Center for Frontiers in Nuclear Science

Brookhaven National Laboratory

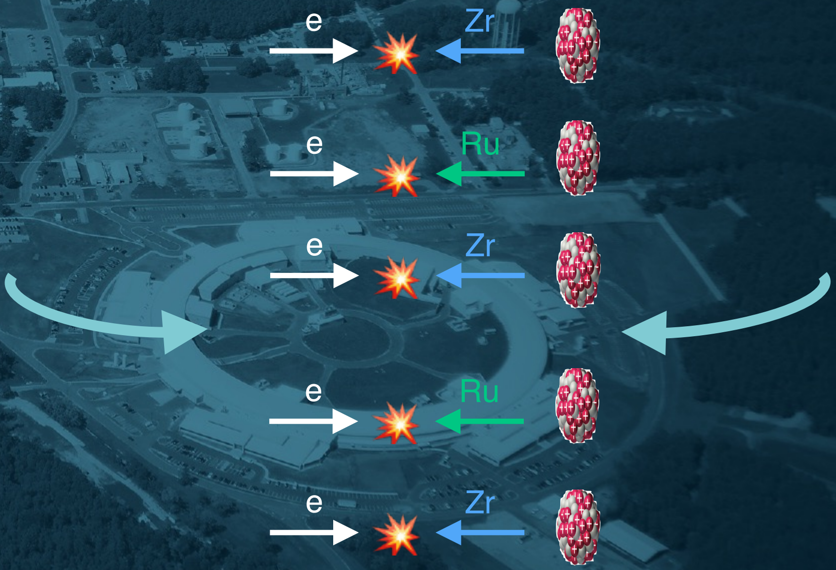
U.S. DEPARTMENT OF ENERGY

Probing the Baryon Junction: e+Isobar collisions at the EIC

Prithwish Tribedy

(Brookhaven National Laboratory)

N. Lewis, Y. Li, T. Tsang, J.D. Brandenburg, R.R. Ma, Z.B. Tang, Z. Xu, (STAR), N. Magdy, Z. Sweger. S. Klein (EIC), H. Klest (HERA), G. Pihan, W.B. Zhao, B. Schenke, C. Shen, D. Kharzeev, Z.W. Lin (Theory) and more….

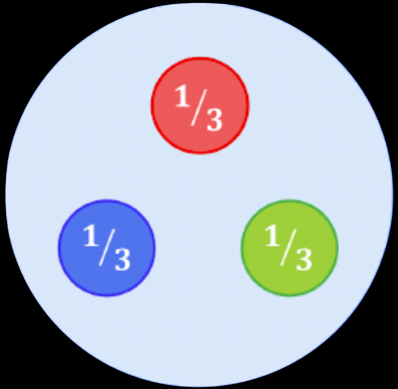


CFNS workshop: Electron-Nuclei Interaction at EIC
CFNS, Stony Brook University, 5th-7th July 2023

What carries the baryon number

https://en.wikipedia.org/wiki/Proton
https://en.wikipedia.org/wiki/Baryon

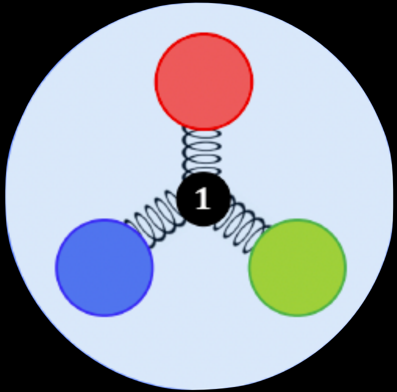
Baryons, along with mesons, are hadrons, particles composed of quarks. Quarks have baryon numbers of $B = \frac{1}{3}$ and antiquarks have baryon numbers of $B = -\frac{1}{3}$. The term "baryon" usually refers to *triquarks*—baryons made of three quarks ($B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$).



1963-70

Baryon number is a strictly conserved quantum number & assumed to be carried by the valence quarks each carrying 1/3

Goldberg and Y. Ne'eman, Nuovo Cimento 27 (1963) 1
Gell-Mann, Zweig, 1964, SLAC 1970
Review: hep-ph/9301246



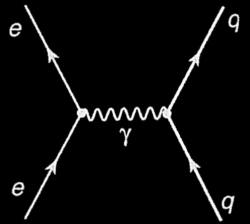
1975-

Baryon number may flow with the flow of the Y-shaped string junction (QCD topology)

X. Artru, Nucl. Phys. B 85, 442–460 (1975), G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep.63(1980) 149
Kharzeev, Phys. Lett. B, 378 (1996) 238-246

No experiment has established either scenario

Electric charge of Quarks



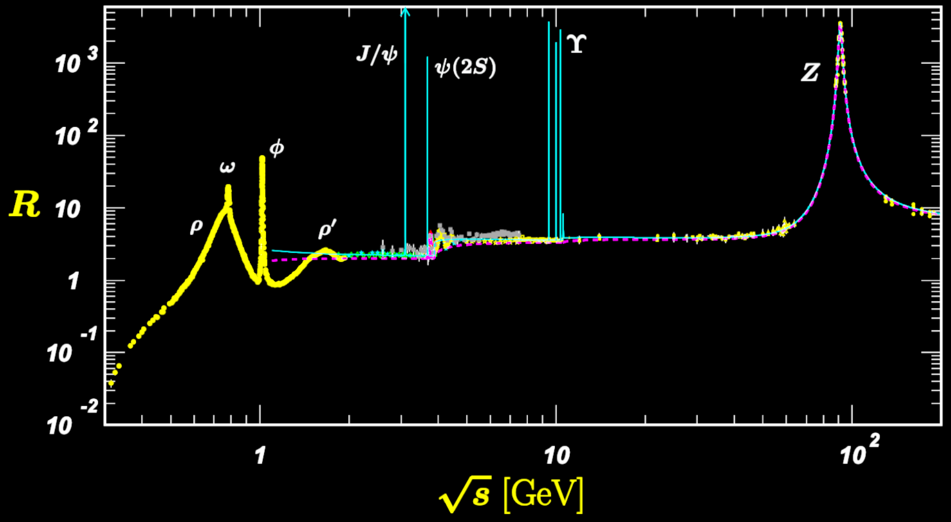
Scattering cross section $\sigma \propto e_q^2$

$(2/3)^2+(1/3)^2+(1/3)^2=2/3$

$(2/3)^2+(2/3)^2+(1/3)^2=1$

$(1/3)^2+(1/3)^2+(1/3)^2=1/3$

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



PDG

Figure 53.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model

Riordan, Science 1992

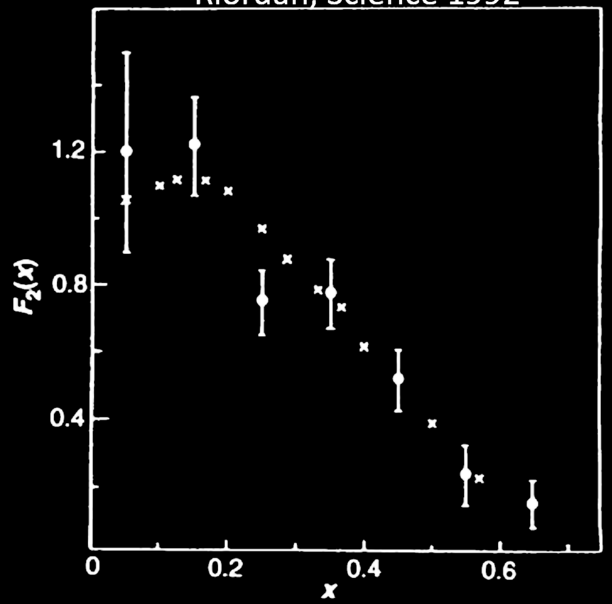
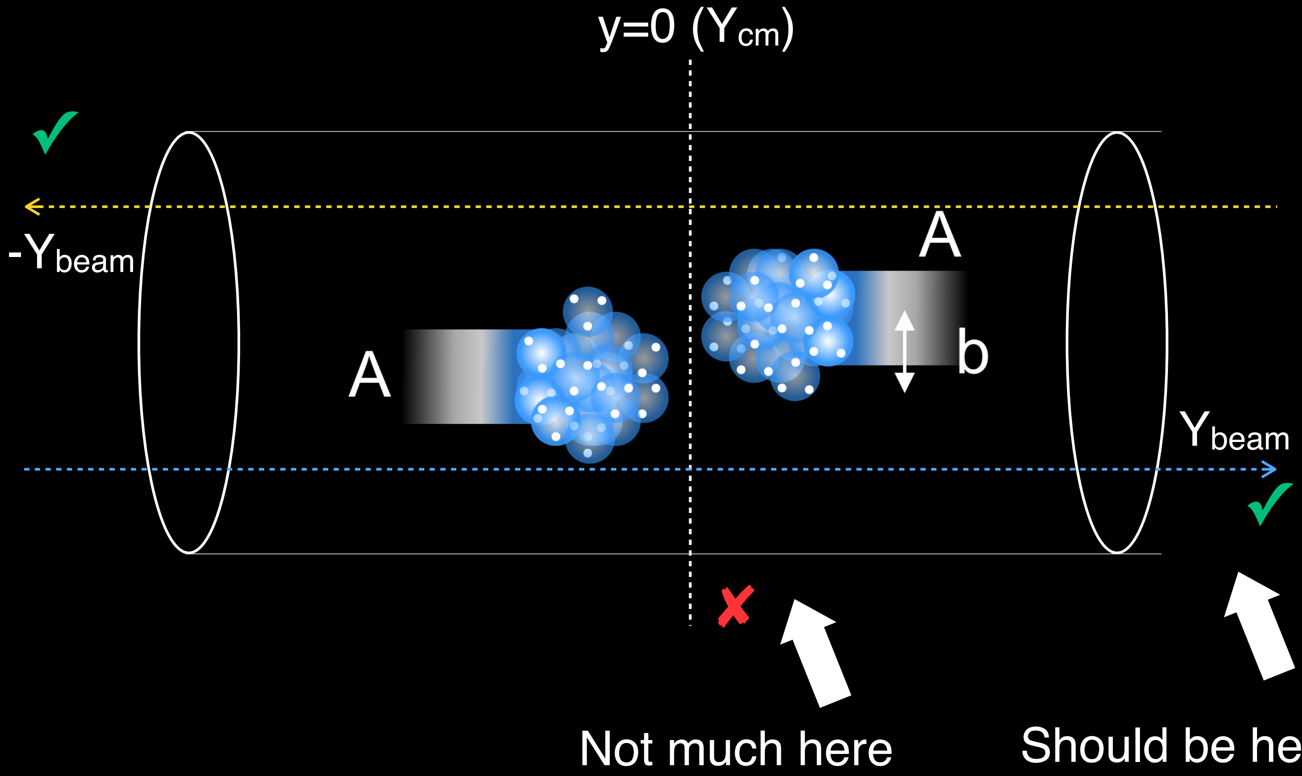


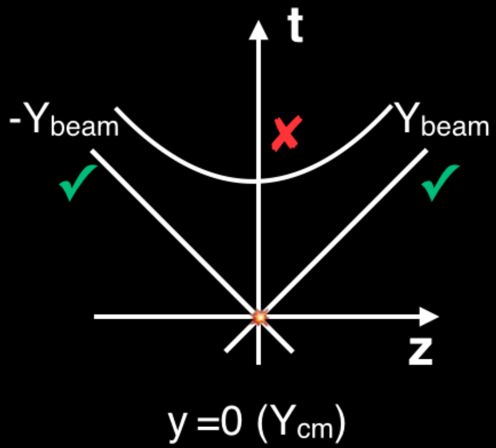
Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data

