重庆大学STAR区域研讨会，2024年10月10-15日

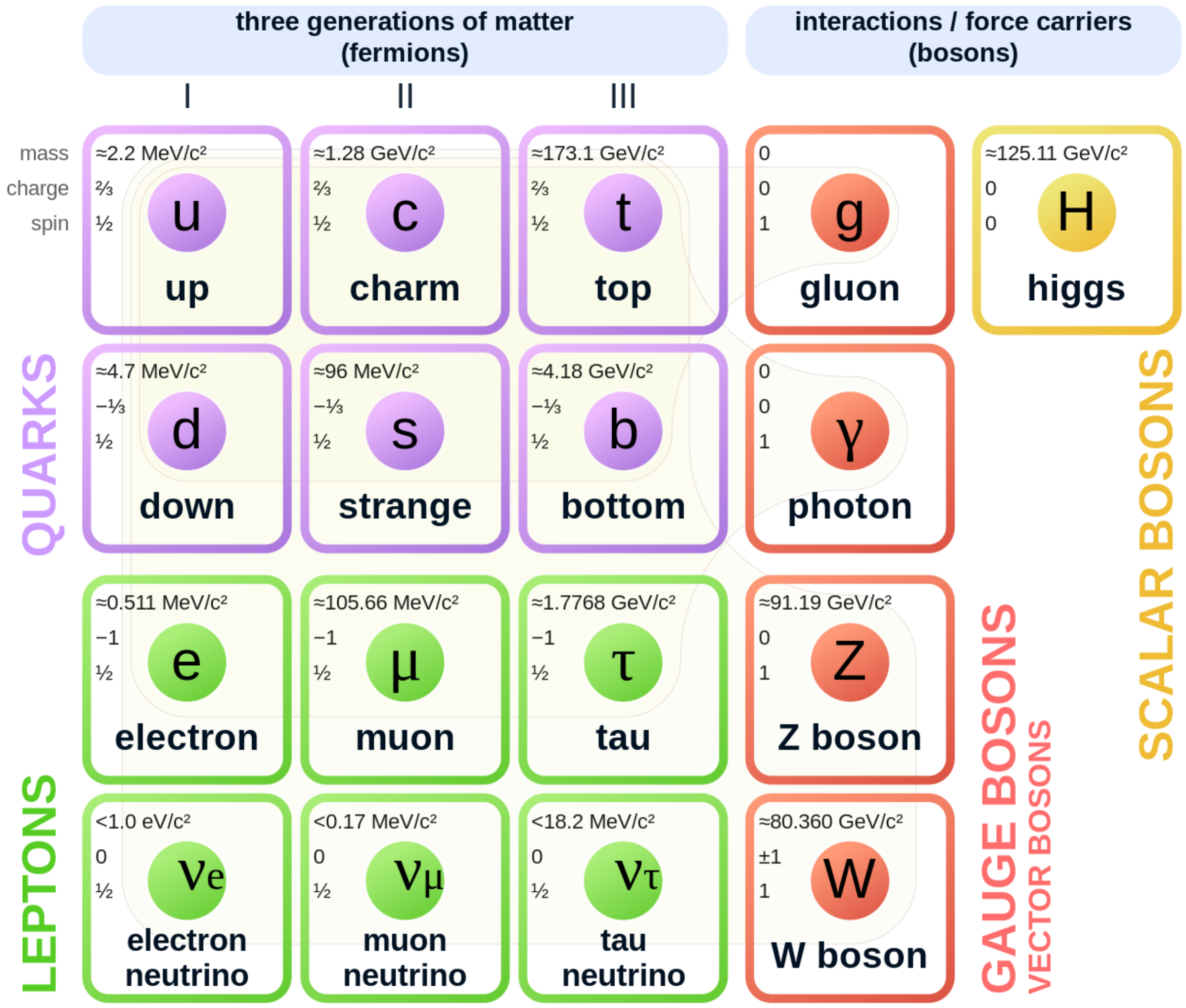
Track Baryon Number with Heavy Ion Collisions

Zebo Tang
Department of Modern Physics,
State Key Laboratory of Particle Detection and Electronics,
University of Science and Technology of China

STAR, arXiv:2408.15441, submitted to Science
Nicole Lewis et al., EPJC84, 590 (2024)
W. Lv et al., CPC48, 044001 (2024)

Quark Model and Baryon Number Carrier

Standard Model of Elementary Particles

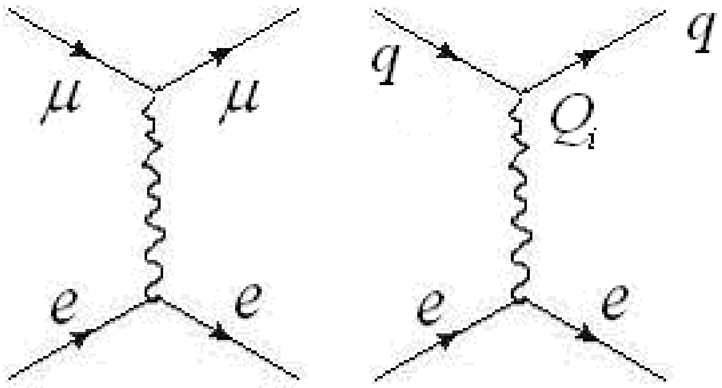


https://en.wikipedia.org/wiki/Quark

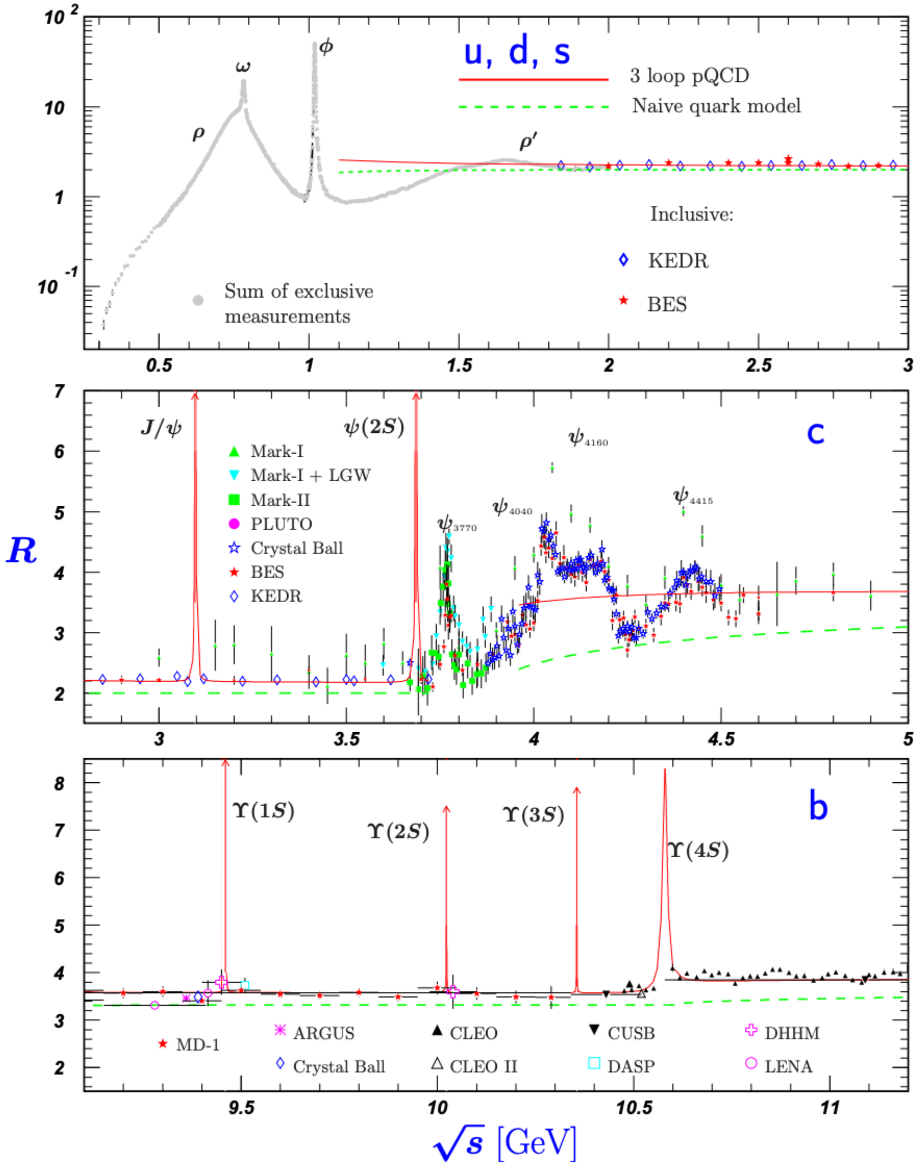
As building brick of matter, a quark has:

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

R-Value



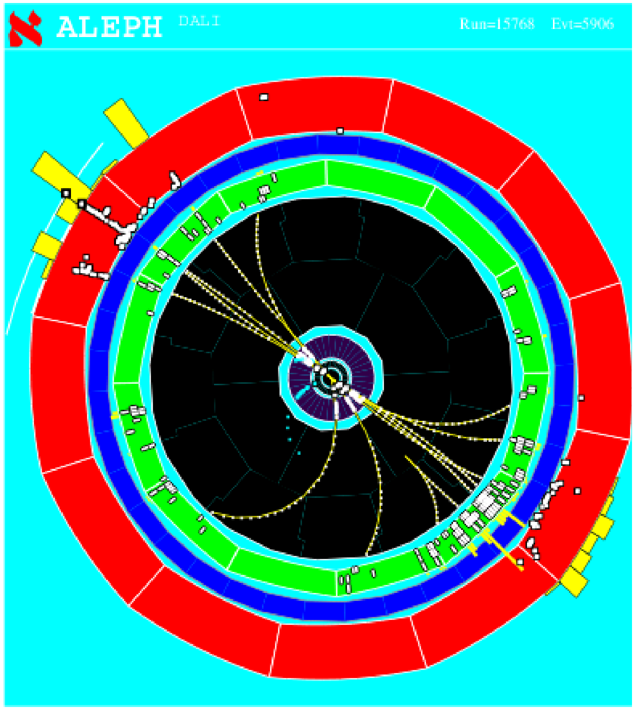
$$R = N_c \sum_f Q_f^2$$

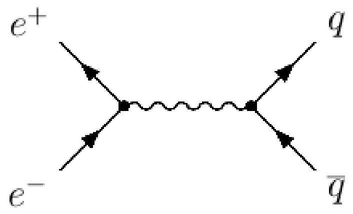


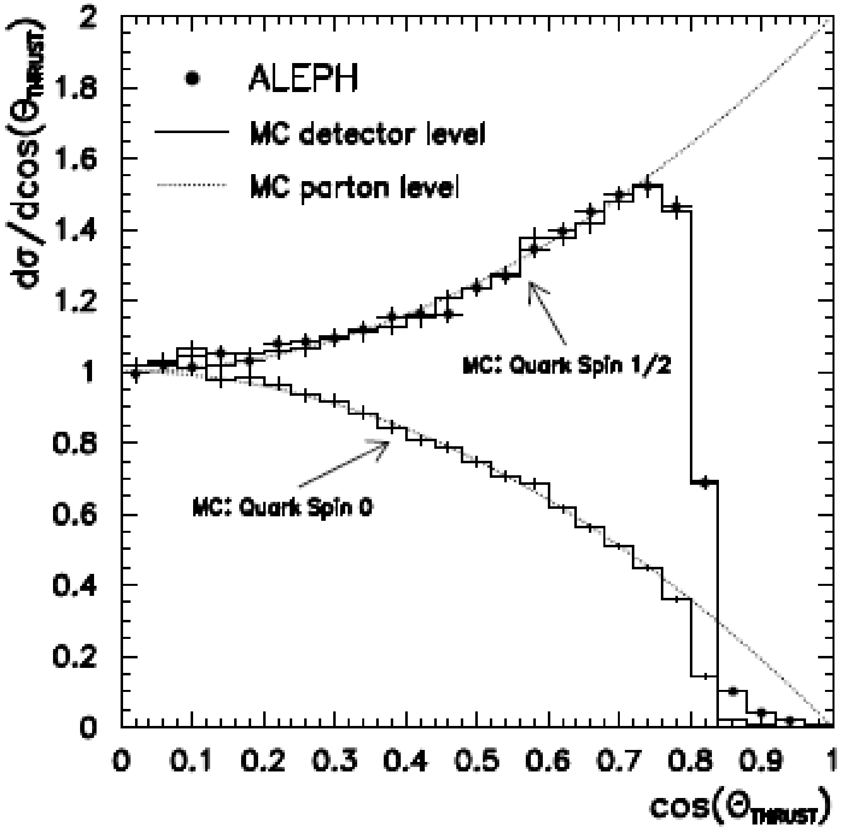
Evidence of quark' s

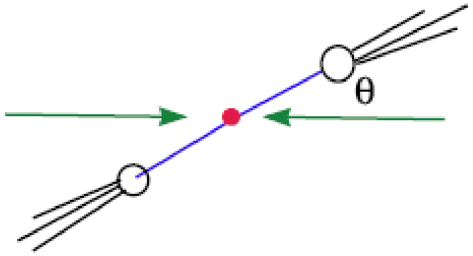
- Color (N_c=3)
- Flavor and mass
- Charge

Spin of Quark









ALEPH, Phys. Rep. 294, 1 (1998)

Spin-1/2 curve in excellent agreement with data

Spin-0 variant is clearly incompatible with data

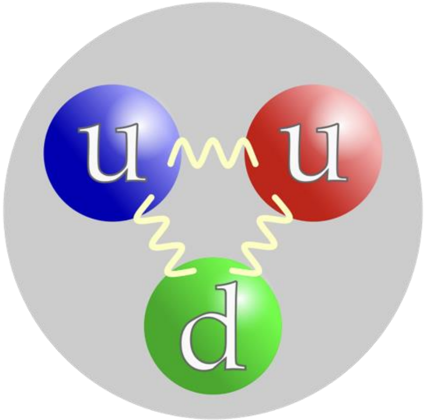
Does Quark Carry Baryon Number?

PDG particle data group

15.2 Quantum numbers of the quarks

As gluons carry no intrinsic quantum numbers beyond color charge, and because color is believed to be permanently confined, the quantum numbers of strongly interacting particles are given by the quantum numbers of their constituent quarks and antiquarks.

Quarks are strongly interacting fermions with spin 1/2 and, by convention, positive parity. Antiquarks have negative parity. Quarks have the additive baryon number 1/3, antiquarks -1/3.



https://en.wikipedia.org/wiki/Quark

- PDG says: Baryon number 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?

