Measurements of identified particle spectra in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV by STAR

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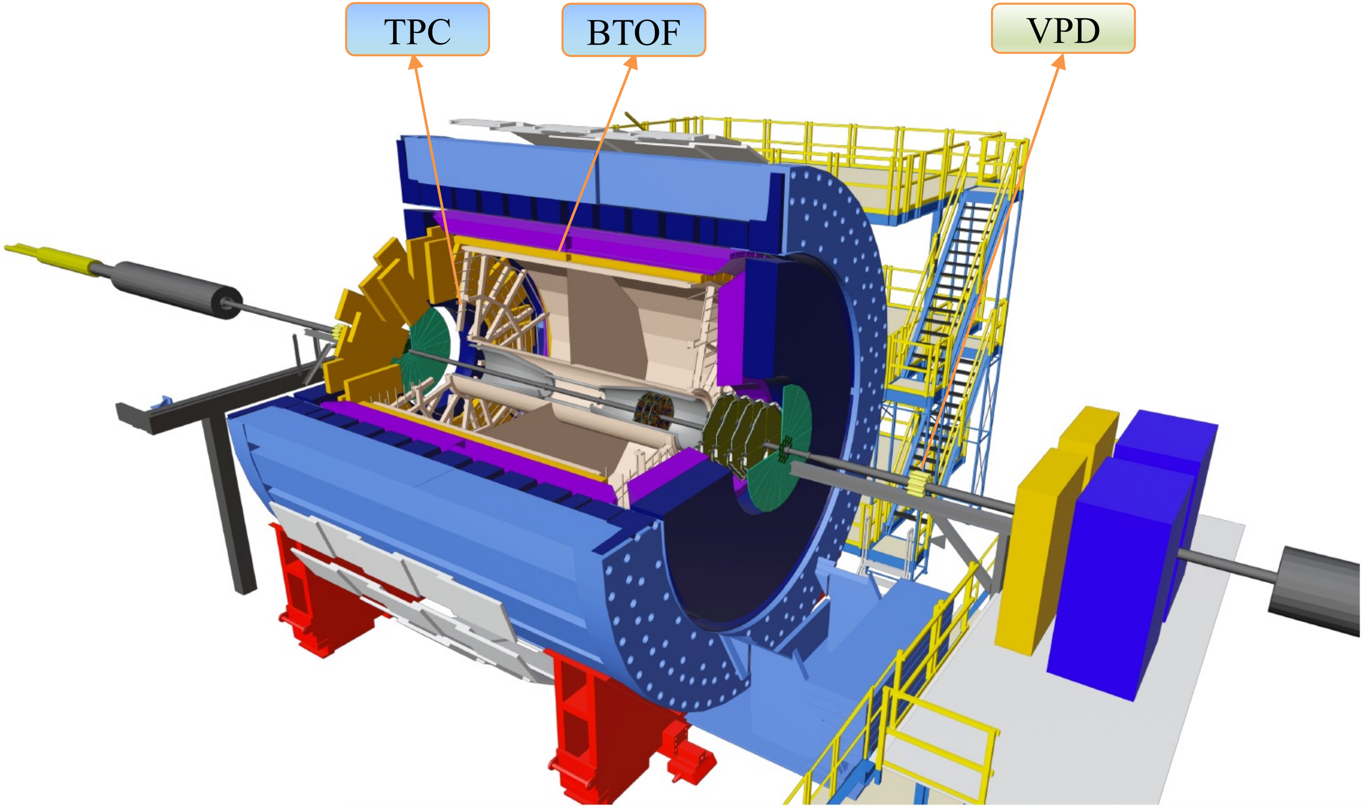
America/Denver timezone

