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Brookhaven National Laboratory

Recent STAR Results on Baryon Number Carrier

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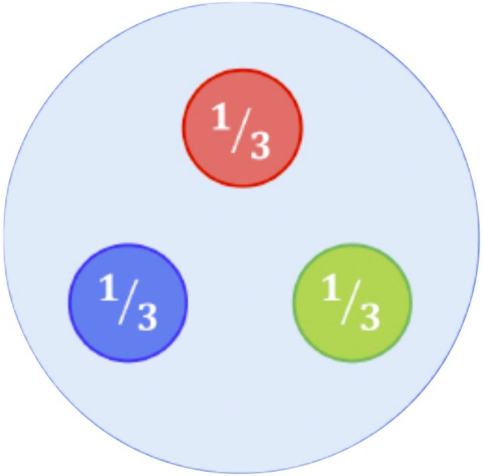
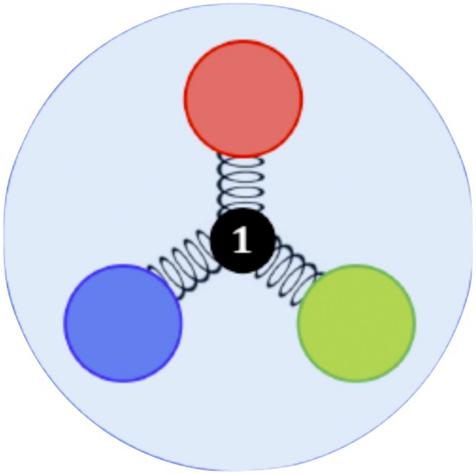
01/22/2024

1st Workshop on Baryon Dynamics from RHIC to EIC

What Carries the Baryon Number?

Valence Quarks vs. **Junctions**

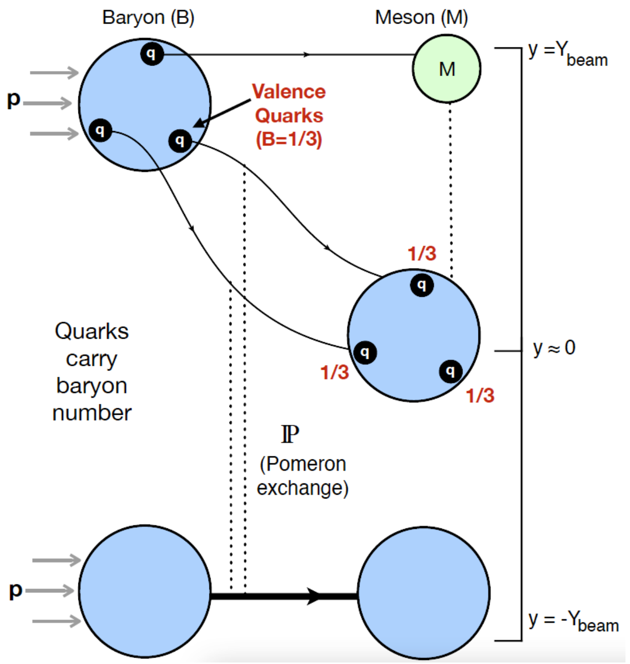




X. Artru, Nucl. Phys. B 85 (1975) 442
G. C. Rossi, G. Veneziano, Nucl. Phys. B 123 (1977) 507

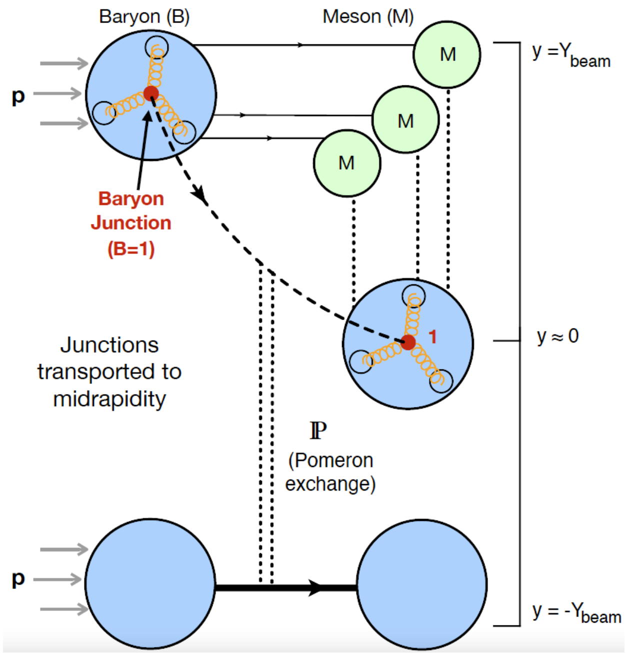
What Carries the Baryon Number?

Valence Quarks



VS.

Junctions



What Carries the Baryon Number?

Valence Quarks

- Carry large momentum fractions
- Hard to be stopped at midrapidity
  - $dN/d\Delta y \sim \exp(-2.4\Delta y)$ (PYTHIA)
  - $\Delta y = Y_{\text{beam}} - y$
- Ensemble basis: $Q \sim B \times Z/A$

Junctions

- Consist of low-momentum gluons
- Easier to be stopped at midrapidity
  - $dN/d\Delta y \sim \exp(-0.5\Delta y)$ (theory)

