Track Baryon Number with Heavy Ion Collisions

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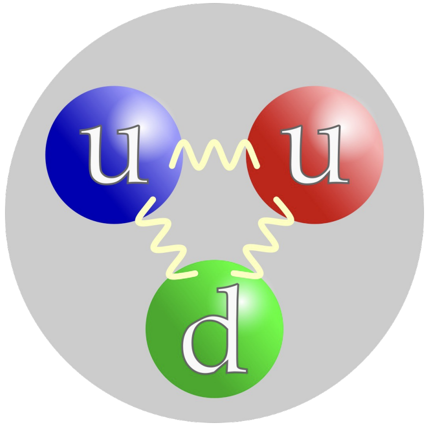
Quark Model and Baryon Number Carrier

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

- Baryon number are carried by quarks
- Any experimental evidence? NO!
- Is it the only reasonable picture? NO!

Quark Model and Baryon Number Carrier

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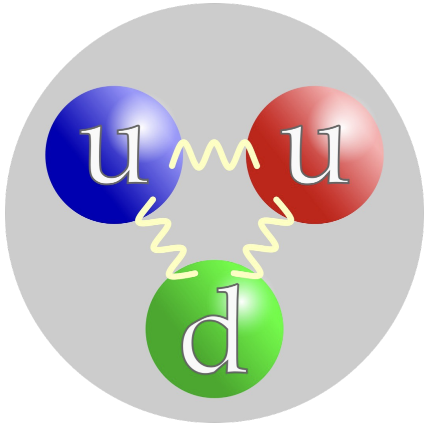
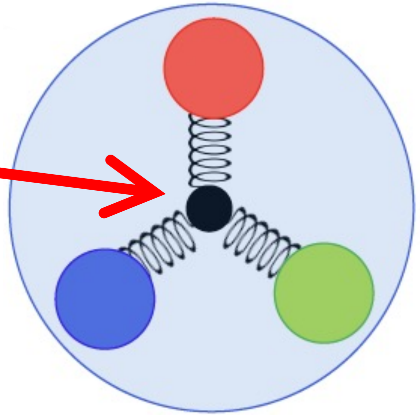


https://en.wikipedia.org/wiki/Quark

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

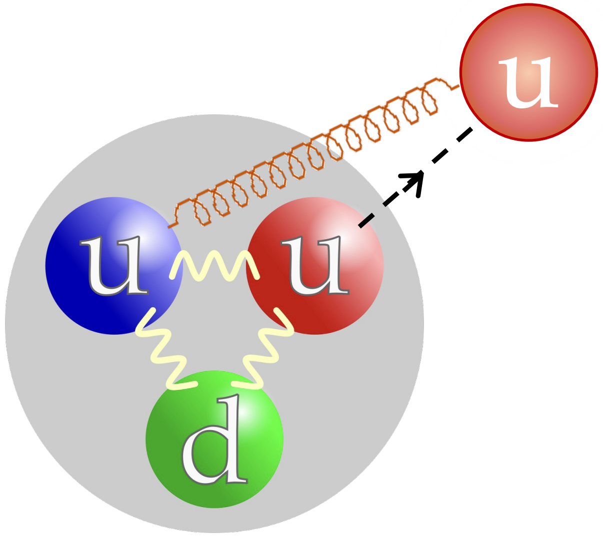


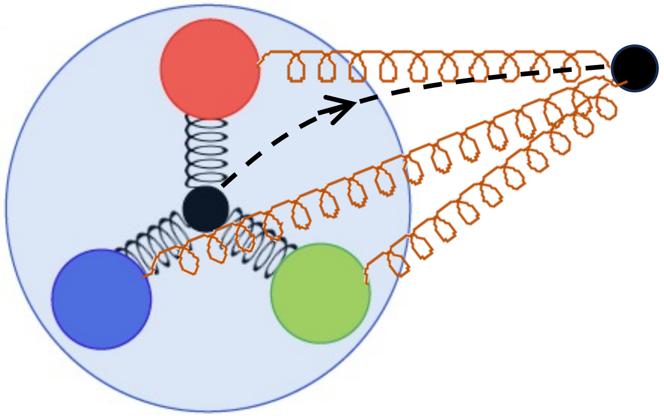
X. Artru, NPB85, 442 (1975)
G. Rossi and G. Veneziano, NPB123, 507 (1977)

How to Probe the Baryon Number?

Pull them out:

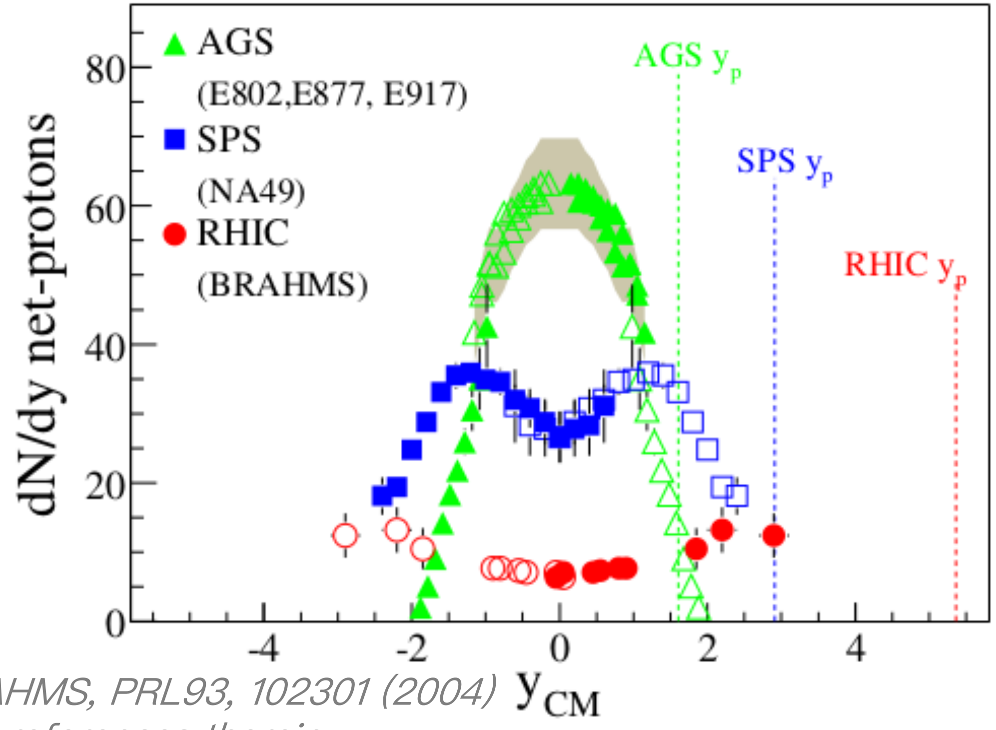
Measure baryon stopping at mid-rapidity in p+p and A+A collisions





D. Kharzeev, PLB378, 238 (1996)

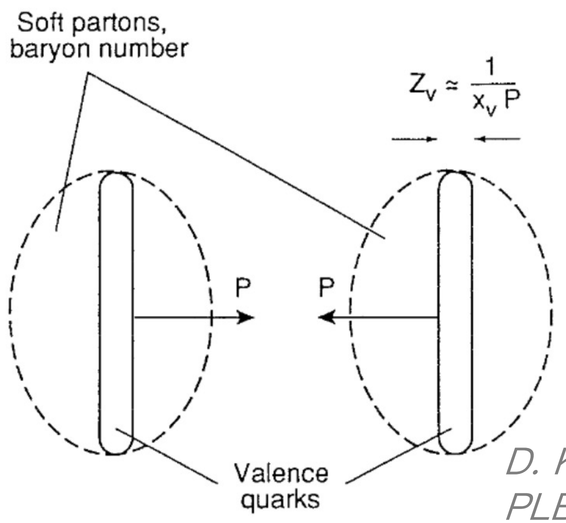
Net–Baryons Rapidity Distribution



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?

