Tracking the baryon quantum number with heavy-ion collisions

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Kent State University

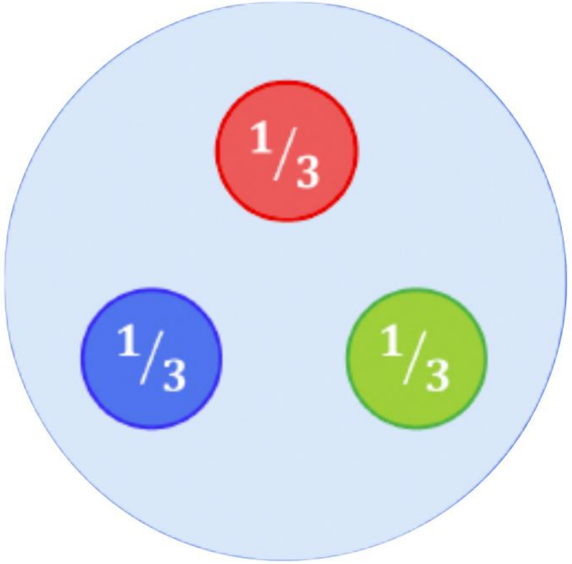
For STAR 25th year celebration

12/17/2025

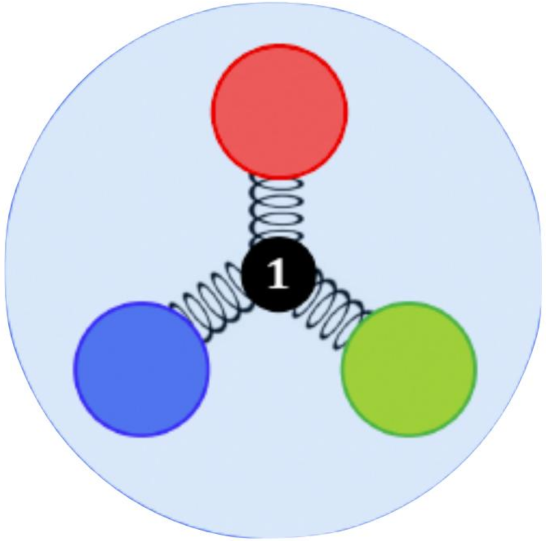
Supported in part by:

What carries baryon number, valence quark vs. baryon junction?

Valence quark



Baryon junction [1, 2]

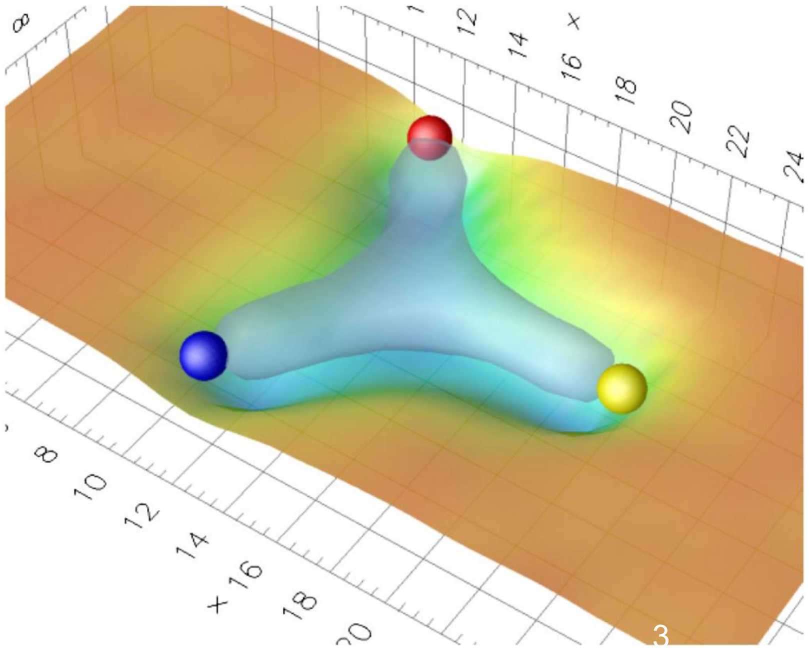


[1]: Nucl. Phys. B 85, 442–460 (1975).
[2]: Nucl. Phys. B 123, 507–545 (1977)

Theoretical considerations for baryon junction

- **Lattice calculations suggested the formation of a Y-shaped color flux tube.**
  - PRL. **86**, 18 (2001)
  - PRD. **65**, 114509 (2002)

Figure from PRD. **76**, 114512 (2007)



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

"there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons"

- Quote from PLB 378, 238 (1996)

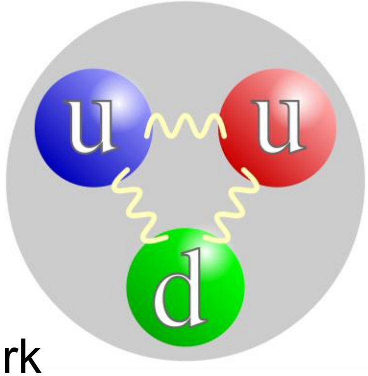


Figure from https://en.wikipedia.org/wiki/Quark

Baryon transport from various mechanisms

Figure from PLB 378, 238 (1996)

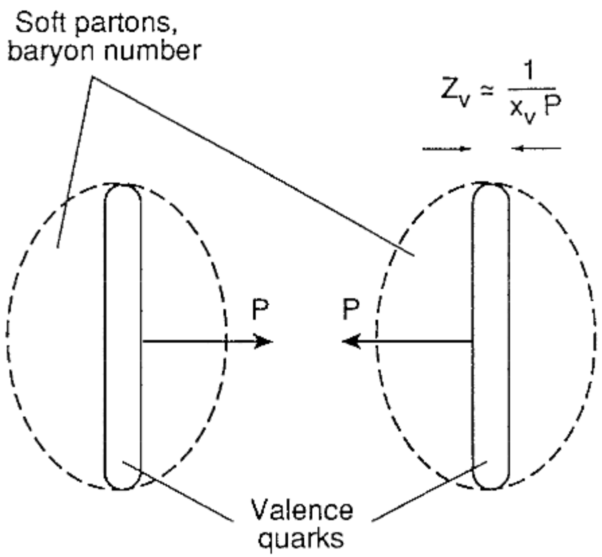


Fig. 2.

Carrier	Composed of	Momentum	Carry electric charge?	Stopped by interaction
Junction	Gluons	Low	No	Relatively Easy
Valence quark	Quarks	High	Yes	Relatively Hard

Baryon transport from junction

- Three methods to test the hypothesis:

    1. Net-Baryon vs. Net-Electric charge difference in Isobar collisions

    2. Net-proton in photonuclear collisions

    3. Net-proton yield as a function of rapidity in hadronic Au+Au collisions

Baryon transport from junction

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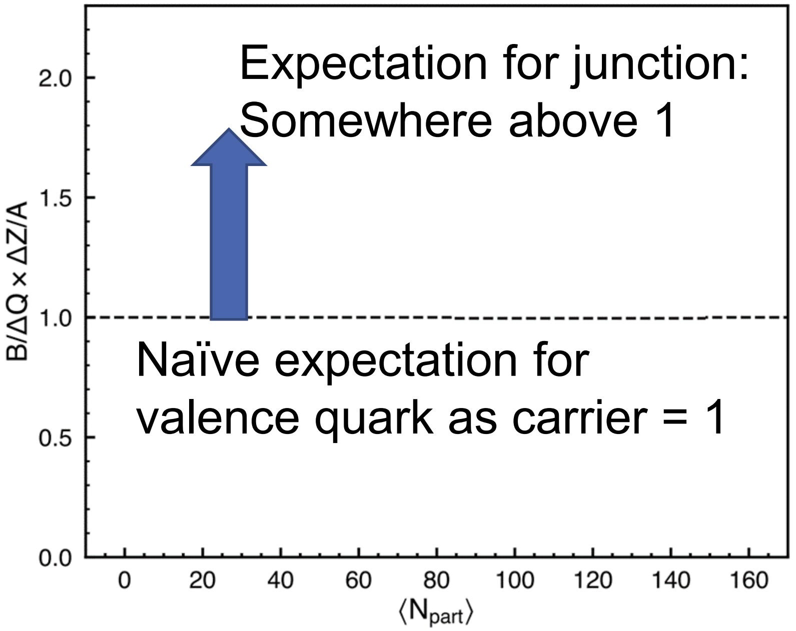
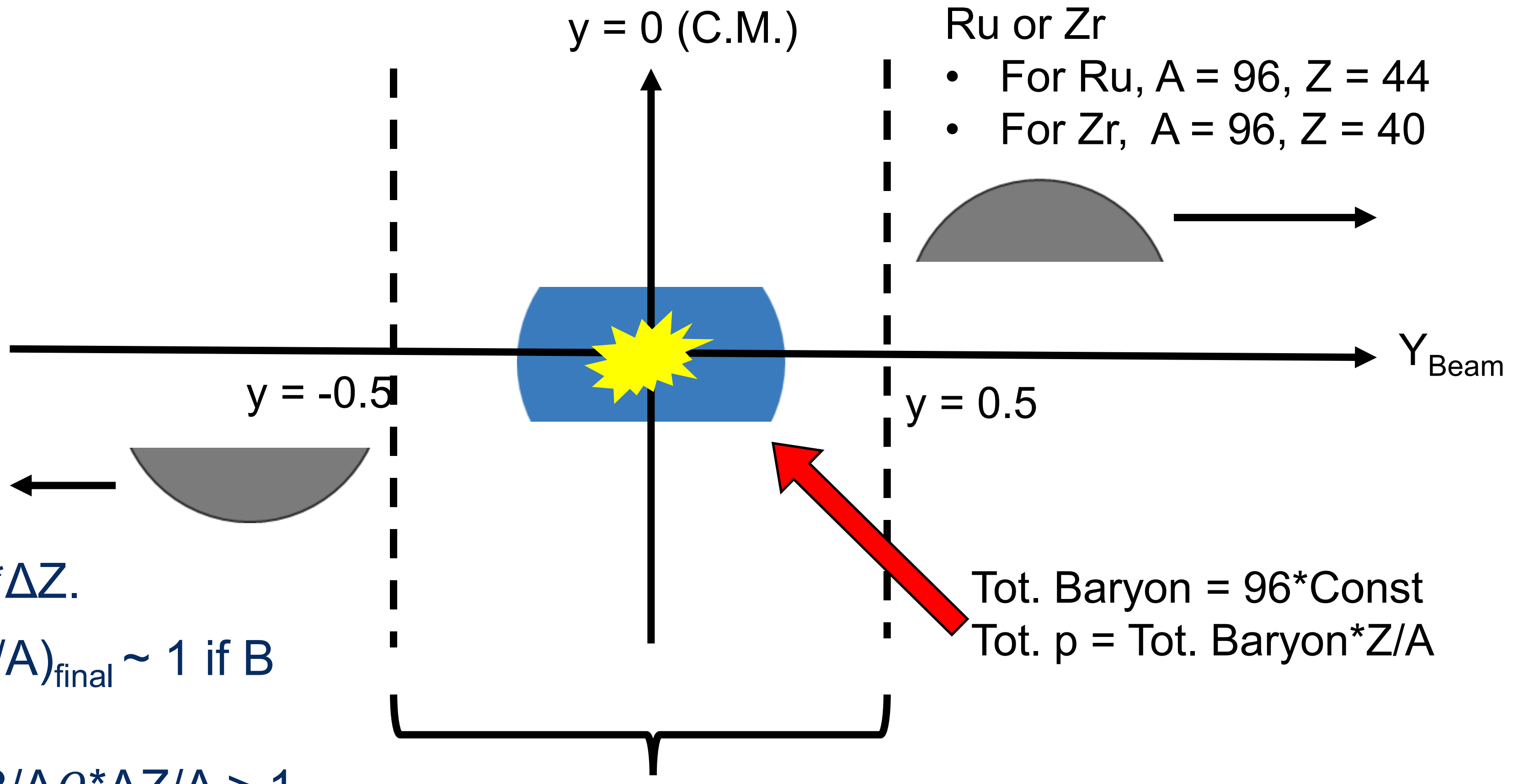
Observable: B/ΔQ*ΔZ/A for isobar reactions (Ru and Zr)

