Tracing the Baryon Number Carrier and Its Transport from STAR

Prithwish Tribedy for the STAR collaboration

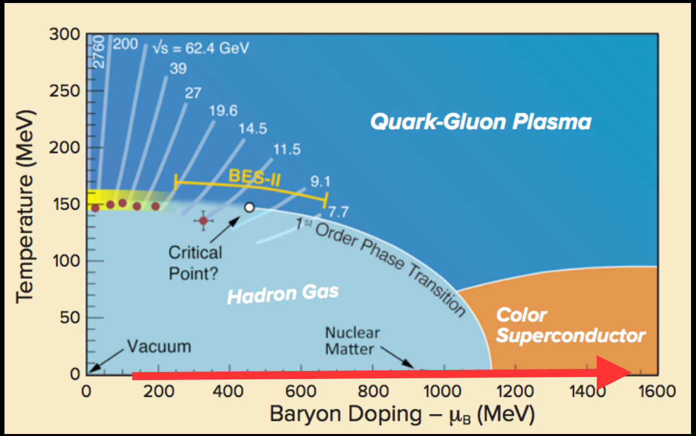
(Brookhaven National Laboratory)

Brookhaven National Laboratory

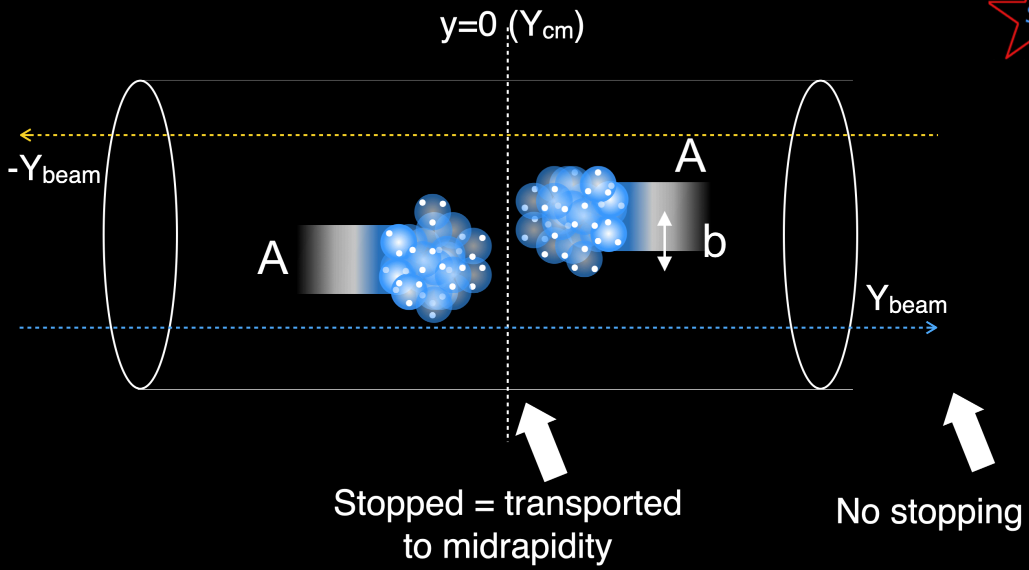
In part supported by U.S. DEPARTMENT OF ENERGY

15th Workshop on Critical Point and Onset of Deconfinement, May 20-24, 2024, LBL, CA

Outline



Doping the medium created by heavy-ion collisions with baryons: key to mapping QCD phase diagram



Transport: A baryon appear at $y<Y_{beam}$
No transport: baryon ends up at $y=Y_{beam}$

However, what is the microscopic picture behind transporting a baryon to midrapidity ?

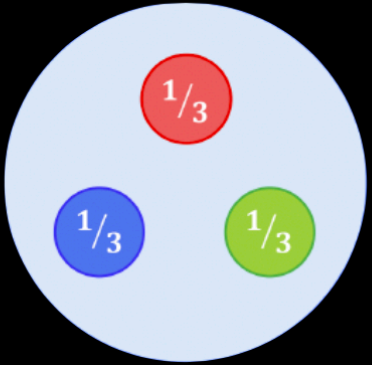
STAR collaboration performs three measurements to identify the baryon number carrier and its mechanism of transport

What carries the baryon number?

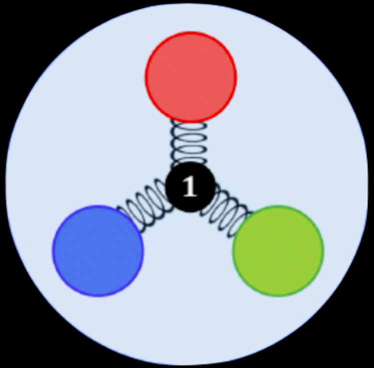
https://en.wikipedia.org/wiki/Proton
https://en.wikipedia.org/wiki/Baryon

In particle physics, the **baryon number** is a strictly conserved additive quantum number of a system.

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



1975-

In conventional picture, baryon number is 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

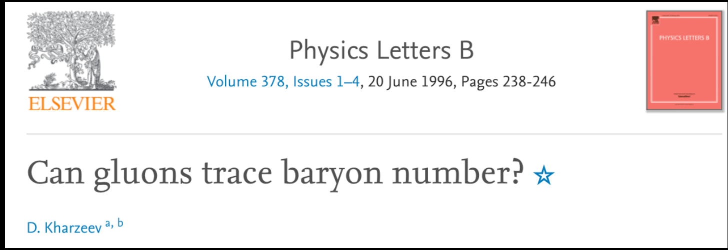
Baryon number may flow with the flow of the Y-shaped string junction (QCD topology)

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

Gluonic junction as a carrier of baryon number

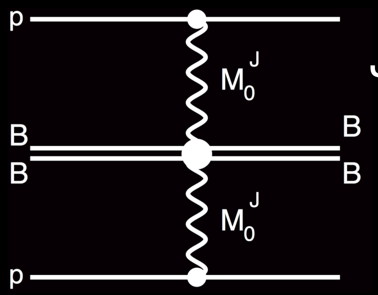
Kharzeev, Phys. Lett. B, 378 (1996) 238-246, Lewis et. al, arXiv:2205.05685


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

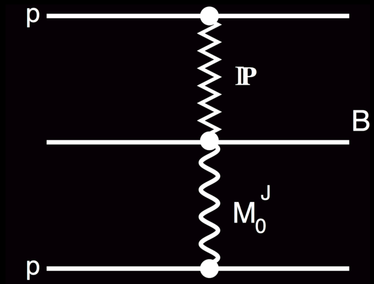
Can gluons trace baryon number? ☆

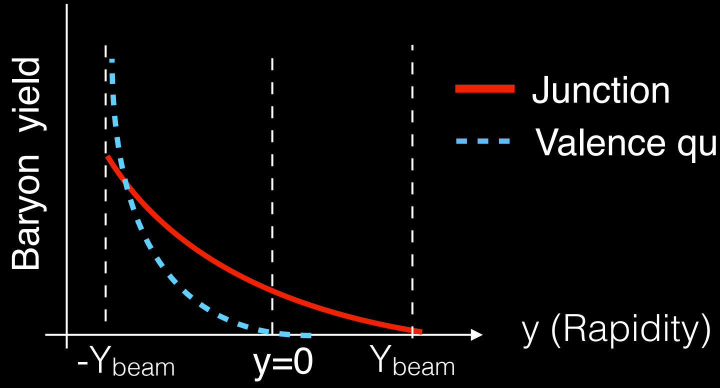
D. Kharzeev [a, b]