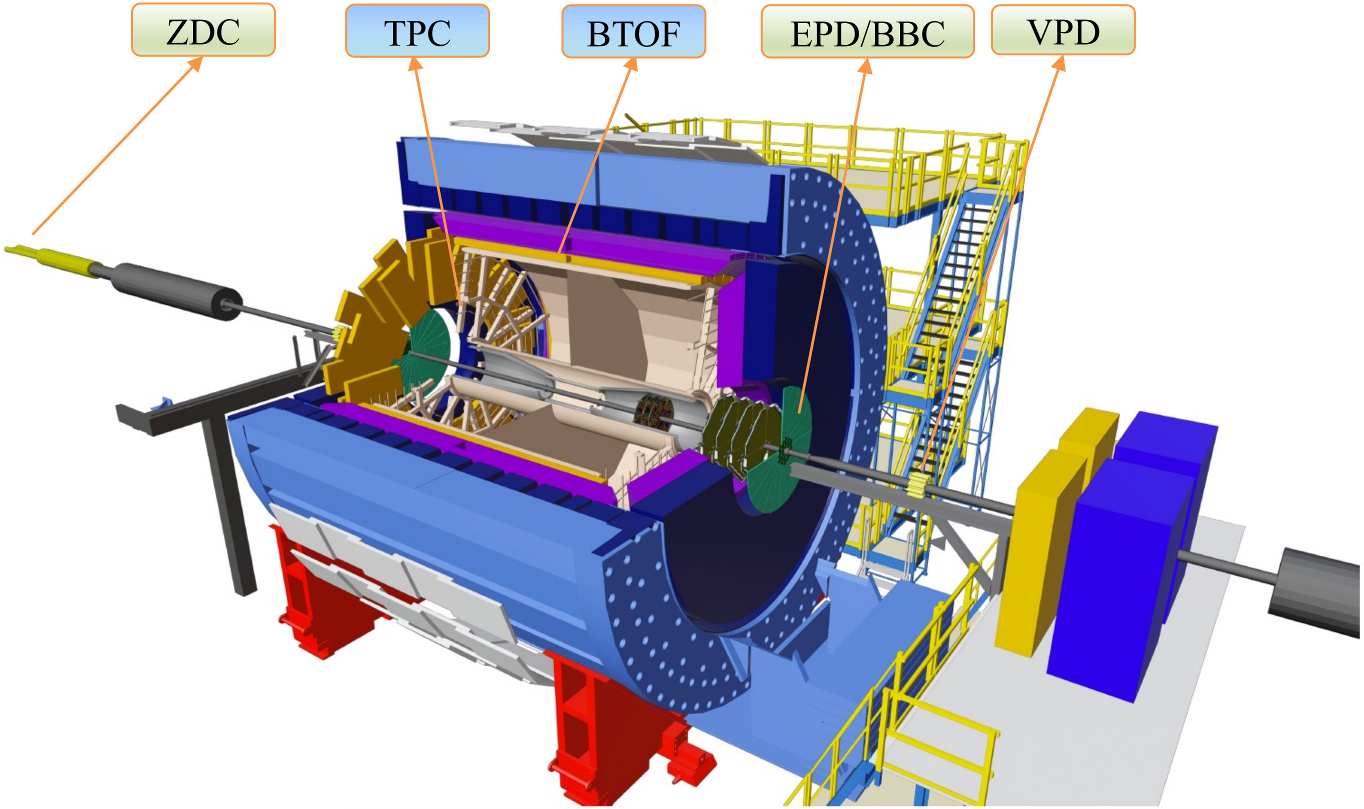
Theory: D. Kharzeev, PLB 378 (1996) 238

- Ensemble basis: $Q < B \times Z/A$

✓ **THREE TESTS**

1) Compare Q vs. $B \times Z/A$ in Ru+Ru and Zr+Zr collisions
2) Net-proton $dN/d\Delta y$ in γ+Au events
3) Net-proton $dN/d\Delta y$ in hadronic Au+Au collisions

STAR Detector



Test 1

Q vs. $B \times Z/A$ in Isobar collisions

Charge and Baryon Transport

➢ Measured within midrapidity: |y| < 0.5

✓ Charge transport: net-charge number

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

✓ Baryon transport: net-baryon number

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

Charge and Baryon Transport

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

✓ Baryon transport: net-baryon number

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

- Almost all particles decay to π, K, p, n
  - Missing deuteron contribution to $B \sim 0.8\%$
- Measured spectra include resonance and weak decays (DCA < 3 cm)
  - Missing weak decays contribute ~ 1%
- Neutron yield estimated using proton and deuteron yields in thermal/coalescence picture
  - Uncertainty ~ 3-5%

The Double-ratio Method

- Very difficult to measure net-charge with needed precision
- Instead, we can measure the net-charge difference between $^{96}_{44}Ru$+$^{96}_{44}Ru$ and $^{96}_{40}Zr$+$^{96}_{40}Zr$ collisions

$$\Delta Q = Q_{\mathrm{Ru+Ru}} - Q_{\mathrm{Zr+Zr}} \approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$$

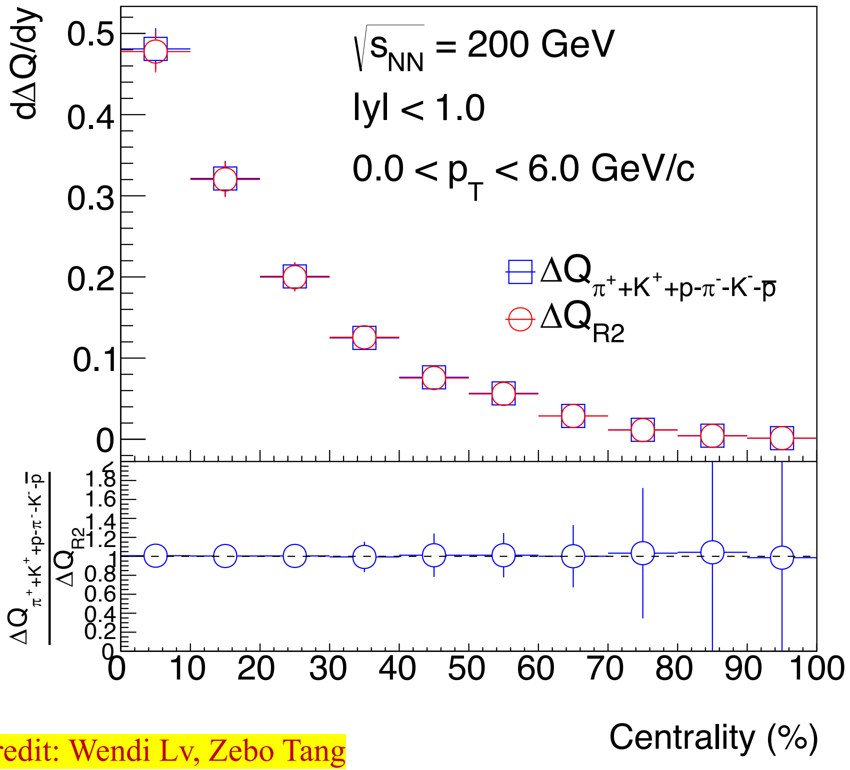
$$R2_\pi = (N_{\pi^+}/N_{\pi^-})_{\mathrm{Ru+Ru}}/(N_{\pi^+}/N_{\pi^-})_{\mathrm{Zr+Zr}}$$