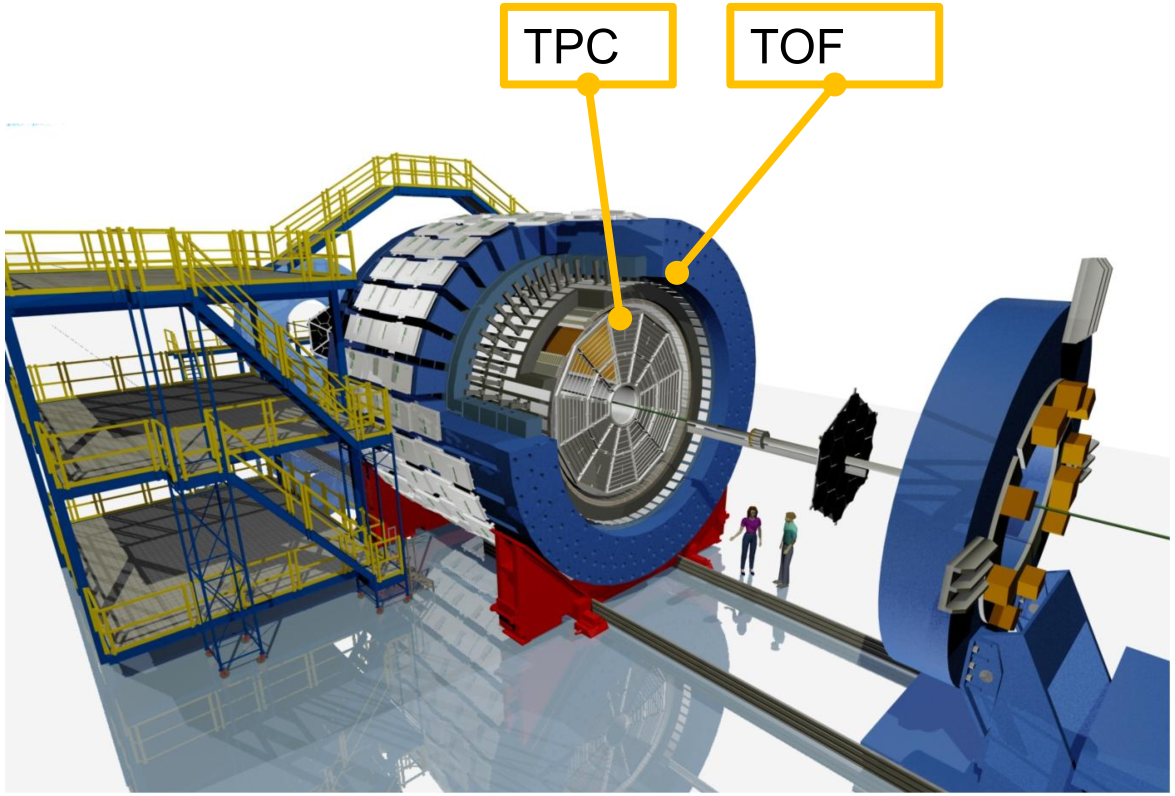




- B_{init}=A*Const.
- $\Delta Q_{init} = Q_{init}\,(Ru - Zr)$=Const*ΔZ.
- (B/ΔQ*ΔZ/A)$_{init}$ = 1 => (B/ΔQ*ΔZ/A)$_{final}$ ~ 1 if B and Q shared same carrier.
- For junction, B is enhanced so B/ΔQ*ΔZ/A > 1.

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

STAR detector



- **Time Projection Chamber (TPC)**
  - Track curvature => momentum (p)
  - Energy loss per unit length (dE/dx) => charge state.
  - p and dE/dx provides particle identification
- **Time-Of-Flight (TOF)**
  - Extends momentum
  - Pile-up rejection
- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})$

Net-Baryon number (B) and net-Charge (Q)

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- Primordial (anti-)neutron yields estimation [1],
  - $\boldsymbol{N_n^{pri} = N_{\bar{p}}^{pri}\sqrt{\frac{N_d}{N_{\bar{d}}}},\ N_{\bar{n}}^{pri} = N_p^{pri}\sqrt{\frac{N_{\bar{d}}}{N_d}}}.$
- Feed-down yields estimated with data driven method with thermal models.

$$N_d = F(m_d, T)\exp(2\mu_B + \mu_Q)$$
$$N_{\bar{d}} = F(m_d, T)\exp(-2\mu_B - \mu_Q)$$
$$N_p = F(m_p, T)\exp(\mu_B + \mu_Q)$$
$$N_{\bar{p}} = F(m_p, T)\exp(-\mu_B - \mu_Q)$$
$$N_n = F(m_n \approx m_p, T)\exp(\mu_B)$$

Therefore,

$$\frac{N_d}{N_p^2} = \frac{F(m_d, T)}{F(m_p, T)^2}\exp(-\mu_Q)$$
$$\frac{N_{\bar{d}}}{N_{\bar{p}}^2} = \frac{F(m_d, T)}{F(m_p, T)^2}\exp(\mu_Q)$$
$$\frac{N_n}{N_p} = \exp(-\mu_Q)$$

Therefore,

$$\frac{N_n}{N_p} = \sqrt{\frac{d/p^2}{\bar{d}/\bar{p}^2}} = \frac{\bar{p}}{p}\sqrt{\frac{d}{\bar{d}}}$$

STAR Collaboration, PRC 99, 064905 (2019)

- $\Delta Q = \left[\left(N_{\pi^+} + N_{K^+} + N_p\right) - \left(N_{\pi^-} + N_{K^-} + N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}},$
- Define $R2_\pi = \frac{\left(N_{\pi^+}/N_{\pi^-}\right)_{Ru}}{\left(N_{\pi^+}/N_{\pi^-}\right)_{Zr}},$
- Let $N_\pi = 0.5 \times \left(N_{\pi^+} + N_{\pi^-}\right)$, then change of variable [1],
- $\Delta Q \approx \mathrm{N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)}.$
- Double ratio cancels sys. Uncertainty => reduction in sys. Uncertainty for $\boldsymbol{\Delta} Q$.

Experimental result on Net-Charge and Net-Baryon

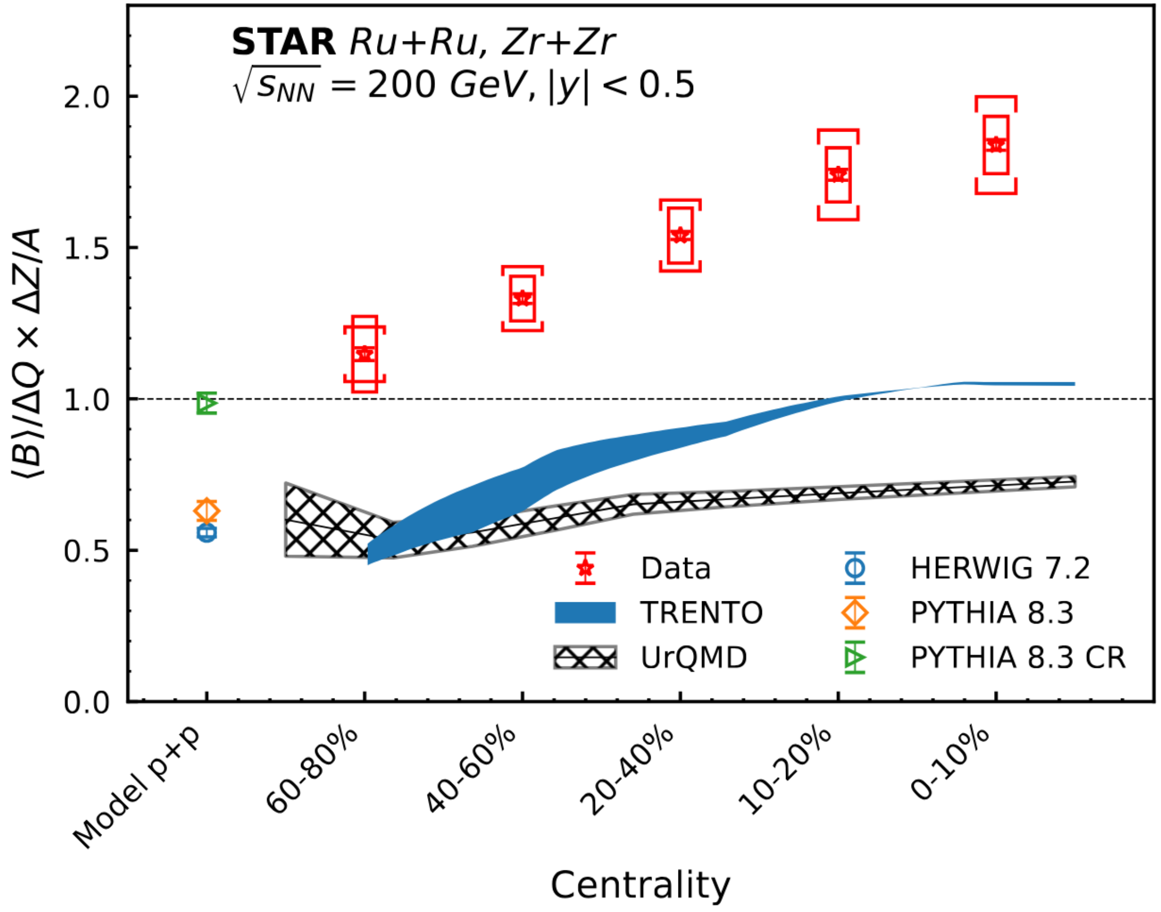


Figure from Ref. [4]

- **B/ΔQ∗ΔZ/A > 1.**
- PTYHIA, Herwig $p + p$ (B/Q*Z/A, Z=A=1) [1] and UrQMD [2] **cannot describe our data**.
- (Optional) Peripheral collision show lower B/ΔQ values.
  - Similar trend from Trento model [3].
  - Trento model estimates (B/ΔQ*ΔZ/A)$_{init}$ from nuclear geometry only. *No parton interaction!.*
  - Trend partially explained by nuclear geometry.

