SEARCH FOR BARYON JUNCTIONS IN PHOTONUCLEAR PROCESSES AND HEAVY-ION COLLISIONS AT STAR

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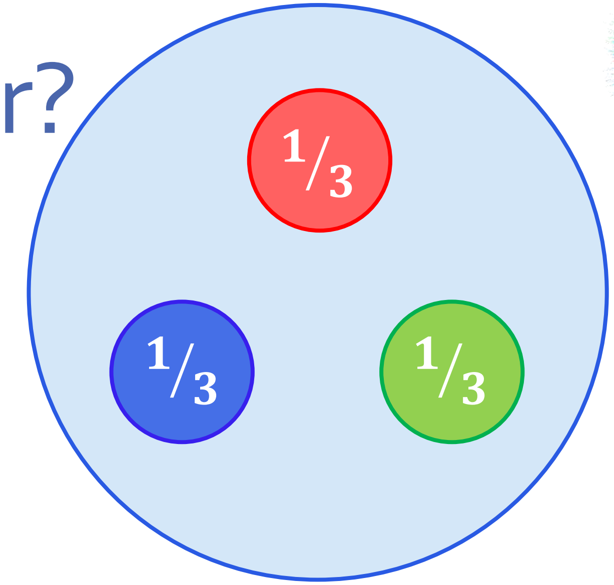
Deep Inelastic Scattering 2023

Supported in part by:

What Carries the Baryon Number?



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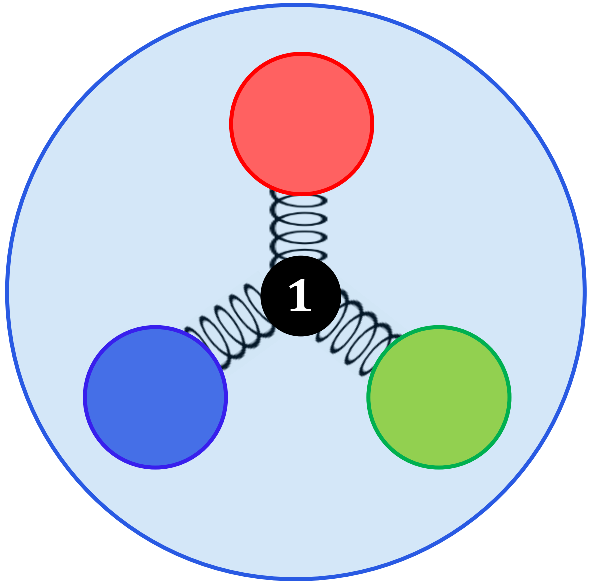


- **Baryon number –** a strictly conserved quantum number
- Generally assumed to be carried by the valence quarks:

$$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\ \right)$$

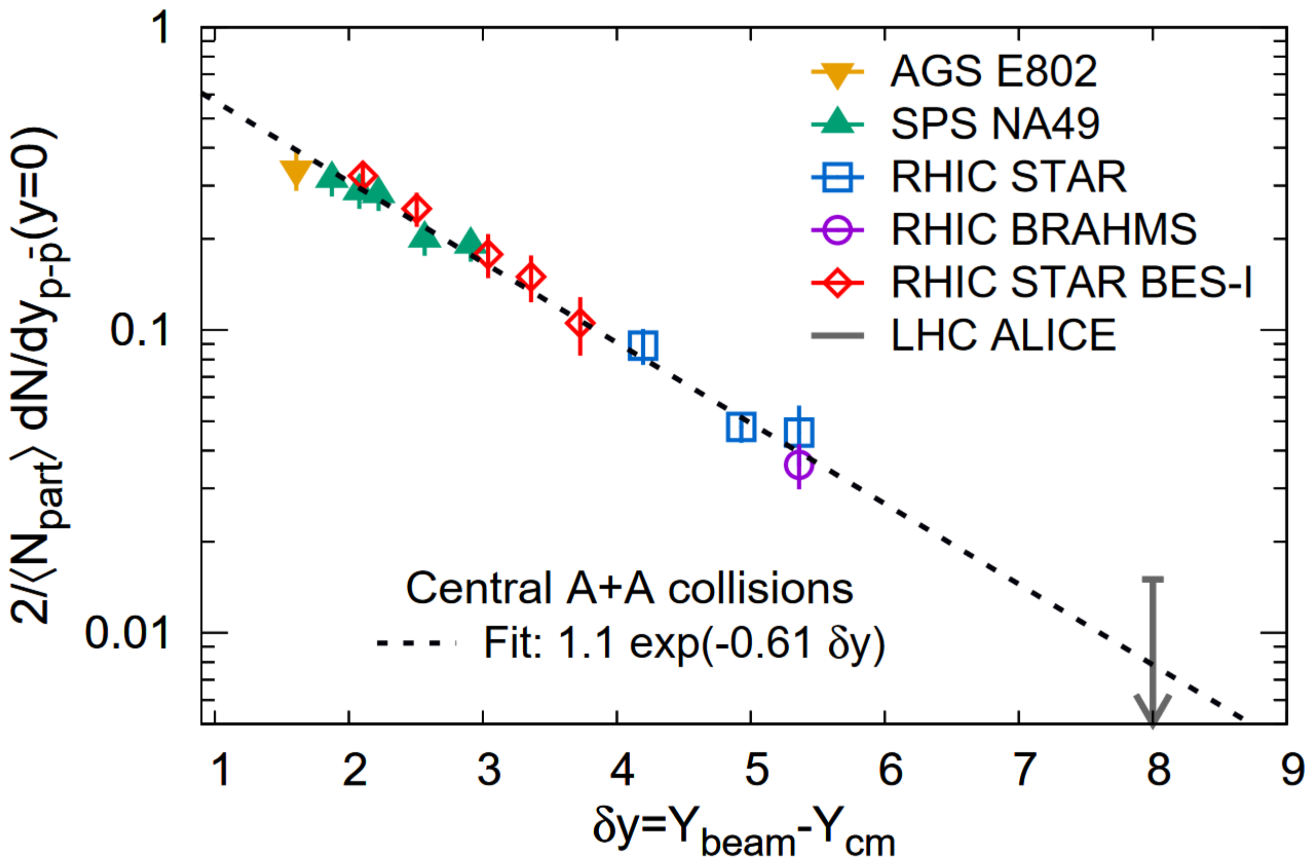
- Alternative model: the baryon junction
  - Nonperturbative configuration of low momentum gluons linked to all three valence quarks
  - Carries the baryon number

    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- Neither scenarios have been verified experimentally

Baryon Stopping

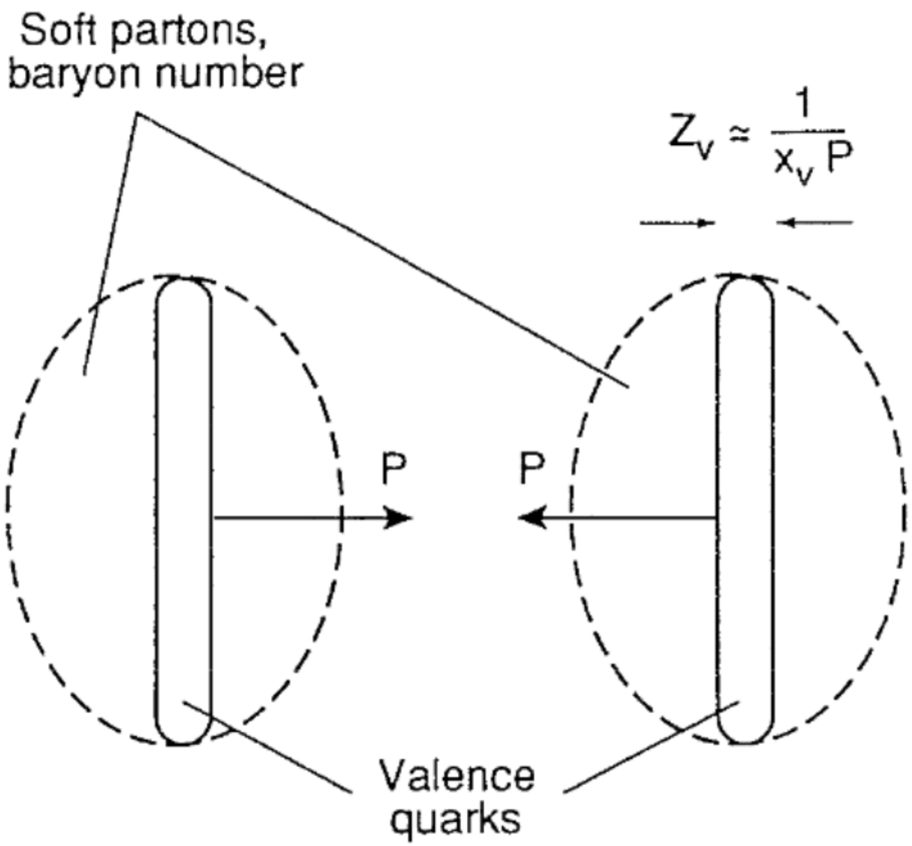
- Can be used to investigate what internal structure carries the baryon number
- Net-baryon yield is closely related to the net-proton yield: difference in number of protons and anti-protons
- Baryon stopping has been measured for a wide range of collision energies
  - Clear exponential dependence on δy
  - Cannot be explained in the valence quark picture

    C. Shen and B. Schenke, PRC **105,** 064905 (2022)



J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Baryon Stopping from the Junction



D. Kharzeev, Physics Letters B **378**, 238 (1996)

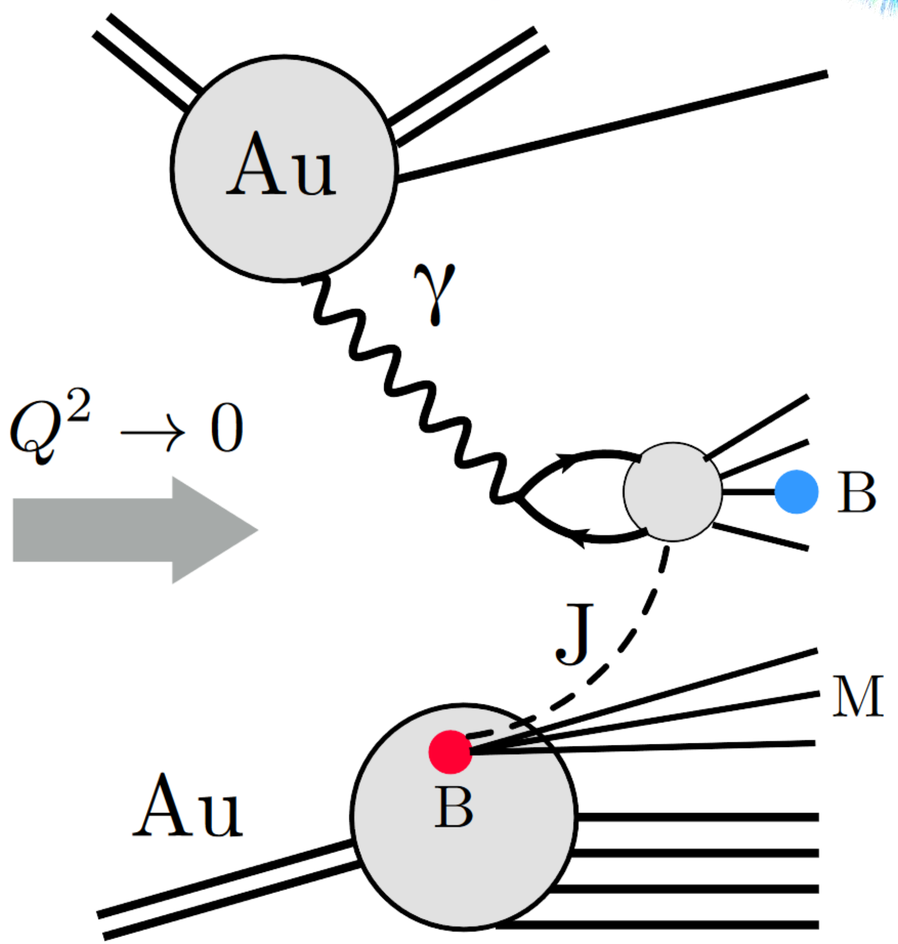
- Time available for quark stopping is very short: $t_{\mathrm{coll}} \sim (x_v P)^{-1}$
- Junctions carry a much lower momentum fraction, $x_J \ll x_v$
  - Has enough time to interact with and be stopped
  - Predicted characteristic rapidity distribution of $\frac{dN}{dy} \propto \exp\left(-\frac{y}{2}\right) + \exp\left(+\frac{y}{2}\right)$