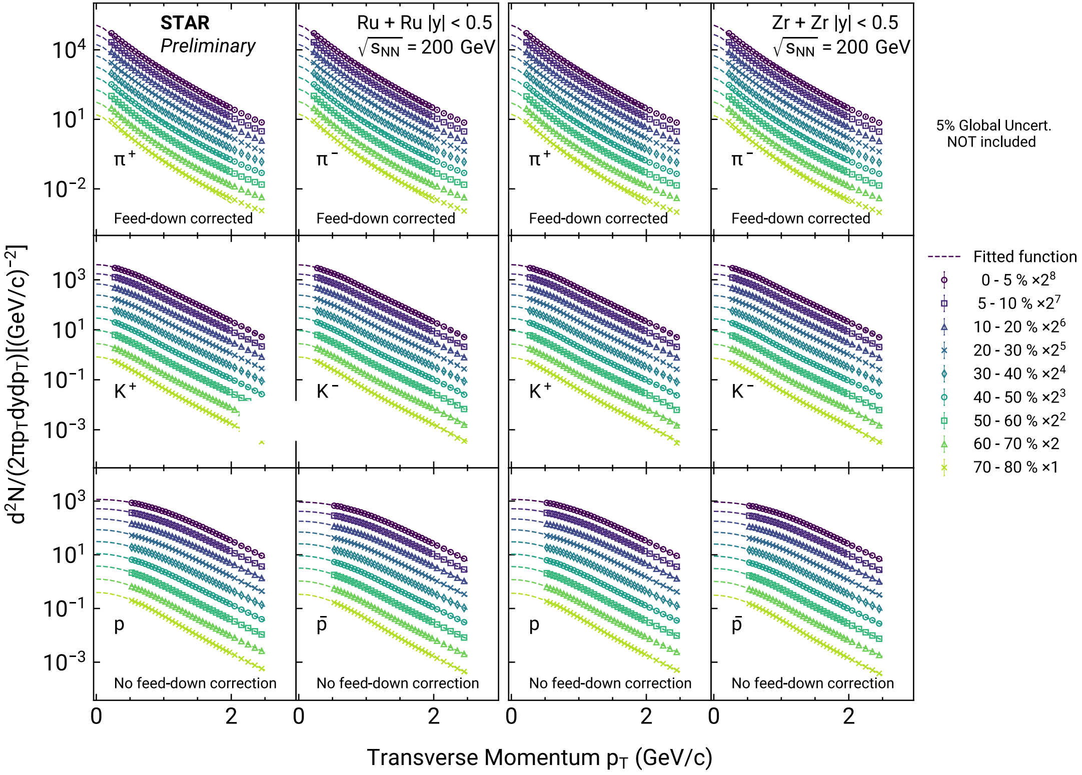
Outline

- STAR Detector
- Identified Particle Spectra
  - Bulk Properties
  - Baryon Number Carrier
- Conclusions

STAR Detector



Identified Particle Spectra



- Measured $\pi^{+/-}$, $K^{+/-}$, p, $\bar{p}$ spectra within $|y| < 0.5$
  - Low p_T: TPC
  - Higher p_T: BTOF

- Extrapolate down to zero p_T with fits
  - π: Bose-Einstein
  - K, p: Blast-wave

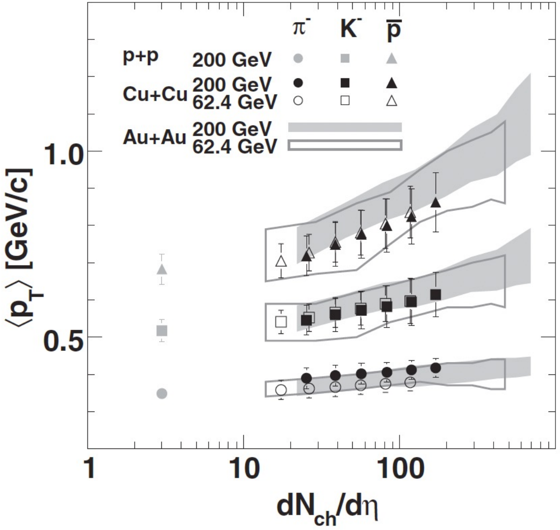
Bulk Properties

What Can We Learn?

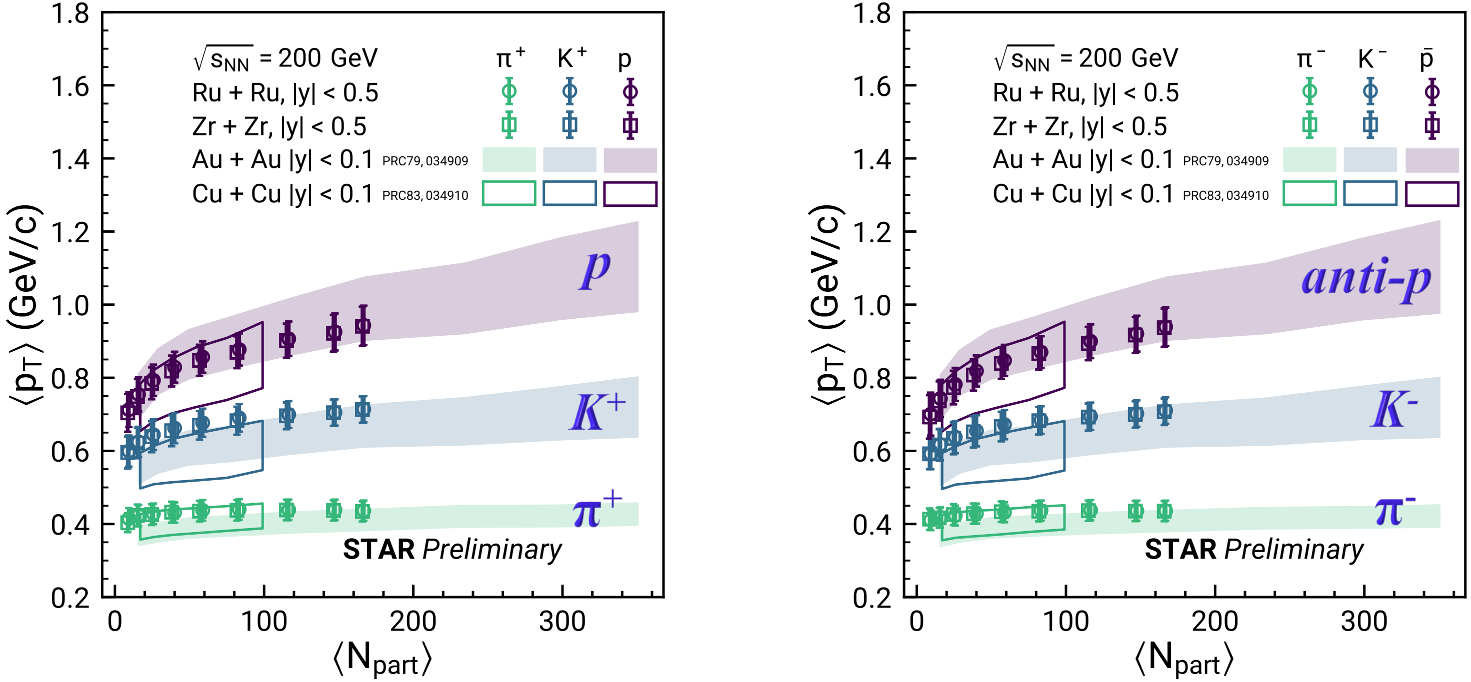
- Fundamental properties of the QGP created in Isobar collisions
  - Critical constraints to model calculations