[1]: Eur. Phys. J.C. 80 5, 452 (2020)
[2]: J. Phys. G. 25, 1859 (1999)
[3]: PRC 105, L011901 (2022)
[4]: arXiv:2408.15441

Baryon transport from junction

- Three methods to test the hypothesis:

  1. Net-Baryon vs. Net-Electric charge difference in Isobar collisions
  2. Net-proton in photonuclear collisions
  3. Net-proton yield as a function of rapidity in hadronic Au+Au collisions

Net-Baryon in photonuclear collisions

- Quasi-real $\gamma \to q\bar{q}$.
- Interact with a junction or quark in target Au nucleus.
- Regge theory: $dN_{net-B}/dy \propto e^{-\alpha_B \delta y}$ [1],
  - $\delta y = \; y_{beam} - y$.
  - α_B sensitive to what kind of things are interacting [1].

If valence quark picture is true:

- Few baryons are transported far away from y_{beam}.
- **Larger $|\alpha_B|$** than junction picture.
  - dN/dy drops fast when α_B is large.

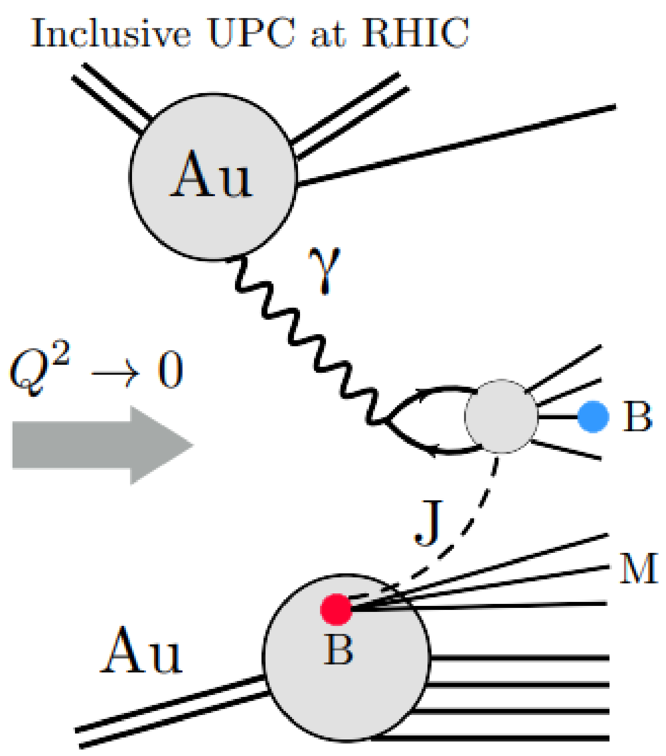
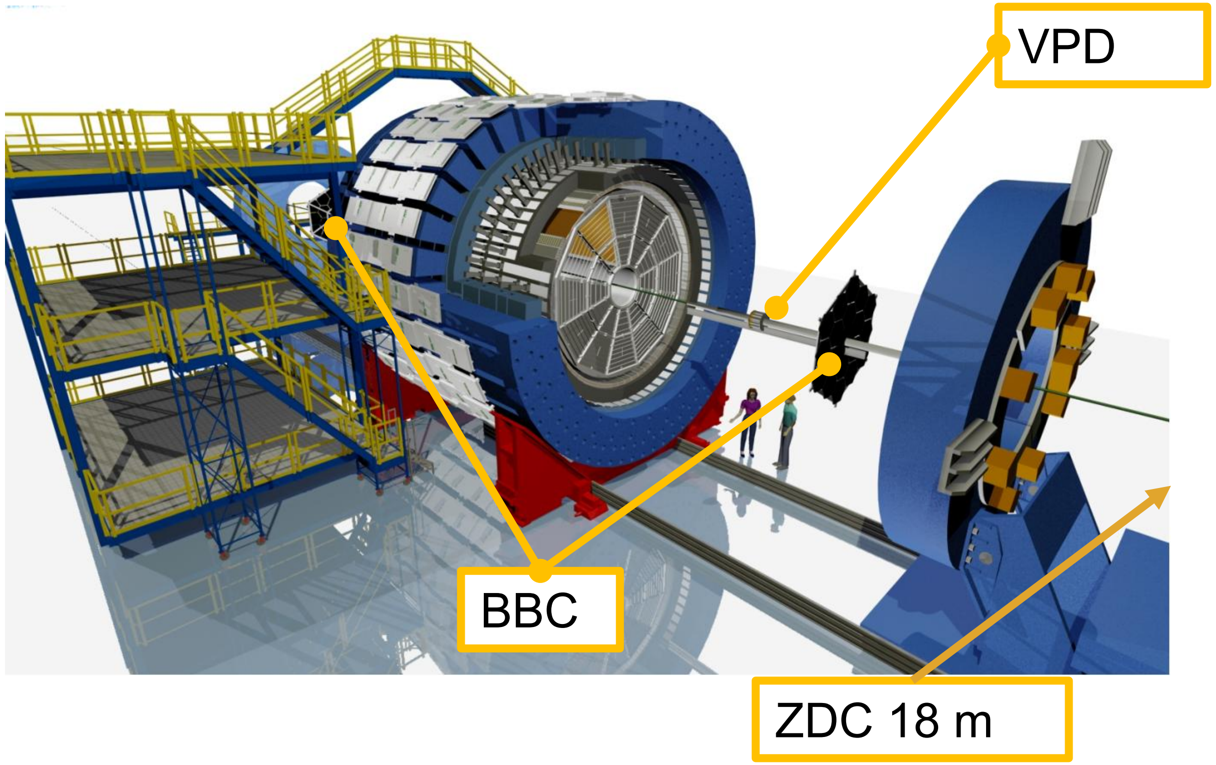


Figure from Ref. [1]

[1]: Eur. Phys. J. C (2024) 84:590

STAR detector

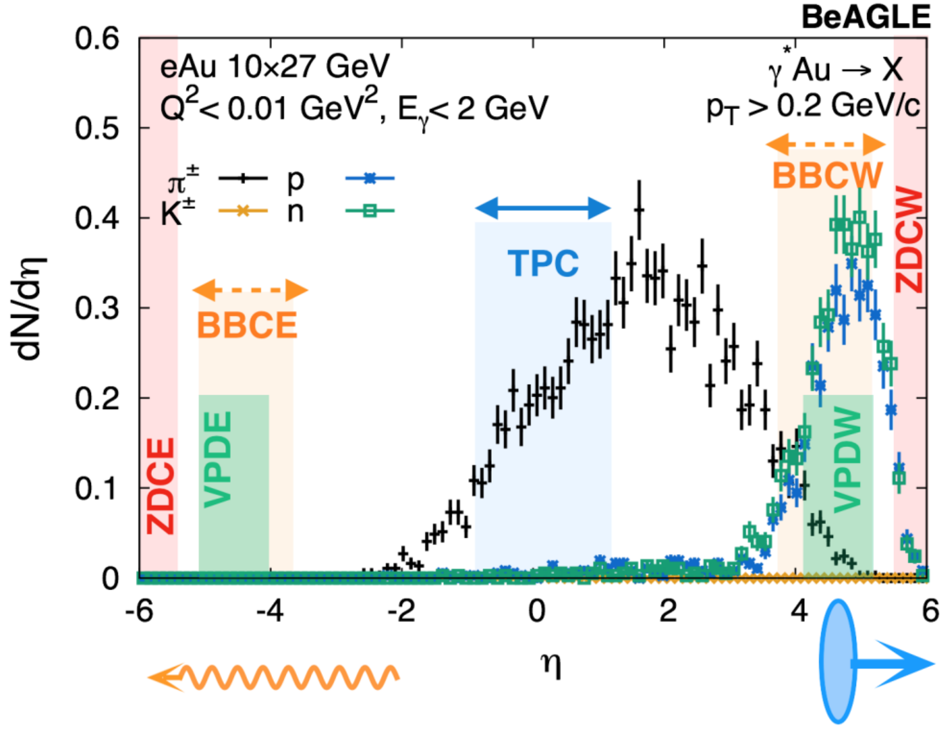


- **Vertex Position Detector (VPD)**
  - One on the east and one on the west.
  - Averaged time of particle detection on both sides => vertex position.
- **Zero Degree Calorimeter (ZDC)**
  - Detect forward neutrons for event selection
- **Beam-Beam counter (BBC)**
  - Detector forward and backward beam fragments

Selecting photonuclear events in Au + Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV

- Asymmetric collision: target can only be traveling in one direction
- Select events with,
  - Single neutron (1n) on ZDC east (ZDCE)
  - No activity in BBC east
  - Multiple neutron (Xn) on ZDC west (ZDCW)
  - Activity in BBC west
  - $|V_z(VPD) - V_z(TPC)| > 10$ cm
  - vice versa (east ⇔ west)

- **TLDR: Lots of activity on one side, but nothing on the other.**

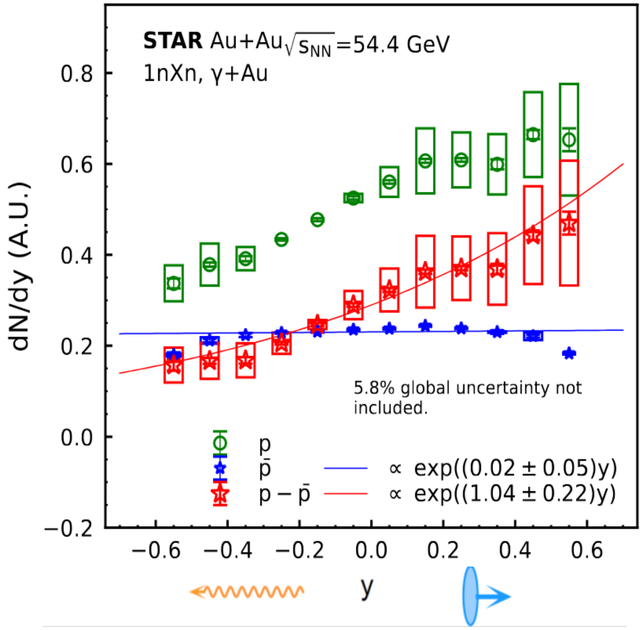


Figures from Eur. Phys. J. C (2024) 84:590

BeAGLE: PRD **106,** 012007 (2022)

Net-proton yield in Au + Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV

- Measured $\mathrm{dN}_{\mathrm{p}-\bar{\mathrm{p}}}/\mathrm{dy} \propto exp(-(\alpha_B = 1.04 \pm 0.22)\delta y)$.
- PYTHIA-8.3 and 8.3 CR **overestimate** α_B.
- **Consistent** with theory estimation of junction interaction.