Quarks carry electric charge and three color, however no experiment has established if it carries baryon number

Puzzles with the Baryon number of quarks

Kharzeev, Phys. Lett. B, 378 (1996) 238-246



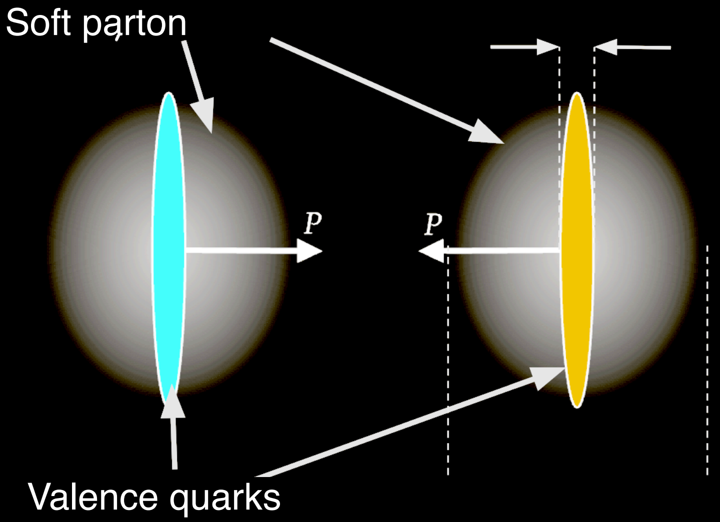


If baryon number flows with valence quarks, then they should end up near beam rapidity Y_{beam} and not near y=0 or Y_{cm}

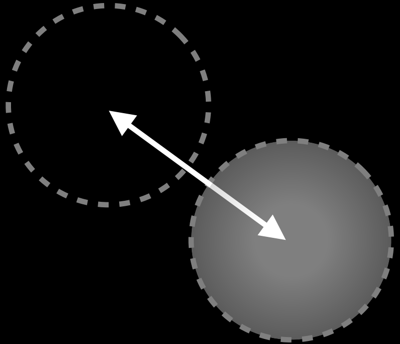
Puzzles with the Baryon number of quarks

Kharzeev, Phys. Lett. B, 378 (1996) 238-246

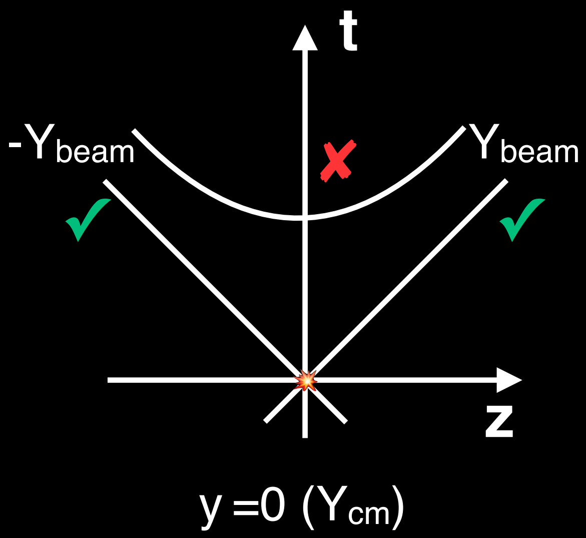
Longitudinal direction



Transverse plane



Space-Time



Time available

$$t_{\rm coll} \sim (x_V P)^{-1} = (1/3 \times 100)^{-1}\ \mathrm{GeV}^{-1} = 0.006\ \mathrm{fm}$$

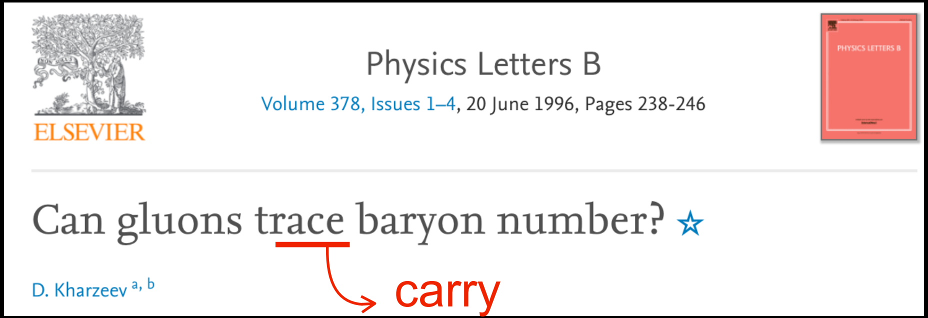
Time required

$$t_{\rm int} \sim \mathcal{O}(1)\ \mathrm{fm}$$

Available time too short for valence quark stopping at y~0

Alternative carrier of baryon numbers

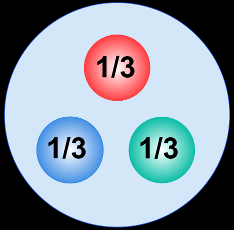
G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep.63(1980) 149
Kharzeev, Phys. Lett. B, 378 (1996) 238-246


Physics Letters B
Volume 378, Issues 1–4, 20 June 1996, Pages 238-246

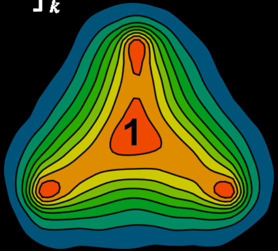
Can gluons trace baryon number? ☆

D. Kharzeev [a, b]

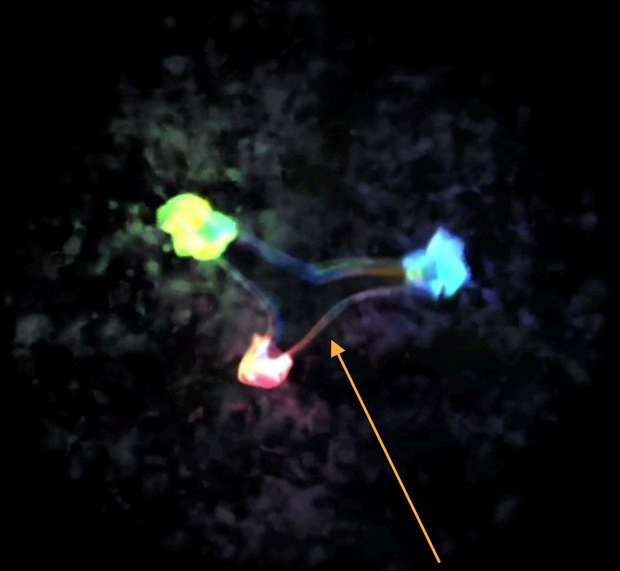
$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_j \times \left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_k$$



Baryon number flows with the valence quarks



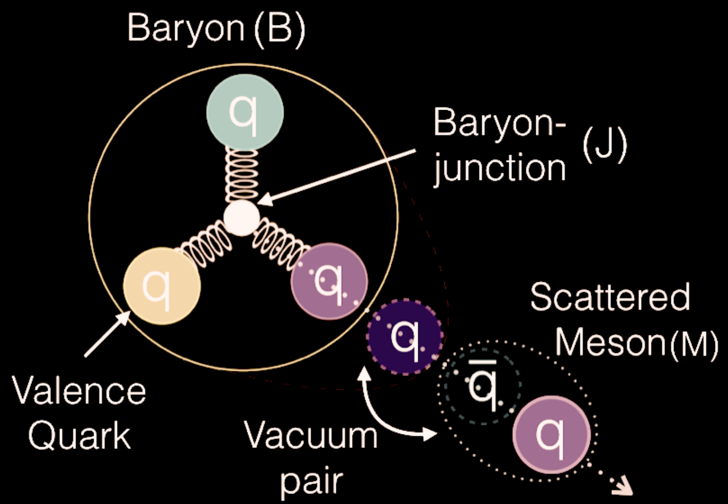
Baryon number flows with the junction

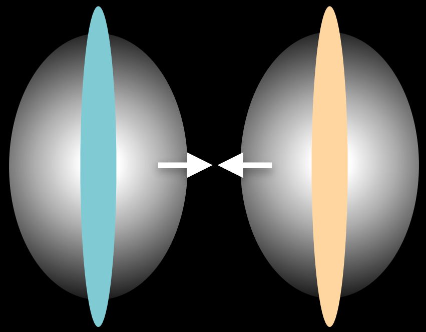


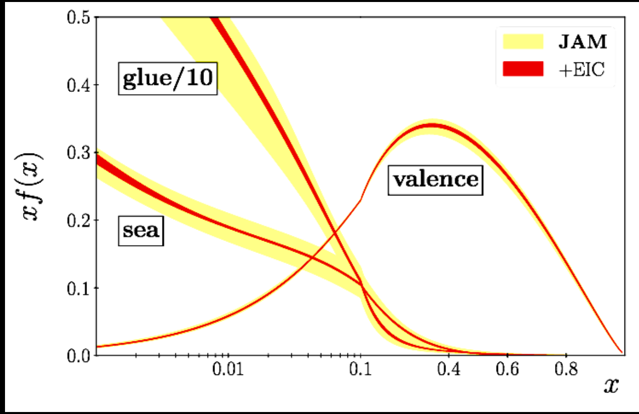
String-junction made of gluons

Non-perturbative configuration of gluons

Arguments for a junction as a baryon number carrier







Pulling a quark stops a meson not a baryon, you have to stop the junction to stop a baryon

$$t_{\rm coll} \sim (x_V P)^{-1} = (1/3 \times 100)^{-1}\ \mathrm{GeV}^{-1} = 0.006\ \mathrm{fm}$$