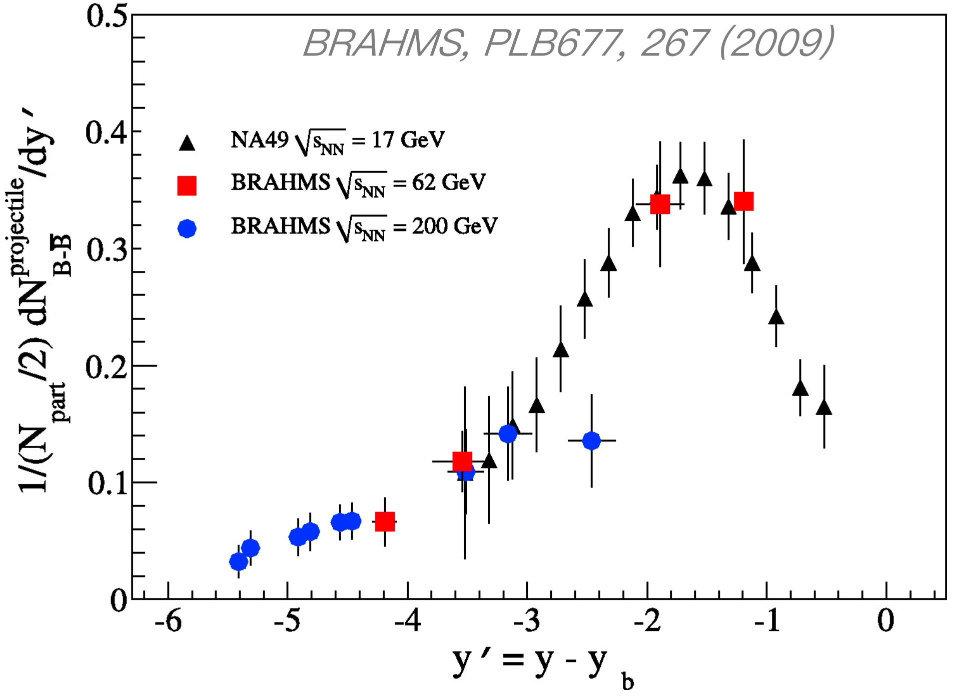


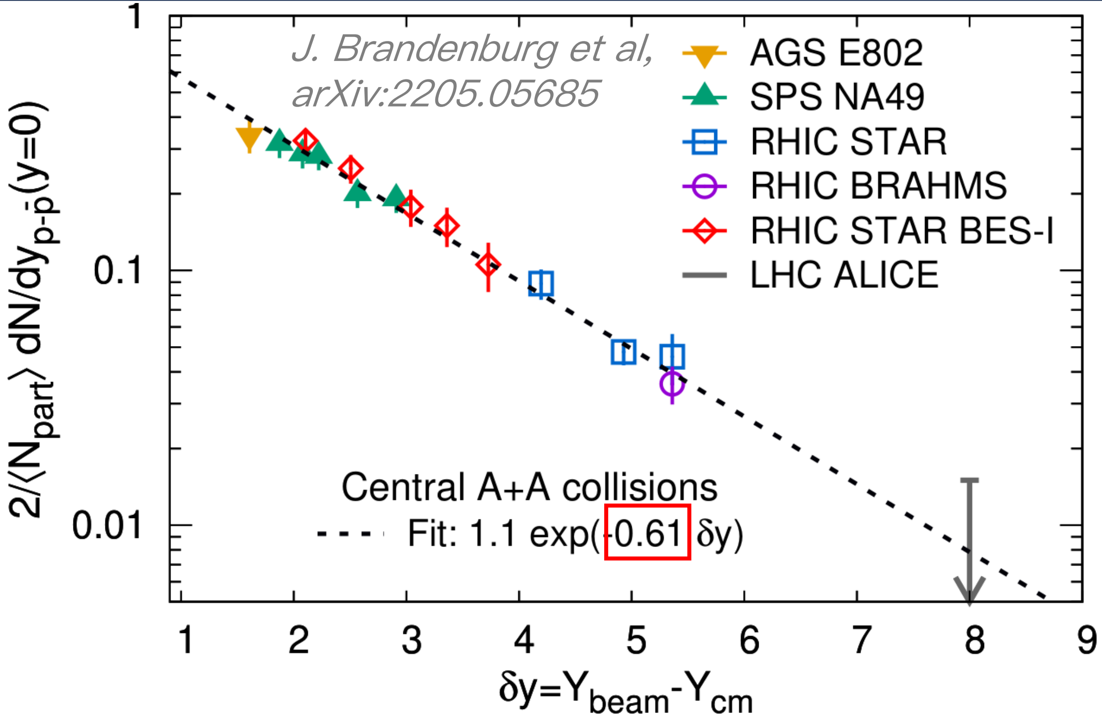
$x_J \ll x_v$

D. Kharzeev, PLB378, 238 (1996)

- Valence quarks have short time to interact due to Lorentz contraction, but multiple scattering may give rise to large rapidity loss
- Baryon junctions carry a much lower x and have enough time to interact and be stopped at mid–y

Net–Baryons Rapidity Distribution





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

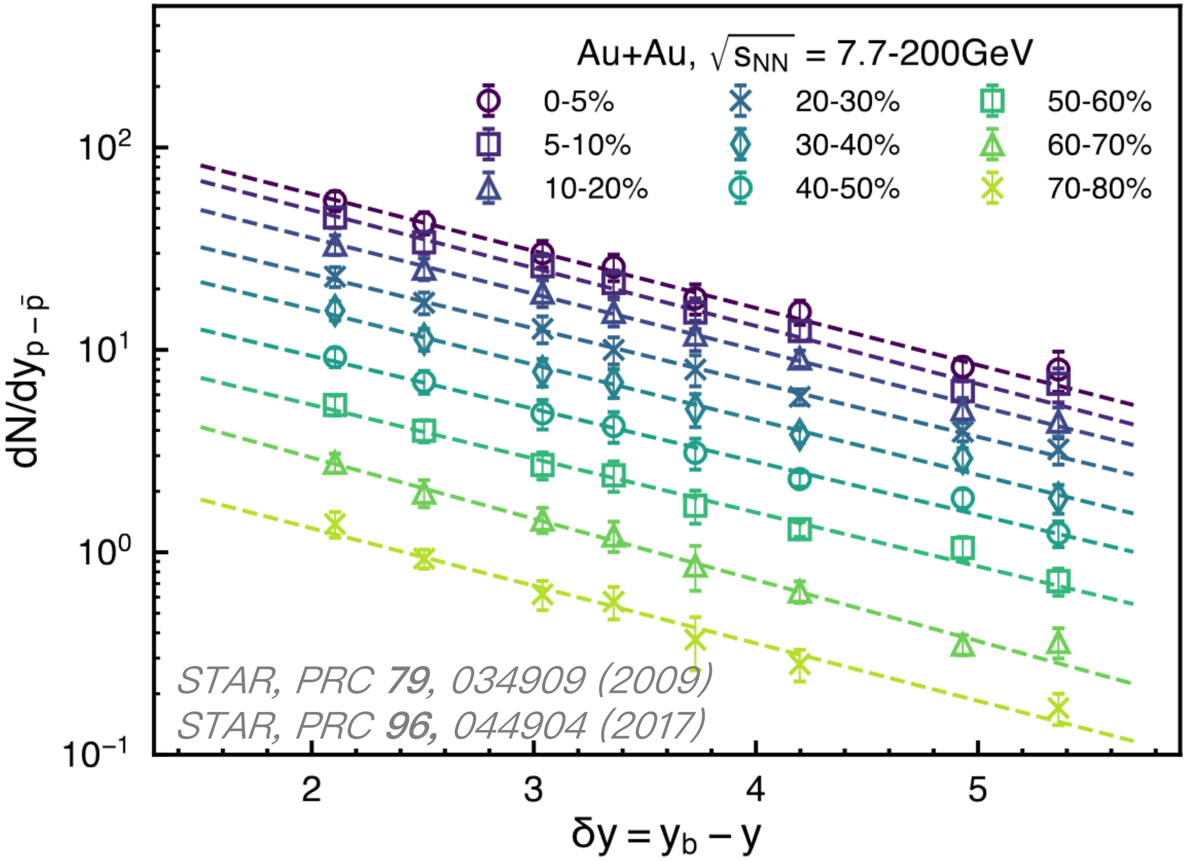
$$\alpha_B = \begin{cases} 1 & double - baryon\ stopping \\ 0.42 & single - baryon\ stopping \end{cases}$$