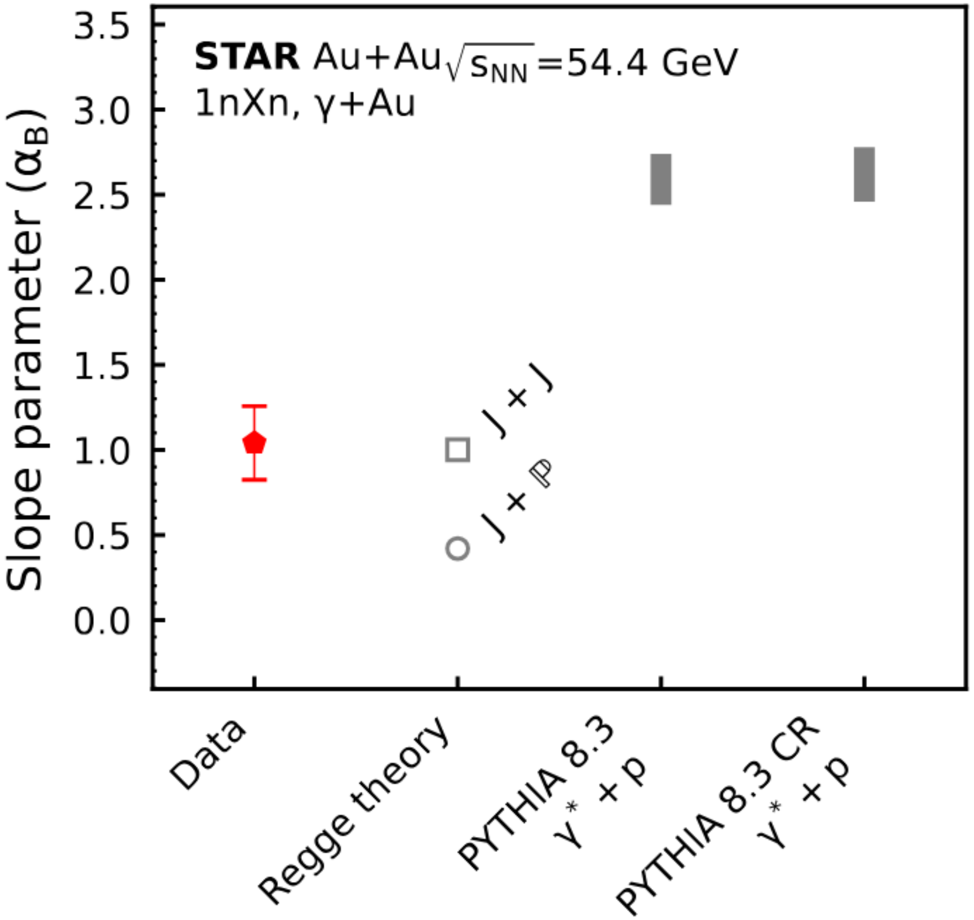


Figure from arXiv:2408.15441

Baryon transport from junction

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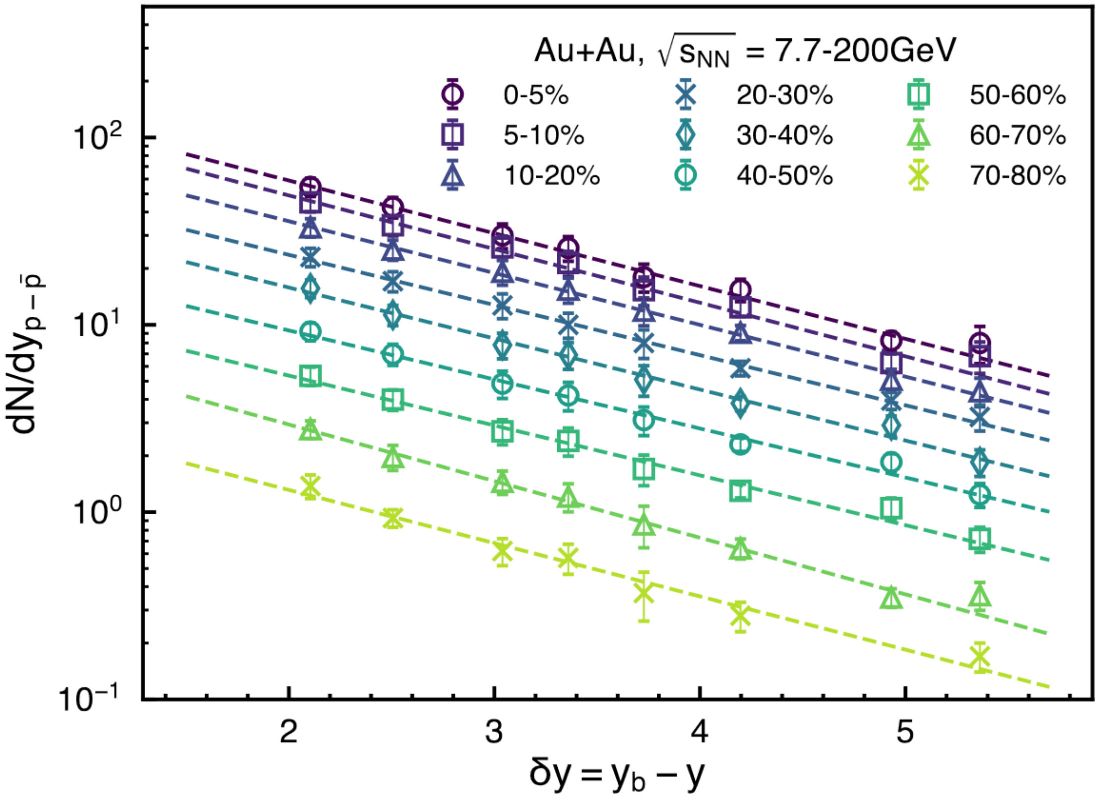
Net-proton yield at mid-rapidity as a function of beam rapidity in hadronic Au+Au collisions

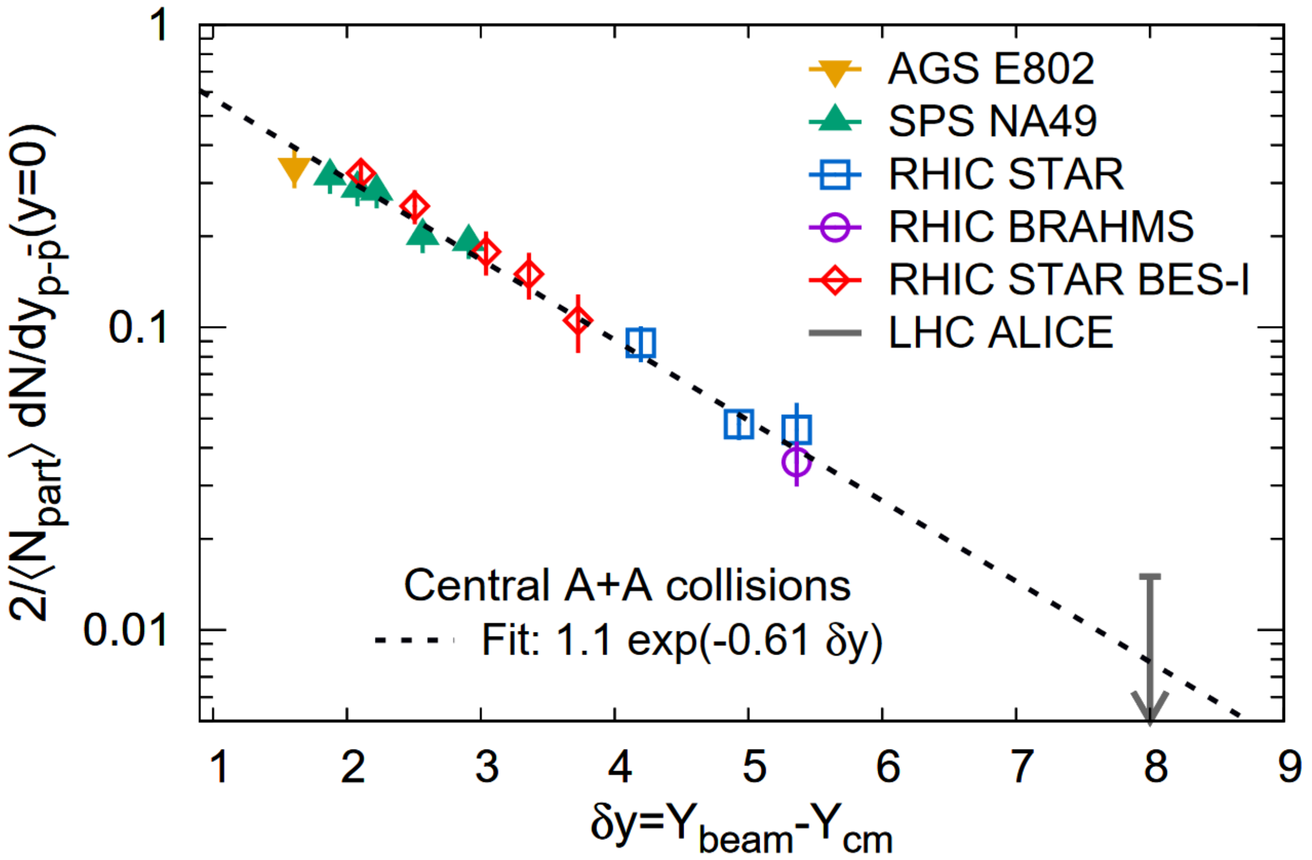
$\mathrm{Au} + \mathrm{Au}$ BES-I data

Figure from Eur. Phys. J. C (2024) 84:590

- Regge theory: $dN/dy \propto e^{-a_B \delta y}$.
  - $\delta y = y_{beam} - y$.
- For hadron:
  $dN/dy \propto e^{-a_B(y_{beam}-y)} + e^{-a_B(y_{beam}+y)}$.
  - Symmetric target and projectile.
- **If we fix y = 0,** $dN/dy \propto e^{-a_B y_{beam}}$
- Measured $a_B \approx 0.65$.



Net-proton yields from other experiments



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

Net-proton exponential slope (α_B)

- Measured $a_B \approx 0.65$.
- **Too small (flat)** compared to PYTHIA and HERWIG predictions [1].
- Slope does not depend on centrality
  - Valence quark transport is expected to depend on multiple scatterings and thus on centrality.
  - UrQMD shows centrality dependence [1].