$$t_{\rm int} \sim \mathcal{O}(1)\ \mathrm{fm}$$

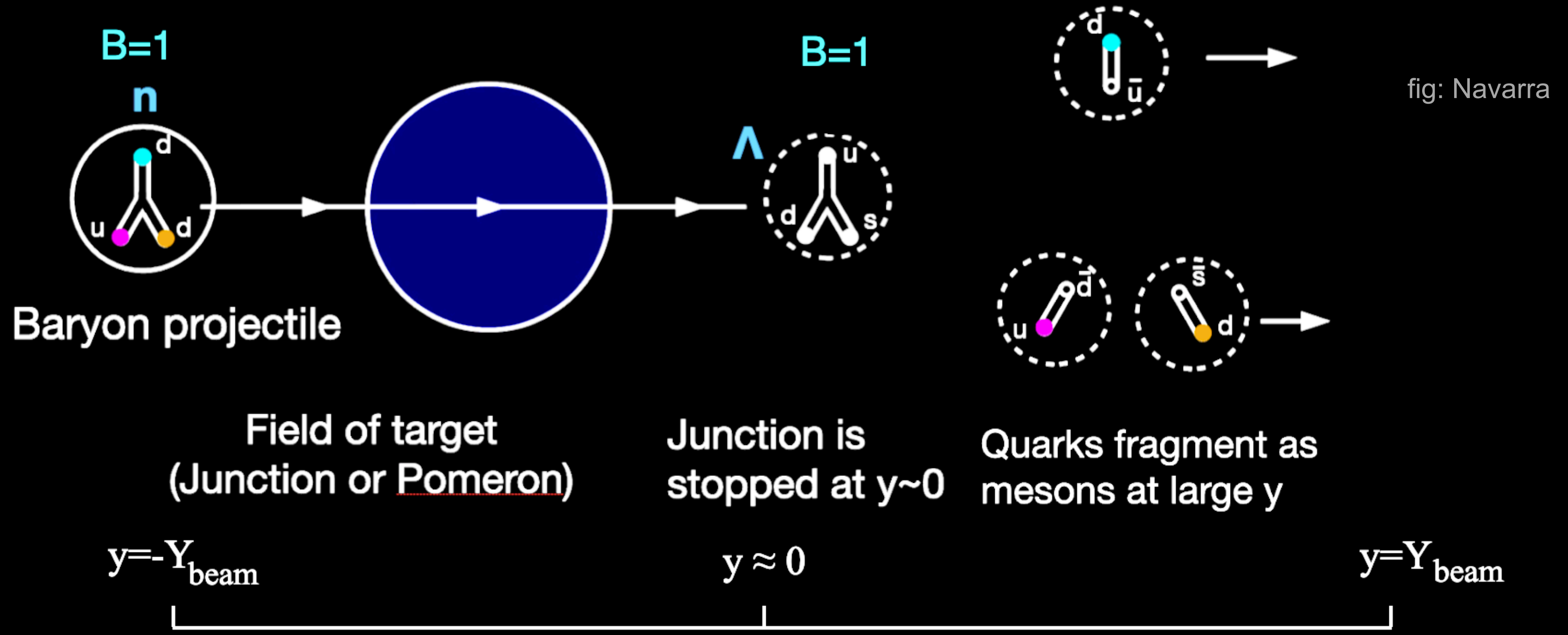
Junction is made of infinite low-x gluons so they have enough time to be stopped

$$x_J \ll x_V \qquad ((x_J P)^{-1} \gg (x_V P)^{-1})$$

How a baryon junction can be stopped?

Kharzeev, Phys. Lett. B, 378 (1996) 238-246

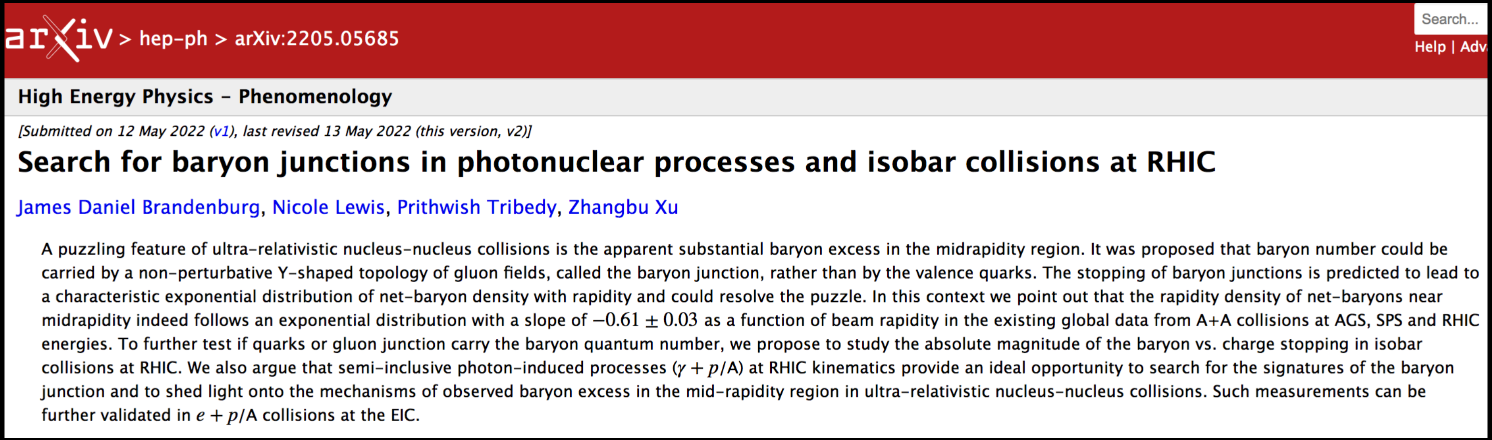
A string-junction from a projectile can be stopped by the soft parton field of the target and vice versa



How to experimentally test this ?

Three different approaches to search for baryon junctions

Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685


arXiv > hep-ph > arXiv:2205.05685

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High Energy Physics – Phenomenology

[Submitted on 12 May 2022 (v1), last revised 13 May 2022 (this version, v2)]

Search for baryon junctions in photonuclear processes and isobar collisions at RHIC

James Daniel Brandenburg, Nicole Lewis, Prithwish Tribedy, Zhangbu Xu

A puzzling feature of ultra-relativistic nucleus-nucleus collisions is the apparent substantial baryon excess in the midrapidity region. It was proposed that baryon number could be carried by a non-perturbative Y-shaped topology of gluon fields, called the baryon junction, rather than by the valence quarks. The stopping of baryon junctions is predicted to lead to a characteristic exponential distribution of net-baryon density with rapidity and could resolve the puzzle. In this context we point out that the rapidity density of net-baryons near midrapidity indeed follows an exponential distribution with a slope of -0.61 ± 0.03 as a function of beam rapidity in the existing global data from A+A collisions at AGS, SPS and RHIC energies. To further test if quarks or gluon junction carry the baryon quantum number, we propose to study the absolute magnitude of the baryon vs. charge stopping in isobar collisions at RHIC. We also argue that semi-inclusive photon-induced processes ($\gamma + p$/A) at RHIC kinematics provide an ideal opportunity to search for the signatures of the baryon junction and to shed light onto the mechanisms of observed baryon excess in the mid-rapidity region in ultra-relativistic nucleus-nucleus collisions. Such measurements can be further validated in $e + p$/A collisions at the EIC.

1. Artru Method: In γ+Au collision, rapidity asymmetry can reveal the origin

2. Kharzeev-STAR Method: If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

3. STAR Method: Charge (Q) stopping vs baryon (B) stopping, if valence quarks carry Q and B, Q=B at middle rapidity

see talk by Zhangbu Xu,1st workshop on the 2nd EIC detector

Artru Method: In γ+Au collision

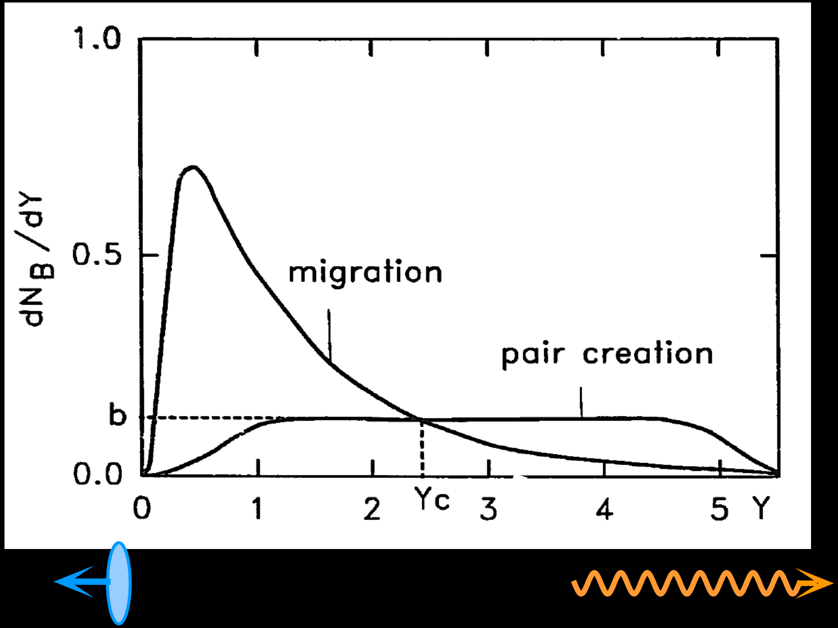
Artru Method: rapidity asymmetry in γ+p/A

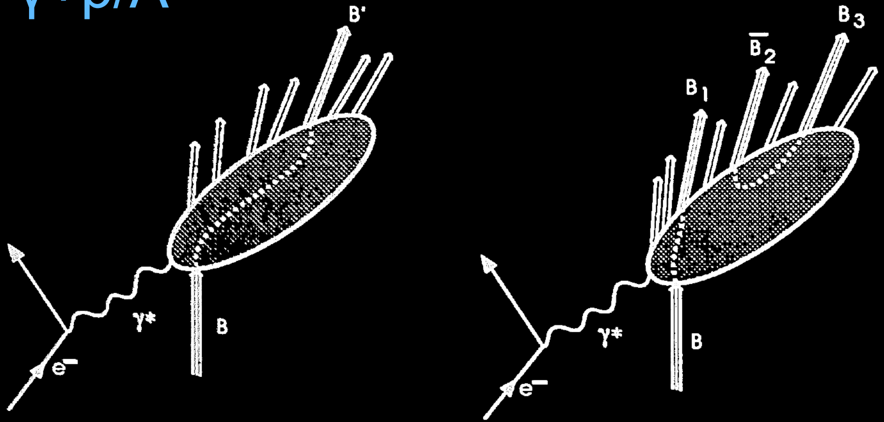
Nuclear Physics A532 (1991) 351c–358c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

What can we learn from unpolarized and polarized electroproduction of fast baryons?

X. Artru[a] and M. Mekhfi[b]





$$Y < Y_C \simeq \beta^{-1} \ln(\beta/b) \qquad\qquad Y > Y_C$$

Photon is a baryon-free projectile, baryon distribution in γ+p/A —> cleanest way to identify baryon carrier

$$dN_B/dY \simeq \beta\,(2p \cdot p'/m^2)^{-\beta} \simeq \beta\,\exp(-\beta Y)$$

This can be studied with HERA data,
Photonuclear collisions at RHIC and at the EIC

Measurements from the HERA data

Baryon-Anti-baryon asymmetry in e+p photoproduction at HERA

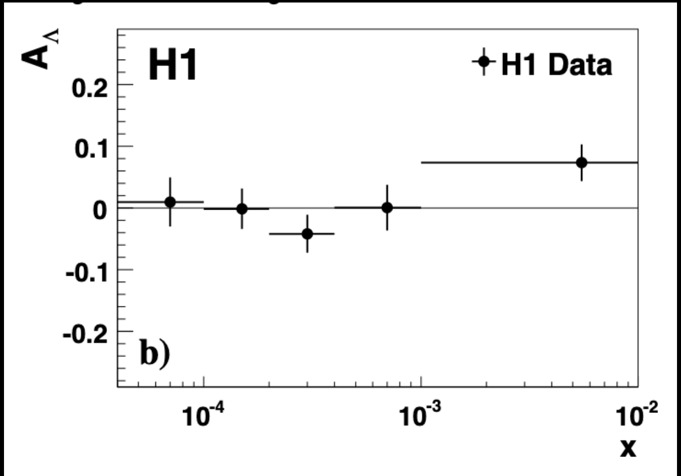
C. Adloff et al. (H1 Collaboration), ICHEP 1998

https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.34.469&rep=rep1&type=pdf

$$A_B = 2\,\frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}$$

Lambda - anti-Lambda asymmetry

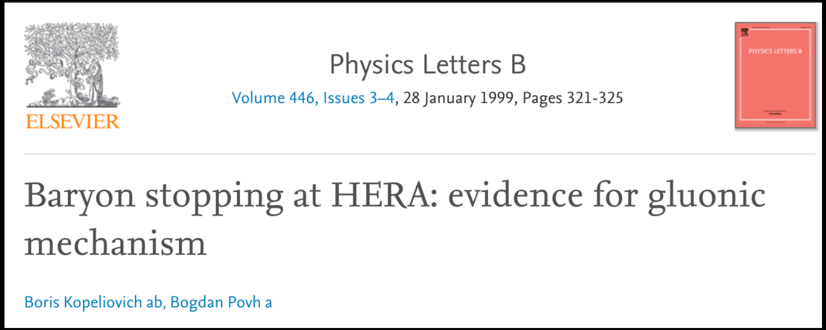
H1 Collaboration, Eur. Phys. J. C61:185-205,2009



$$A_\Lambda = \frac{\sigma_{vis}(ep \to e\Lambda X) - \sigma_{vis}(ep \to e\bar{\Lambda} X)}{\sigma_{vis}(ep \to e\Lambda X) + \sigma_{vis}(ep \to e\bar{\Lambda} X)}$$