    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- No signature of baryon junction has been cleanly identified experimentally

Photonuclear Collisions and the Baryon Junction

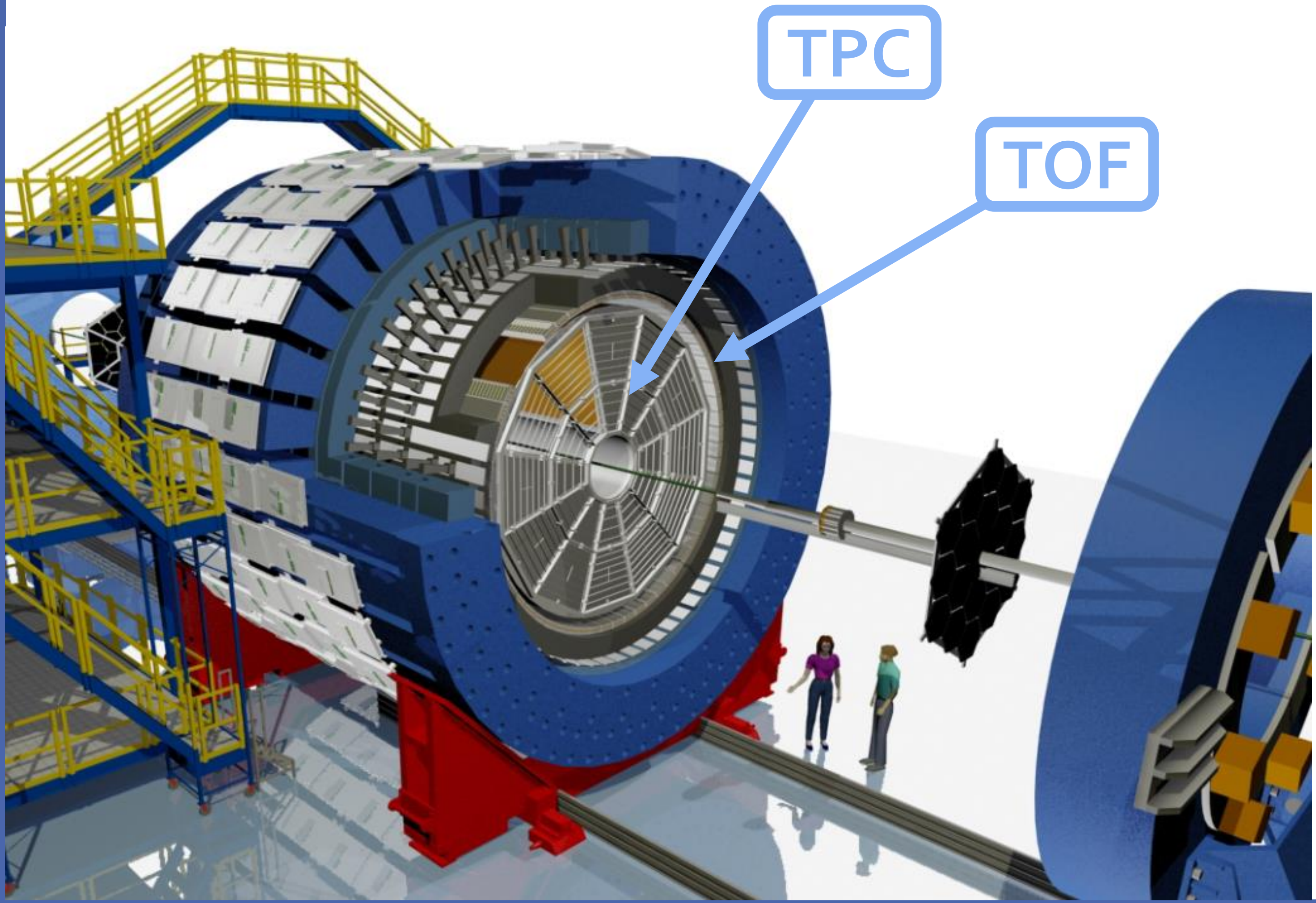
- Inclusive particle production in photonuclear collisions
  - Similar to eA collisions except that the photon has much smaller virtuality
- Can be used to study baryon stopping with the cleanest possible process
  - Probing the nucleon at very low x
  - Asymmetric collision: target can only be traveling in one direction
    - Predicted rapidity distribution of $dN/dy \propto \exp(-y/2)$

      D. Kharzeev, Physics Letters B **378**, 238 (1996)



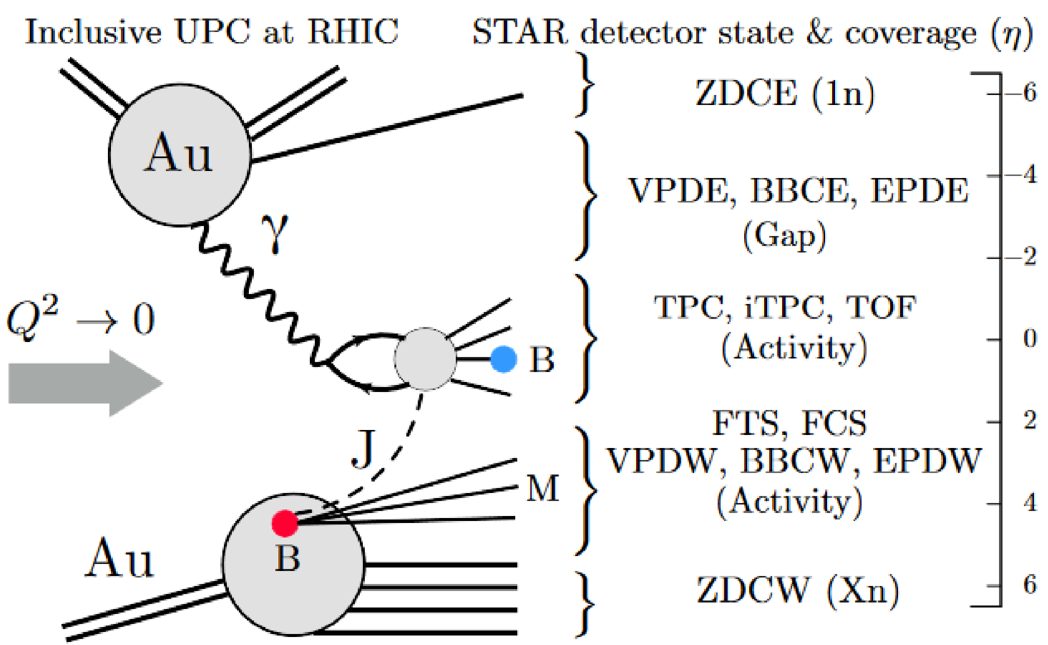
J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Tracking and Particle Identification with the STAR Detector

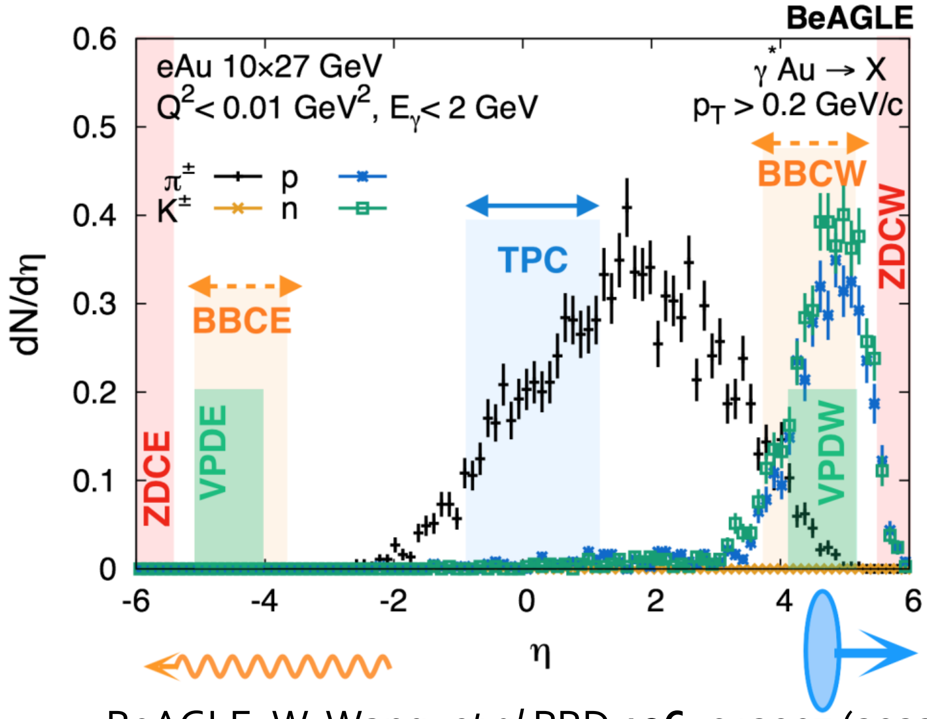


- Time Projection Chamber (TPC)
  - Track reconstruction
  - Identifies particles using ionization energy loss, dE/dx
- Time-Of-Flight detector (TOF)
  - Extend particle identification to high p_T
  - Pile-up rejection

Photonuclear Events Are Selected With Rapidity Gaps



J. D. Brandenburg, N. Lewis,
P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)



BeAGLE: W. Wang, *et al* PRD **106,** 012007 (2022)

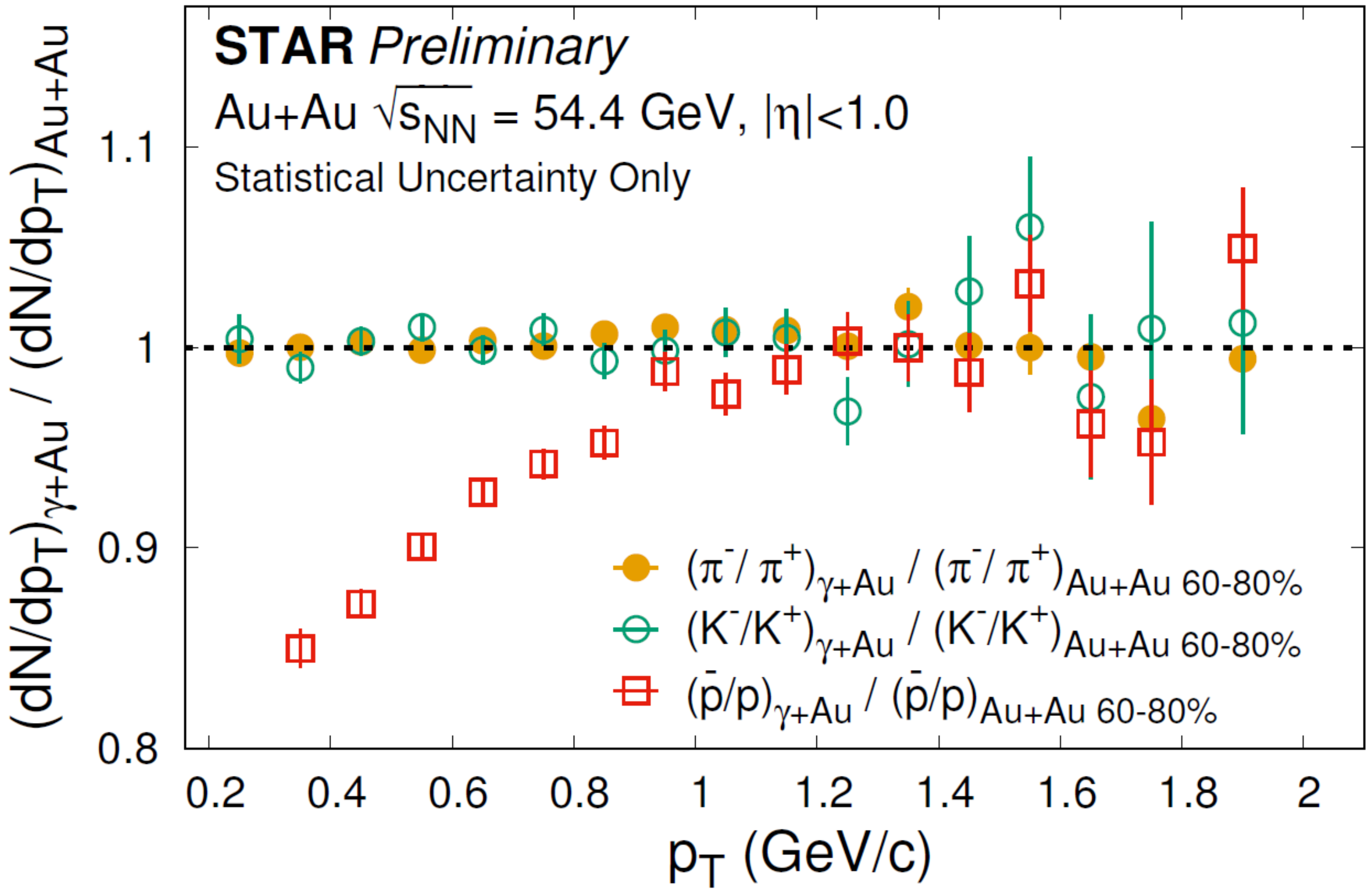
Similar technique used by LHC photonuclear measurements:

ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021) and CMS Collaboration, arXiv:2204.13486 (2022)

For data collected in 2017, Au + Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV, trigger did not require coincidence in both sides of the detector

Low p_T Baryon Enhancement in γA

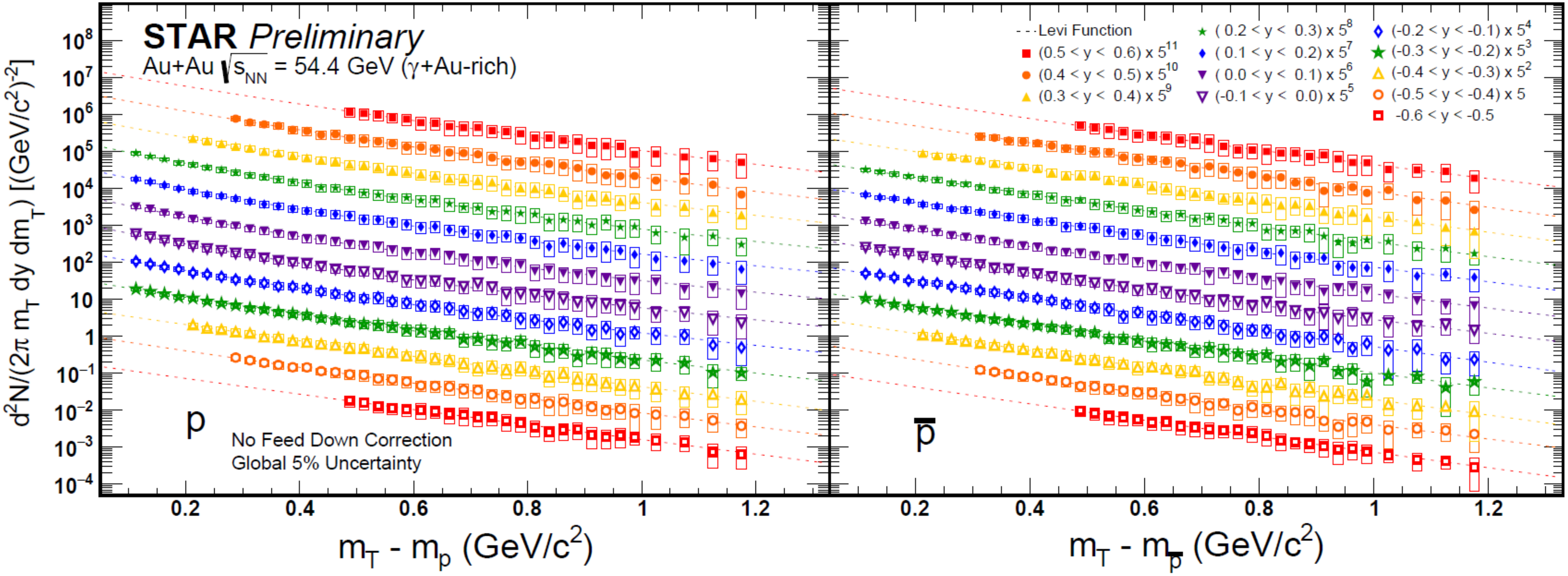
- Double ratio: antiparticle/particle in $(\gamma A)/(AA)$
- $\bar{p}/p < 1$ for $p_T \lesssim 1$ GeV$/c$
  → Indication of soft baryon stopping in γA collisions
- Not corrected for efficiency, but largely cancels in the double ratio



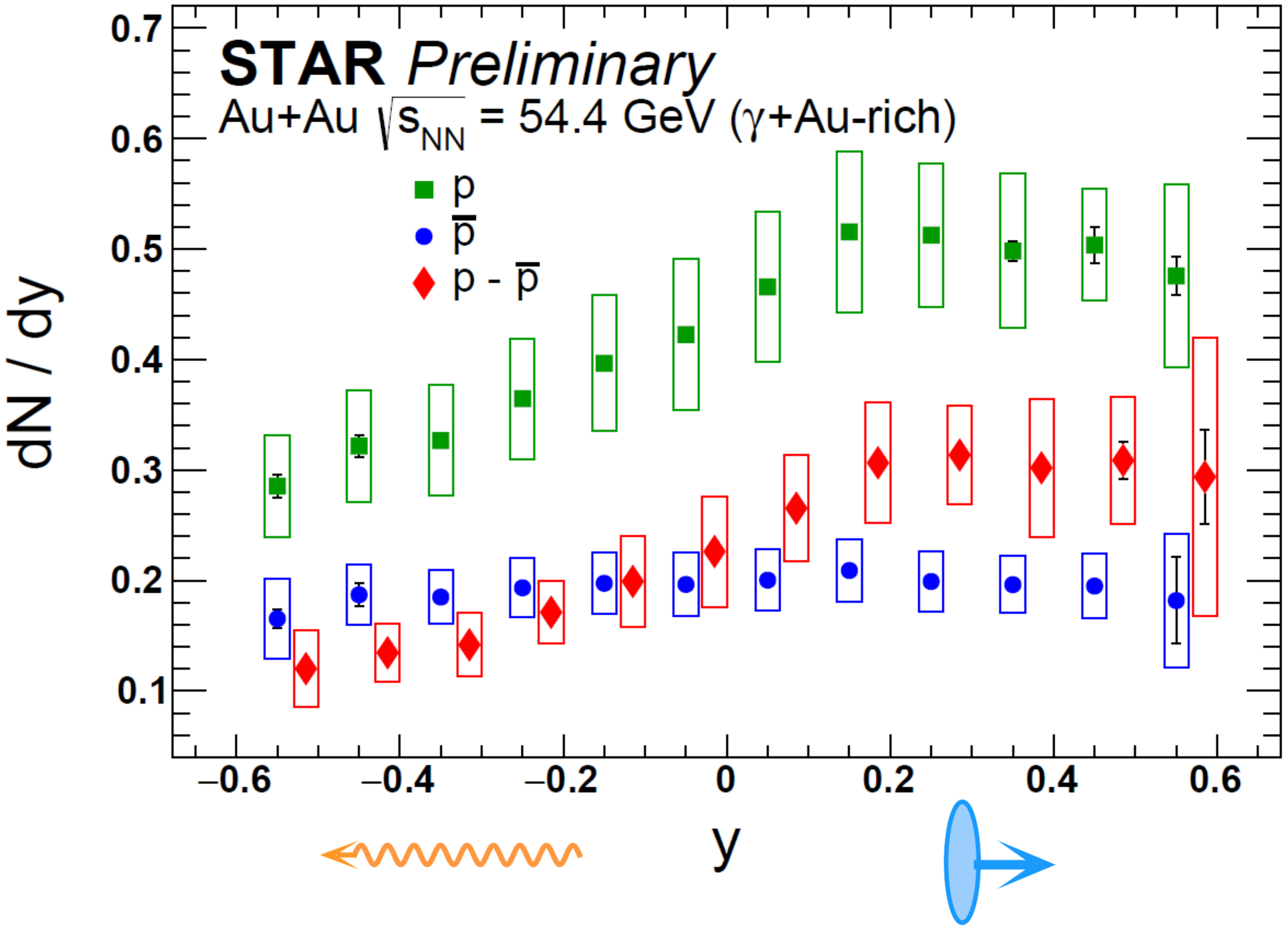
Proton/Anti-proton Spectra in $\gamma + Au$-Rich Sample

Corrected for background contribution from peripheral AA collisions

- Contamination from peripheral AA events estimated to be about 10%
- Estimating the behavior of this background by measuring the spectra in peripheral AA collisions with centrality $60 - 80\%$



Net-proton Yield



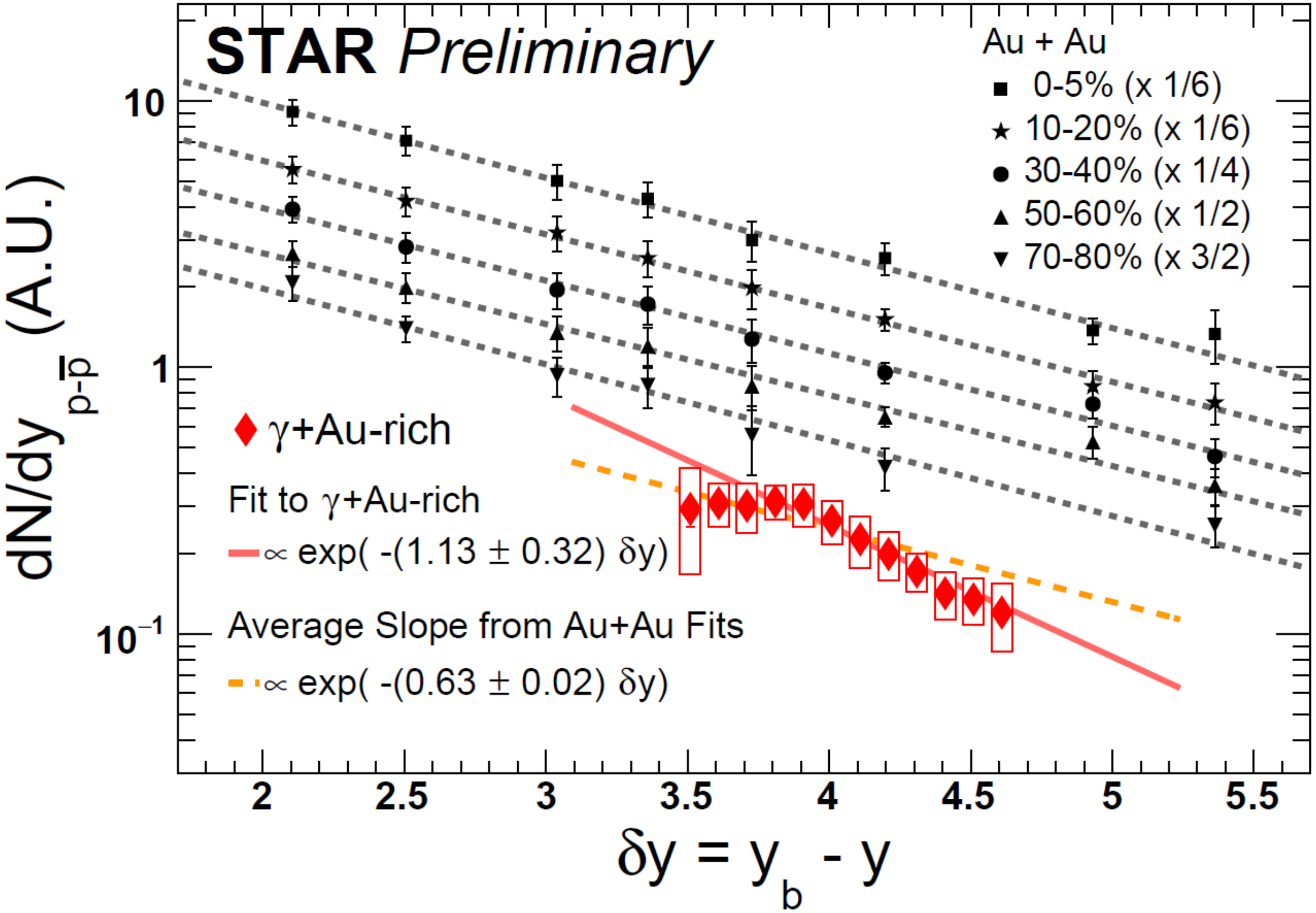
- $\bar{p}\ dN/dy$ slope is flat with y
  - Positive slope: asymmetric particle production in γA
  - Negative slope: Regge theory predicts that $p\bar{p}$ pair production should have an opposite rapidity dependence to the junction mechanism