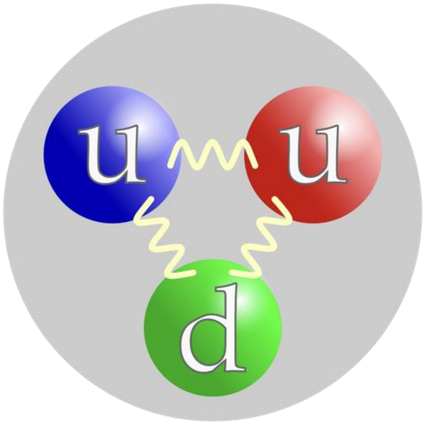
    NO! Valence quarks are not the only objects in a baryon

Alternative Baryon Number Carrier

15.2 Quantum numbers of the quarks

As gluons carry no intrinsic quantum numbers beyond color charge, and because color is believed to be permanently confined, the quantum numbers of strongly interacting particles are given by the quantum numbers of their constituent quarks and antiquarks.

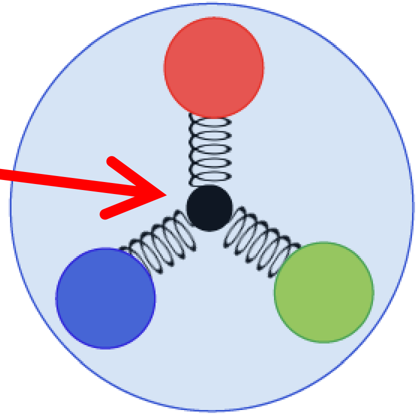
Quarks are strongly interacting fermions with spin 1/2 and, by convention, positive parity. Antiquarks have negative parity. Quarks have the additive baryon number 1/3, antiquarks -1/3.



https://en.wikipedia.org/wiki/Quark

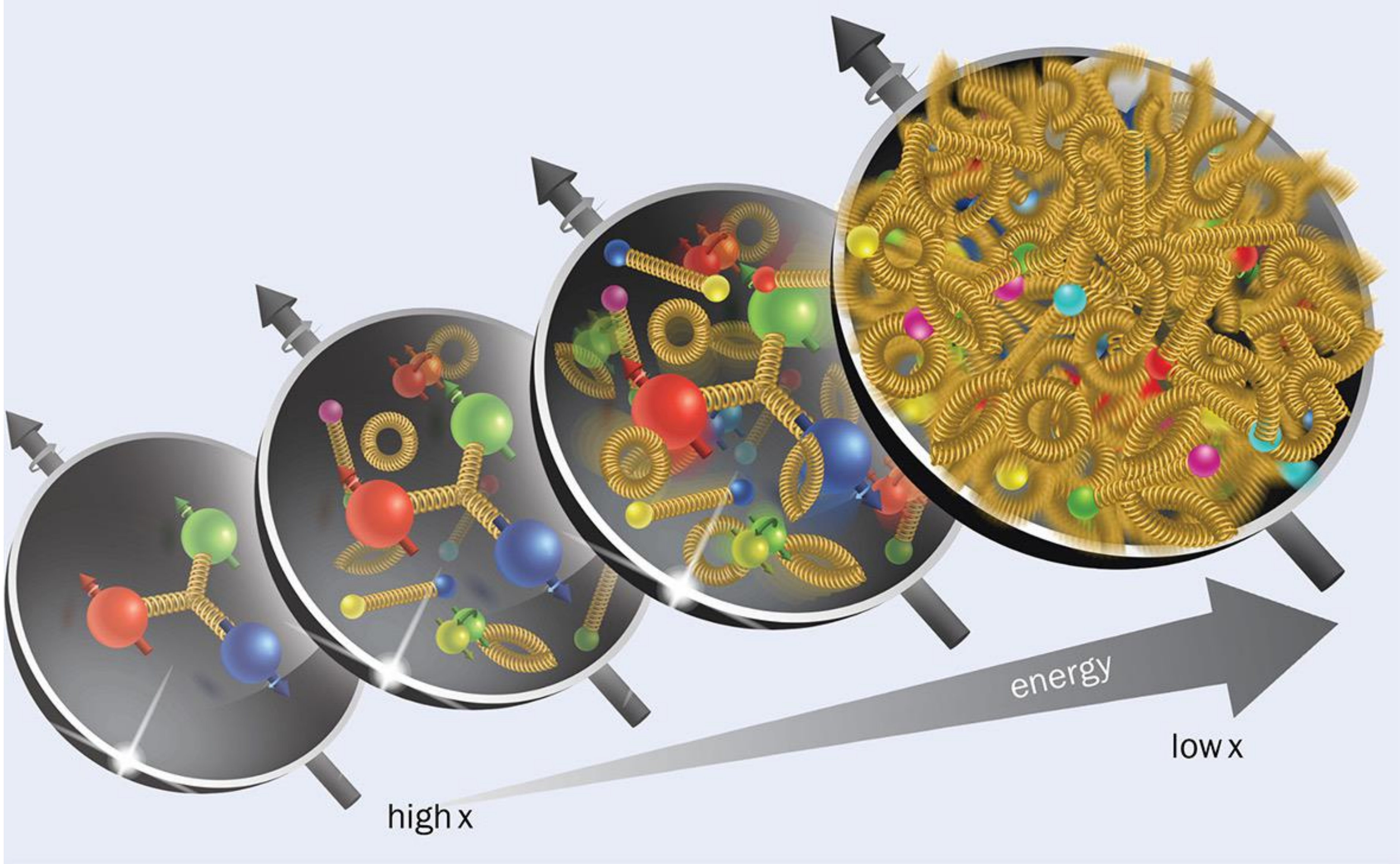
Alternative picture of a proton

- A Y-shaped gluon junction topology carries baryon number (baryon junction)
- Valence quarks are connected to the end of the junction
- Valence quarks do not carry baryon number
- Proposed in 1970s



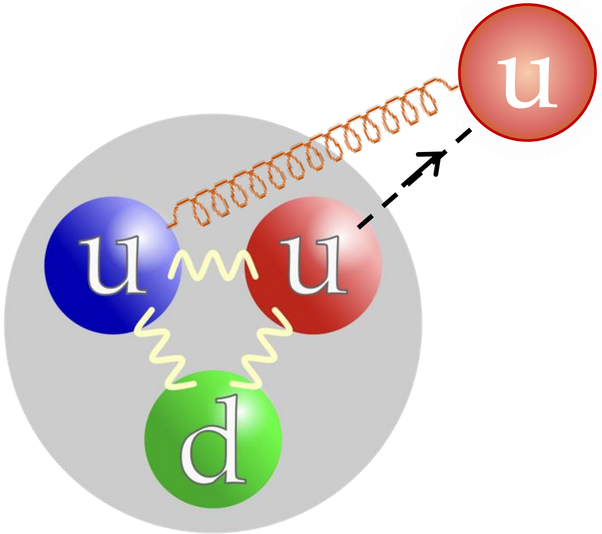
X. Artru, NPB85, 442 (1975)
G. Rossi and G. Veneziano, NPB123, 507 (1977)

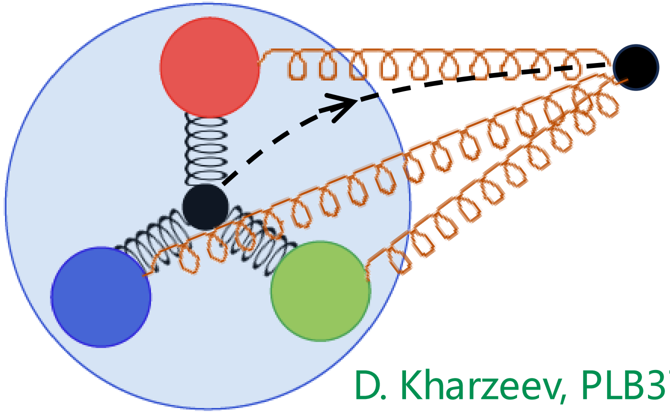
The Simplest QCD Topology



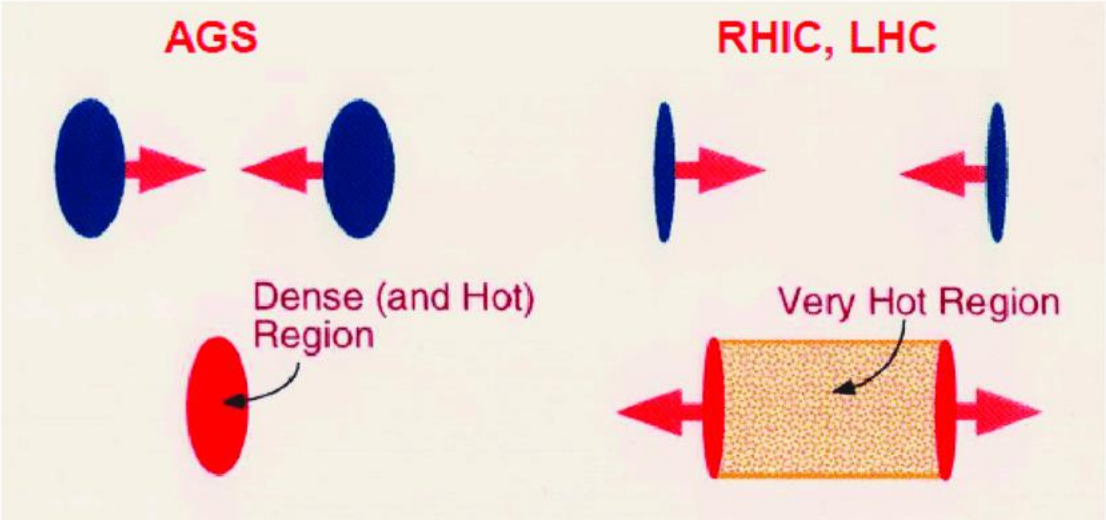
How to Probe the Baryon Number?

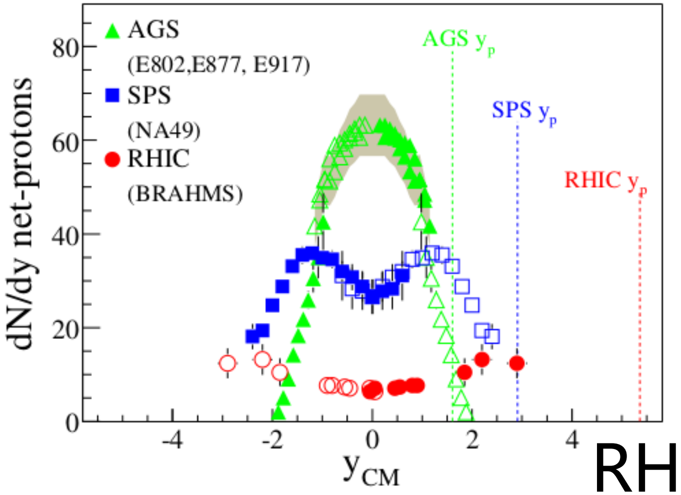
Pull them out: Measure baryon stopping at mid-rapidity in A+A collisions





D. Kharzeev, PLB378, 238 (1996)





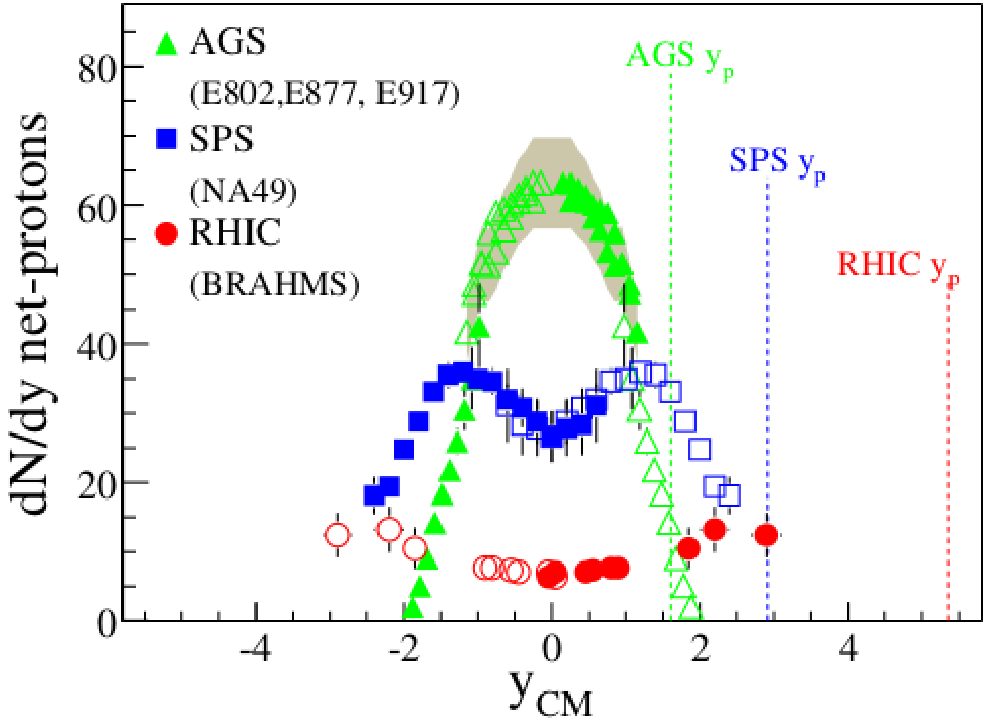
BRAHMS, PRL93, 102301 (2004) and references therein