D. Kharzeev, PLB378, 238 (1996)

Experiments observe: $\alpha_B = 0.61 \pm 0.03$

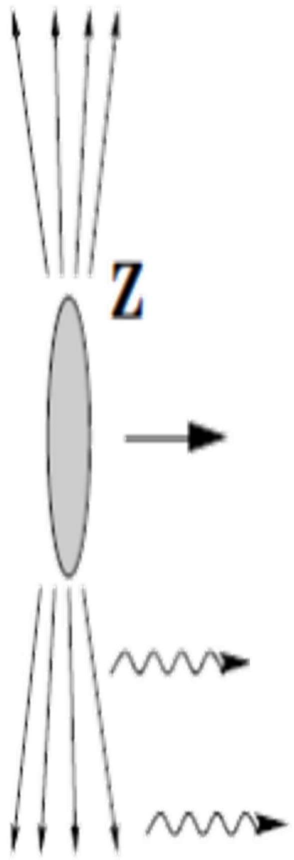
Consistent with baryon junction transport by gluons

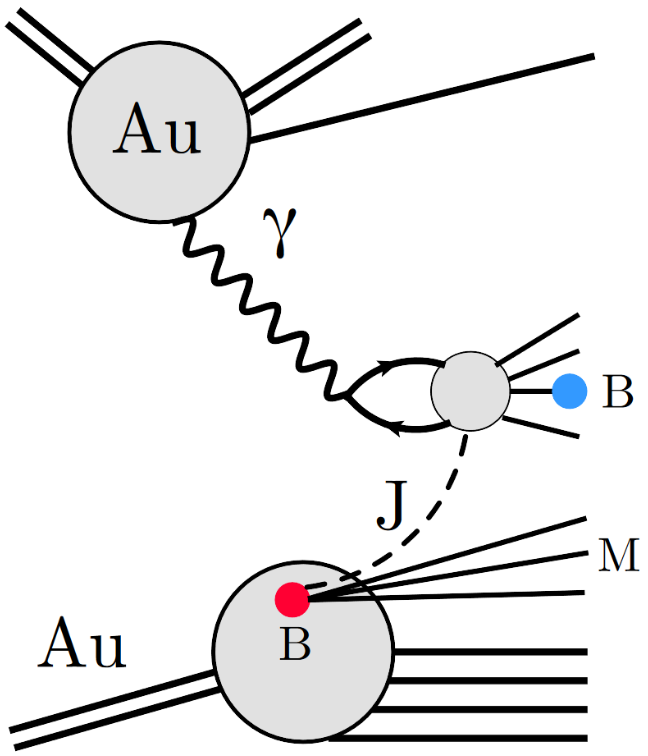
Centrality Dependence



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

Net-Baryons in Photon+Au Events

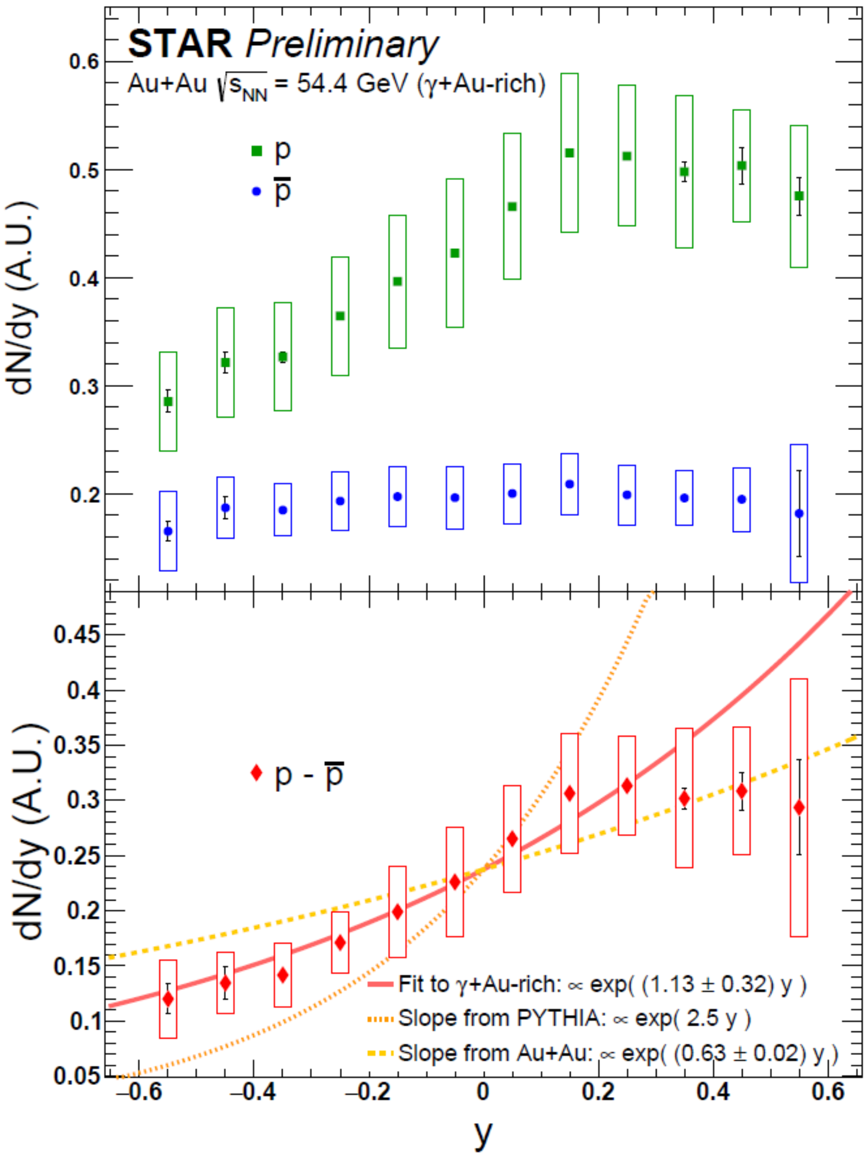




- Strong electromagnetic field accompanies the nuclei in relativistic heavy-ion collisions
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux
- Photon fluctuates into a quark-antiquark pair and interact with the nucleus target

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

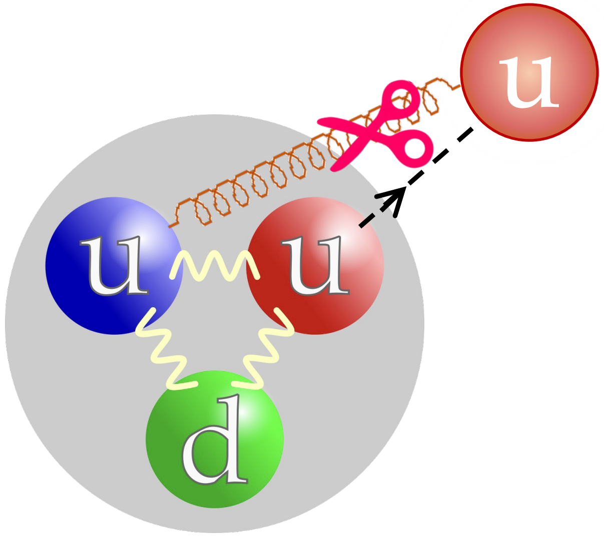
Net–Baryons in Photonuclear Events



- photon+Au collisions selected from 54.4 GeV 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