B.Z. Kopeliovich, B. Povh, Phys.Lett. B446 (1999) 321-325

B.Z. Kopeliovich, Z.Phys.C75:693-699,1997



ELSEVIER

Physics Letters B

Volume 446, Issues 3–4, 28 January 1999, Pages 321-325

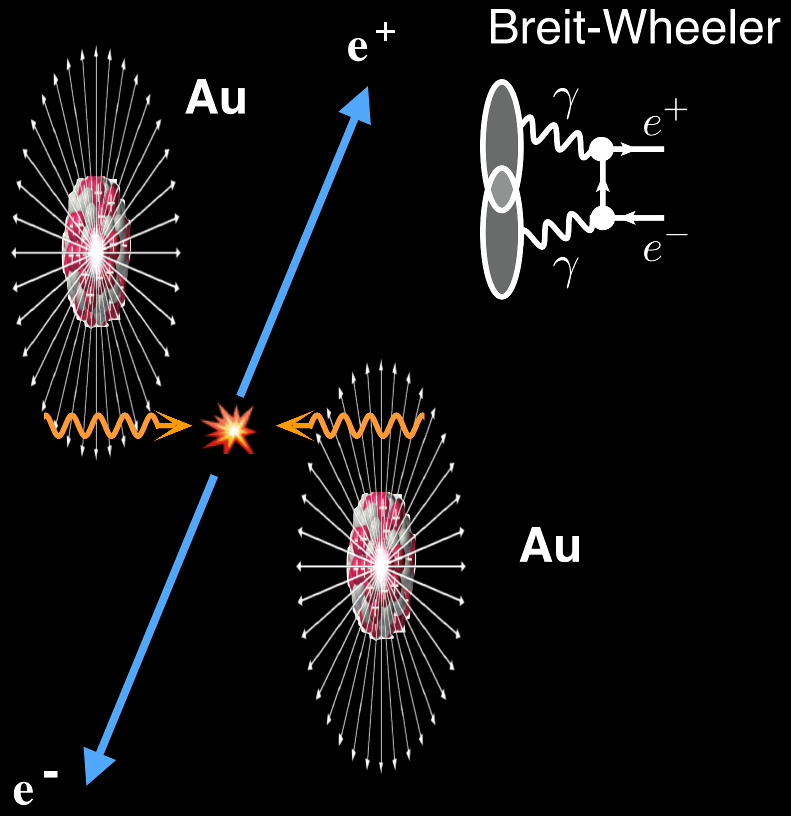
Baryon stopping at HERA: evidence for gluonic mechanism

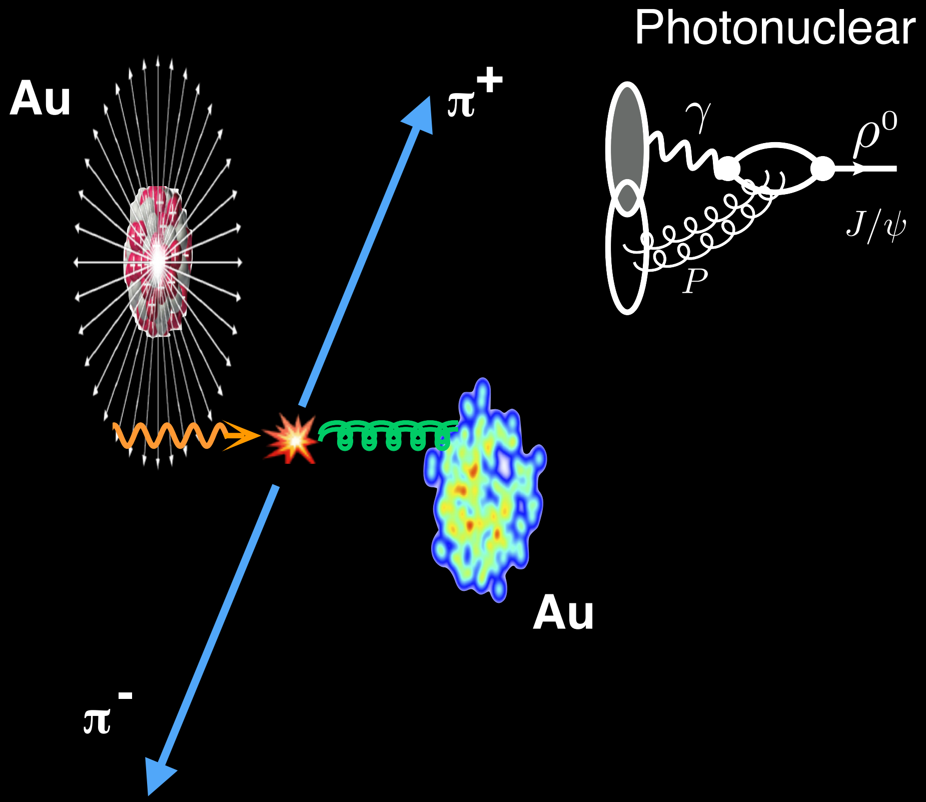
Boris Kopeliovich ab, Bogdan Povh a

Early theory paper invoke gluonic mechanism

What do the existing HERA data tells us about carriers of the baryon number ?

Photon-induced processes before EIC era

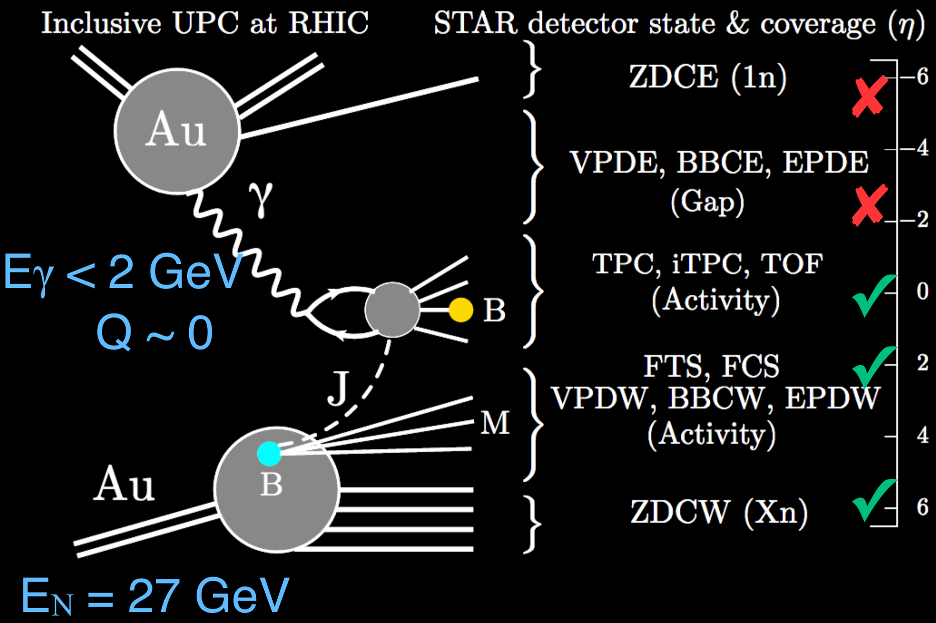


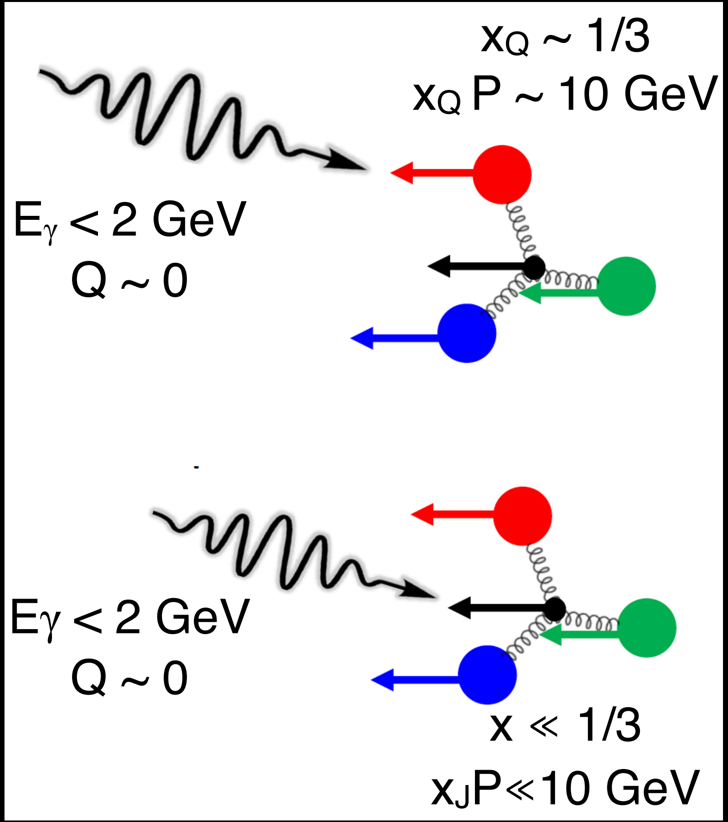


Ultra-peripheral heavy ion collisions can be used to trigger γ-γ or γ+Au collisions