    D. Kharzeev, Physics Letters B **378**, 238 (1996)
- p and net-proton dN/dy increases with y
  - Possibly due to the baryon junction mechanism

γ + Au-Rich vs Au + Au

- In hadronic Au + Au, the net-proton dN/dy consistently has a slope of ~ -0.6 with rapidity
- Slope for γ + Au-rich collisons is comparable
  - Some indication that the slope could be larger than Au + Au
  - Consistent with baryon junction prediction
  - PYTHIA, which does not include a baryon junction mechanism, predicts a slope of ~ -2.5

    J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)



STAR Collaboration, PRC **79**, 034909 (2009) and PRC **96,** 044904 (2017)

Charge Stopping vs Baryon Stopping

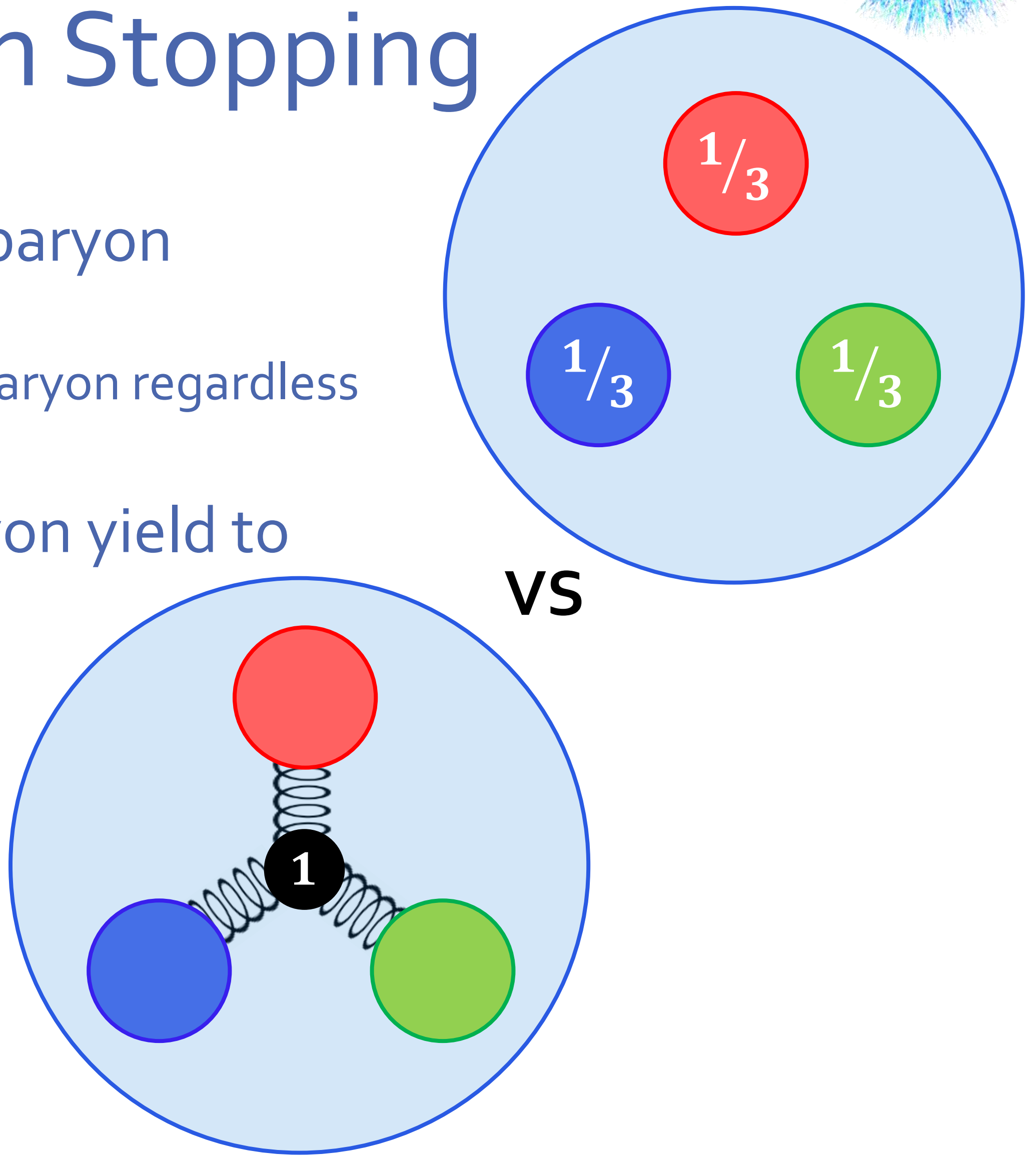
- Another observable to study what carries baryon number
  - Valance quarks carry the (electric) charge of the baryon regardless of what carries baryon number
- Compare inclusive particle yields: net-baryon yield to net-charge yield

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

vs

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

- Complications from detector effects



Precisely Measure the Charge Difference Using Isobar Data

$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$
with $\sqrt{s_{NN}} = 200$ GeV

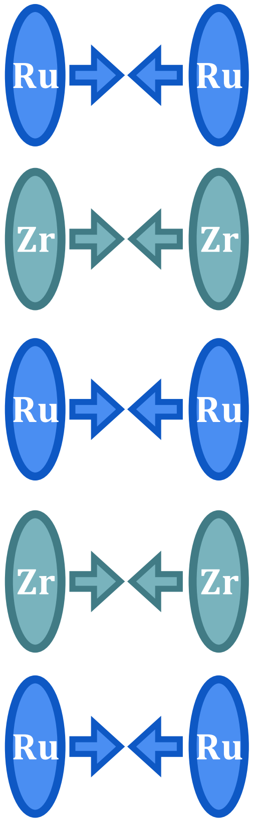
- Special run to minimize systematics by:
  - Fill-by-fill switching
  - Luminosity leveling
- Construct double ratios: $R2_\pi = \frac{(N_{\pi^+}/N_{\pi^-})_{\mathrm{Ru}}}{(N_{\pi^+}/N_{\pi^-})_{\mathrm{Zr}}}$
- Precisely measure the charge difference at midrapidity

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

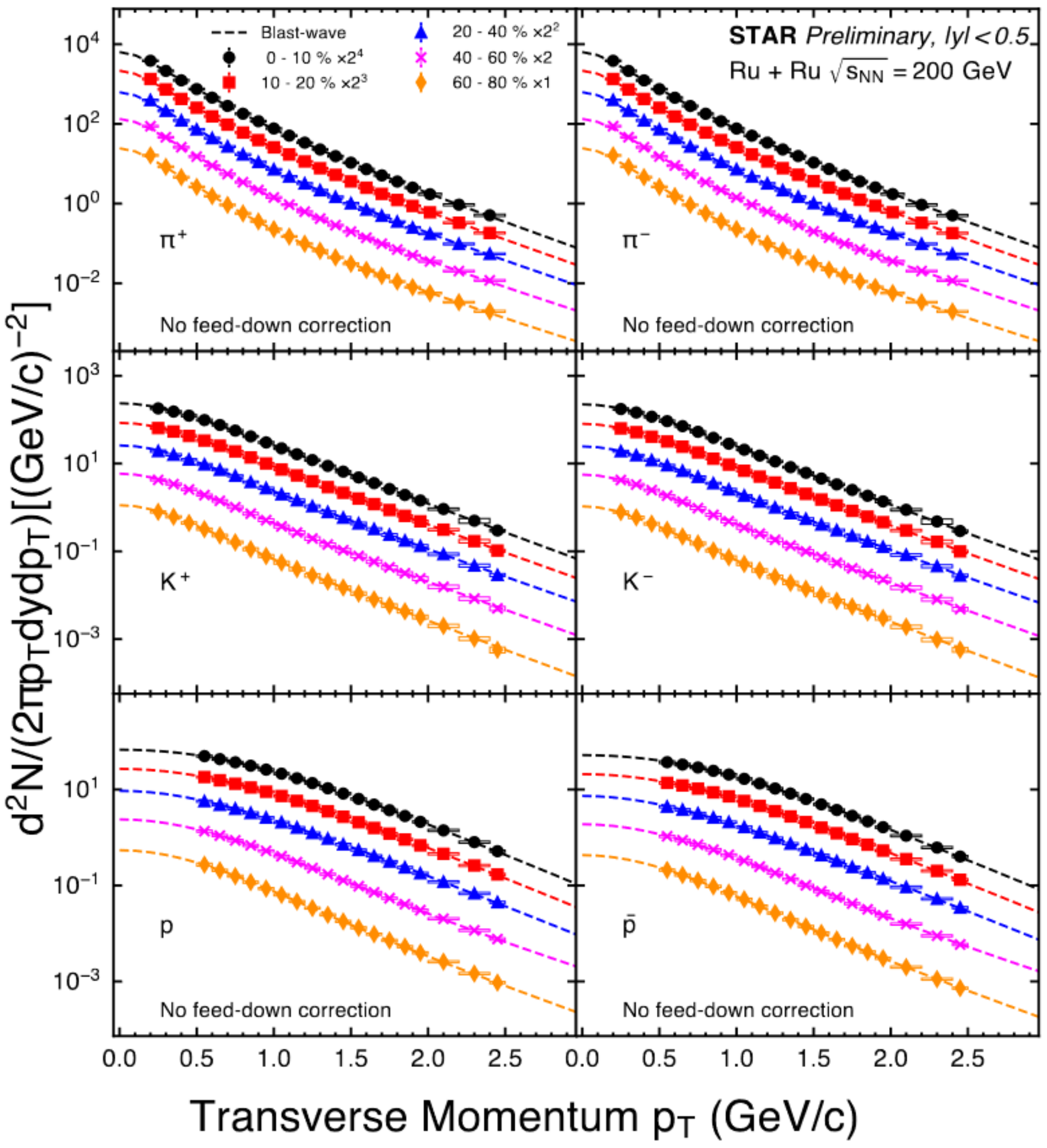
J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

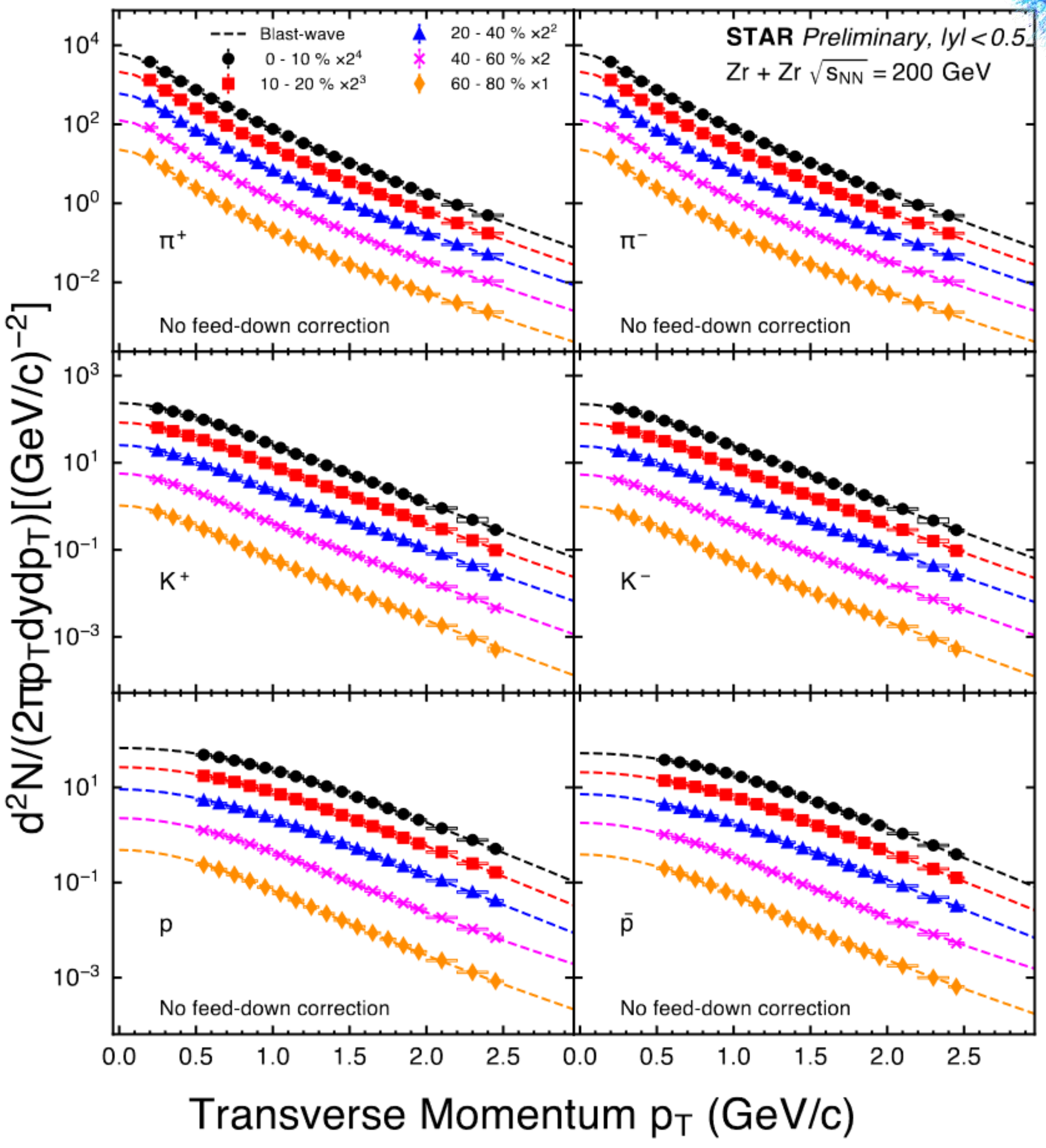
- Baryon stopping is the same between the two collision species

$$B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}}) \approx (N_p - N_{\bar{p}}) + \left(N_{\bar{p}} \sqrt{\frac{N_d}{N_{\bar{d}}}} - N_p \sqrt{\frac{N_{\bar{d}}}{N_d}} \right)$$