  - Double ratios take care of multiplicity mismatch between two isobar collisions for a given centrality

✓ We compare:

$$\Delta Q \text{ vs. } B\times\frac{\Delta Z}{A} \qquad \Delta Z = 44 - 40 = 4,\ A = 96$$

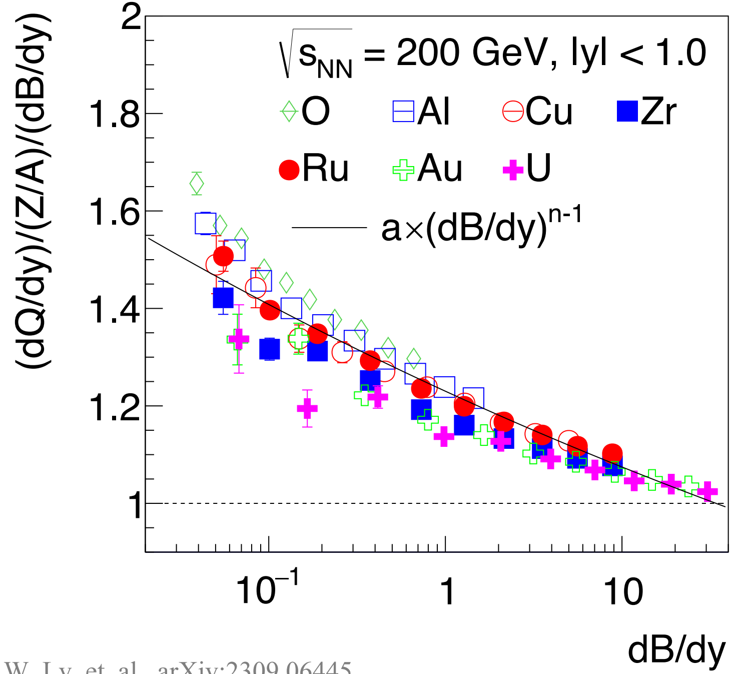
Verify Double-ratio Method



- UrQMD: net-charge difference calculated with truth information and double-ratio method
- At midrapidity, the two methods **agree within 1%**

Credit: Wendi Lv, Zebo Tang

Baseline: UrQMD



W. Lv, et. al., arXiv:2309.06445

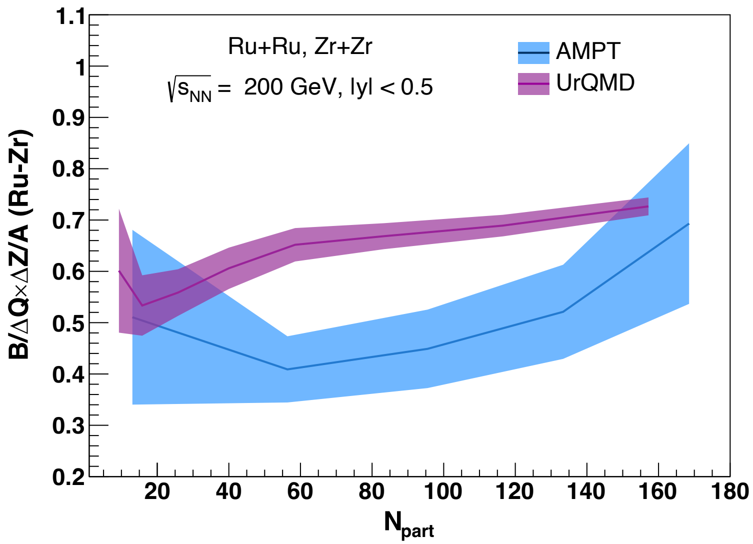
- UrQMD: valence quarks as the baryon number carrier
- *Q/B×A/Z* → 1 towards central collisions of large nuclei
  - Largely statistical; detailed dynamics less important
- For smaller nuclei, UrQMD predicts *B/Q×Z/A* < 1

❖ See Z. Tang's talk today at 16:10

Baseline: UrQMD vs. AMPT

$$\Delta Q = Q_{Ru+Ru} - Q_{Zr+Zr}$$

$$B = (B_{Ru+Ru} + B_{Zr+Zr})/2$$

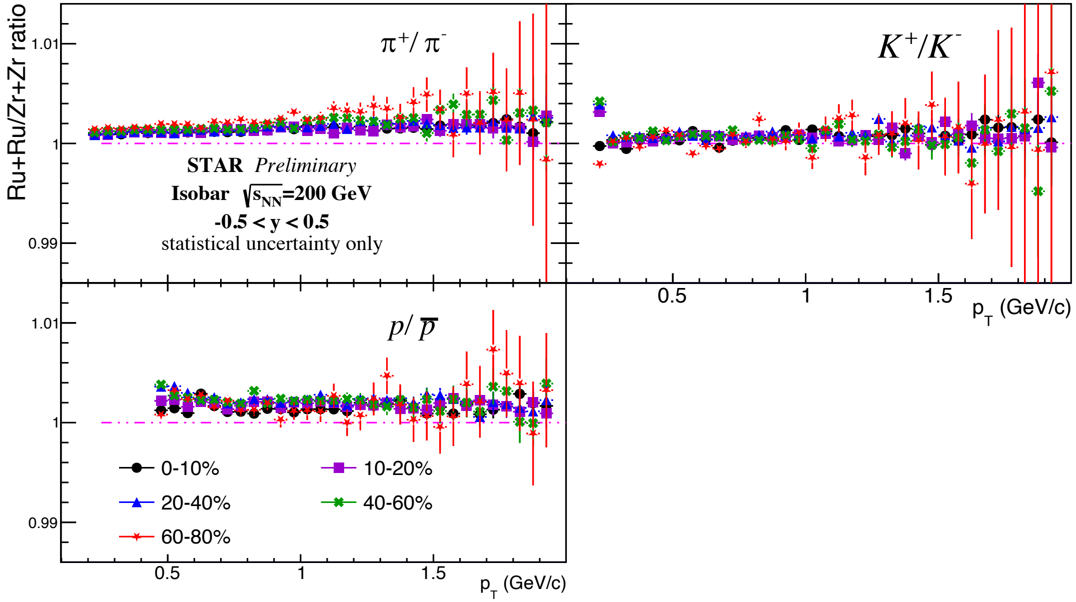


J. Brandenburg, N. Lewis, et. al., arXiv:2205.05685

❖See Z. Lin's talk today at 15:40

- Both UrQMD and AMPT predict $B/\Delta Q \times \Delta Z/A < 1$
- The less-than-one value is attributed to more anti-*s* quarks than *s* quarks at midrapidity
  - Strange quark: ΔB = anti-*s* – *s* = -2/3, ΔQ = anti-*s* – *s* = 2/3