RHIC is the right place

Method I

Net-Baryon at Mid-rapidity in A+A

Net-Baryons Rapidity Distribution

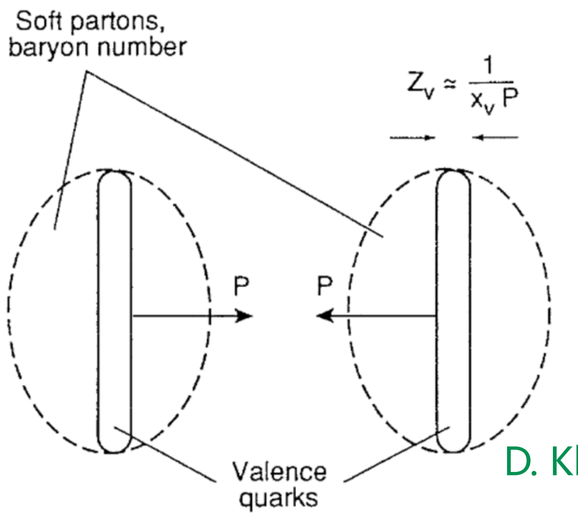


BRAHMS, PRL93, 102301 (2004) and references therein

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



$x_J \ll x_v$

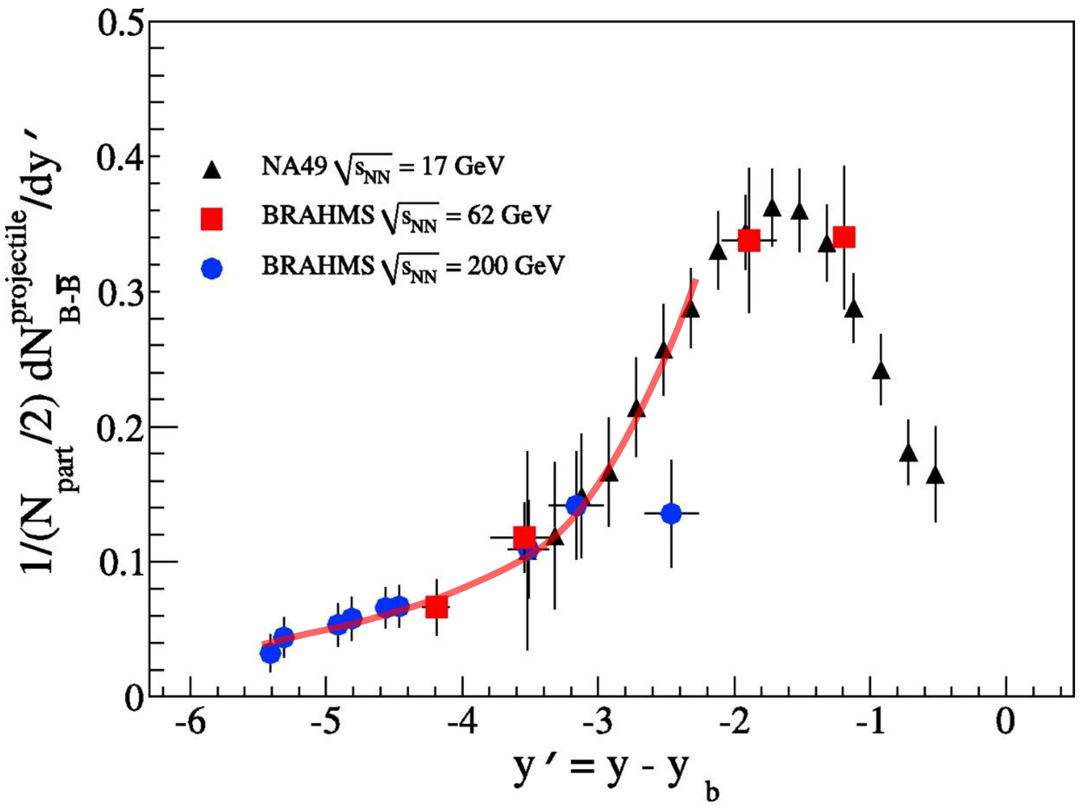
D. Kharzeev, PLB378, 238 (1996)

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

- But multiple scattering may give rise to large rapidity loss

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

Quantifying Baryon Number Transport



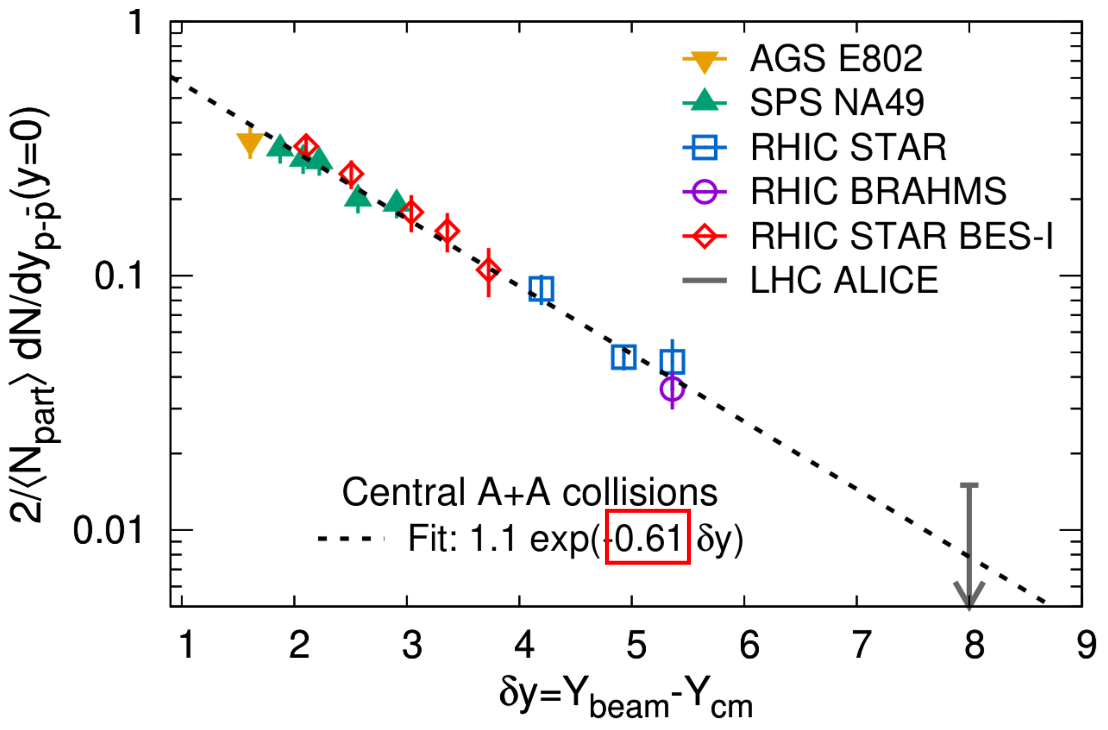
BRAHMS, PLB677, 267 (2009)

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 Mid-y from Various Energies



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

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

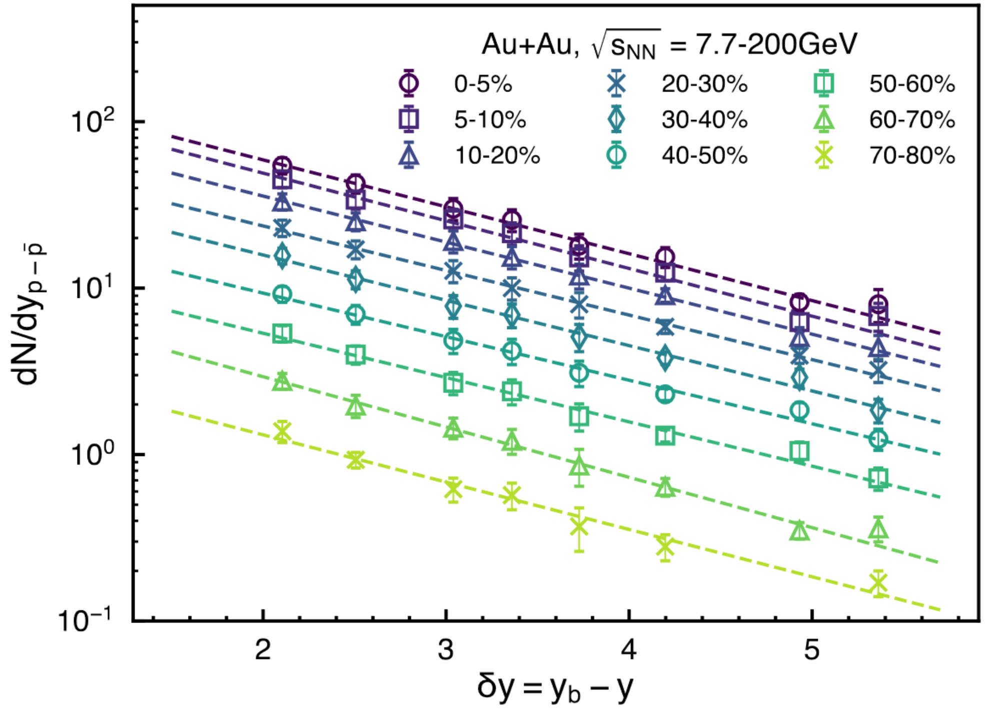
Prediction with junction: $\alpha_B = \begin{cases} 1 & double-baryon\ stopping \\ 0.42 & single-baryon\ stopping \end{cases}$

D. Kharzeev, PLB378, 238 (1996)

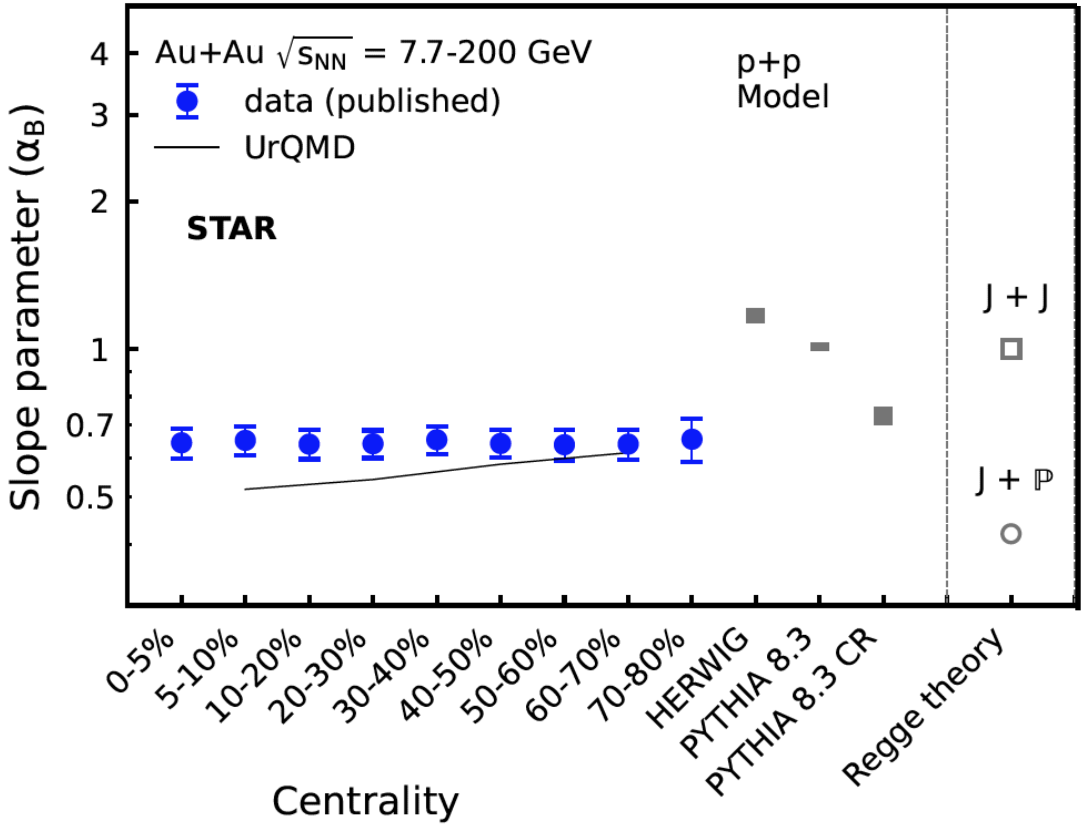
Experiment observation: $\alpha_B = 0.61 \pm 0.03$

Consistent with baryon junction transport by gluons

Centrality Dependence



STAR, PRC 79, 034909 (2009)
STAR, PRC 96, 044904 (2017)

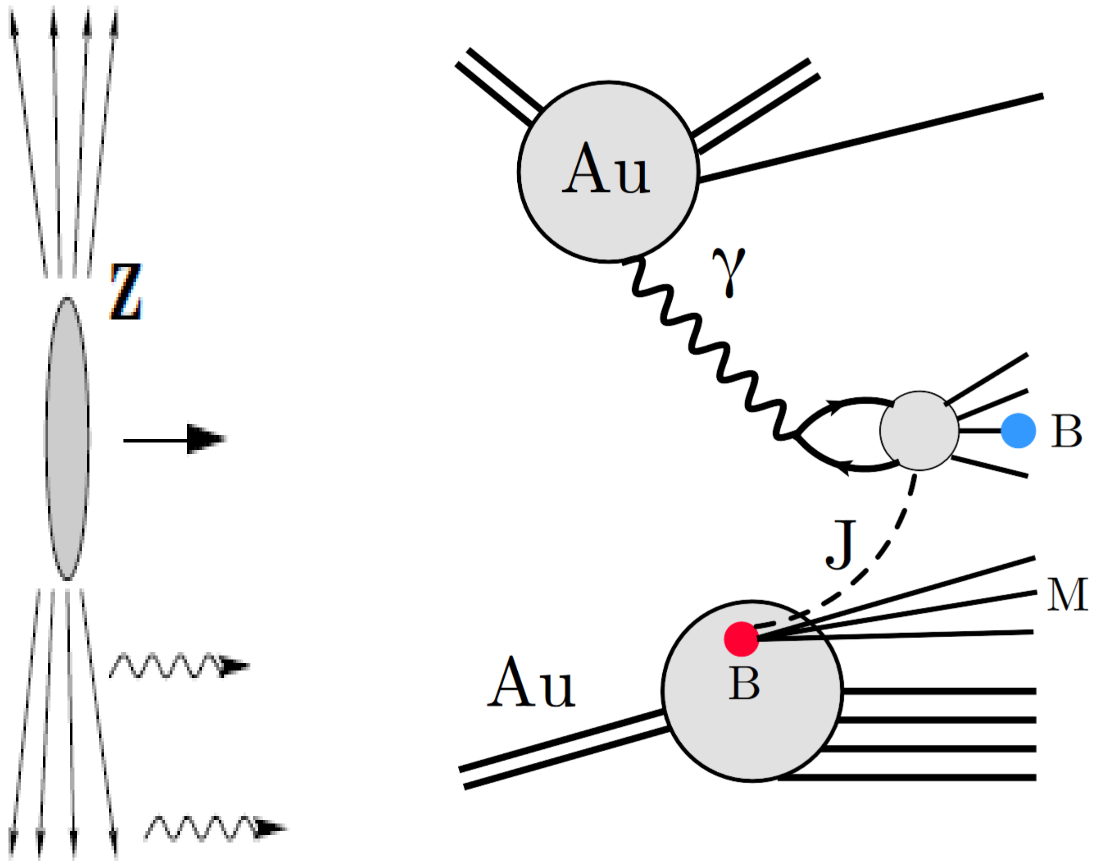


- Scaling in all centralities and collision energies
- Slopes do not depend on centrality
  - Baryon stopping at mid-y is not due to multiple scattering

