Tracing the baryon number carrier through photon induced processes from STAR

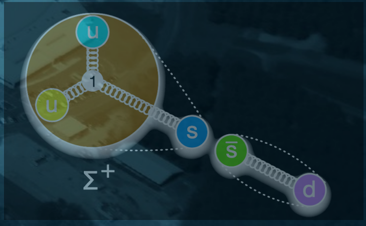
Brookhaven National Laboratory

In part supported by U.S. DEPARTMENT OF ENERGY

Prithwish Tribedy for the STAR collaboration

(Brookhaven National Laboratory)

The 39th Winter Workshop on Nuclear Dynamics, Jackson, WY, Feb. 11-17, 2024

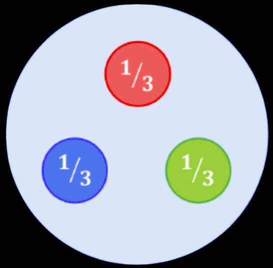


What carries the baryon number

Reviews in Physics 2 (2017) 3–18,
Komargodski, 1812.09253

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

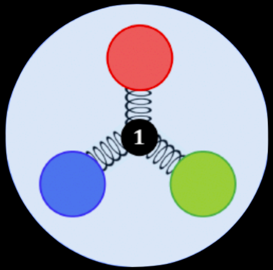
Baryons, along with mesons, are hadrons, particles composed of quarks. Quarks have baryon numbers of $B = \frac{1}{3}$ and antiquarks have baryon numbers of $B = -\frac{1}{3}$. The term "baryon" usually refers to *triquarks*—baryons made of three quarks ($B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} =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



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



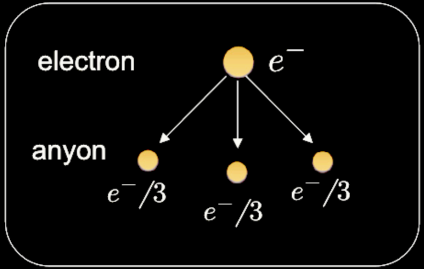
1975-

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

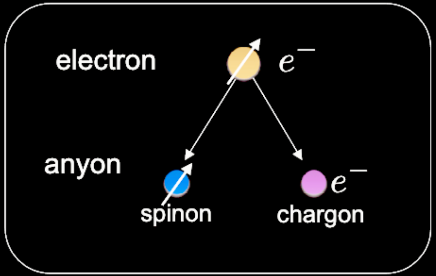
No experiment has conclusively established the true carrier of baryon number, two different carriers for Q & B inside a baryon possible

Condensed matter analogies



(a) $\nu = 1/3$ fractional quantum Hall

Fractional charge of e⁻ → fractional electric charge of quarks



(b) spin-charge separation

ē spilt to quasiparticles carrying charge & spin → separate carriers of Q & B for a baryon

Understanding of baryon junctions as a carrier of baryon number

G. Veneziano, 1st workshop on baryon dynamics, SBU, 2024

1970s

Nuclear Physics B
Volume 85, Issue 2, 27 January 1975, Pages 442-460

String model with baryons: Topology; classical motion

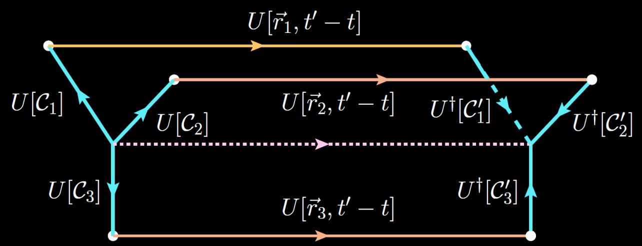
X. Artru ‡

Nuclear Physics B
Volume 123, Issue 3, 30 May 1977, Pages 507-545

A possible description of baryon dynamics in dual and gauge theories

G.C. Rossi *, G. Veneziano **

String models for hadrons,
a Y-shaped junction for baryons,
hadrons as "irreducible" gauge-invariant operators



1990s

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]

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

Can gluons trace baryon number? ☆

D. Kharzeev[a, b]

Physics Letters B
Volume 443, Issues 1–4, 10 December 1998, Pages 45-50

Baryon number transport via gluonic junctions

Stephen E. Vance a, Miklos Gyulassy a, Xin-Nian Wang b

Antihyperon Enhancement through Baryon Junction Loops
Stephen E. Vance and Miklos Gyulassy
Phys. Rev. Lett. **83**, 1735 – Published 30 August 1999

Baryon junction loops and the baryon-meson anomaly at high energies
V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, X. N. Wang, and N. Xu
Phys. Rev. C **70**, 064906 – Published 21 December 2004

Manifestations of junction in high-energy collisions, junctions in Monte-Carlo

2022-

Backward-angle (u-channel) production at an electron-ion collider
Daniel Cebra, Zachary Sweger, Xin Dong, Yuanjing Ji, and Spencer R. Klein
Phys. Rev. C **106**, 015204 – Published 15 July 2022

arXiv > hep-ph > arXiv:2205.05685
High Energy Physics – Phenomenology
[Submitted on 12 May 2022 (v1), last revised 2 Dec 2023 (this version, v4)]
Search for baryon junctions in photonuclear processes and isobar collisions at RHIC
Nicole Lewis, Wendi Lv, Mason Alexander Ross, Chun Yuen Tsang, James Daniel Brandenburg, Zi-Wei Lin, Rongrong Ma, Zebo Tang, Prithwish Tribedy, Zhangbu Xu

arXiv > nucl-th > arXiv:2309.06445
Nuclear Theory
[Submitted on 12 Sep 2023 (v1), last revised 20 Nov 2023 (this version, v2)]
Correlations of Baryon and Charge Stopping in Heavy Ion Collisions
Wendi Lv, Yang Li, Ziyang Li, Rongrong Ma, Zebo Tang, Prithwish Tribedy, Chun Yuen Tsang, Zhangbu Xu, Wangmei Zha

arXiv > hep-ph > arXiv:2312.15039
High Energy Physics – Phenomenology
[Submitted on 22 Dec 2023]
Signatures of baryon junctions in semi-inclusive deep inelastic scattering
David Frenklakh, Dmitri E. Kharzeev, Wenliang Li

arXiv > nucl-th > arXiv:2312.12376
Nuclear Theory
[Submitted on 19 Dec 2023]
Tracing baryon and electric charge transport in isobar collisions
Gregoire Pihan, Akihiko Monnai, Björn Schenke, Chun Shen

Experimental test of the true carriers of the baryon number

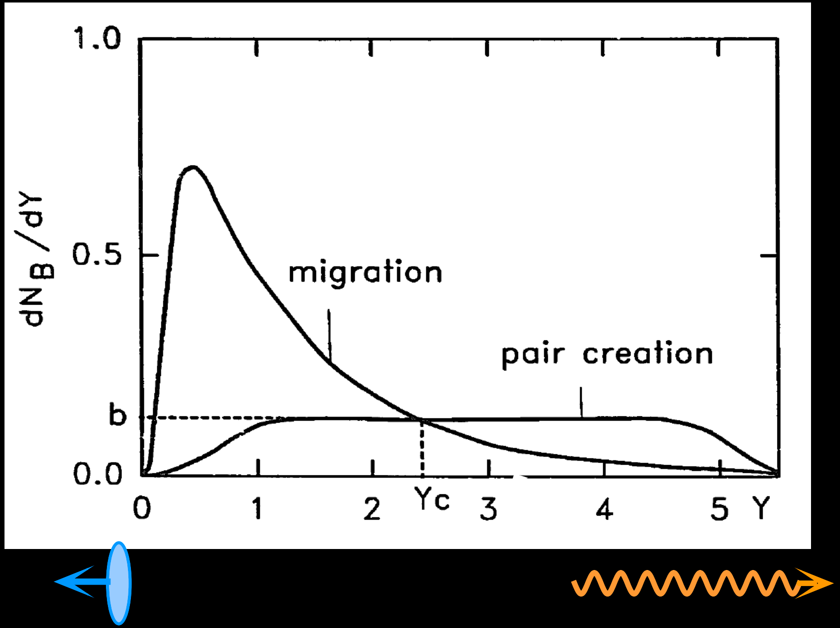
Using photon-induced processes to identify the baryon carrier

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

NUCLEAR PHYSICS A

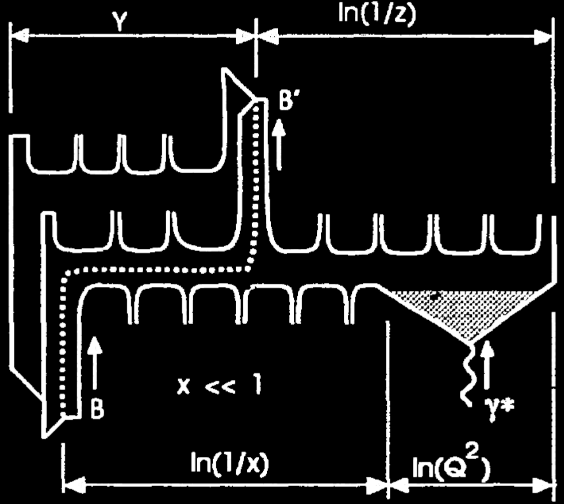
What can we learn from unpolarized and polarized electroproduction of fast baryons?