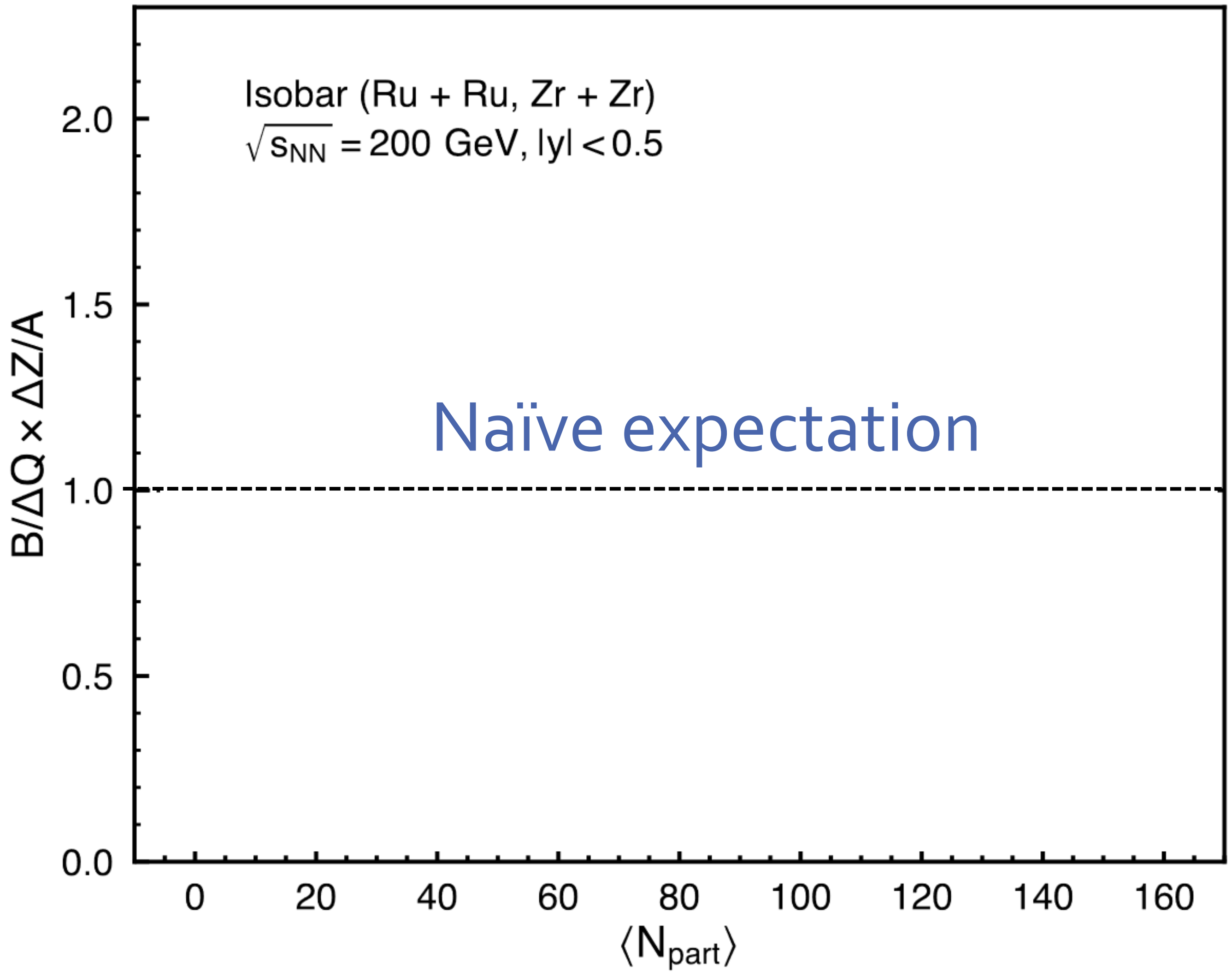


Spectra From Isobar Data





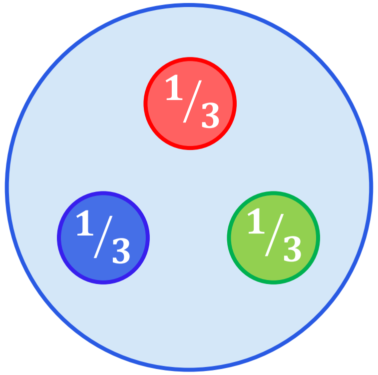
Charge Stopping vs Baryon Stopping



For $^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr}$: $\frac{\Delta Z}{A} = \frac{4}{96}$

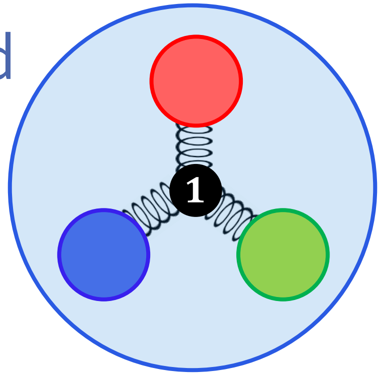
If quarks carry baryon number:

$$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} = 1$$

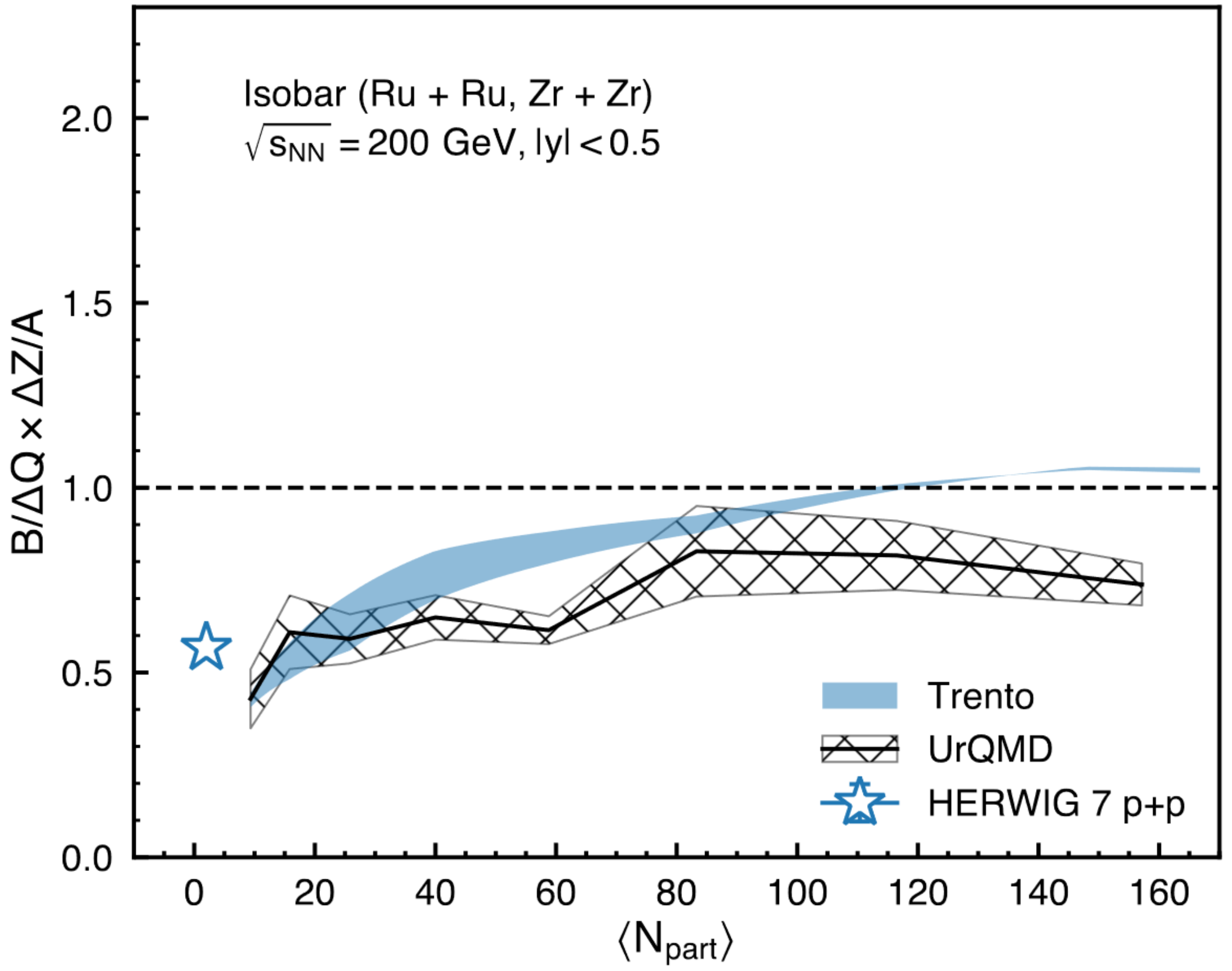


If the baryon number is carried by the junction:

$$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} > 1$$



Charge Stopping vs Baryon Stopping

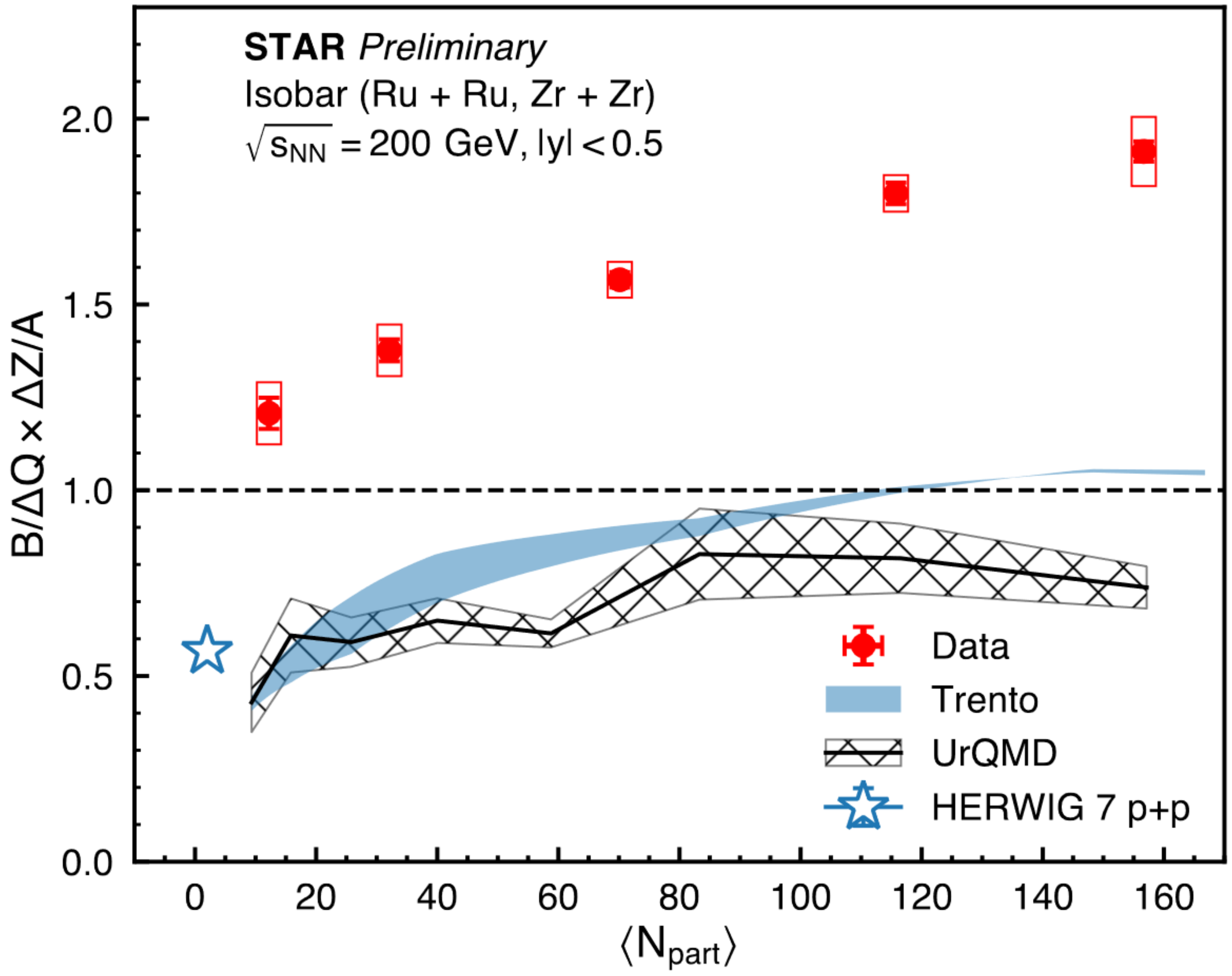


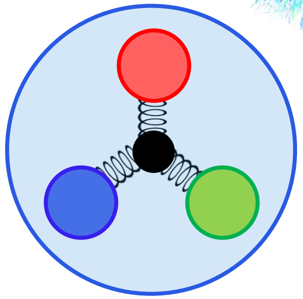
According to simulations:

$$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} < 1$$

- Soft interactions: Herwig $p + p$
  J. Bellm *et al*, Eur. Phys. J.C. **80** 5, 452 (2020)
- Medium effects: UrQMD
  M. Bleicher *et al*, J. Phys. G. **25,** 1859 (1999)
- Effects from the neutron skin: Trento
  H. Xu *et al*, PRC **105,** L011901 (2022)

Charge Stopping vs Baryon Stopping





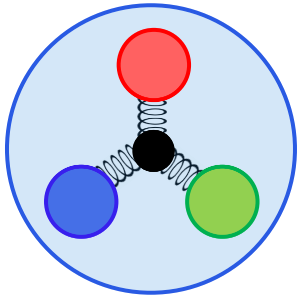
- Data:

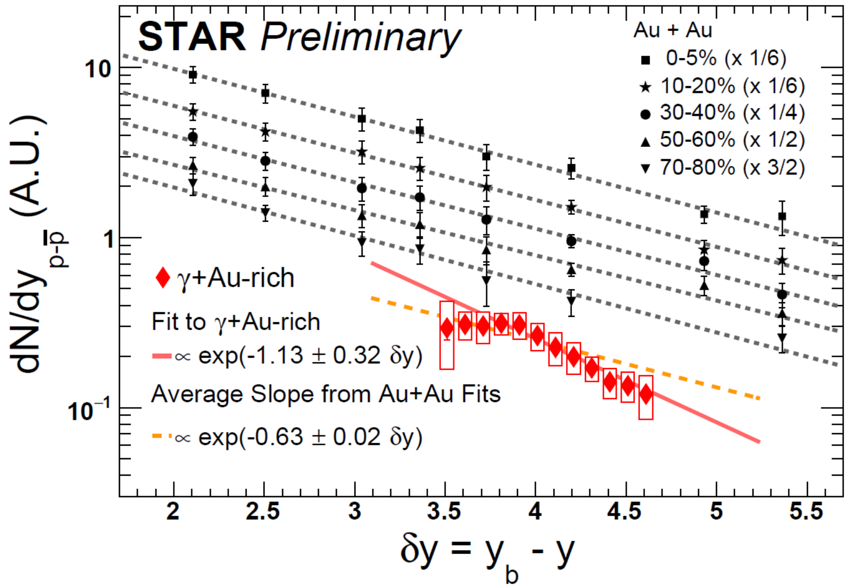
$$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} > 1$$

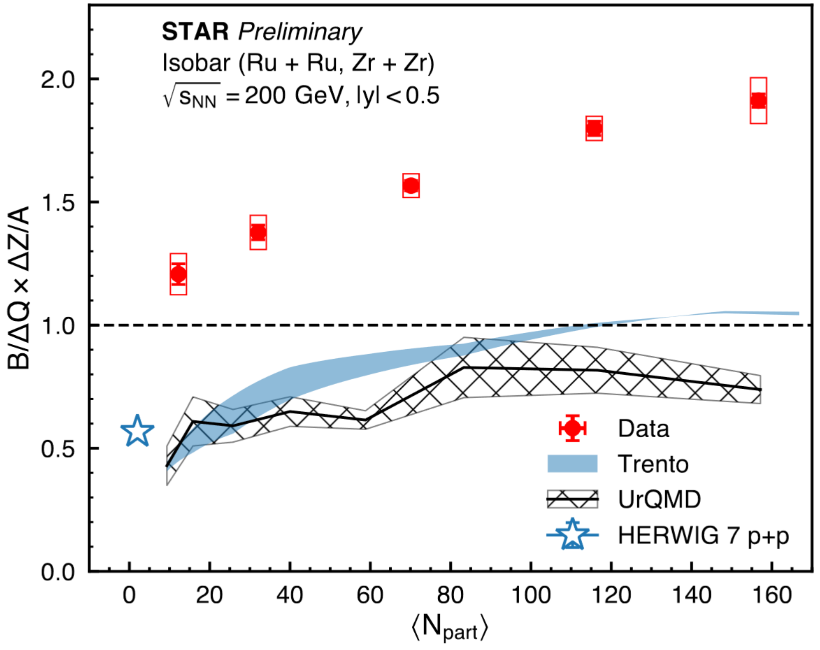
- This is consistent with baryon junction prediction
  - Junctions carry a much smaller momentum fraction compared to valence quarks
  - Larger reaction cross section, more baryon stopping
- Ratio decreases with decreasing multiplicity due to effects from the neutron skin

Summary

- Observed baryon stopping in γ + Au-rich collisions with a qualitatively comparable (possibly steeper) slope to hadronic Au + Au collisions
- Observed more baryon stopping than charge stopping using isobar data
- Both are consistent with the baryon junction prediction: a Y-shaped configuration of low momentum gluons which carries the baryon number

