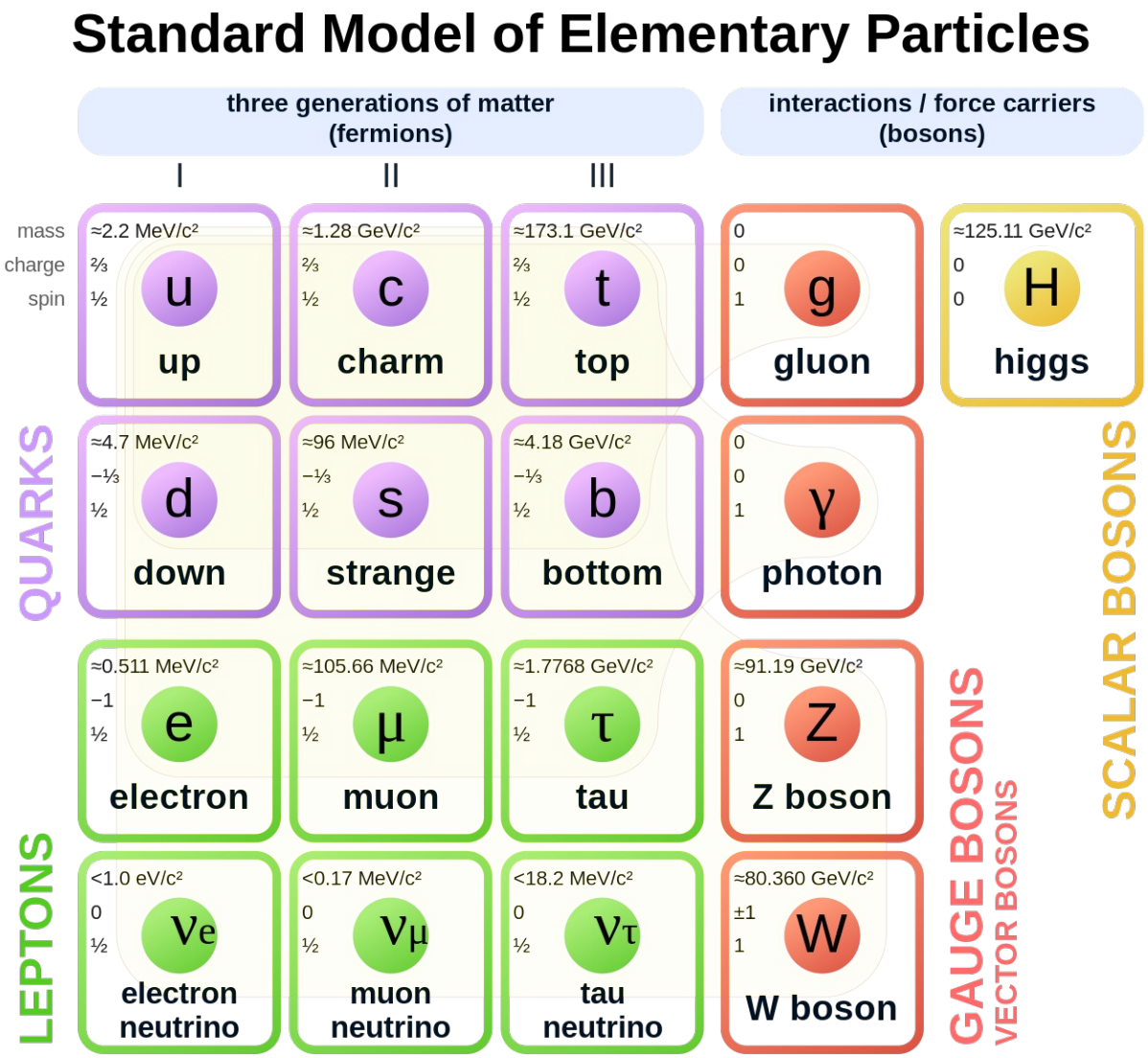
Physics at High Baryon Density (PHD2025)
Central China Normal University, Wuhan, Oct. 16-18, 2025

Search for Baryon Junction with Heavy Ion Collisions at RHIC Energies

Zebo Tang (唐泽波)
Department of Modern Physics
University of Science and Technology of China

STAR, arXiv:2408.15441, submitted to Science
Yang Li, PhD thesis, USTC (2023)
Wendi Lv et al., CPC48, 044001 (2024)
N. Lewis et al., EPJC84, 590 (2024)

Quark Model and Baryon Number Carrier



As building brick of matter, a quark has:

- Flavor
- Color
- Mass
- Charge
- Spin
- Baryon number
- …

Baryon Number Carrier

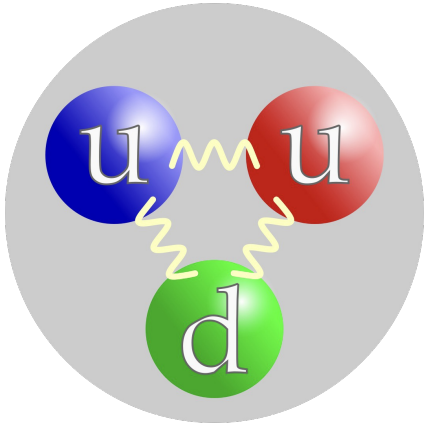
PDG says: Baryon numbers are carried by quarks (1/3 for each)

- Any experimental evidence?

NO! Simply because there are three valence quarks in a baryon

- Is quark the only candidate?

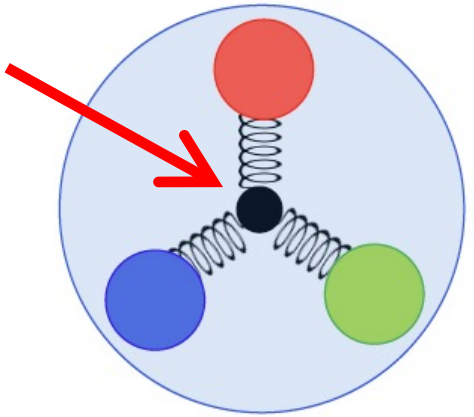
NO! Valence quarks are not the only objects in a baryon



Wikipedia

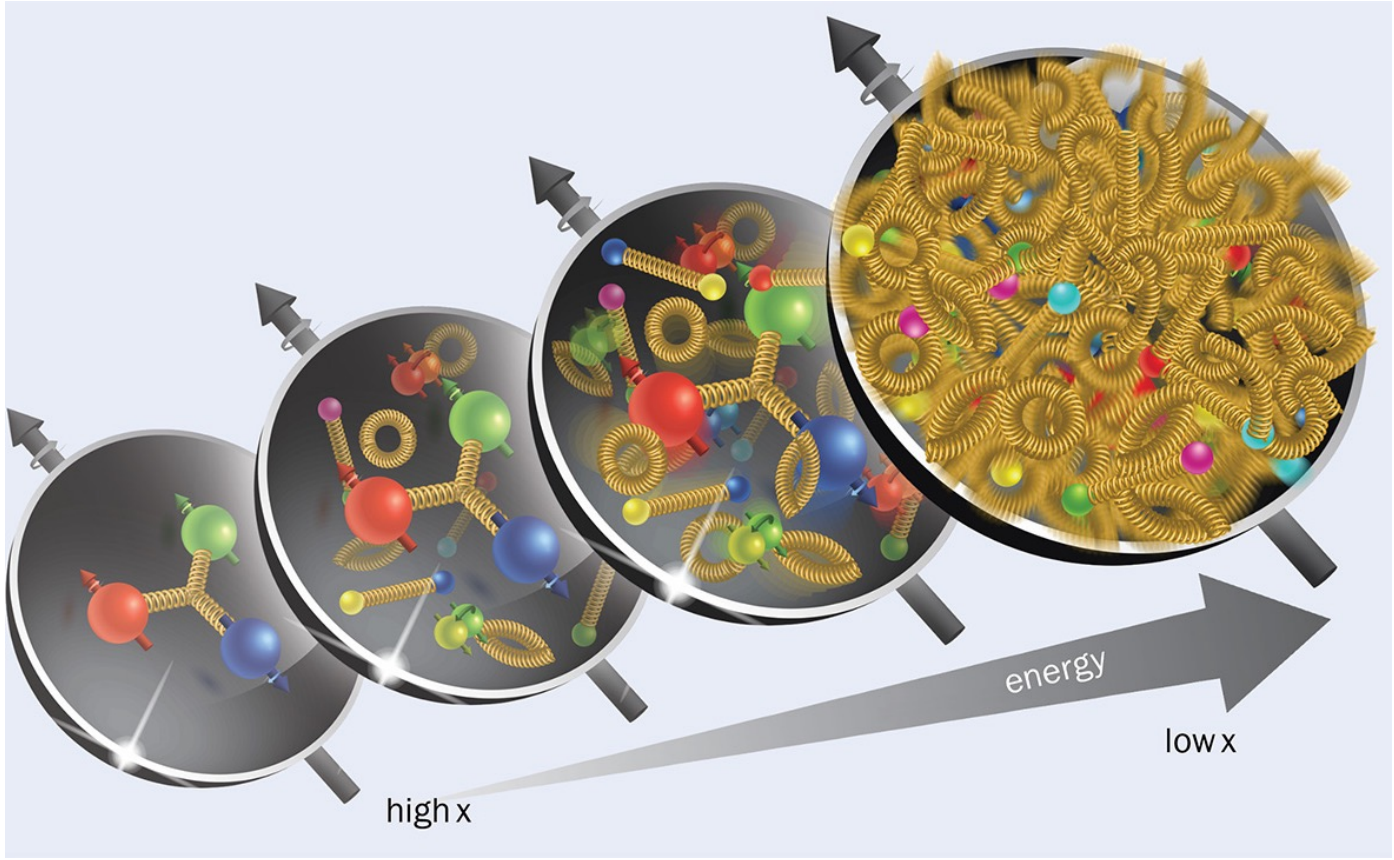
Alternative picture of a proton:

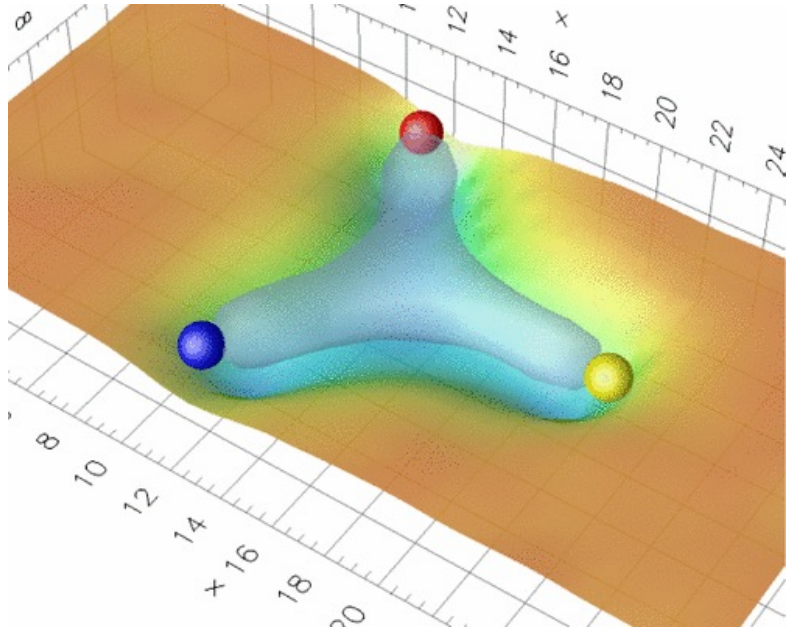
- A Y-shaped gluon junction topology carries baryon number (baryon junction)
- Valence quarks are connected to the end of the junction
- Proposed in 1970s