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



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

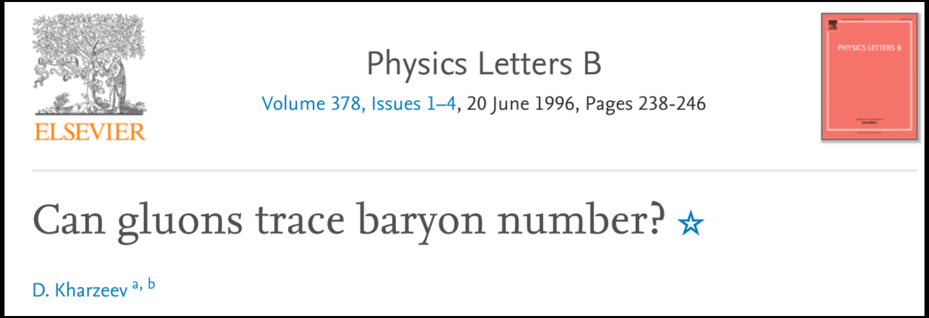
$$dN_B/dY \simeq \beta\,(2p\cdot p'/m^2)^{-\beta} \simeq \beta\,\exp(-\beta Y)$$



Rapidity asymmetry from colliding a source of photon at various energies on baryon —> reveal the junction-like structure of a baryon

Gluonic junction as a carrier of baryon number

Talk by D. Franklakh
(Mon, 9 AM)


ELSEVIER

Physics Letters B

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

Can gluons trace baryon number? ☆

D. Kharzeev [a, b]

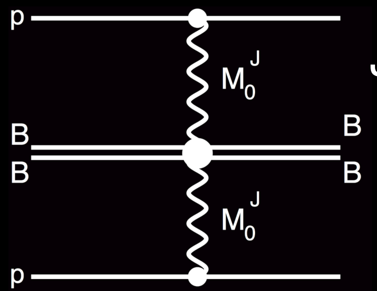
String-junction:
non-perturbative
gluon configuration

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

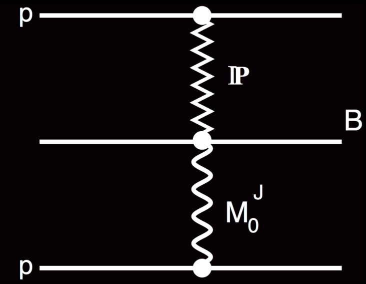
Baryon junction: $e^{-\alpha_B(y-Y_{\mathrm{beam}})}$ $\boxed{0.42 \leq \alpha_B \leq 1}$

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

Junction-Junction



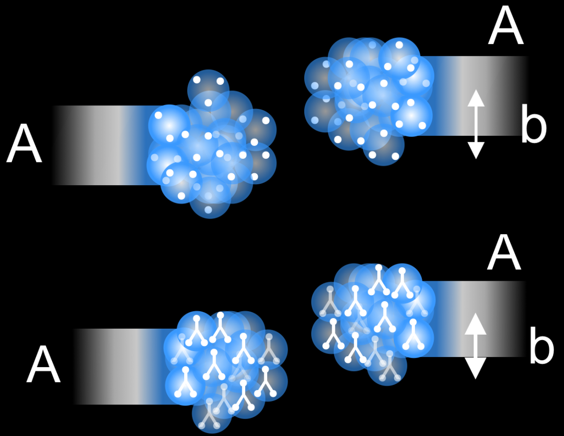
Junction-Pomeron



Regge theory predicts larger baryon transport to mid-rapidity for stopping gluonic junctions than valence quarks

Strategies for tracing the baryon carrier

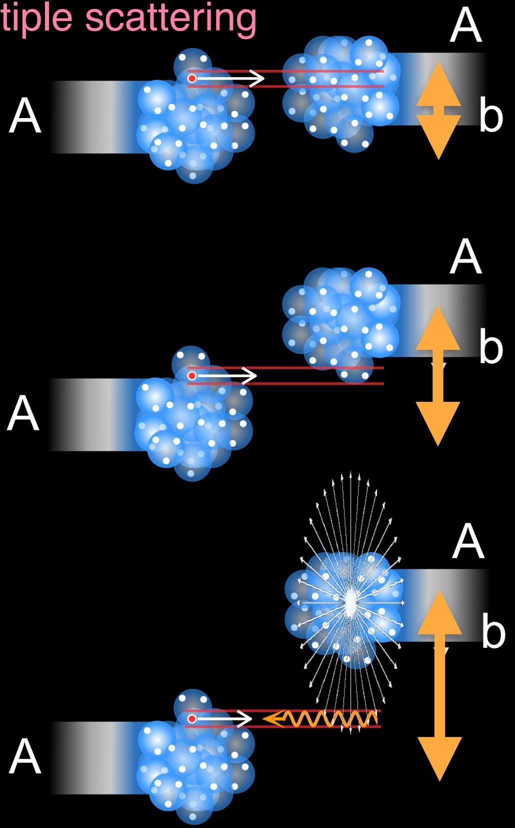
Check if charge and baryon are carried by the same object



Compare electric-charge with baryon transport

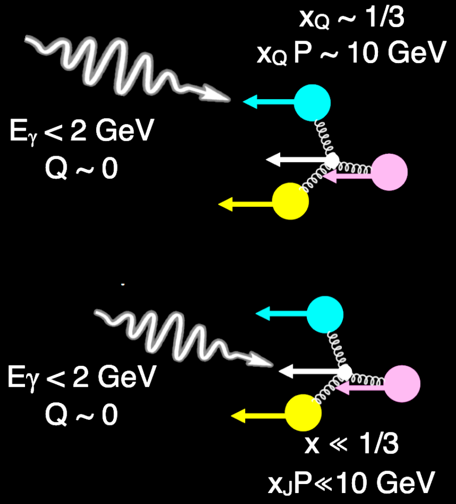
Q <-> Z/A x B

Baryon carrier suffer multiple scattering



Centrality dependence of dn/dy(B) vs. Y_{beam}

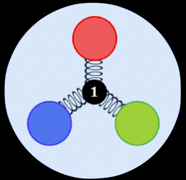
Find if the baryon carrier is a gluonic object by colliding with a photon of very small stopping power



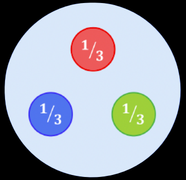
Yield and rapidity dependence of dn/dy(B) in γ+A collisions

Measurements in isobar collisions: different carriers for Q & B?

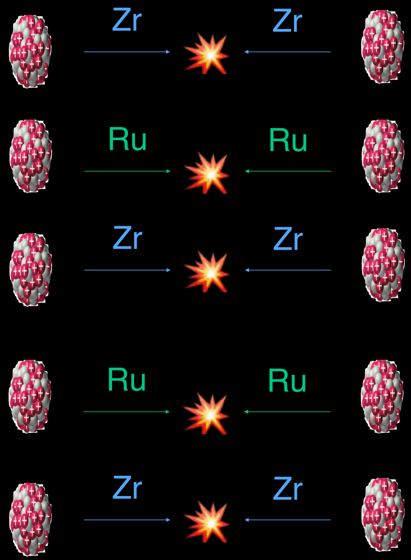
Talk by Rongrong Ma (Mon, 11 am)



B:junction
Q:valence quarks



B & Q: valence quarks

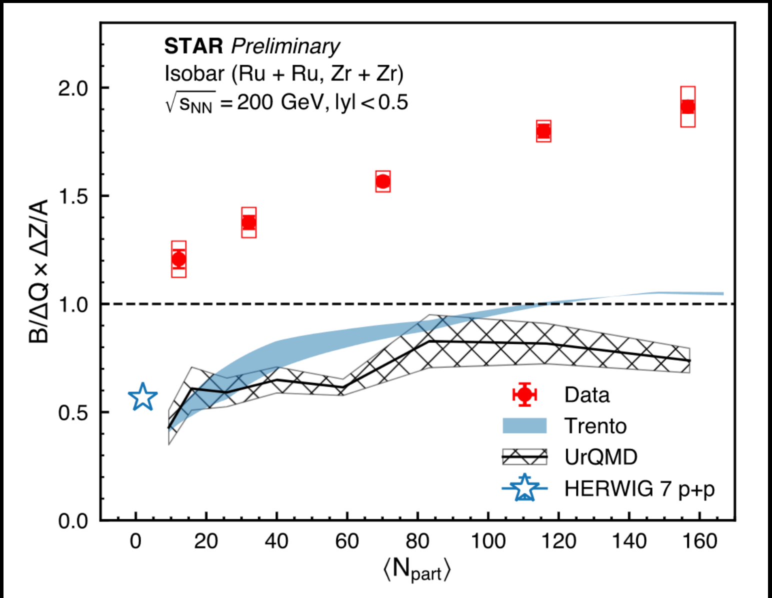


Zirconium:
A=96 (Total baryon)
Z=40 (Total charge)