Method II

Net-Baryon Rapidity Distribution in γ+A

Net-Baryons in Photon+Au Events



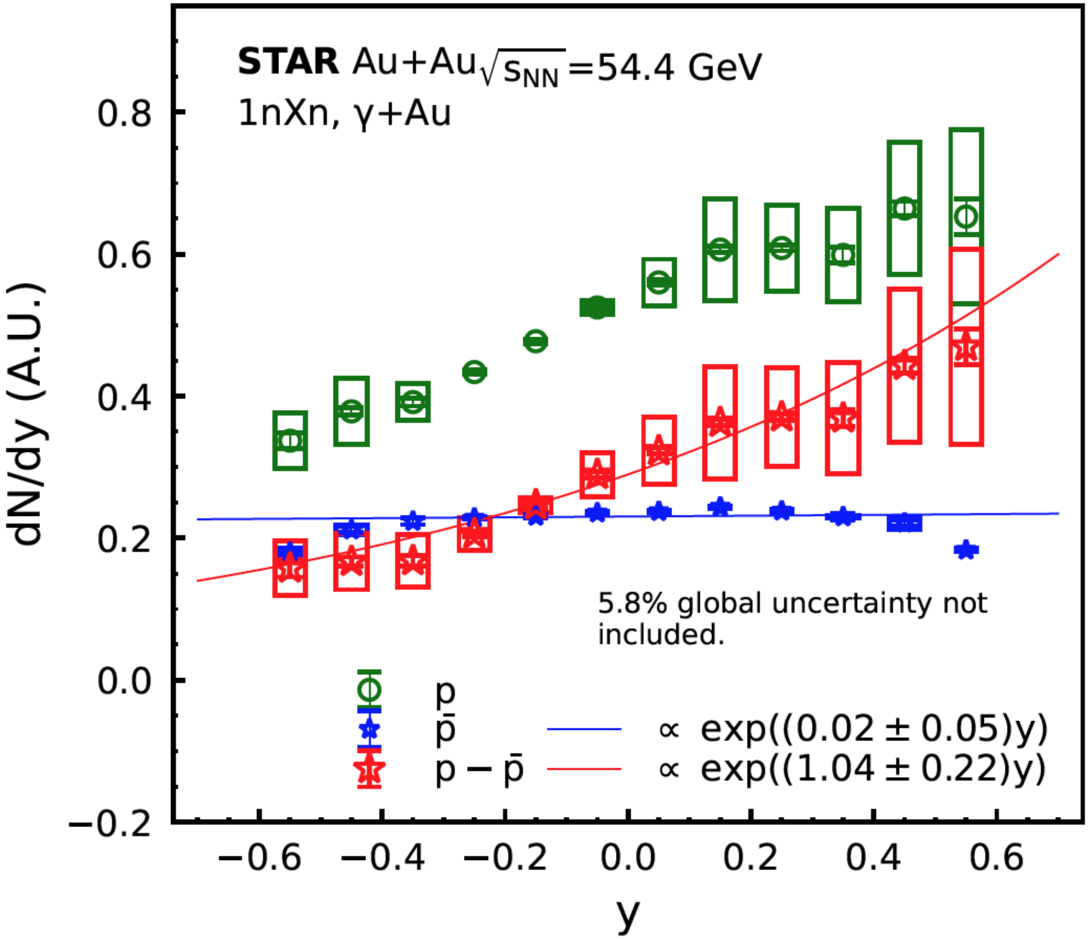
- Strong electromagnetic field accompanies the nuclei in relativistic heavy-ion collisions
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux
- Photon fluctuates into a quark-antiquark pair and interact with the nucleus target

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

- STAR, PRL127, 052302 (2021)
- STAR, PRL123, 132302 (2019)
- STAR, PRL121, 132301 (2018)

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

Net-Baryons in Photonuclear Events



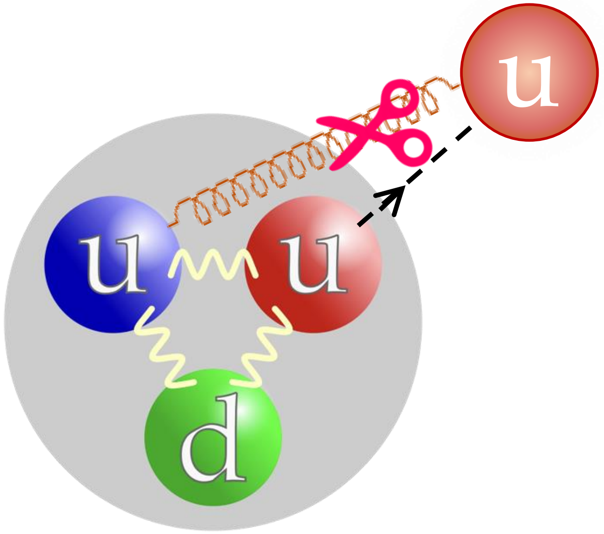
- photon+Au collisions selected from ultra-peripheral Au+Au collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic exponential increase towards nucleus side
- $\alpha_B = 1.0 \pm 0.2$ for net-proton
  - Consistent with predictions from baryon junction stopping

Method III

Correlation of Net-Baryon and Net-Charge

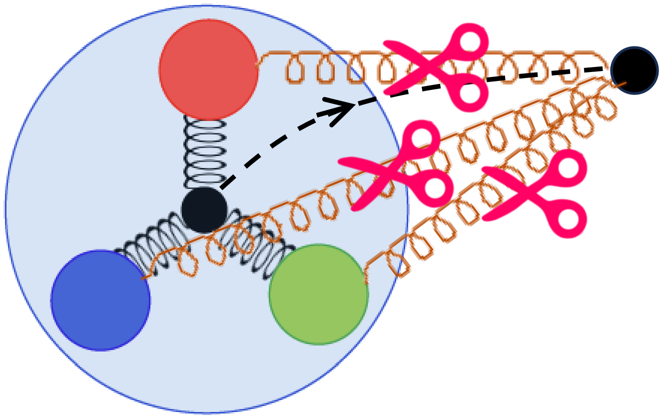
Net-Charges vs. Net-Baryons

Valence quark stopping



- Net quarks are all transported from projectile and target nuclei
- The ratio of net-charge and net-baryon should be highly correlated with Z/A of projectile and target

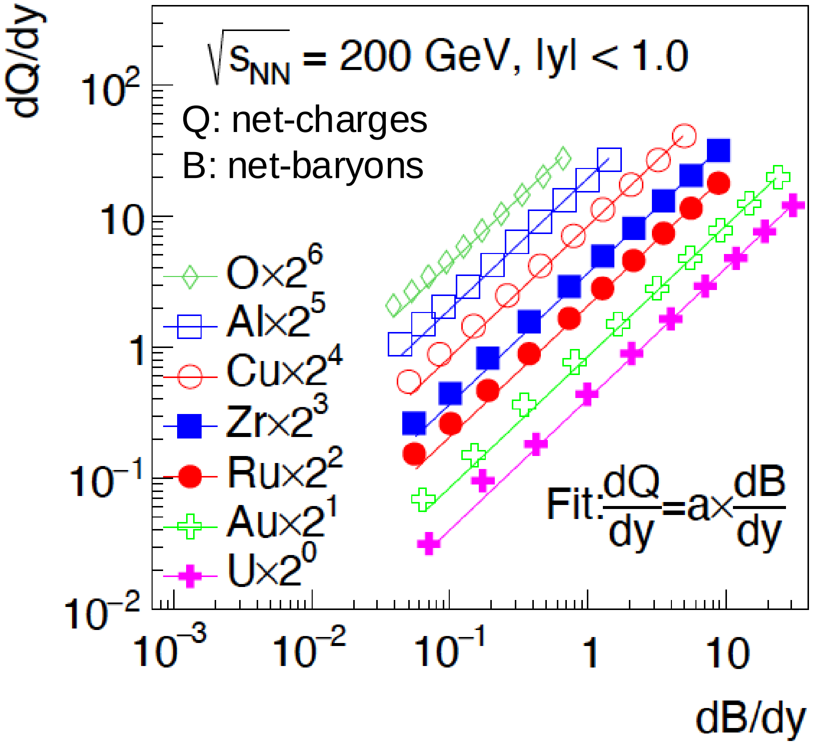
Baryon junction stopping

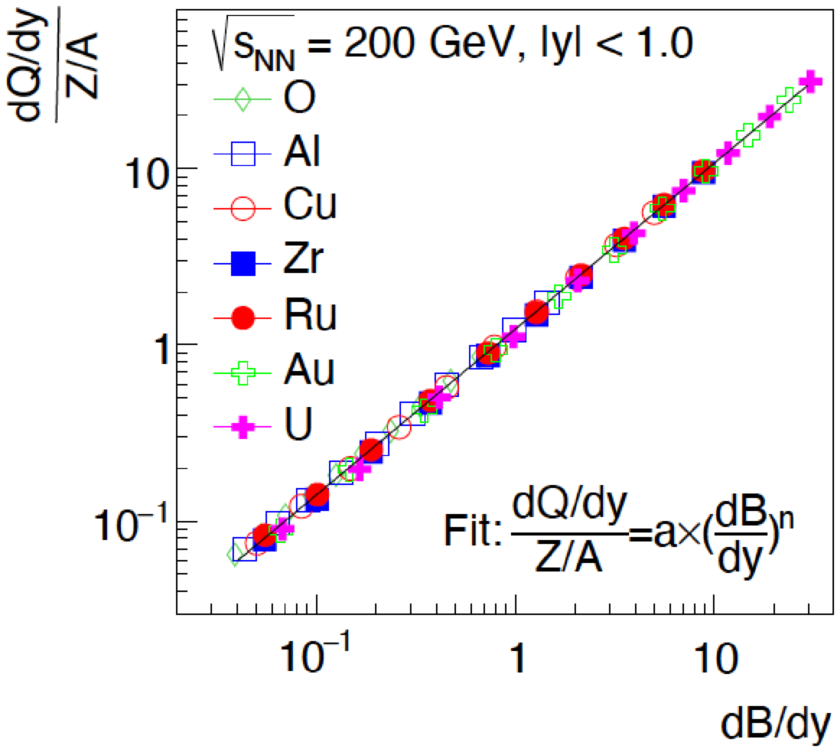


- Quarks connected to the stopped junction are sea quarks
- The ratio of net-charge and net-baryon is not related to the quark composition of projectile and target

Net-Charges vs. Net-Baryons from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering



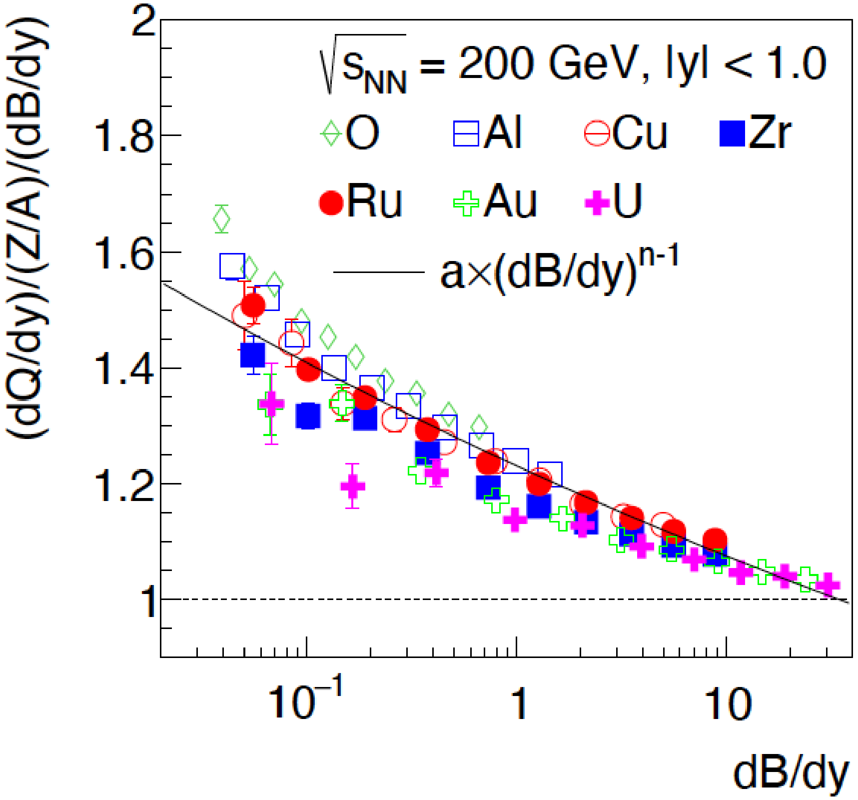


Nucleus	Z	A	Z/A
O	8	16	0.500
Al	13	27	0.481
Cu	29	64	0.453
Zr	40	96	0.417
Ru	44	96	0.458
Au	79	197	0.401
U	92	238	0.386