- What drives the bulk properties?
  - Previous Au+Au and Cu+Cu measurements show multiplicity scaling regardless of nuclear size
  - Further test this picture with Isobar collisions ($R_{\mathrm{Cu}} < R_{\mathrm{Ru}} \sim R_{\mathrm{Zr}} < R_{\mathrm{Au}}$)

STAR, PRC 83 (2011) 034910



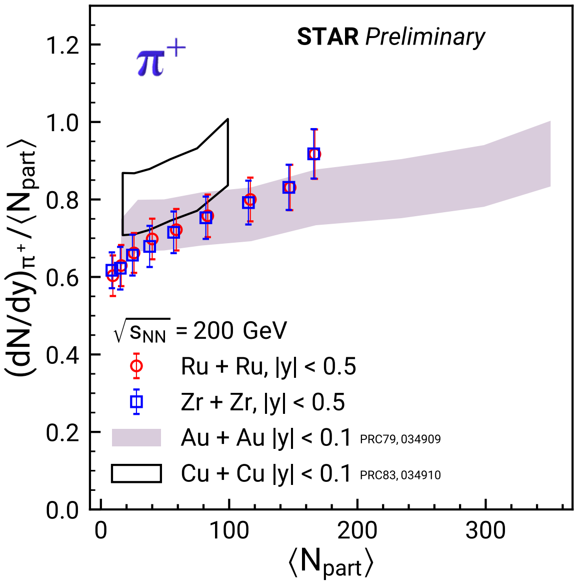
Particle $<p_T>$

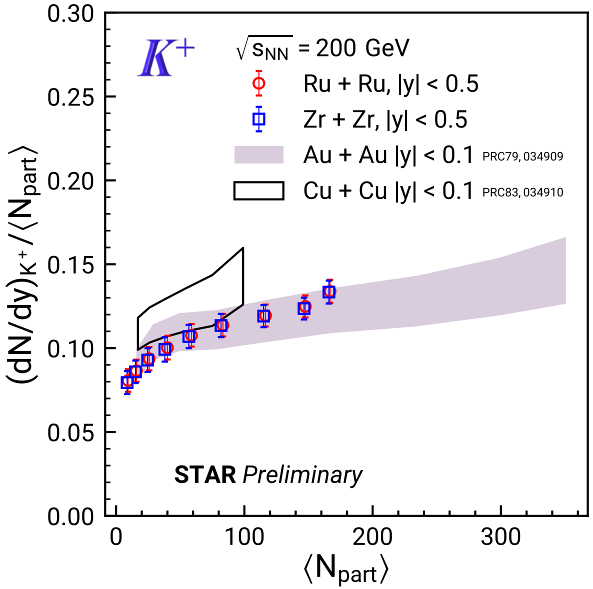


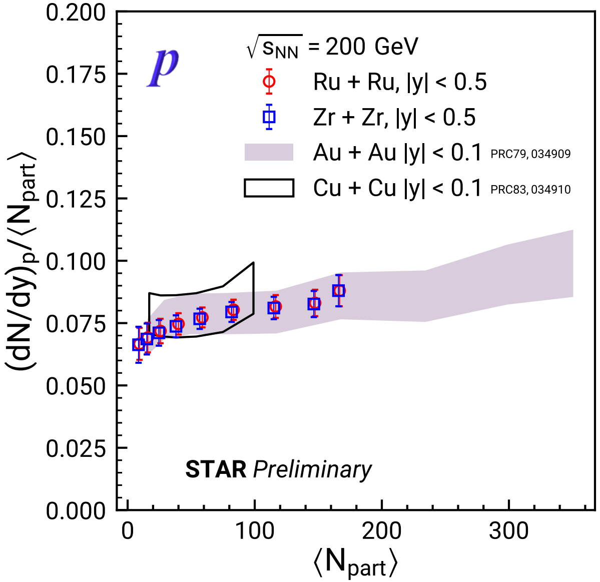
- Increasing $<p_T>$ with centrality and particle mass → radial flow