X. Artru, NPB85, 442 (1975)
G. Rossi and G. Veneziano, NPB123, 507 (1977)

The Simplest QCD Topology

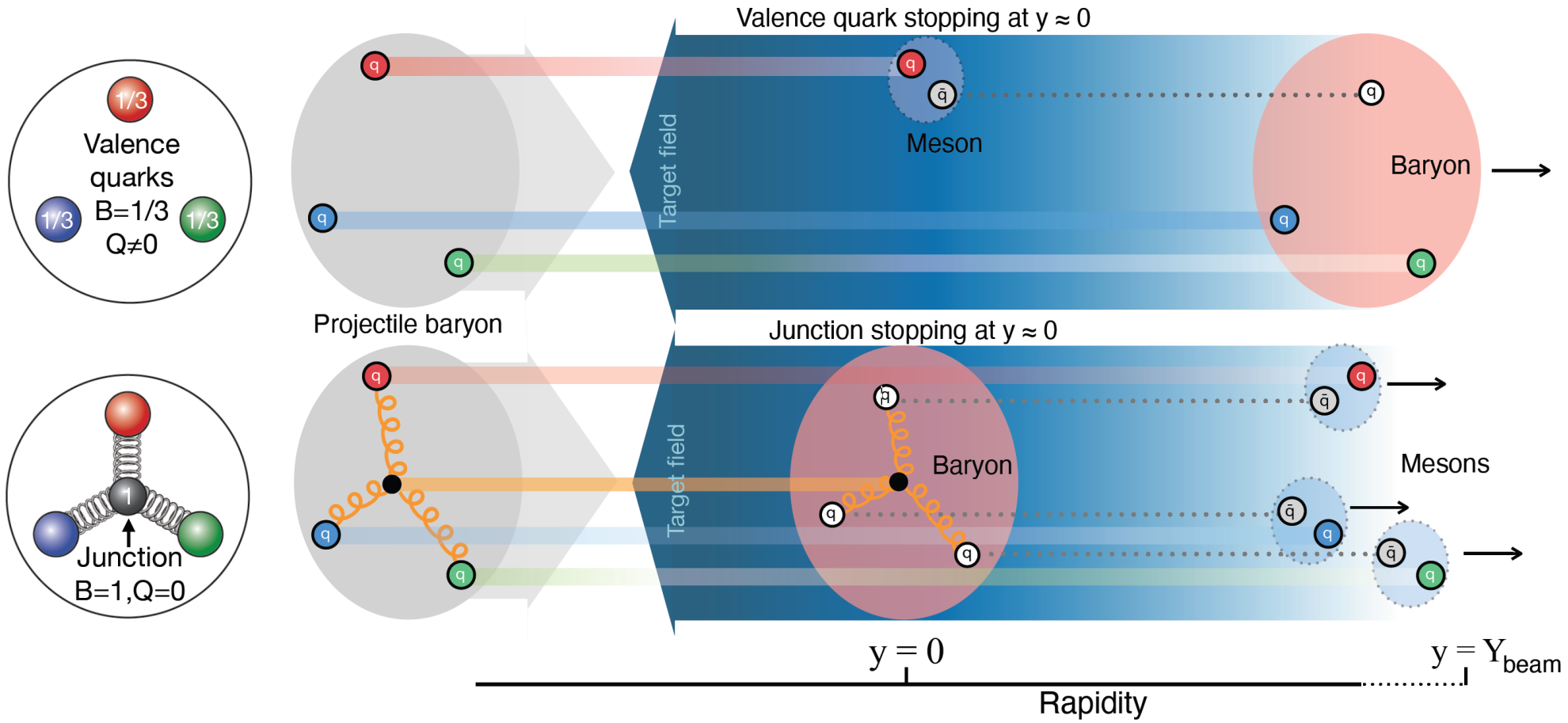




D. F. Bissey, F. Cao, A. Kitson et al.,
Phys. Rev. D 76, 114512 (2007)

How to Track the Baryon Number

Pull them out: Measure baryon stopping at mid-rapidity in A+A collisions D. Kharzeev, PLB378, 238 (1996)

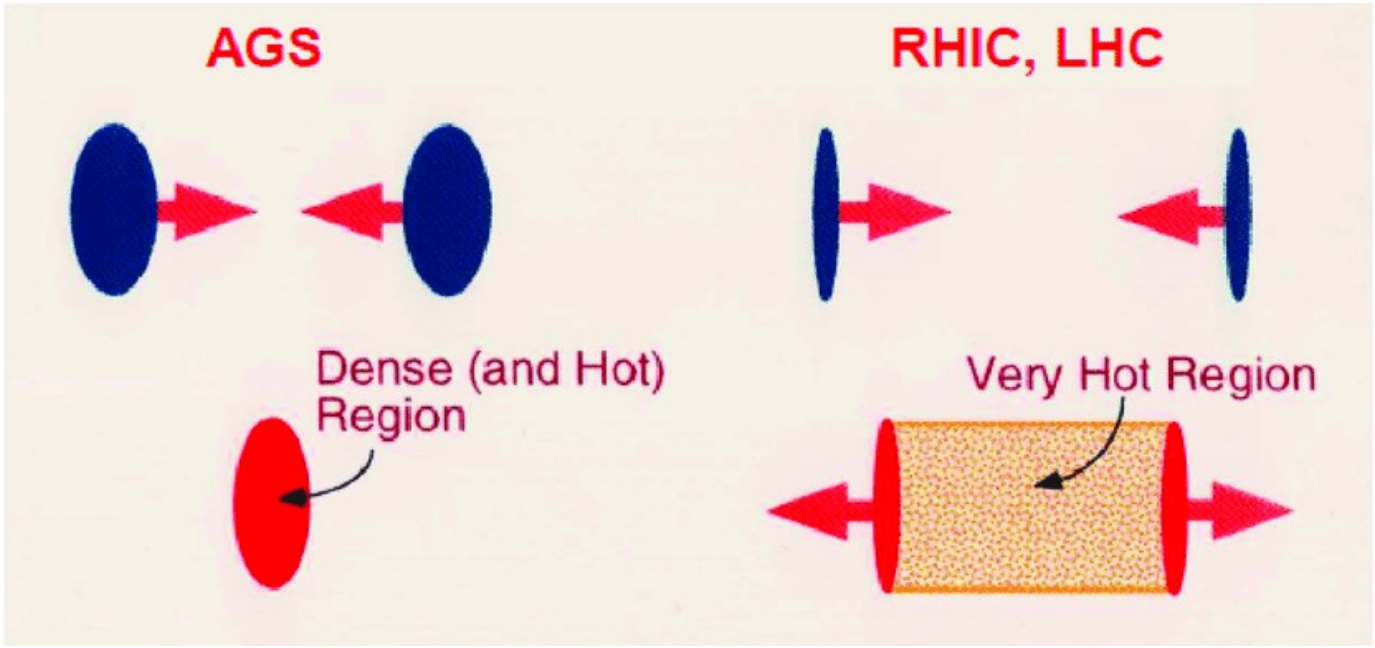


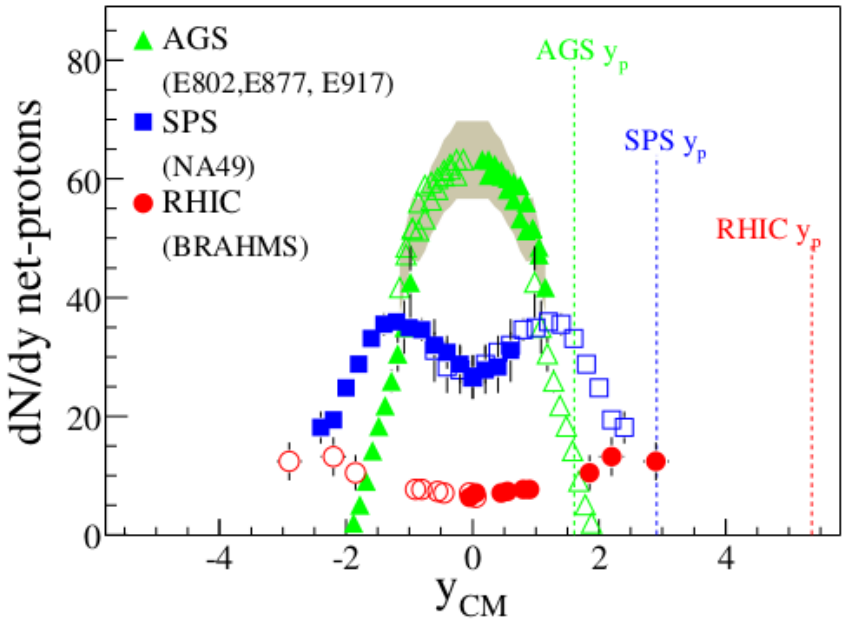
STAR, 2408.15441

Difference in two scenarios:

- Rapidity loss of baryons
- Quark composition of stopped baryons at mid-y

Net-Baryons Rapidity Distribution



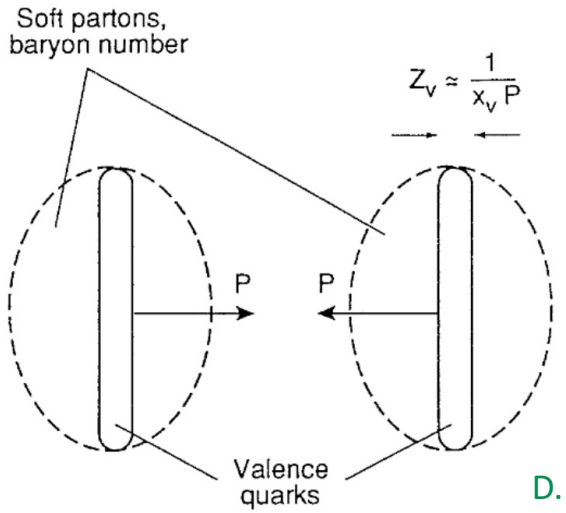


BRAHMS, PRL93, 102301 (2004)
and references therein

Significant baryons stopped at mid-y in heavy-ion collisions, even at RHIC energy ($y_{beam} > 5$)

How can such large y loss happen?