- Strong correlation of Net-B and Net-Q at mid-y
- Slope *a* increase with Z/A

- Net-charges at mid-y scale with Z/A in collisions from O+O to U+U at 200 GeV

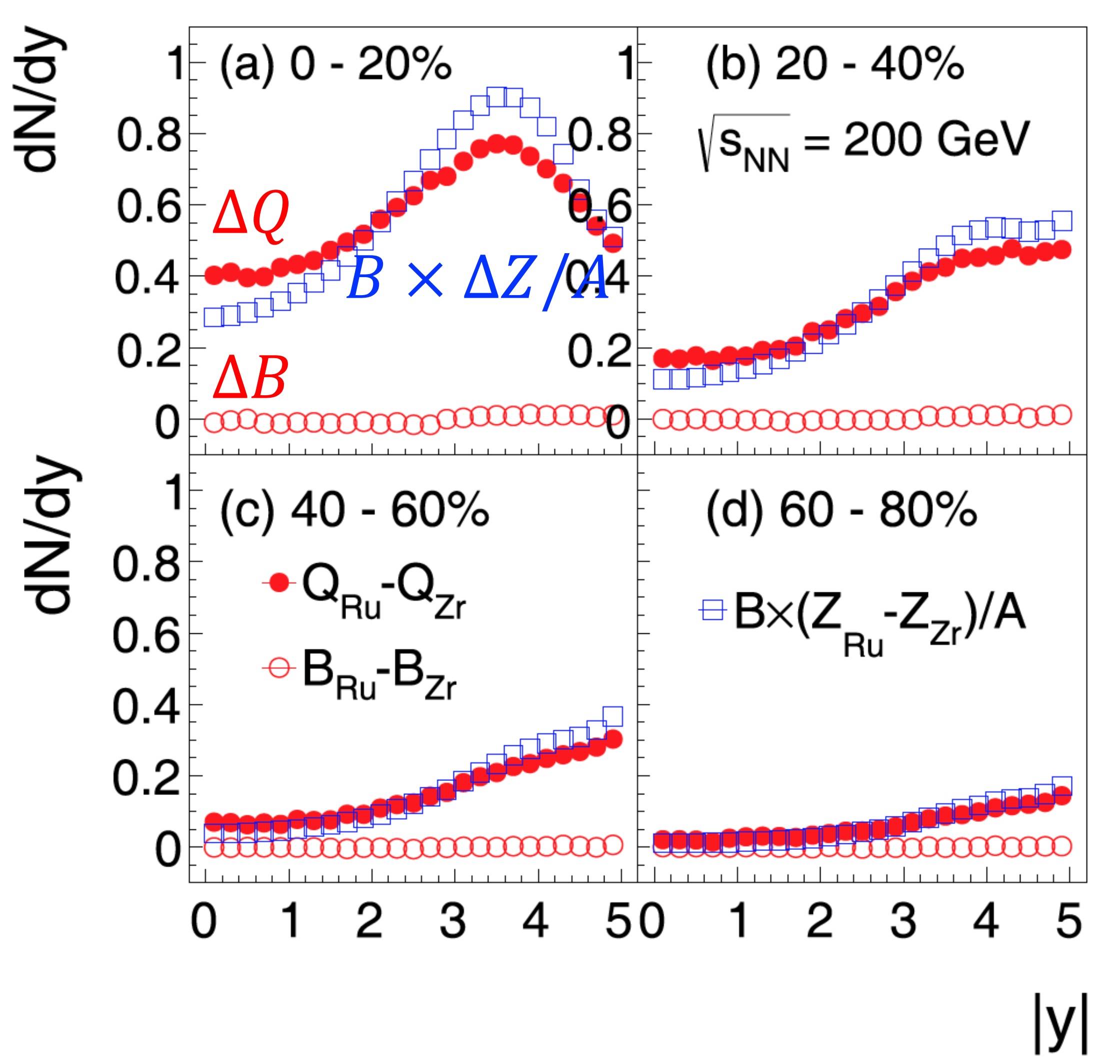
Net-Charges vs. Net-Baryons from UrQMD



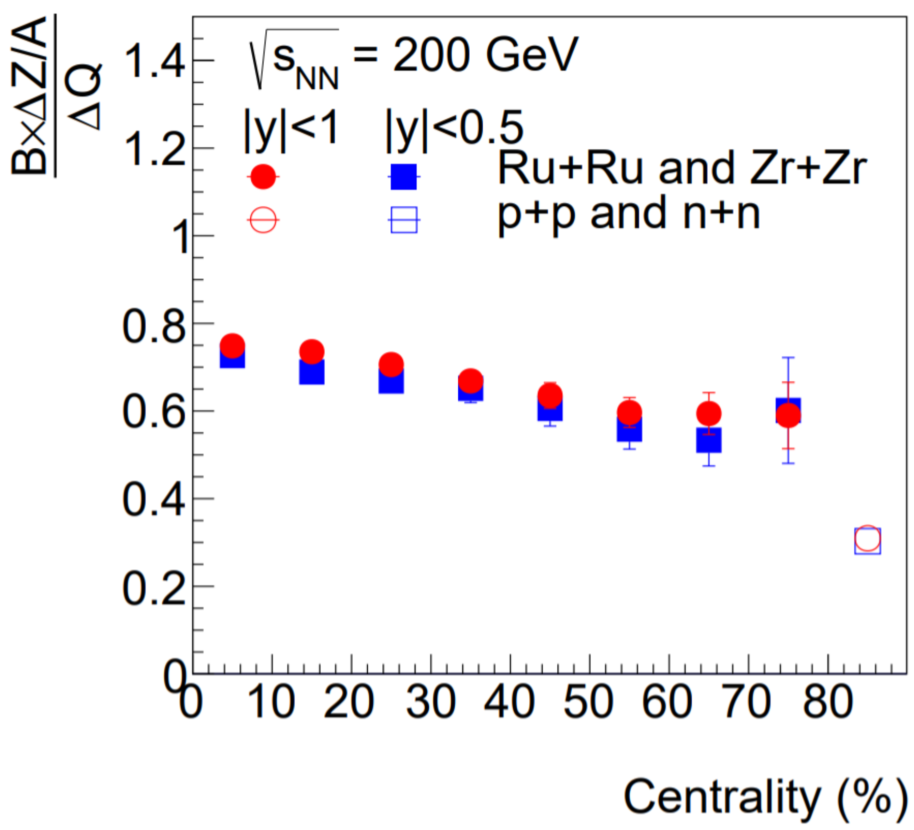
- Q/B x A/Z approaches 1 for large A
- Expect 25% difference of Q/B in O+O and Au+Au collisions
  10% difference of Q/B in Ru+Ru and Zr+Zr collisions
- Isobar collisions provide better experimental opportunities

Net-Charges and Net-Baryons in Isobaric Collisions

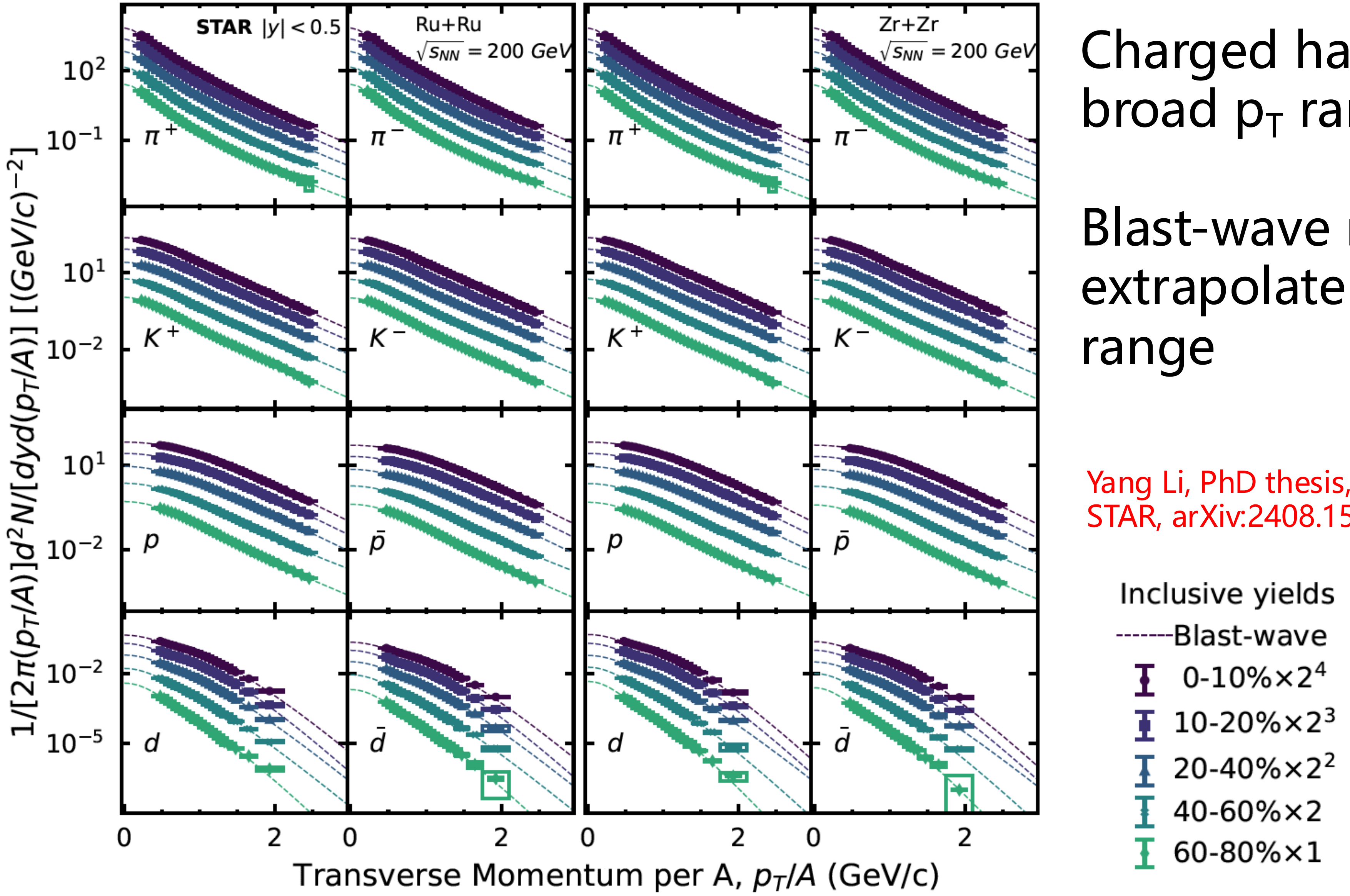
Ru+Ru and Zr+Zr collisions at 200 GeV from UrQMD



- Difference of B is almost zero
- Difference of Q is close to B*ΔZ/A



Identified Particle Spectra in Ru+Ru/Zr+Zr Collisions

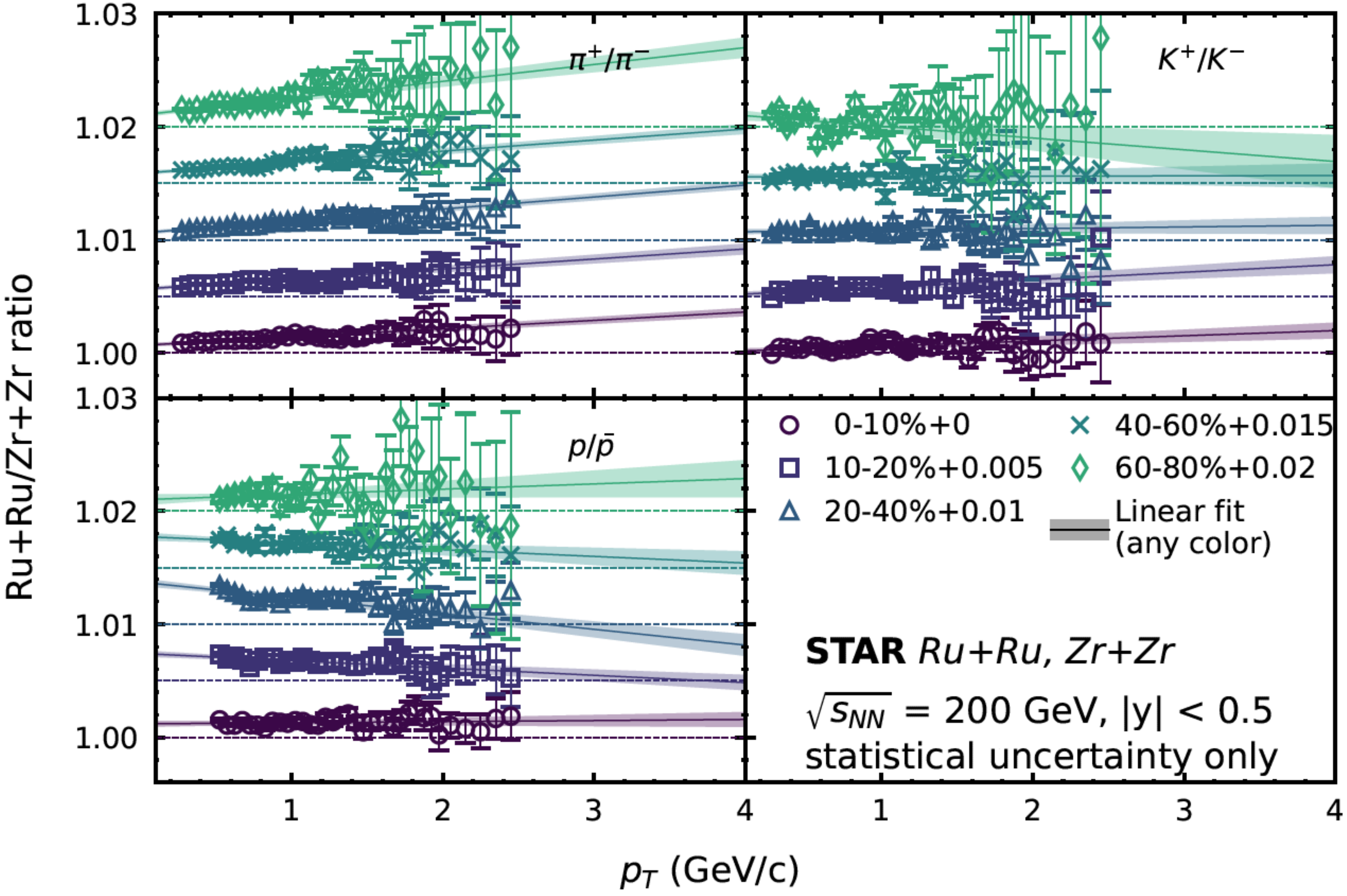


Charged hadrons identified in broad p_T range by TPC +TOF

Blast-wave model used to extrapolate to unmeasured p_T range

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

Measurement of Double Ratios



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

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

Calculation of Net-Charge Difference

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

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

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

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

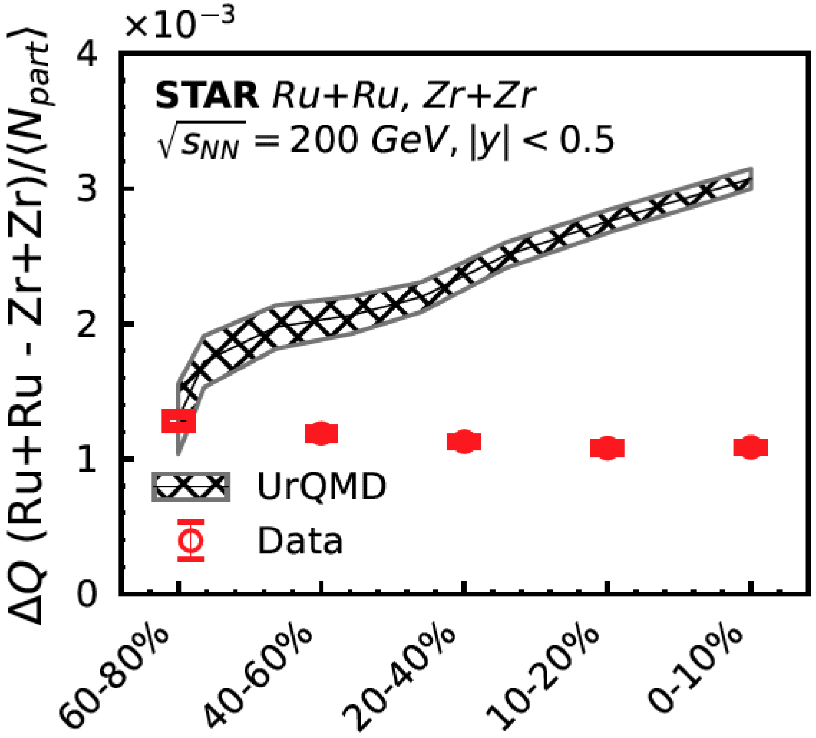
$$(N_{\pi^+} - N_{\pi^-})^{Ru} - (N_{\pi^+} - N_{\pi^-})^{Ru} \approx 2N_{\pi} \left(\frac{R_{\pi}^{Ru} - 1}{R_{\pi}^{Ru} + 1} - \frac{R_{\pi}^{Zr} - 1}{R_{\pi}^{Zr} + 1}\right)$$