Junction-Junction



Junction-Pomeron





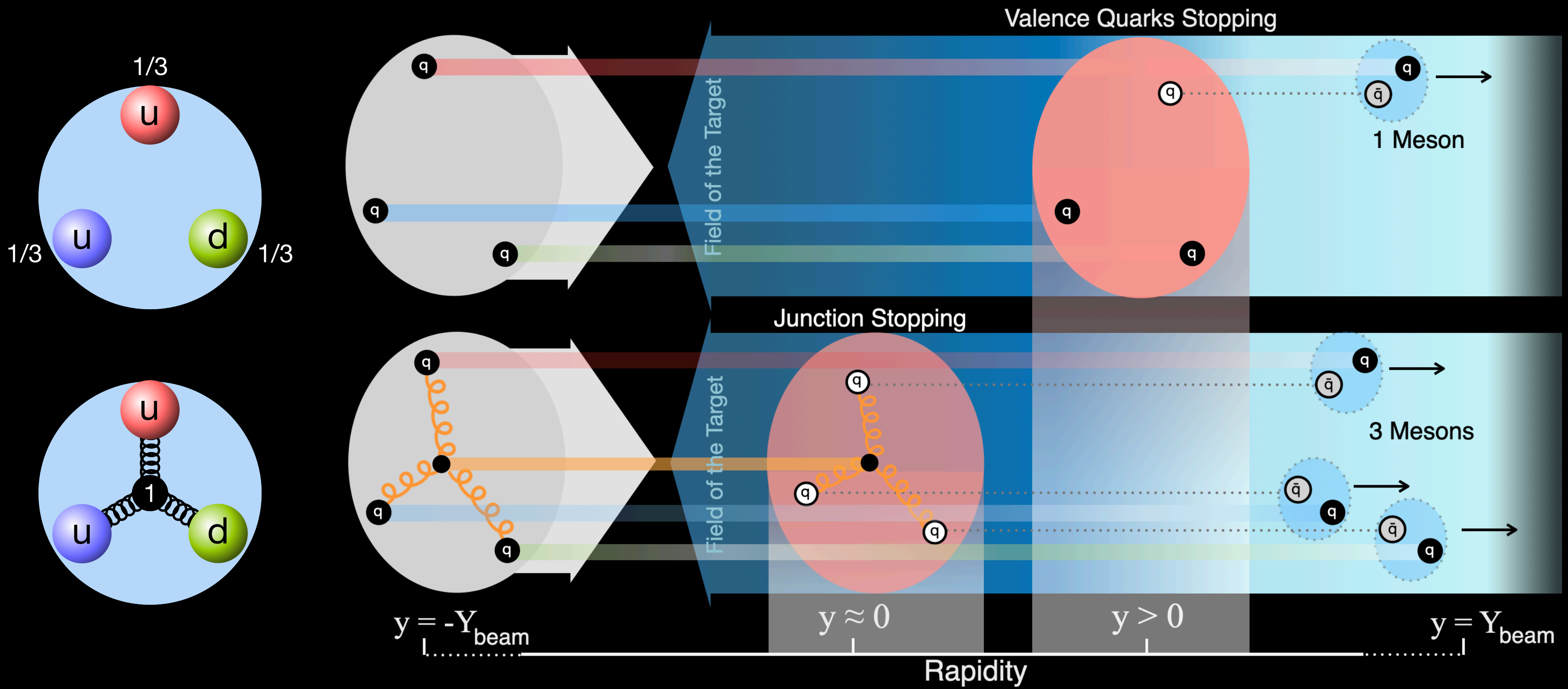
Baryon junction: $e^{-\alpha_B(y-Y_{\text{beam}})}$ $0.42 \leq \alpha_B \leq 1$

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

Regge theory can predict rapidity dependence of baryon stopping for junctions

Larger transport to mid-rapidity for gluonic junction than valence quarks as baryon carrier

How a baryon is transported at midrapidity?

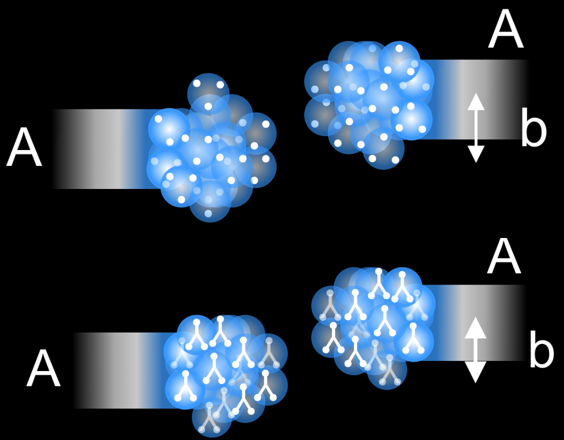


Valence quarks: difficult to stop near y~0 & associated with electric charge stopping

Baryon junction: easier to stop near y~0 & NOT associated electric charge stopping

Strategies for tracing the baryon carrier

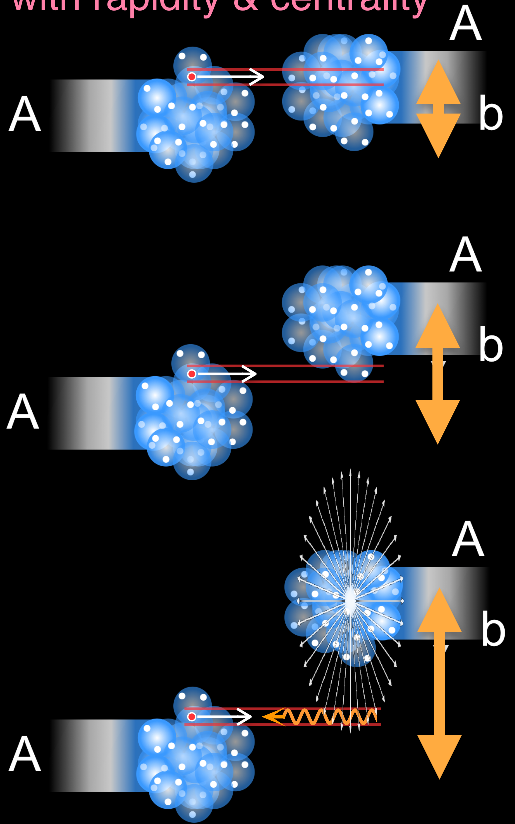
Check if charge and baryon are carried by the same object



Compare electric-charge with baryon transport

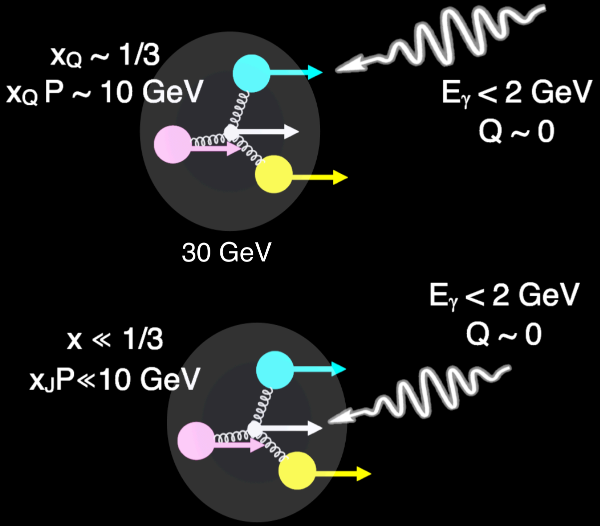
Q <-> Z/A x B

Test expectations for valence quark transport with rapidity & centrality



Centrality dependence of dN/dy(B) vs. $y\text{-}Y_{beam}$

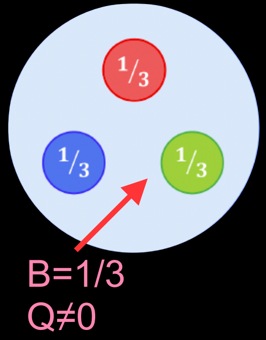
Test if the baryon carrier is a gluonic object by colliding with a photon of very small stopping power



Rapidity dependence of dN/dy(B) in γ+A collisions

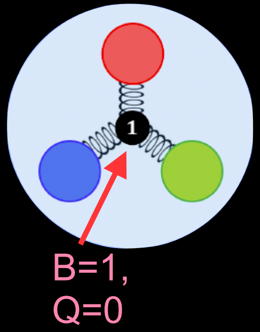
Strategy one: Baryon vs. electric charge transport

Electric charge vs. baryon transport



Valence quarks carry electric charge & baryon

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



Valence quarks carry electric charge & junction carry baryon

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

Baryon transport at mid-rapidity:

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

Not difficult except for “n” measurement

Charge transport at mid-rapidity:

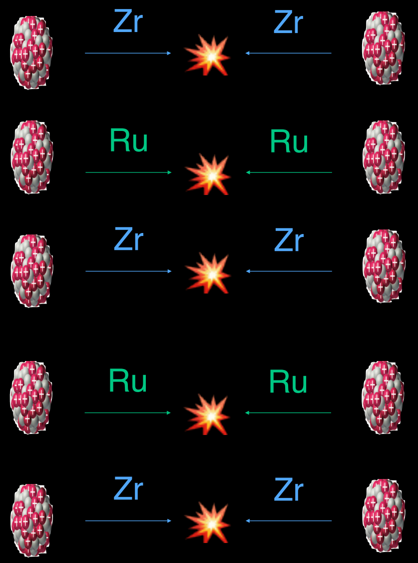
$$Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})$$

Precision measurement is difficult : isospin conservation, efficiency effects

ΔQ and B transport should correlated for valence quark picture not for junctions

Precision measurements in isobar collisions

STAR



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

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

Overcome precision problem: 1) compare two isobars, 2) express difference as ratios:

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

Q transport difference between isobars:

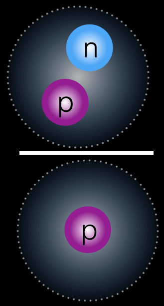
$$\Delta Q = N_\pi \left[(R2_\pi - 1) + \frac{N_K}{N_\pi}(R2_K - 1) + \frac{N_p}{N_\pi}(R2_p - 1) \right]$$

Neutron using deuteron, proton

B transport, same in two isobars:

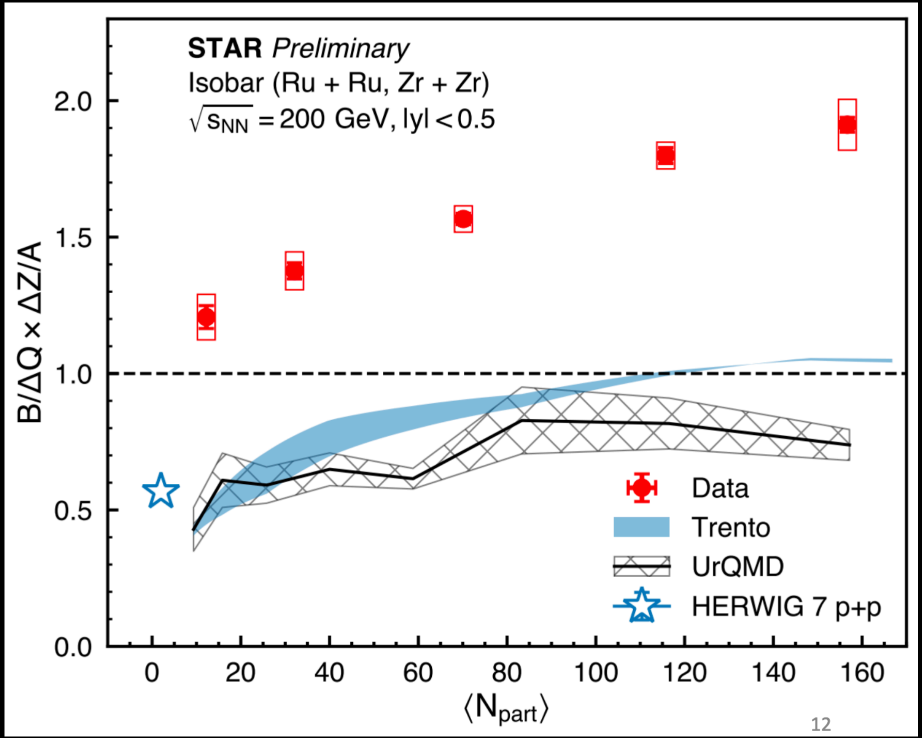
$$B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$$

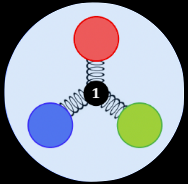
$$\frac{N_{\bar{n}}}{N_n} = \frac{N_p}{N_{\bar{p}}} \frac{N_{\bar{d}}}{N_d}$$



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

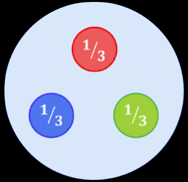
Precision measurements in isobar collisions





First measurements of electric charge stopping using isobar collisions

Data: More baryon transported to central rapidity than electric charge



Non-junction Models (Trento, UrQMD, HERWIG): equal or less baryon compared to electric charge

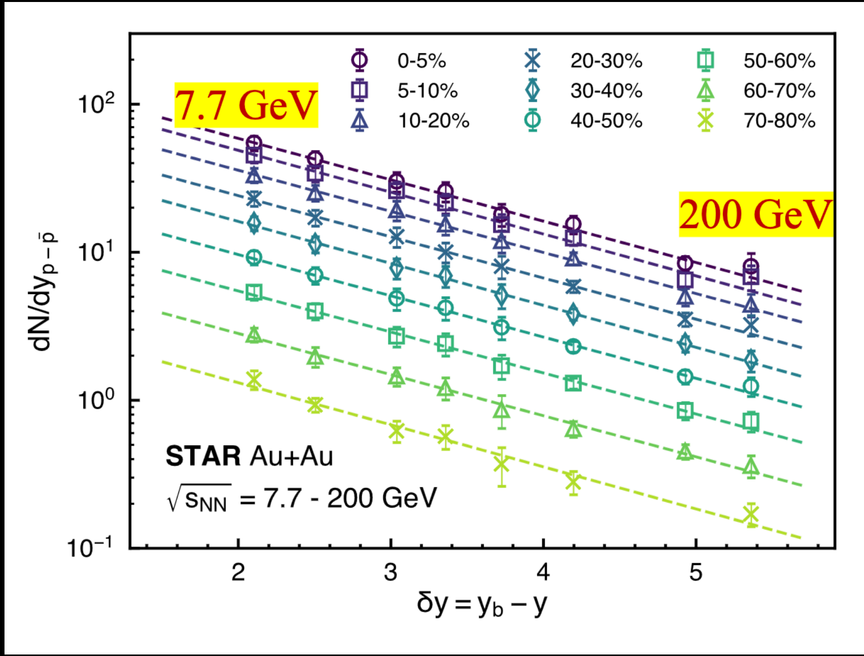
Not compatible with same carrier of electric charge and baryon

Strategy two: Rapidity slope of transport (with centrality)

Rapidity distribution of baryon production: Global data

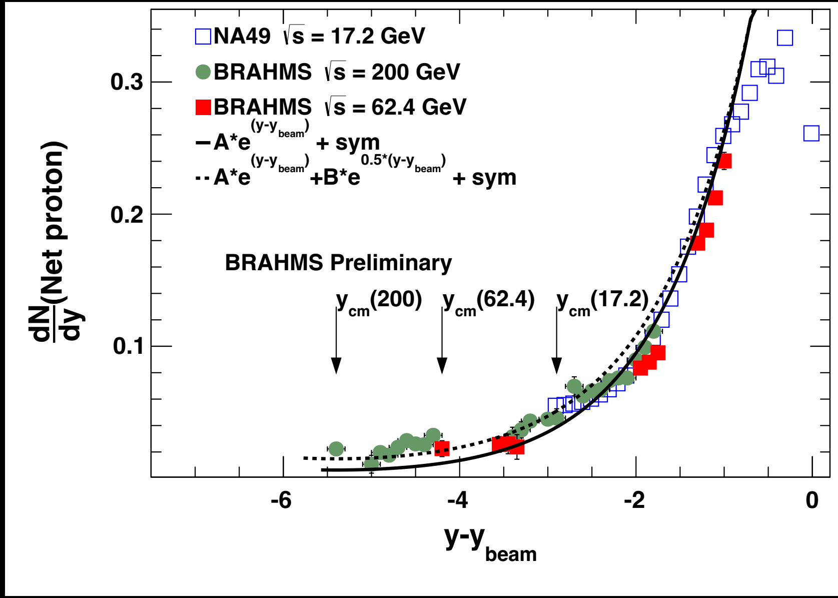
STAR data: N. Lewis, et. al., arXiv:2205.05685, BRAHMS+NA49: F. Videbaek, 1st workshop on baryon dynamics, SBU, 2024

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



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

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

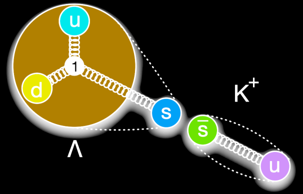


At higher energy rapidity slope closer to~0.5 lower energy ($|y-Y_{beam}|<2$) rapidity slope ~1