Explanations



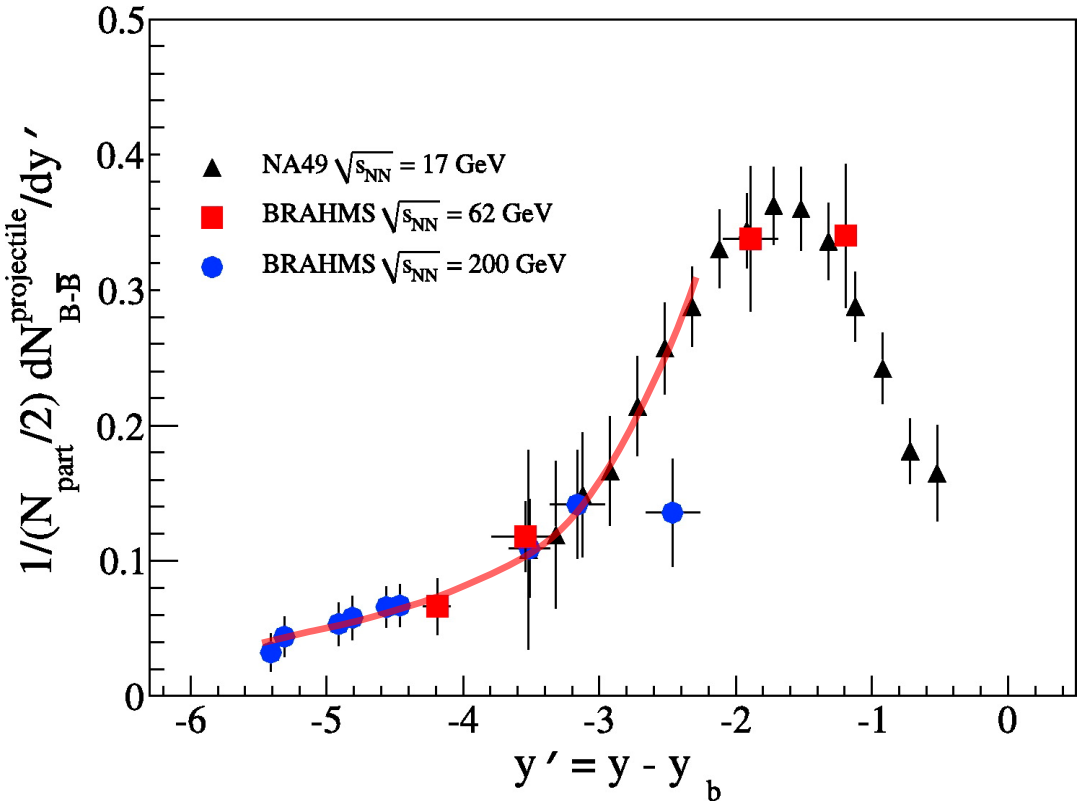
D. Kharzeev, PLB378, 238 (1996)

Scenario A: Valence quarks have short time to interact due to Lorentz contraction

- But multiple scattering may give rise to large rapidity loss

Scenario B: Baryon junctions carry a much lower x and have enough time to interact and be stopped at mid-y

Quantifying Baryon Number Transport



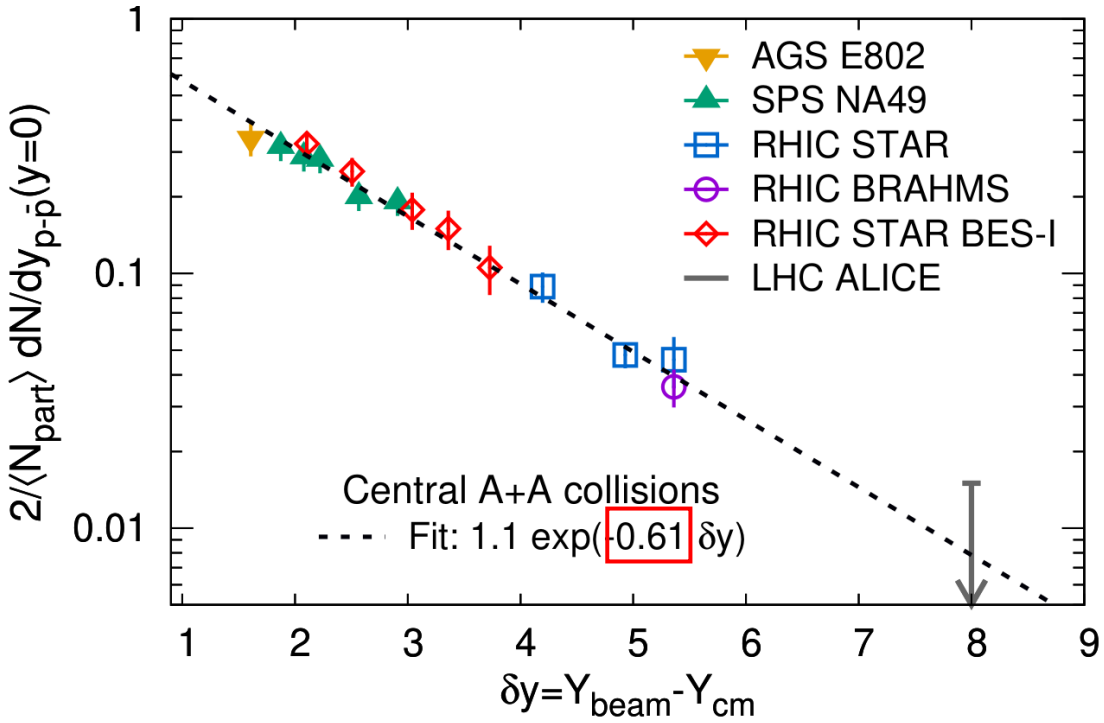
BRAHMS, PLB677, 267 (2009)

Regge theory:

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

$$\xrightarrow{y=0} 2e^{-\alpha_B y_{beam}}$$

Net-Proton Yield at Various Energies



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

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

Prediction with junction:

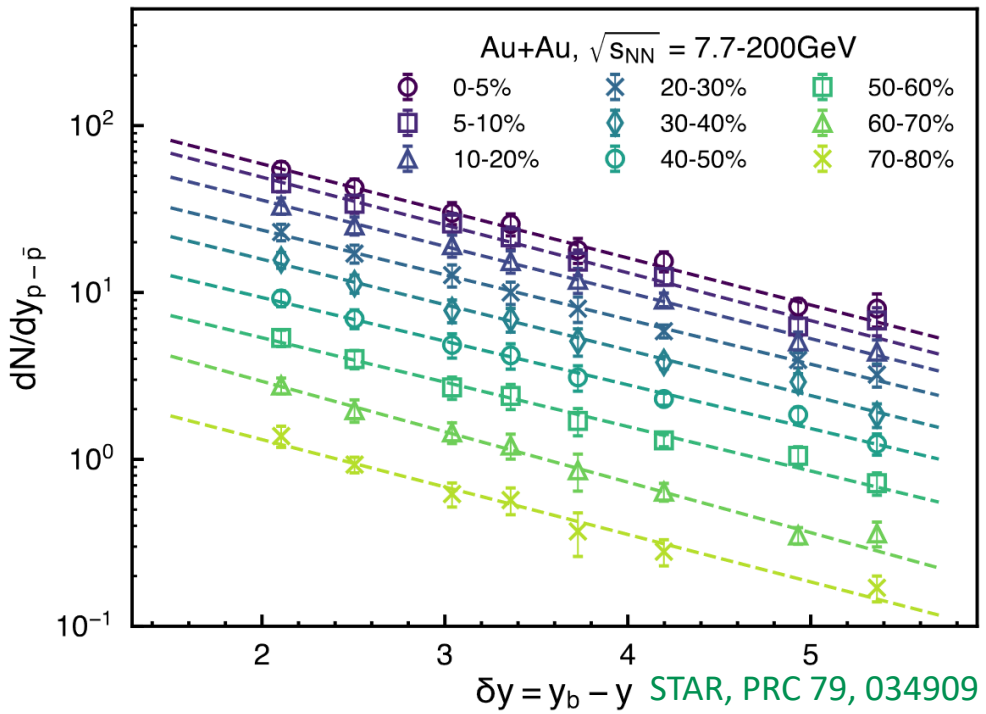
$$\alpha_B = \begin{cases} 1 & double-baryon\ stopping \\ 0.42 & single-baryon\ stopping \end{cases}$$

D. Kharzeev, PLB378, 238 (1996)

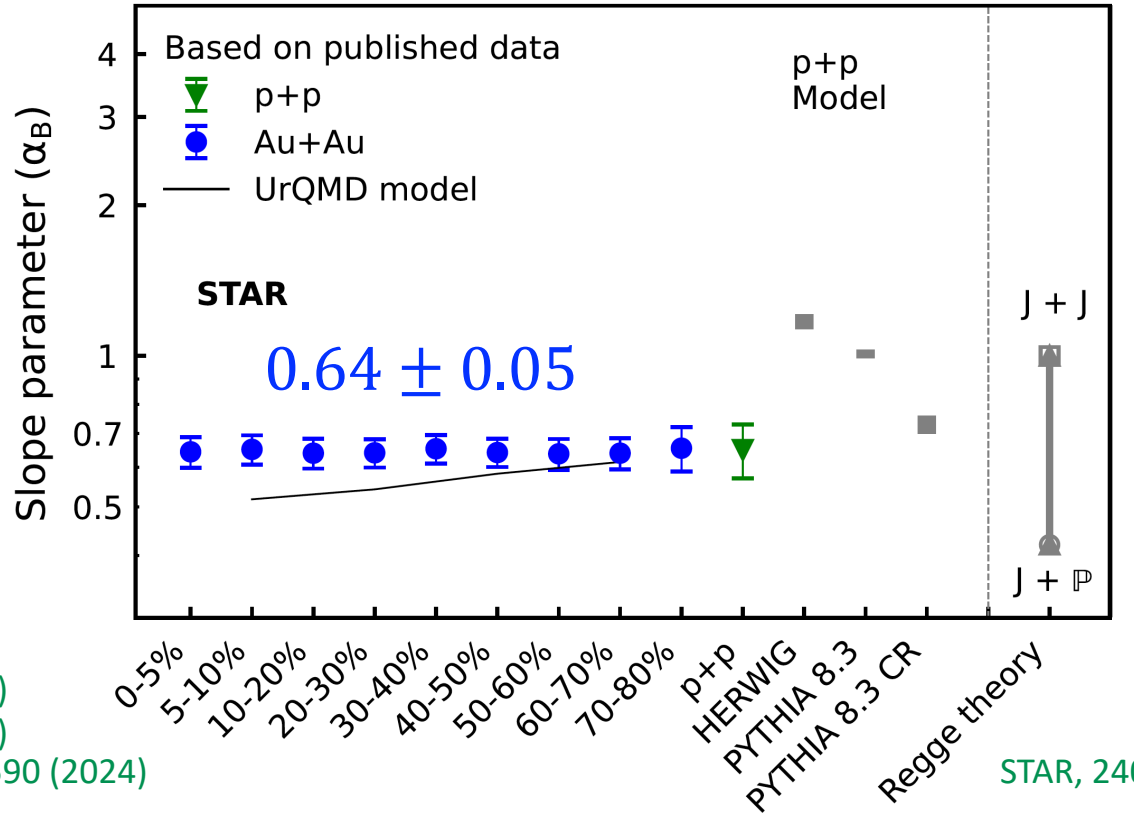
Experiment observation: $\alpha_B = 0.61 \pm 0.03$