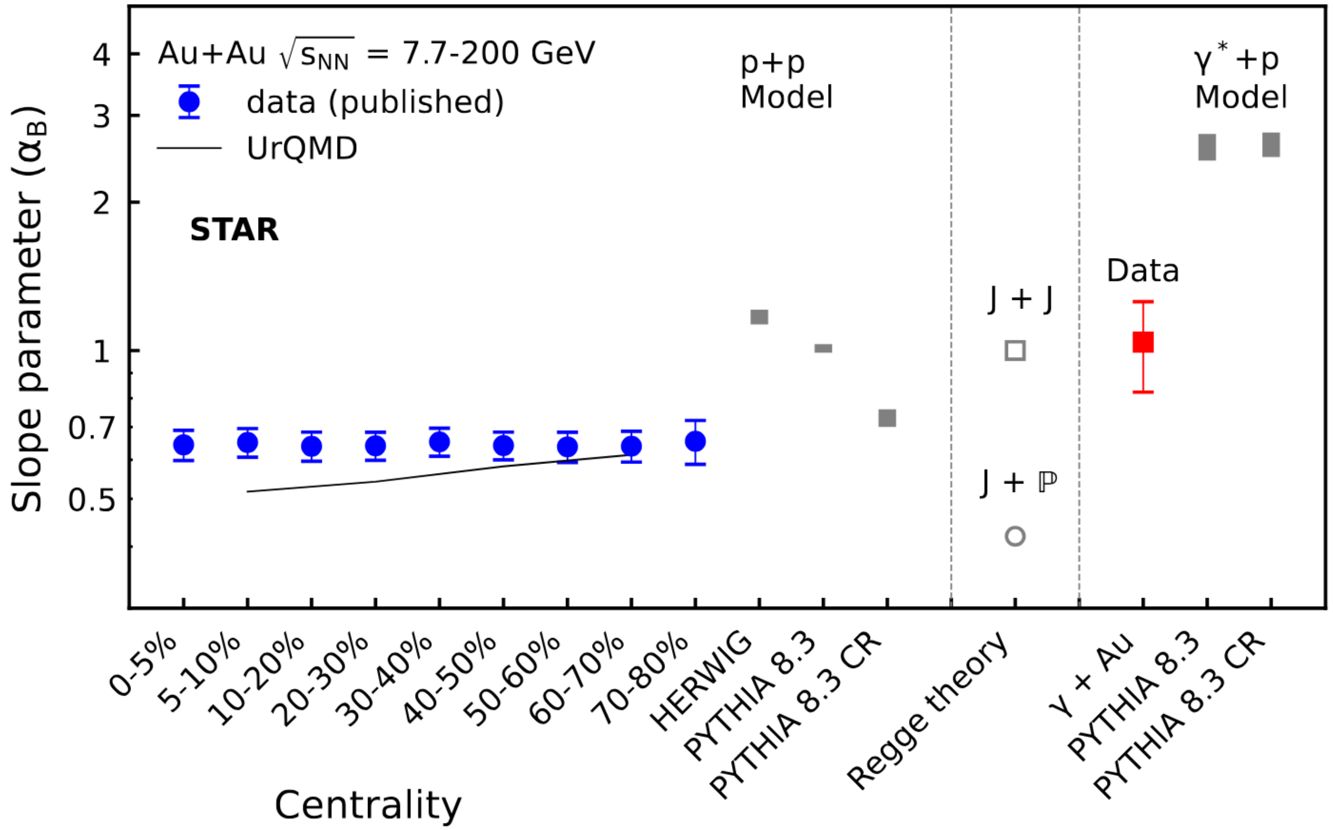
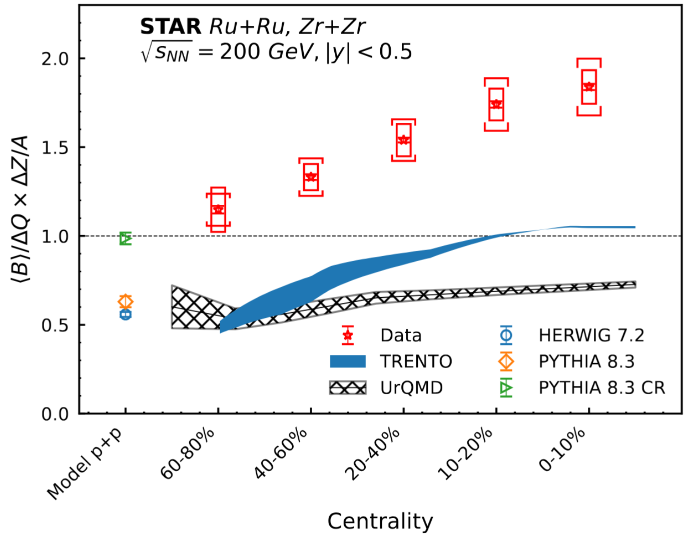


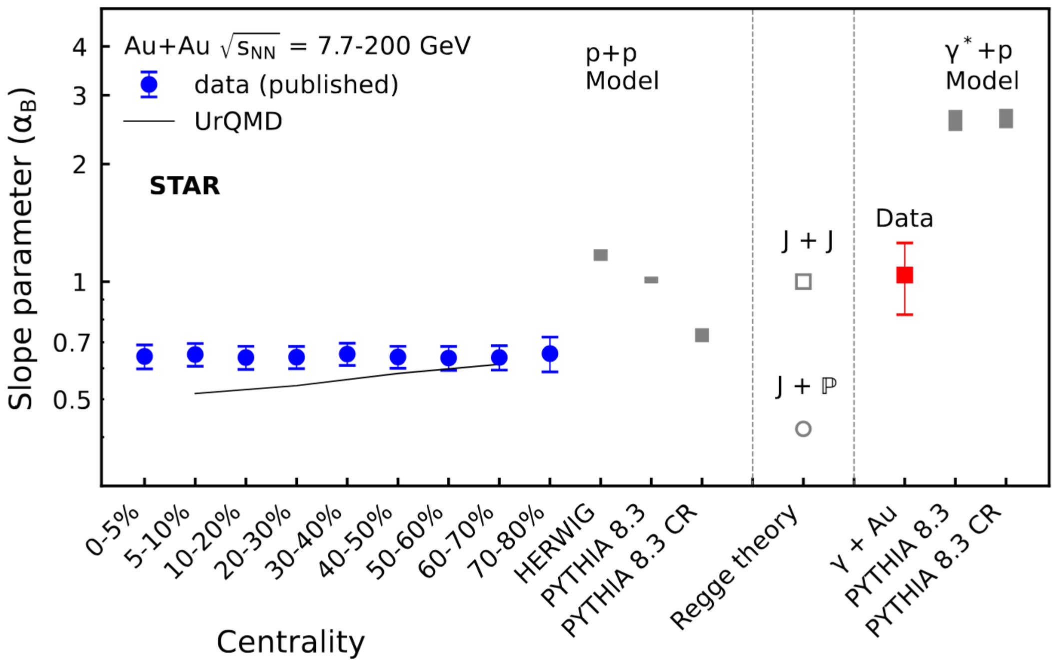
Figure from Ref. [1]

[1]: arXiv:2408.15441

Conclusion

- α_B from hadronic Au+Au < naïve quarks model predictions.
- α_B from $\gamma + Au$ < naïve quarks model predictions.
- B/ΔQ*ΔZ/A > 1 on Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV.
  - Inconsistent with predictions from models (UrQMD, PYTHIA, HERWIG) with valence quark picture.
- Our results disfavor the assertion that valence quarks carry the baryon number.





Thanks

Backup slides

Net-Baryon number (B)

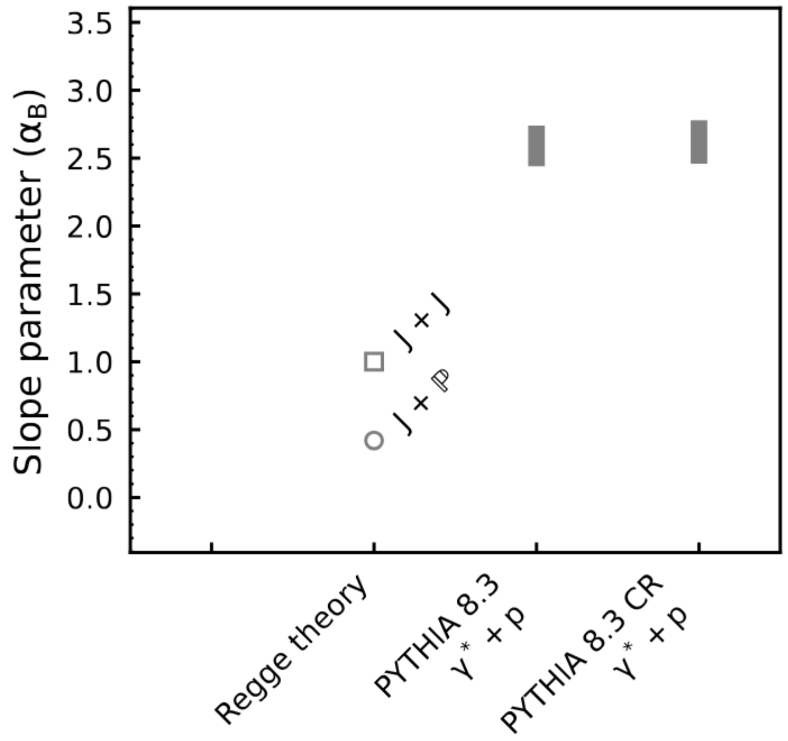
- $B = \left(N_p - N_{\bar{p}}\right) + (N_n - N_{\bar{n}})$
- Primordial (anti-)neutron yields estimation [1],
  - $N_n^{pri} = N_{\bar{p}}^{pri}\sqrt{\frac{N_d}{N_{\bar{d}}}},\ N_{\bar{n}}^{pri} = N_p^{pri}\sqrt{\frac{N_{\bar{d}}}{N_d}}.$
  - Fraction of feed-down (anti-)proton taken from Ref. [2].

- Feed-down yields estimated with data driven method [3].
  - Data driven estimation of proton feed-down fraction -> Weighted sum of hyperon yields.
  - $\Lambda:\Xi:\Omega$ yield ratios from THERMUS model estimation.
  - Estimate feed-down neutrons from scaled hyperon yields.

[1]: arXiv:2408.15441
[2]: PRC. 79 (2009) 34909
[3]: PRL. 97, 152301 (2006)

Expectations of α_B from various pictures.

- Regge theory: $dN_{net-B}/dy \propto e^{-\alpha_B \delta y}$
- PYTHIA-8.3 and 8.3 CR predicts **larger** α_B.
  - Neither simulates junction interactions.
  - 8.3 CR includes a junction-like mechanism in final-state hadronization [1].
- Theory of junction interaction predicts **smaller** α_B [2].
  - J+J: Junction-junction interaction.
  - J+P: Junction-pormeron interaction.
- Note: smaller α_B -> dN/dy do not drop quickly with increasing δy -> Enhanced stopping.



[1] JHEP 08, 003 (2015). 1505.01681.
[2] Phys. Lett. B 378, 238–246 (1996).nucl-th/9602027.