Measurements in ultra-peripheral collisions from STAR

Triggering photonuclear processes
with STAR detector

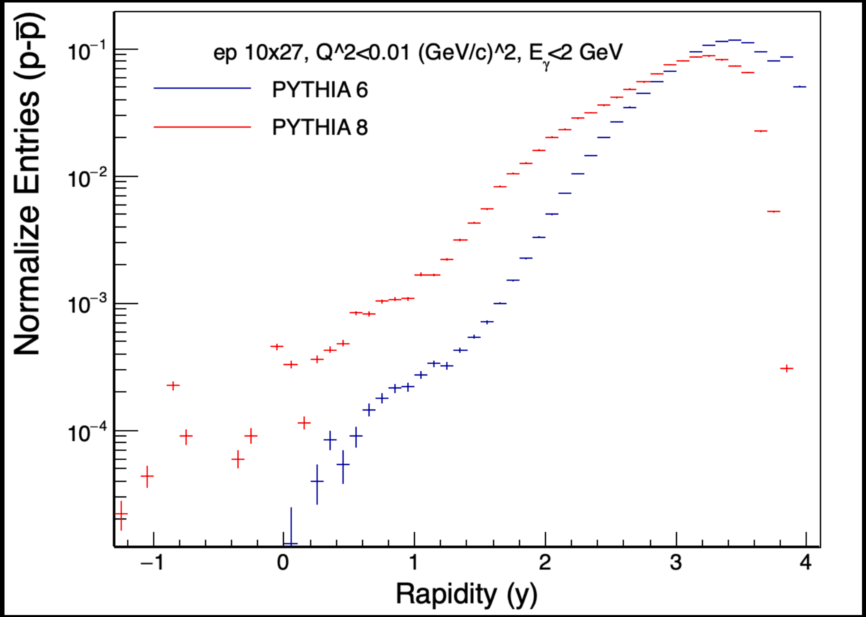


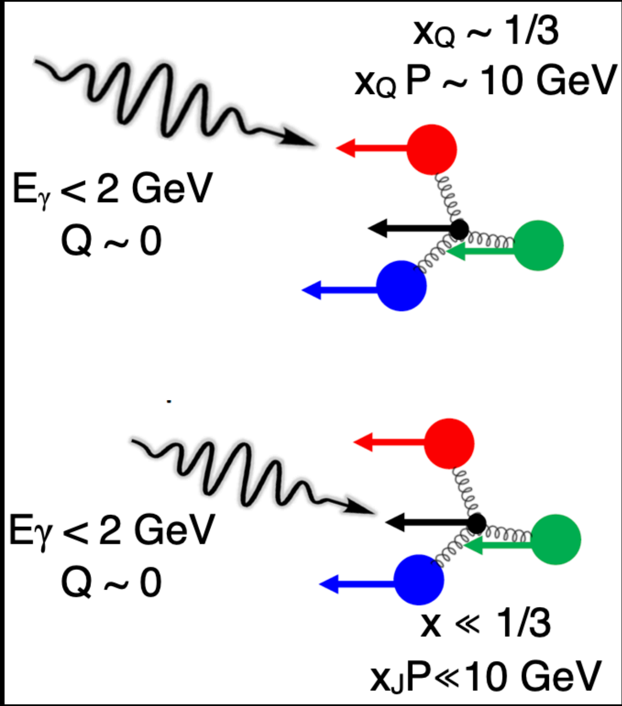


Search for non-zero net-baryon in photon-ion collisions near central-rapidity

PYTHIA simulation by mimicking RHIC photonuclear collisions

PYTHIA 6: Quark carries baryon
PYTHIA 8: Quark + mimic string-junction

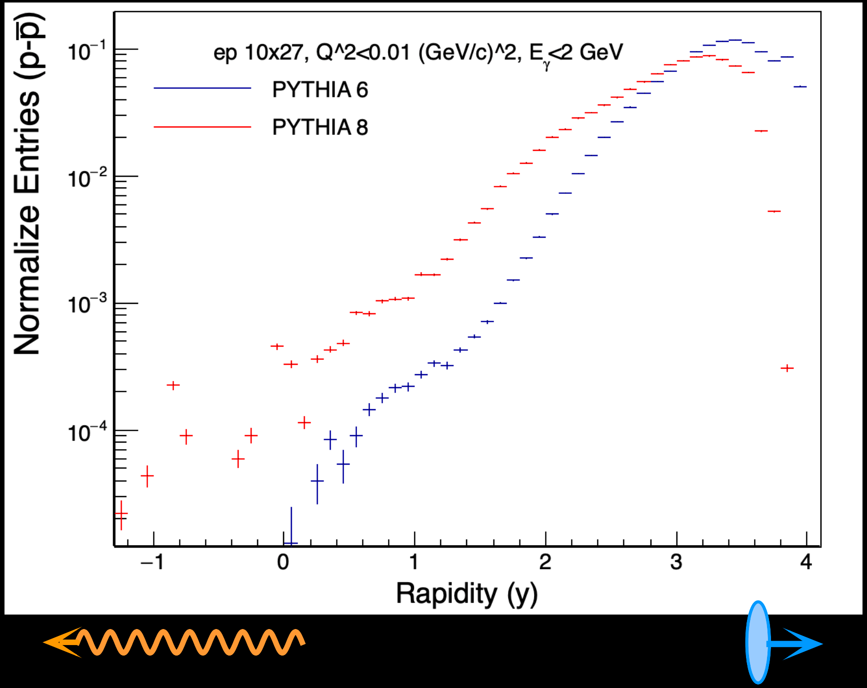


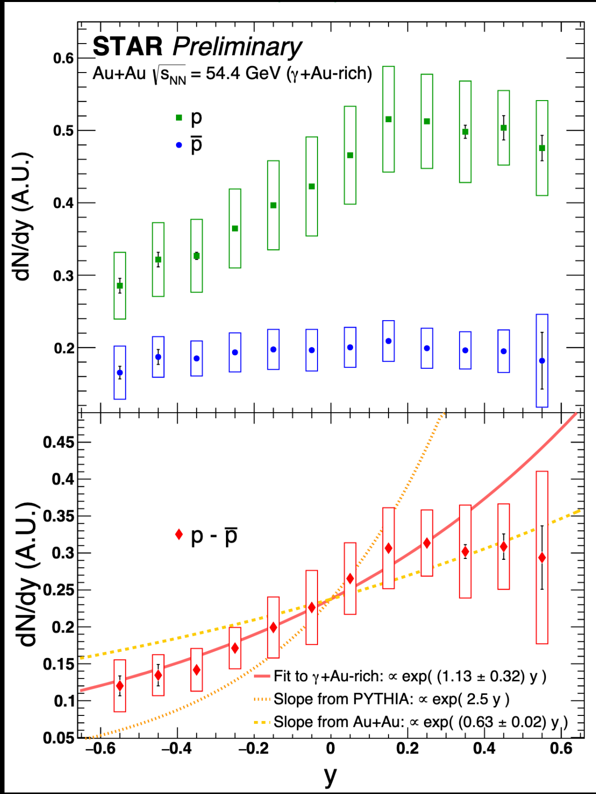


Nearly vanishing net-proton density near y ~0, sharp falling distribution with y

Measurements in ultra-peripheral collisions (UPC) from STAR

PYTHIA simulation in UPC the kinematics
PYTHIA 6: Quark carries baryon
PYTHIA 8: Quark + mimic string-junction





Non-zero net-proton & rapidity asymmetry seen in data

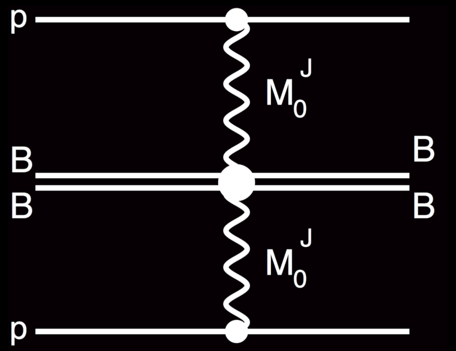
X

Kharzeev-STAR Method: Characteristic rapidity slope

Predictions from Regge Theory

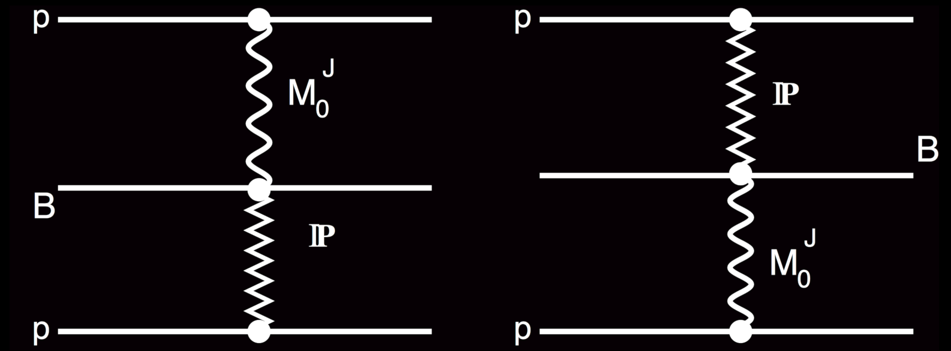
Kharzeev, Phys. Lett. B, 378 (1996) 238-246

Junction stops another junction



$$\sigma \sim e^{\pm Y_{\mathrm{beam}}}$$

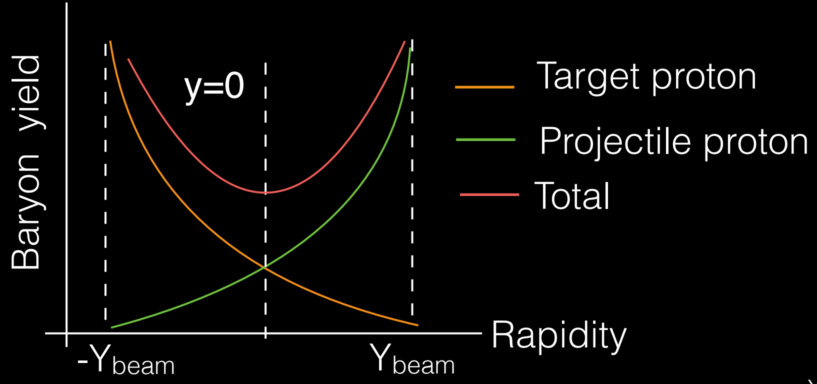
Junction stopped by Pomeron



$$e^{0.16\, Y_{\mathrm{beam}}} \times \left(e^{-0.58(y+Y_{\mathrm{beam}})} + e^{0.58(y-Y_{\mathrm{beam}})} \right)$$

Baryon junction: $e^{-\alpha_B (y-Y_{\mathrm{beam}})}$ $\boxed{0.42 \leq \alpha_B \leq 1}$

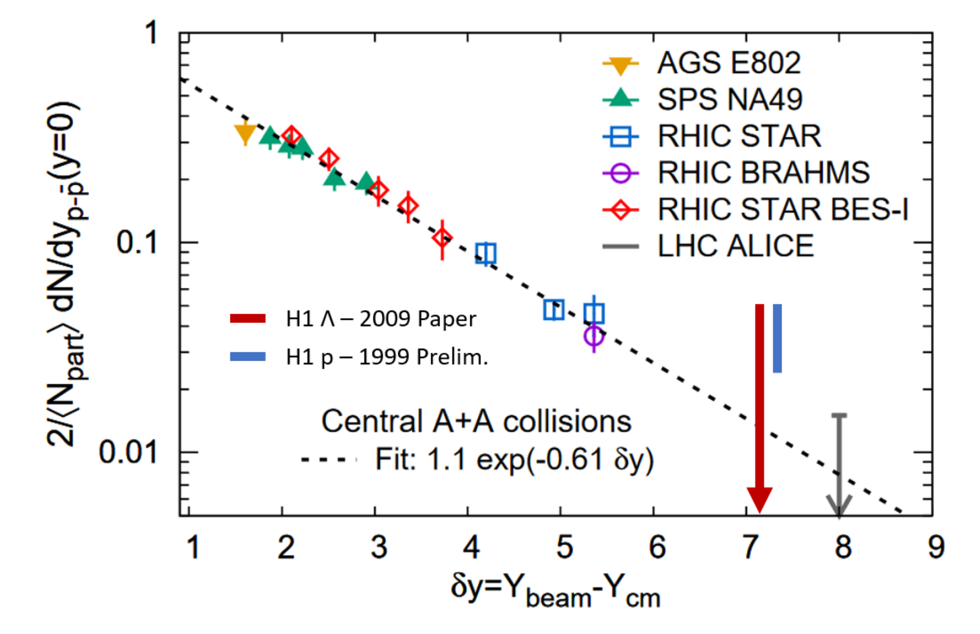
PYTHIA 6 (Quarks): $\sigma \sim e^{2.5(y-Y_{\mathrm{beam}})}$



