Track Baryon Number Carrier with Heavy Ion Collisions

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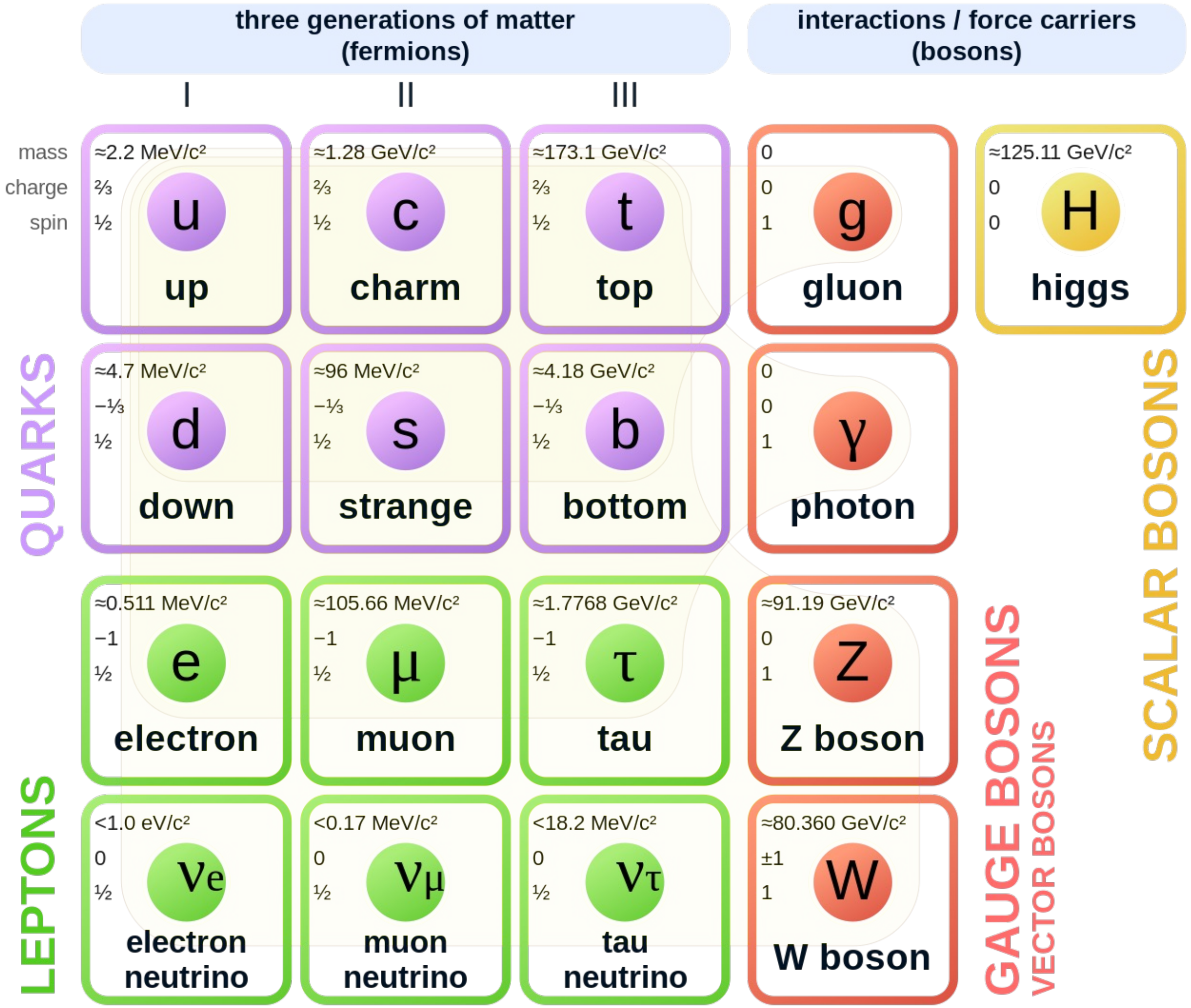
Based on STAR Preliminary results and arXiv:2205.05685, arXiv:2309.06445

Standard Model of Elementary Particles

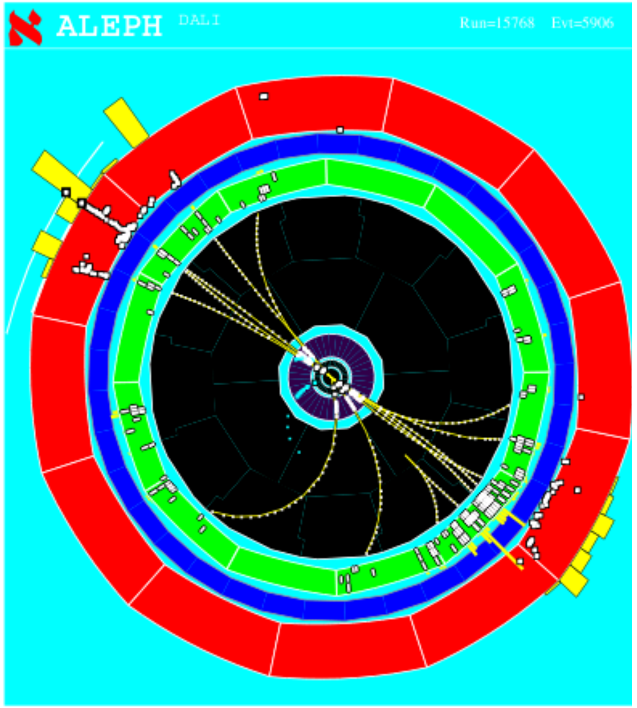


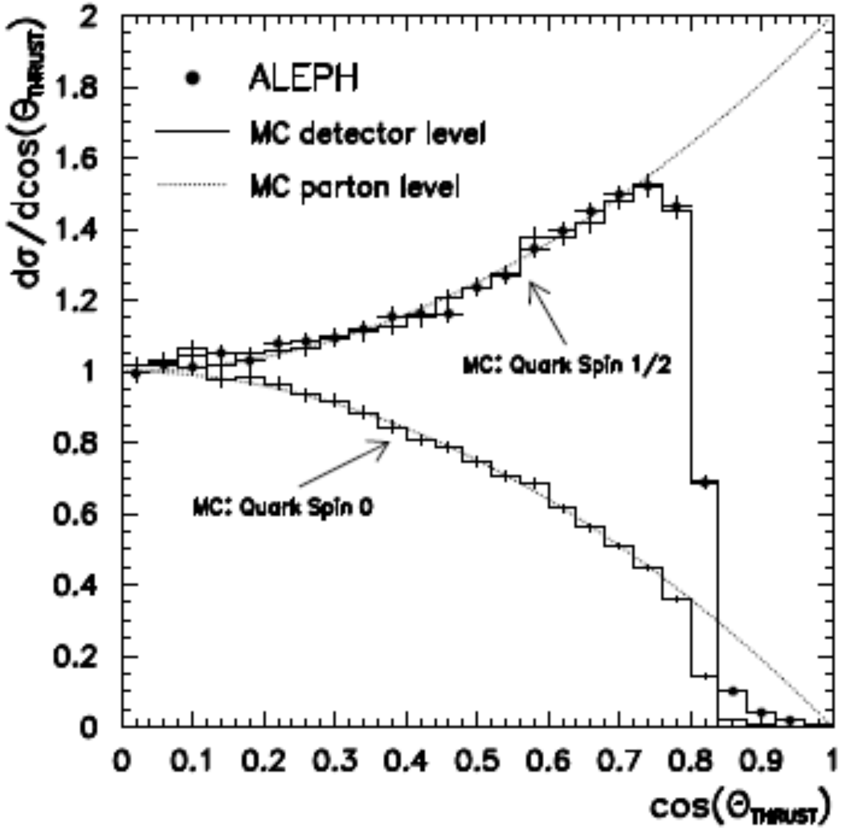
https://en.wikipedia.org/wiki/Quark

As building brick of matter, a quark has:

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

Spin of Quark

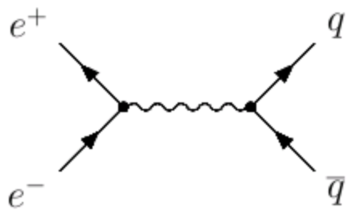


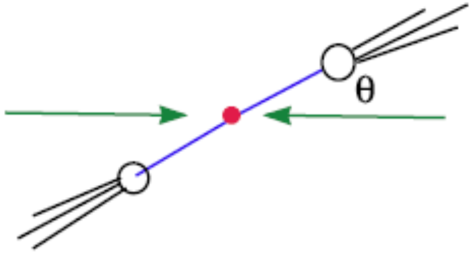


ALEPH, Phys. Rep. 294, 1 (1998)

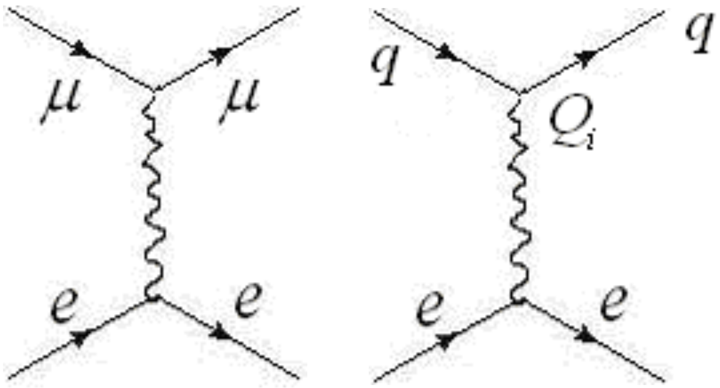
Spin–1/2 curve in excellent agreement with data