Normalized Particle Yields

Positive



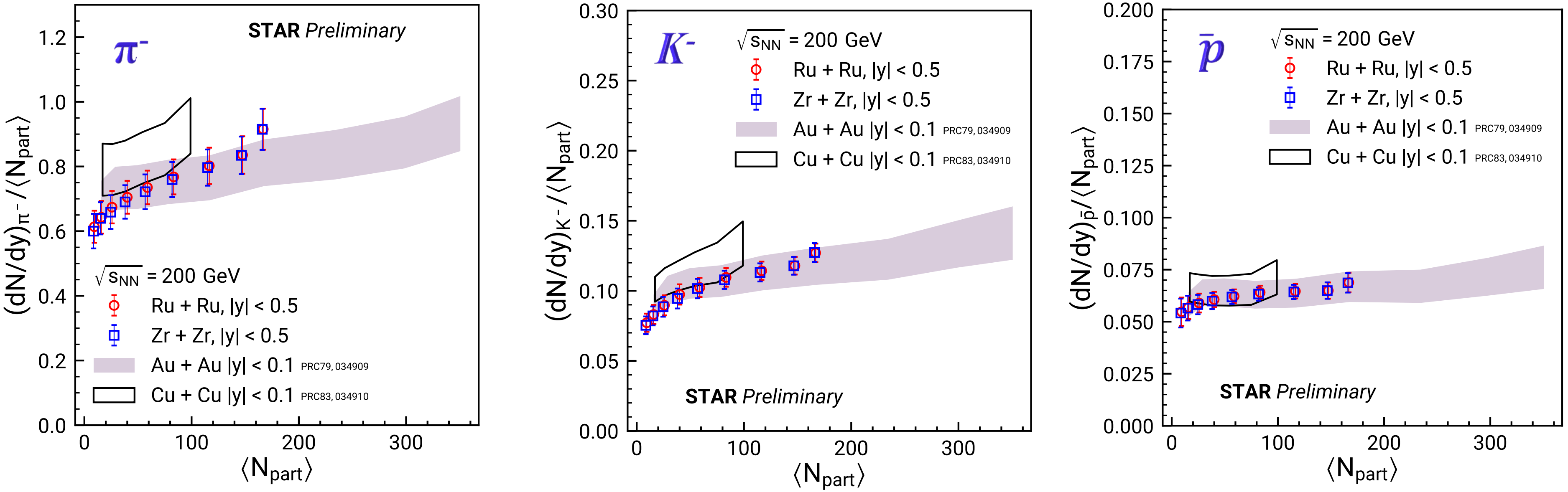




- Increases with centrality; scales with N_{part}

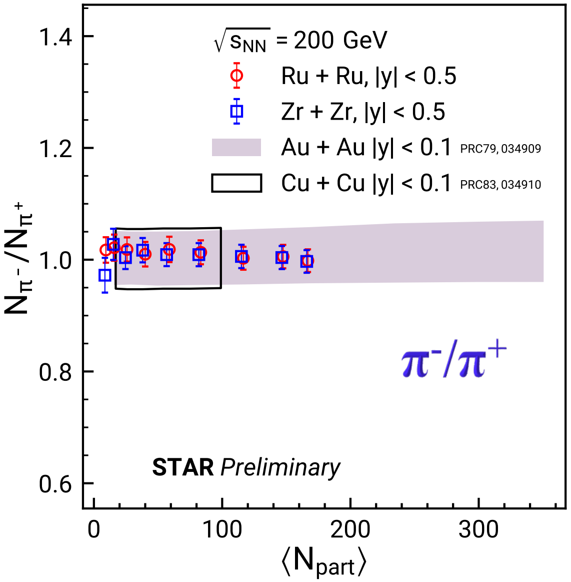
Normalized Particle Yields

Negative

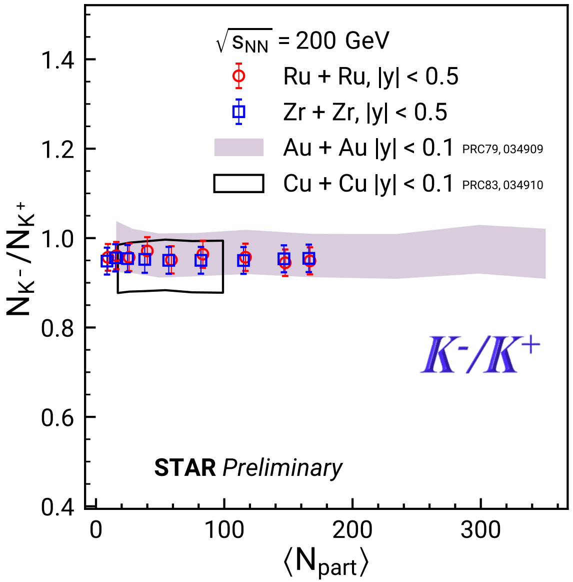


- ➢ Increases with centrality; scales with N_{part}

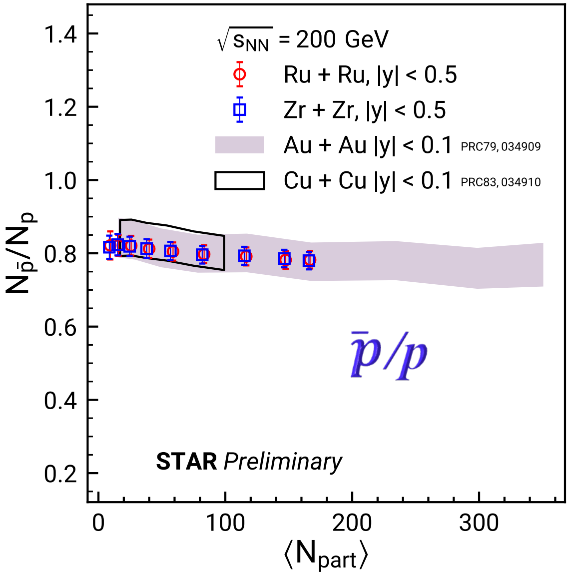
Anti-particle to Particle Ratio



$\frac{\pi^-}{\pi^+} > \sim 1$ → isospin

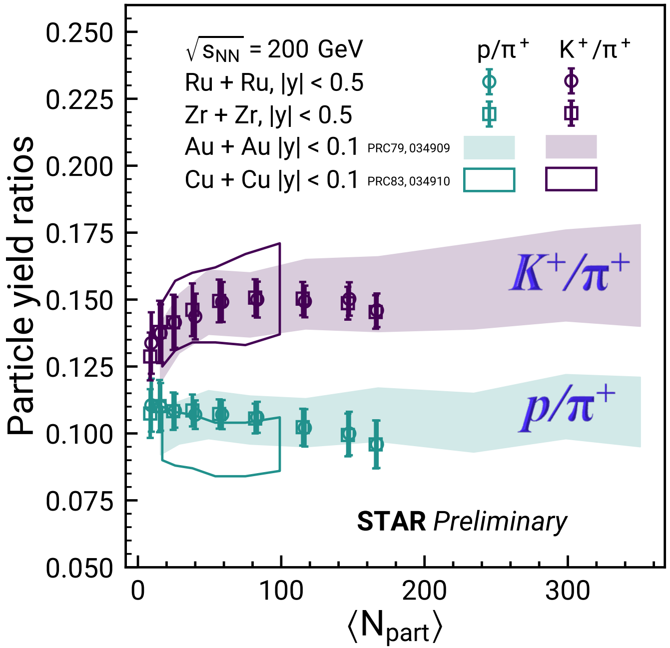


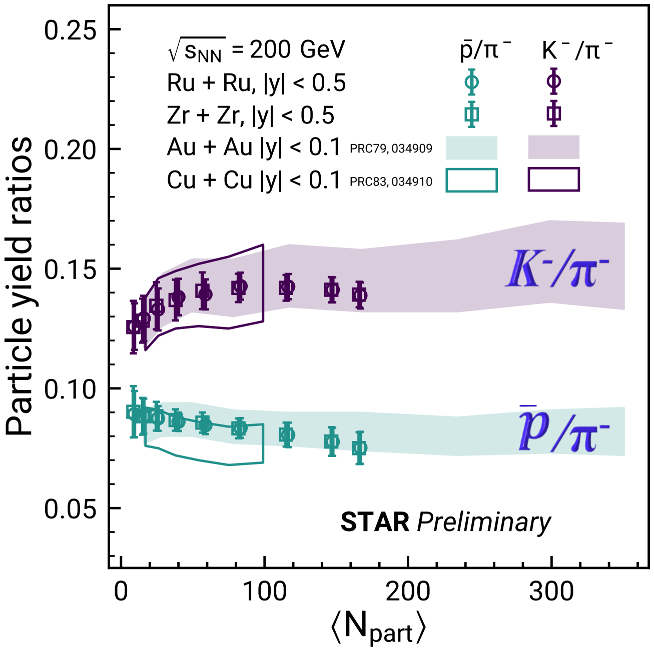
$\frac{K^-}{K^+} \sim 0.95$ → associated production



$\frac{\bar{p}}{p} < 1$ → baryon transport

Cross-Particle Ratios



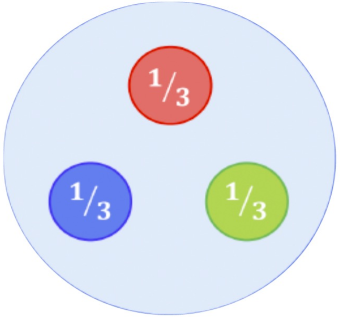


- Hint of increasing *K/π* ratio in peripheral collisions; while the centrality dependence for *p/π* is weaker

Baryon Number Carrier

What Carries the Baryon Number?

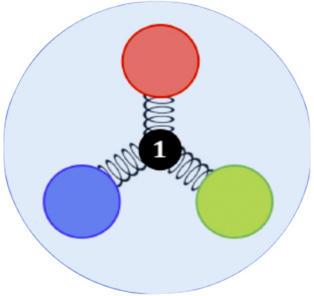
Valence Quarks



- Carry large momentum fractions
- Hard to be stopped at midrapidity
- Ensemble basis: $Q \sim B \times Z/A$

VS.

Junctions



- Consist of low-momentum gluons
- Easier to be stopped at midrapidity
- Ensemble basis: $Q < B \times Z/A$

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

Compare Q vs. $B \times Z/A$ in Ru+Ru and Zr+Zr collisions

Charge and Baryon Transport

✓ Charge transport: net-charge number

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

✓ Baryon transport: net-baryon number

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

- Measured within $|y| < 0.5$
  - Large rapidity transport: $\Delta y \sim 5.4$
  - Almost all particles decay to π, K, p, n
  - Measured spectra include resonance and weak decays
  - Neutron yields estimated based on proton and deuteron yields following the thermal model