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

Goal is to test:

$$\Delta Q \leftrightarrow \frac{\Delta Z}{A} \times B$$



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

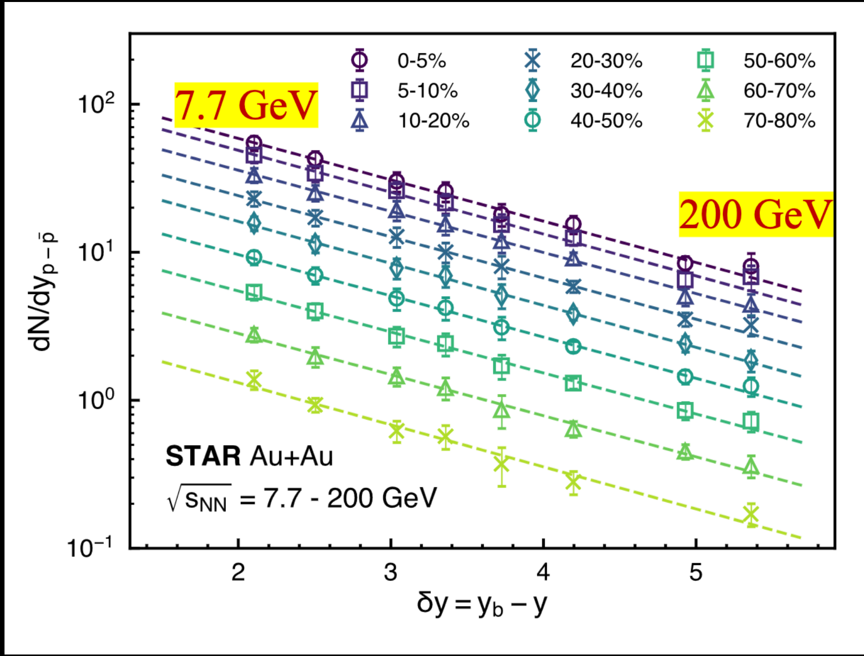
$$\Delta Q = N_{\pi}\left[(R2_{\pi}-1) + \frac{N_K}{N_{\pi}}(R2_K - 1) + \frac{N_p}{N_{\pi}}(R2_p - 1)\right]$$

STAR data: stronger baryon vs net-electric charge transport at mid-rapidity: hints different carriers for baryon & electric charge

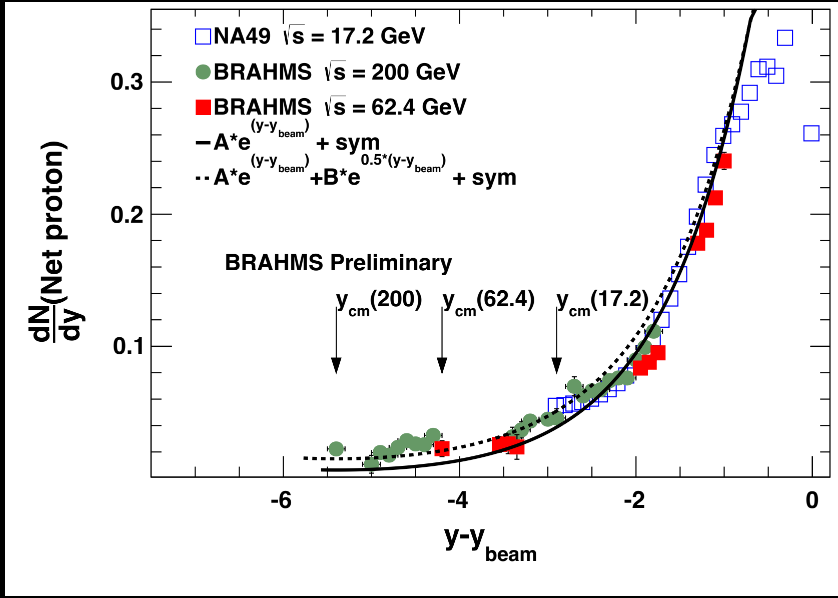
Rapidity distribution of baryon production: Global data

STAR data: N. Lewis, et. al., arXiv:2205.05685, BRAHMS+NA49: F. Videbaek, 1st workshop on baryon dynamics, SBU, 2024

Baryon transport with rapidity loss ($y-Y_{beam}$)



BRAHMS + NA49 data (wider $y-Y_{beam}$)



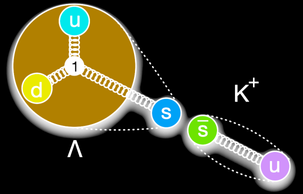
Exponential with slope -0.63±0.2, no change with centrality for $2<Y_{beam}<5.5$

At higher energy rapidity slope closer to~0.5 lower energy ($|y-Y_{beam}|<2$) rapidity slope ~1

Rapidity slope of baryon density: centrality independent, depends on $|y-Y_{beam}|$ range

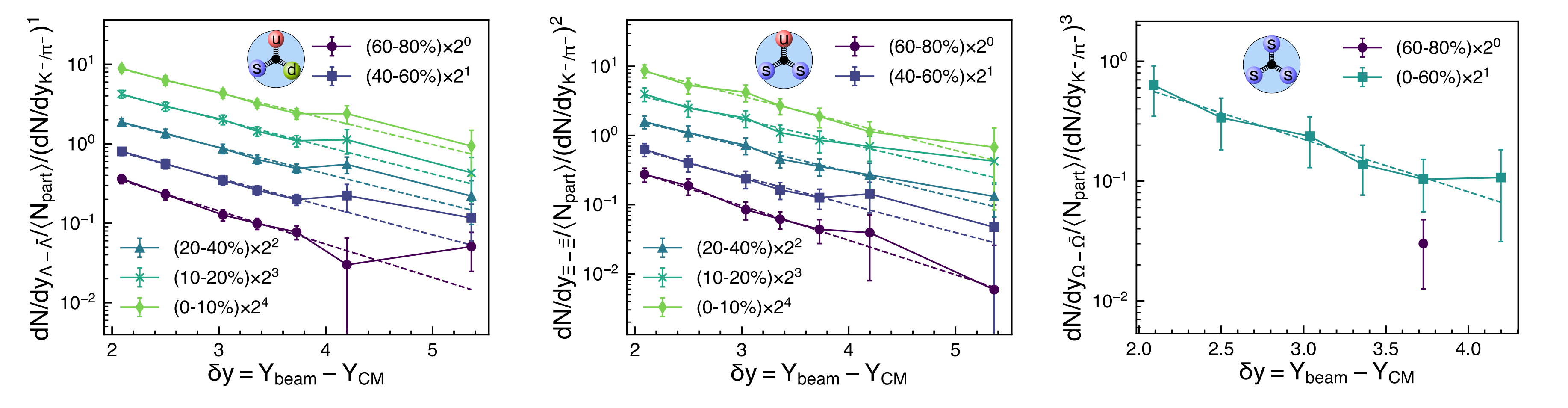
Rapidity distribution of strange baryons

Strange baryon production requires replacing incoming quark(s) in p &n through s-$\bar{s}$ production



STAR data for BES-I: G. Agakishiev Phys. Rev. Lett. 98, 062301 (2007),108, 072301 (2012), J. Adam Phys. Rev. C 102, 034909 (2020), Adamczyk et al, Phys. Rev. C 96, 044904 (2017), T. Sang, 1st workshop on baryon dynamics, SBU, 2024

More details: https://indico.cfnssbu.physics.sunysb.edu/event/113/contributions/750/



Net yield is scaled by $(\bar{K}/\bar{\pi})^n$ to compensate for difficulty in "n" s-quark production

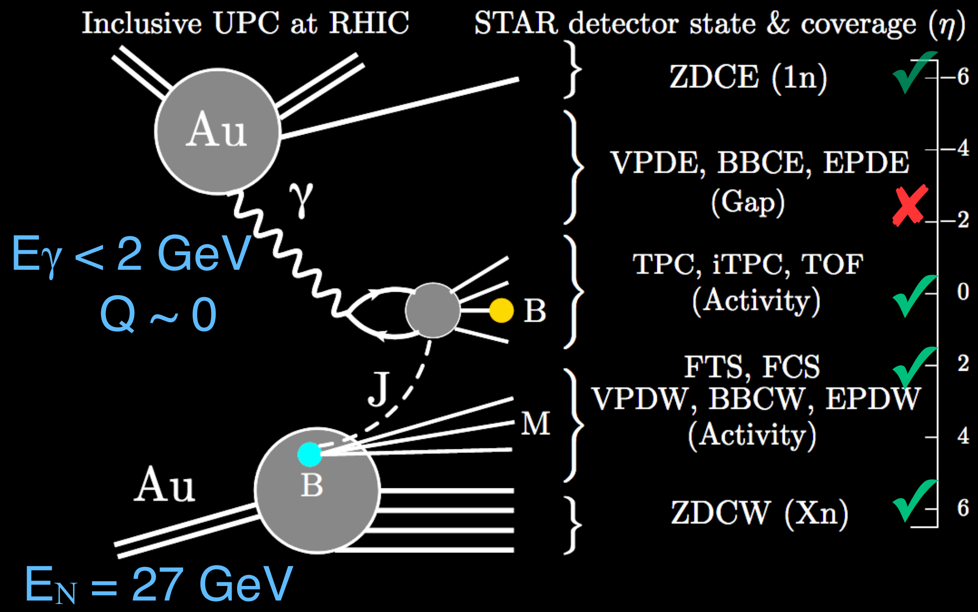
Exponential slope for different net-strange baryons (Λ,Ξ,Ω) seen similar to net-proton