Consistent with baryon junction transport by gluons

Centrality Dependence of the Slope



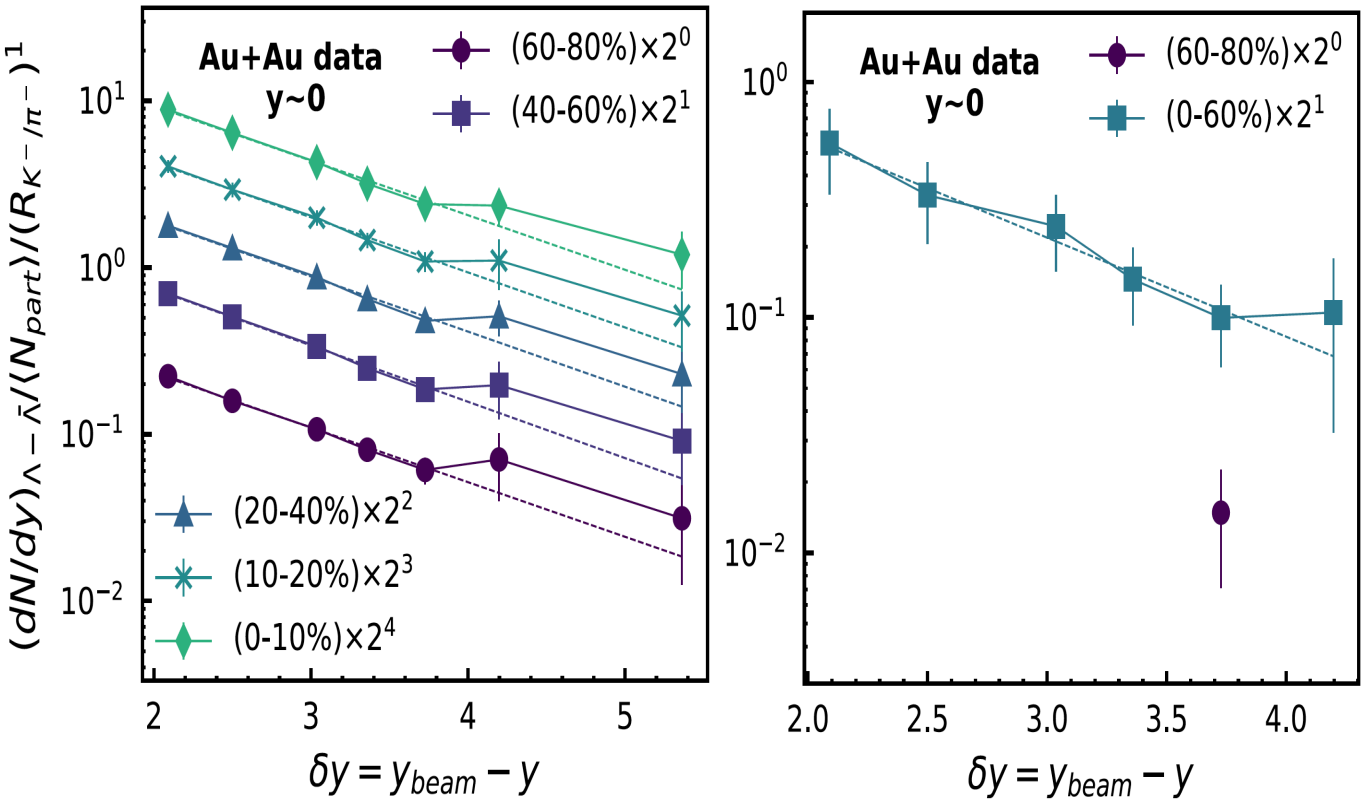
STAR, PRC 79, 034909 (2009)
STAR, PRC 96, 044904 (2017)
Nicole Lewis et al., EPJC84, 590 (2024)



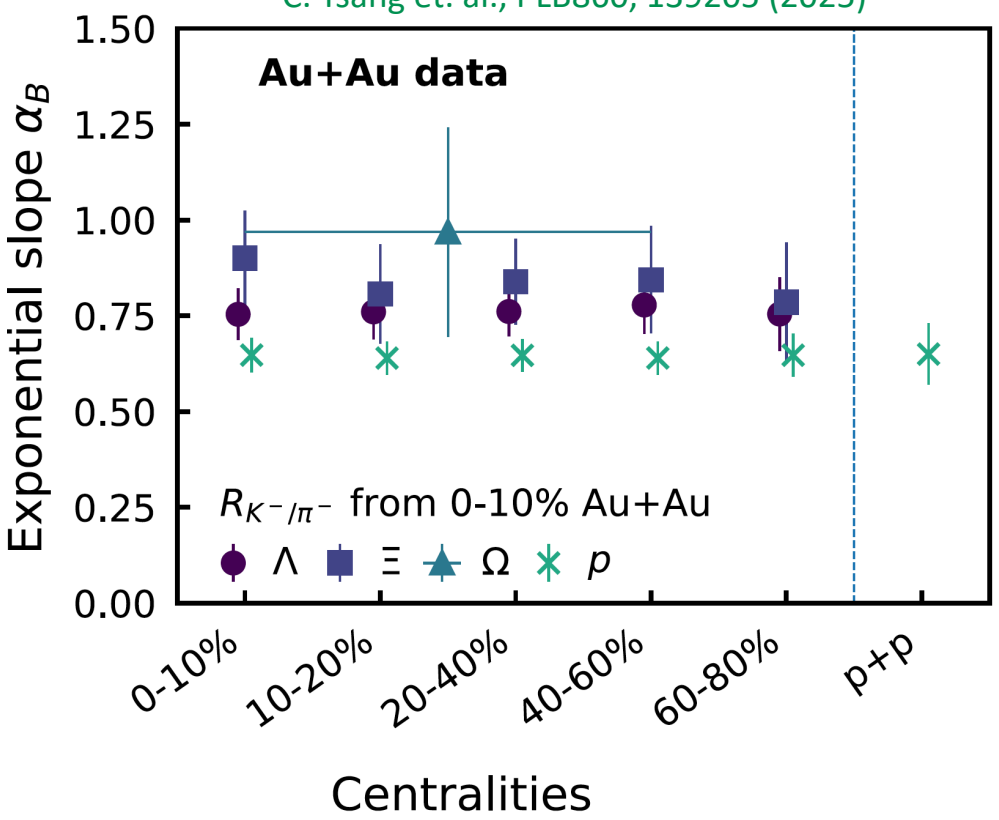
STAR, 2408.15441

- Scaling in all centralities and collision energies
- Slopes do not depend on centrality
  - Different from UrQMD model predictions
  - Baryon stopping at mid-y is not due to multiple scattering
  - PYTHIA with partial implementation of baryon junction describes data better

Slope for Net Hyperons



C. Tsang et. al., PLB860, 139205 (2025)

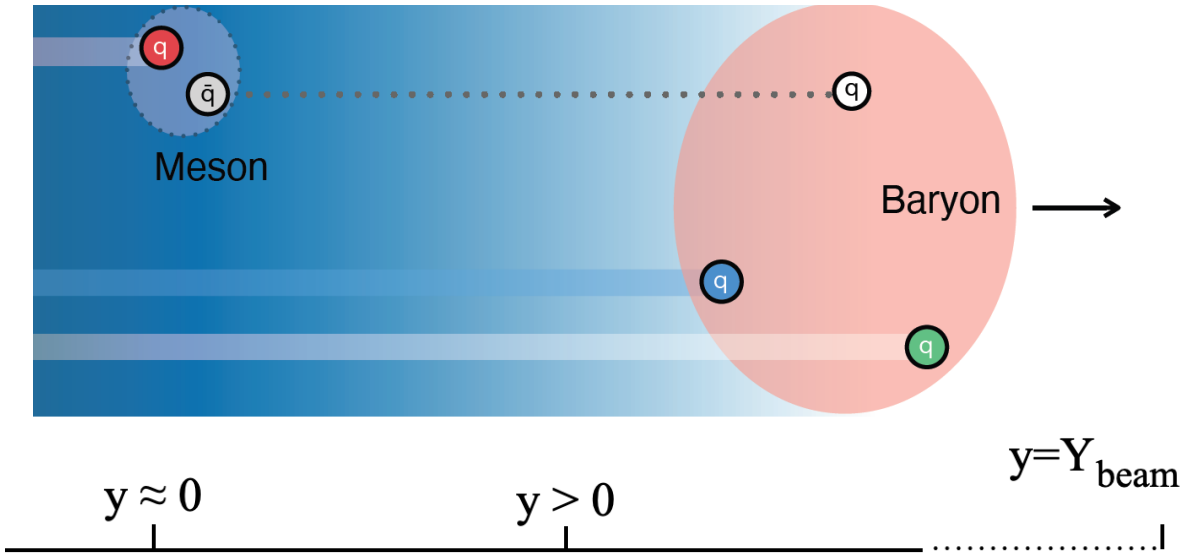


- Net-hyperons yield from BES-I are analyzed
- Suppression of strangeness taken out by $(K/\pi)^n$ factor
- Follows exponential nicely for Λ, Ξ and Ω

- No particle species dependence
- Flavor-blind baryon transport mechanism → baryon junction

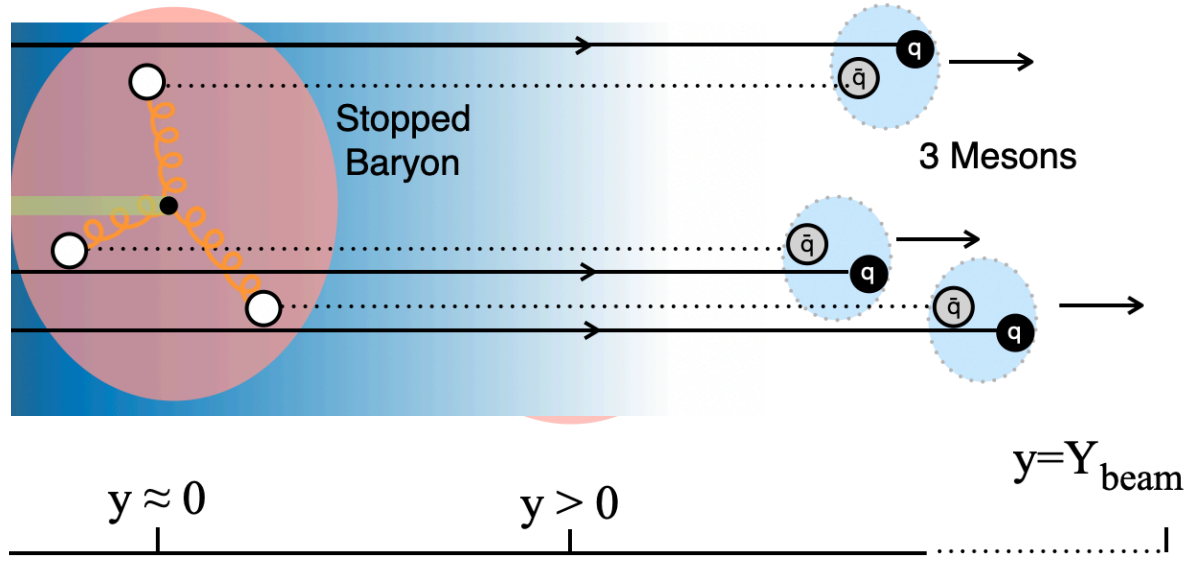
Correlations of Net-Baryons and Net-Charges

Valence quark stopping



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

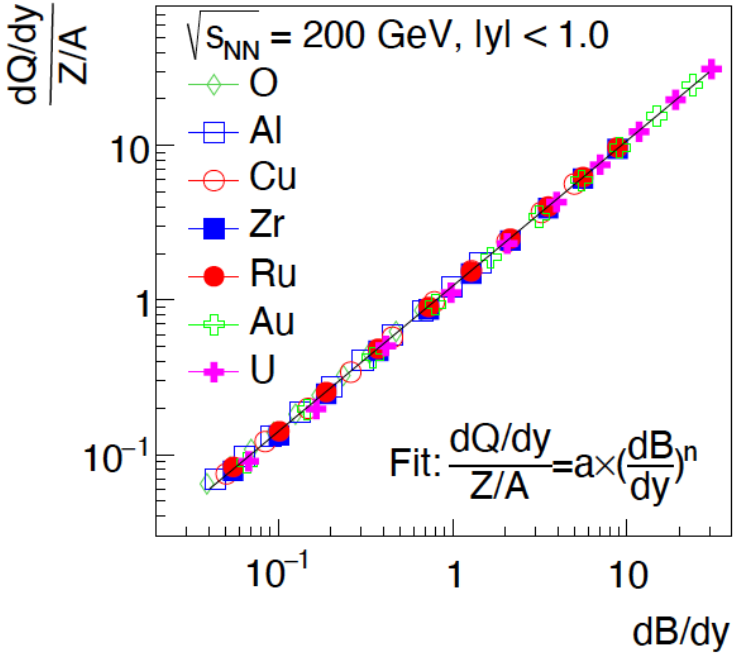
Baryon junction stopping



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

Net–Charges vs. Net–Baryons from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering



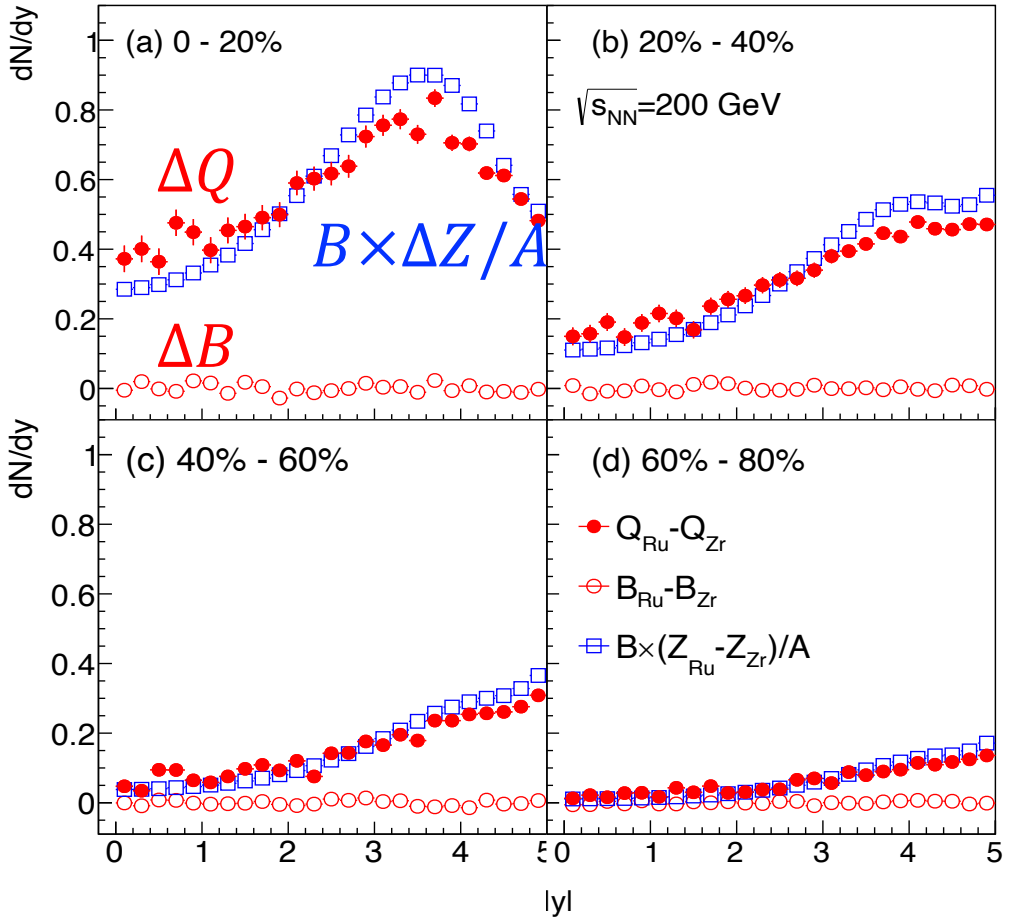
Nucleus	Z	A	Z/A
O	8	16	0.500
Al	13	27	0.481
Cu	29	64	0.453
Zr	40	96	0.417
Ru	44	96	0.458
Au	79	197	0.401
U	92	238	0.386

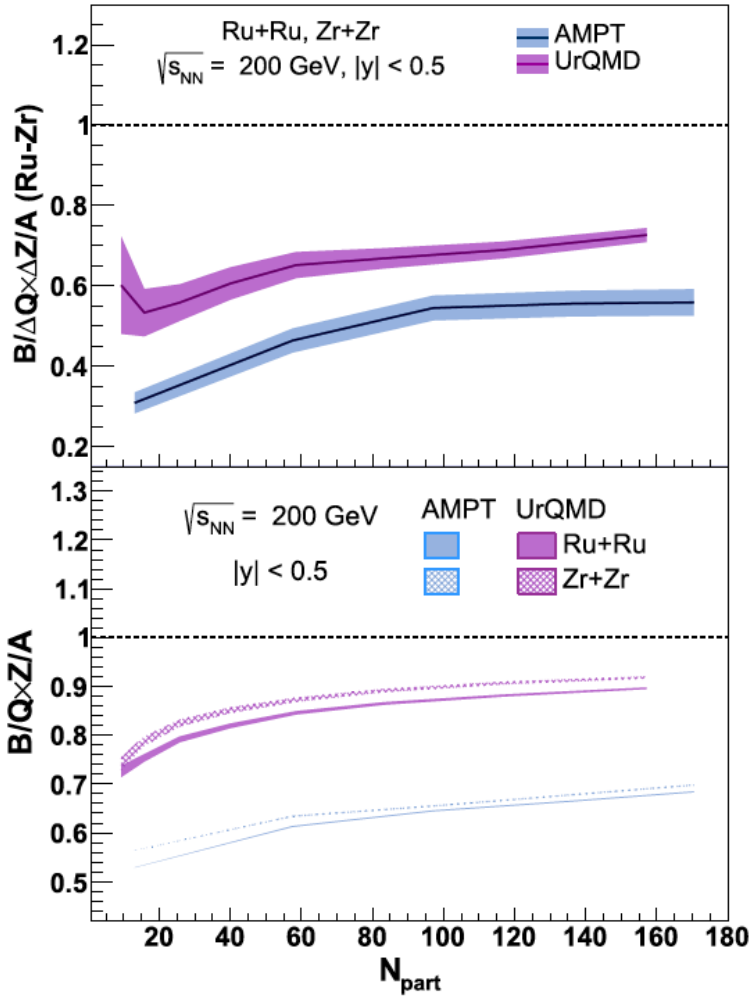
Wendi Lv et al., CPC48, 044001 (2024)

- Net-charges vs. net-baryons scales with Z/A in UrQMD
- Expected different between quark stopping and junction stopping:
  - 25% in O+O vs. Au+Au collisions
  - 10% in Ru+Ru vs. Zr+Zr collisions
- Isobar collisions provide unique experimental opportunities

Net-Charges and Net-Baryons in Isobaric Collisions

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

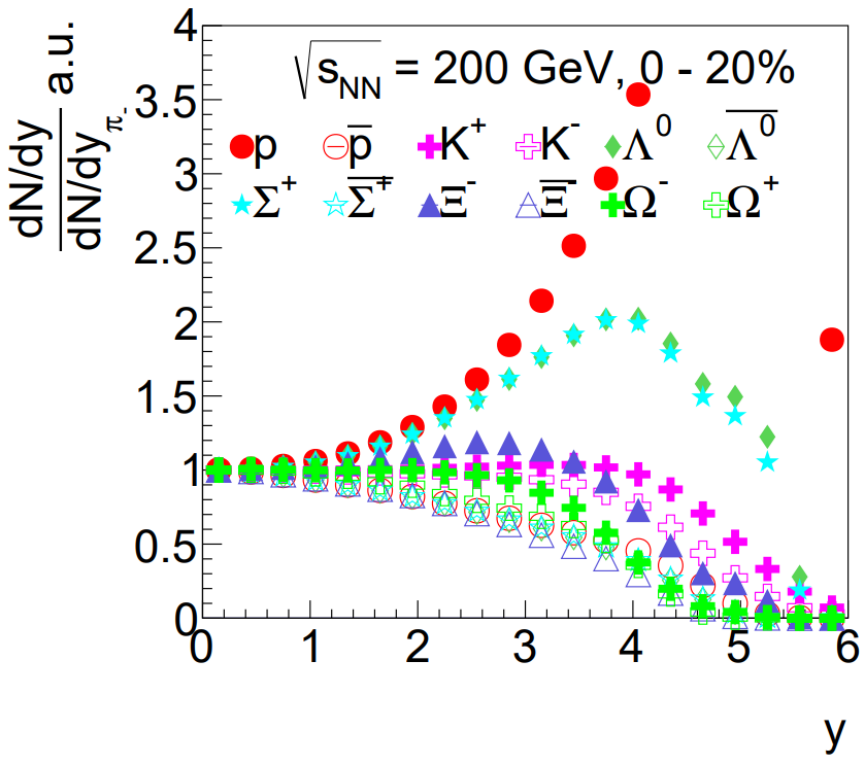


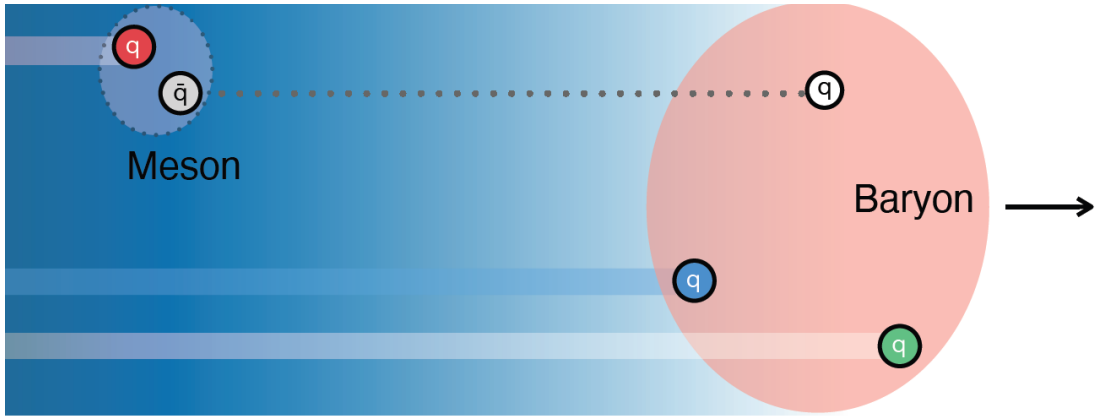


- ΔB is almost zero
- ΔQ is close to BxΔZ/A

B/ΔQxΔZ/A is less than unity in all centralities

Why Is It Smaller Than Unity?





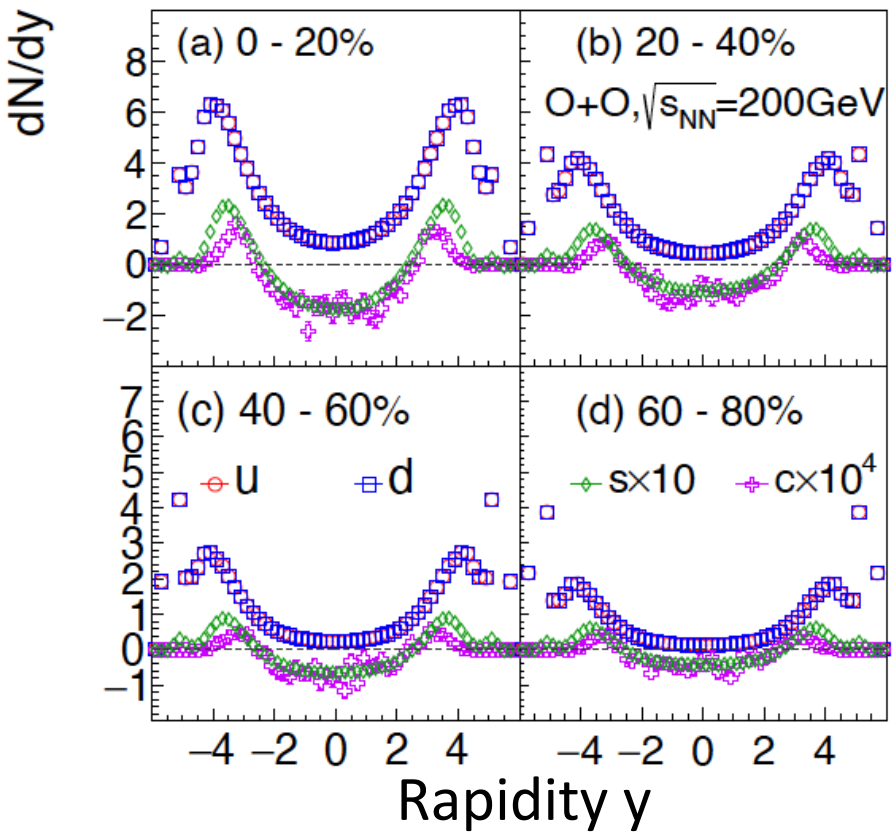
- Strange quarks seem be dragged to fragmentation rapidity to form hyperons