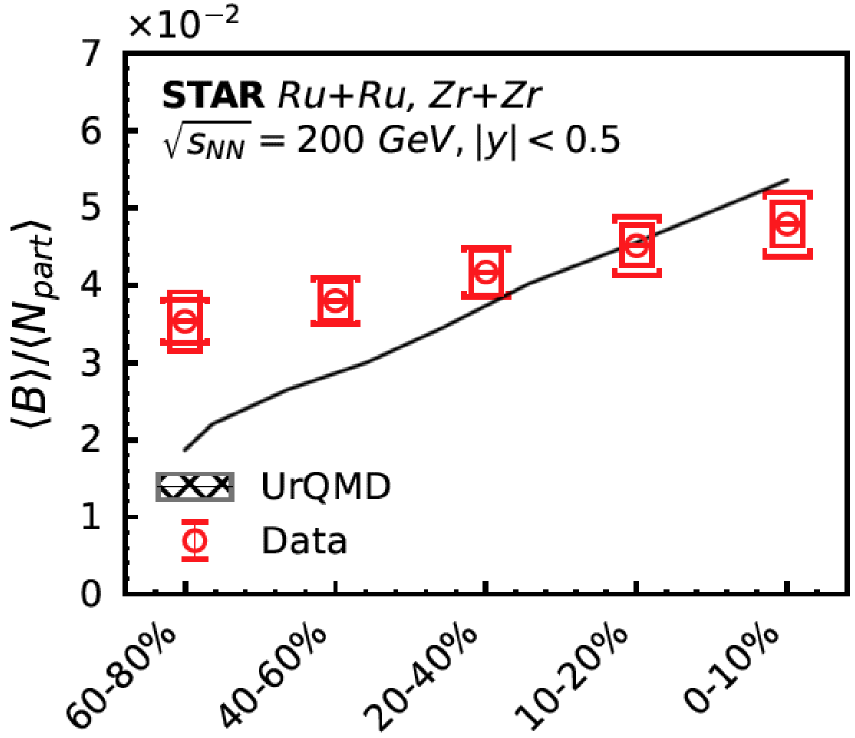
$$R_{\pi} = \frac{\pi^+}{\pi^-}$$

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

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

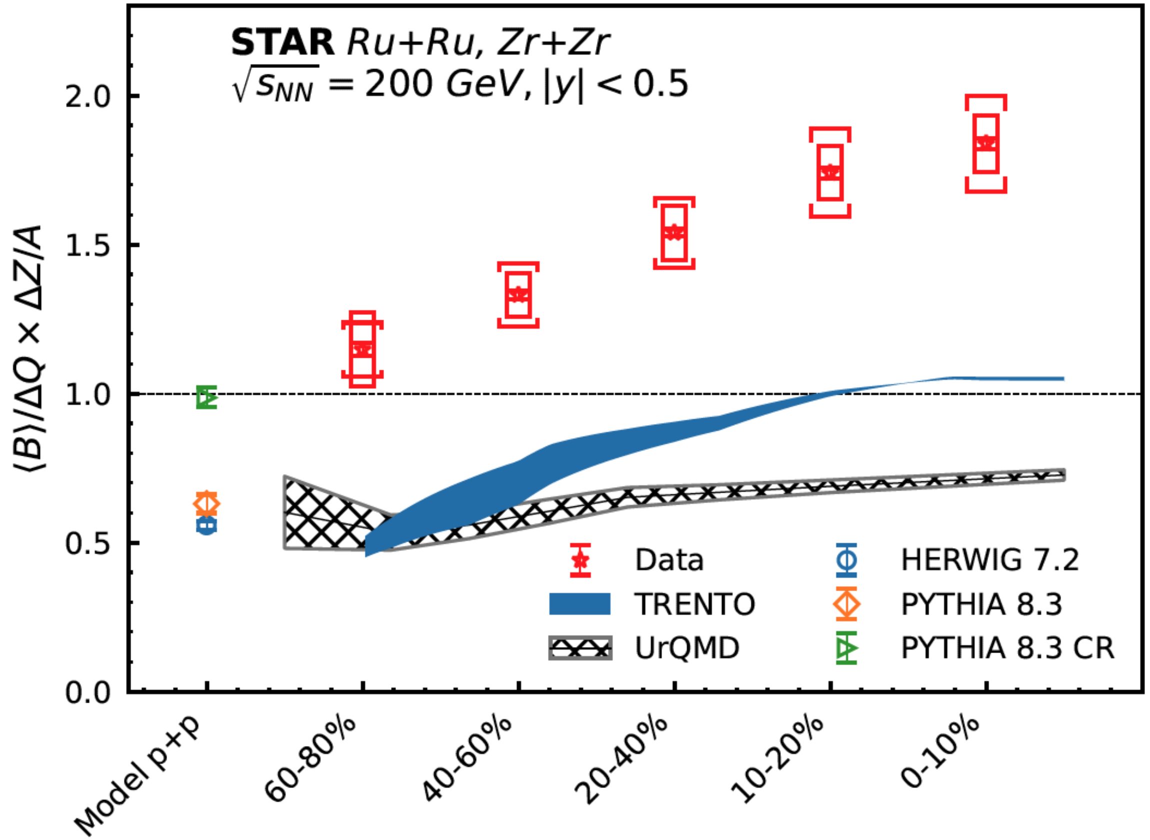
Net-Charge and Net-Baryon Compared to UrQMD





- UrQMD reproduces baryon stopping at mid-rapidity in central collisions, probably because UrQMD has been tuned to net-proton measurements
- Overpredict ΔQ by a factor of 3 in central collisions
- Underestimate B in peripheral collisions

Net-Charges and Net-Baryons in Ru+Ru/Zr+Zr

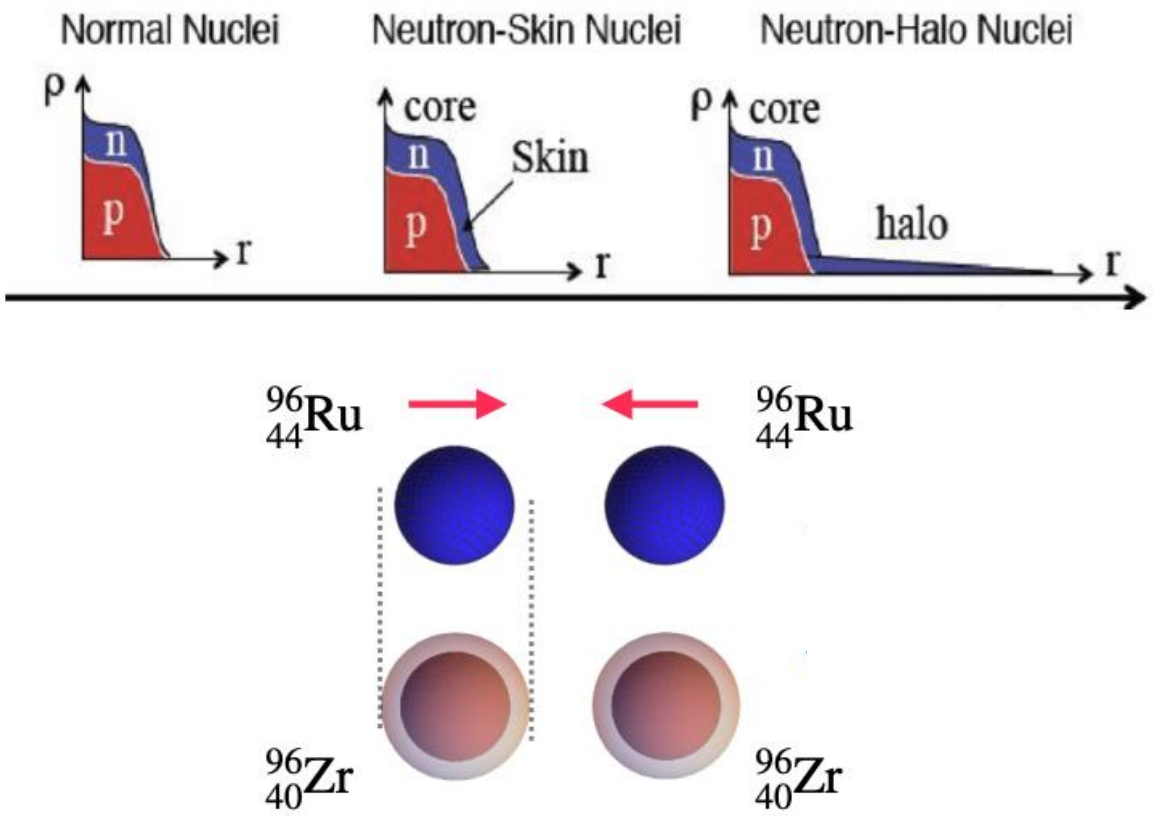


HERWIG: J. Bellm et al, EPJC80, 452 (2020)

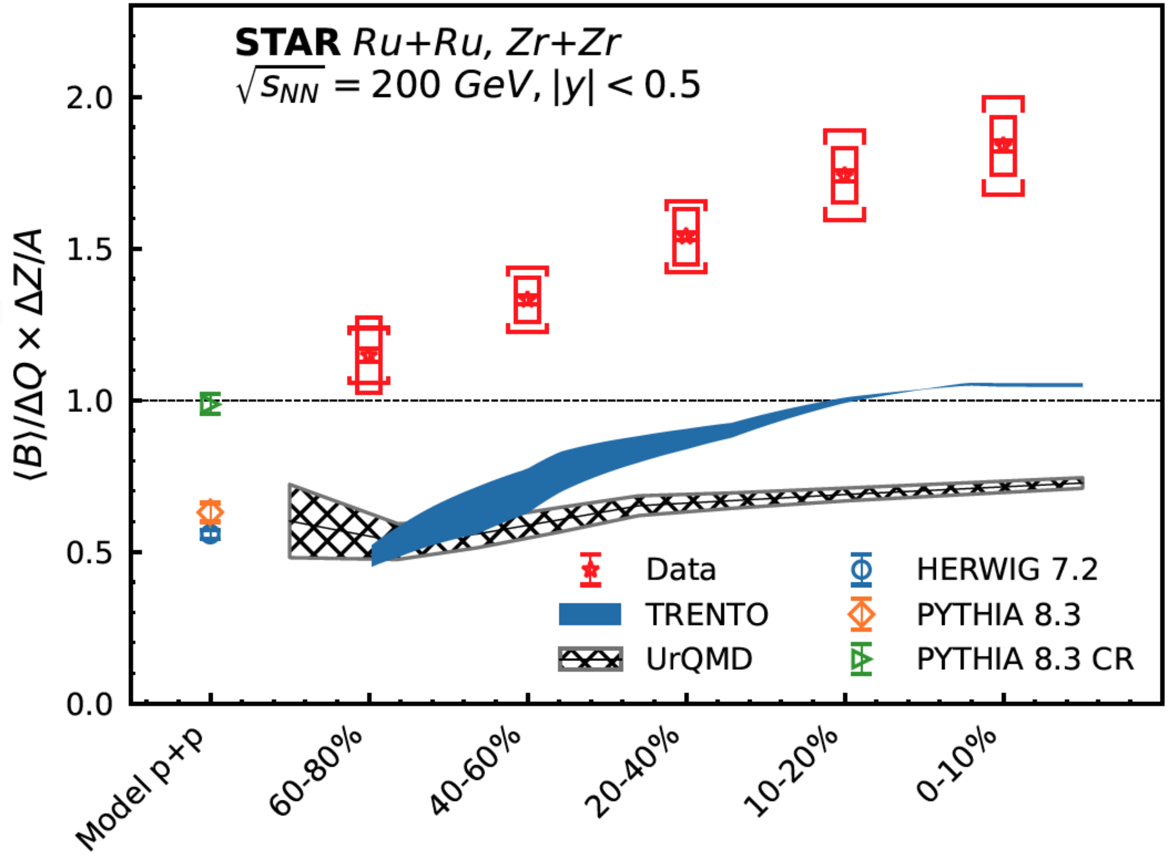
UrQMD: M. Bleicher et al, JPG25, 1859 (1999)

- 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 by a factor of 1.5-2

Net-Charges and Net-Baryons in Ru+Ru/Zr+Zr



H. Xu et al, PRC105, L011901 (2022)

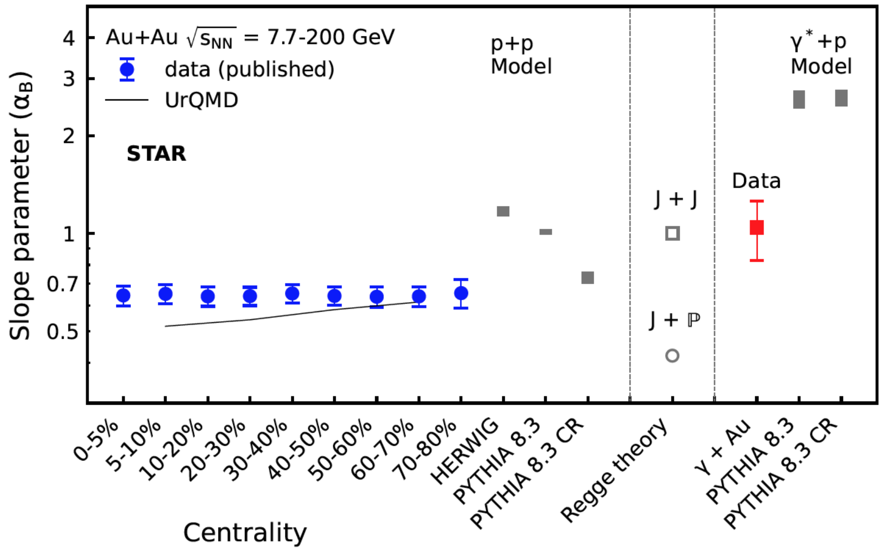


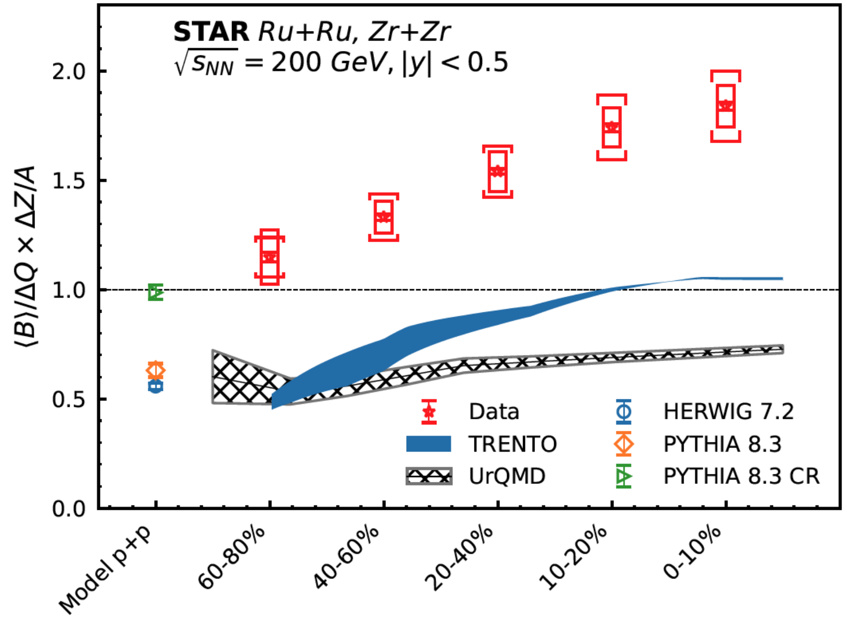
J. Moreland et al, PRC92, 011901(R) (2015)