Rapidity slope of baryon density has no strong flavor dependence

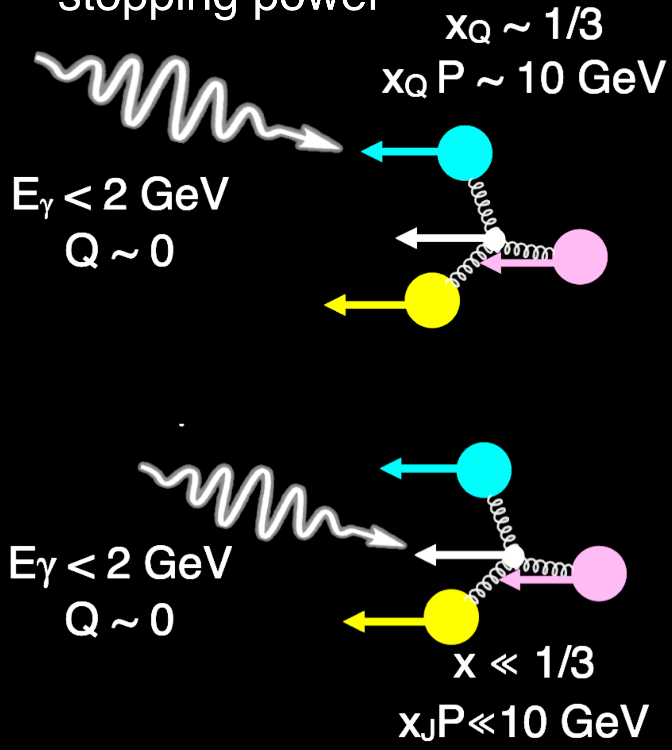
Probing baryon structure with photon-induced processes

Fig: Lewis et. al, arXiv: 2205.05685, Sweger, CA EIC consortia meet

We trigger on γ+Au events in Ultra-peripheral collisions of Au+Au at 54.4 GeV
Approximate γ+Au $\sqrt{s_{\gamma N}}$~10 GeV



UPC photons have very low stopping power

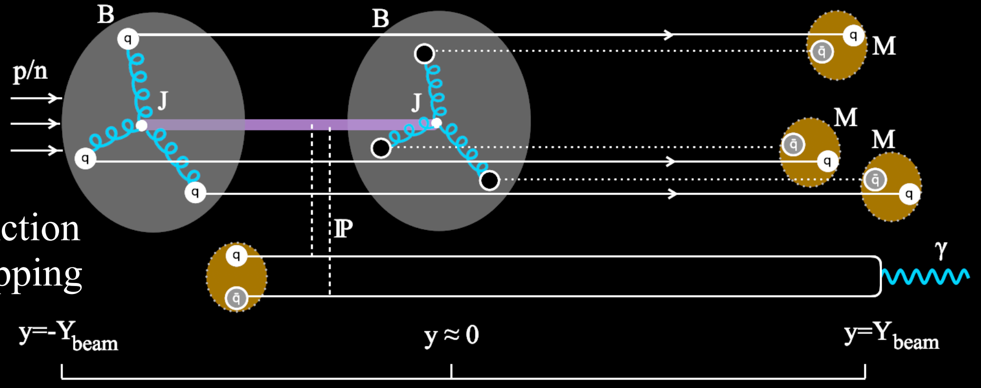


Search for non-zero net-baryon in photon-ion collisions near central-rapidity

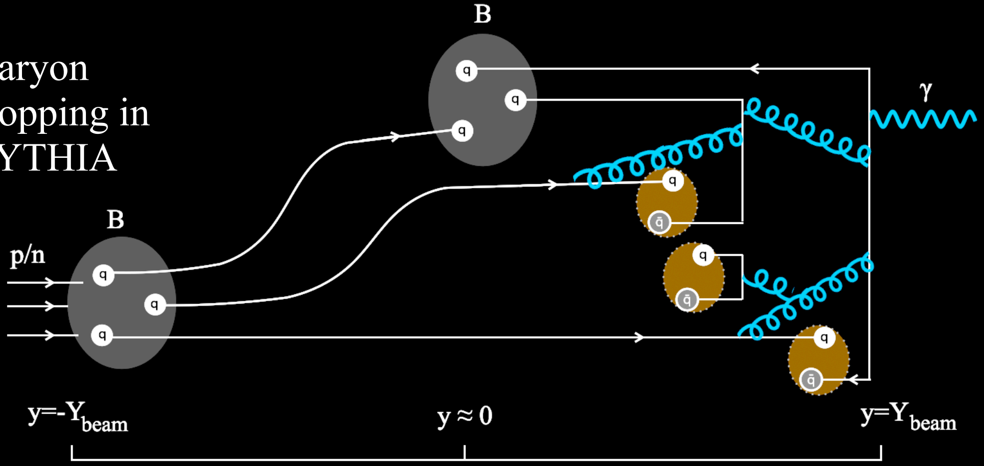
Probing baryon structure with photon-induced processes

Lewis et. al, arXiv:2205.05685
Dumitru, CFNS workshop on target fragmentation, 2022

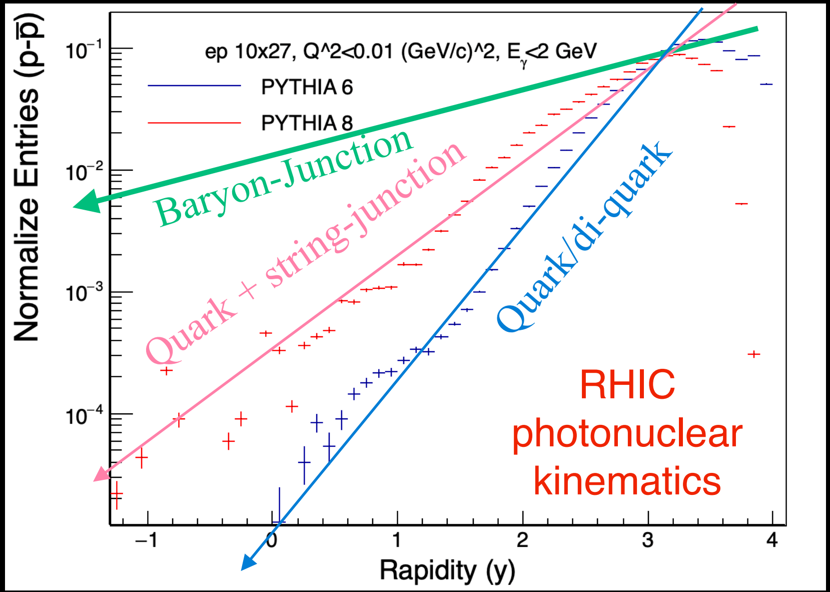
Junction stopping



Baryon stopping in PYTHIA



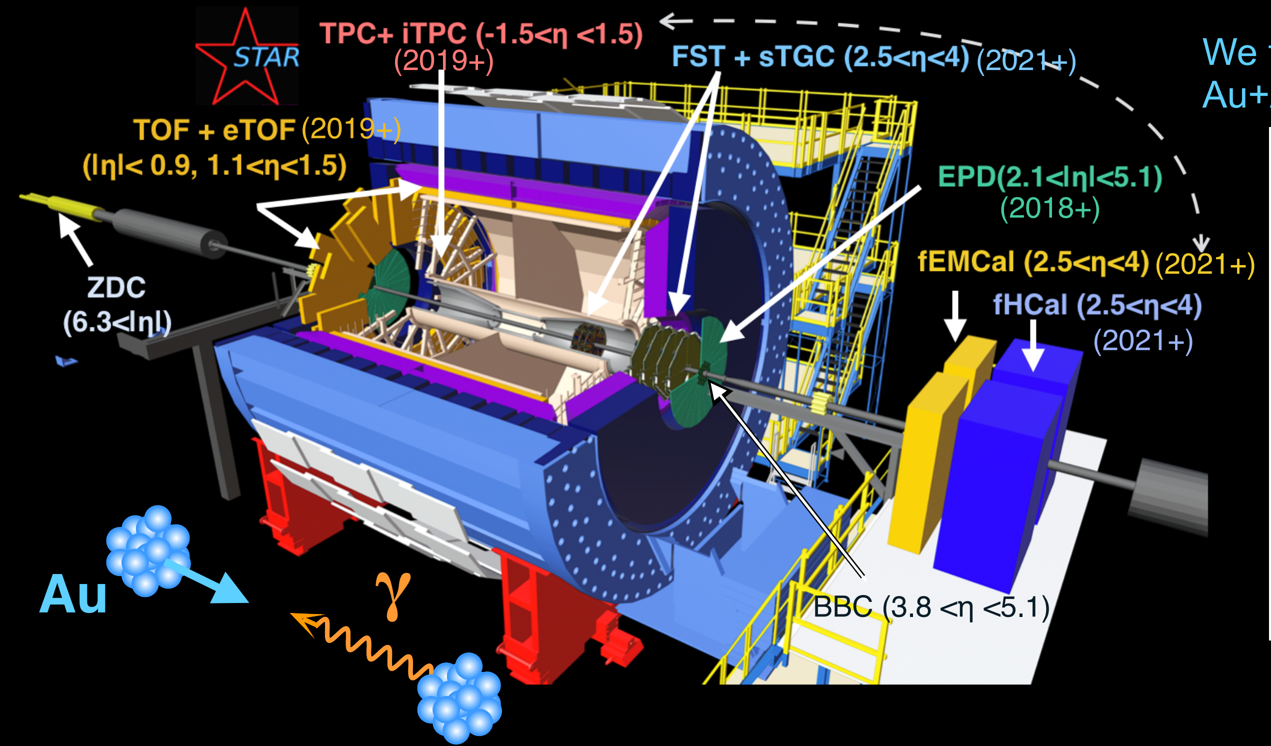
PYTHIA 6: Quark carries baryon
PYTHIA 8: Quark + mimic string-junction