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

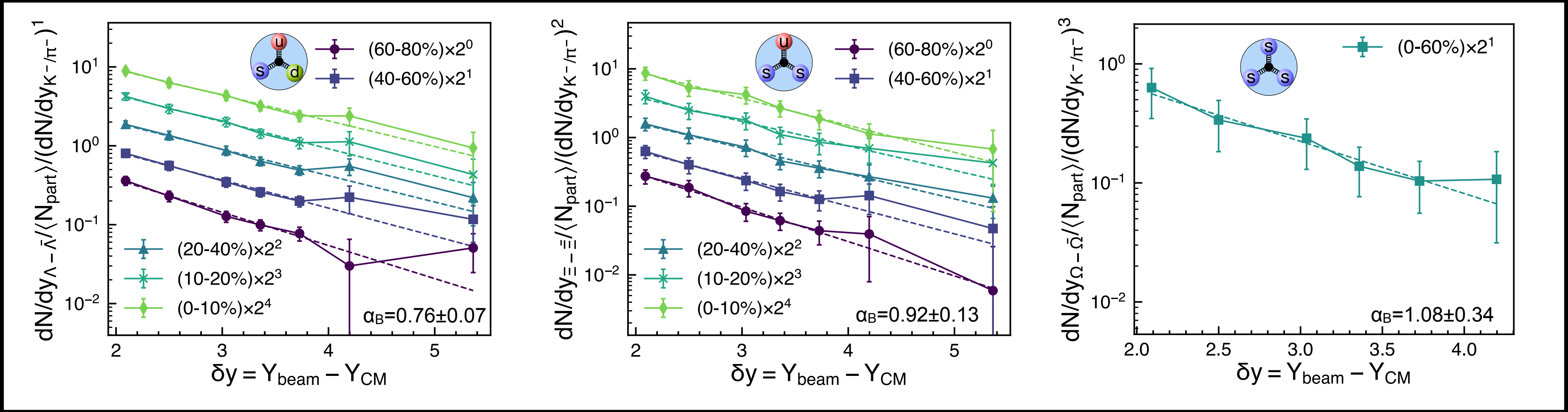
Rapidity distribution of strange baryons

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) seem similar to net-proton

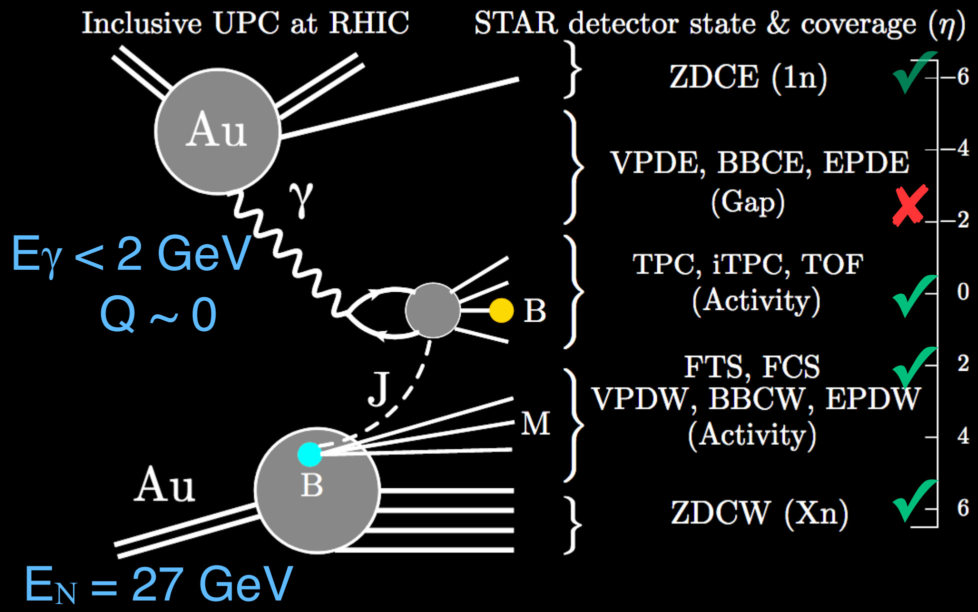
Rapidity slope of baryon density has no strong flavor dependence

Strategy three: Baryon transport in photon-induced process

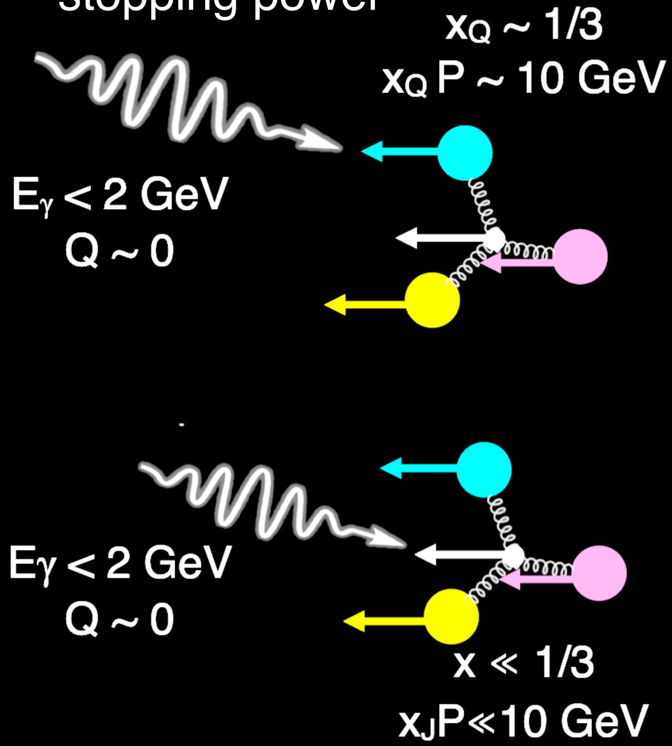
Probing baryon structure with photon-induced processes

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



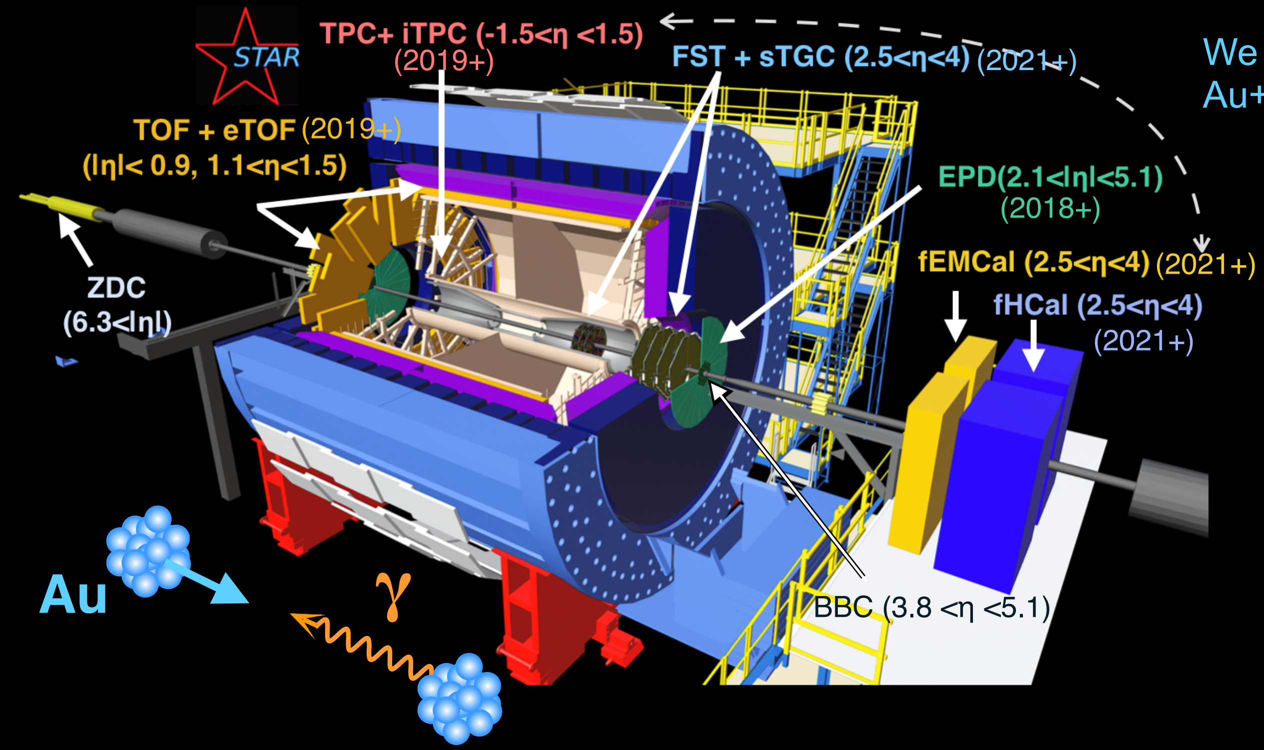
UPC photons have very low stopping power