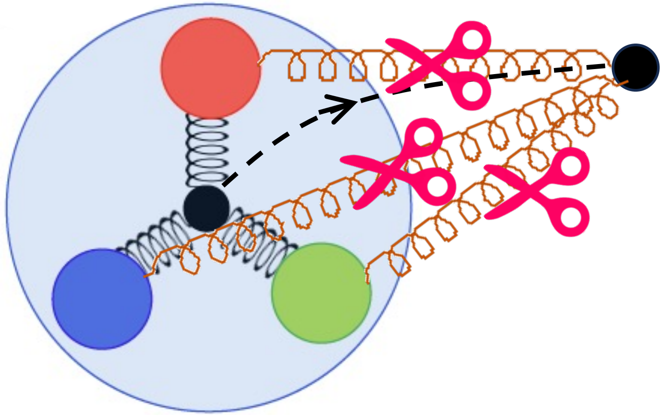
Net-Charges vs. Net-Baryons

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

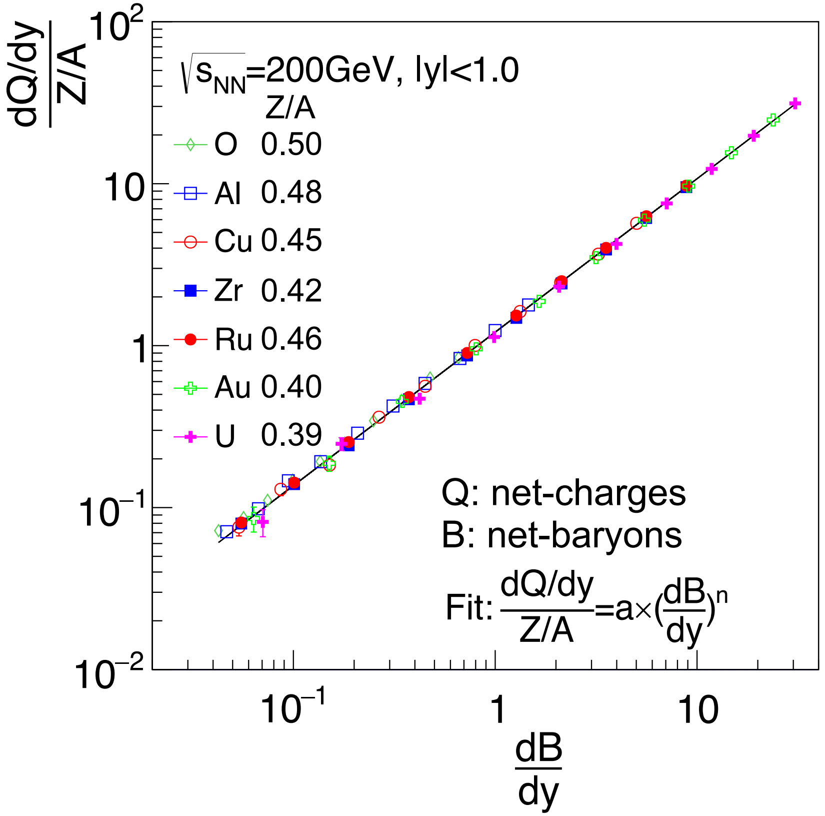
Baryon junction stopping

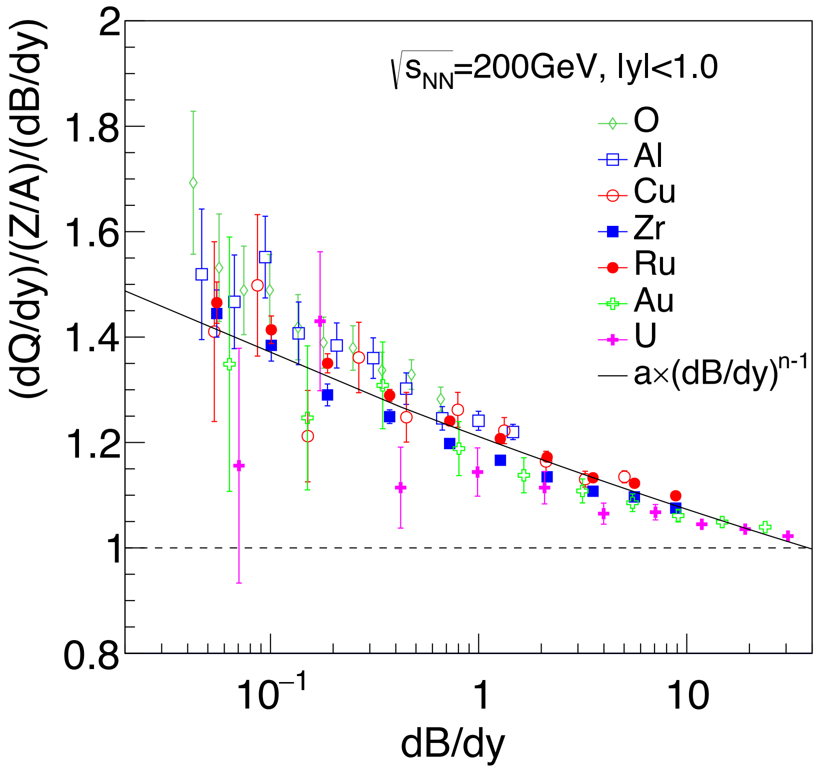


- Quarks connected to the stopped junction are sea quarks
- The ratio of net-charge and net-baryon is not related to the quark composition of projectile and target

Net–Charges vs. Net–Baryons from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering

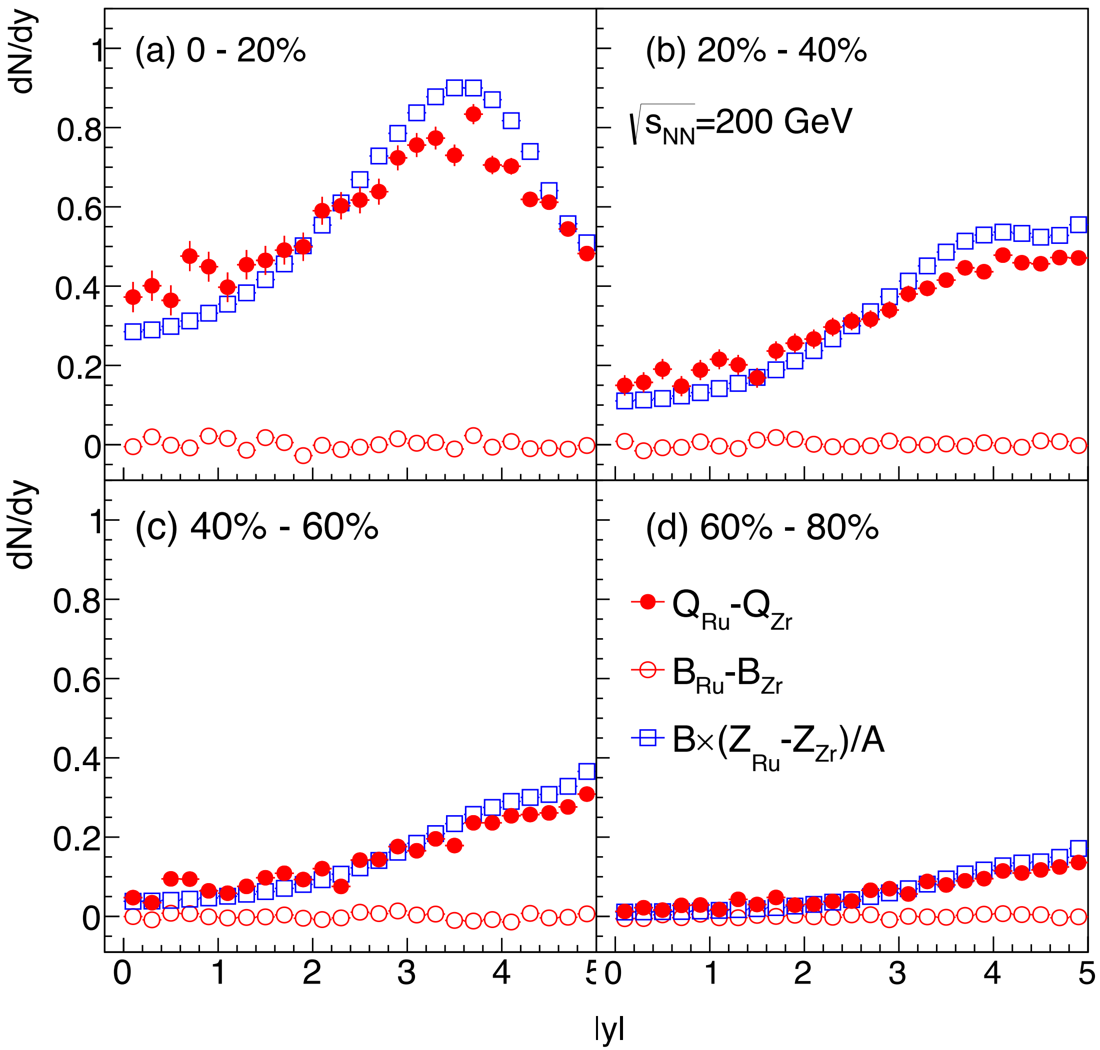




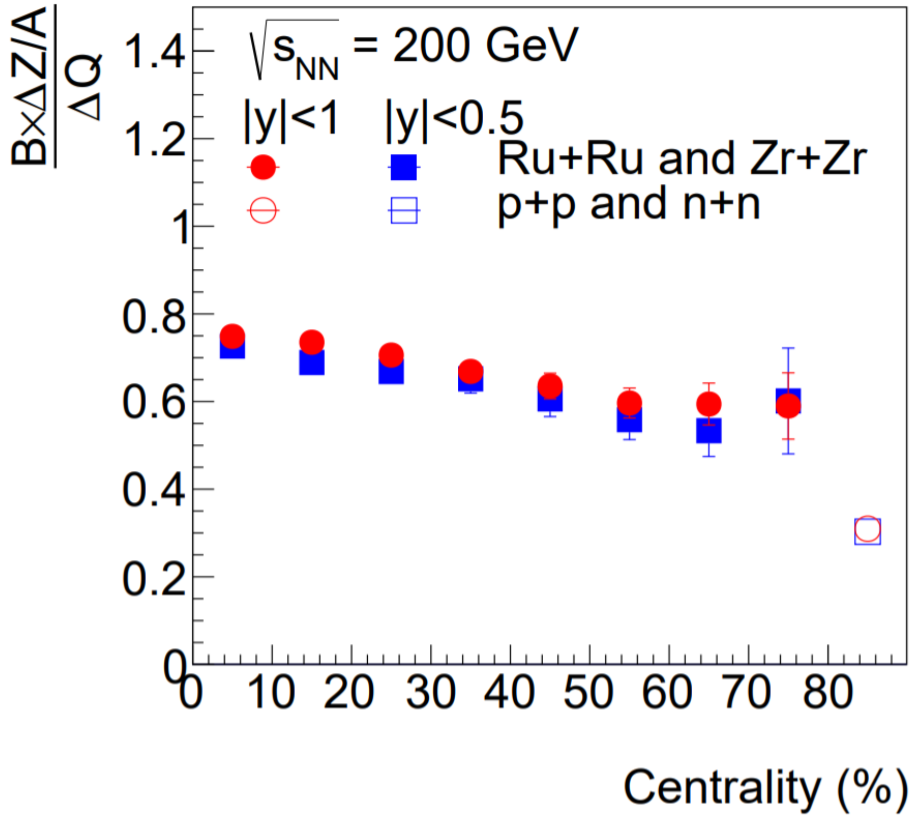
- Net–charges at mid–y scale with Z/A in O+O to U+U collisions at 200 GeV
- Q/B x A/Z approaches 1 for large A
- Expect 25% difference of Q/B in O+O and Au+Au collisions

Net-Charges and Net-Baryons in Isobaric Collisions

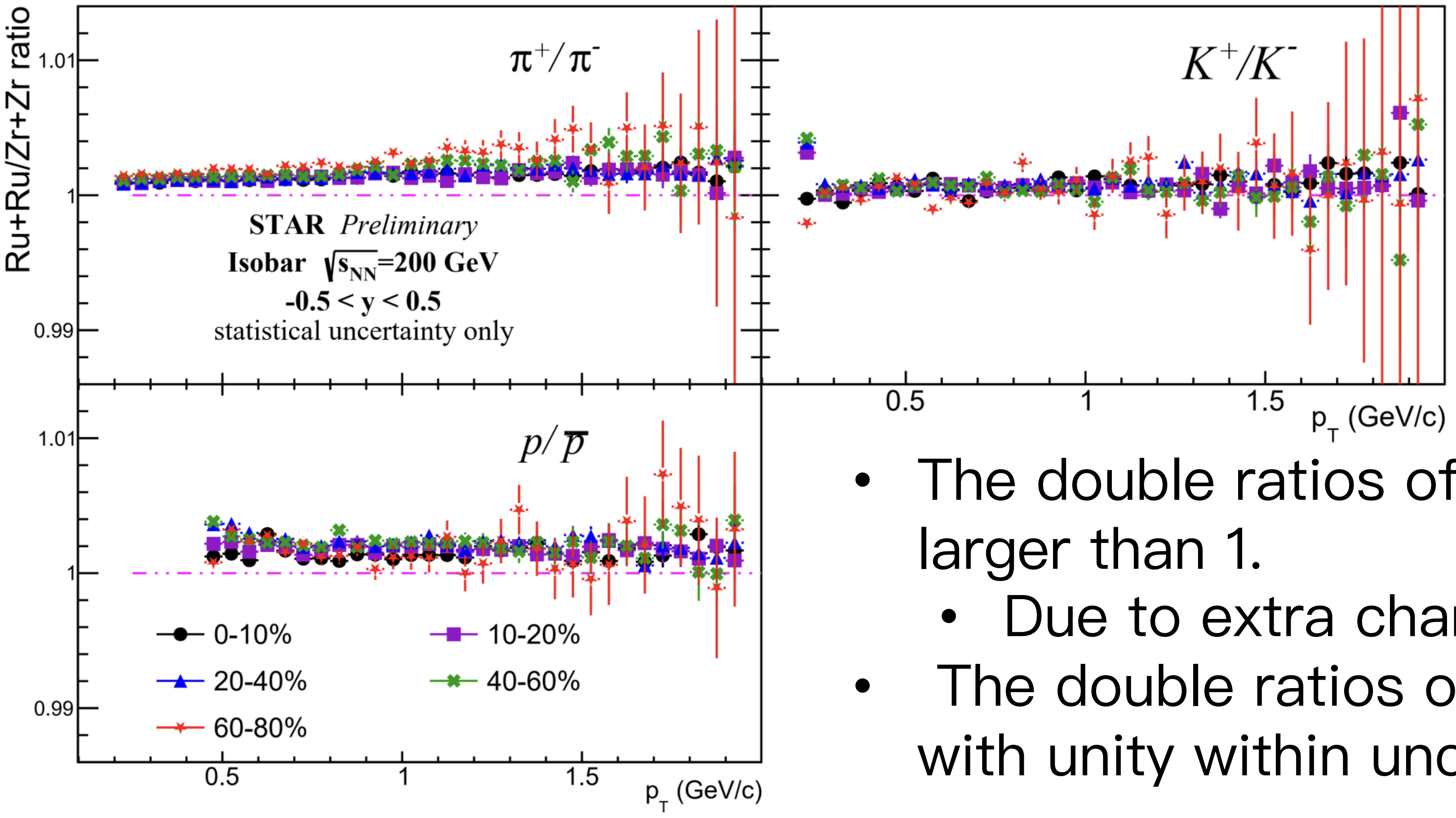
Ru+Ru and Zr+Zr collisions at 200 GeV from UrQMD



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



Measurement of Double Ratios

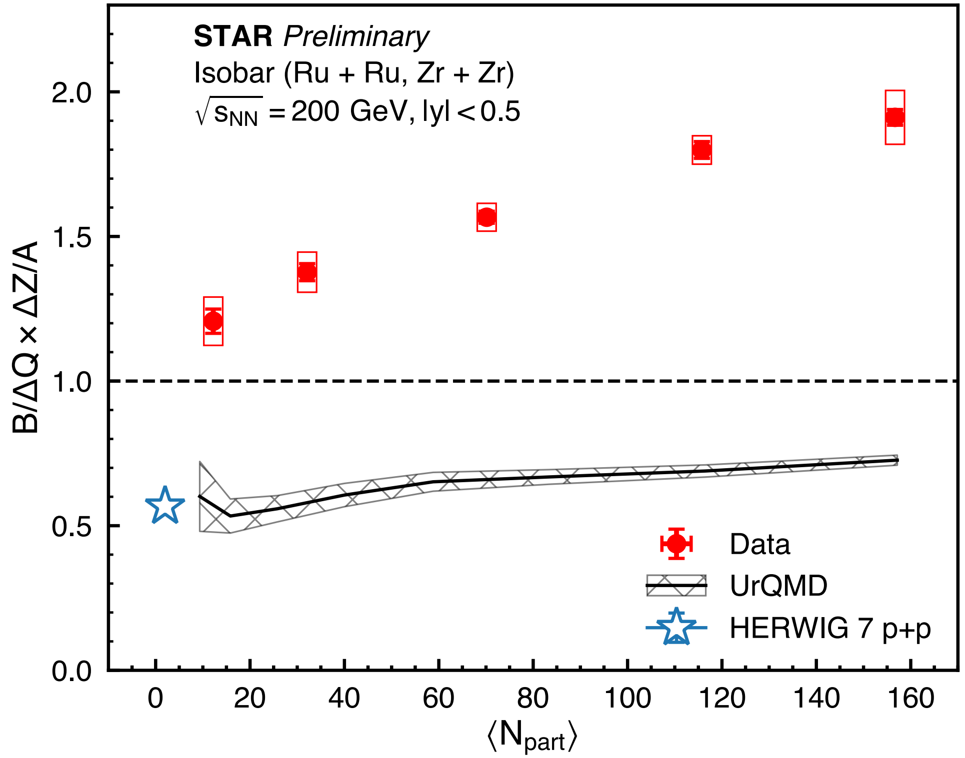


J. Brandenburg et al, arXiv:2205.05685

- 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.