Regge theory predicts a weaker rapidity dependence than quark models

Rapidity distribution of baryon production:

Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685
Henry Klest (SBU) HERA data



Fit to global data on central A+A:

$$\frac{2}{N_{\text{part}}}\left.\frac{dN_{\text{p}-\bar{\text{p}}}}{dy}\right|_{A+A} = N_B\, e^{-\alpha_B (Y_{\text{beam}} - Y_{\text{cm}})}$$

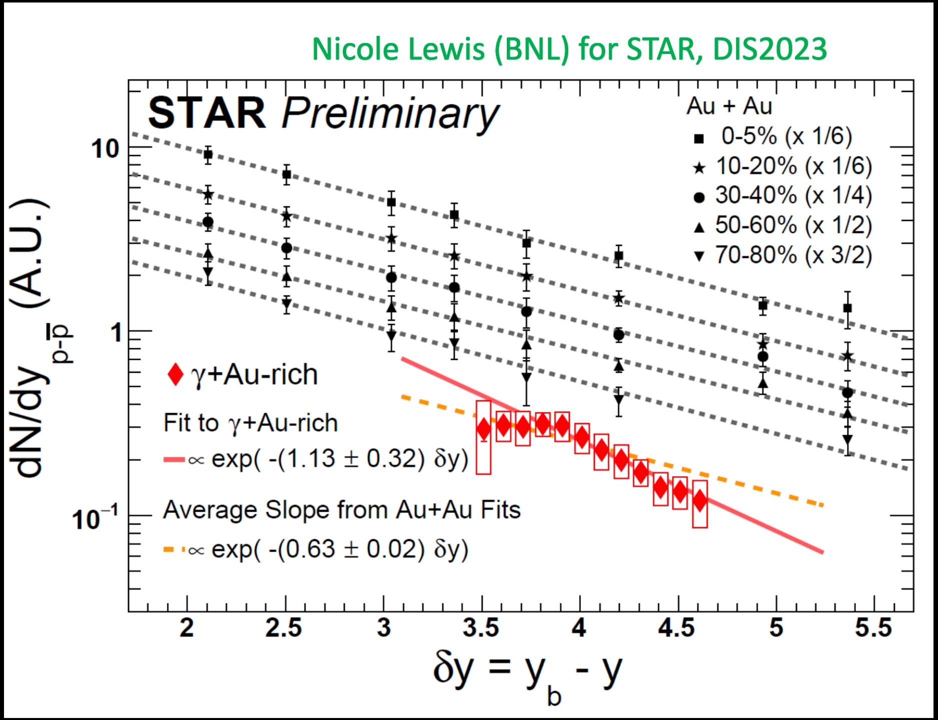
$$\alpha_B = 0.61 \pm 0.03$$

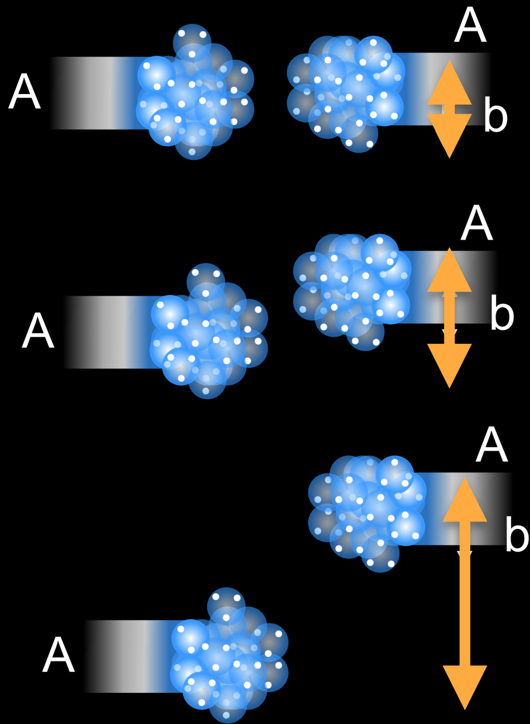
Predictions form Regge theory & baryon junction picture:

$$0.42 \leq \alpha_B \leq 1$$

Midrapidity baryon density slope is consistent with baryon junction prediction

Midrapidity baryon production: Global data





Mimicking baryon-junction explains the data
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905

No slope to change if stopping expected from multiple scattering of quarks in more central collisions

The rapidity distribution of stopping does not change with packing density

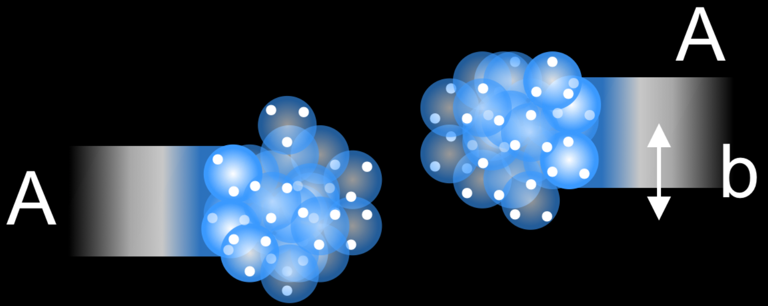
STAR Method: Charge (Q) stopping vs baryon (B)

Charge vs. baryon transport in A+A collisions

Brandenburg, Lewis,Tribedy, Xu, arXiv:2205.05685

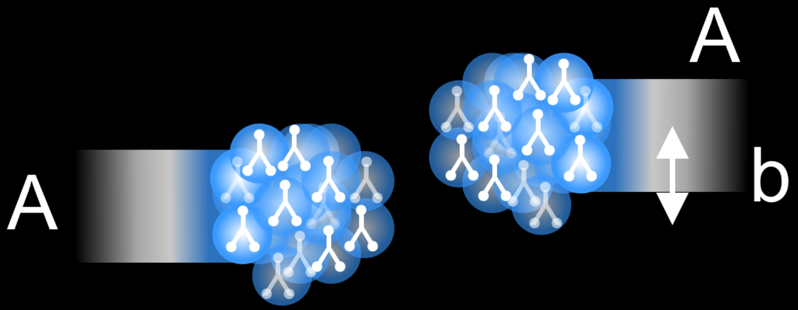
Scenario 1: Valence quarks carry electric charge & baryon number

A=Mass number = Baryon number
Z=Atomic number = Electric charge



$$\text{Charge stopping} \simeq \frac{Z}{A} \times \text{Baryon stopping}$$

Scenario 2: Valence quarks carry electric charge & junctions cary baryon number



$$\text{Charge stopping} < \frac{Z}{A} \times \text{Baryon stopping}$$

Check if charge stopping follows baryon stopping

Challenges in measuring electric charge stopping

Jeon et al. nucl-th/9806047, Wong, hep-ph/0002188, Stankus, AIP Conf. Proc. 842, 156–158 (2006), Park, Wiedemann,arXiv:2107.05129

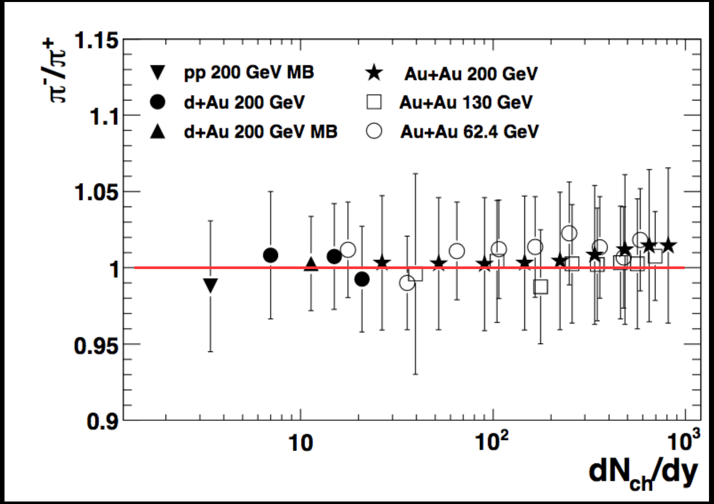
Baryon stopping through net-baryon measurements at mid-rapidity:

$$B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$$

Charge stopping through net-charge measurements at mid-rapidity:

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

STAR collaboration, arXiv: 0808.2041



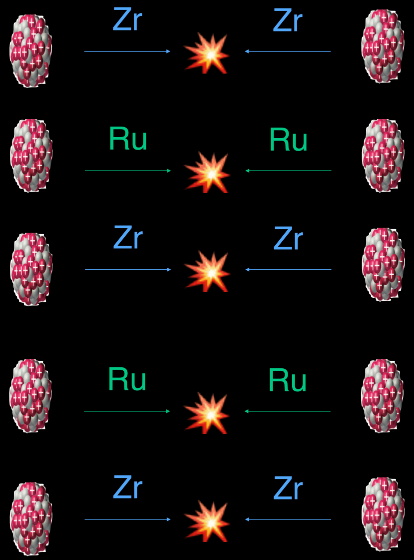
Precision measurement is difficult

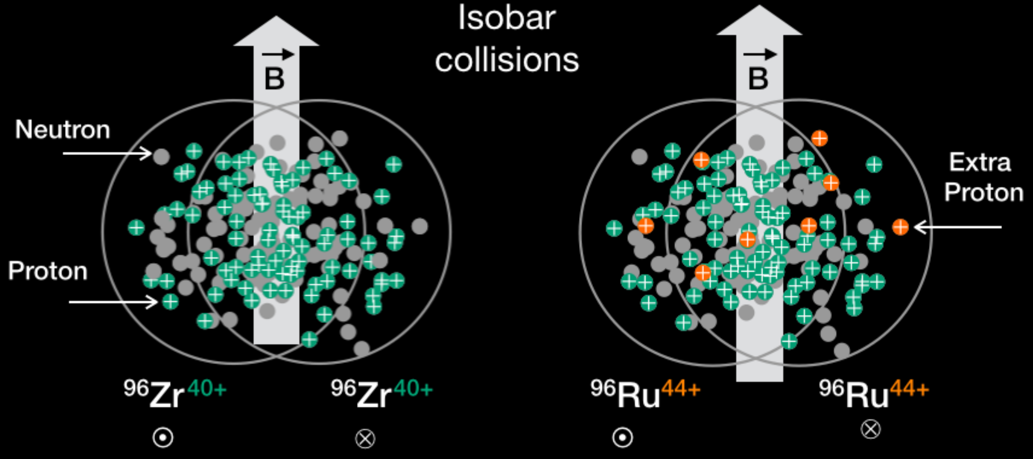
Challenges with charge stopping measurements:

- Charge stopping is 250% smaller than baryon stopping (A/Z~2.5)
- Interaction cross section is different for particles & anti-particles
- Isospin conservation complicates net-charge measurements as larger neutron access in colliding ions makes