Spectra from Isobar Collisions

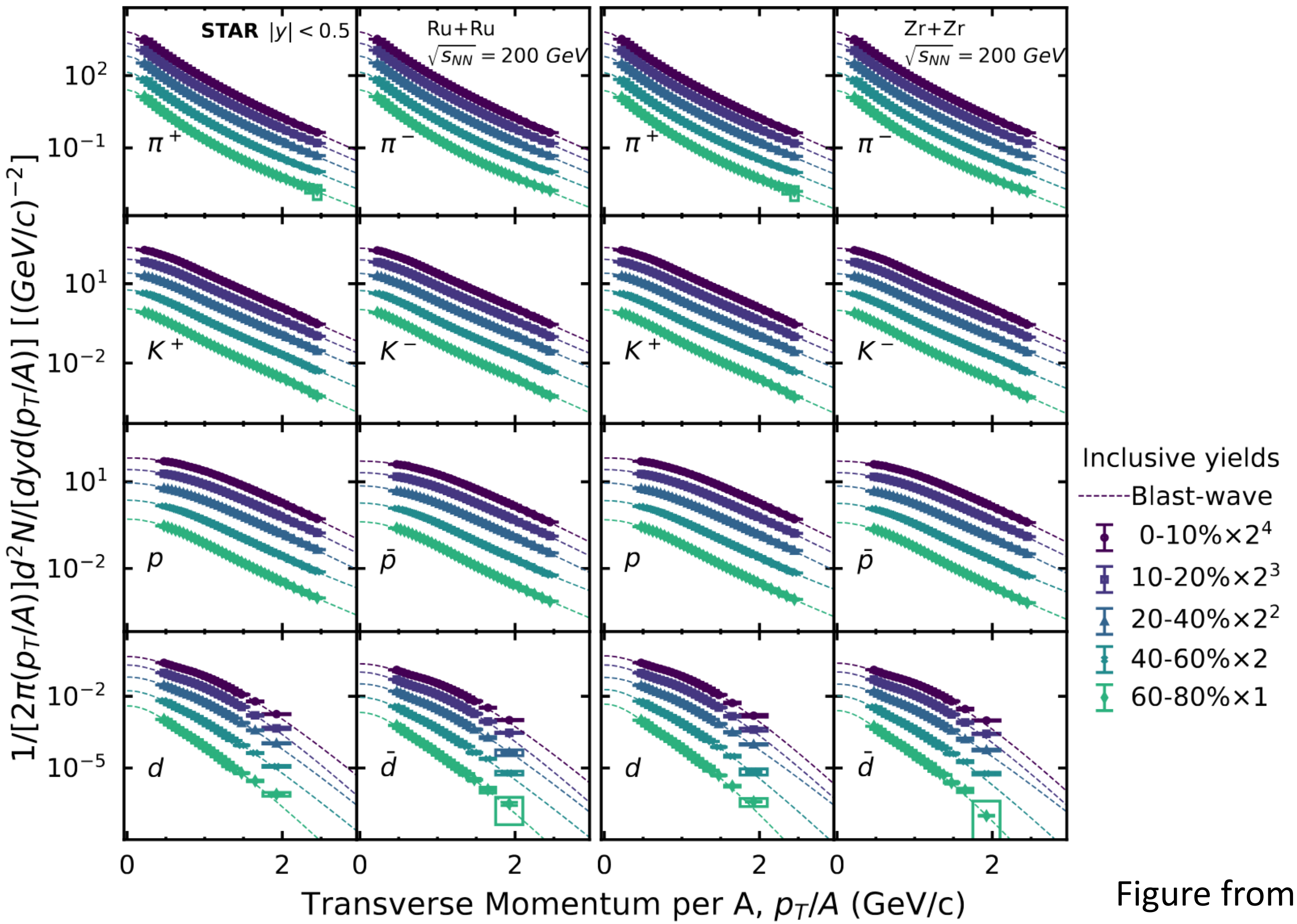


Figure from arXiv:2408.15441

Double ratio R2s

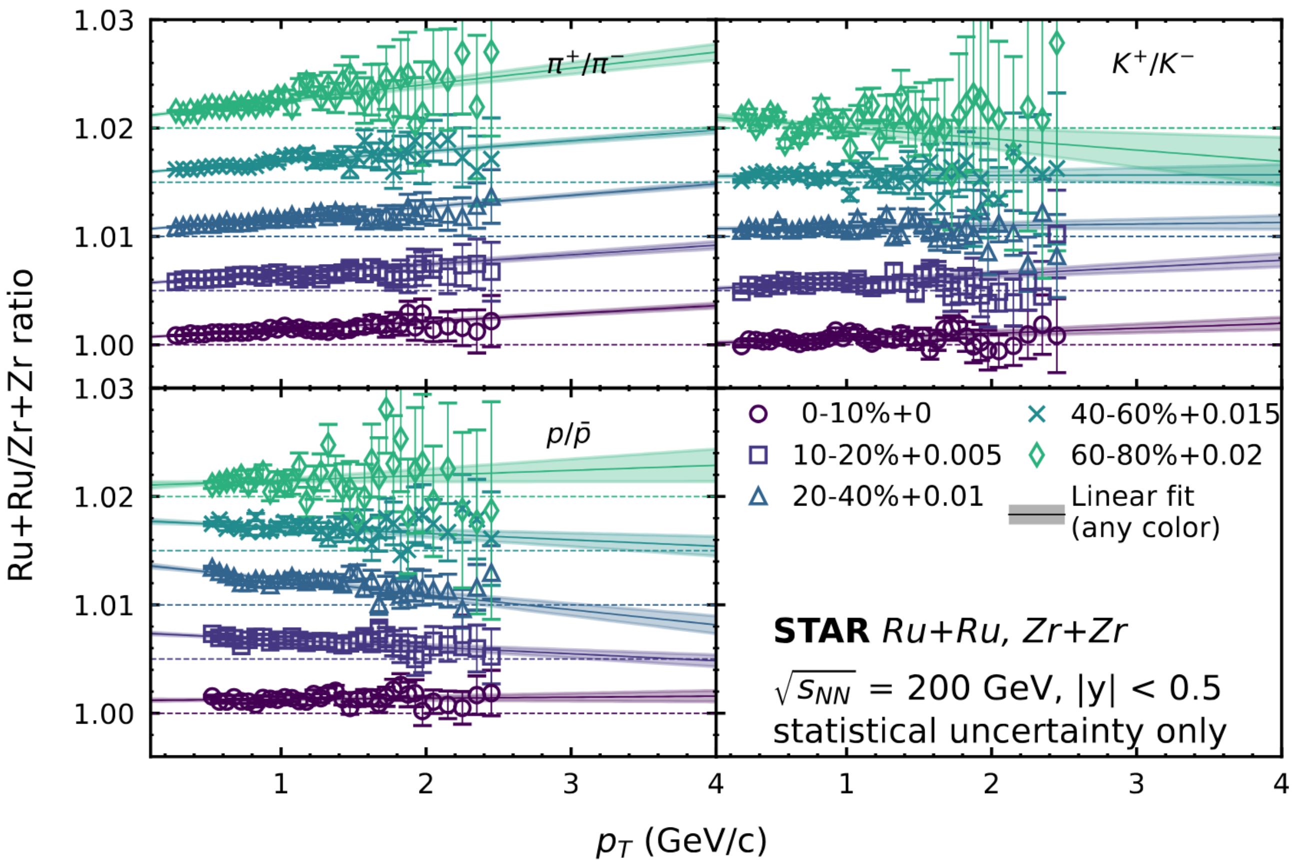
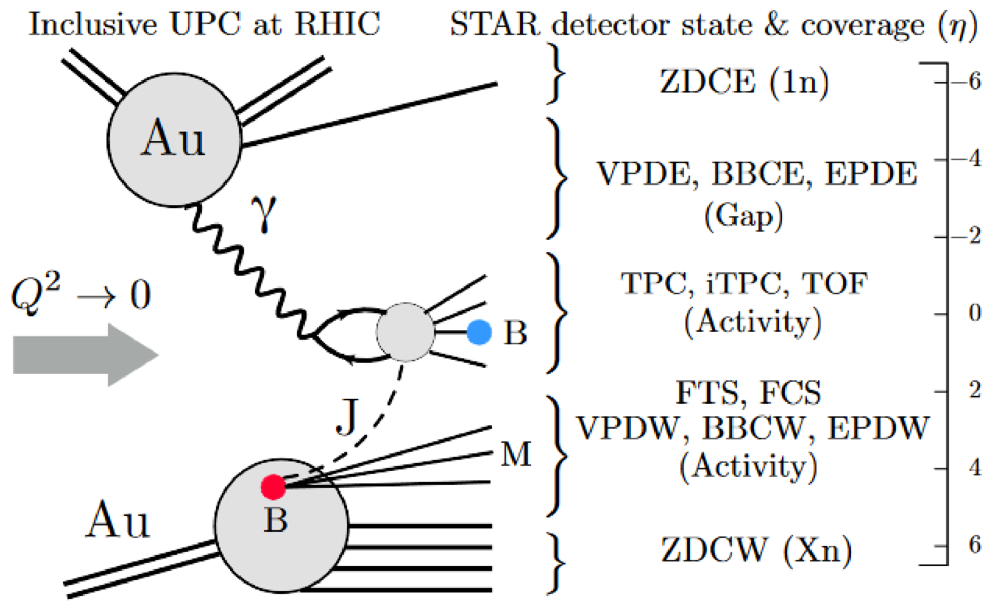