Double-ratios in Isobar Collisions



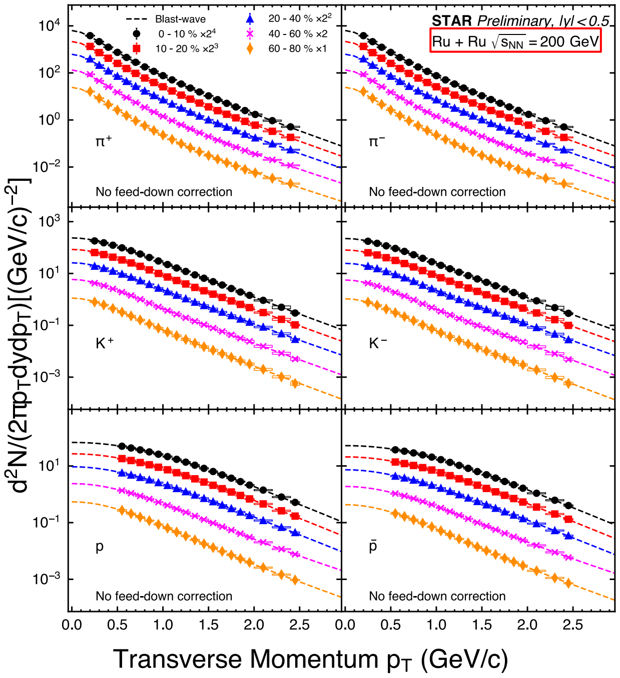
$R2_\pi \sim 0.1\%$

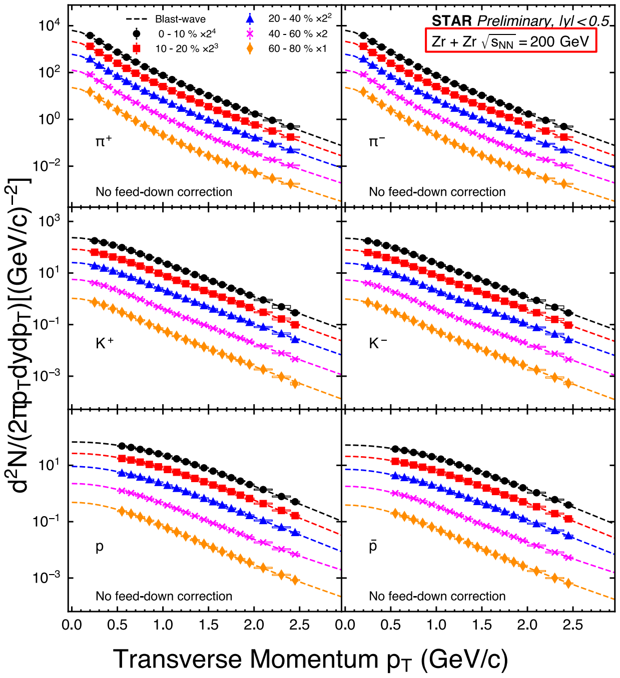
$R2_K \sim 0$

$R2_p \sim 0.1\%$

- Very precise measurement with negligible uncertainties
- Fit with a linear function to extrapolate down to zero p_T

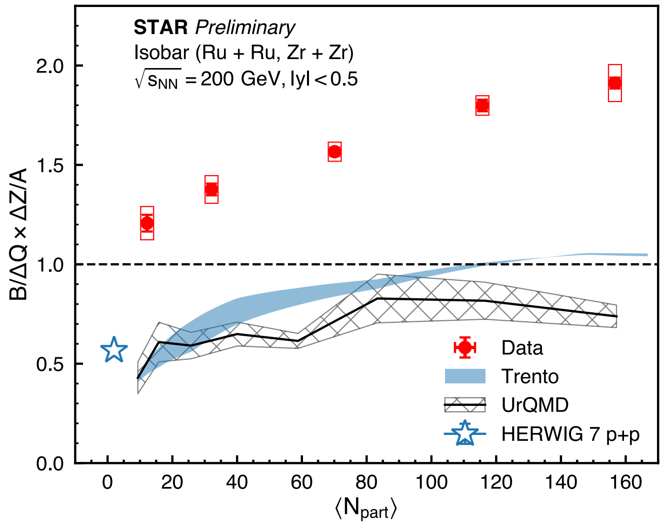
Identified Particle Spectra





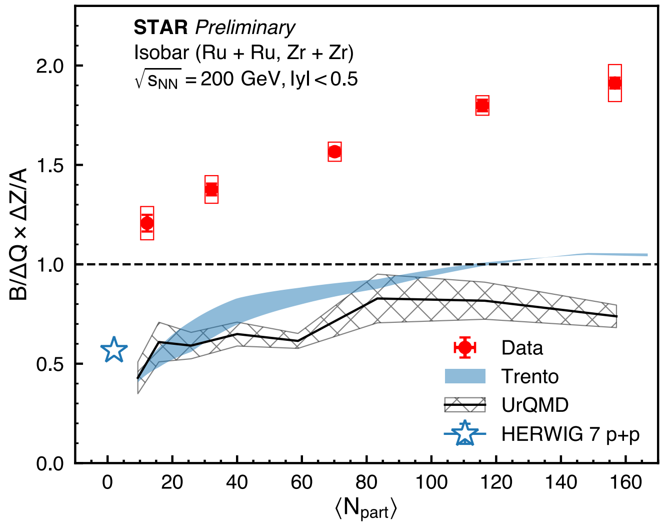
- Blast-wave fit to extrapolate down to zero p_T

$\langle B \rangle / \Delta Q \times \Delta Z/A$ vs. Centrality



- Central collisions, B×ΔZ/A ~ 2×ΔQ → significantly higher than naïve expectation of valence quarks carrying baryon number
- Ratio decreases from central (~2) to peripheral (~1.2) collisions