Spin–0 variant is clearly incompatible with data

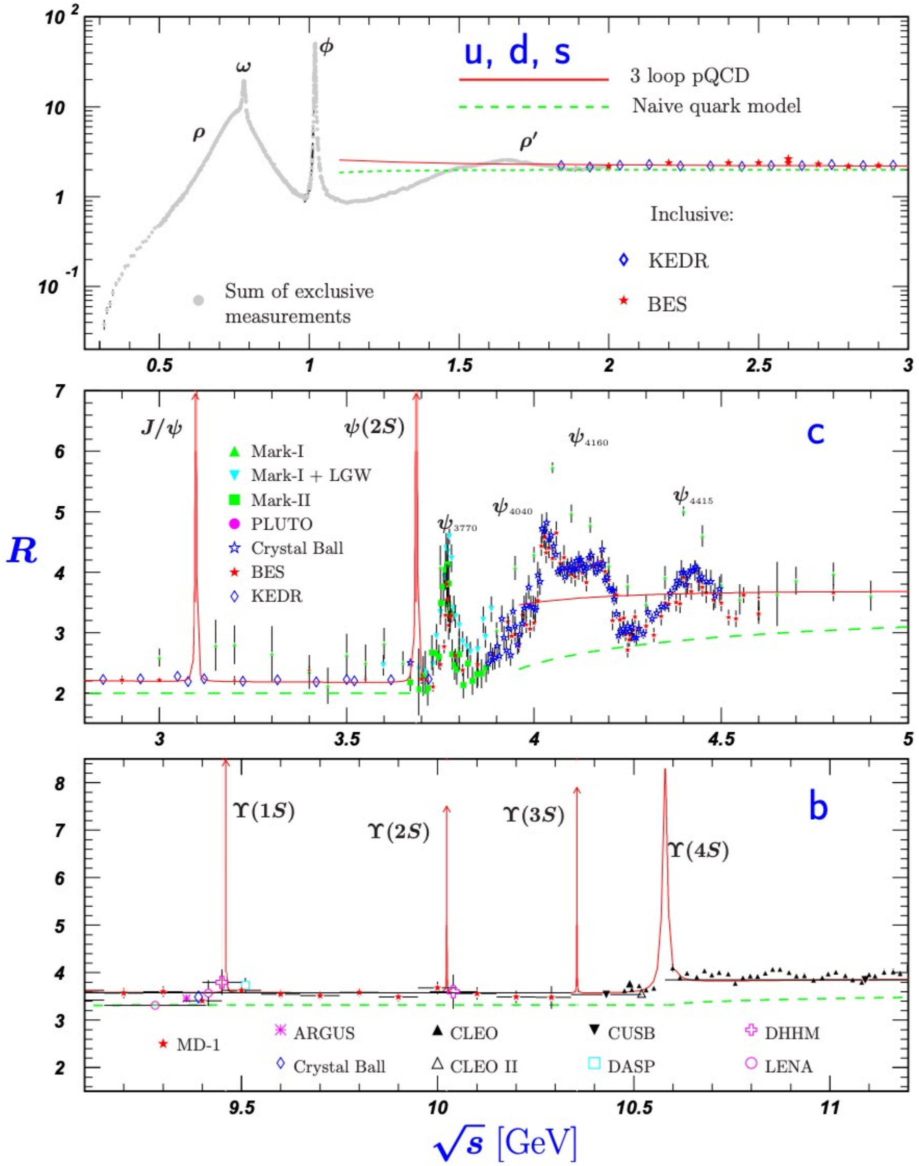




R–Value



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



Evidence of quark's

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

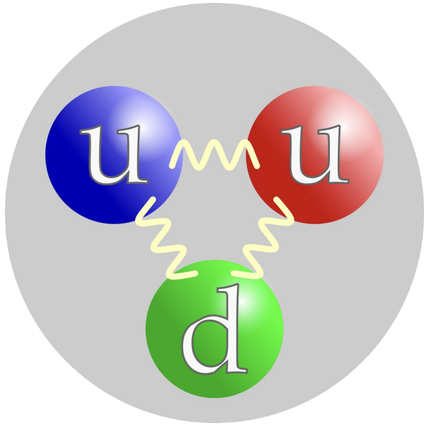
Does Quark Carry Baryon Number?

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

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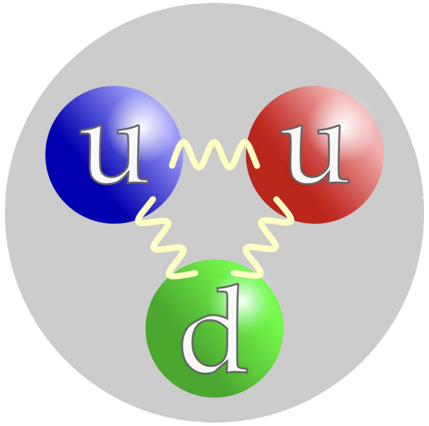
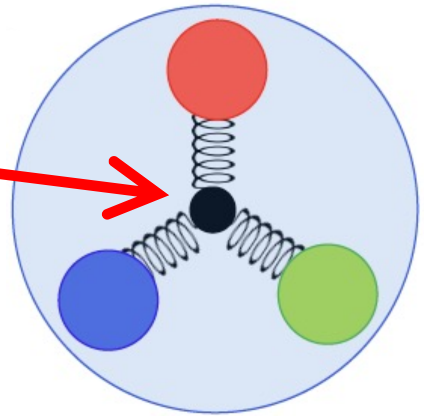


https://en.wikipedia.org/wiki/Quark

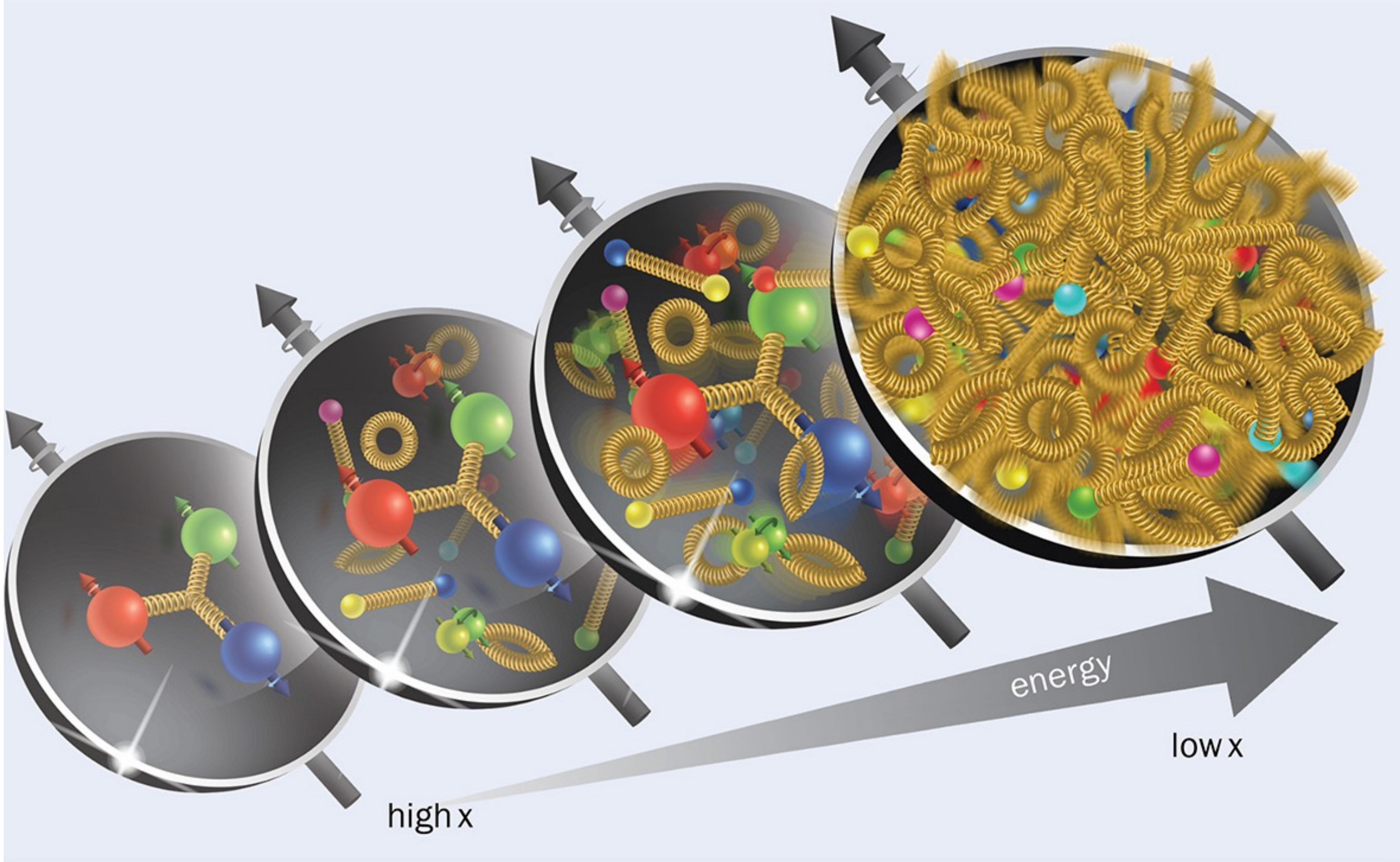
Alternative picture of a proton

- 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)

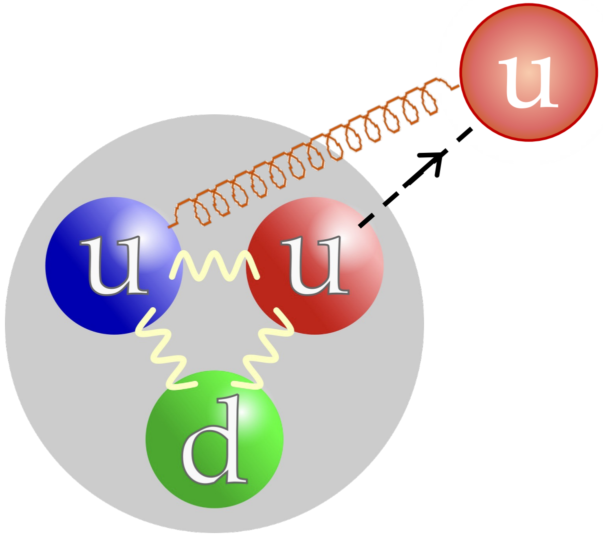
The Simplest QCD Topology

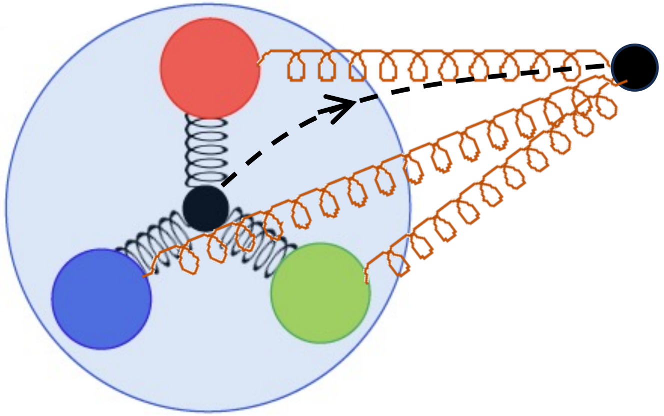


How to Probe the Baryon Number?

Pull them out:

Measure baryon stopping at mid-rapidity in p+p and/or A+A collisions



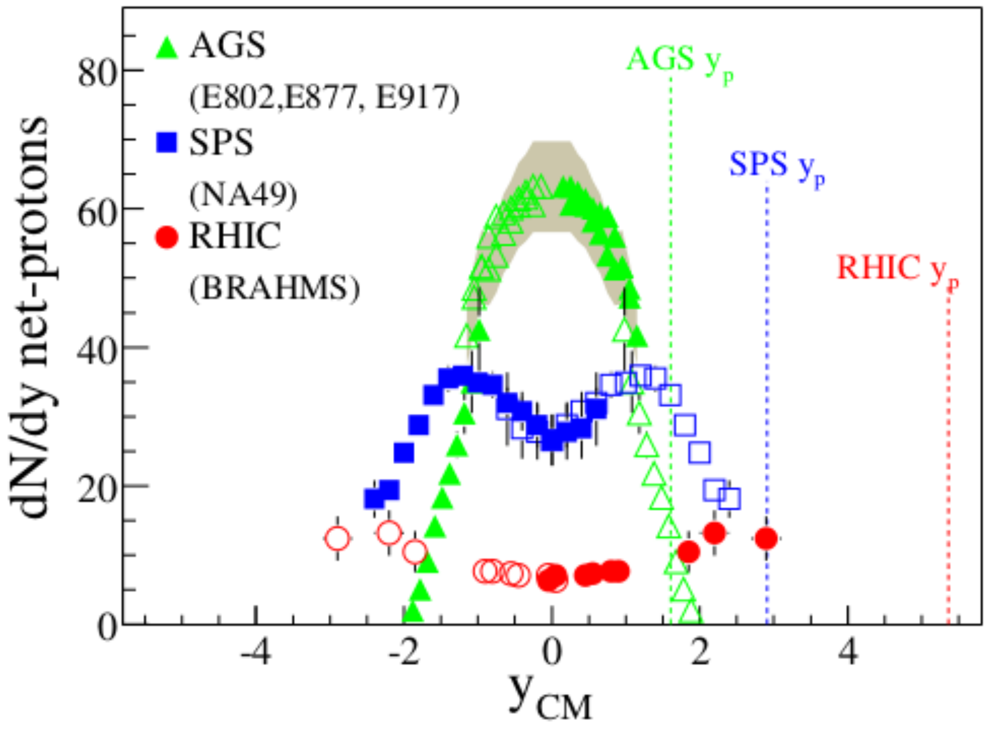


D. Kharzeev, PLB378, 238 (1996)

Method I

Net–Baryon at Mid–rapidity in A+A

Net–Baryons Rapidity Distribution

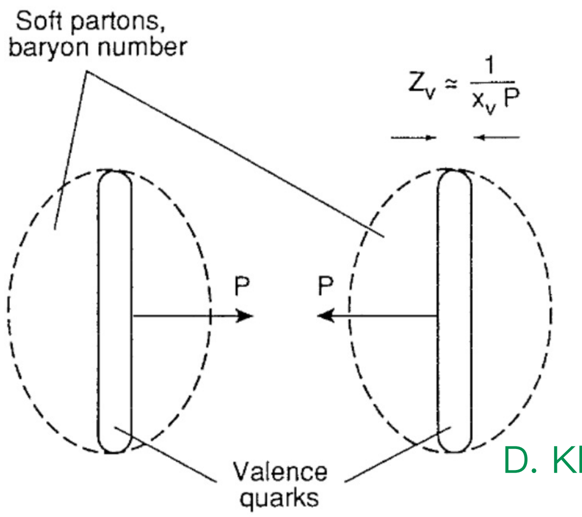


BRAHMS, PRL93, 102301 (2004)
and references therein

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

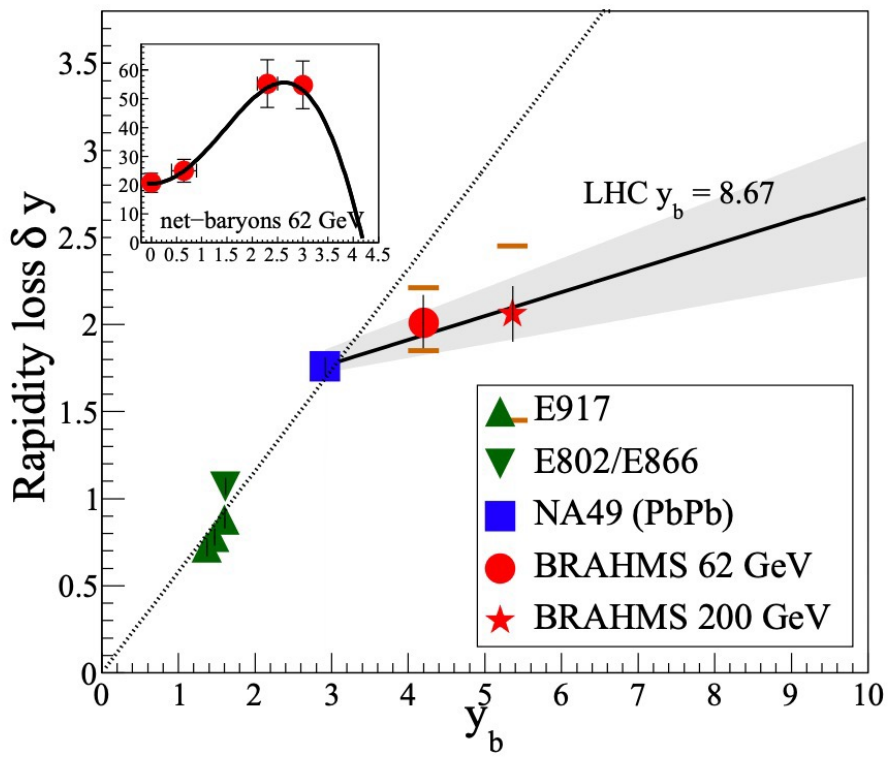
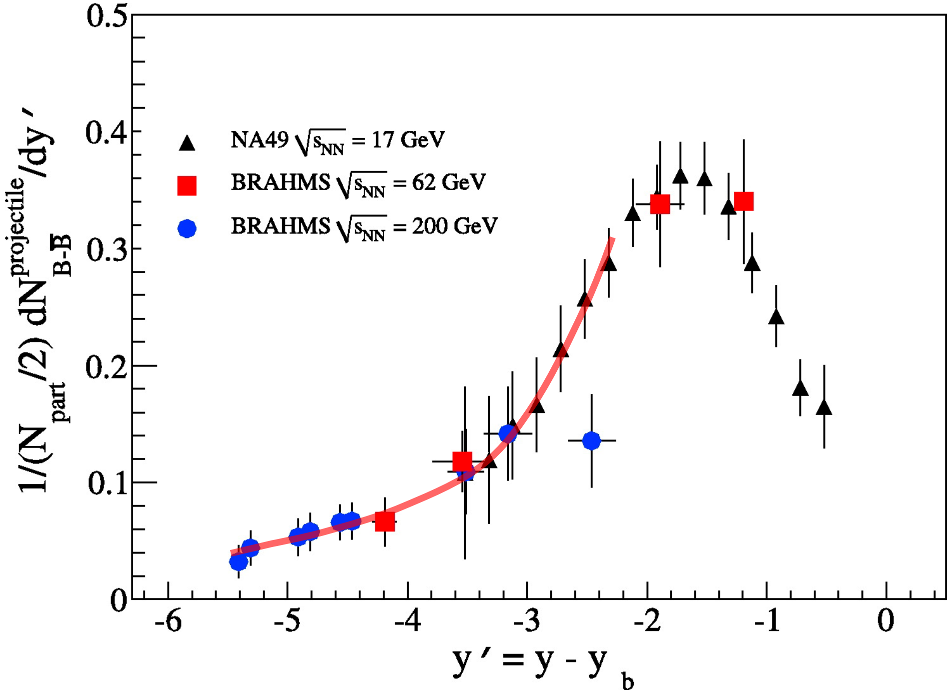


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS, PLB677, 267 (2009)

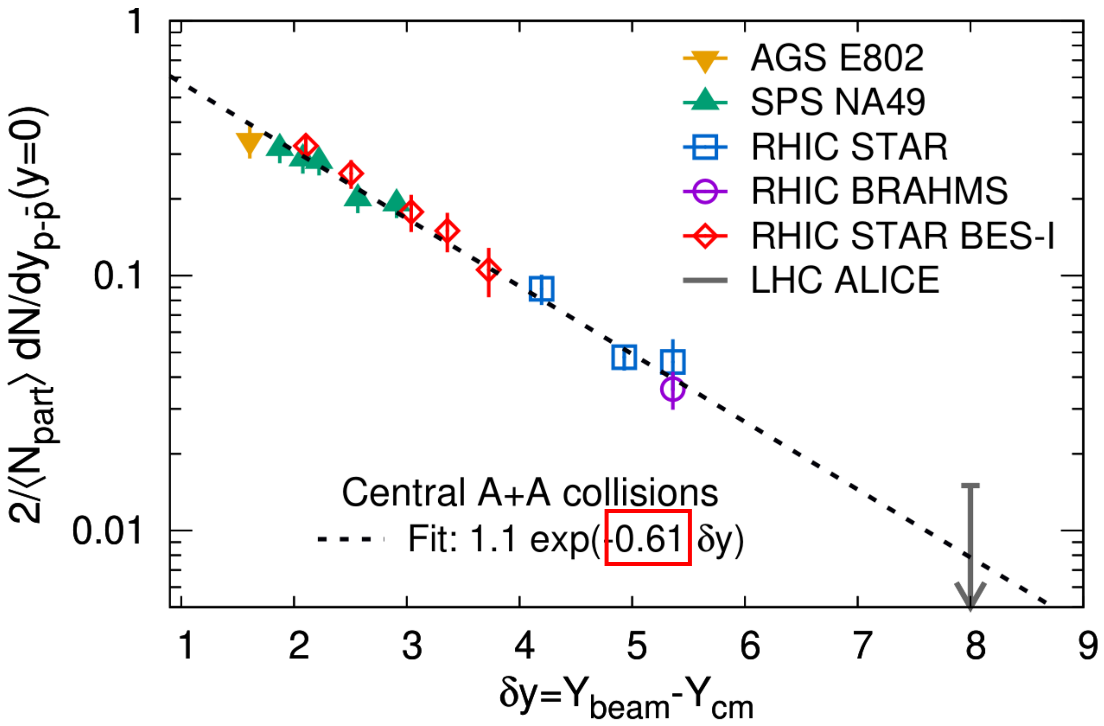


Regge theory:

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

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

Net-proton Yield at Mid-y from Various Energies



J. Brandenburg et al, arXiv:2205.05685

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

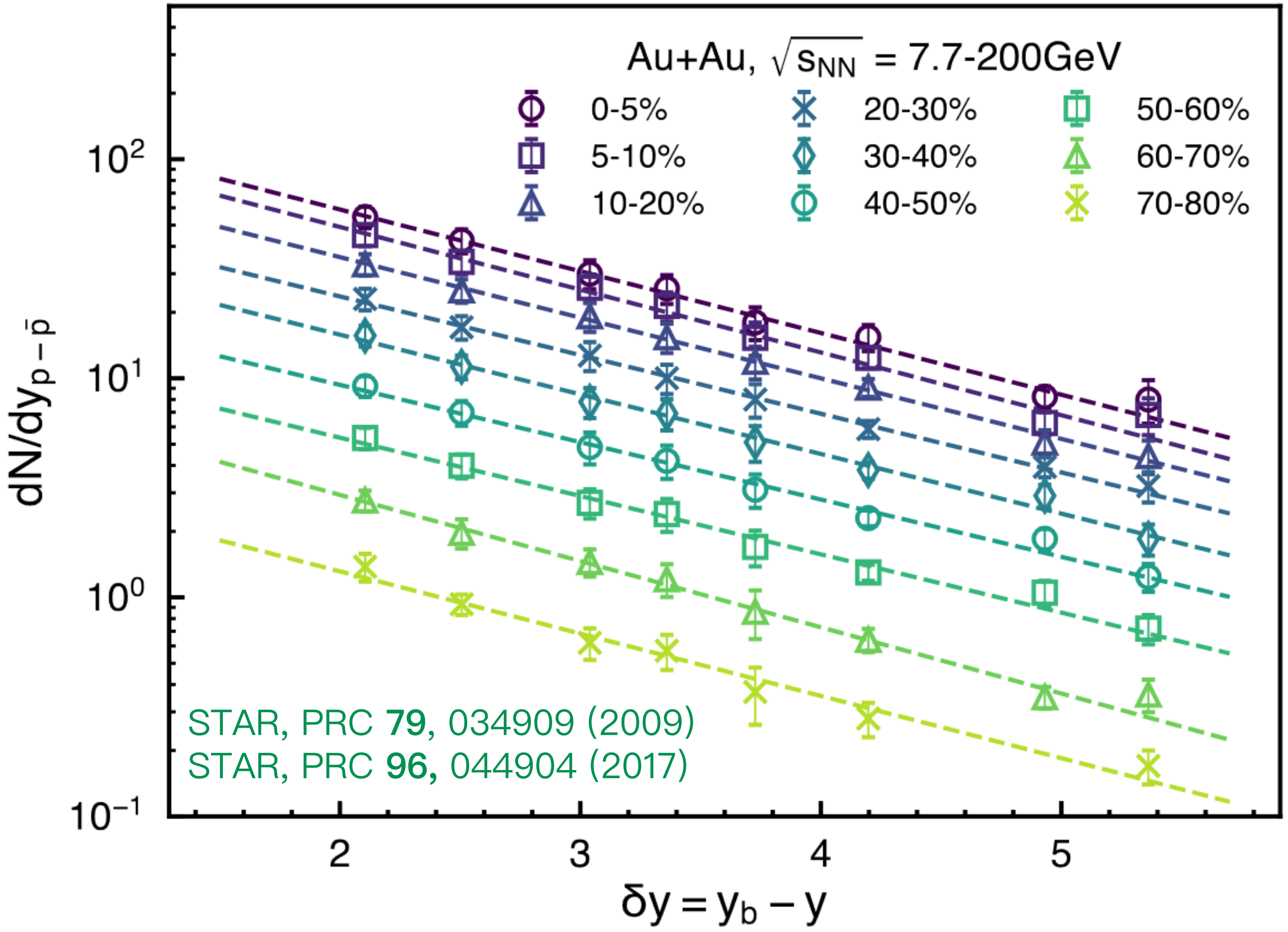
Prediction with junction: $\alpha_B = \begin{cases} 1 & double - baryon\ stopping \\ 0.42 & single - baryon\ stopping \end{cases}$