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

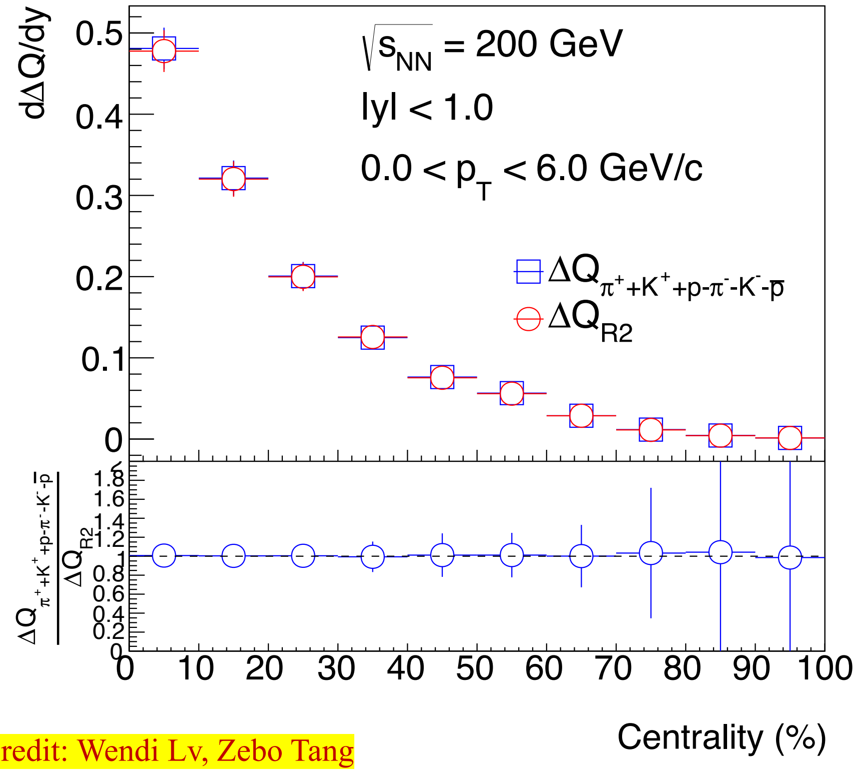
✓ We compare:

$$\Delta Q \text{ vs. } B \times \frac{\Delta Z}{A}$$

$\Delta Z = 44 - 40 = 4$, $A = 96$

B: average between Ru+Ru and Zr+Zr

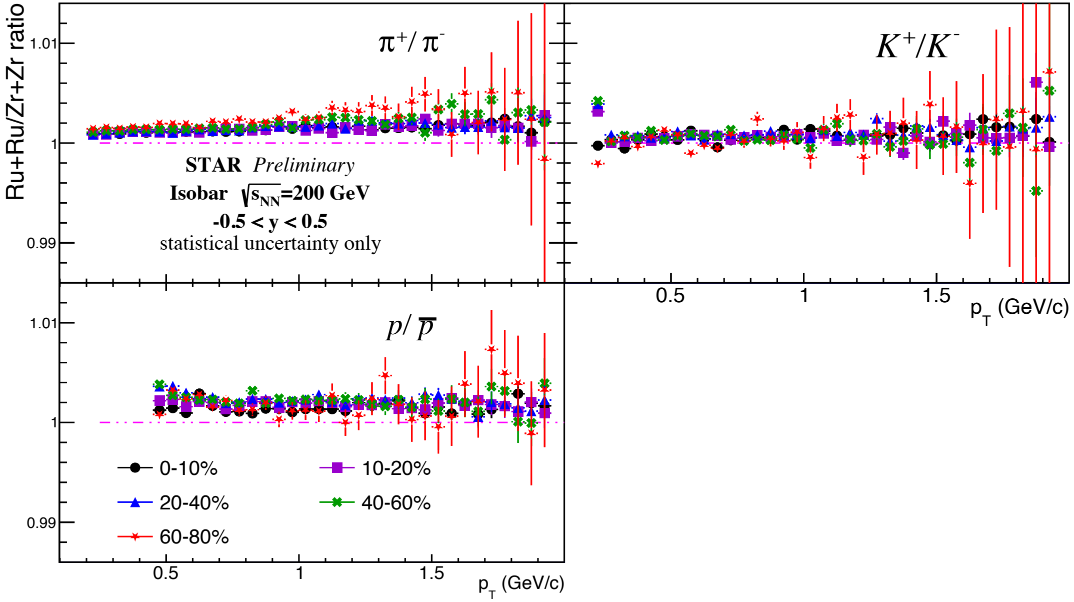
Verify Double-ratio Method



Credit: Wendi Lv, Zebo Tang

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

Double Ratios in Isobar Collisions



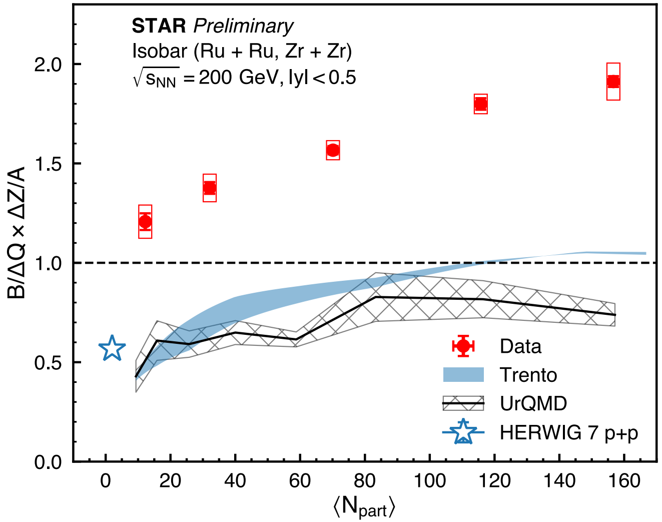
$$R2_\pi - 1 \sim 0.1\%$$

$$R2_K - 1 \sim 0$$

$$R2_p - 1 \sim 0.1\%$$

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

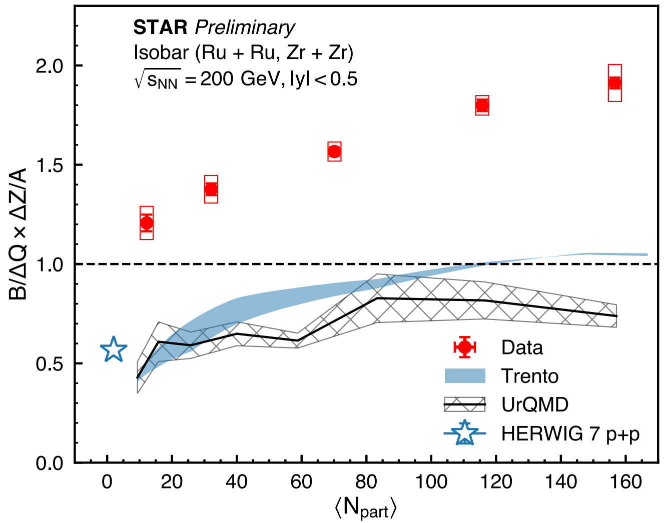
$\langle B\rangle/\Delta Q \times \Delta Z/A$ vs. Centrality



- 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

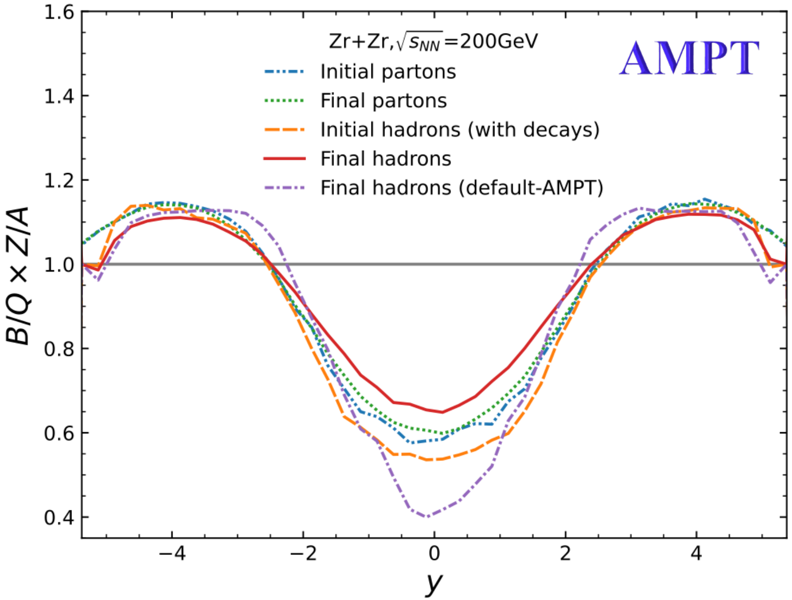
$\langle B\rangle/\Delta Q \times \Delta Z/A$ vs. Centrality



	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 ← Asymmetry in strange quark transport
- Trento: decreasing towards peripheral due to different neutron skins between Ru and Zr

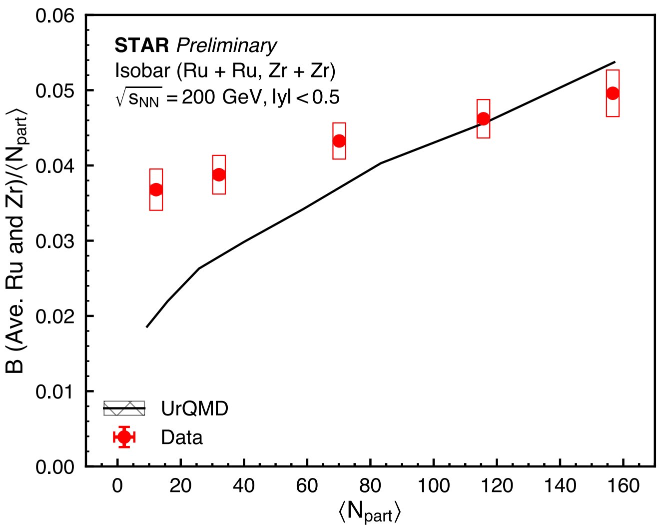
Does medium evolution affect B/Q?

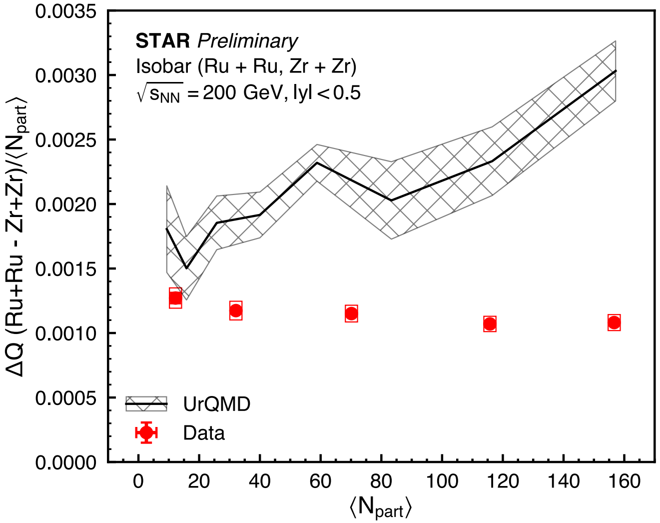


Z. Lin
CFNS workshop on baryon dynamics, 2024

- AMPT predicts similar *B/Q* values at all stages of medium evolution

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

Conclusions & Outlook

- Identified particle ($\pi^{+/-}$, $K^{+/-}$, p, $\bar{p}$) spectra are measured within |y| < 0.5 in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV

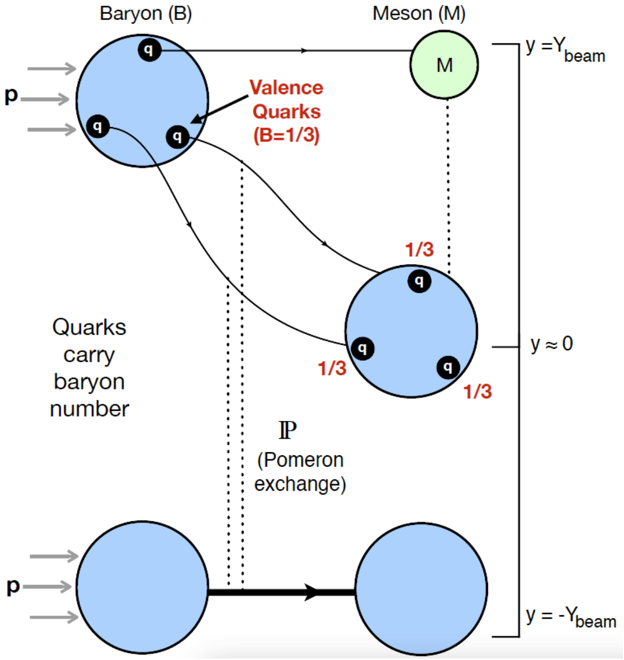
- Bulk properties (<p_T>, yields, yield ratios) scale with N_{part} along with Au+Au and Cu+Cu results → Driven by energy density, rather than geometry
  - ***Future work**: extract freeze-out parameters*

- Significantly more baryon transport than charge transport → incompatible with the scenario where the baryon number is carried by valence quarks
  - See more evidences from γ+Au and Au+Au measurements (Mon 18:30 P. Tribedy)
  - ***Future work**: further investigation at RHIC (strangeness, charge transport, etc); junction PDF at EIC*

Backup

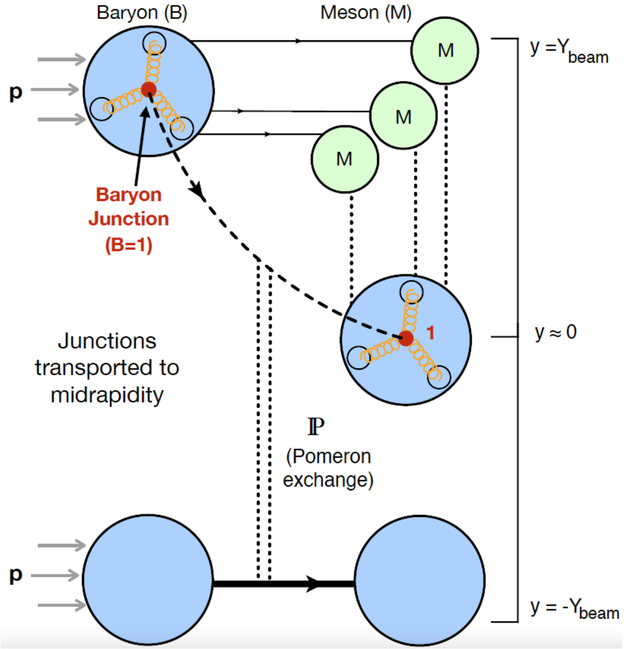
What Carries the Baryon Number?

Valence Quarks



VS.

Junctions



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:

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

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,

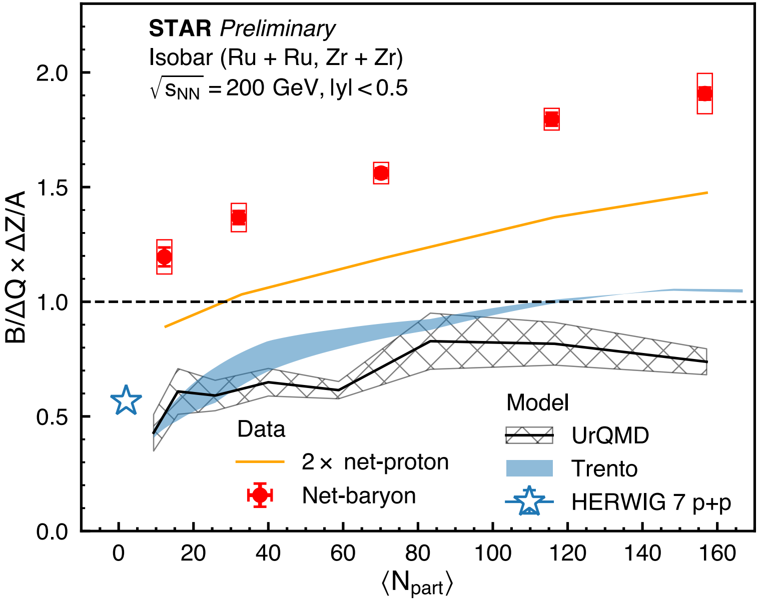
$$N_{\bar{p}} = F(m_p)e^{-\mu_B - \mu_Q} \tag{6}$$

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

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

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

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



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