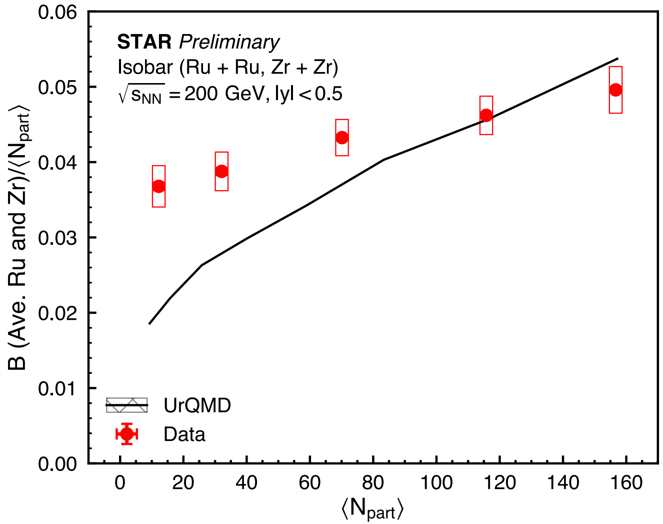
$\langle B\rangle/\Delta Q \times \Delta Z/A$ vs. Centrality

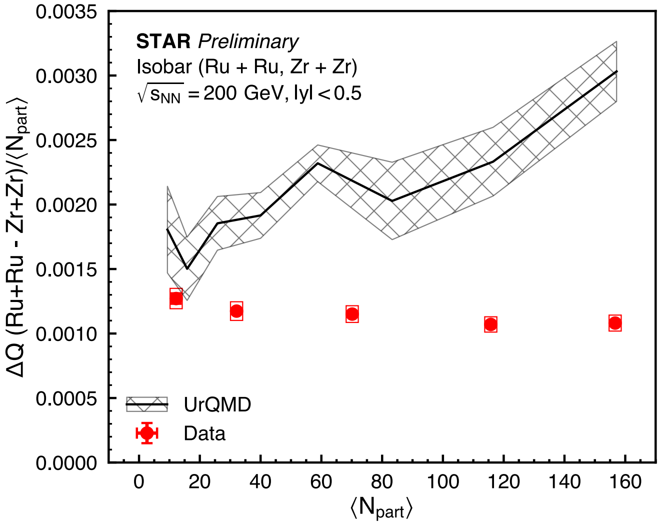


	Has junction?	⟨B⟩/ΔQ ×ΔZ/A
Data		1.3 – 2
UrQMD	No	0.5 – 0.7
		B/Q
HERWIG7	No	0.56
		(n+p)/Δp×ΔZ/A
Trento	N/A	0.5 – 1

- Models predict ratio less than 1
- Trento: decreasing towards peripheral due to different neutron skins between Ru and Zr

Compare ⟨B⟩ and ΔQ Individually





- Central collision: UrQMD can describe baryon number, but significantly overshoots charge number → enhancing baryon transport results in too many quarks stopped at midrapidity
- Correct model should describe both simultaneously

M. Bleicher, et. al., J. Phys. G 25 (1999) 1859

Test 2

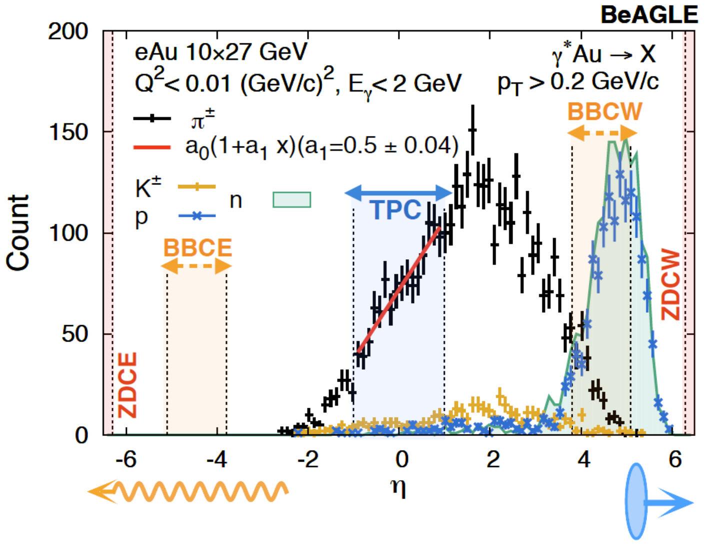
Net-proton $dN/d\Delta y$ in γ+Au Events

Why γ+Au Events?

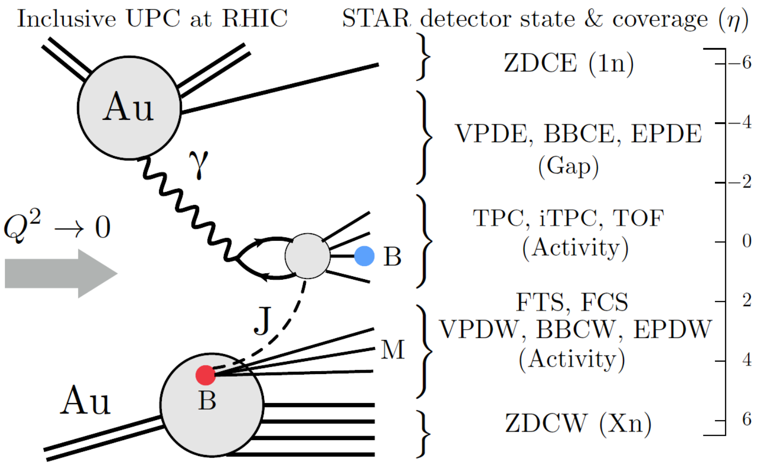
- A simple process with the projectile carrying zero baryon number
- It is very hard for the incoming photon to stop multiple valence quarks simultaneously at midrapidity
  - Valence quark picture: little baryon transport
  - Junction picture: more baryon transport
- Can directly measure net-proton $dN/d\Delta y$ in such asymmetric collisions
  - $\Delta y = Y_{\text{beam}} - y$: Y_{beam} is fixed, y varies