D. Kharzeev, PLB378, 238 (1996)

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

Consistent with baryon junction transport by gluons

Centrality Dependence

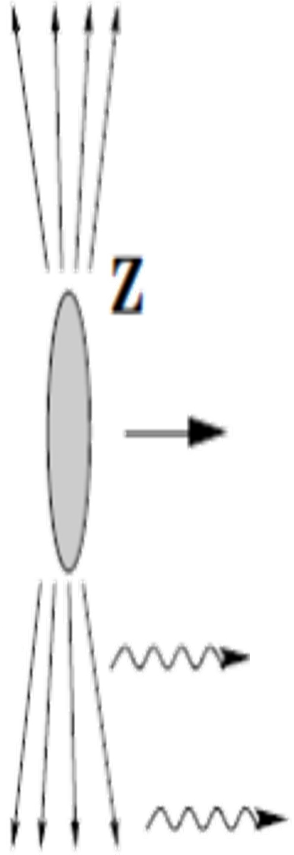


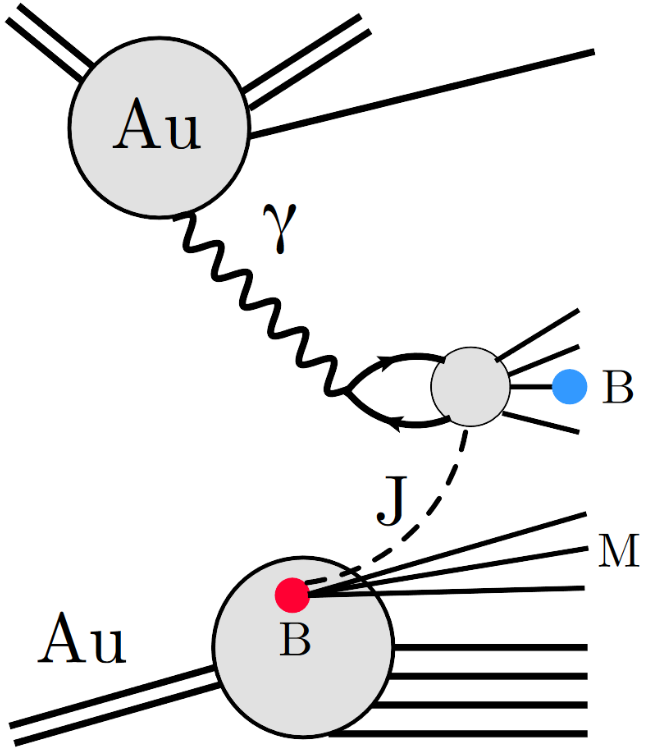
- Scaling in all centralities and collision energies
- Slopes do not depend on centrality
  - Baryon stopping at mid–y is not due to multiple scattering

Method II

Net–Baryon Rapidity Distribution in γ+A

Net–Baryons in Photon+Au Events





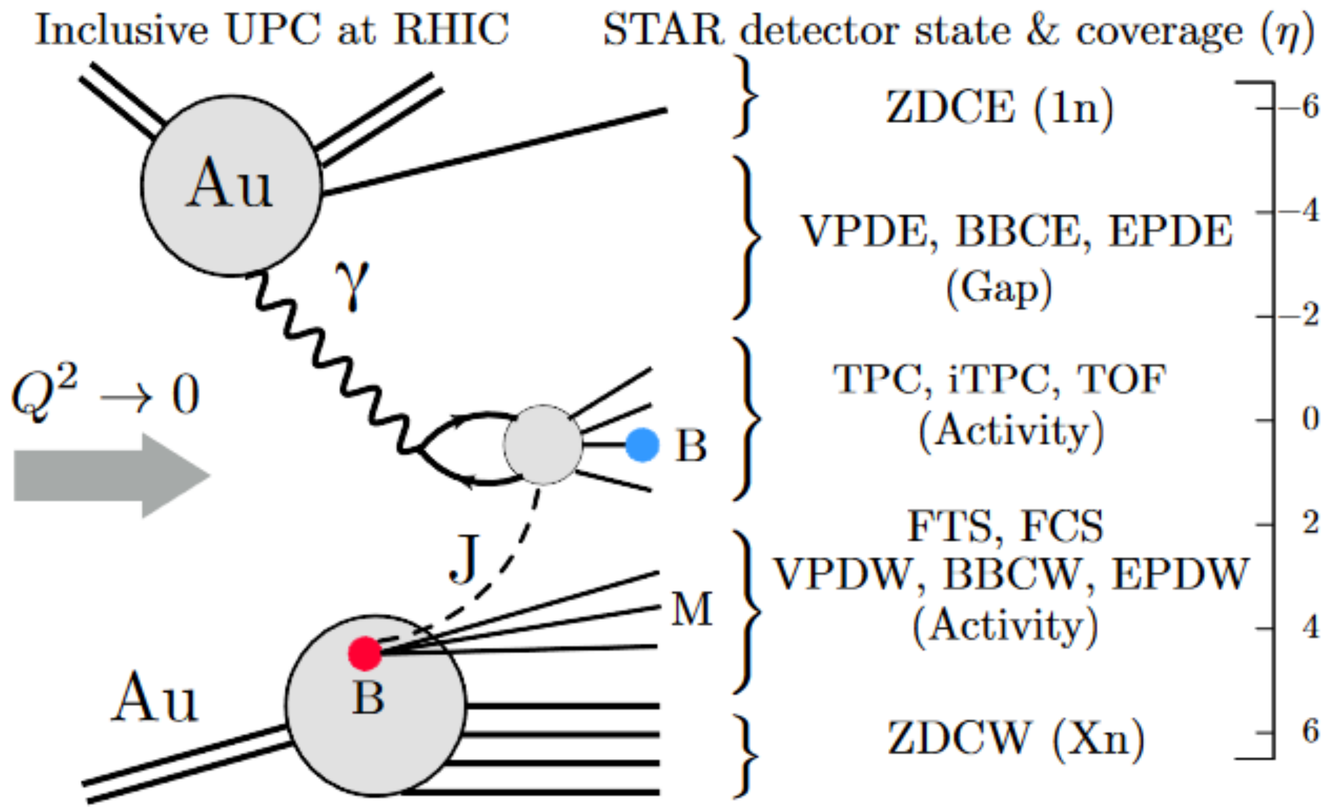
- Strong electromagnetic field accompanies the nuclei in relativistic heavy–ion collisions
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux
- Photon fluctuates into a quark–antiquark pair and interact with the nucleus target

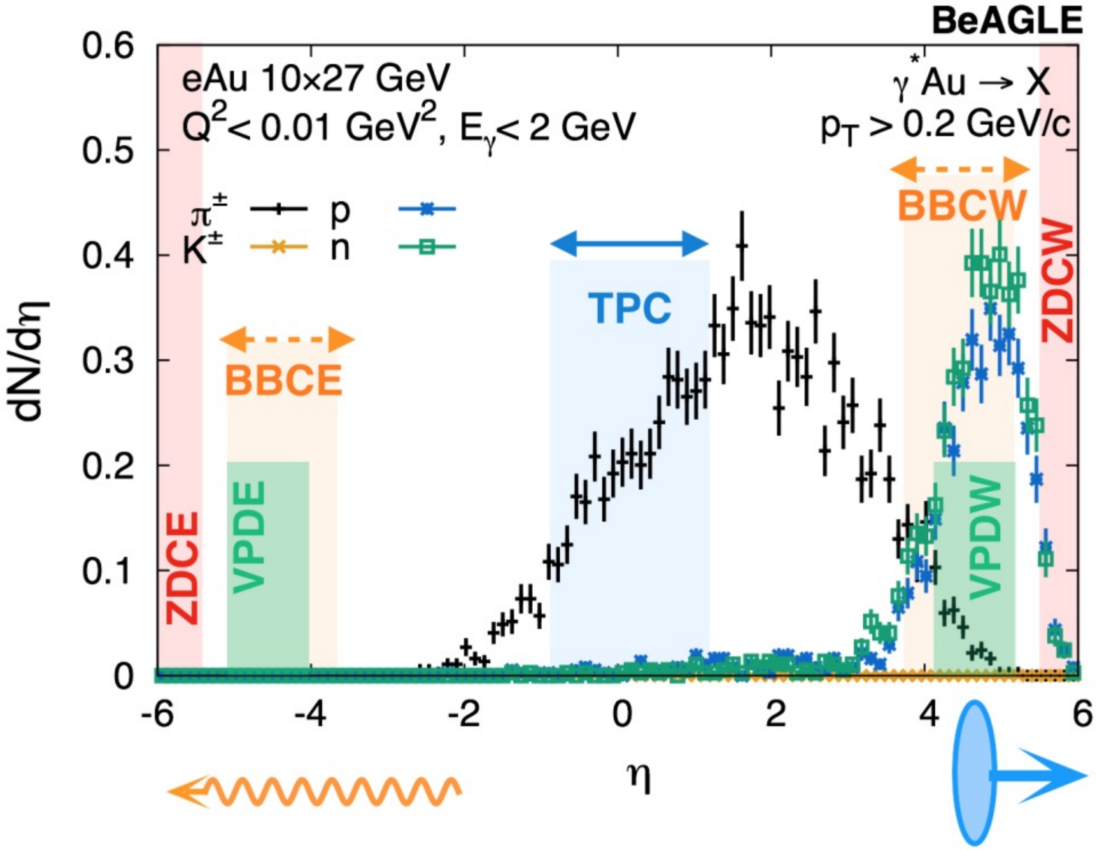
$$\frac{dN}{dy} \propto e^{-\alpha_B(y_{beam}-y)} \propto e^{\alpha_B y}$$