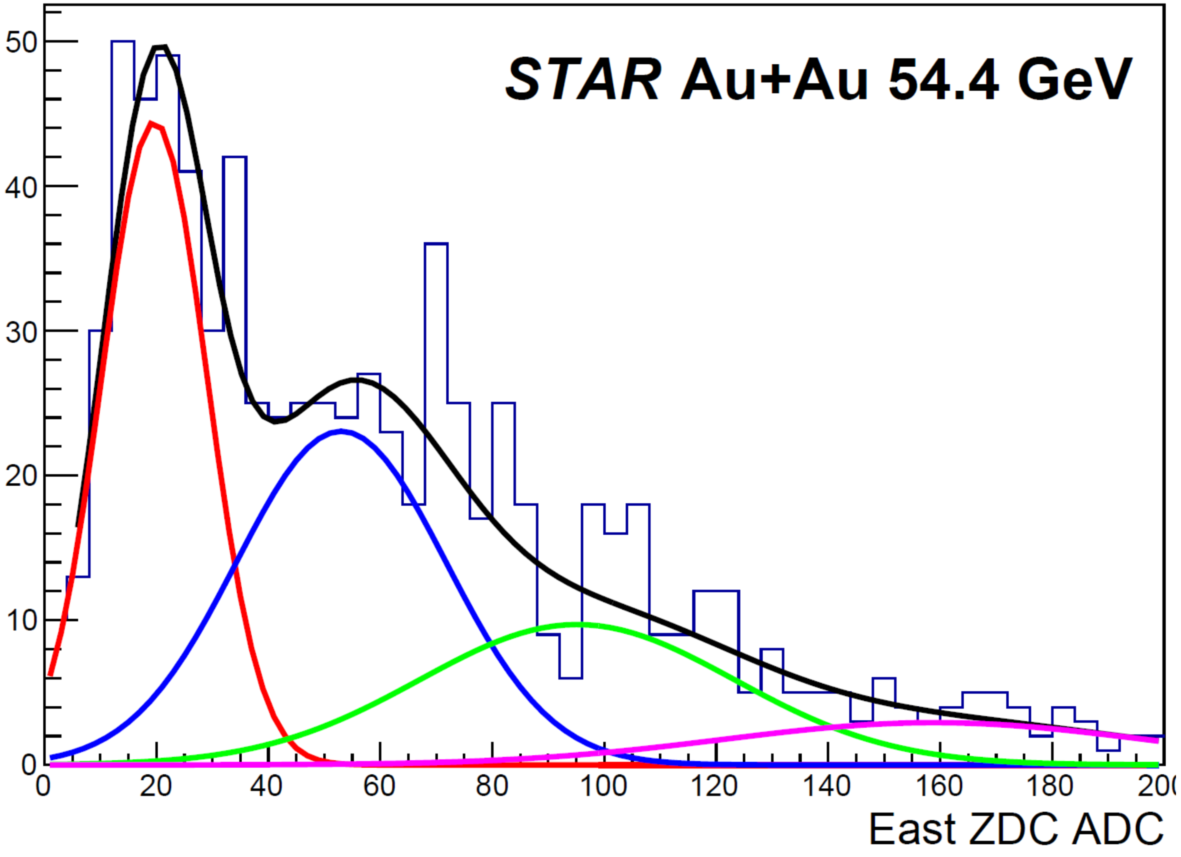


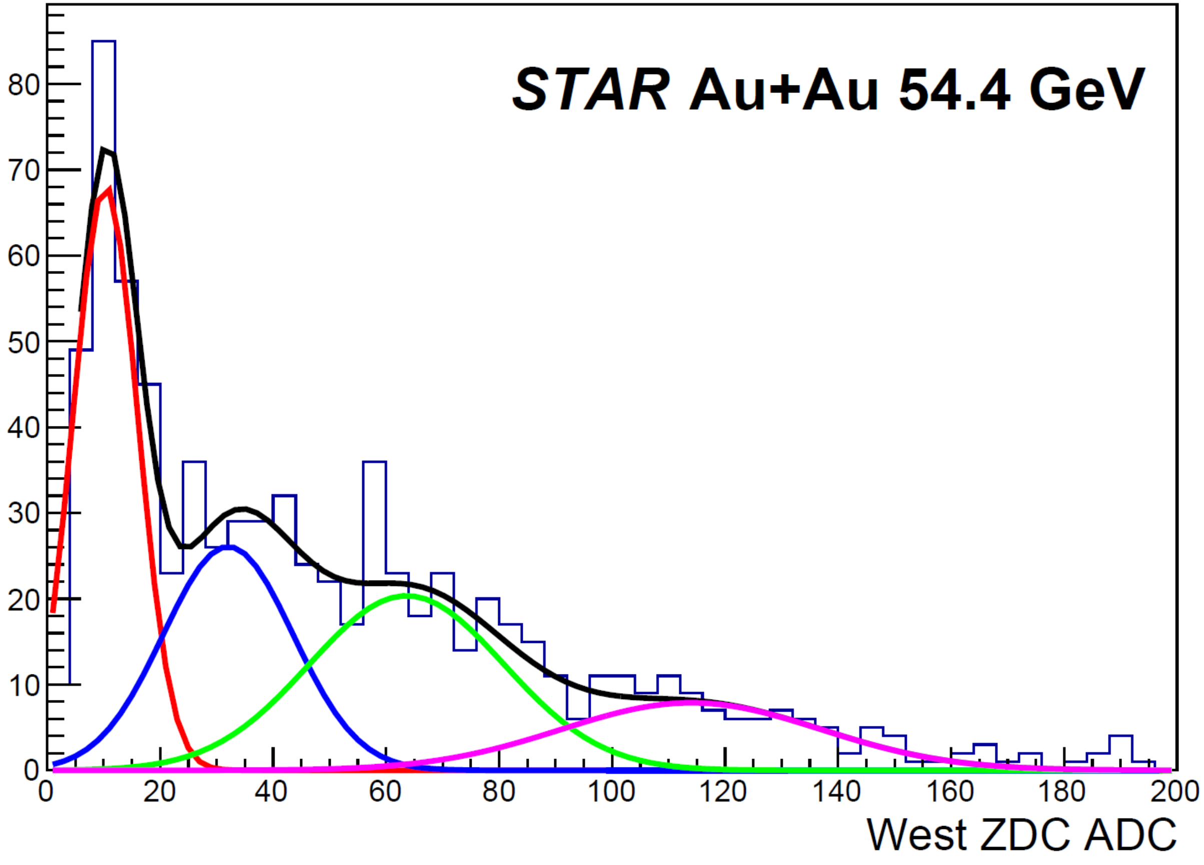




Back Up

γ + Au-rich Events:
Cutting on ZDC Spectra

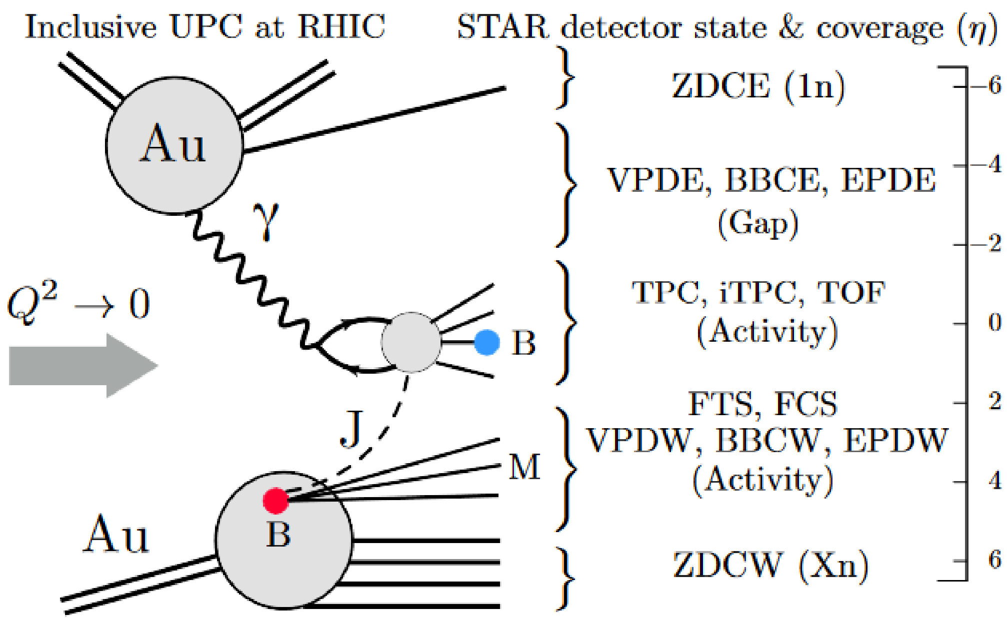




Low multiplicity events collected with ZDC triggers

Cutting on single neutron peak: $1nXn$ $(X > 1)$, dominated by γA events.

Rapidity Asymmetry in γ + Au-Rich Events



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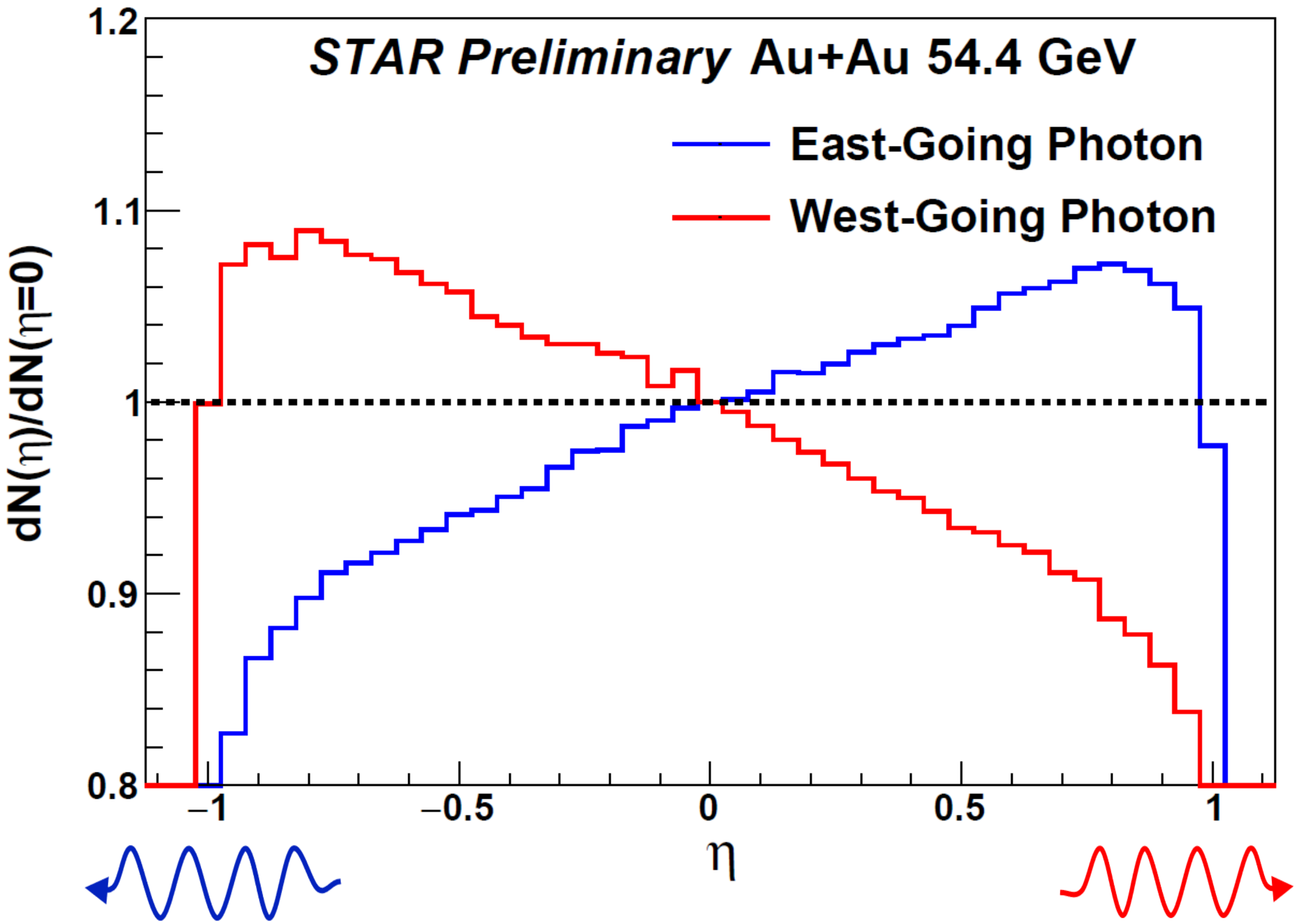
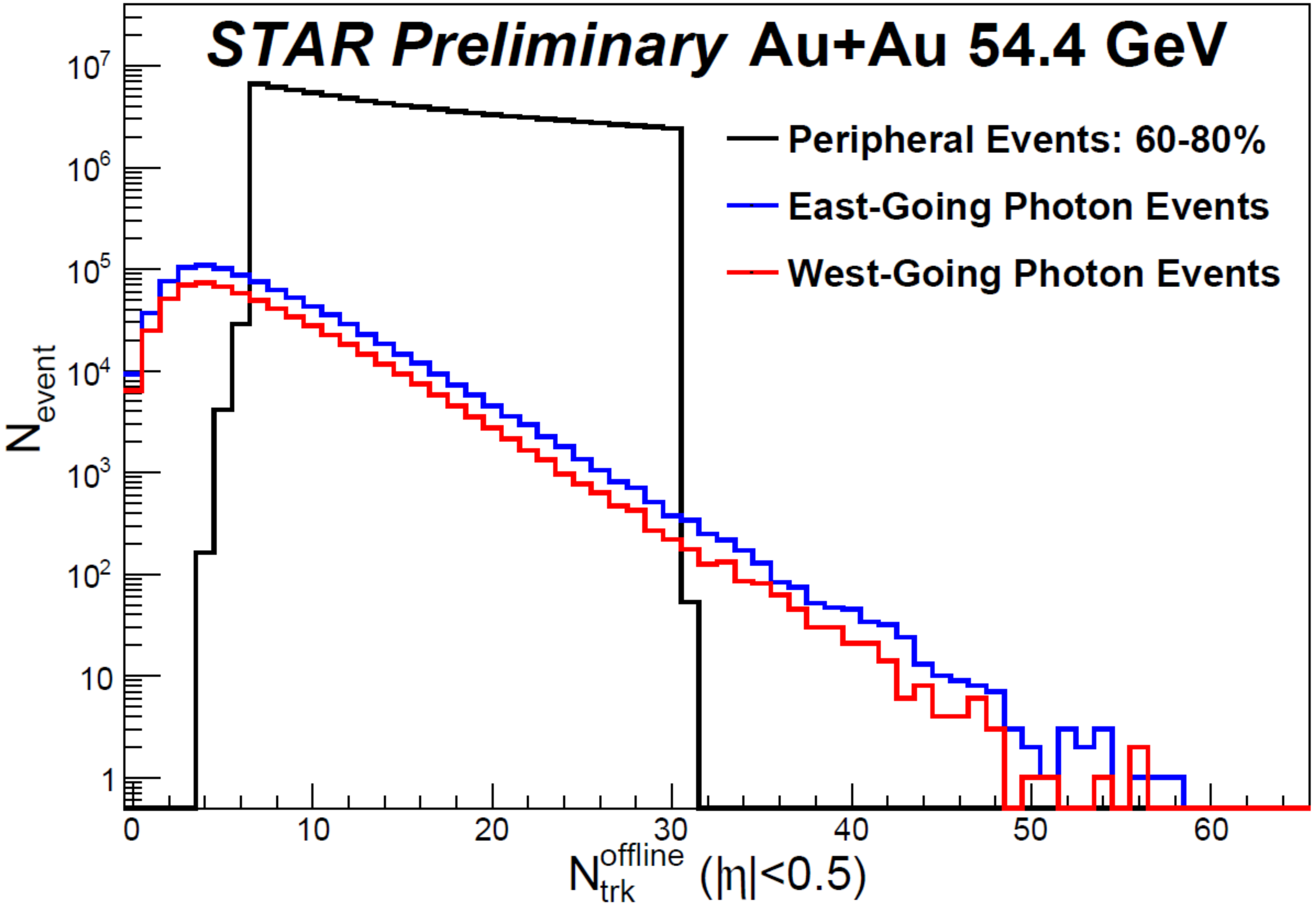
P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)