- Thick halo-type neutron skin in Zr
- More p+p collisions in central Zr+Zr
- Explains the centrality dependence
- But not enough to explain large ratio

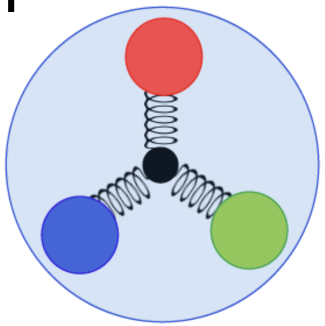
Summary

- 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-bayon over net-charge ratio in Isobaric collisions



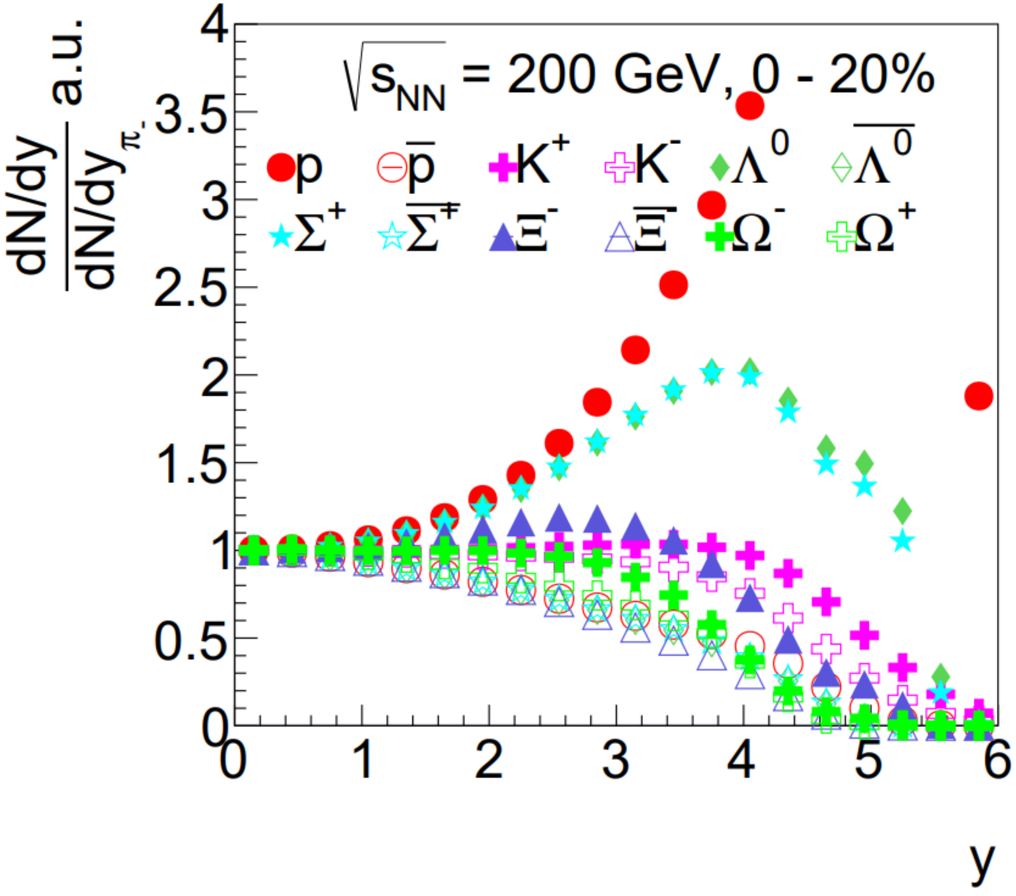


Thanks!



Extra slides

Why Q/B is More Than Naïve Expectation?

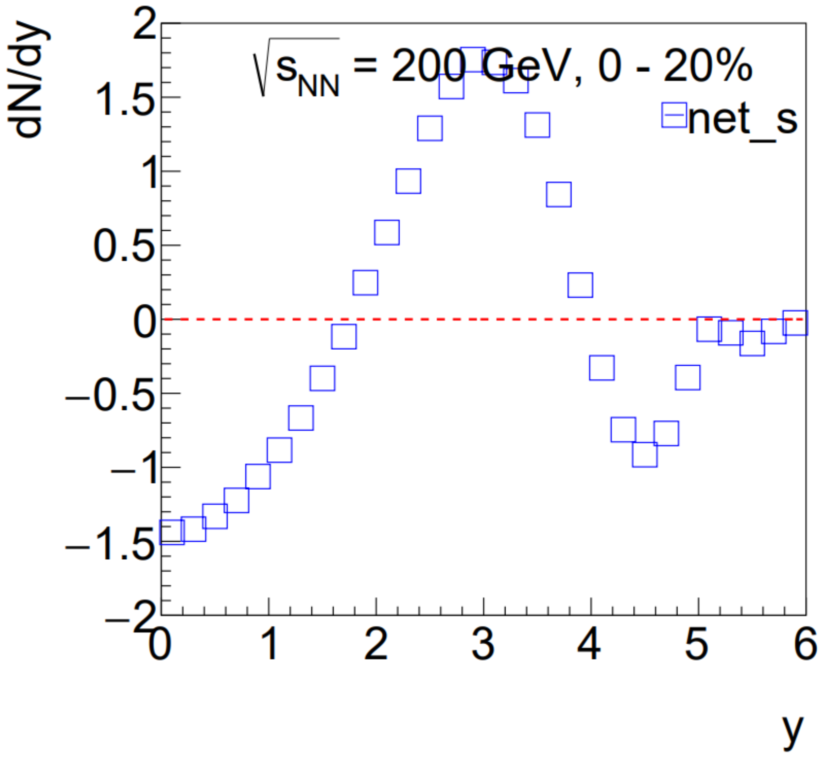


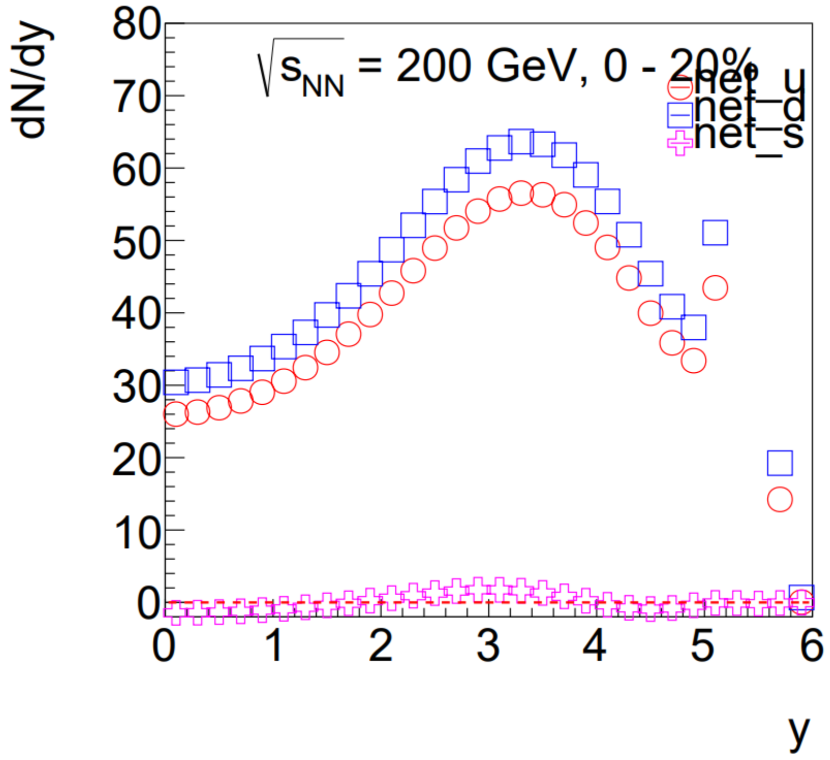
W. Lv et. al., Paper in preparation

Width of the rapidity distribution:

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

Net-Quarks Rapidity Distribution

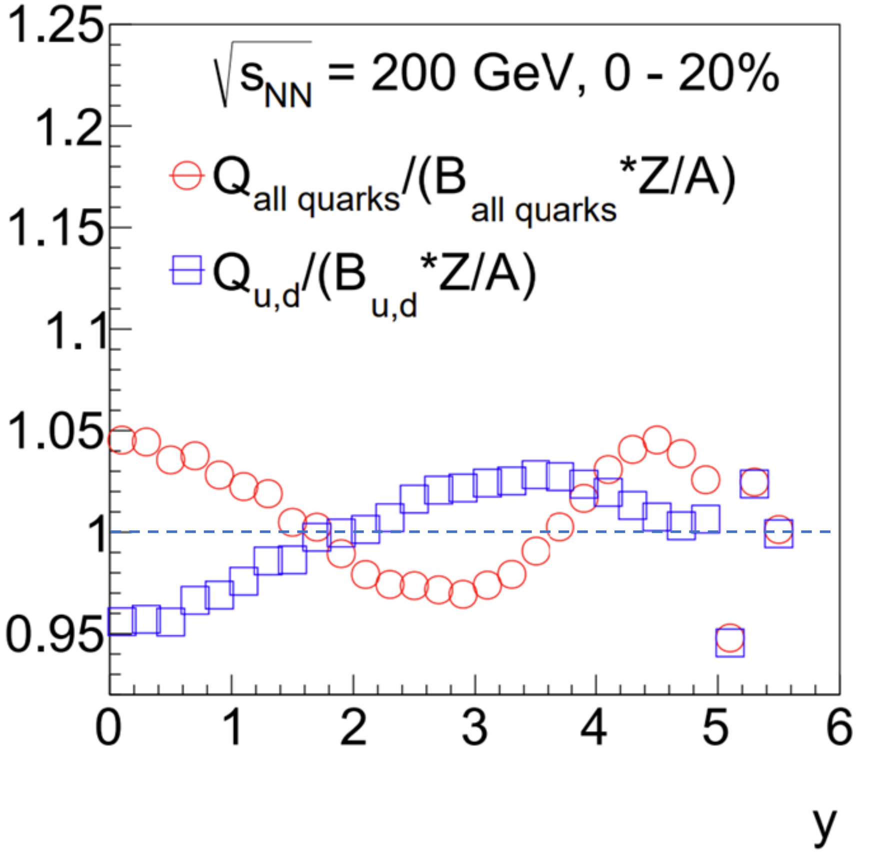


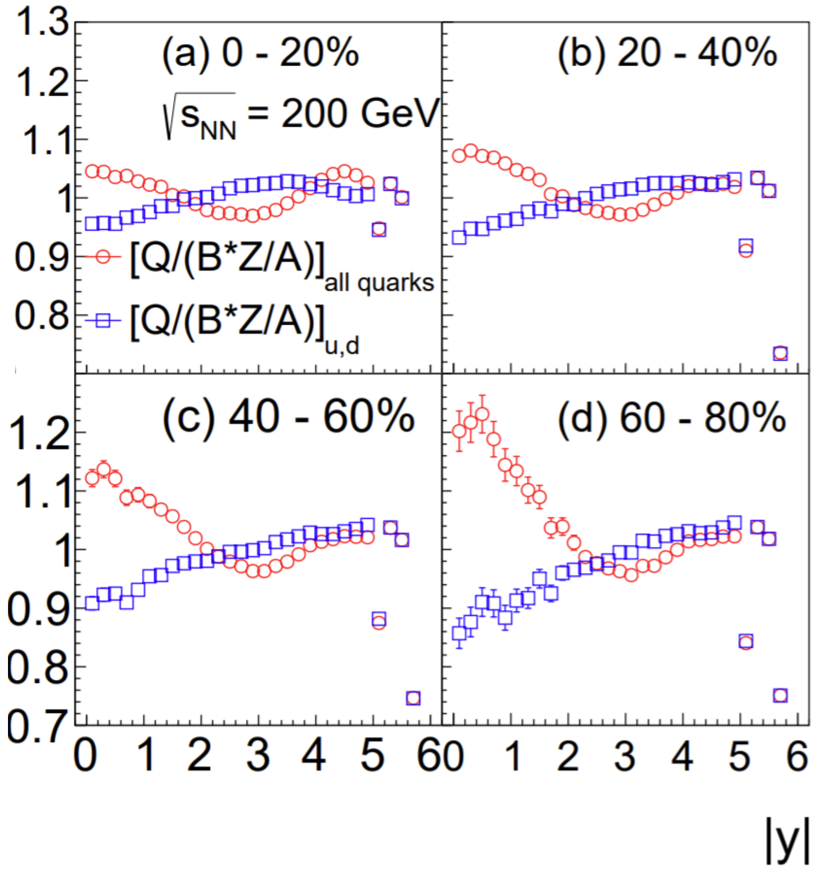


- Net-strange increases from negative at mid-y to positive at forward y

- The trend is similar as transported quarks
- Or affected by transported quarks

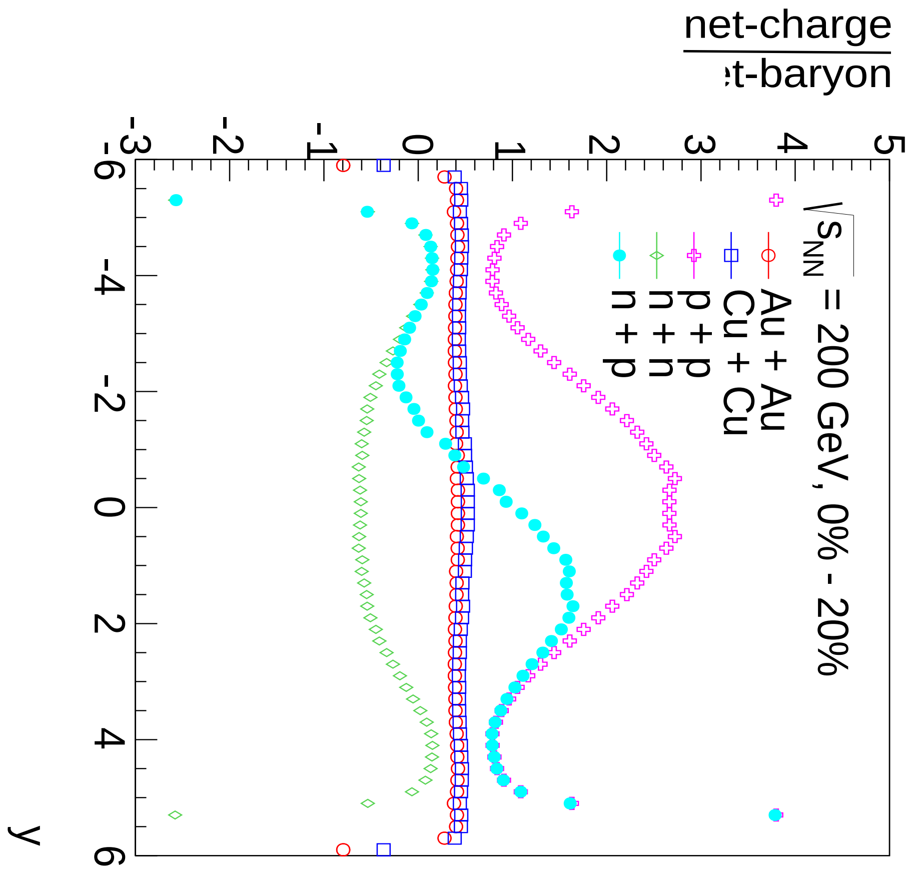
Q/B w/ and w/o Strangeness





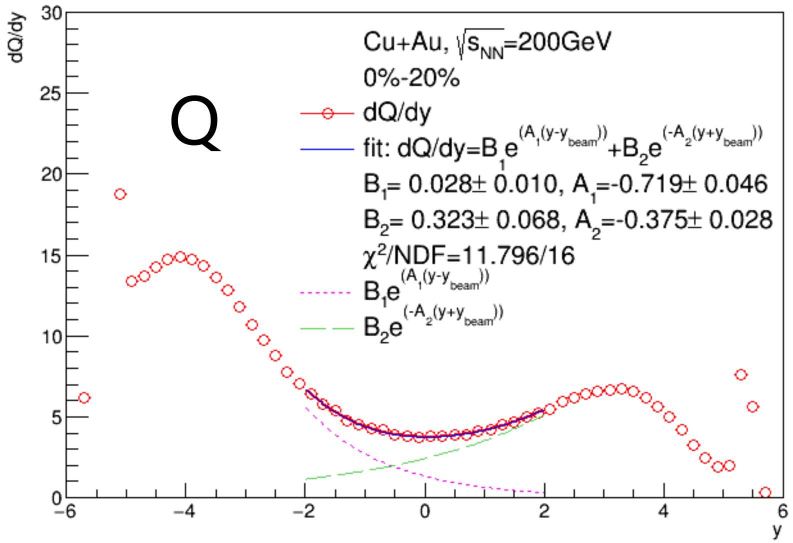
- Q/B ratio is different with or without strangeness
- The difference depends on rapidity
- The difference is smaller in central collisions, likely due to multiple scattering

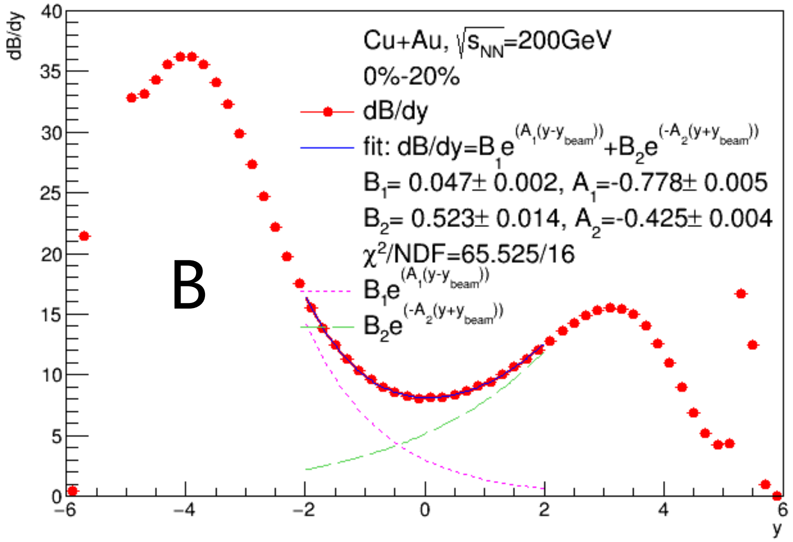
Q/B in Proton and Neutron Collisions

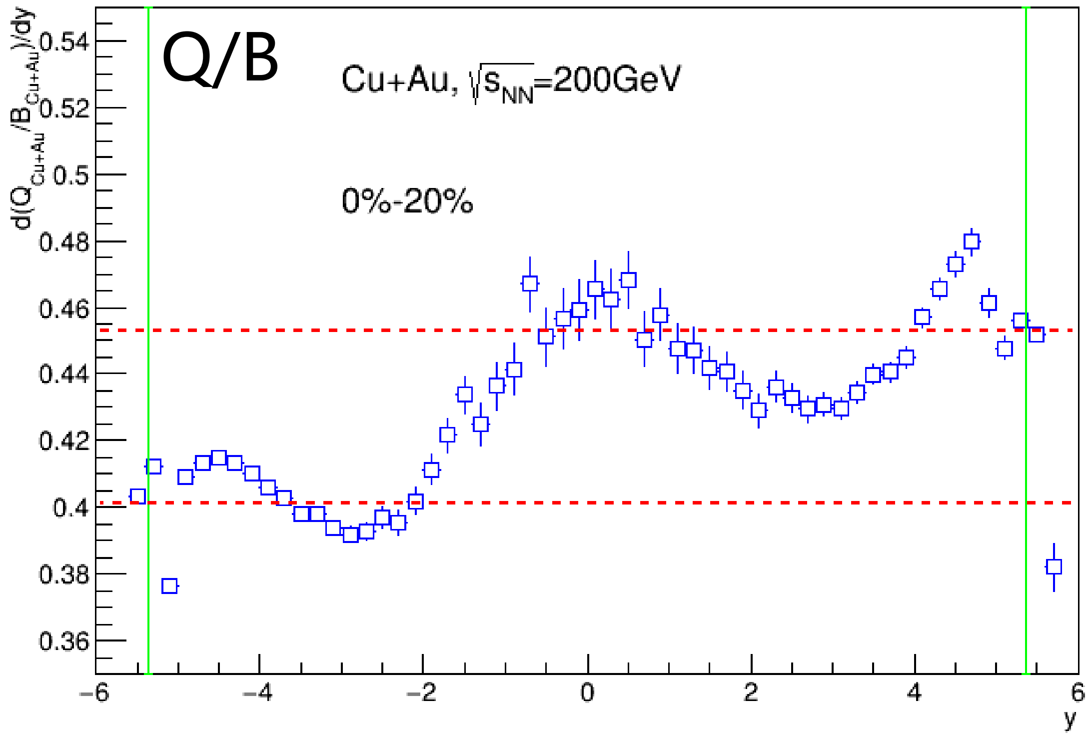


- The Q/B in p+p, n+n is different from the naïve expectation of valence quark stopping
- Detailed baryon and charge transport need to be considered

Q/B in Cu+Au Collisions at 200 GeV

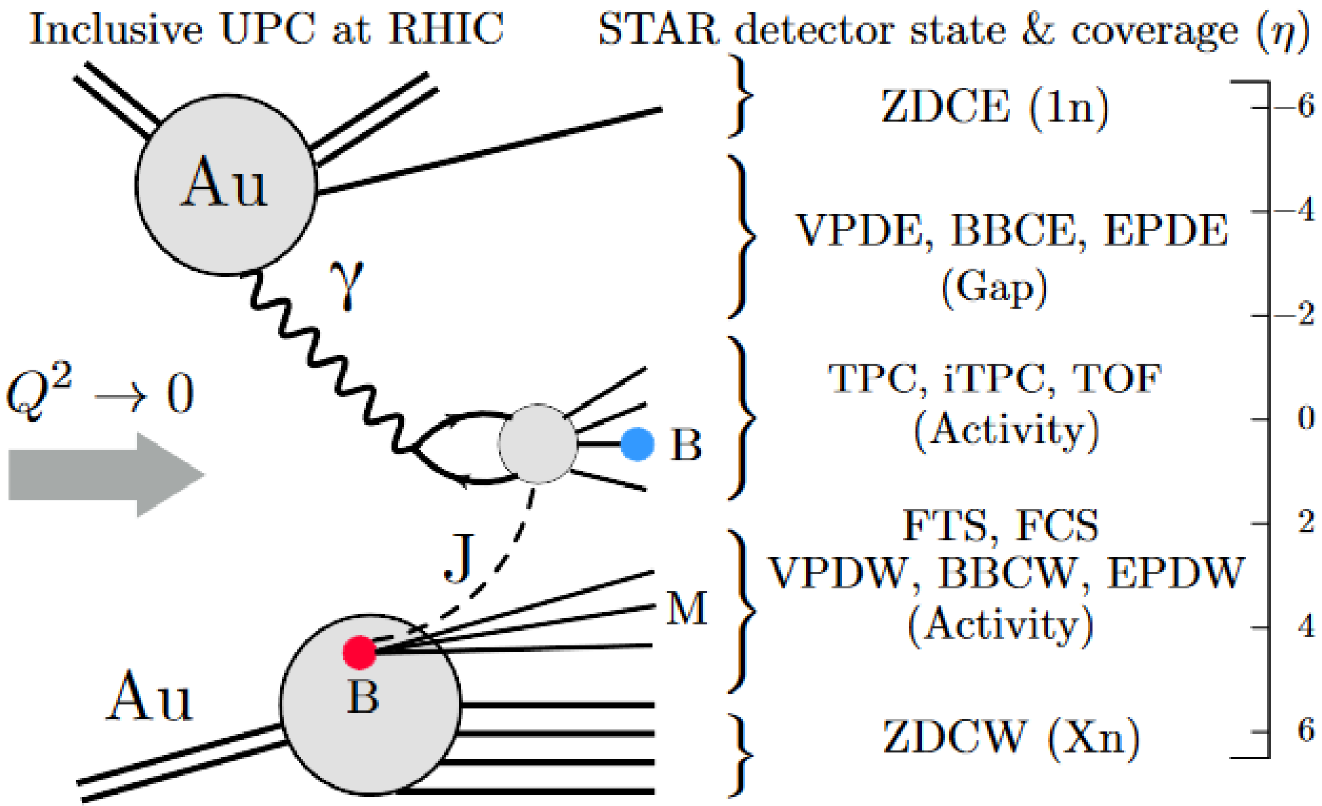


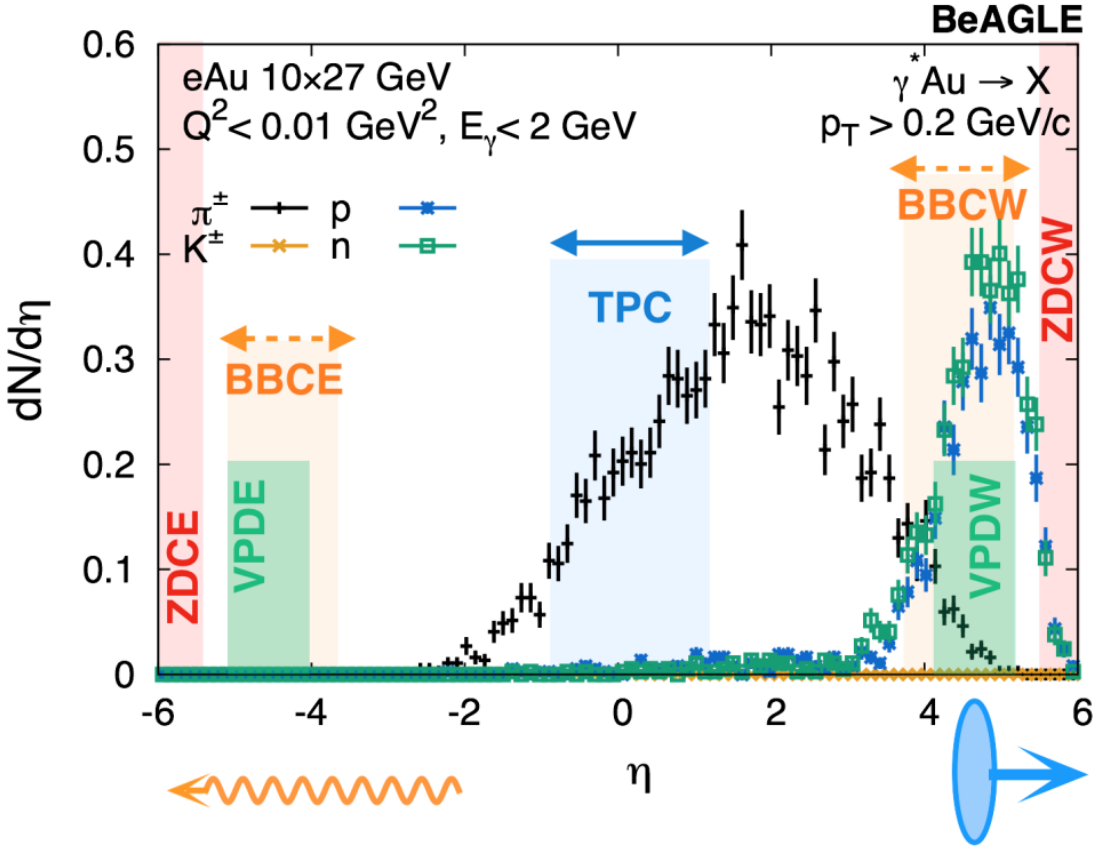




- Q/B significantly depends on rapidity in asymmetric collisions
- Large rapidity acceptance detector needed

Selection of Photonuclear Events





Similar technique used by LHC photonuclear measurements

ATLAS, PRC104, 14903 (2021)
CMS, PLB844, 137905 (2023)

STAR collected γ+Au events with Au+Au collisions at 54.4 GeV in 2017