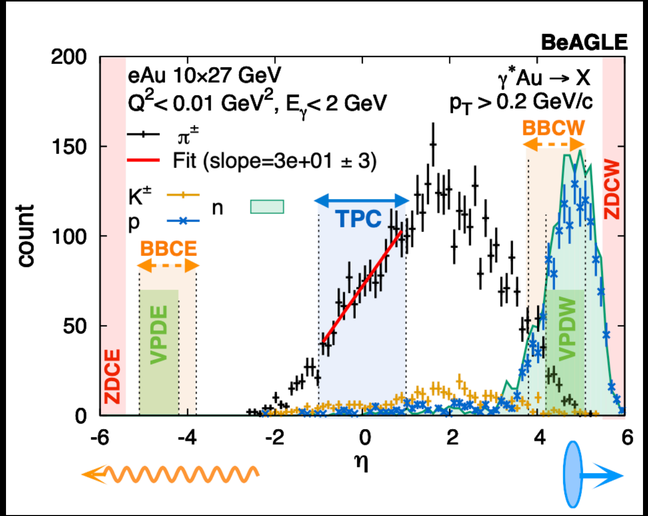
Search for non-zero net-baryon in photon-ion collisions near central-rapidity

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)

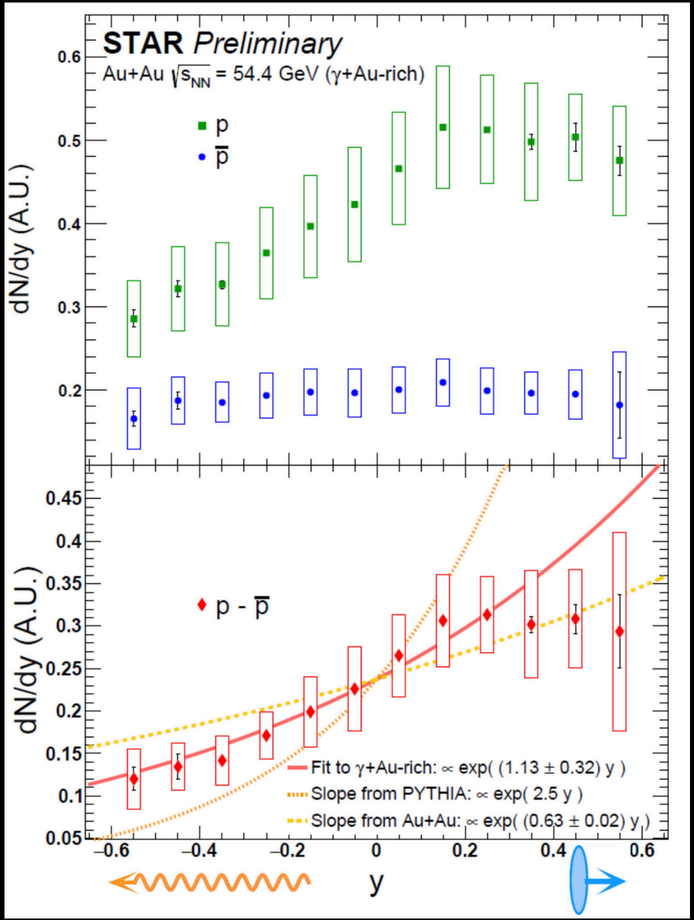
Time Projection Chamber (TPC)

- Track reconstruction
- Identify particles using dE/dx

Time-Of-Flight detector (TOF)

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

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

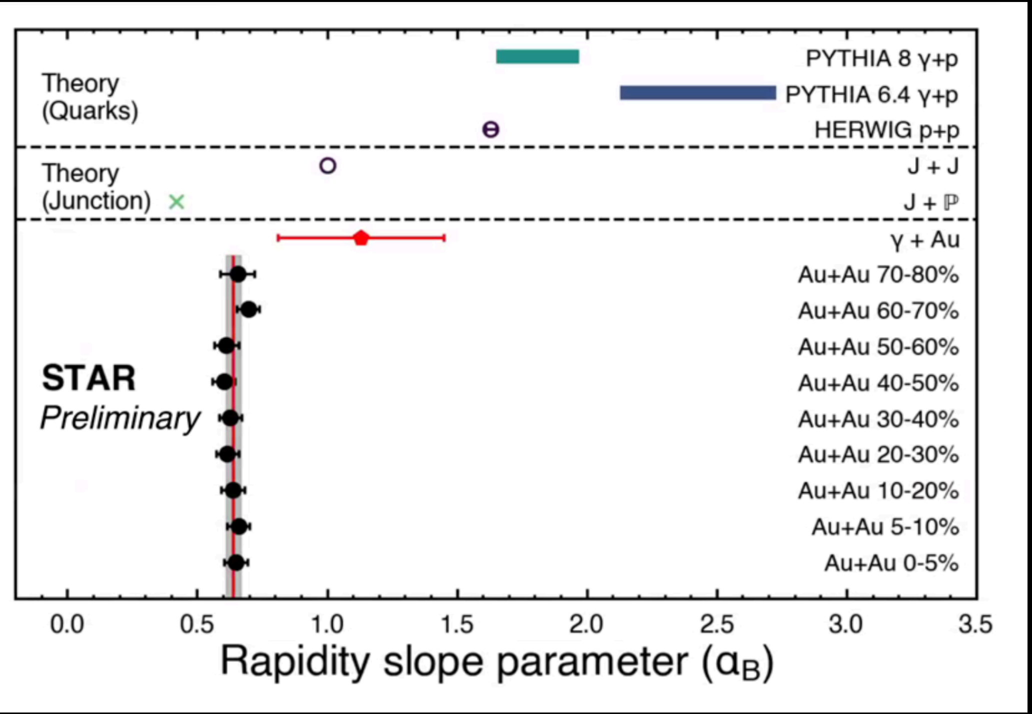
Compared Au+Au slope: 0.63 ± 0.02 ($2<Y_{beam}<5.5$)

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:

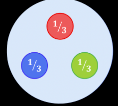
Closer to the fit to BRAHMS + NA49 data slope to ~1 for $Y_{beam} < 2$ (NA49 energy ~17 GeV closer to γ+Au cm energy ~ 10 GeV)

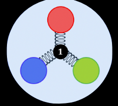
Slope has Y_{beam} (energy) dependence
$\alpha_B = \alpha_B(|y-Y_{beam}|)$

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

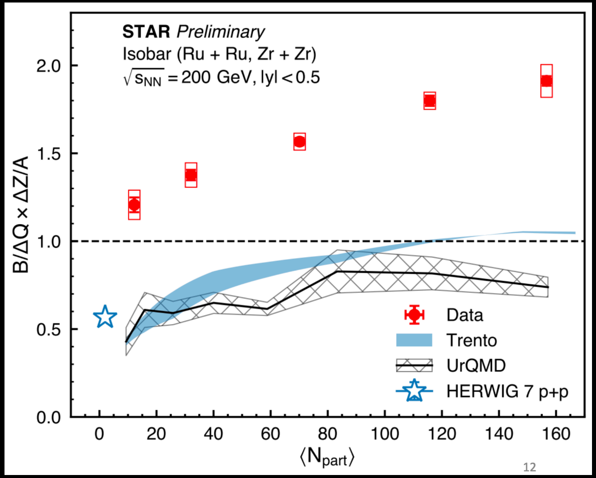
Summary

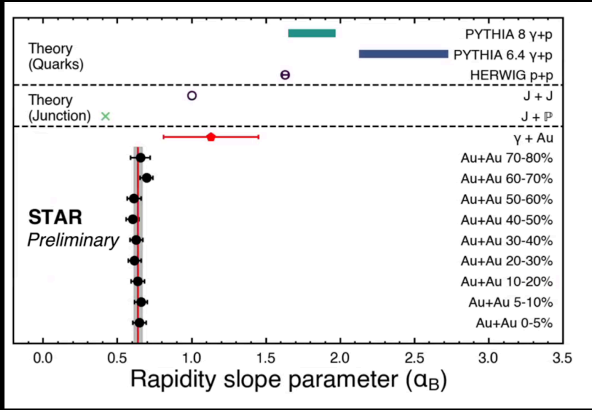




- Baryon number carrier and transport are of fundamental interest:
- STAR@RHIC advantage: BES & Isobar program, low-p_T PID capability, triggering capability for inclusive γ+Au events with low photons energy
- Three approaches to test the carrier of baryon number & transport:
  - Isobar data: less electric-charge transport than baryon transport
  - Au+Au BES/global data: exponential rapidity dependence with slope showing no centrality dependence, flavor blind
  - Significant net-proton in γ+Au at midrapidity: exponential rapidity slope compatible with prediction of Regge theory on baryon junction
- Quark-based models fail to provide simultaneous description of all features of STAR data, seems to be viable in baryon junction picture