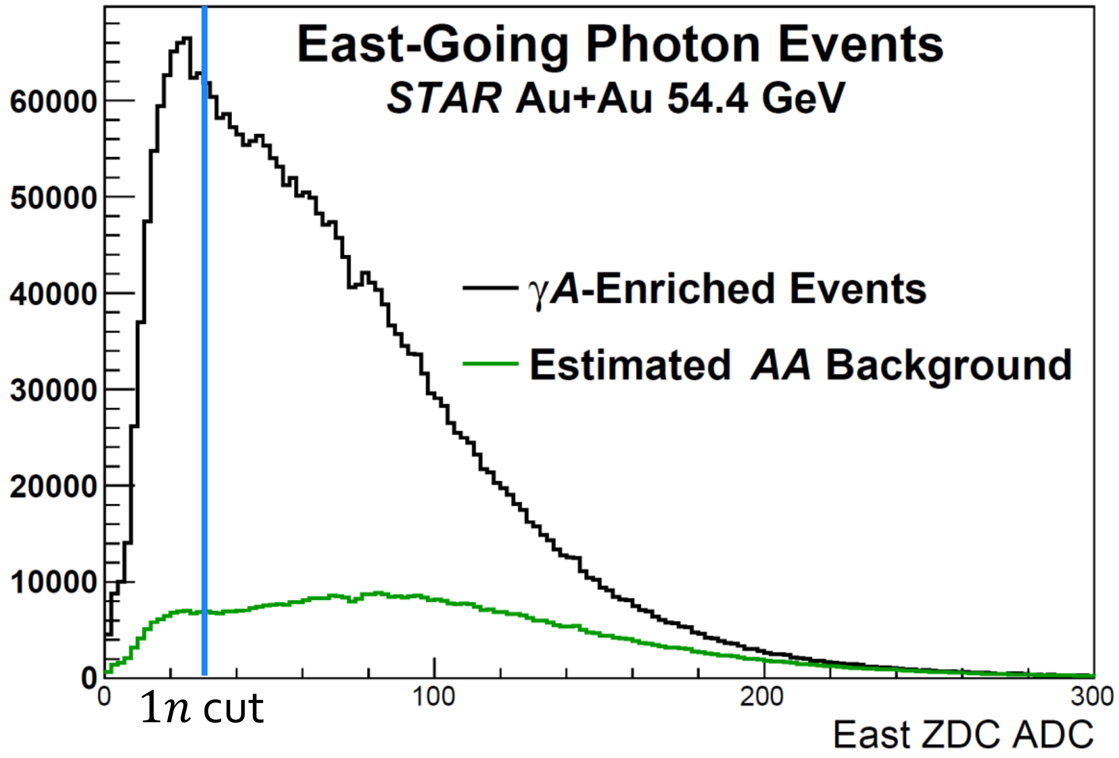
$\gamma + \mathrm{Au}$-Rich Multiplicity Distribution

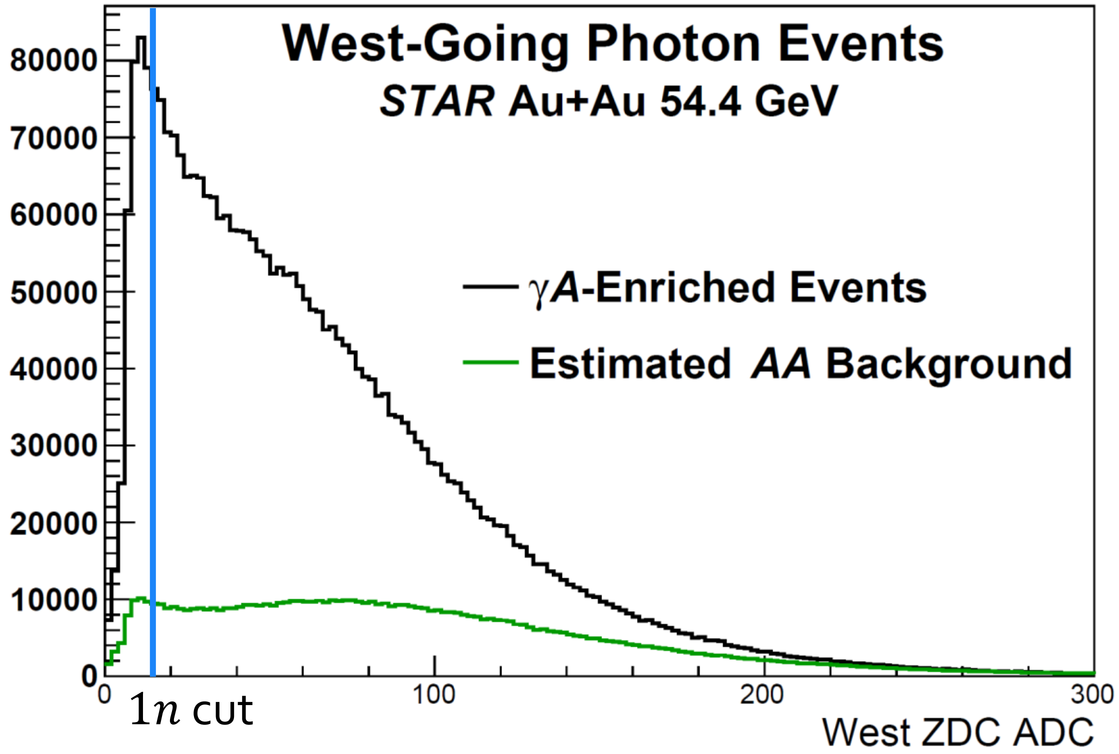


Most photonuclear events have low multiplicity, consistent with very peripheral $\mathrm{Au} + \mathrm{Au}$ collisions

Using $60 - 80\%$ peripheral collisions to estimate behavior of peripheral background

Estimating Background Contamination from Peripheral Collisions





Estimate background contribution utilizing ZDC ADC distributions of peripheral events

- Scale down so the tail matches γA-enriched events, for ADC between 250 and 800
- Background fraction $\sim 10\%$

p_T Dependence of Particle Ratios in $\gamma A/AA$

$K/\pi < 1$ and flat with p_T

$\rightarrow$ less access to strangeness in γA events

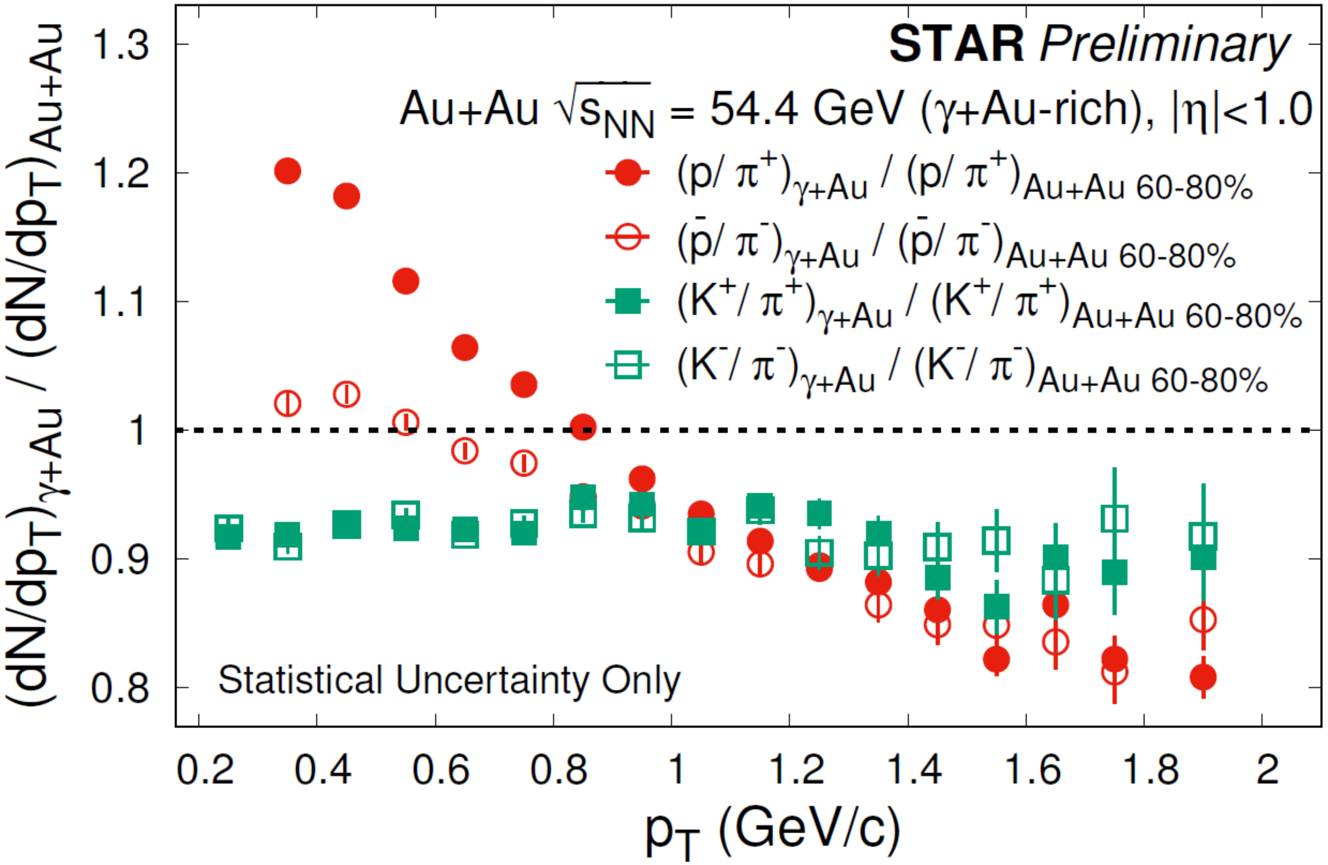
$\bar{p}/\pi$ and p/π steeper than K/π

$\rightarrow$ larger radial flow in $60-80\%\ \mathrm{Au+Au}$

$\boldsymbol{\bar{p}/\pi^- < p/\pi^+}$ **for** $\boldsymbol{p_T \lesssim 1\ \mathrm{GeV}/c}$

$\rightarrow$ **soft baryon stopping**

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



Derivation of the Charge Difference Formula

Double ratios:

$$R2_\pi = \frac{(N_{\pi^+}/N_{\pi^-})_{\text{Ru}}}{(N_{\pi^+}/N_{\pi^-})_{\text{Zr}}} \approx \frac{(1+(N_{\pi^+}-N_{\pi^-})/N_\pi)_{\text{Ru}}}{(1+(N_{\pi^+}-N_{\pi^-})/N_\pi)_{\text{Zr}}} = \frac{1+\Delta R^\pi_{\text{Ru}}}{1+\Delta R^\pi_{\text{Zr}}} \approx 1+\Delta R^\pi_{\text{Ru}} - \Delta R^\pi_{\text{Zr}}$$

And similarly for $R2_K$ and $R2_p$, where $N_\pi = \frac{N_{\pi^+} + N_{\pi^-}}{2}$

For the net charge difference:

$$\Delta Q = Q(\text{Ru}) - Q(\text{Zr}) = \left[(N_{\pi^+}-N_{\pi^-}) + (N_{K^+}-N_{K^-}) + \left(N_p - N_{\bar{p}}\right)\right]_{\text{Ru}} - [\,]_{\text{Zr}}$$

So

$$(N_{\pi^+}-N_{\pi^-})_{\text{Ru}} - (N_{\pi^+}-N_{\pi^-})_{\text{Zr}} = (\,N_\pi \times \Delta R^\pi_{\text{Ru}}\,)_{\text{Ru}} - (\,N_\pi \times \Delta R^\pi_{\text{Zr}}\,)_{\text{Zr}}$$

$$\approx N_\pi(\Delta R^\pi_{\text{Ru}} - \Delta R^\pi_{\text{Zr}}) \approx N_\pi(R2_\pi - 1)$$

And

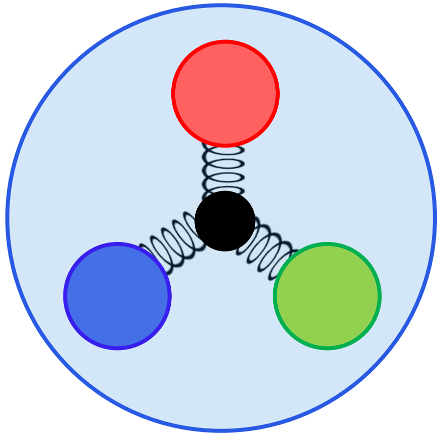
$$\Delta Q = N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p\left(R2_p - 1\right)$$

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

J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Potential Future Measurements

- Baryon stopping in γA for different collision energies and systems
  - $\mathrm{Au} + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ (RHIC)
  - $p + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ (RHIC)
  - $d + \mathrm{Au}$ for a wide range of collision energies, $\sqrt{s_{NN}} = 20 - 200\ \mathrm{GeV}$ (RHIC)
  - $\mathrm{Pb} + \mathrm{Pb}$ at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$ and $p + \mathrm{Pb}$ at $\sqrt{s_{NN}} = 8.16\ \mathrm{TeV}$ (LHC)
  - Measure baryon stopping as a function of multiplicity



- Correlations in γA at RHIC
- Charge stopping at different collision energies
  - Compare charge stopping vs baryon stopping for $\mathrm{Au} + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ and $\mathrm{U} + \mathrm{U}$ at $\sqrt{s_{NN}} = 193\ \mathrm{GeV}$, constructing double ratios for collisions with the same multiplicity
- Investigate baryon stopping at the EIC
  - Backward production of mesons, requires nucleons to shift several units in rapidity
    D. Cebra, *et al*, PRC **106,** 015204 (2022)