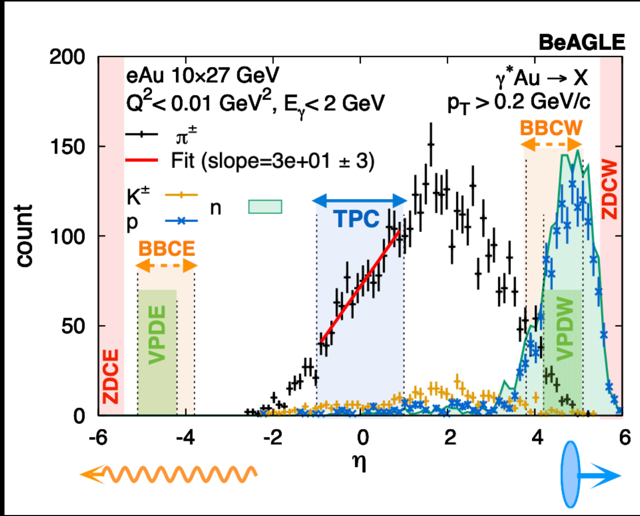
Models with various different carriers predict different rapidity dependence of net-proton yield

Triggering inclusive photon-induced processes by the STAR detector

Lewis et. al, arXiv: 2205.05685, BeAGLE:
W. Chang, et al PRD 106, 012007 (2022)



We trigger γ+Au events in ultra-peripheral Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV



Use characteristic asymmetric particle production to trigger inclusive γ+Au events with help of:

- Beam-Beam counter (BBC),
- Zero-Degree Calorimeter (ZDC),
- Vertex Position Detector (VPD)

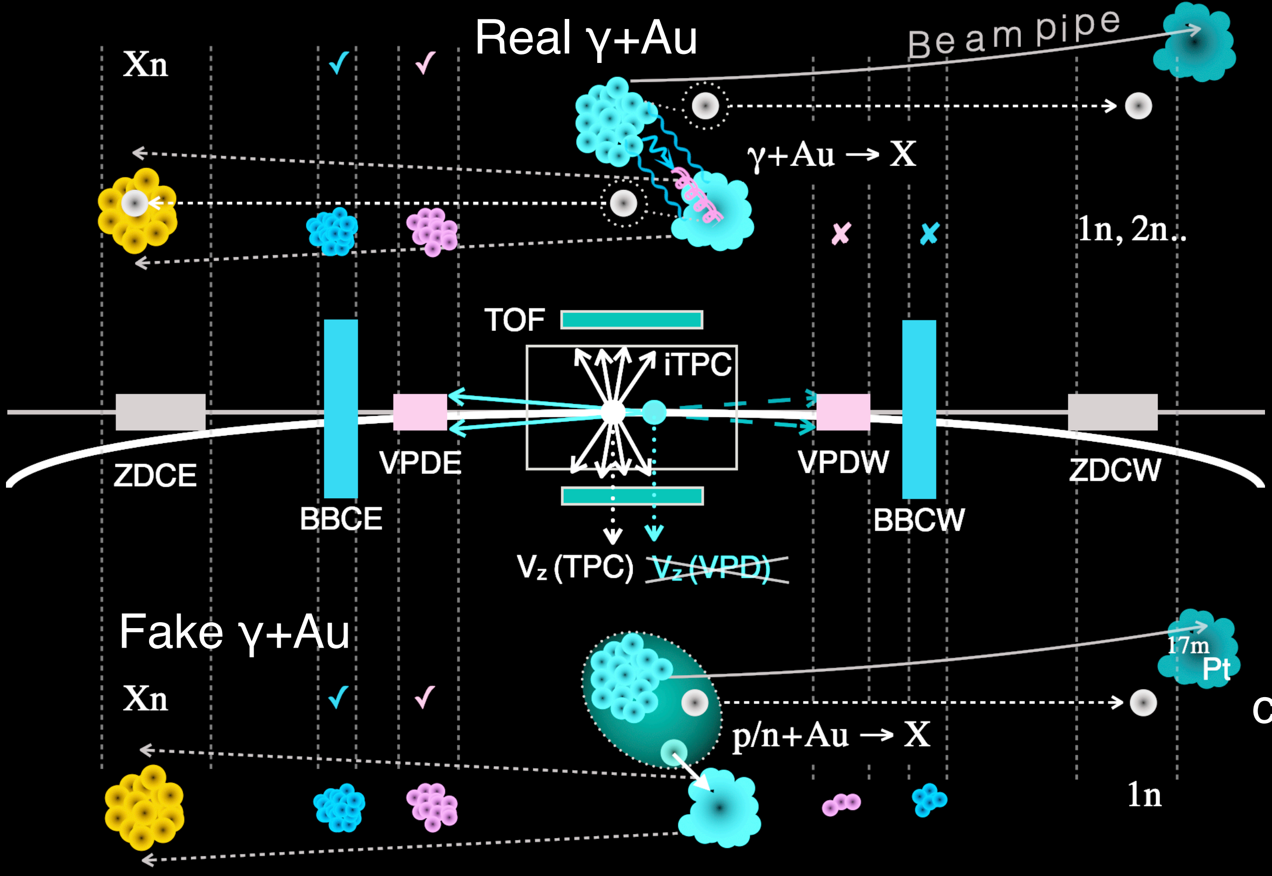
Time Projection Chamber (TPC)

- Track reconstruction
- Identify particles using dE/dx

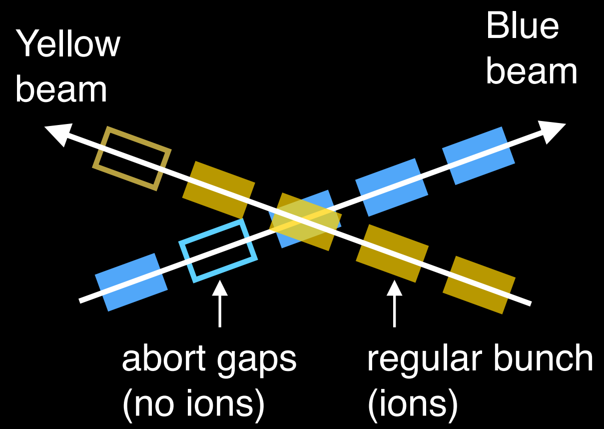
Time-Of-Flight detector (TOF)

- Extend particle identification to high pT
- Pile-up rejection

Triggering inclusive photon-induced processes by the STAR detector



Background
from beam-gas

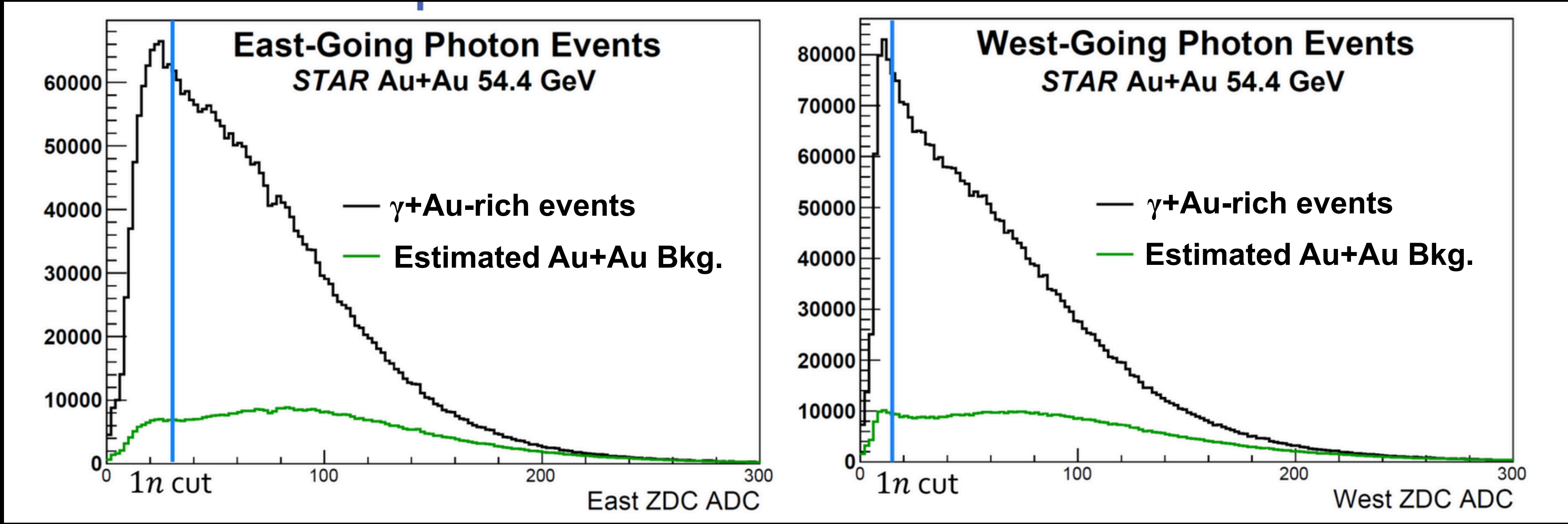


We estimate background contamination from peripheral heavy-ion collisions and beam-gas events

1nXn conditions on ZDCs largely suppress beam-gas background

Trigger efficiency: contamination from peripheral Au+Au events

Unlike Au+Au, in γ+Au events, ZDC dist. is dominated by Coulomb excitation neutrons