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





Recent dedicated workshop on baryon dynamics

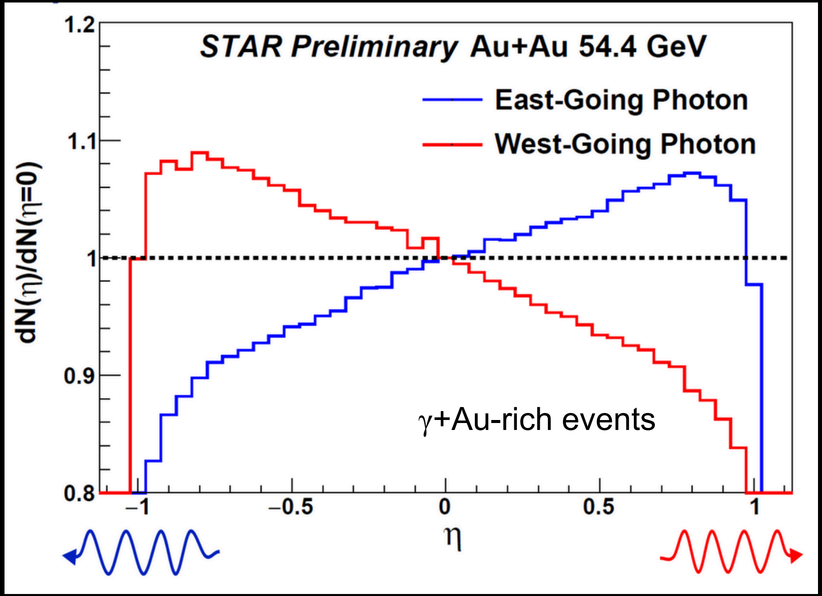
https://indico.cfnssbu.physics.sunysb.edu/event/113/

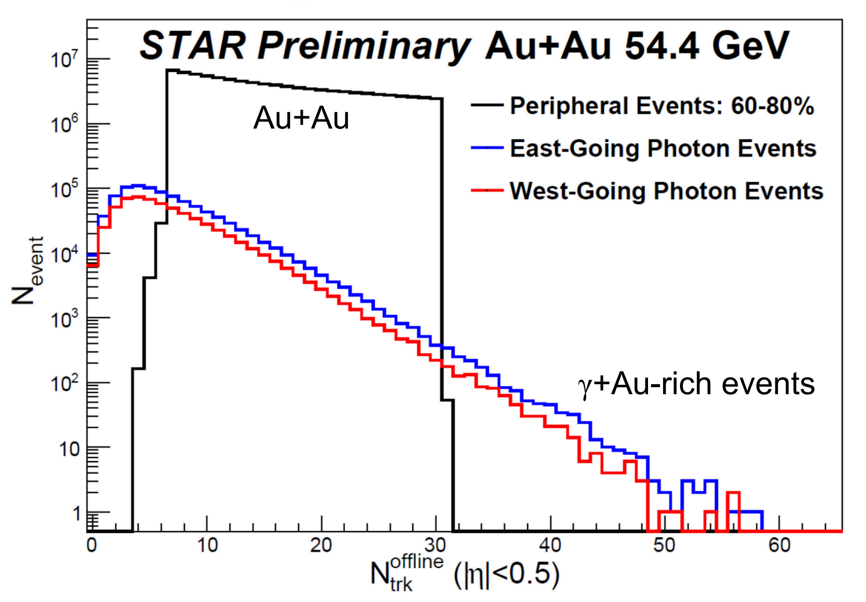
Thanks

Backup slides

Results: characteristic features of γ+Au events

Model calculations:
Lewis et. al, arXiv: 2205.05685





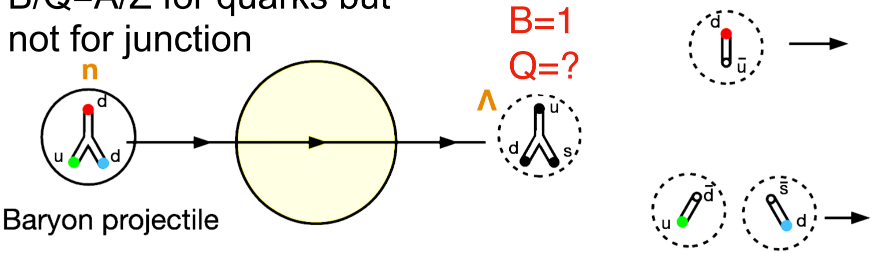
γ+Au events produce rapidity asymmetry that is expected from model predictions

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

B/Q=A/Z for valence quarks, what about junction ?

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



Field of target (Junction or Pomeron)

Junction is stopped at y~0

Quarks fragment as mesons at large y

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

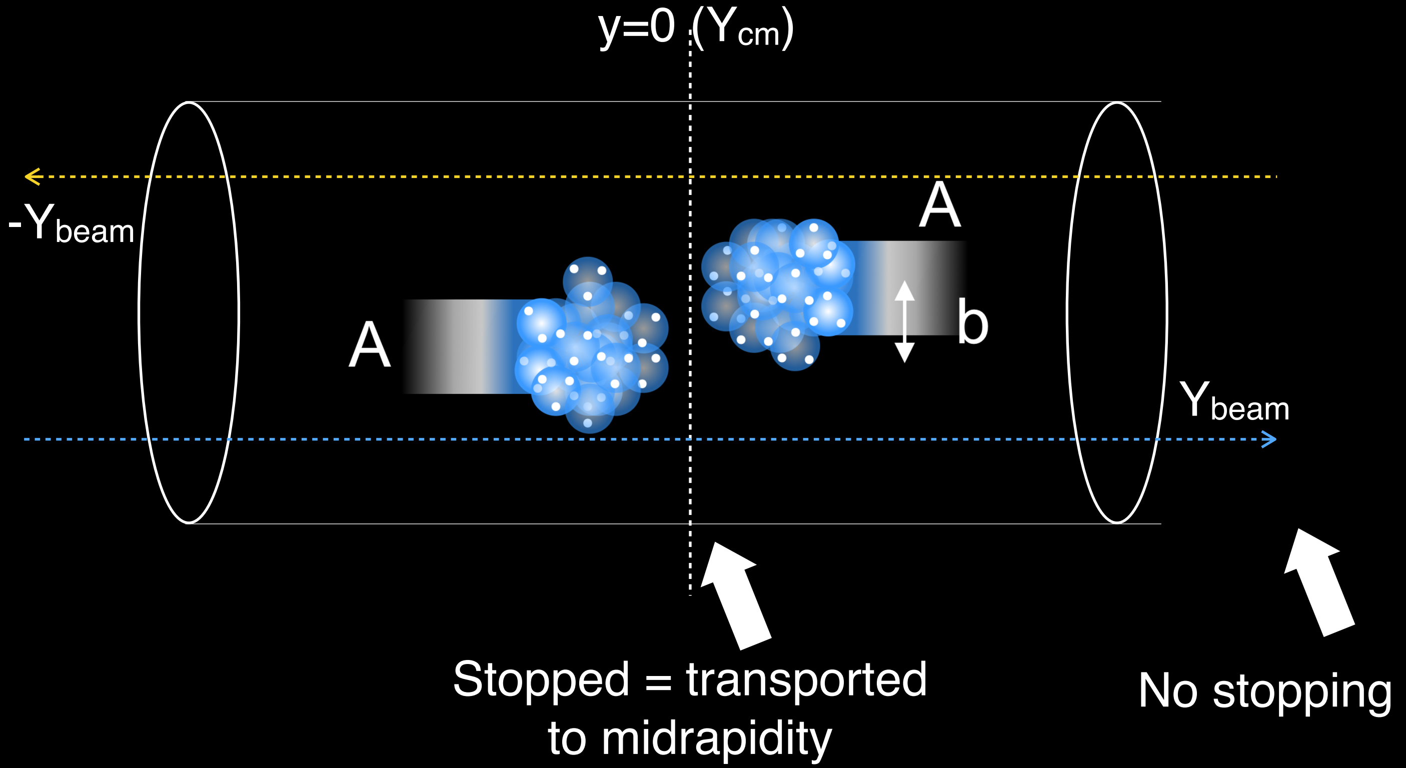
No of flavors: 3
(u)(2/3) + (u)(2/3) + (u)(2/3) = 2
(u)(2/3) + (u)(2/3) + (d)(-1/3) = 1
(u)(2/3) + (u)(2/3) + (s)(-1/3) = 1
(u)(2/3) + (d)(-1/3) + (d)(-1/3) = 0
(u)(2/3) + (d)(-1/3) + (s)(-1/3) = 0
(u)(2/3) + (s)(-1/3) + (s)(-1/3) = 0
(d)(-1/3) + (d)(-1/3) + (d)(-1/3) = -1
(d)(-1/3) + (d)(-1/3) + (s)(-1/3)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