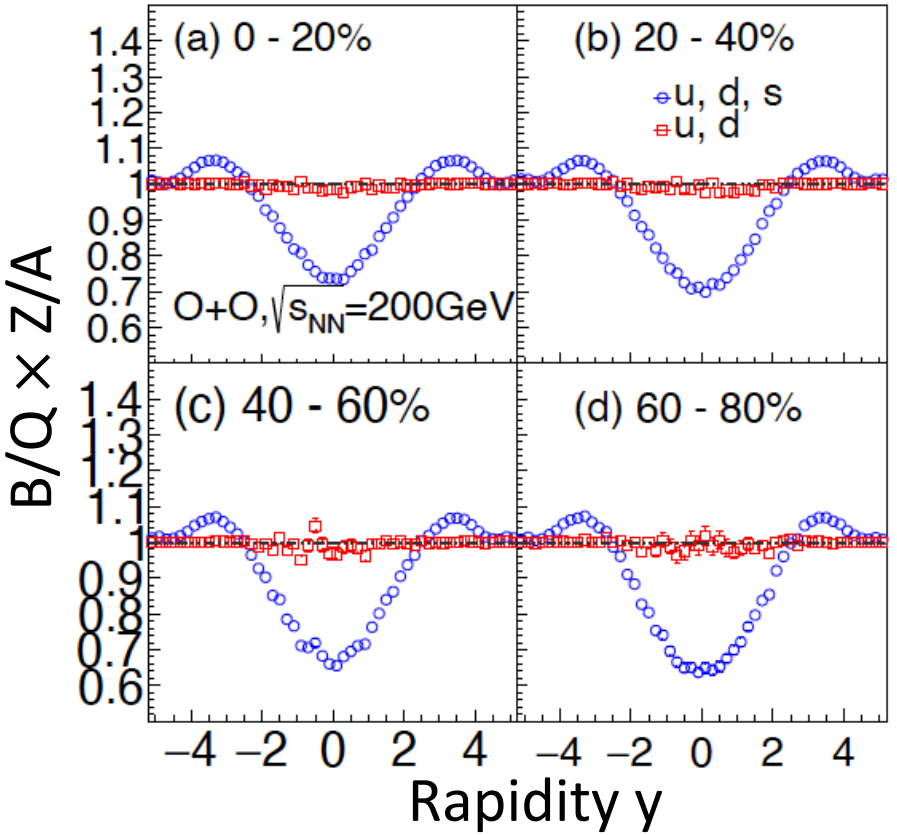
Width of the rapidity distribution:

p/n > Λ/Σ > Ξ ~ K ~ π > Ω > Anti-hyperons

- Leaves anti-strange quark at mid-y

Rapidity Distribution of Net-Quarks and B/Q

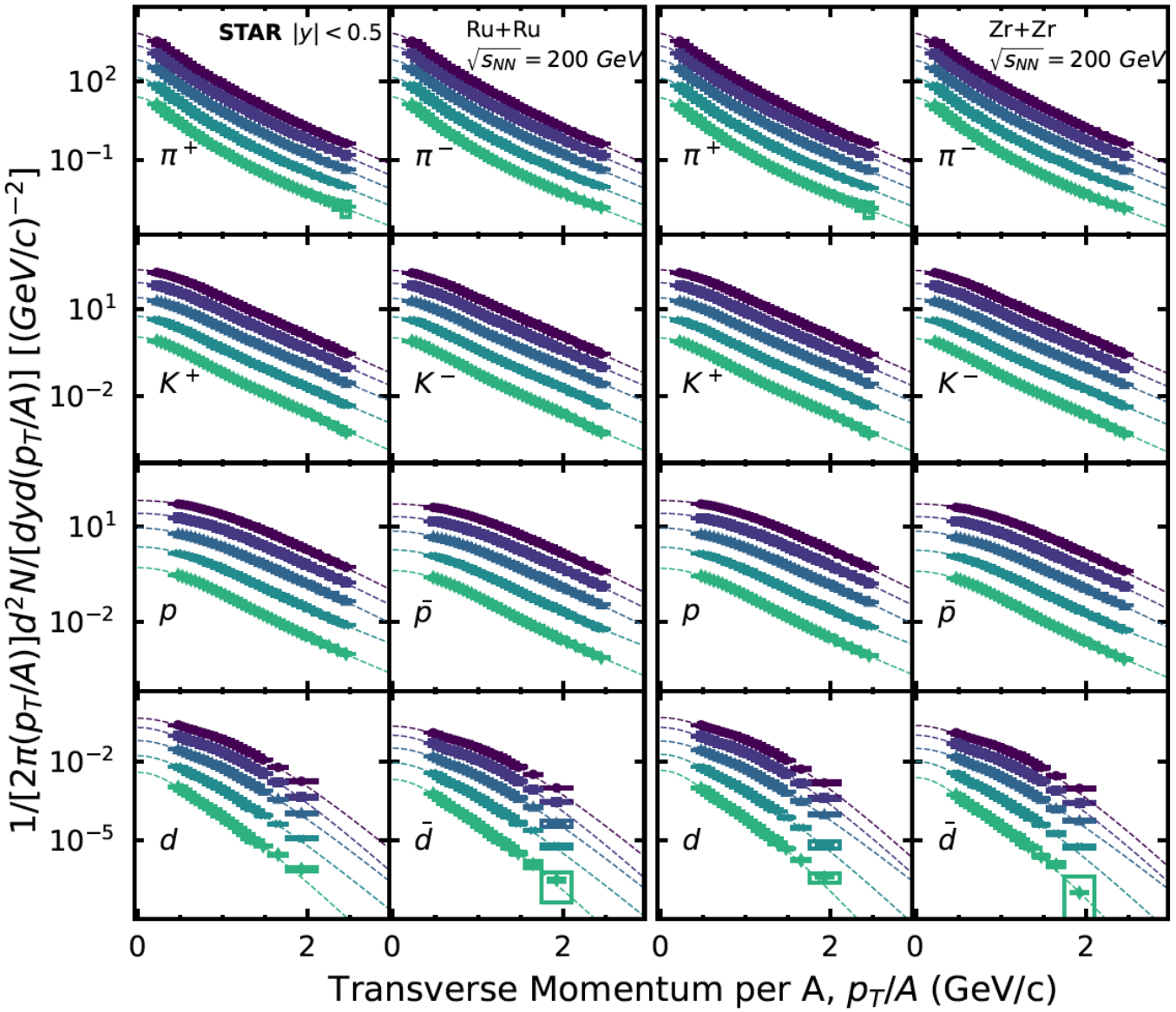




- Net strange quarks increases from negative at mid-y to positive at forward
- Similar behavior for charm quarks (less important due to low yield)

- B/Q ~ A/Z at mid-y when *s*-quarks are excluded from B and Q calculations
- B/Q less than A/Z when s-quarks are included as an anti-*s* contributes +1/3e

Measurements of Spectra in Ru+Ru/Zr+Zr Collisions



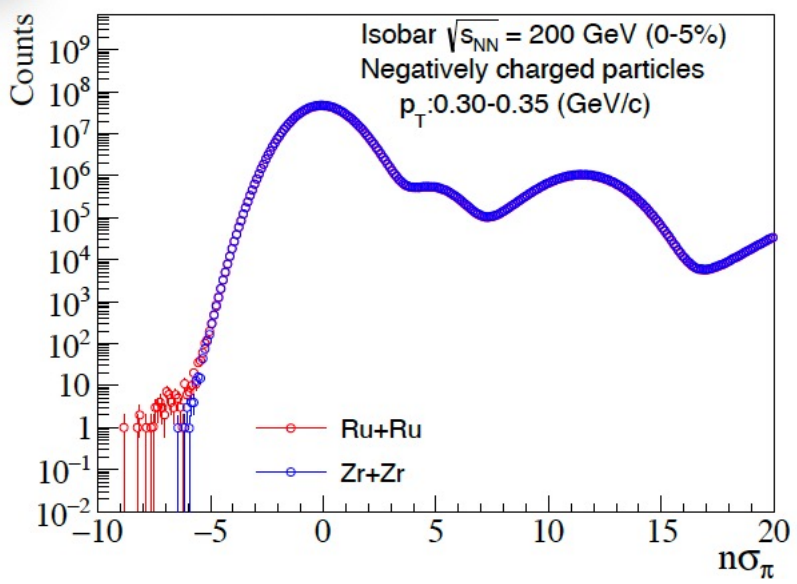
Charged hadrons identified in broad p_T range by TPC+TOF

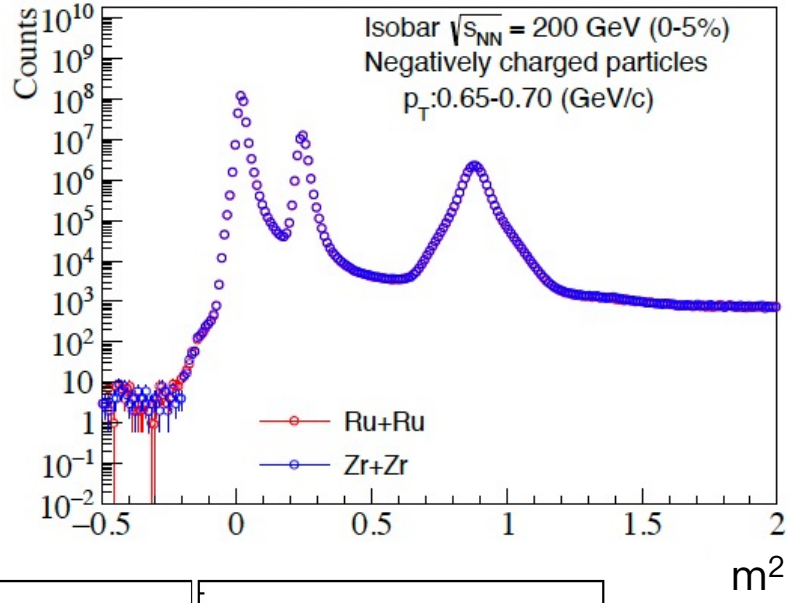
Blast-wave model used to extrapolate to unmeasured p_T range

Yang Li, PhD thesis, USTC (2023)
STAR, arXiv:2408.15441

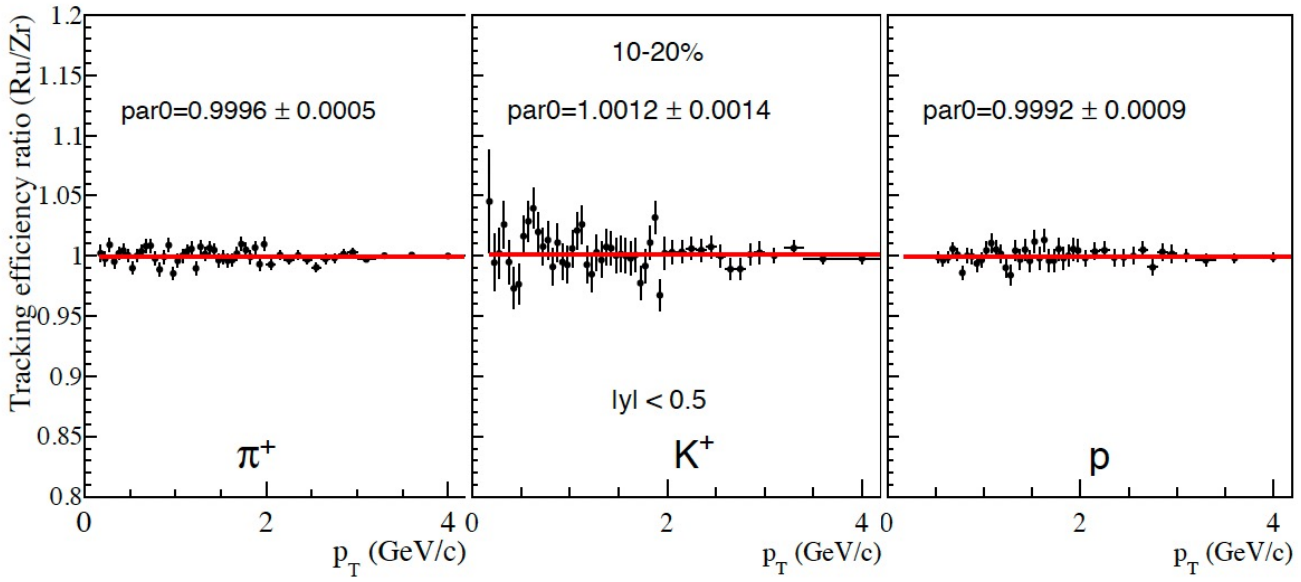
Inclusive yields
Blast-wave
0-10%×2^4
10-20%×2^3
20-40%×2^2
40-60%×2
60-80%×1