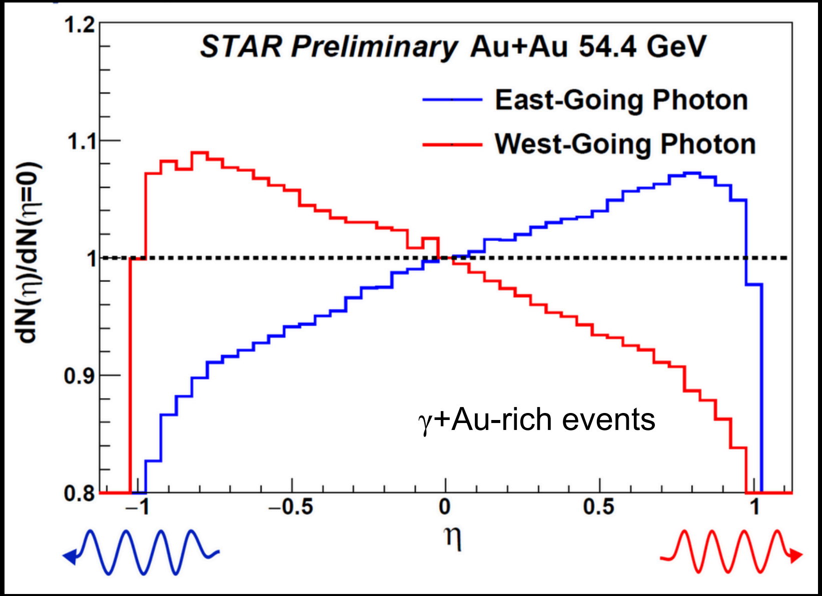
Estimate background contribution utilizing ZDC ADC distributions of peripheral events

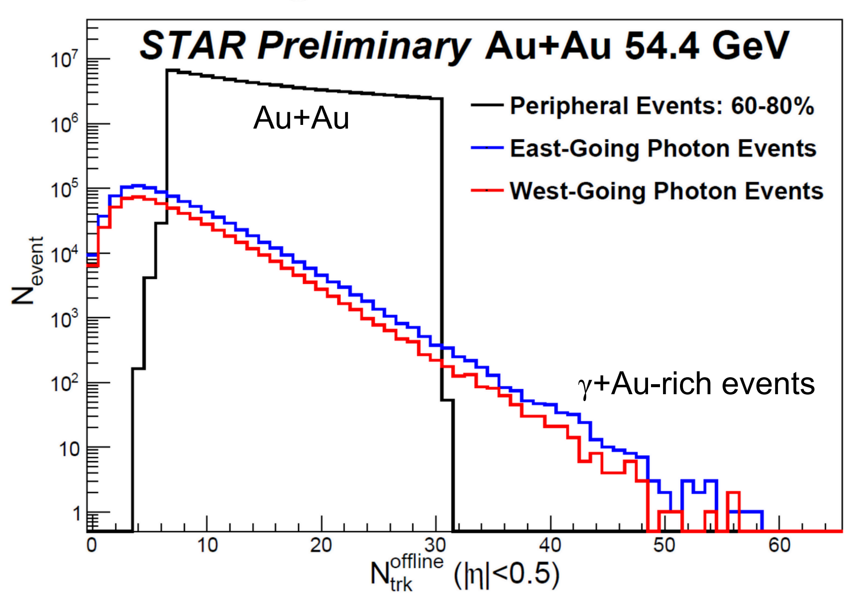
- Scale down so the tail matches γ+Au-enriched events, for large values of ADCs

Contamination from fake γ+Au candidates estimated to be 10% and accounted for

Results: characteristic features of γ+Au events

Model calculations:
Lewis et. al, arXiv: 2205.05685



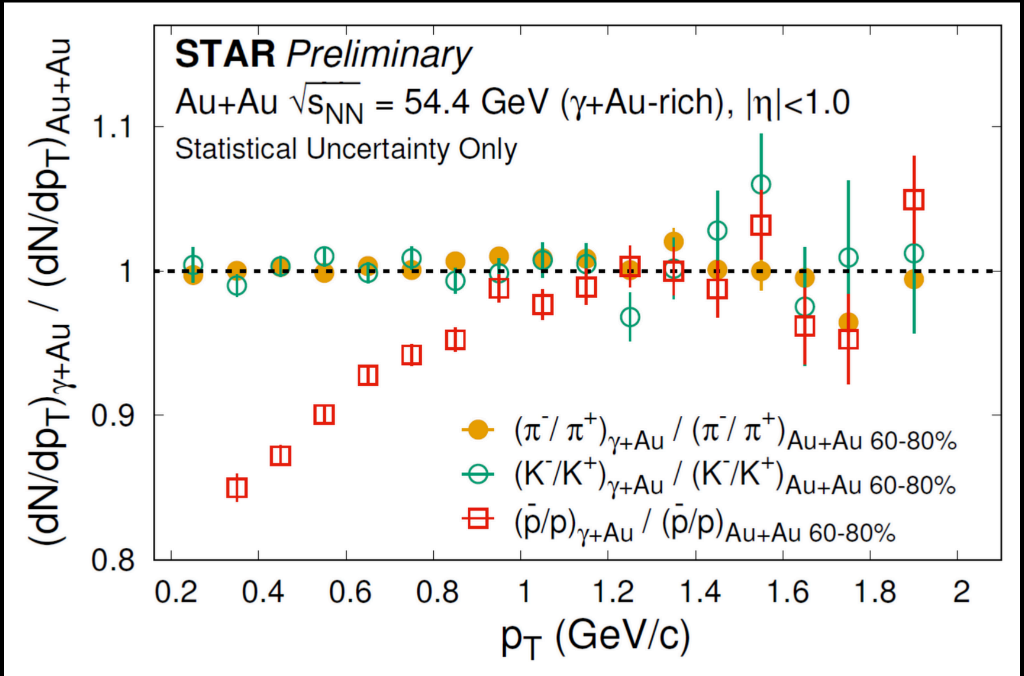


γ+Au events produce rapidity asymmetry that is expected from model predictions

Most photonuclear events have low multiplicity, consistent with very peripheral Au+Au collisions

Bulk features of γ+Au events are consistent with expectations from models

Results: Proton spectra in γ+Au collisions relative to peripheral Au+Au



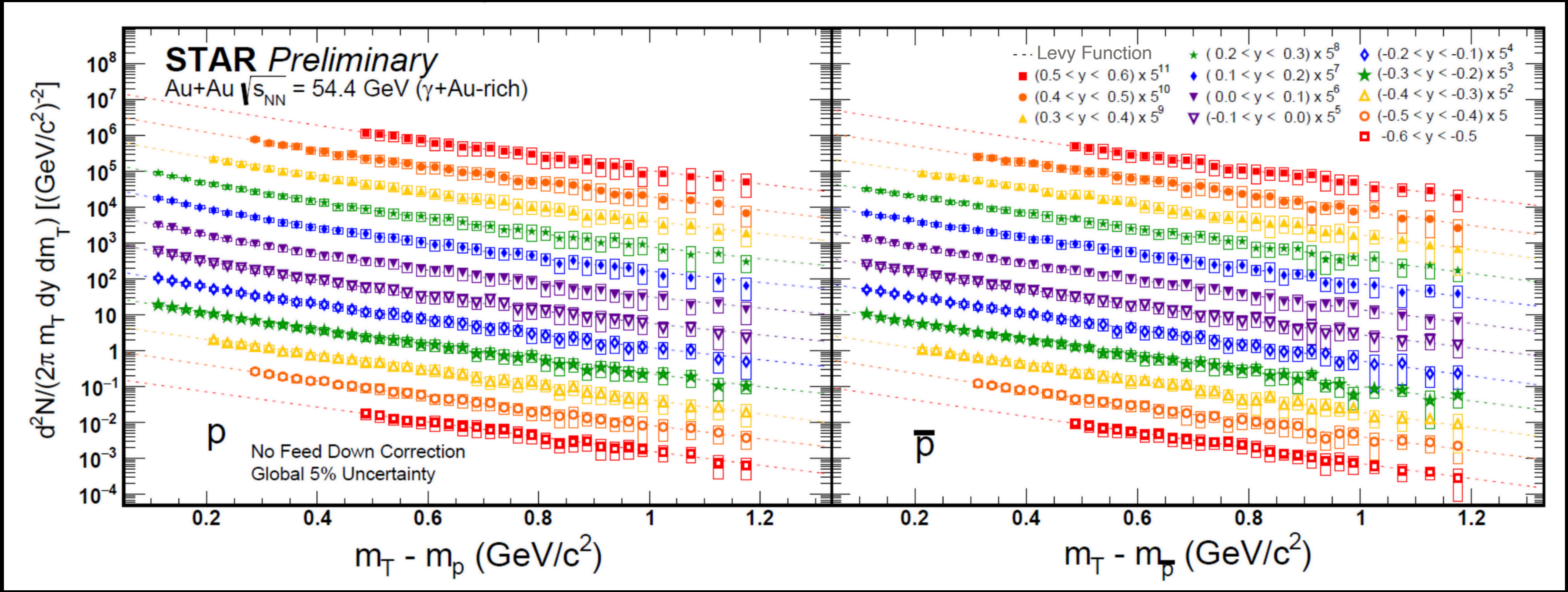
Double ratio: antiparticle/particle in (γ+Au)/(Au+Au)

$\bar{p}/p < 1$ for pT ≲ 1 GeV/c → Indication of soft baryon stopping in γ+Au collisions