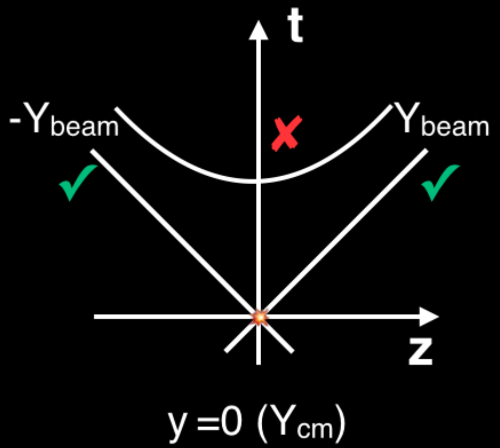
B/Q >= 2
(Independent of A/Z)

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

Puzzles with the Baryon number of quarks

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



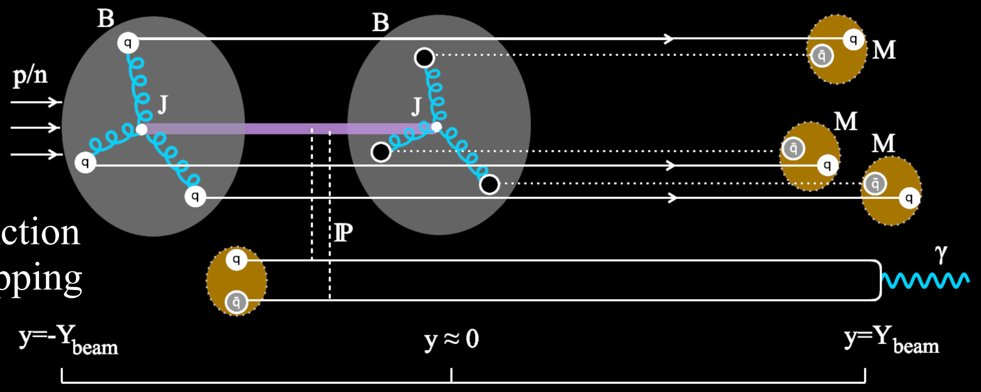


If baryon number flows with valence quarks, then they should end up near beam rapidity Y_{beam} and not near y=0 or Y_{cm}

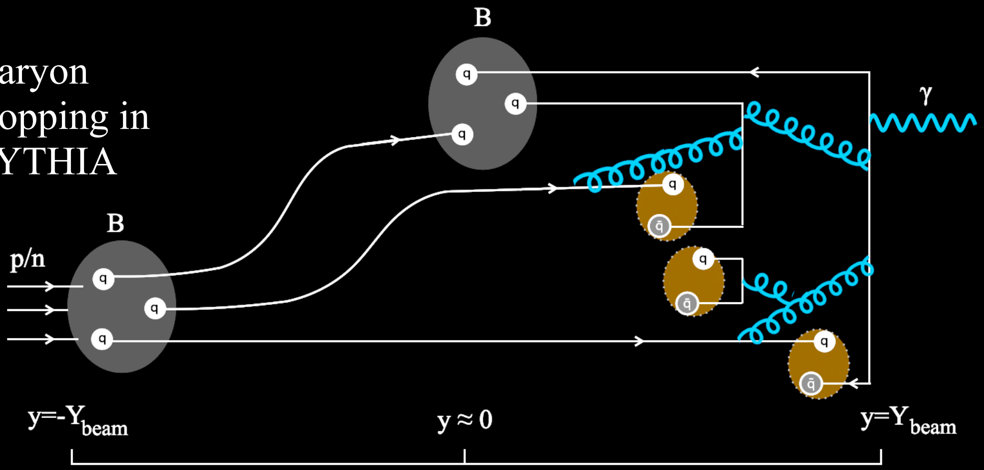
Probing baryon structure with photon-induced processes