- Net–charges can be calculated from the double ratios with high precision
- Contribution of neutrons is estimated via the measurement of $d/\bar{d}$

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



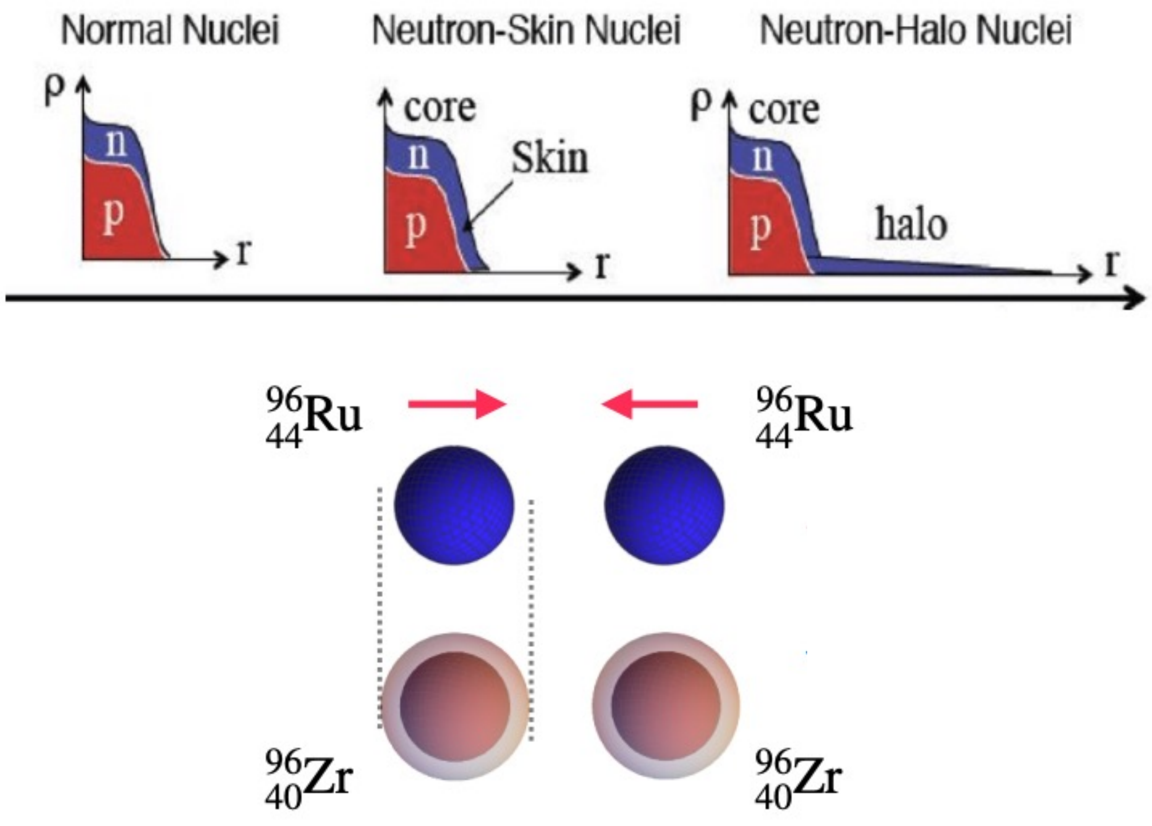
HERWIG: J. Bellm et al, EPJC80, 452 (2020)

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

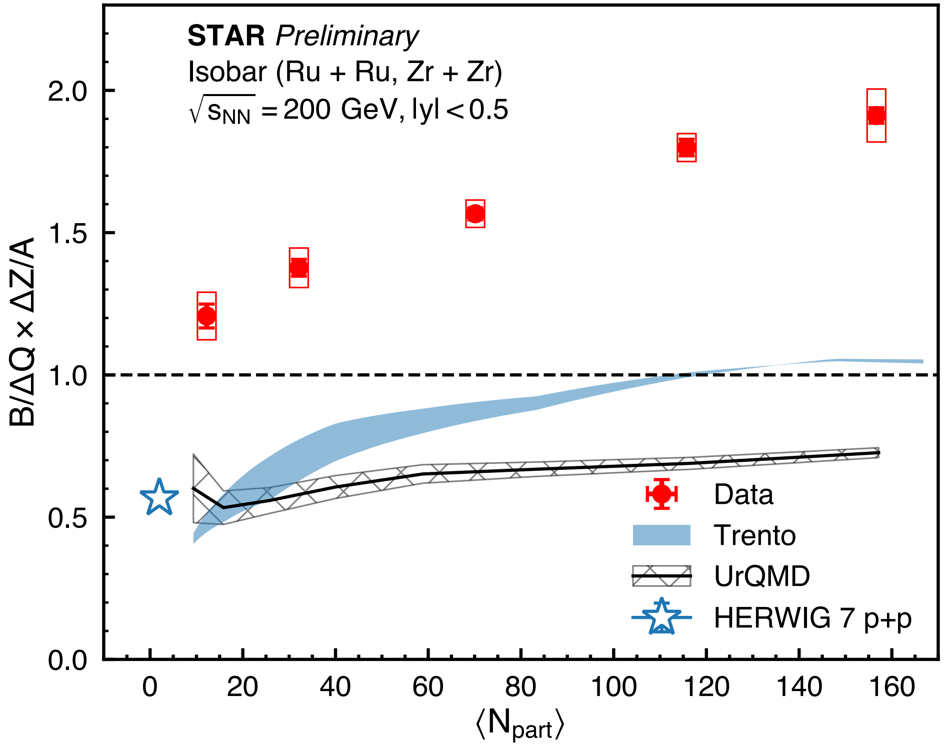
- Experimental observation:
  More baryon transported to mid–y than charge by a factor of up to 2

- 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)



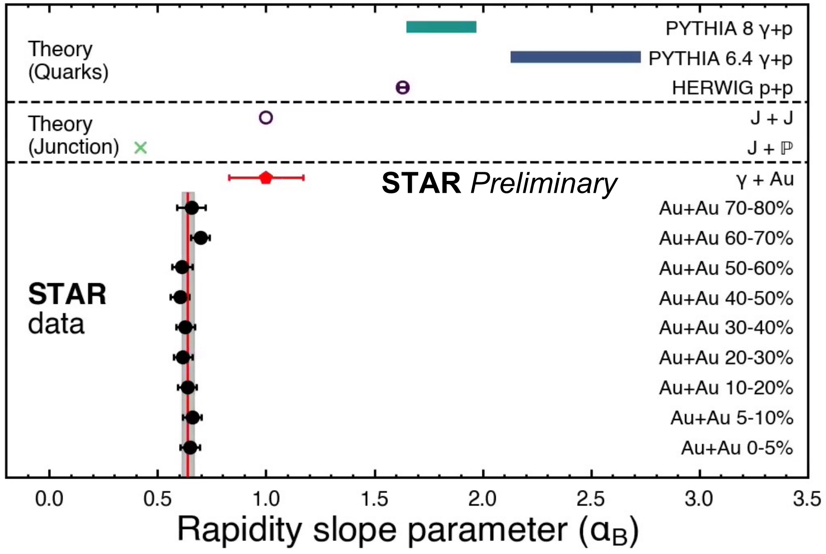
J. Moreland et al, PRC92, 011901(R) (2015)