Exactly Same Behaviors in Difference Systems





Same distributions of dE/dx and m^2



Same efficiency

Calculation of Net-Charge Difference

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

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

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

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

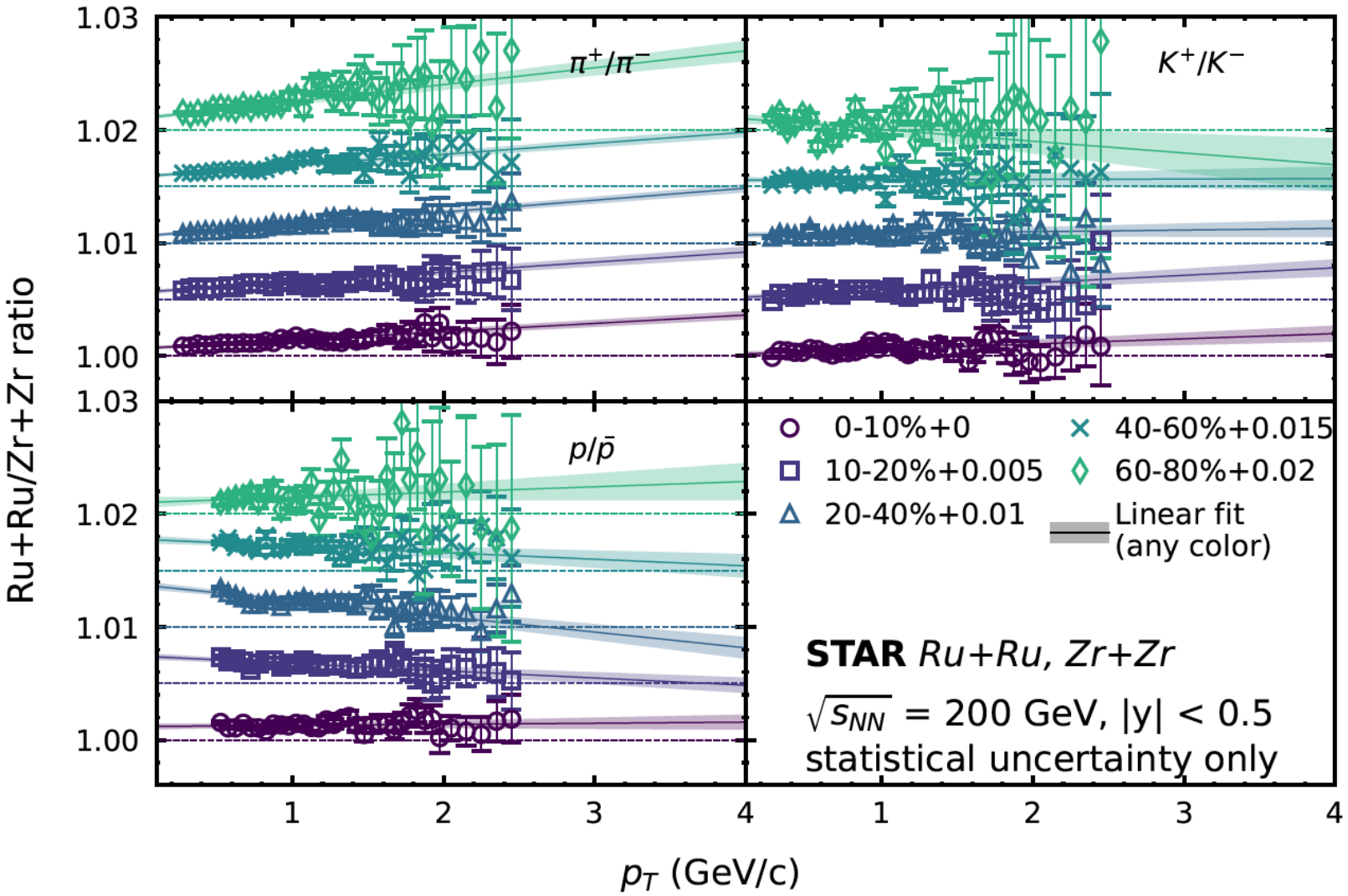
$$\left(N_{\pi^+} - N_{\pi^-}\right)^{Ru} - \left(N_{\pi^+} - N_{\pi^-}\right)^{Ru} \approx 2N_{\pi}\left(\frac{R_{\pi}^{Ru} - 1}{R_{\pi}^{Ru} + 1} - \frac{R_{\pi}^{Zr} - 1}{R_{\pi}^{Zr} + 1}\right)$$

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

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

Double ratio method to preserve high precision measurements of net-charge and net-baryon

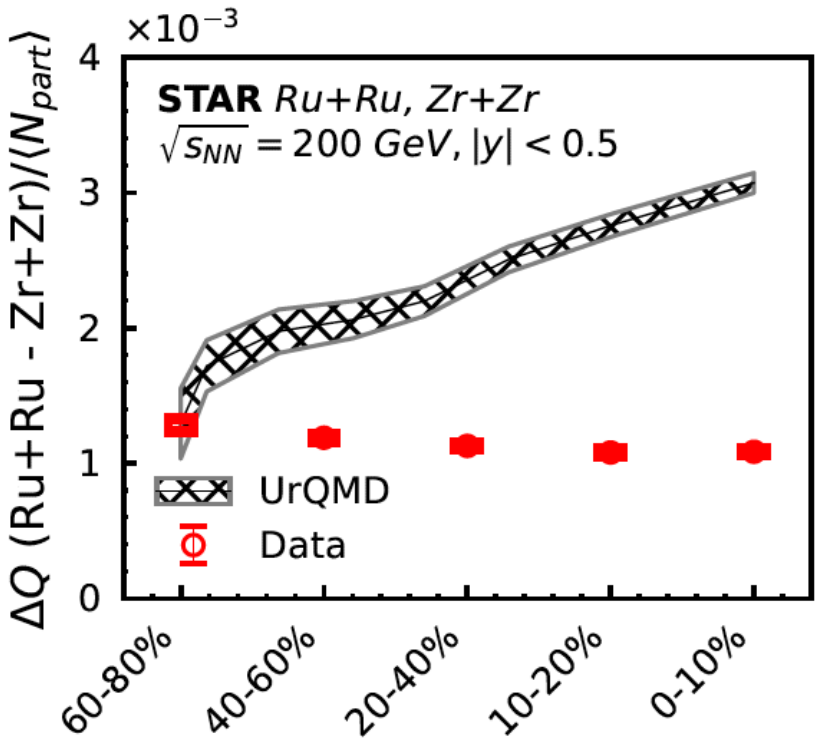
Measurement of Double Ratios

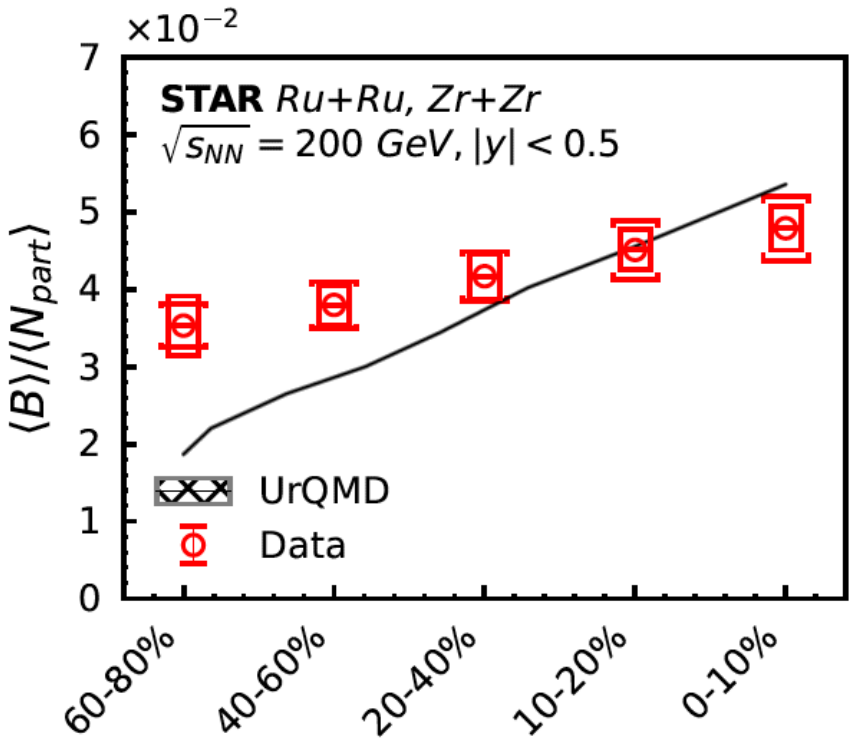


- Precise measurement of double ratios of identified charged particles
- Systematic uncertainties largely cancel out
- The double ratios of both π^+/π^- and $p/\bar{p}$ are larger than 1

Yang Li, PhD thesis, USTC (2023)
STAR, arXiv:2408.15441

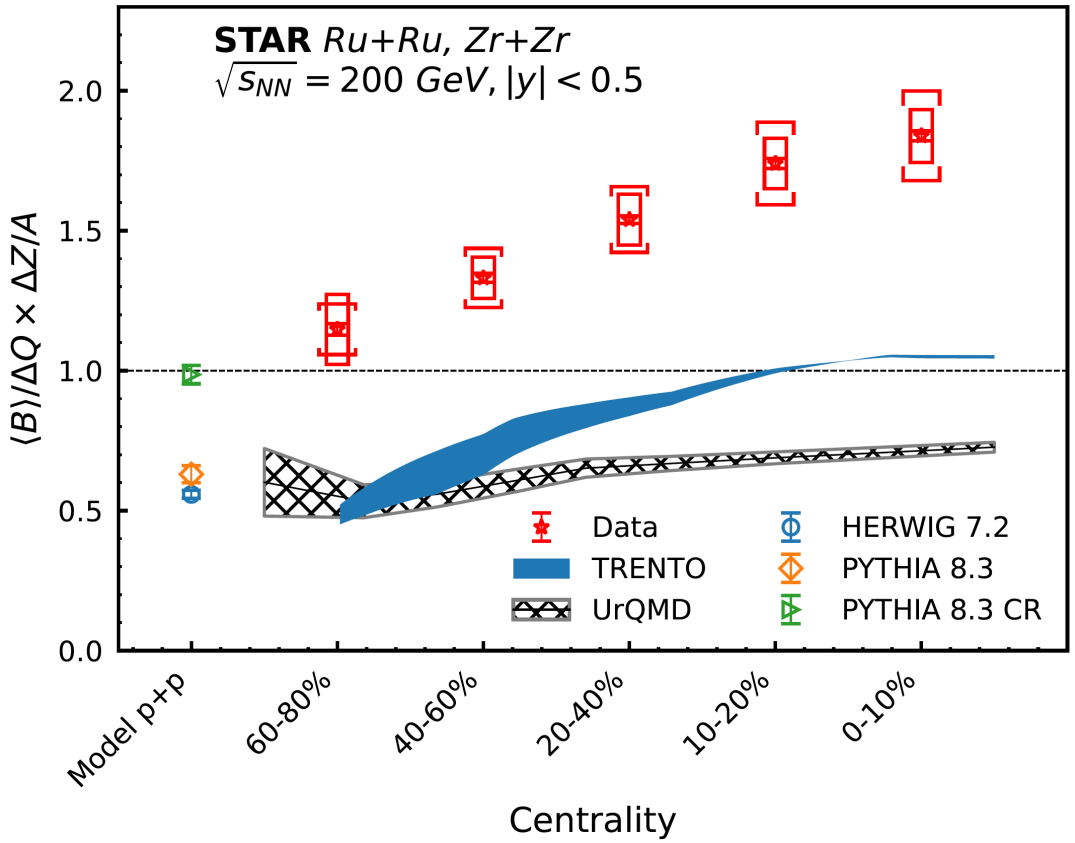
Net-Charge and Net-Baryon Compared to UrQMD