Select γ+Au Events

➤ Asymmetric east vs. west event activity



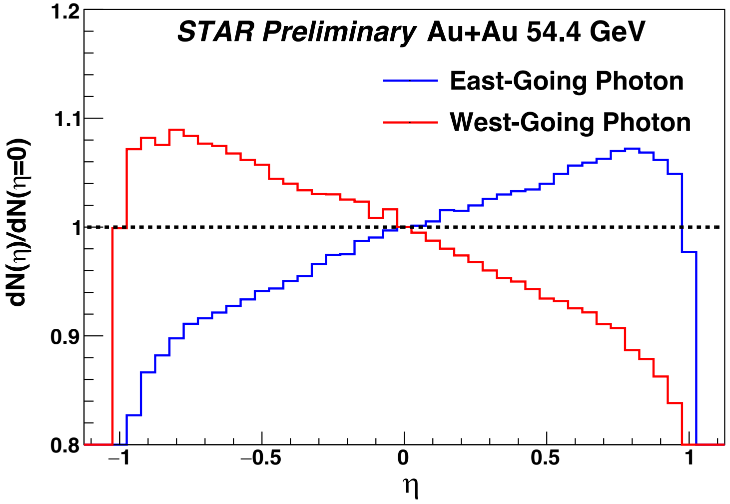
BeAGLE: W. Chang, et. al., PRD 106 (2022) 012007

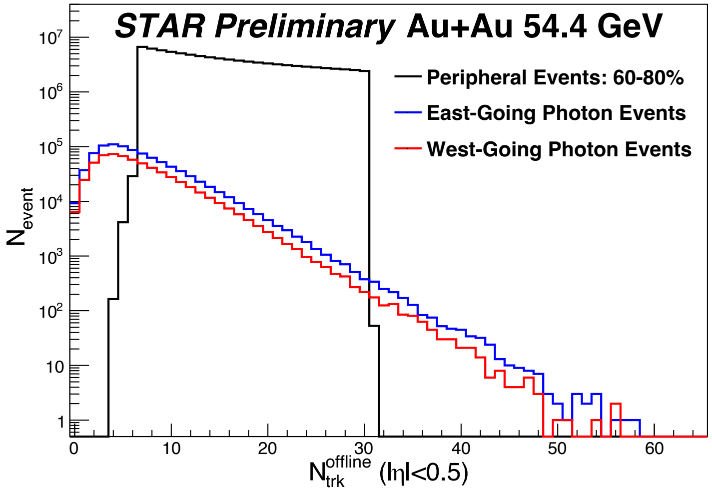


J. Brandenburg, N. Lewis, et. al., arXiv:2205.05685

Select γ+Au Events

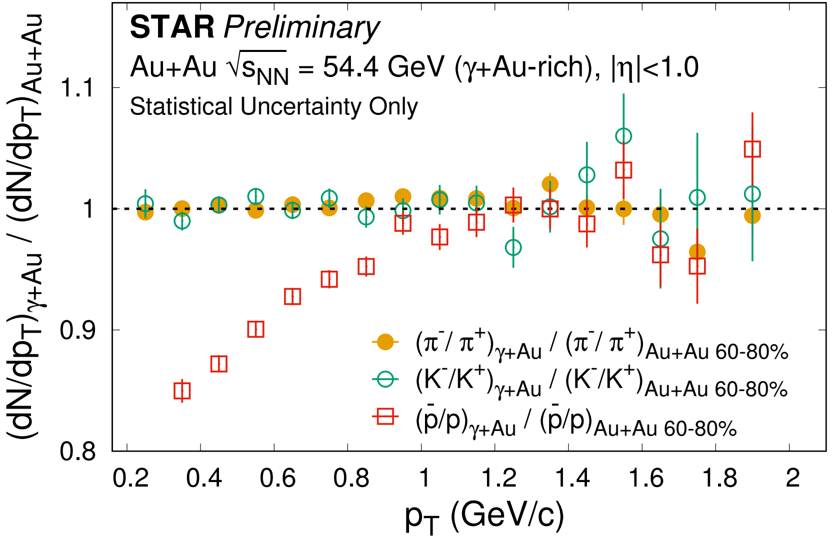
- Asymmetric east vs. west event activity