Controlling systematics in net-charge measurement is difficult

Precision measurements in isobar collisions





Zirconium:
A=96 (Total baryon)
Z=40 (Total charge)

Ruthenium:
A=96 (Total baryon)
Z=44 (Total charge)

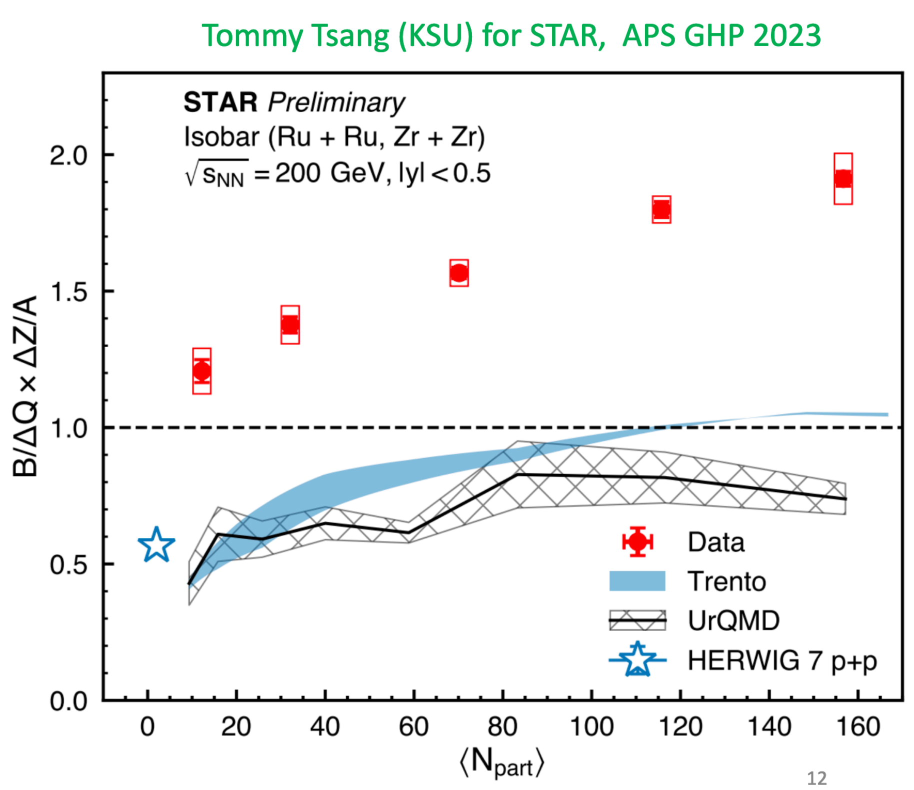
$$R2_\pi = \frac{(N_{\pi^+}/N_{\pi^-})^{\mathrm{Ru}}}{(N_{\pi^+}/N_{\pi^-})^{\mathrm{Zr}}}$$

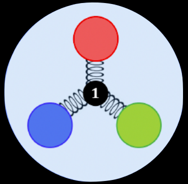
$$\Delta Q = N_\pi \left[(R2_\pi - 1) + \frac{N_K}{N_\pi}(R2_K - 1) + \frac{N_p}{N_\pi}(R2_p - 1) \right]$$

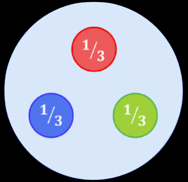
Goal is to test: $\Delta Q \leftrightarrow \frac{\Delta Z}{A} \times B$

Isobar collisions is the best possible control on systematics

Precision measurements in isobar collisions







First measurements of electric charge stopping using isobar collisions

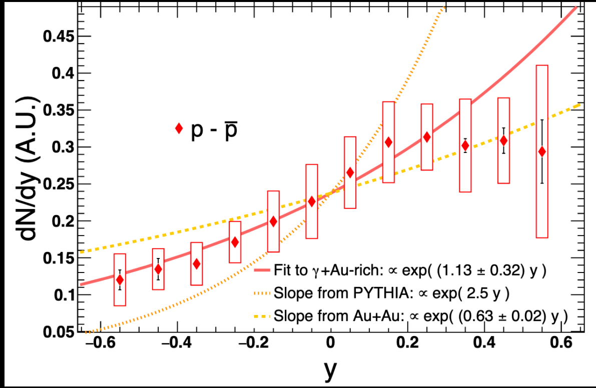
Data: More baryon transported to central rapidity than electric charge

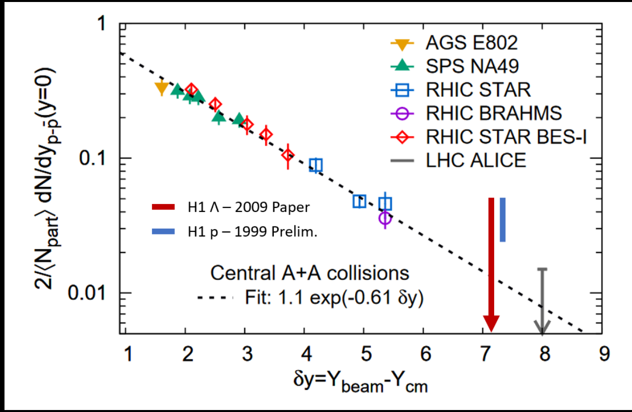
Quark Models: equal or less baryon compared to electric charge

Not compatible with same carrier of electric charge and baryon is not

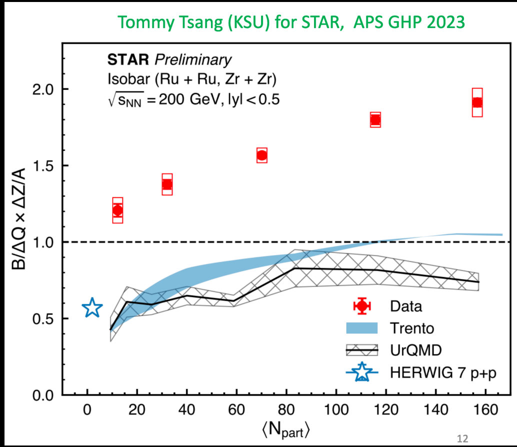
Three different approaches to search for baryon junctions

1. Artru Method: In γ+Au collision, rapidity asymmetry can reveal the origin





2. Kharzeev-STAR Method: If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory



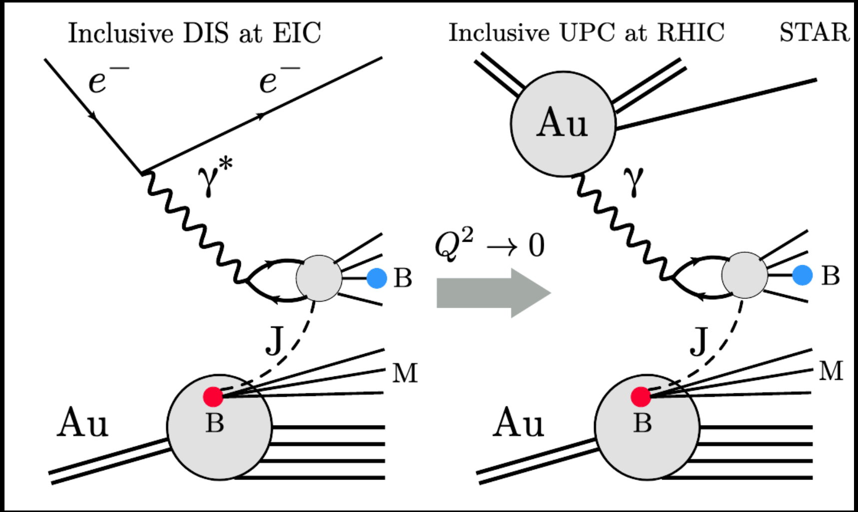
3. STAR Method: Charge (Q) stopping vs baryon (B) stopping, if valence quarks carry Q and B, Q=B at middle rapidity

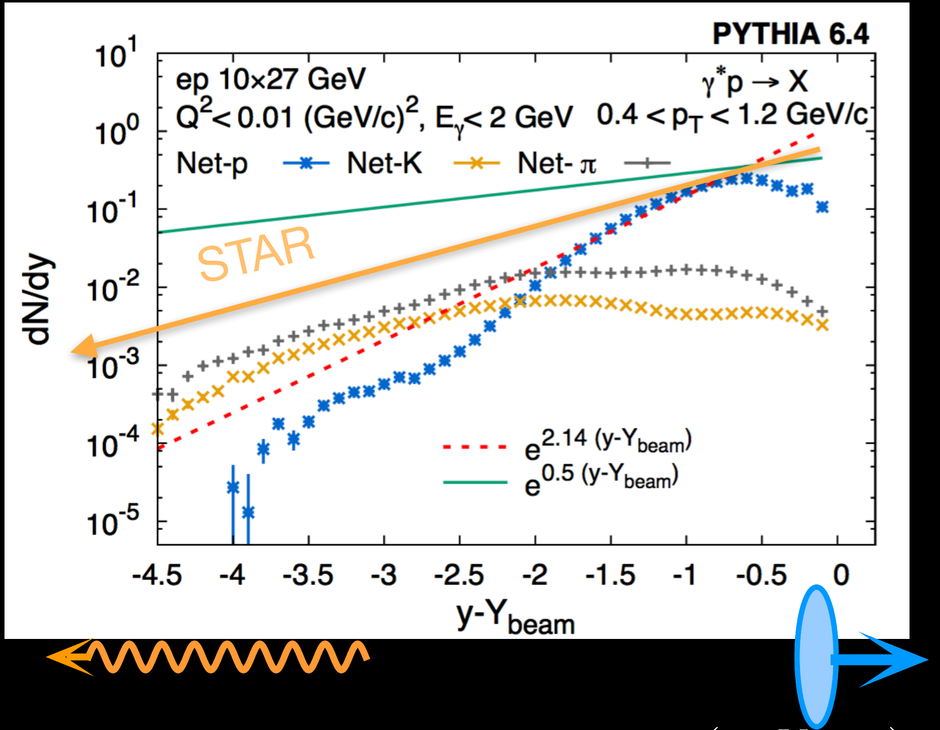
At EIC we can combine all the approaches into one

Measurements at the EIC

Lessons from RHIC photonuclear events

Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685





Expect low yield for baryons
Need low momentum PID
Scan the low Q^2
Need scan of x-Q^2
Need data-driven baseline

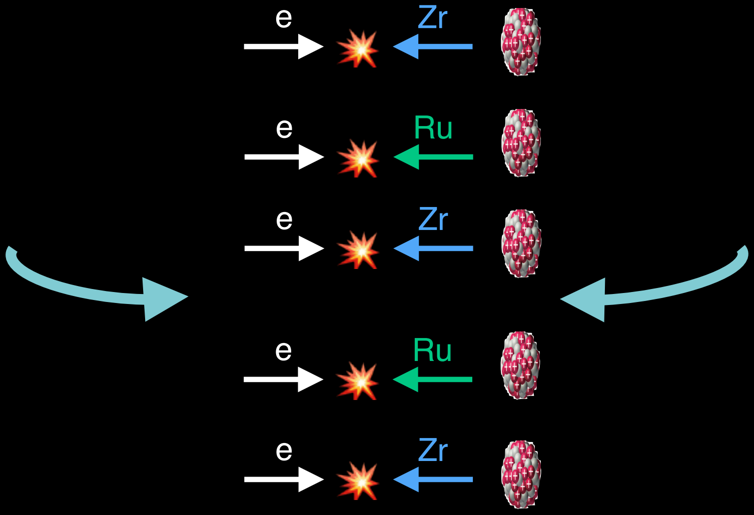
Junction as baryon carrier: $\sim e^{0.58(y-Y_{\rm beam})}$