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

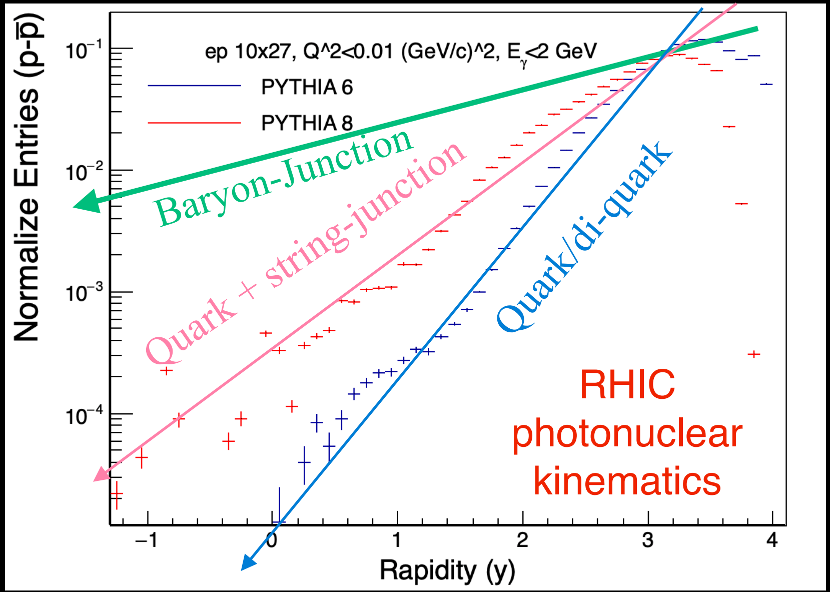
Junction stopping



Baryon stopping in PYTHIA

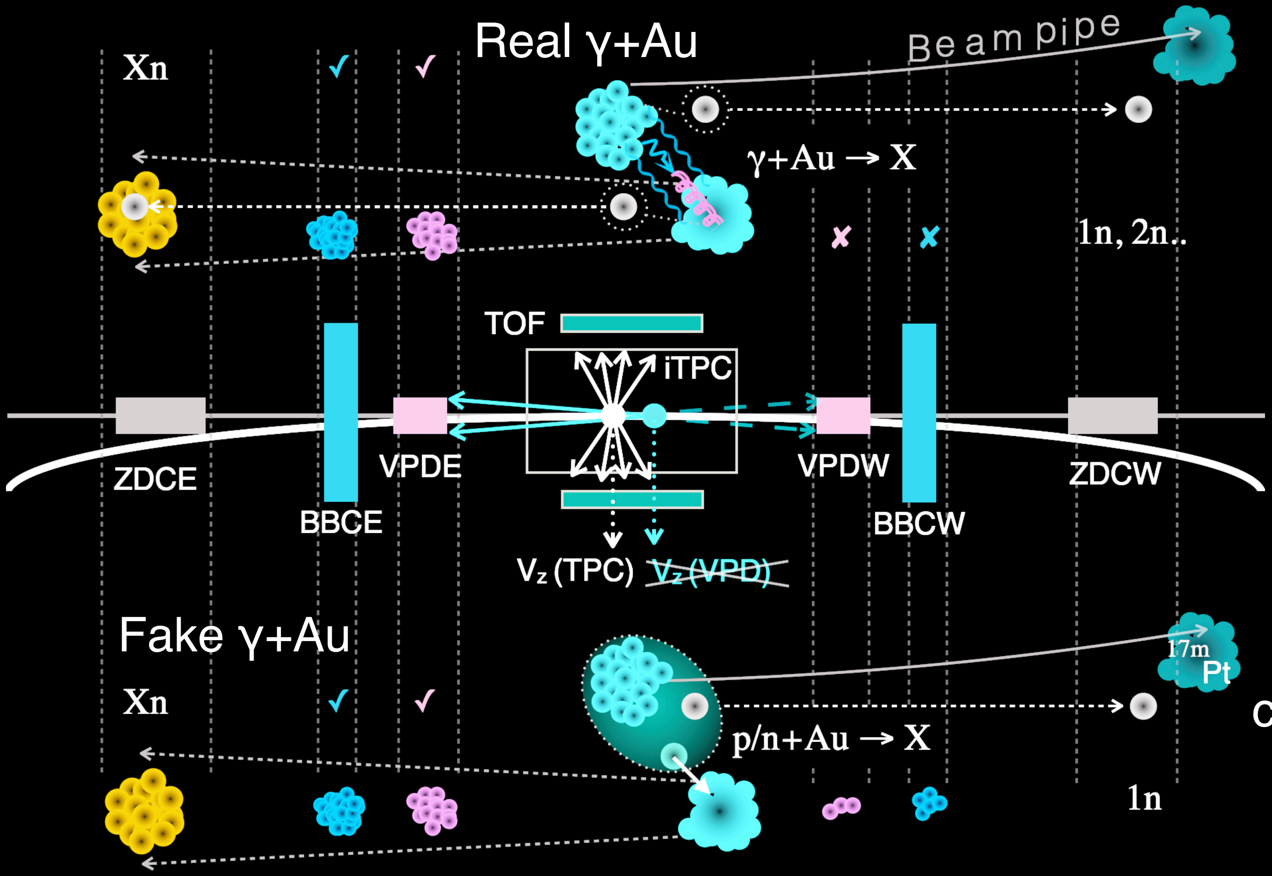


PYTHIA 6: Quark carries baryon
PYTHIA 8: Quark + mimic string-junction

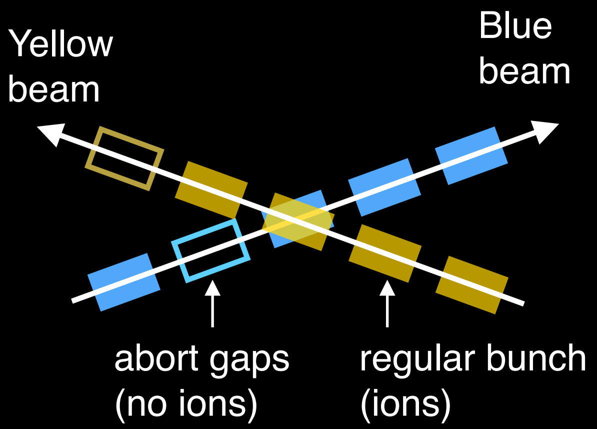


Models with various different carriers predict different rapidity dependence of net-proton yield

Triggering inclusive photon-induced processes by the STAR detector



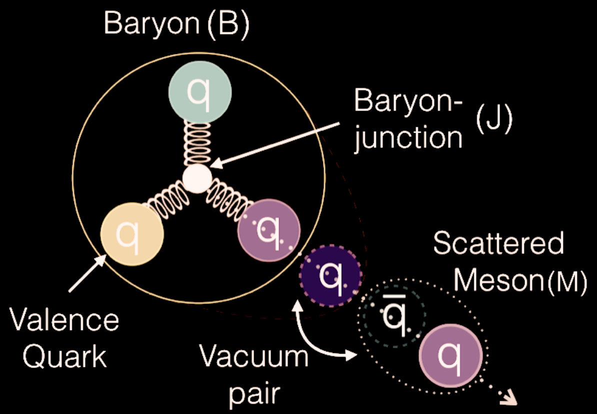
Background from beam-gas

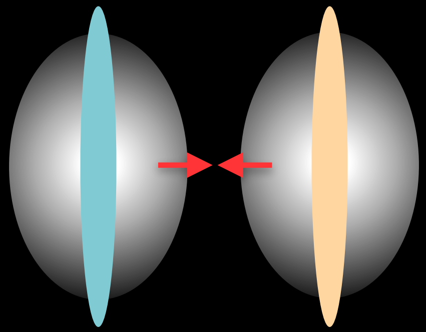


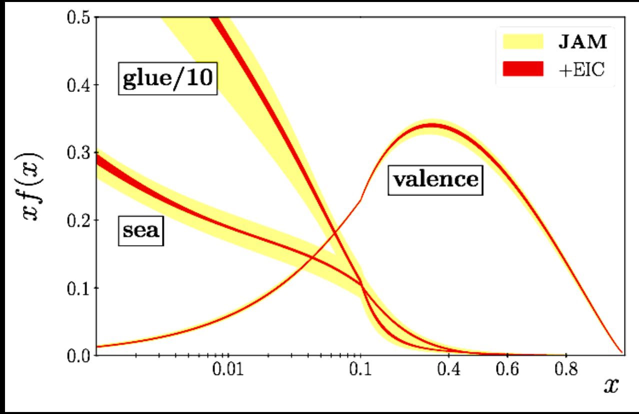
We estimate background contamination from peripheral heavy-ion collisions and beam-gas events

1nXn conditions on ZDCs largely suppress beam-gas background

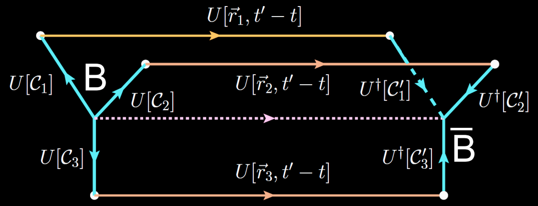
Arguments for a junction as a baryon number carrier







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



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

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

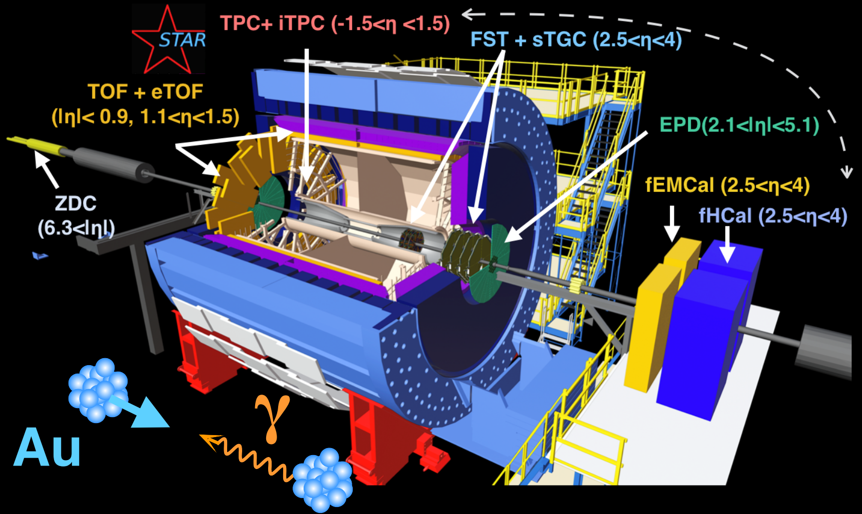
$$t_{\text{int}} \sim \mathcal{O}(1)\ \text{fm}$$

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

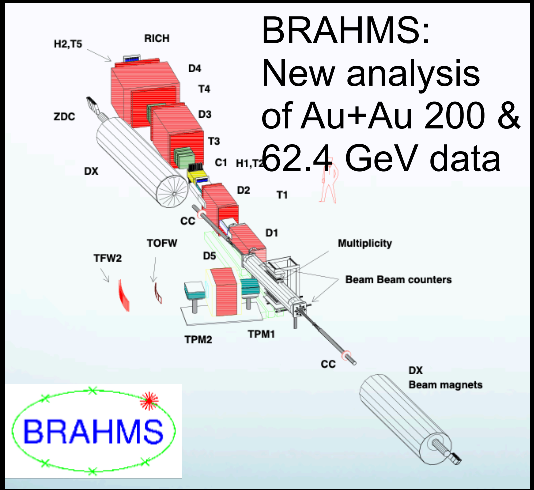
$$x_J \ll x_V \qquad ((x_J P)^{-1} \gg (x_V P)^{-1})$$

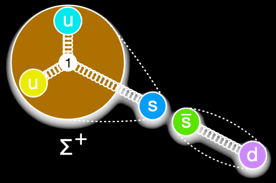
Future experiments on baryon carrier search

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

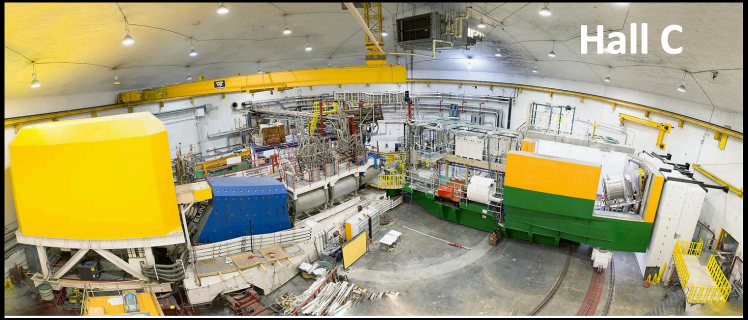


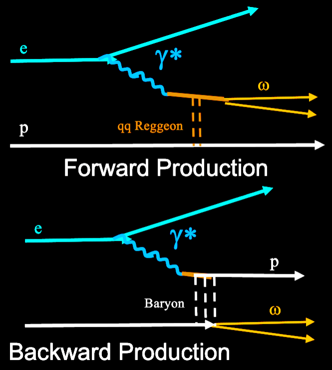
STAR: RHIC Run 23-25
high statistics γ+Au collisions using Au+Au 200 GeV UPC, p/d/He3+Au, strange baryon production





JLab e+p, u-channel backward production





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