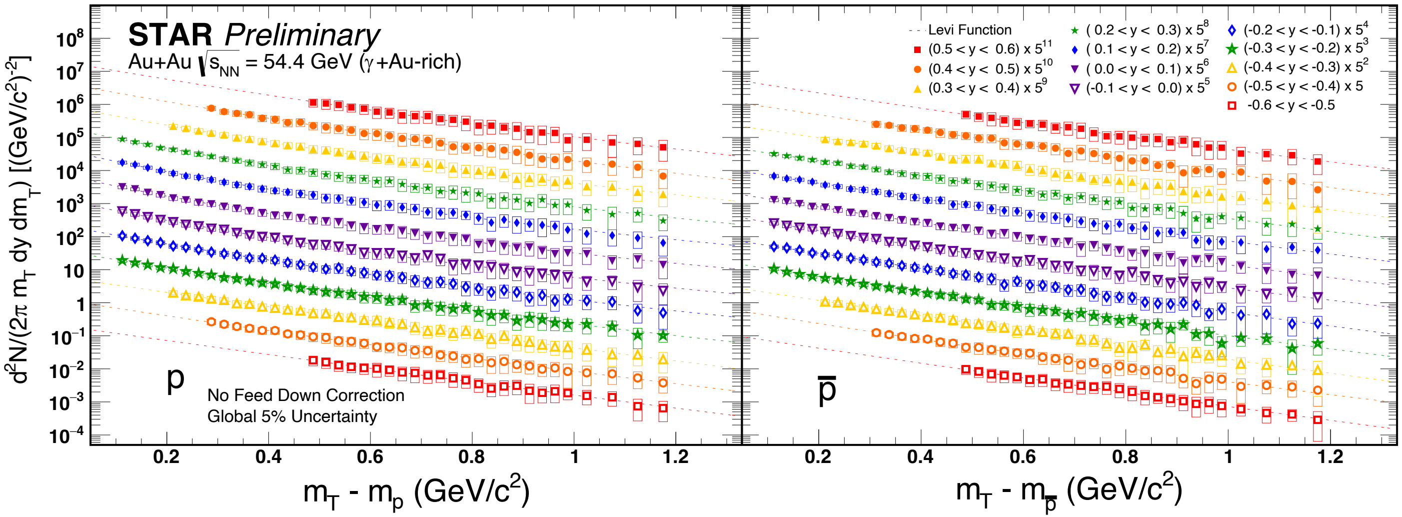


γ+Au vs. Peripheral Collisions

- **Significant baryon transport** in γ+Au events
  - No difference in mesons

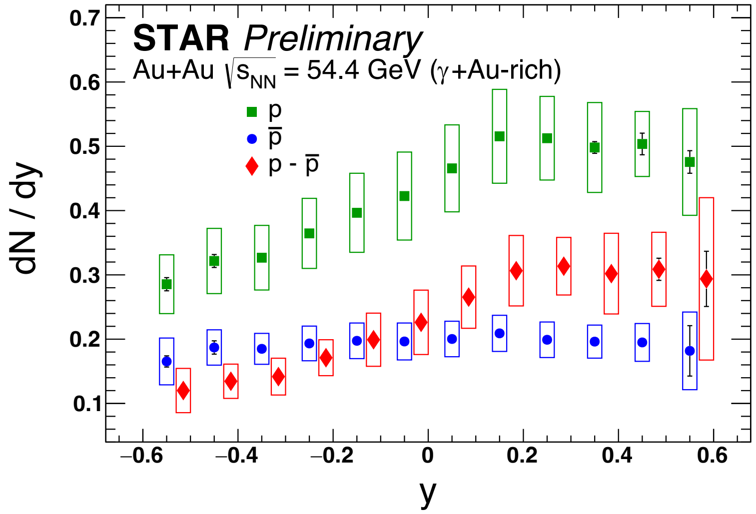


Proton Spectra



- Measured in 12 different rapidity regions
- Extrapolated down to 0 p_T with Levy function

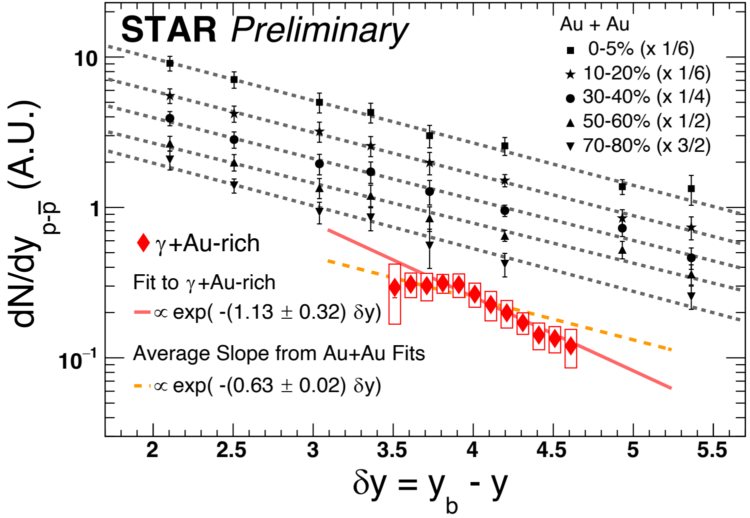
Rapidity Densities



$y = Y_{\text{beam}} - \Delta y$

- Clear excess of *p* over anti-*p* → incoming photons can stop baryon number
- Flat distribution of anti-*p* → net-*p* slope is not created artificially by event selection

Rapidity Slope of Net-Proton



$y = Y_{\text{beam}} - \Delta y$

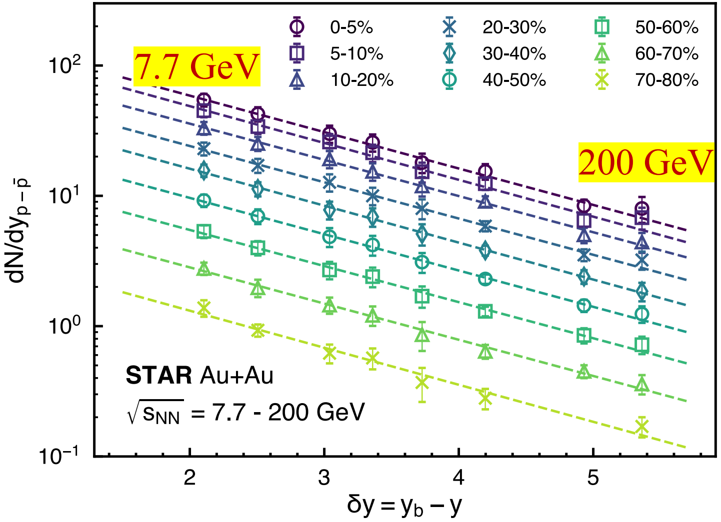
- ➢ Clear rapidity dependence of net-*p* → slope ~ 1.13

Test 3

Net-proton $dN/d\Delta y$ in Au+Au Events

Net-proton vs. Rapidity Shift

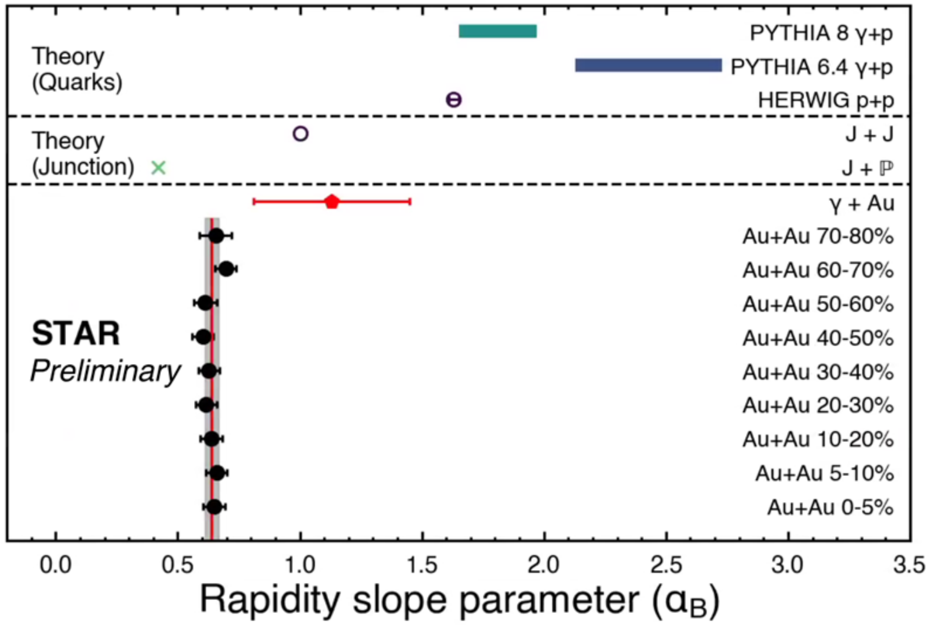
- $\Delta y = Y_{\text{beam}} - y$: Y_{beam} changes with energy while $y \sim 0$ is fixed