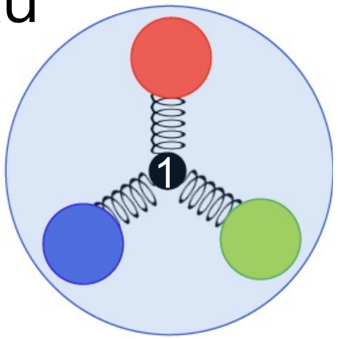
- Thick halo-type neutron skin in Zr
- More p+p collisions in central Zr+Zr
- Explains the centrality dependence
- But not enough to explain large ratio

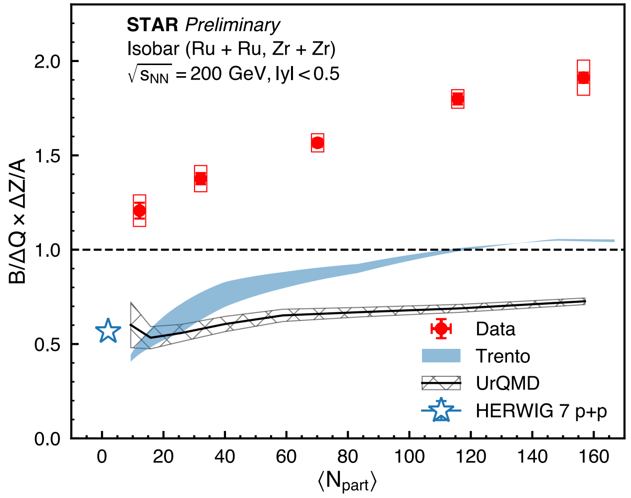
Summary

- 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 Ru+Ru and Zr+Zr collisions