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

J. Brandenburg et al, arXiv:2205.05685

Selection of Photonuclear Events

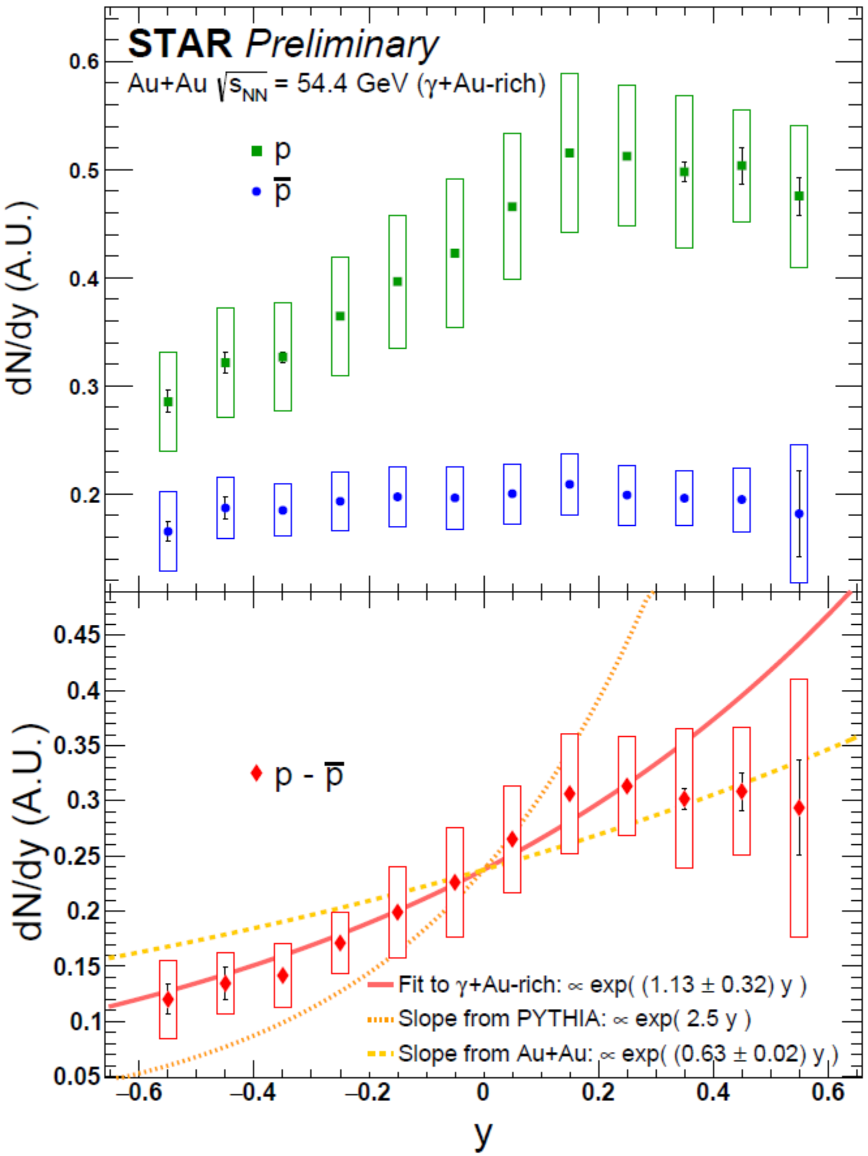




Similar technique used by LHC photonuclear measurements ATLAS, PRC104, 14903 (2021) CMS, PLB844, 137905 (2023)

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

Net–Baryons in Photonuclear Events



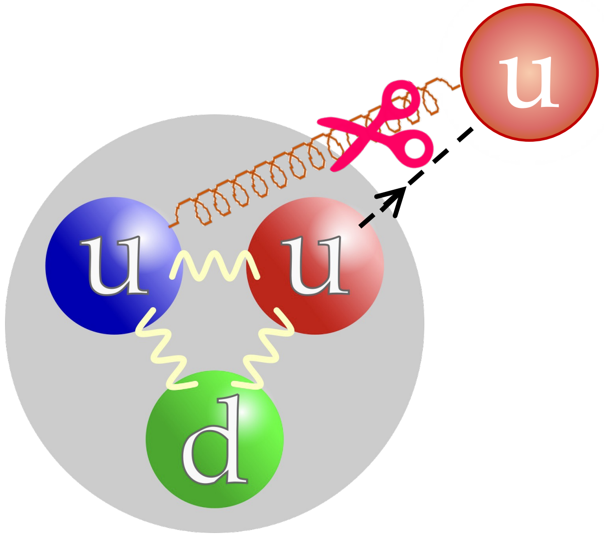
- photon+Au collisions selected from ultra–peripheral Au+Au collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic exponential increase towards nucleus side
- $\alpha_B = 1.13 \pm 0.32$ for net–proton
  - Closer to heavy–ion BES results than PYTHIA

Method III

Correlation of Net-Baryon and Net-Charge

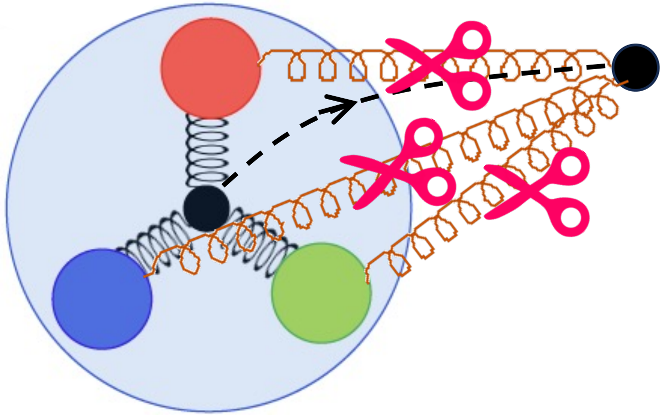
Net–Charges vs. Net–Baryons

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

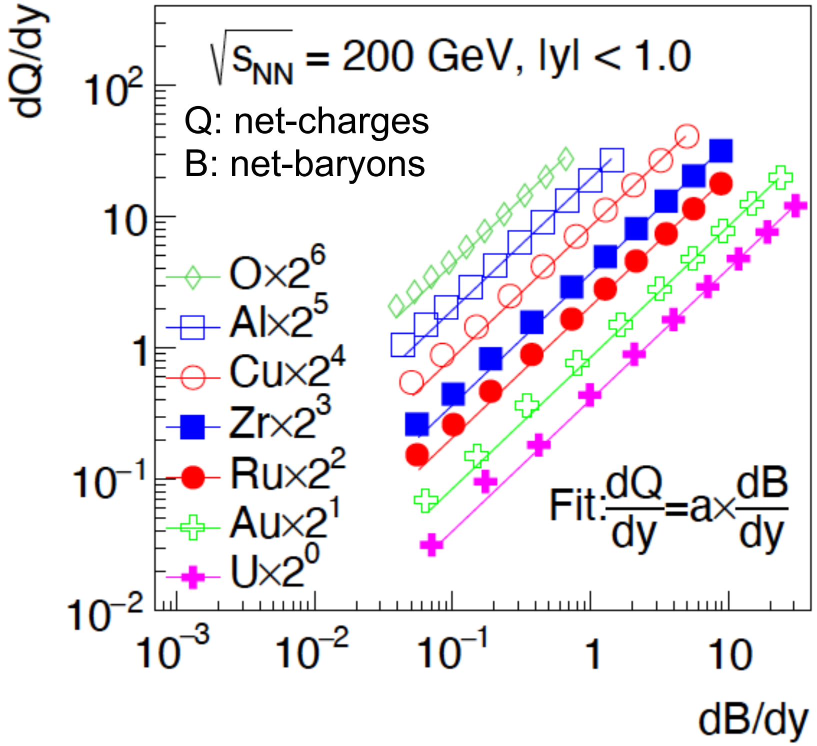
Baryon junction stopping

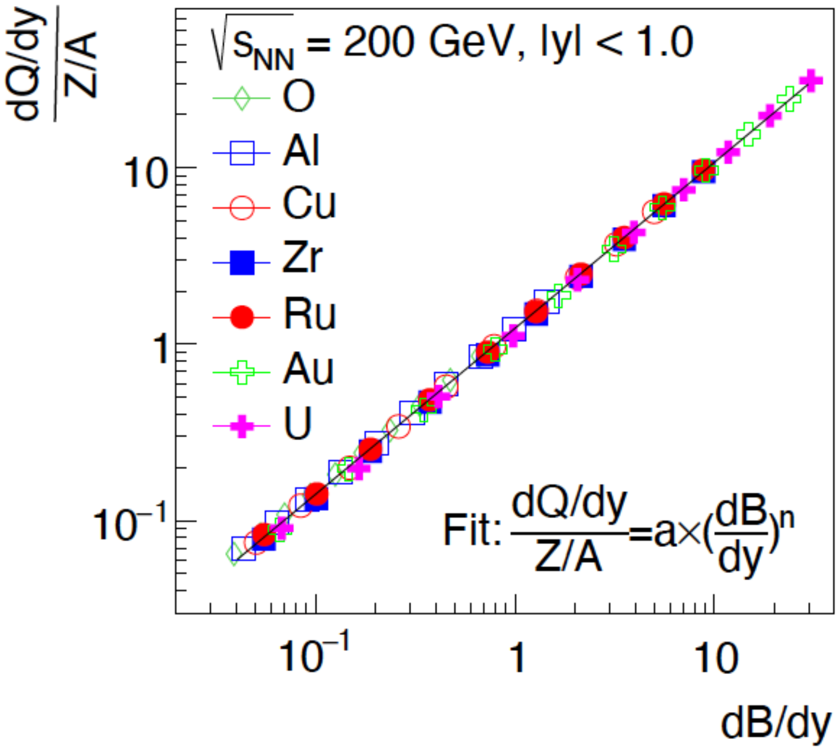


- Quarks connected to the stopped junction are sea quarks
- The ratio of net–charge and net–baryon is not related to the quark composition of projectile and target

Net–Charges vs. Net–Baryons from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering



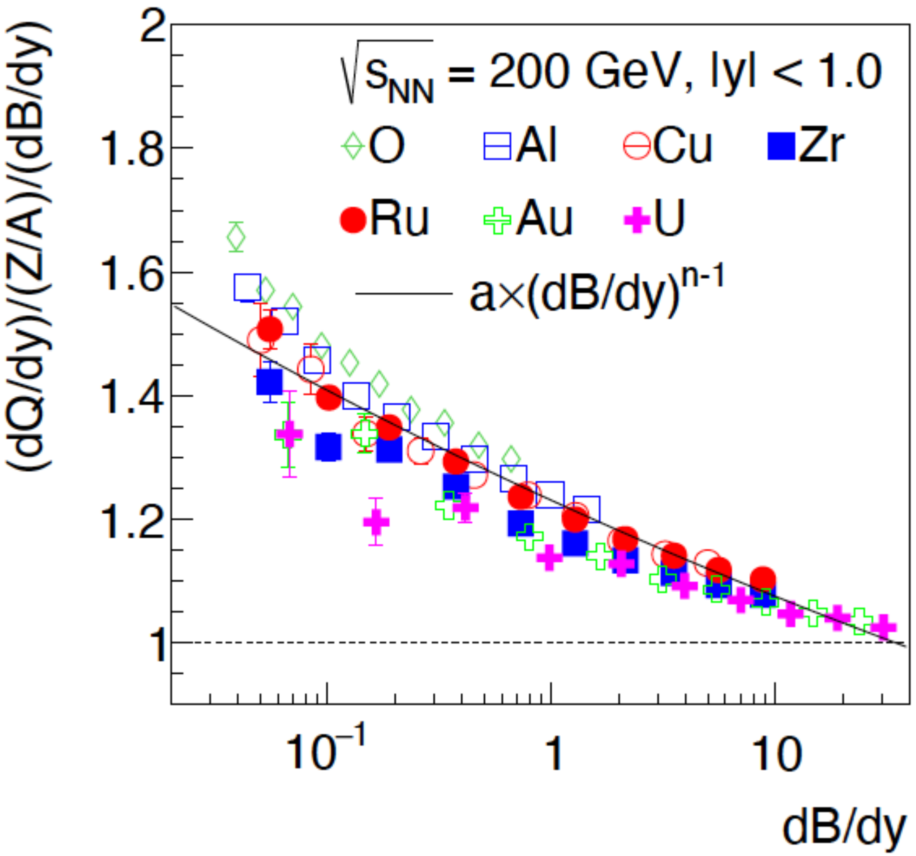


- Strong correlation of Net–B and Net–Q at mid–y
- Slope a increase with Z/A

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

Net–Charges vs. Net–Baryons from UrQMD

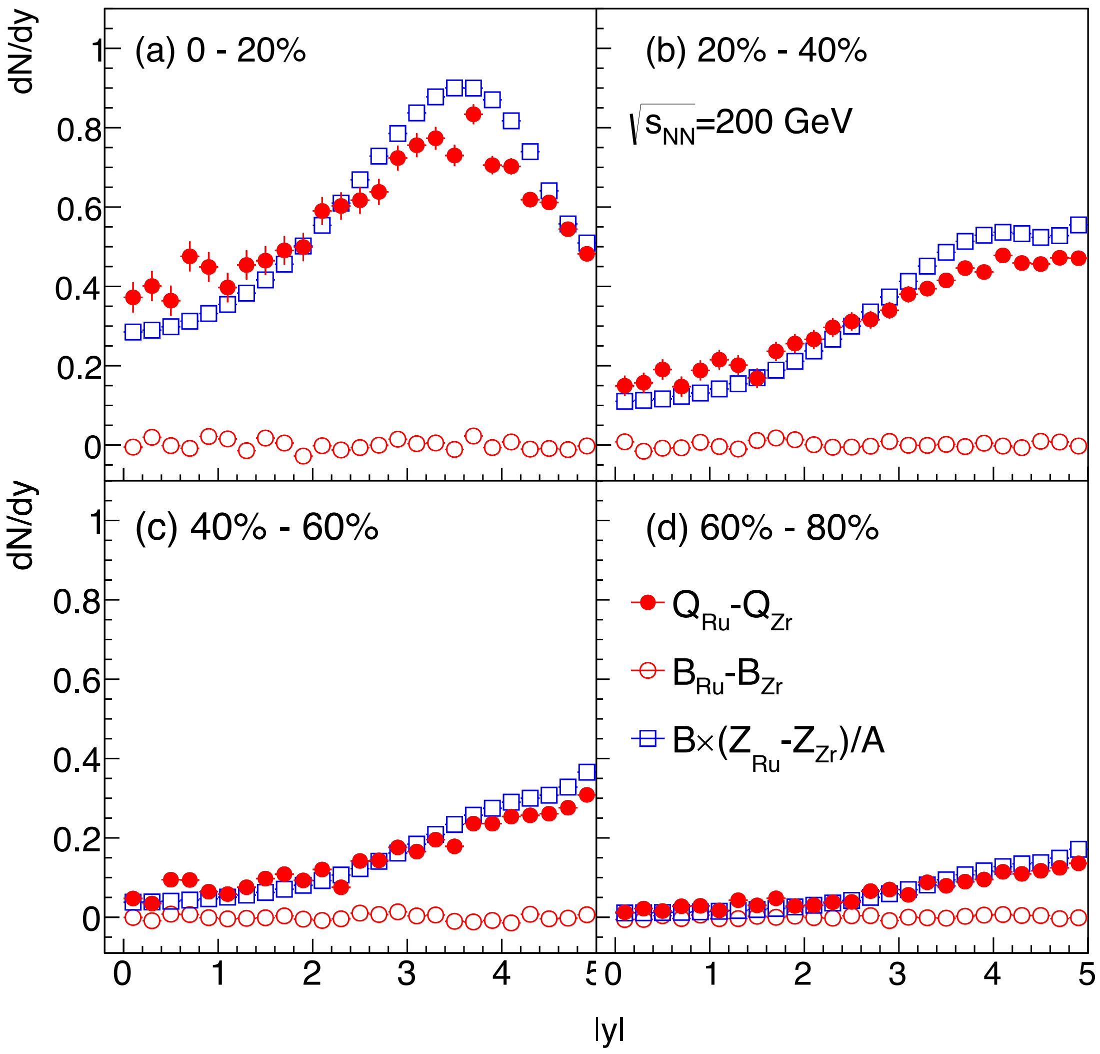
Baryon stopping in UrQMD: valence quark stopping + multiple scattering



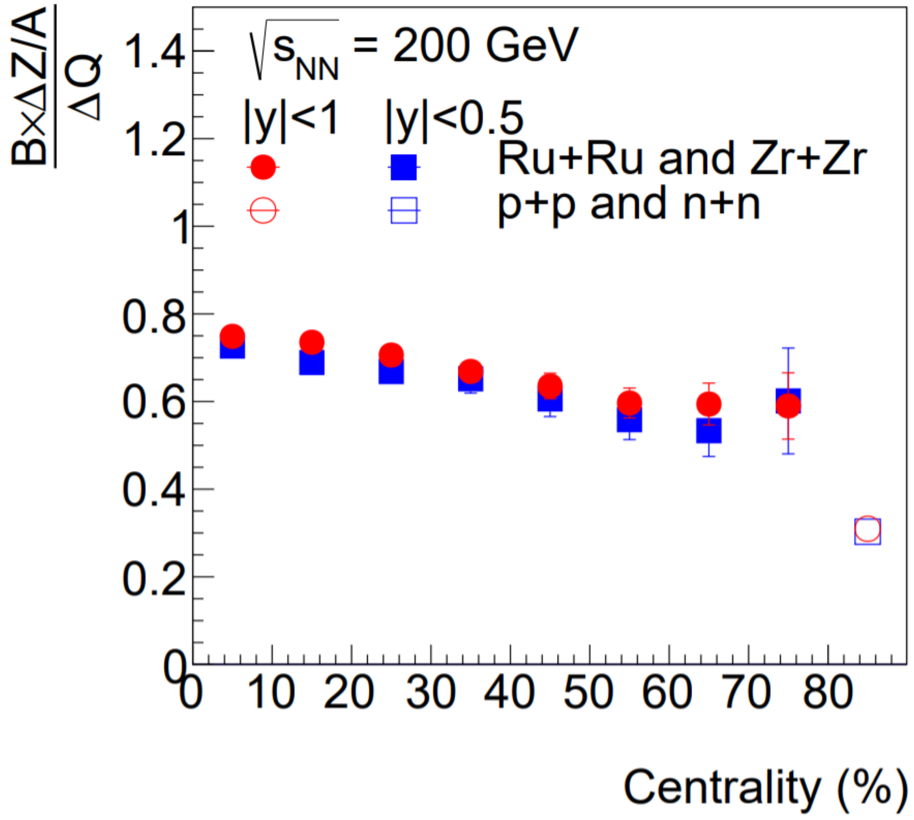
- Q/B x A/Z approaches 1 for large A
- Expect 25% difference of Q/B in O+O and Au+Au collisions

Net-Charges and Net-Baryons in Isobaric Collisions

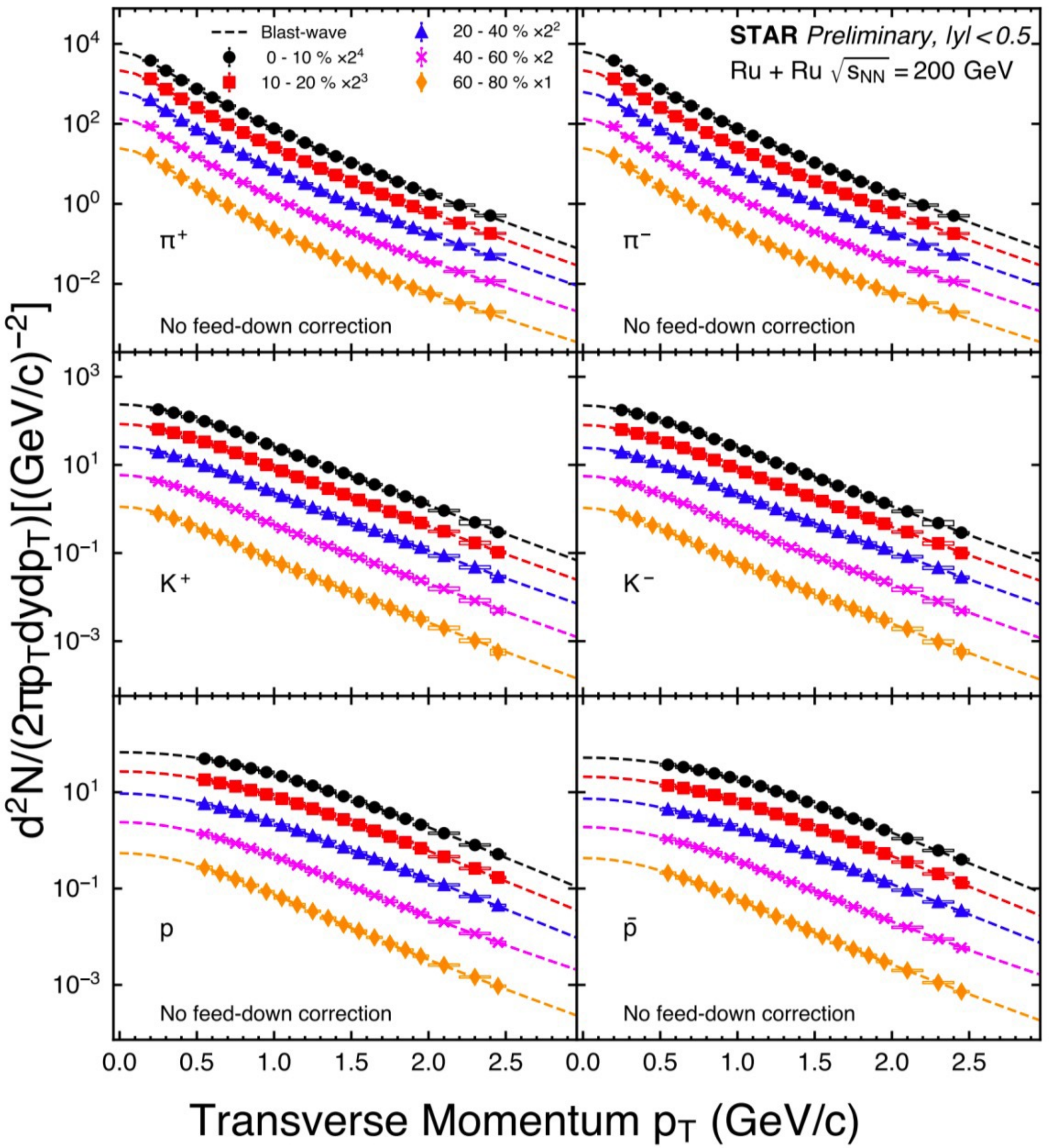
Ru+Ru and Zr+Zr collisions at 200 GeV from UrQMD