Not corrected for efficiency, but largely cancels in the double ratio

Baryon enhancement seen in γ+Au relative to Au+Au only at low momentum

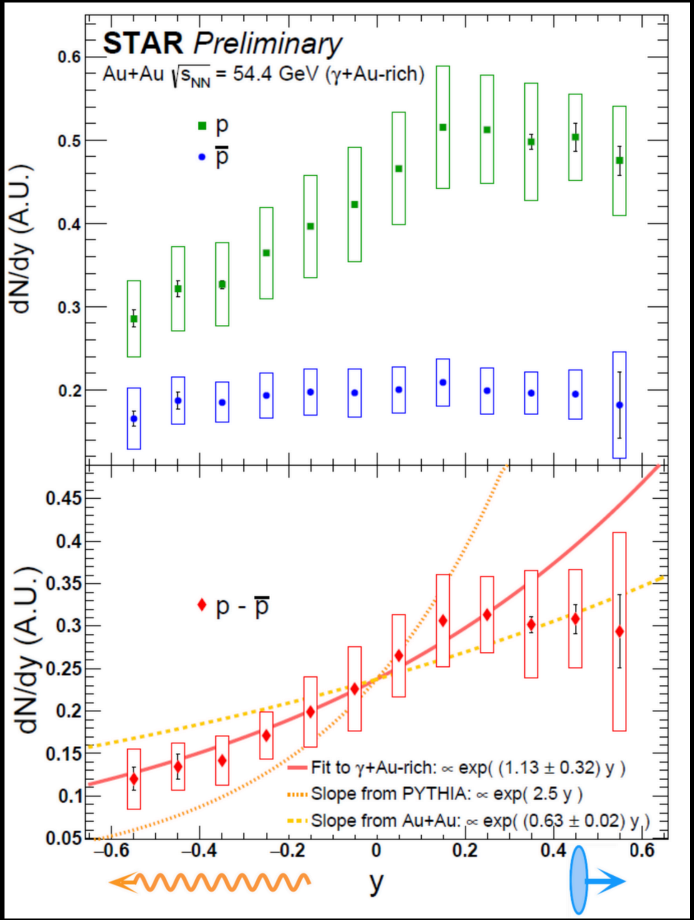
Results: Proton spectra in γ+Au collisions at various rapidity bins



- Peripheral Au+Au contamination ~10% from baseline Au+Au (60-80%) measurements
- Measurement extrapolated to pT ~0 using Levy fits

Transverse momentum distribution of p and $\bar{p}$ measured at various rapidities

Results: Rapidity distribution of net-proton in γ+Au events



p and net-proton dN/dy with y described by an exponential with slope: 1.13 ± 0.32

Anti-proton distribution is near constant with y

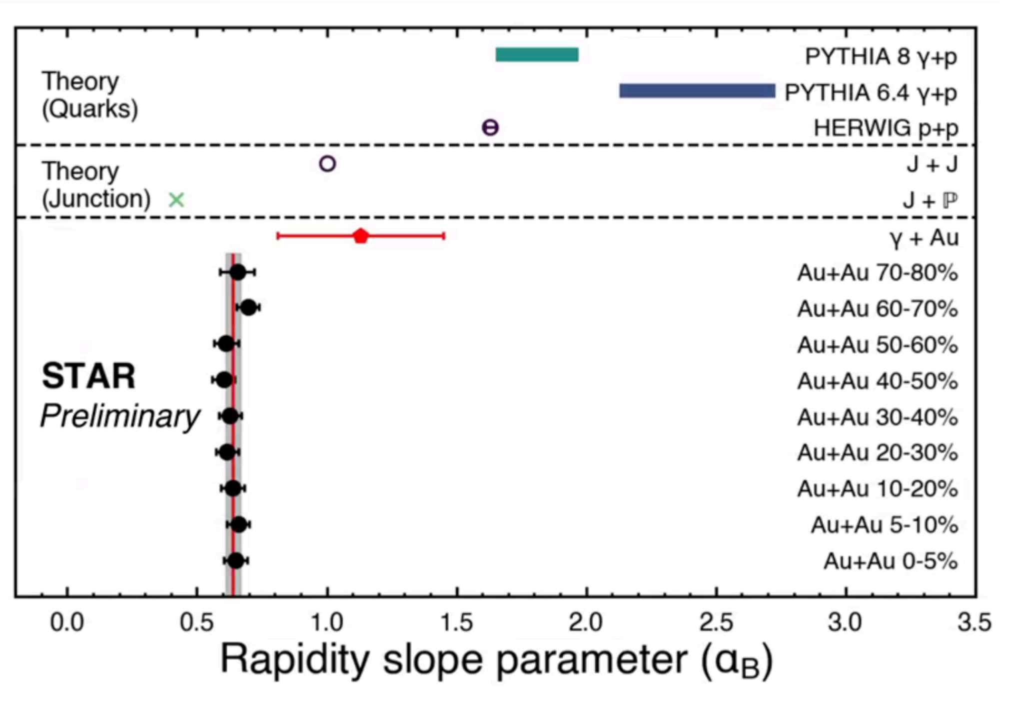
Compared Au+Au slope: 0.63 ± 0.02 (2<Y_{beam}<5.5)

Compared to PYTHIA, which does not include a baryon junction mechanism, predicts a slope of 2.5

Exponential slope of rapidity dependence of net-proton lower than PYTHIA predictions

Rapidity slope of net-proton: Global data

X. Artru, M. Mekhfi, Nucl. Phys. A 532 (1991) 351
BRAHMS+NA49: Videbaek, 1st workshop on baryon dynamics, SBU 2024



Au+Au slope same for all centrality

Slope γ+Au >~ Slope Au+Au:

Closer to the fit to BRAHMS + NA49 data slope to ~1 for $Y_{beam} < 2$ (NA49 energy ~17 GeV closer to γ+Au cm energy ~ 10 GeV)

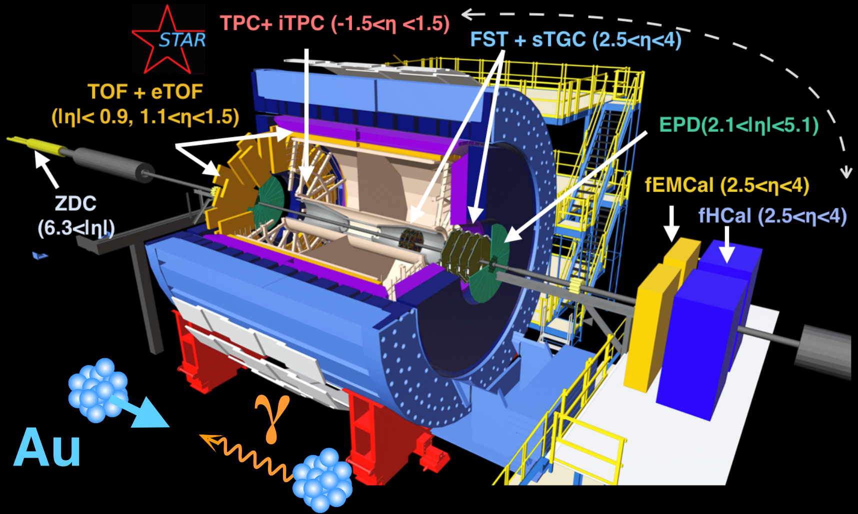
Slope has Y_{beam} (energy) dependence
$\alpha_B = \alpha_B(|y-Y_{beam}|)$

Consistent with Regge theory baryon-junction prediction but smaller than PYTHIA/HERWIG

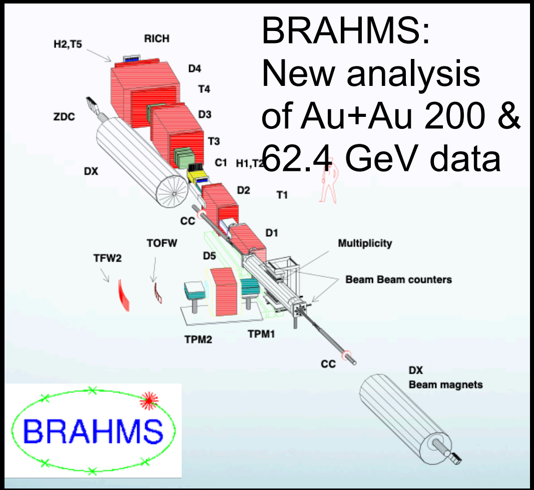
Rapidity dependence of net-proton in γ+Au collisions compatible with junction picture

Future experiments on baryon carrier search

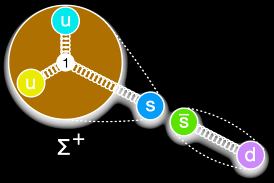
Huber, Klein, Videbaek, Magdy, 1st workshop on baryon dynamics, SBU 2024



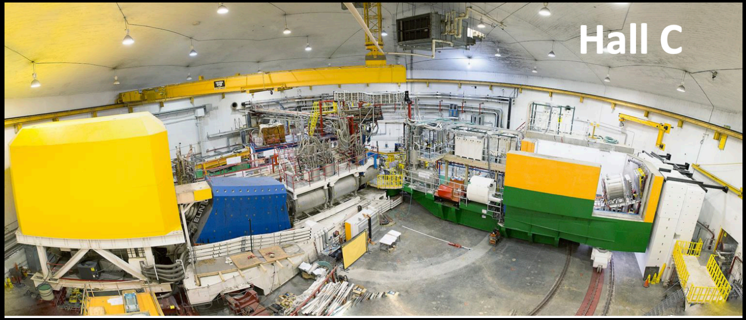
STAR: RHIC Run 23-25
high statistics γ+Au collisions using Au+Au 200 GeV UPC, p/d/He3+Au, strange baryon production