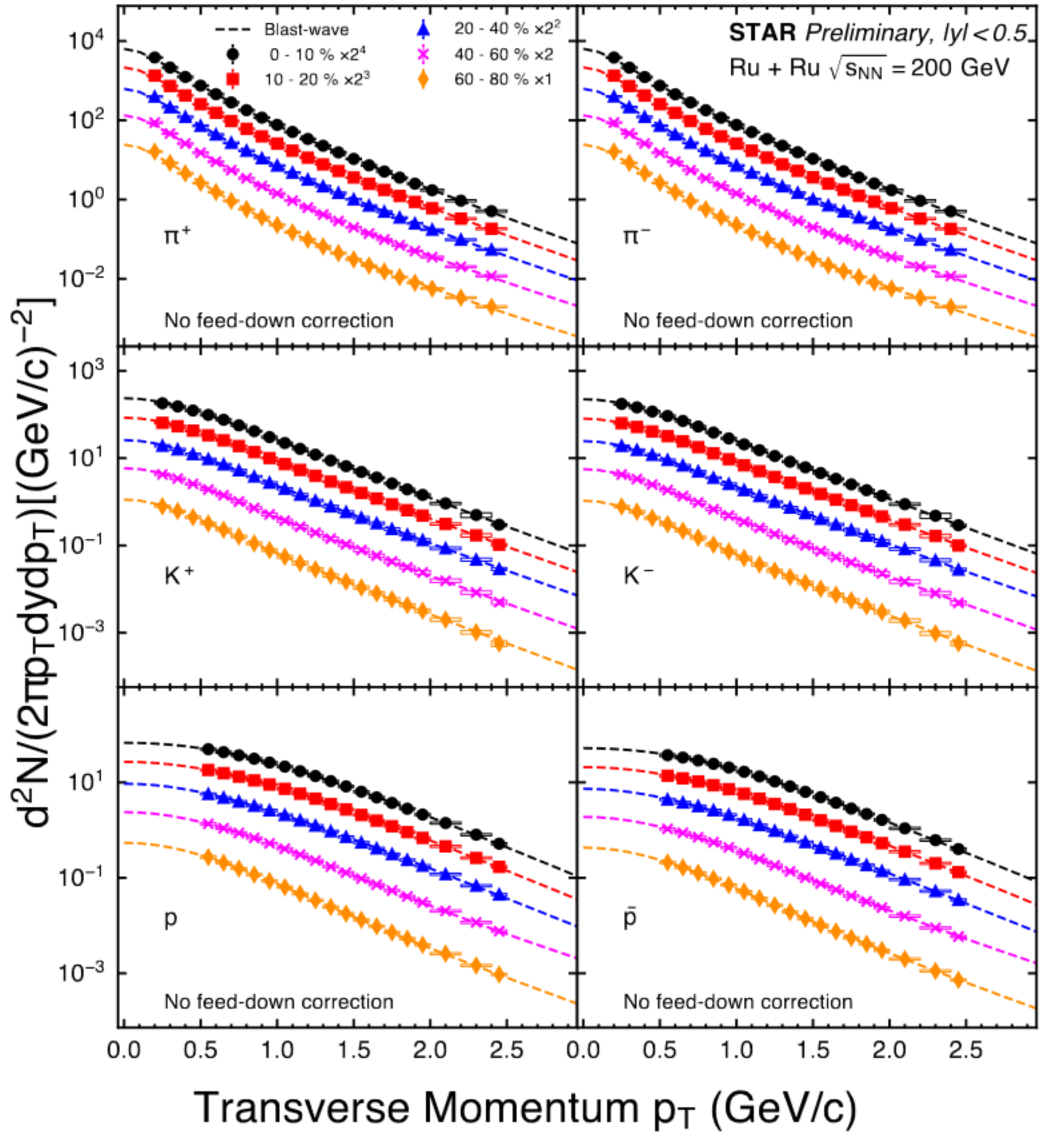


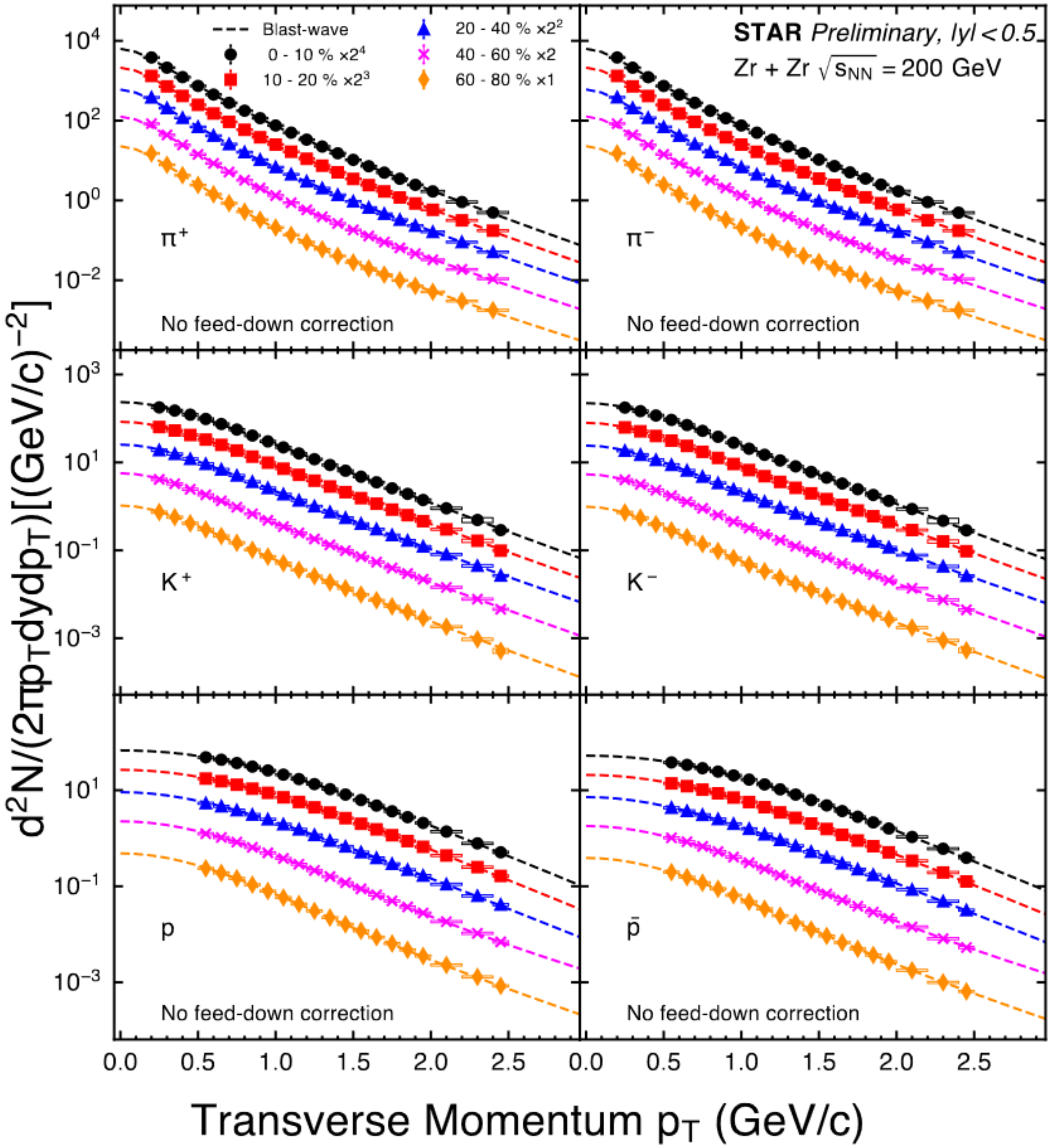


Thanks!

Extra slides

Identified Particle Spectra in Ru+Ru/Zr+Zr





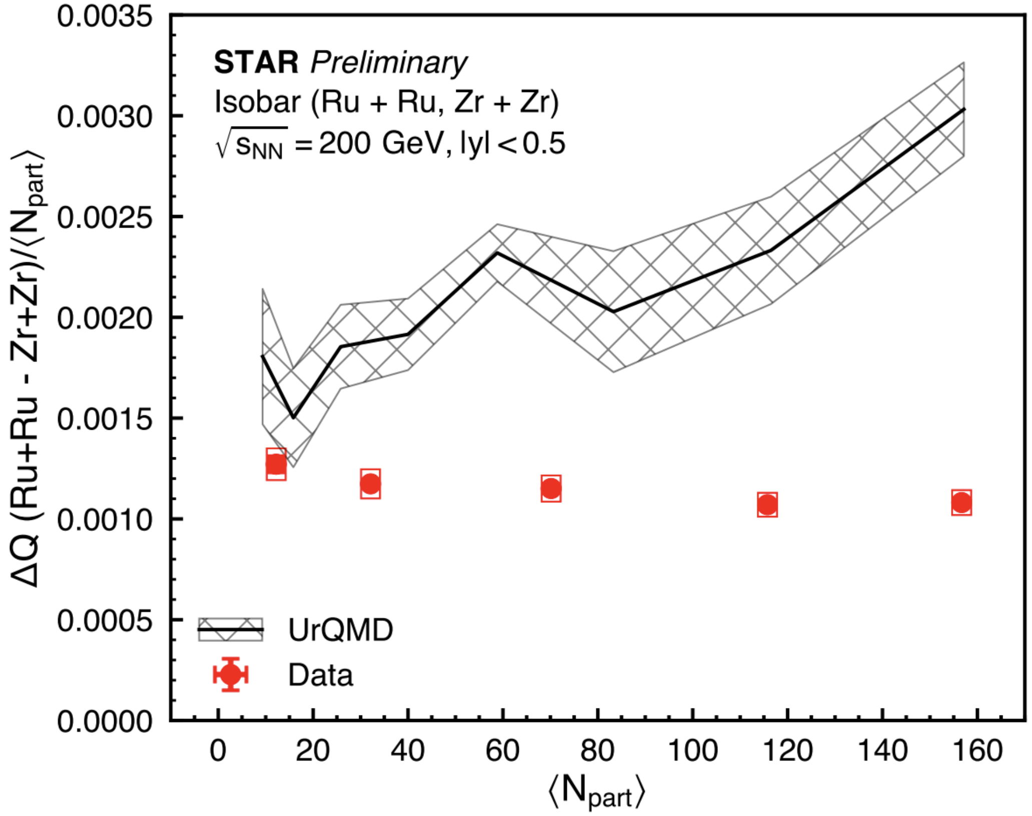
Net-Charge Difference Calculation

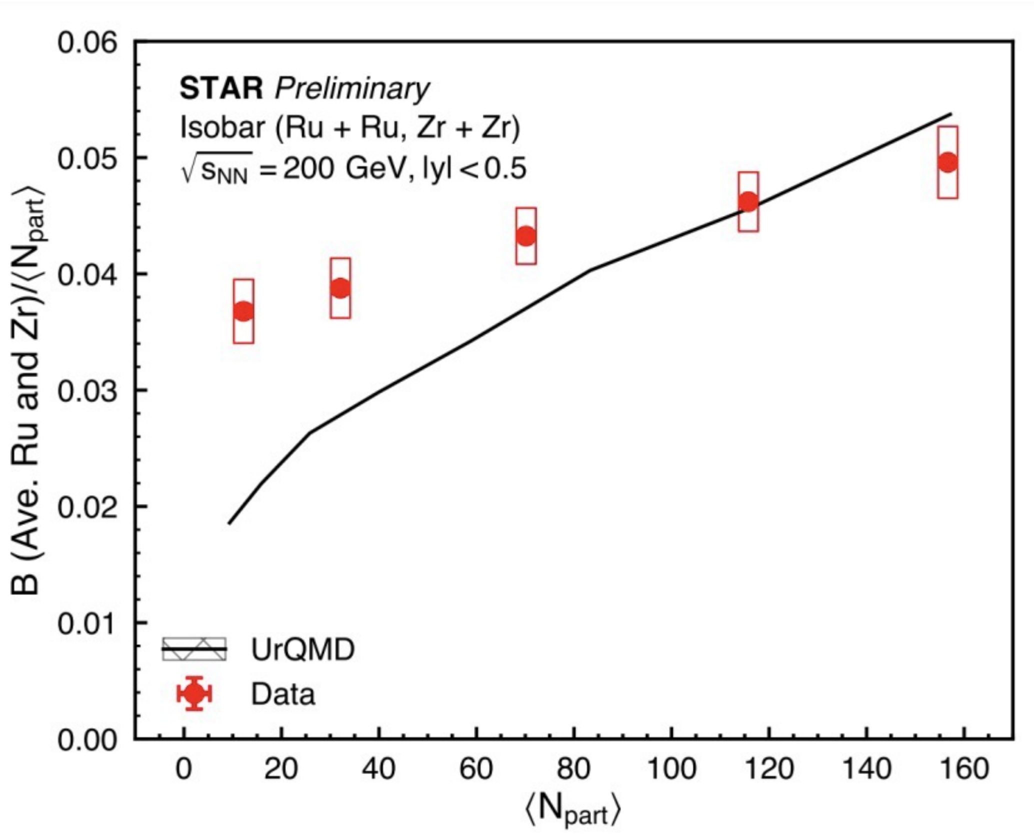
J. Brandenburg et al, arXiv:2205.05685

Net-charge difference (Ru+Ru – Zr+Zr)

- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+ - N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+ - N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta\mathrm{R_{Ru}}}{1+\Delta\mathrm{R_{Zr}}} \approx 1 + \Delta\mathrm{R_{Ru}} - \Delta\mathrm{R_{Zr}}$
- $\Delta Q = \left[\left(N_\pi^+ + N_K^+ + N_p\right) - \left(N_\pi^- + N_K^- + N_{\bar{p}}\right)\right]_{\mathbf{Ru}} - []_{\mathbf{Zr}}$
- **Focus on pion terms,**
- $(N_\pi^+ - N_\pi^-)_{Ru} - (N_\pi^+ - N_\pi^-)_{Zr} = N_{\pi,Ru} \times \Delta\mathrm{R_{Ru}} - \mathrm{N}_{\pi,Zr} \times \Delta\mathrm{R_{Zr}}$
- $\approx N_\pi(\Delta\mathrm{R_{Ru}} - \Delta\mathrm{R_{Zr}}) = \mathrm{N}_\pi \times (R2_\pi - 1)$
- **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 and Net Baryon in Ru/Zr





It is not possible to describe charge and baryon stopping simultaneously with UrQMD