J. Brandenburg, N. Lewis, et. al., arXiv:2205.05685

➢ Fit with an exponential function

γ+Au vs. Au+Au vs. Theory



Junction theory: D. Kharzeev, PLB 378 (1996) 238

- No centrality dependence of the slope → not expected for valence quark stopping
- $Slope_{\gamma+Au}$ >~ $Slope_{Au+Au}$: possibly collision energy or process dependence

  X. Artru, M. Mekhfi, Nucl. Phys. A 532 (1991) 351
- Qualitatively consistent with baryon junction prediction
- Smaller than HERWIG and PYTHIA predictions

Conclusions

- Presented three independent experimental measurements that are all incompatible with the scenario where the baryon number is carried by valence quarks
  - **Isobar collisions**: significantly more baryon transport than charge transport
  - **γ+Au**: clear baryon transport with a rapidity slope smaller than PYTHIA and HERWIG predictions
  - **Au+Au**: rapidity slope independent of centrality

Backup

Net-charge Number

$$N_{\pi^+}^{Ru} = N_\pi^{Ru} + \delta_1$$
$$N_{\pi^-}^{Ru} = N_\pi^{Ru} - \delta_1$$
$$N_{\pi^+}^{Zr} = N_\pi^{Zr} + \delta_2$$
$$N_{\pi^-}^{Zr} = N_\pi^{Zr} - \delta_2$$
$$N_\pi^{Ru} = N_\pi + \delta$$
$$N_\pi^{Zr} = N_\pi - \delta$$

$$\Delta Q_\pi = (N_{\pi^+}^{Ru} - N_{\pi^-}^{Ru})\frac{N_\pi}{N_\pi + \delta} - (N_{\pi^+}^{Zr} - N_{\pi^-}^{Zr})\frac{N_\pi}{N_\pi - \delta}$$
$$= \frac{2N_\pi}{N_\pi^2 - \delta^2}(N_\pi(\delta_1 - \delta 2) - \delta(\delta_1 + \delta_2))$$
$$\simeq 2(\delta_1 - \delta_2) - \frac{2\delta}{N_\pi}(\delta_1 + \delta_2)$$
$$-2(\frac{\delta}{N_\pi})^3(\delta_1 + \delta_2) + [...]$$

$$R2_\pi = \frac{(N_{\pi^+}^{Ru}/N_{\pi^-}^{Ru})}{(N_{\pi^+}^{Zr}/N_{\pi^-}^{Zr})}$$
$$= \frac{(N_{\pi^+}^{Ru} \times N_{\pi^-}^{Zr})}{(N_{\pi^+}^{Zr} \times N_{\pi^-}^{Ru})}$$
$$= \frac{(N_\pi + \delta + \delta_1)(N_\pi - \delta - \delta_2)}{(N_\pi - \delta + \delta_2)(N_\pi + \delta - \delta_1)}$$
$$= \frac{N_\pi^2 + N_\pi(\delta_1 - \delta_2) - (\delta + \delta_1)(\delta + \delta_2)}{N_\pi^2 - N_\pi(\delta_1 - \delta_2) - (\delta - \delta_1)(\delta - \delta_2)}$$

$$R2_\pi \simeq 1 + \frac{2}{N_\pi}(\delta_1 - \delta_2) - \frac{2\delta}{N_\pi^2}(\delta_1 + \delta_2)$$
$$+\frac{2}{N_\pi^2}(\delta_1 - \delta_2)^2 + (1/N_\pi)^3[...] + [...]$$

$$R2_\pi = 1 + \Delta Q_\pi / N_\pi$$
$$\Delta Q_\pi = N_\pi(R2_\pi - 1)$$

Estimate Neutron Yields

In the framework of the statistical thermal model, the production yield for a particle is given by:

$$N = F(m)e^{B\mu_B + S\mu_S + Q\mu_Q}, \quad (5)$$

where $F(m)$ is a function of the particle mass (m). B, S, and Q_i are the baryon number, strangeness, and electric charge of the particle, while μ_B, μ_S, and μ_Q are the chemical potentials of the corresponding conserved quantum numbers. Consequently,

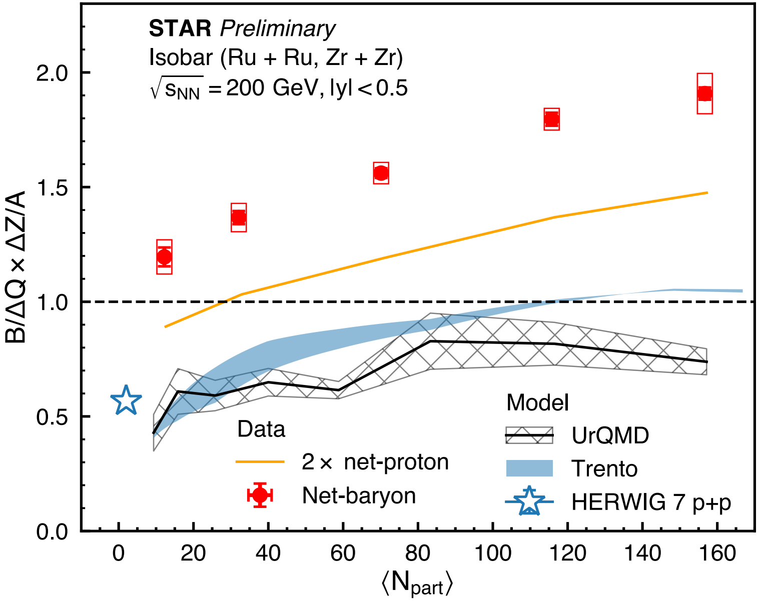
$$N_{\bar{p}} = F(m_p)e^{-\mu_B - \mu_Q} \quad (6)$$

$$N_d = F(m_d)e^{2\mu_B + \mu_Q} \quad (7)$$

$$N_{\bar{d}} = F(m_d)e^{-2\mu_B - \mu_Q} \quad (8)$$

$$N_n = F(m_n \approx m_p)e^{\mu_B} = N_{\bar{p}}\sqrt{N_d/N_{\bar{d}}} \quad (9)$$

$\langle B\rangle/\Delta Q \times \Delta Z/A$ vs. Centrality



- ➢ Yellow line: use 2×net-proton as the lower limit
  - ○ More neutrons than protons in the incoming nuclei