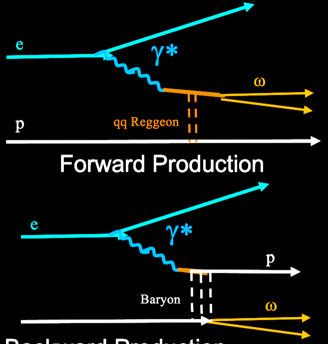


BRAHMS: New analysis of Au+Au 200 & 62.4 GeV data

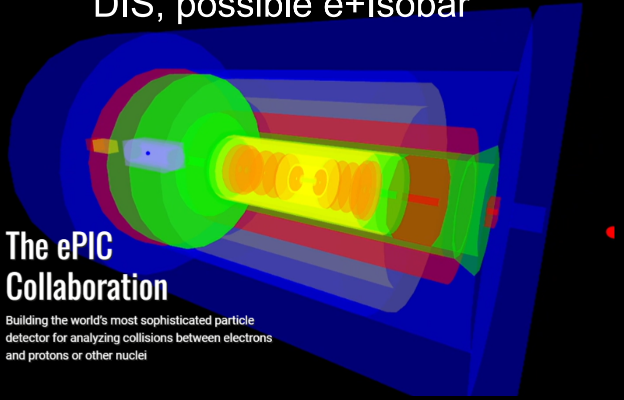


JLab e+p, u-channel backward production

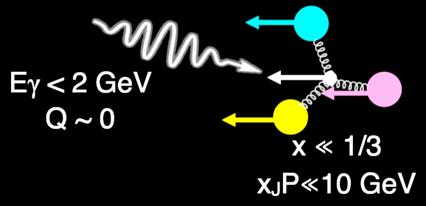




HERA & EIC: Baryon spectra in DIS, possible e+Isobar



Summary



- Baryon number carrier and transport are of fundamental interest: Photon-induced processes are clean probes

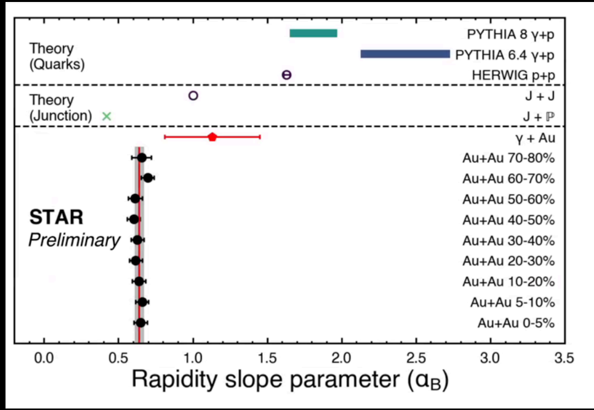
- STAR and low-p_T PID capability & RHIC Au+Au 54.4 GeV UPC: inclusive γ+Au with low photons (E_γ < 2 GeV low stopping power)

- Significant net-proton in γ+Au at midrapidity: exponential rapidity slope compatible with prediction of Regge theory on baryon junction

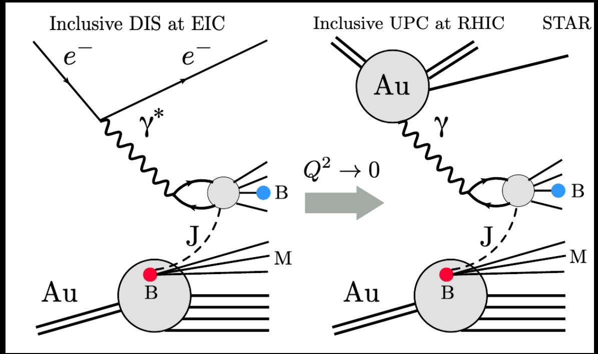
- Au+Au global data: rapidity slope show no centrality dependence, flavor blind, lower than γ+Au for RHIC energy, compatible at NA49 energy

- Isobar data: less electric-charge transport than baryon transport

- Quark-based models fail to explain data



Multiple observations indicate baryon transport in high-energy collisions not compatible with valence quark as carriers of baryon number



Outlook: Future RHIC, EIC, other experiments can further probe baryon carrier and transport mechanisms with controlled photon kinematics

Recent dedicated workshop on baryon dynamics

https://indico.cfnssbu.physics.sunysb.edu/event/113/

Thanks

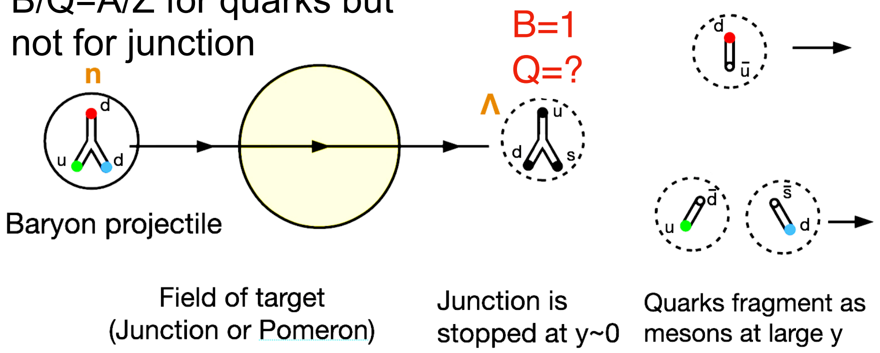
There are two more slides
(please take a look)

Homework slides (based on Q&A at the meeting)

Following slides are not part of the talk in behalf of the STAR collaboration but stimulated by discussions at the WWND workshop during Q&A and discussion session

Shouldn't B/Q=A/Z always once a baryon is formed: question from Abhijit

B/Q=A/Z for quarks but not for junction



The junction is flavor-blind, so when it is stopped, it will acquire any three quarks from vacuum

If a junction (flavor-blind) is stopped, we can estimate how much electric charge will be stopped depends on no. of flavors

No of flavors	Quarks	Combinations $\binom{n+r-1}{r}$	$\langle Q \rangle$	$\langle B \rangle$
2	u d	4	1/2	1
3	u d s	10	0	1
4	u d s c	20	1/2	1
5	u d s c b	35	1/5	1
6	u d s c b t	56	1/2	1

No of flavors: 2
(u)(2/3) + (u)(2/3) + (u)(2/3) = 2
(u)(2/3) + (u)(2/3) + (d)(-1/3) = 1
(u)(2/3) + (d)(-1/3) + (d)(-1/3) = 0
(d)(-1/3) + (d)(-1/3) + (d)(-1/3) = -1

No of flavors: 3
(u)(2/3) + (u)(2/3) + (u)(2/3) = 2
(u)(2/3) + (u)(2/3) + (d)(-1/3) = 1
(u)(2/3) + (u)(2/3) + (s)(-1/3) = 1
(u)(2/3) + (d)(-1/3) + (d)(-1/3) = 0
(u)(2/3) + (d)(-1/3) + (s)(-1/3) = 0
(u)(2/3) + (s)(-1/3) + (s)(-1/3) = 0
(d)(-1/3) + (d)(-1/3) + (d)(-1/3) = -1
(d)(-1/3) + (d)(-1/3) + (s)(-1/3) = -1
(d)(-1/3) + (s)(-1/3) + (s)(-1/3) = -1
(s)(-1/3) + (s)(-1/3) + (s)(-1/3) = -1

B/Q >= 2
(Independent of A/Z)

No of flavors: 4
(u)(2/3) + (u)(2/3) + (u)(2/3) = 2
(u)(2/3) + (u)(2/3) + (d)(-1/3) = 1
(u)(2/3) + (u)(2/3) + (s)(-1/3) = 1
(u)(2/3) + (u)(2/3) + (c)(2/3) = 2
(u)(2/3) + (d)(-1/3) + (d)(-1/3) = 0
(u)(2/3) + (d)(-1/3) + (s)(-1/3) = 0
(u)(2/3) + (d)(-1/3) + (c)(2/3) = 1
(u)(2/3) + (s)(-1/3) + (s)(-1/3) = 0
(u)(2/3) + (s)(-1/3) + (c)(2/3) = 1
(u)(2/3) + (c)(2/3) + (c)(2/3) = 2
(d)(-1/3) + (d)(-1/3) + (d)(-1/3) = -1
(d)(-1/3) + (d)(-1/3) + (s)(-1/3) = -1
(d)(-1/3) + (d)(-1/3) + (c)(2/3) = 0
(d)(-1/3) + (s)(-1/3) + (s)(-1/3) = -1
(d)(-1/3) + (s)(-1/3) + (c)(2/3) = 0
(d)(-1/3) + (c)(2/3) + (c)(2/3) = 1
(s)(-1/3) + (s)(-1/3) + (s)(-1/3) = -1
(s)(-1/3) + (s)(-1/3) + (c)(2/3) = 0
(s)(-1/3) + (c)(2/3) + (c)(2/3) = 1
(c)(2/3) + (c)(2/3) + (c)(2/3) = 2

Does perturbative picture of valence quark stopping explain data

https://indico.cfnssbu.physics.sunysb.edu/event/113/contributions/730/attachments/142/204/CFNS_Baryon_Dynamics_2024.pdf

K. Itakura, YK, L. McLerran, D. Teaney, 2003 calculated the valence quark stopping in small-x limit, Qs is perturbatively large

Perturbative QCD at small *x*:

$$q_{\rm val}(x, Q^2) \sim \left(\frac{1}{x}\right)^{\sqrt{\frac{2\alpha_s C_F}{\pi}}} \sim \left(\frac{1}{x}\right)^{\sqrt{\frac{\alpha_s N_c}{\pi}}}$$