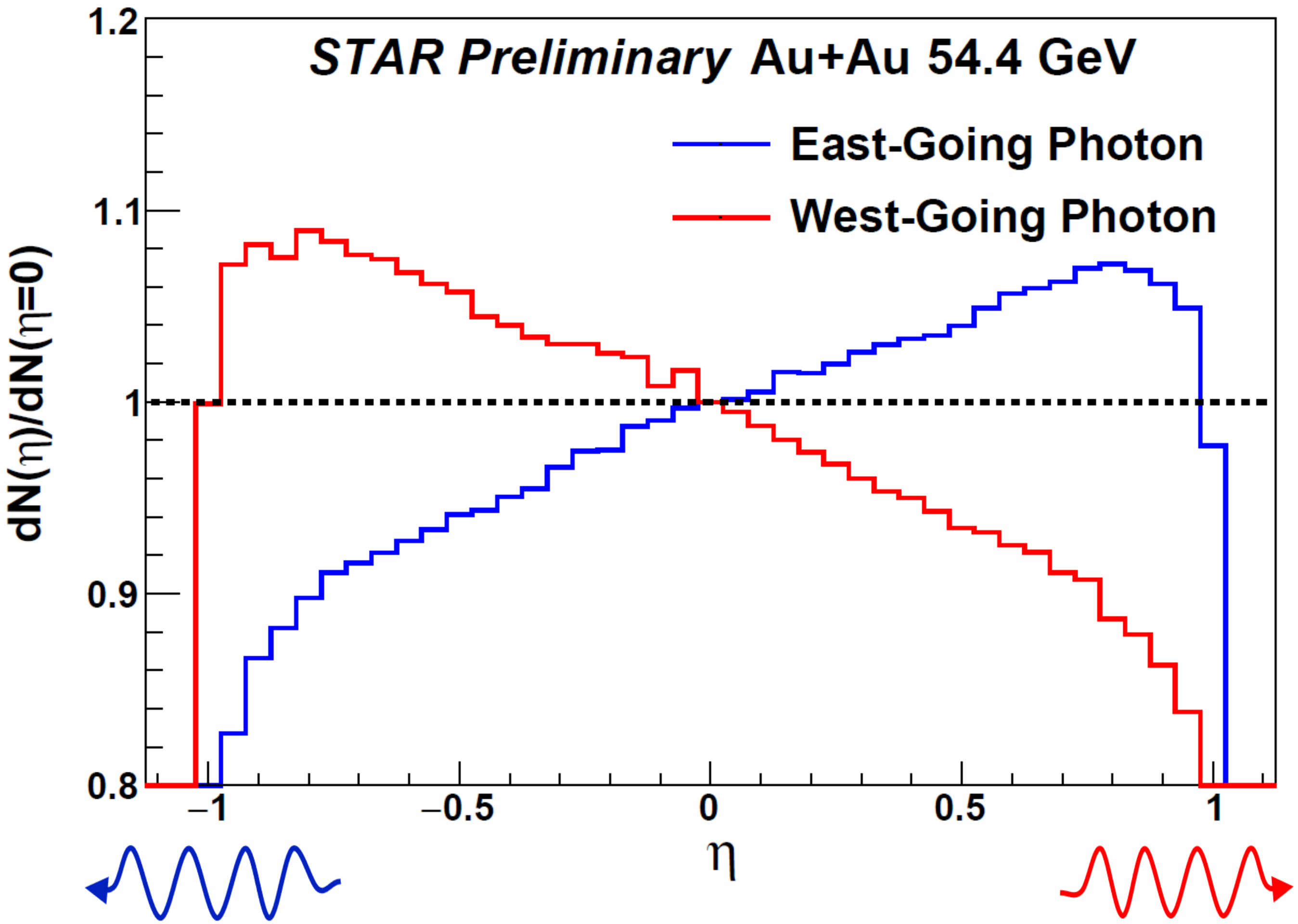
Figure from arXiv:2408.15441

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

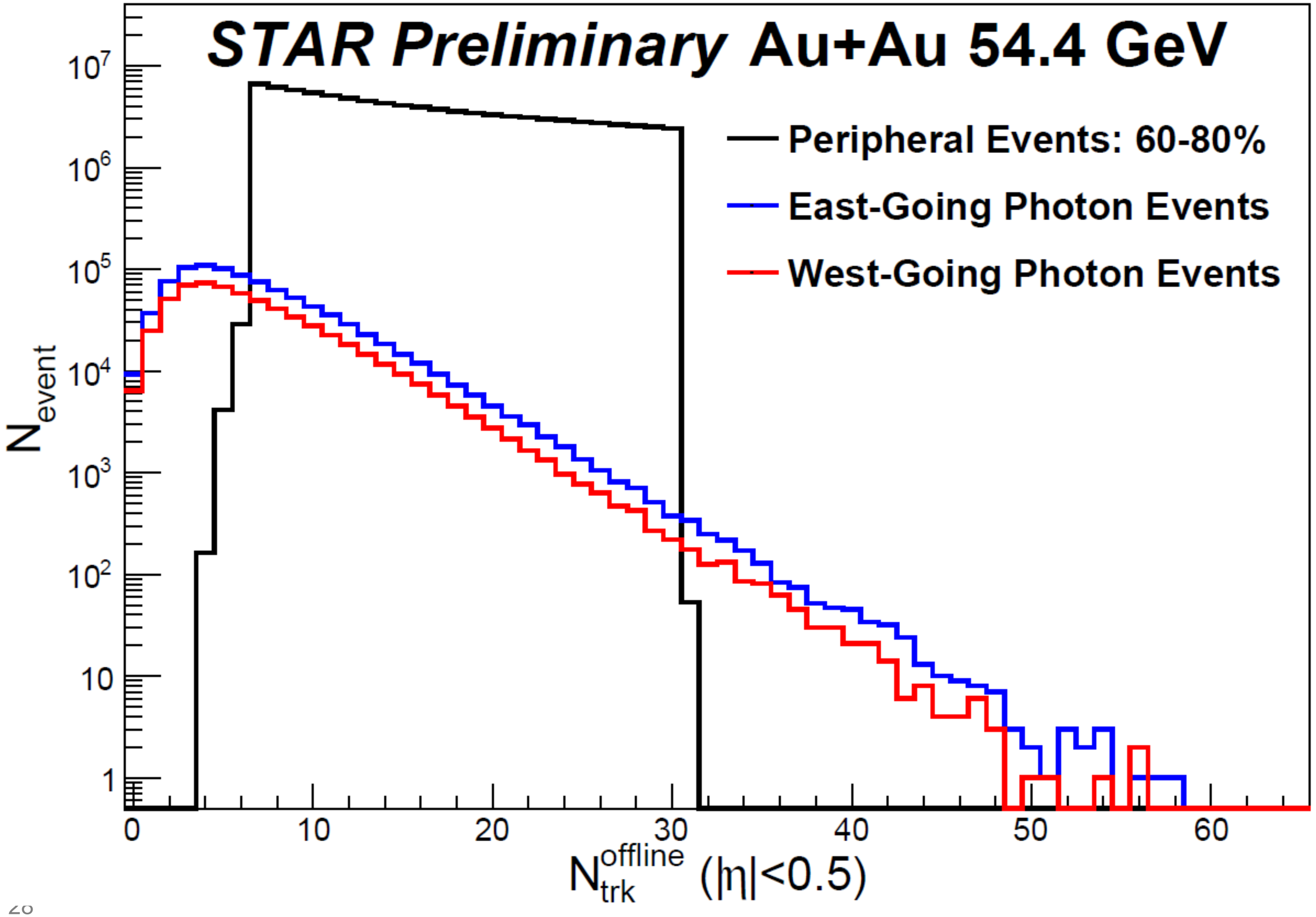
Rapidity asymmetry in γA-rich events



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



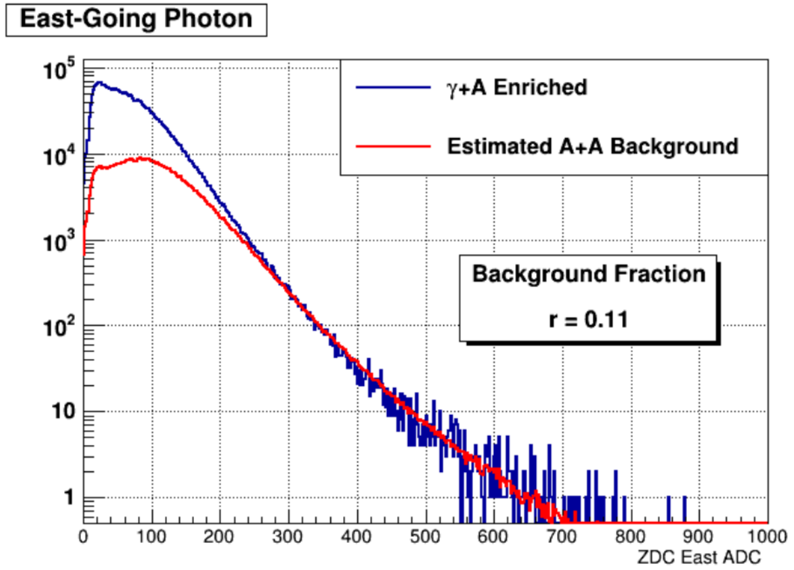
Defining γA and AA event classes

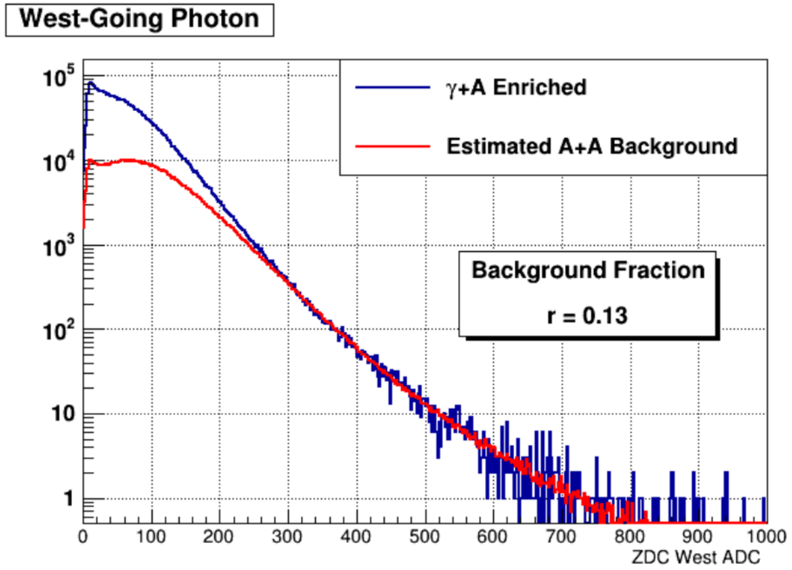


Most photonuclear events have low multiplicity, consistent with very peripheral $\mathrm{Au+Au}$ collisions

Using $60-80\%$ peripheral collisions as a baseline and to estimate behavior of peripheral background

A+A background estimation





X-axis ∝ N.O. of fragments detected

Baryon transport from various mechanisms

- Valence quarks carry most of the momentum.
  - contracted into thin “pancakes”.
  - Less time to interact => less stopping at mid-rapidity.