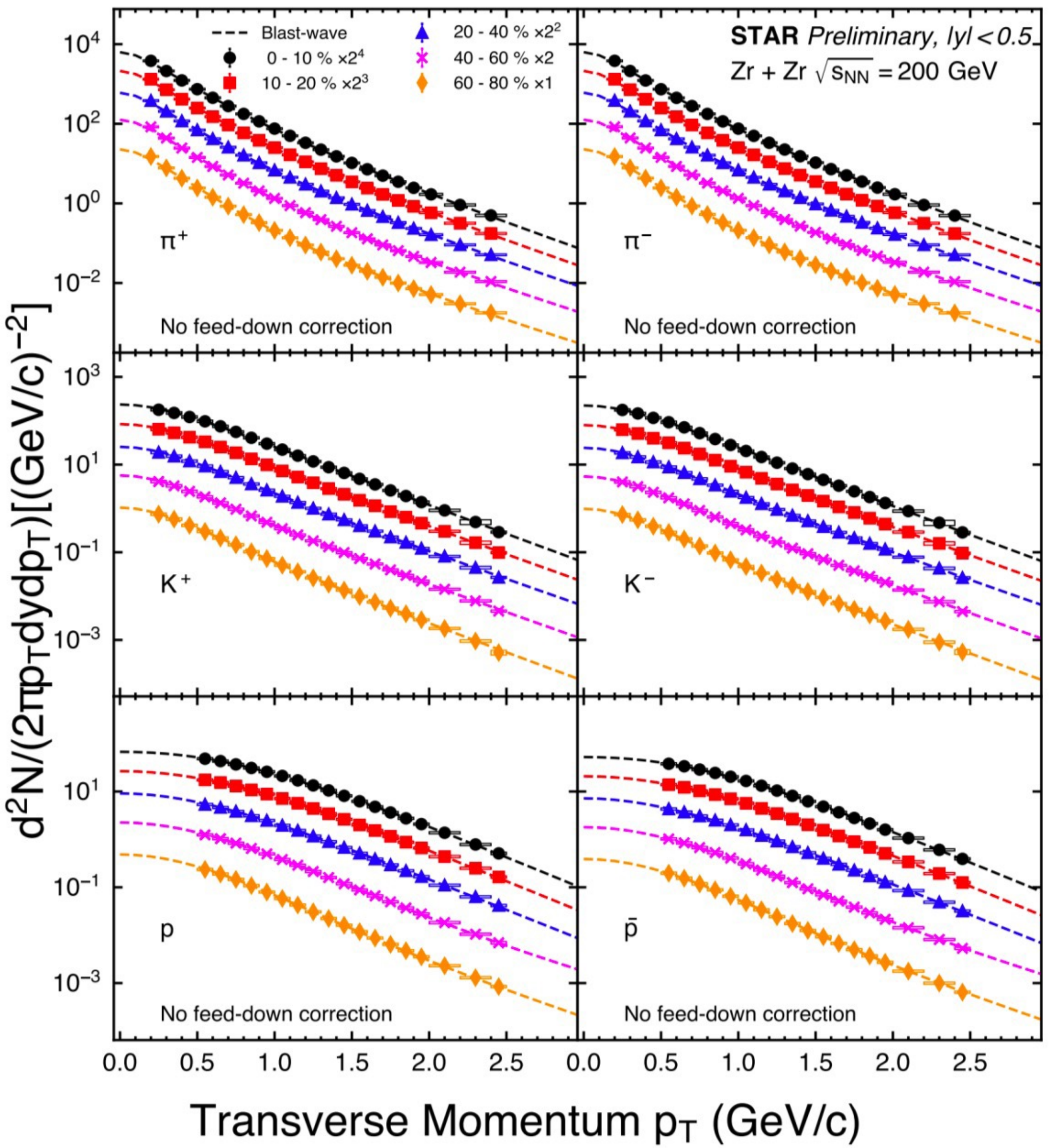


- Difference of B is almost zero
- Difference of Q is close to B*ΔZ/A

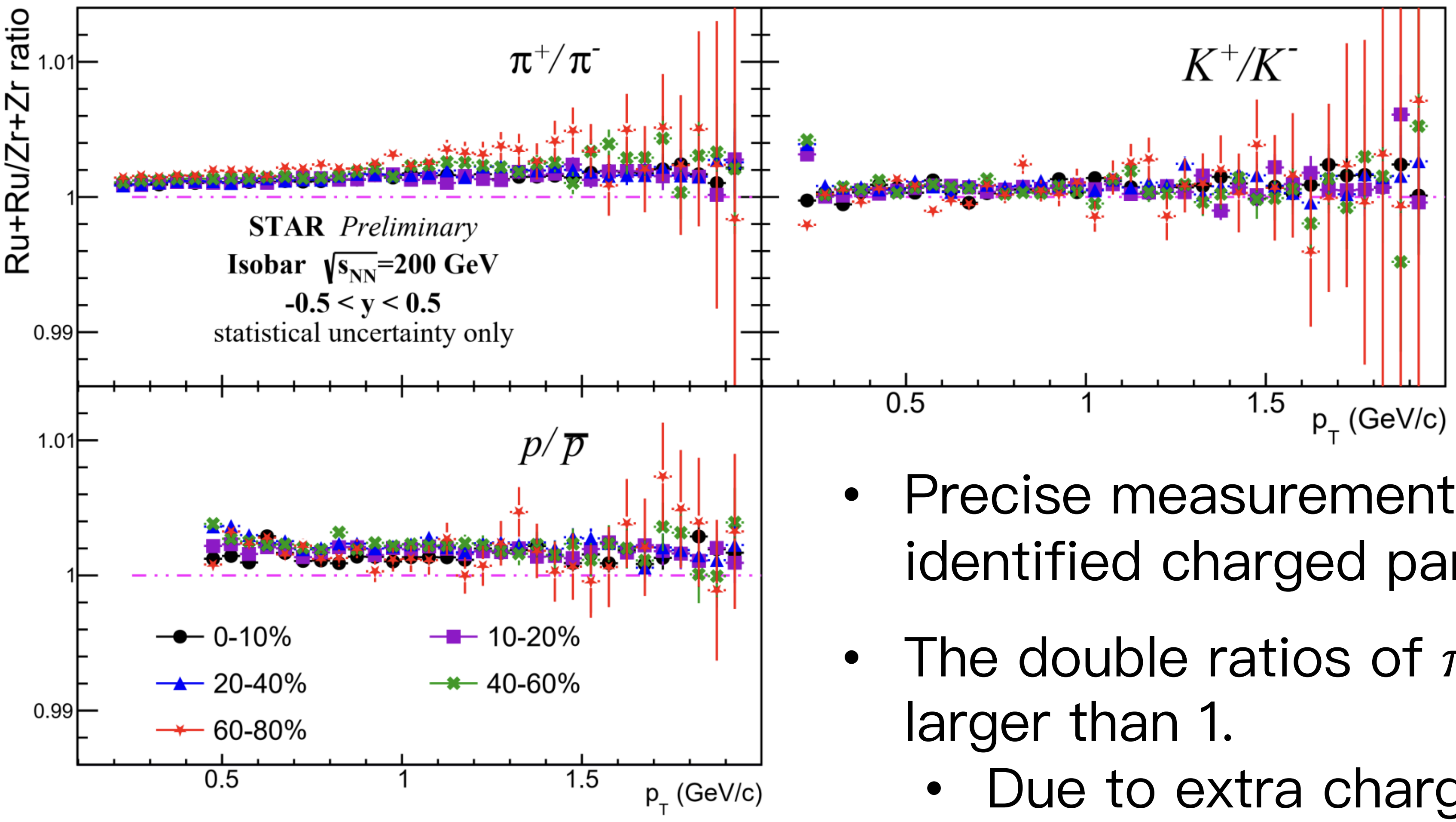


Identified Particle Spectra in Ru+Ru/Zr+Zr Collisions





Measurement of Double Ratios



Yang Li, PhD thesis, USTC (2023)

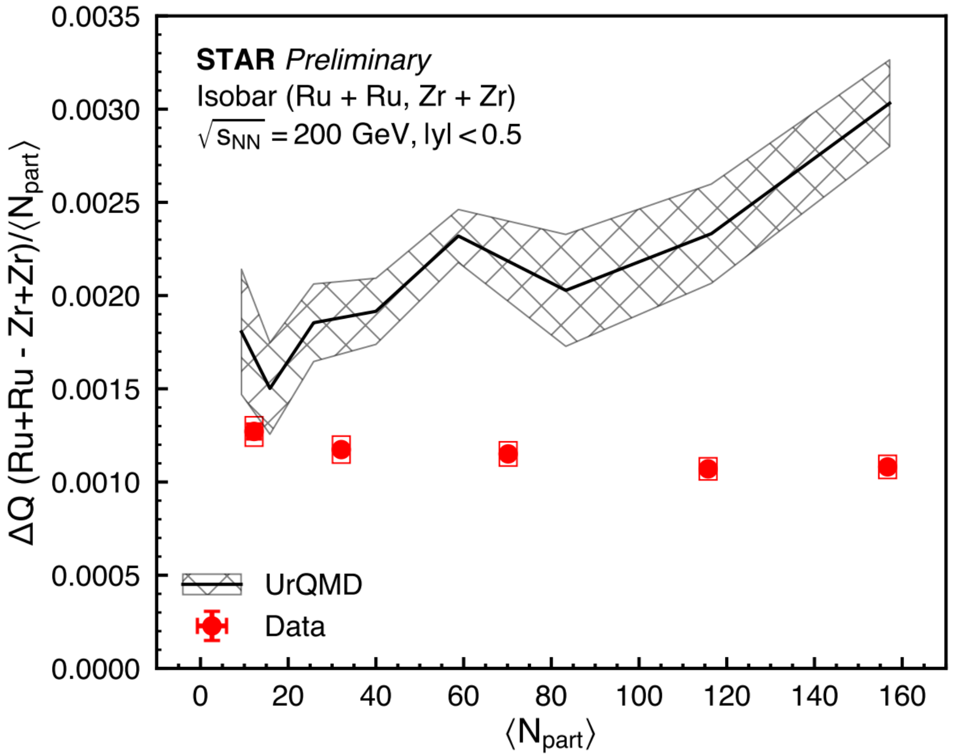
- Precise measurement of double ratios of identified charged particles
- The double ratios of π^+/π^- and $p/\bar{p}$ are larger than 1.
  - Due to extra charge in Ru?
- The double ratios of K^+/K^- is consistent with unity within uncertainties.

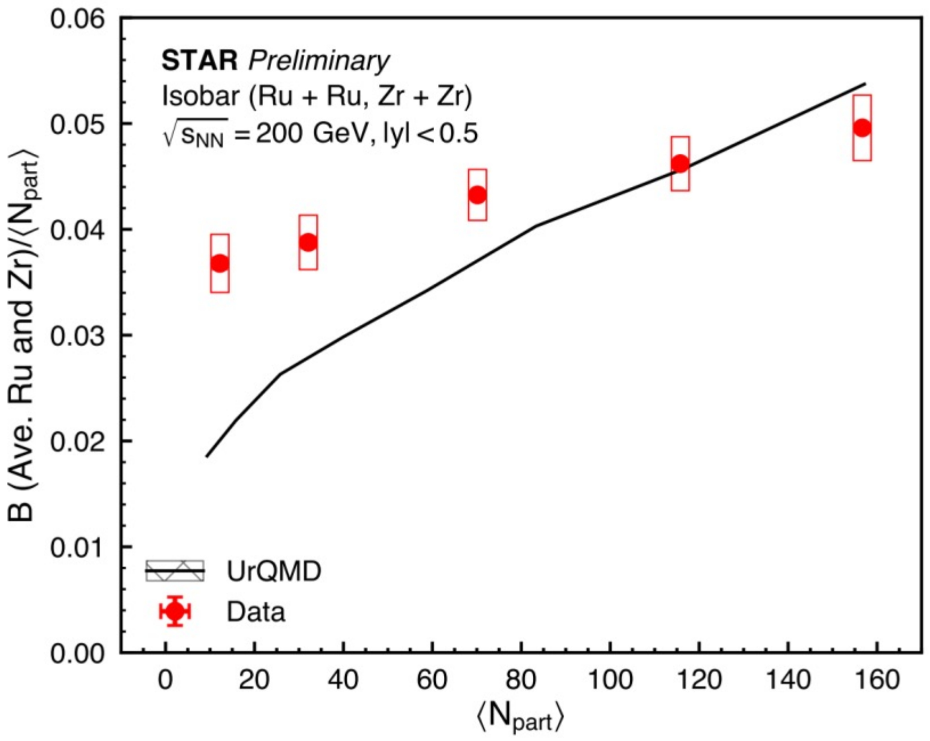
Calculation of Net-Charge Difference

- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta\mathrm{R}_{\mathrm{Ru}}}{1+\Delta\mathrm{R}_{\mathrm{Zr}}} \approx 1 + \Delta\mathrm{R}_{\mathrm{Ru}} - \Delta\mathrm{R}_{\mathrm{Zr}}$
- $\Delta Q = \left[\left(N_\pi^+ + N_K^+ + N_p\right) - \left(N_\pi^- + N_K^- + N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$
- Focus on pion terms,
- $(N_\pi^+ - N_\pi^-)_{Ru} - (N_\pi^+ - N_\pi^-)_{Zr} = N_{\pi,Ru} \times \Delta\mathrm{R}_{\mathrm{Ru}} - \mathrm{N}_{\pi,Zr} \times \Delta\mathrm{R}_{\mathrm{Zr}}$
- $\approx N_\pi(\Delta\mathrm{R}_{\mathrm{Ru}} - \Delta\mathrm{R}_{\mathrm{Zr}}) = \mathrm{N}_\pi \times (R2_\pi - 1)$
- Where $N_\pi = 0.5 \times (N_\pi^+ + N_\pi^-)$
- Therefore, $\Delta Q = \mathrm{N}_\pi(\mathrm{R2}_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$