PYTHIA (Quark as baryon carrier): $\sim e^{2.14(y-Y_{\rm beam})}$

Measure net-baryon and net-charge with rapidity

Towards the first simulation at the EIC

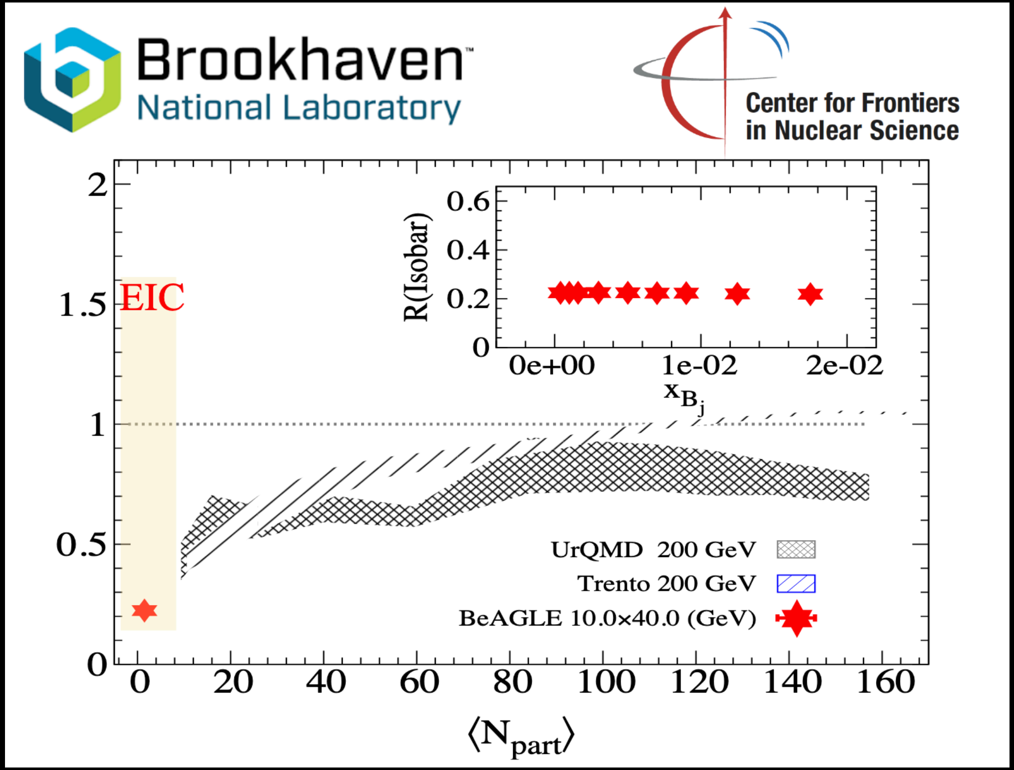
Niseem Magdy (SBU) et al.



$$R(Isobar) = \left(\frac{B_{Ru}}{\Delta Q}\right)\left(\frac{\Delta Z}{A}\right)$$

$R(Isobar) > 1$; gluons carry the flow of baryon number

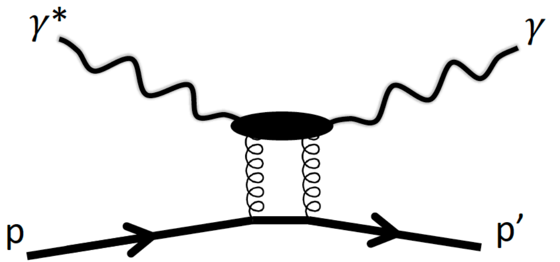
$R(Isobar) < 1$; quarks carry the flow of baryon number



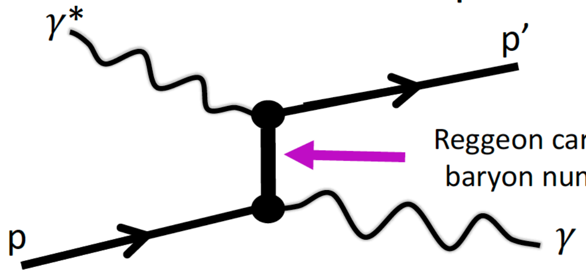
Measure net-baryon and net-charge with rapidity

Other approaches: backward vector meson production

Forward scattering off proton's gluon field



Backward scattering off proton's… baryon number?
gluon junction?
di-quark clusters?



Backward Xsecs → partonic correlations and baryon number?

- Forward production maps parton distributions within proton/nucleus
- Recent (2021) work by Pire et al. formulates a similarly meaningful interpretation of backward cross sections
- They argue backward reactions may map transverse distribution of quark clusters and baryon number

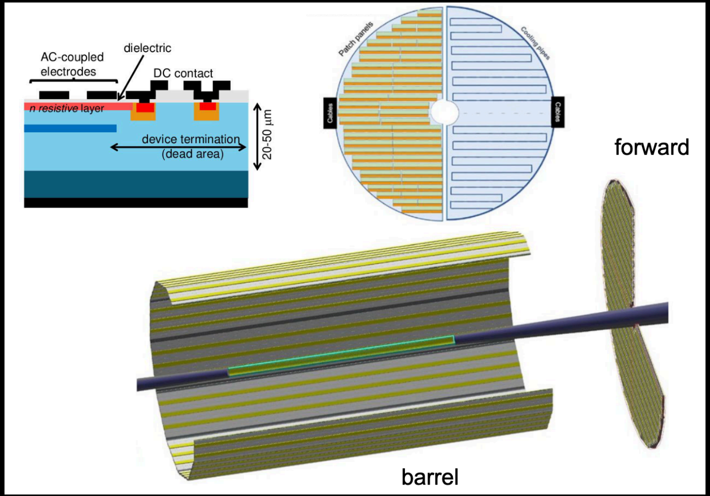
"baryon-to-meson (and baryon-to-photon) TDAs share common features both with baryon DAs and with GPDs and encode a conceptually close physical picture. They characterize partonic correlations inside a baryon and give access to the momentum distribution of the baryonic number inside a baryon. Similarly to GPDs, TDAs – after the Fourier transform in the transverse plane – represent valuable information on the transverse location of hadron constituents."

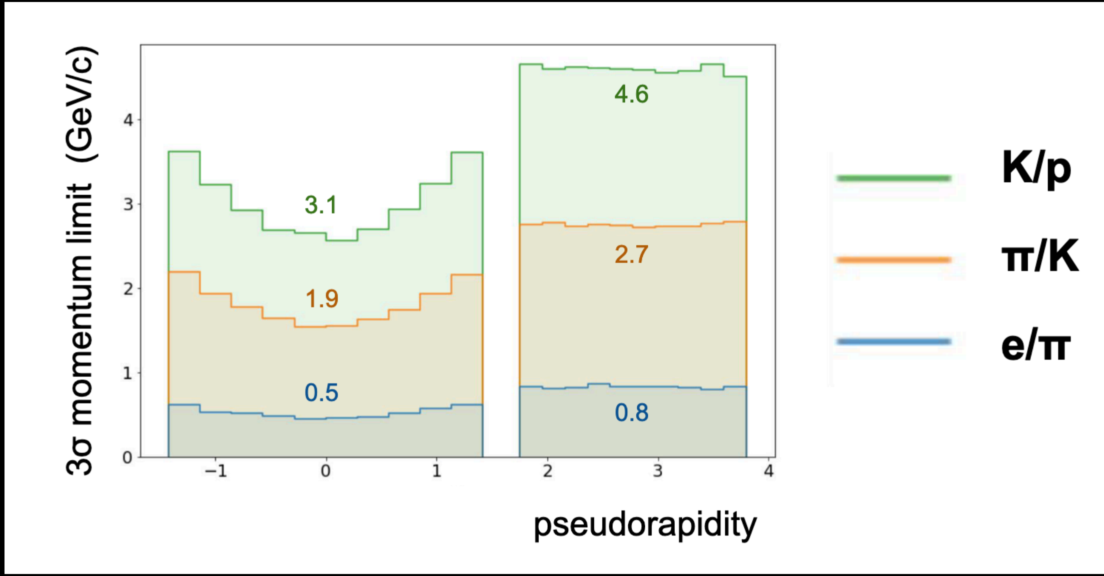
B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, Phys. Rept. 940, 1 (2021), arXiv:2103.01079 [hep-ph].

Detector capabilities

Roberto Preghenella, DIS 2023

Precision low-momentum particle identification necessary

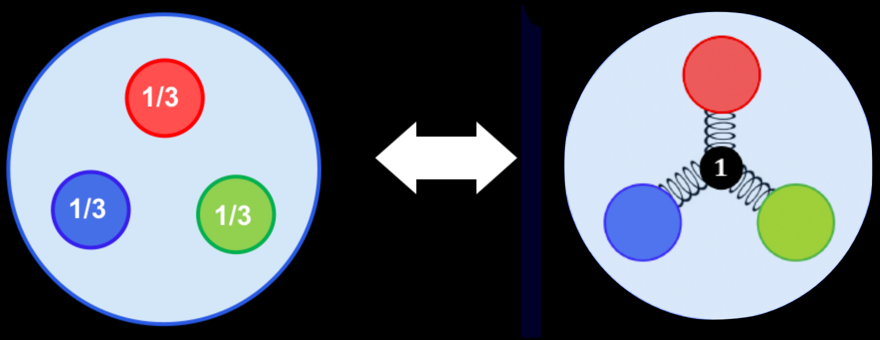


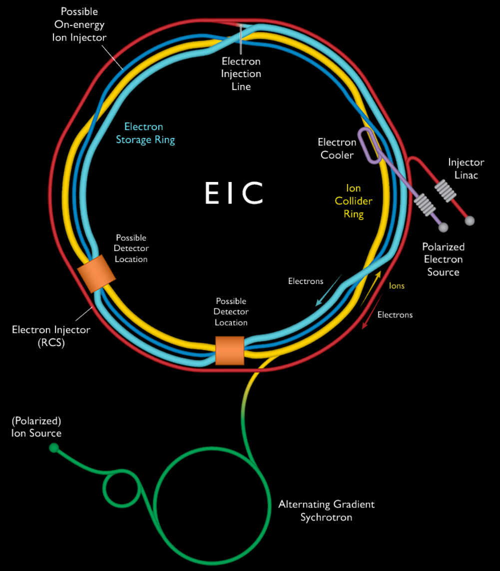


PID with ePIC at the EIC provides the ideal opportunity, low-Q^2 capability at Det-2 also provides unique opportunities

Summary

What carries the baryon number and how it is stopped is of fundamental interest





Three methods to search for baryon junctions are based on rapidity asymmetry, Regge scaling, and charge-baryon correlation have been explored so far

Search for Baryon junction as a carrier at EIC: potential discovery of a non-perturbative unique QCD topology

Kinematics & detectors: small Q2 and low-momentum hadron PID

Collider: Isobar collisions to a measure of charge transport