- Precise measurement of net-charge difference and net-baryon
- UrQMD reproduces baryon stopping at mid-y in central collisions
  - Probably because UrQMD has been tuned to net-proton measurements
- But overpredict ΔQ by a factor of 3 in central collisions

Measurement of B/ΔQ in Ru+Ru/Zr+Zr Collisions

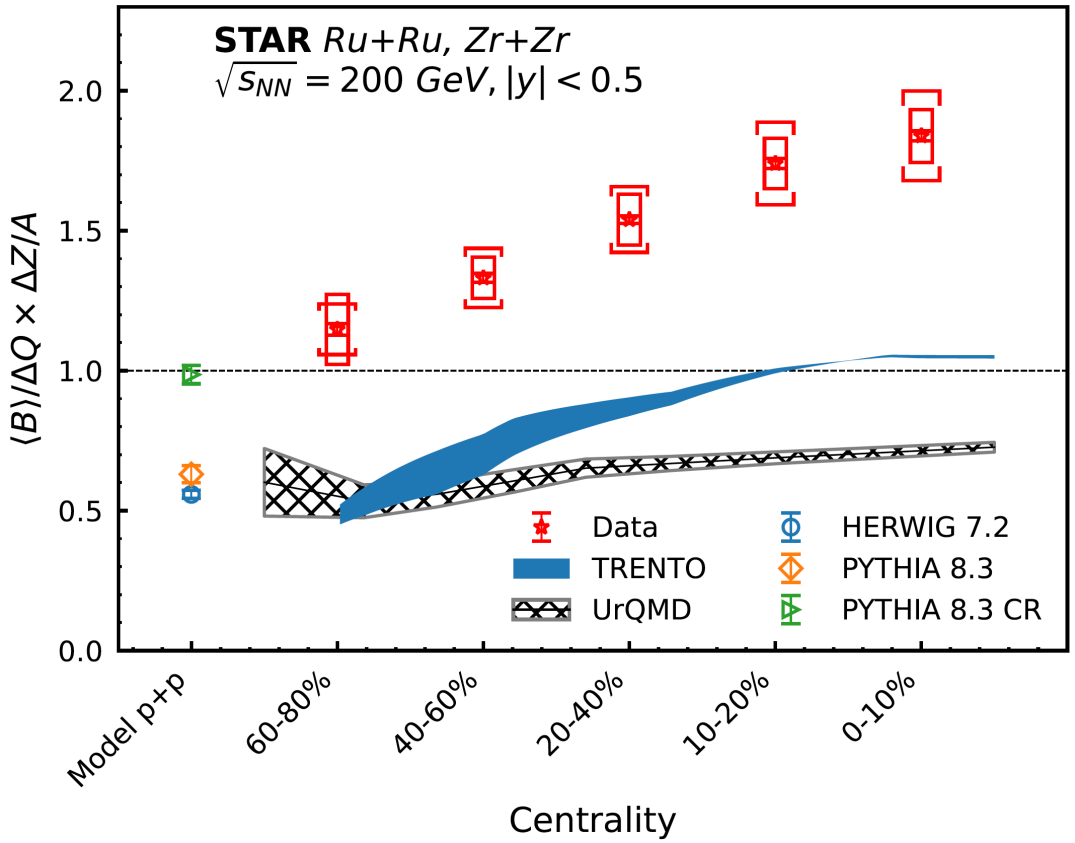


HERWIG: J. Bellm et al, EPJC80, 452 (2020)

UrQMD: M. Bleicher et al, JPG25, 1859 (1999)

- 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/ΔQ in Ru+Ru/Zr+Zr Collisions



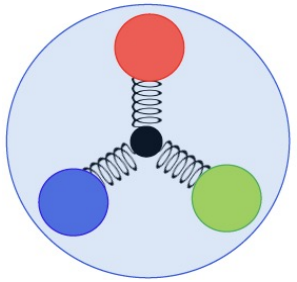
HERWIG: J. Bellm et al, EPJC80, 452 (2020)

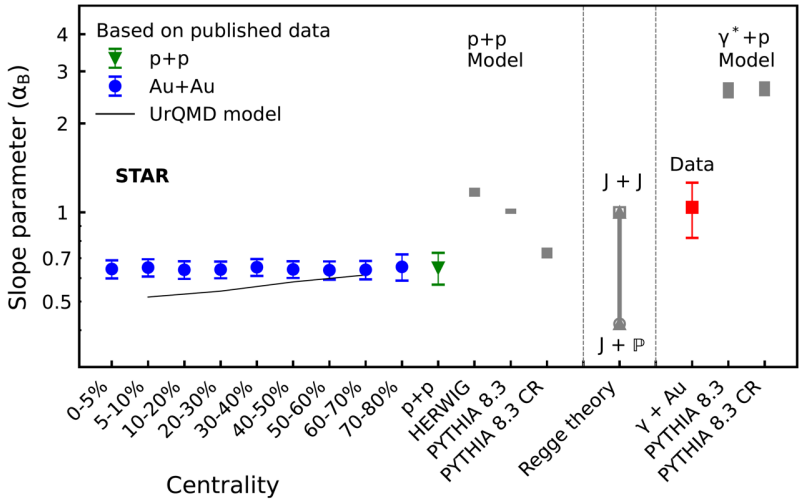
UrQMD: M. Bleicher et al, JPG25, 1859 (1999)

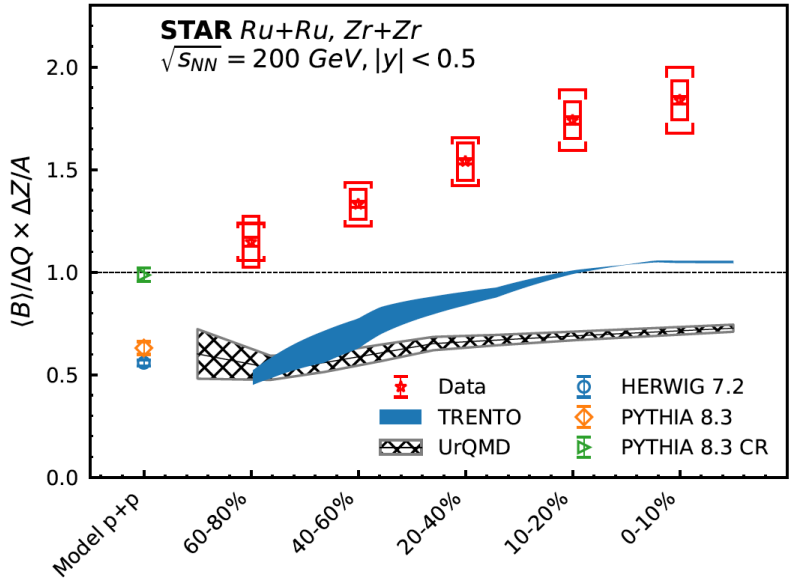
- PYTHIA with CR (baryon junction implemented in baryon formation) describes better the data than the default PYTHIA
- Scenario of quark carrying baryon number is disfavored

Summary

- What carries baryon number, baryon junctions or valence quarks, it is a question
- Three experimental observations favor baryon junctions against valence quarks
  - Slope of net-proton rapidity loss distribution in Au+Au collisions
  - Slope of net-proton rapidity distribution in photon+Au collisions
  - Net-baryon over net-charge ratio in Isobar collisions



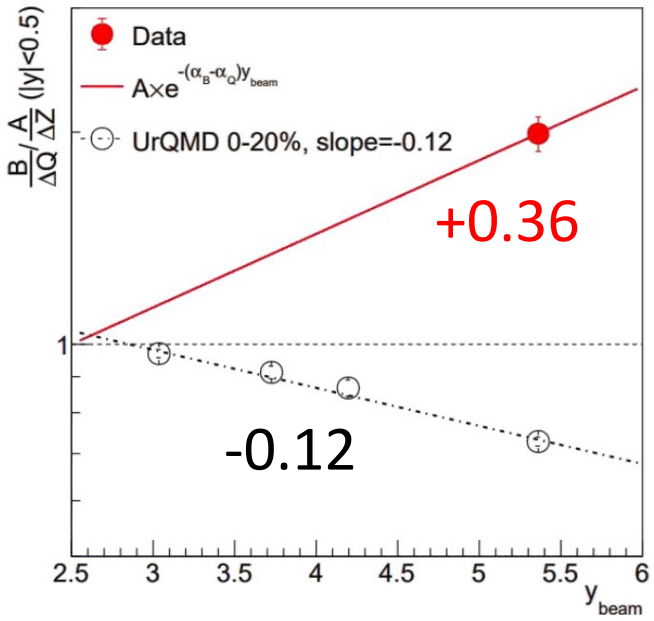




Outlook

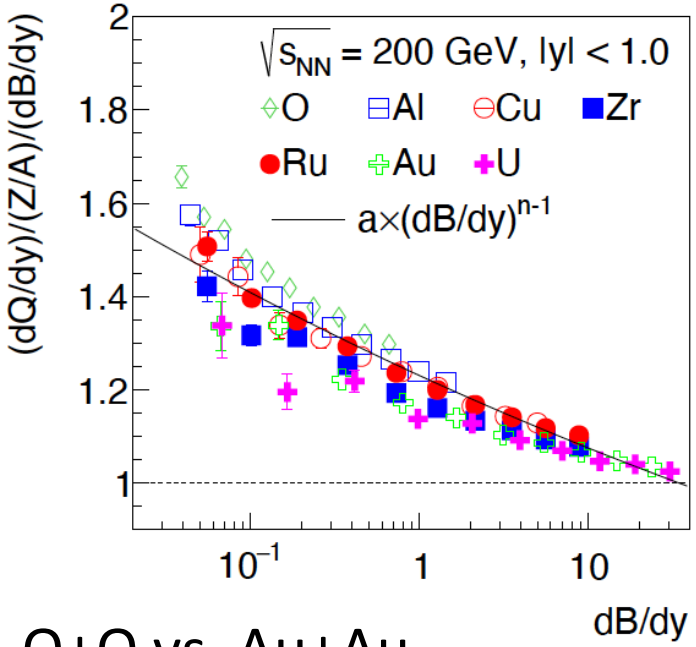
Rapidity loss method

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



Thanks!

Baryon-flavor correlation method



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

- Beam energy scan of isobar collisions