Net-charge difference (ΔQ) can be precisely measured via double-ratios

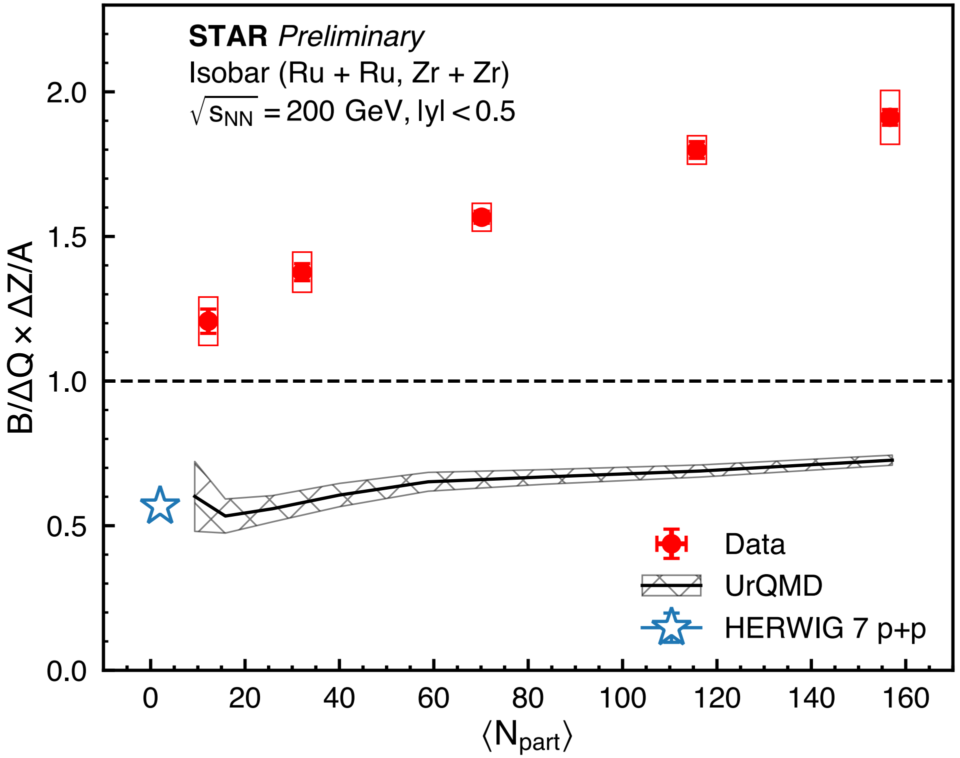
Net-Charge and Net-Baryon Compared to UrQMD





UrQMD accurately reproduces baryon stopping at mid-rapidity in central collisions but not ΔQ, probably because UrQMD has been tuned to net-proton measurements

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



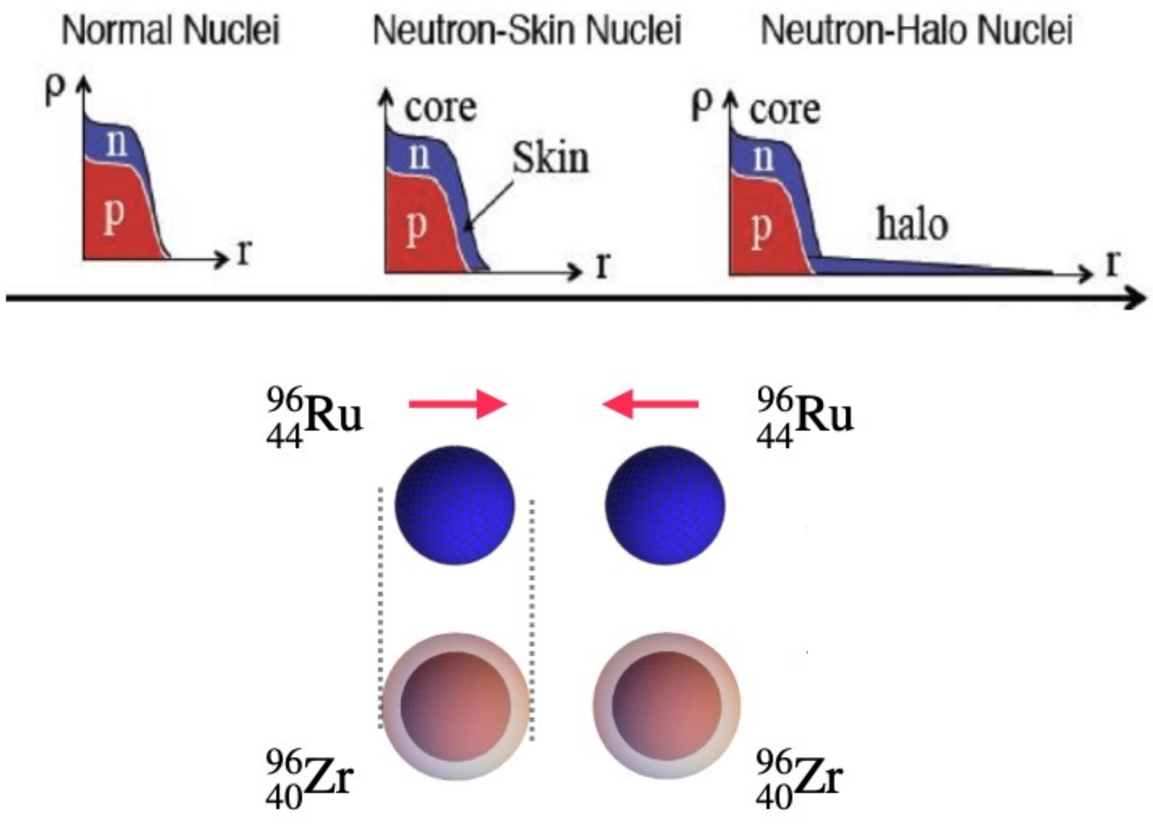
HERWIG: J. Bellm et al, EPJC80, 452 (2020)

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

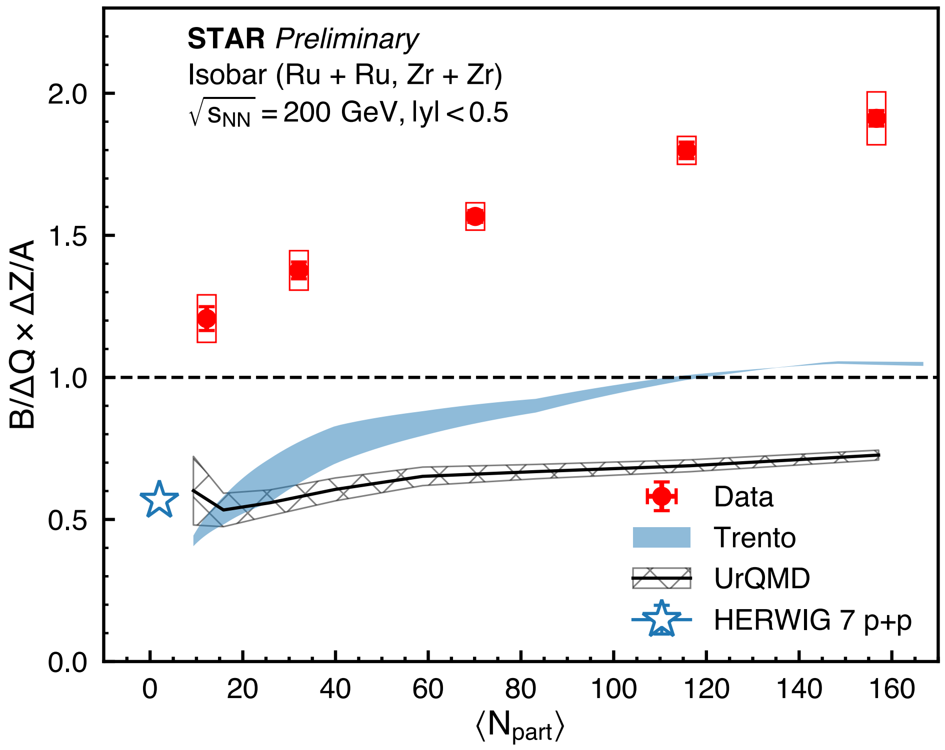
- Experimental observation:
  More baryon transported to mid–y than charge by a factor of up to 2

- Model with valence quark stopping:
  Less baryon transported to mid–y than charge by a factor of 1.5–2

Neutron Skin Effect?



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

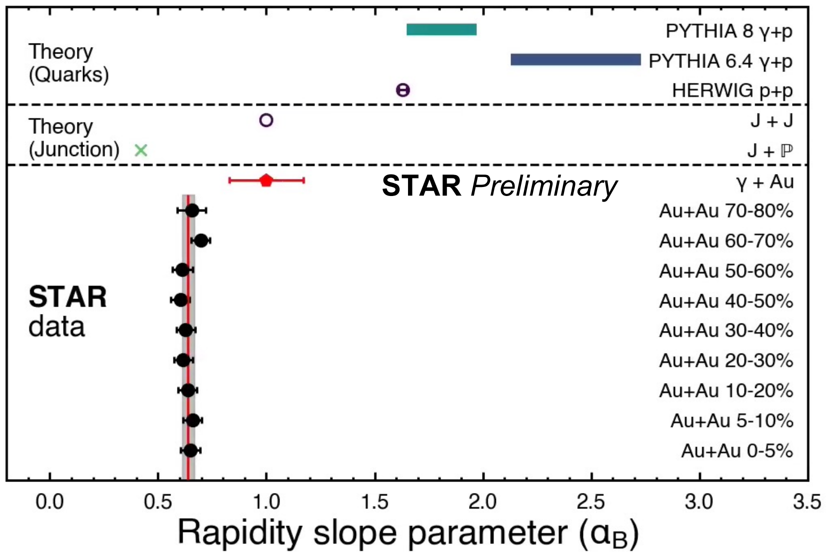


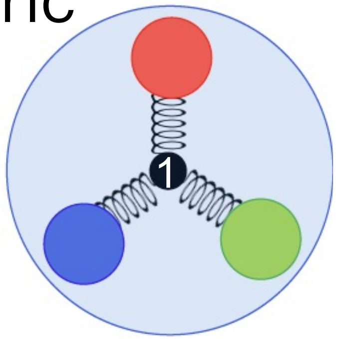
J. Moreland et al, PRC92, 011901(R) (2015)

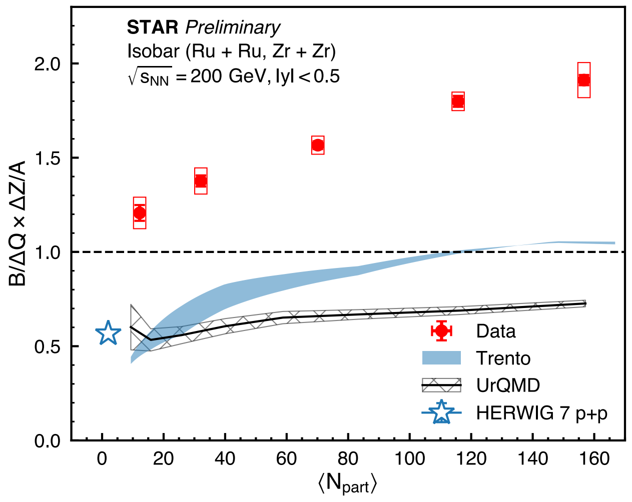
- Thick halo-type neutron skin in Zr
- More p+p collisions in central Zr+Zr
- Explains the centrality dependence
- But not enough to explain large ratio

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 the Ratio is Less Than One in UrQMD?