- Junction carries lower momentum.
  - Made of low-x gluons
  - Enhanced baryon transport to mid-rapidity
  - Not made of quarks -> Stopping is independent of quark flavor

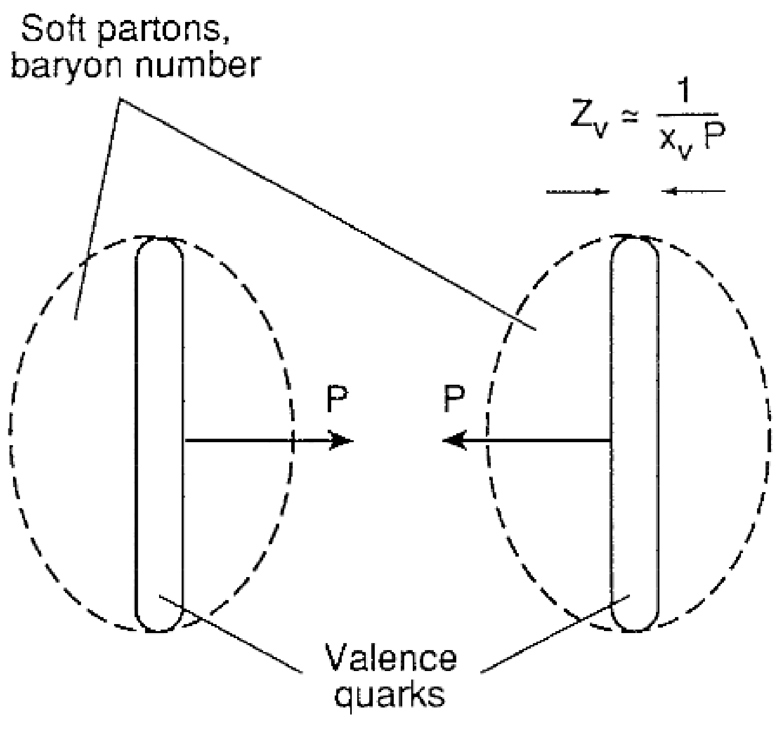
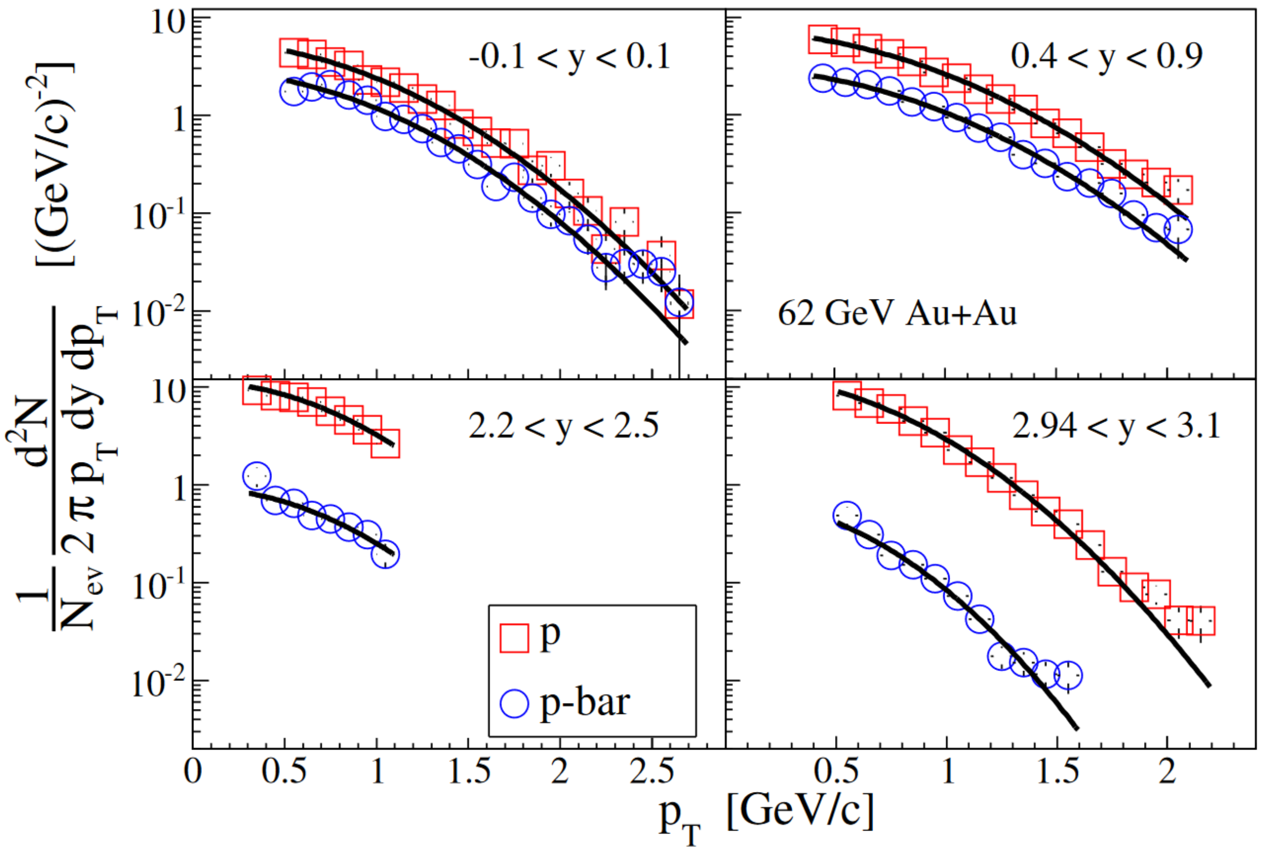


Fig. 2.

Figure from PLB 378, 238 (1996)

Net-Baryon at mid-rapidity



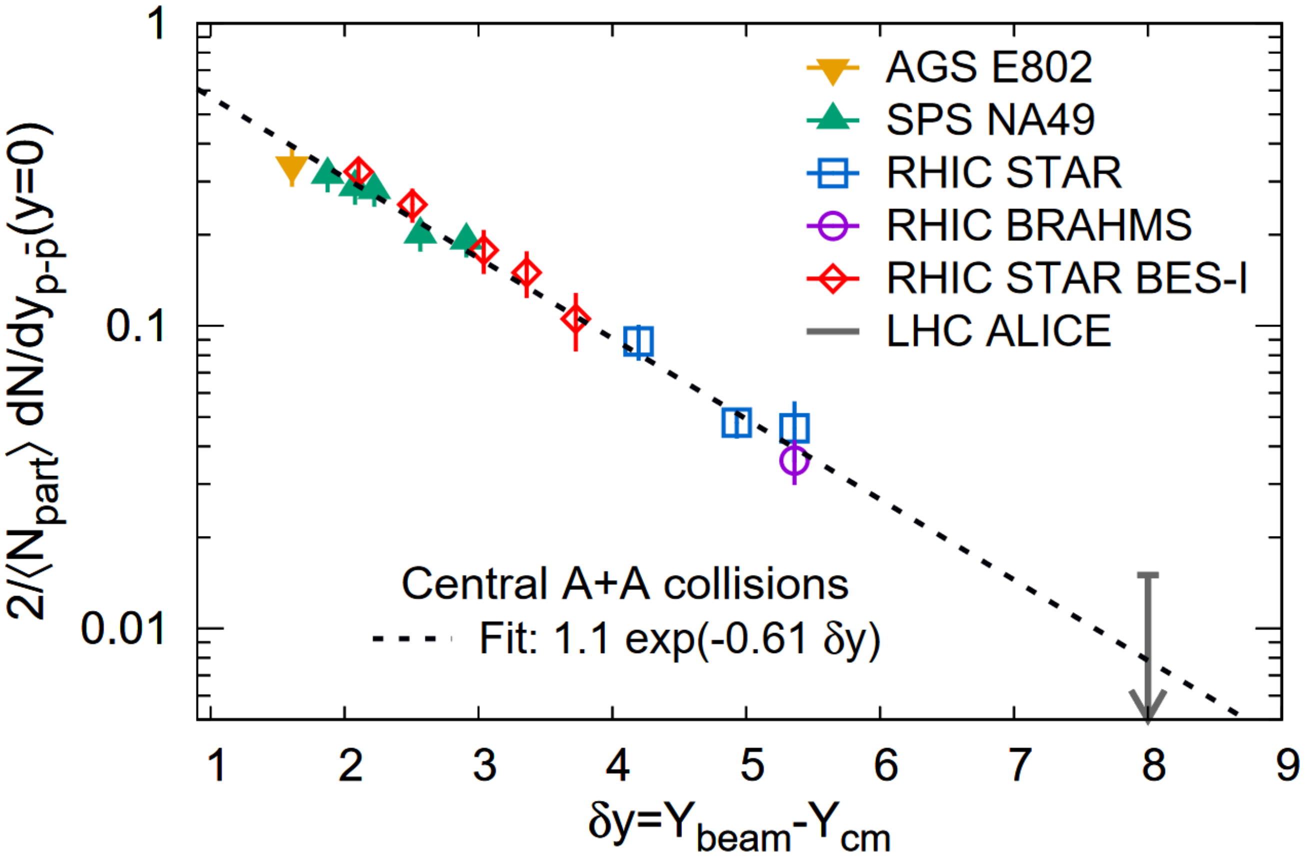
BRAHMS Collaboration, Phys. Lett. B **677,** 267-271 (2009)

- **Net-Baryon =** $p - \bar{p}$
- **More baryons than antibaryons, even at midrapidity**
- **Expected yield of** $p - \bar{p}$ **is low**
- **Collision time is too short for a lot of valence quarks to be stopped**

Net-Baryon at mid-rapidity

- **Changes with collision energy**
  - Higher energy => Less interaction time
- **Normalized net-Baryon yield at mid-rapidity shows a clear exponential dependence on δy**
  - Exponential factor too small to be explained by 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)

Riordan, Science 1992

Electric charge of quarks

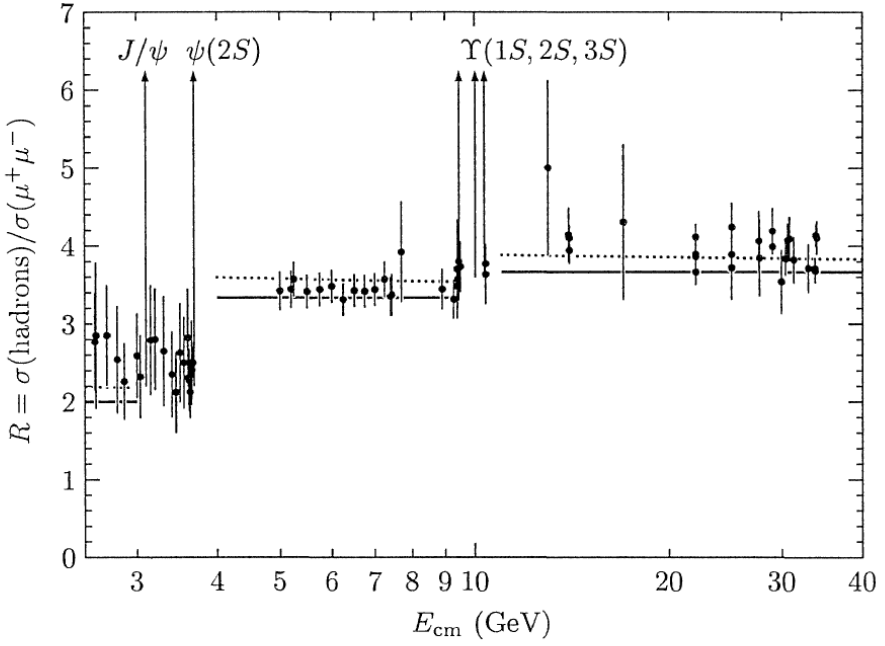
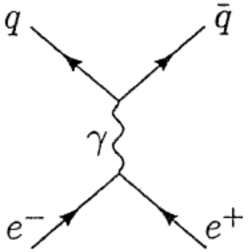


Figure 5.3. Experimental measurements of the total cross section for the reaction $e^+e^- \to$ hadrons, from the data compilation of M. Swartz, *Phys. Rev.* D (to appear). Complete references to the various experiments are given there. The measurements are compared to theoretical predictions from Quantum Chromodynamics, as explained in the text. The solid line is the simple prediction (5.16).



$$\sigma(e^+e^- \to \text{hadrons}) \xrightarrow[E_{\rm cm}\to\infty]{} 3\cdot\left(\sum_i Q_i^2\right) \text{R}, \qquad (5.16)$$

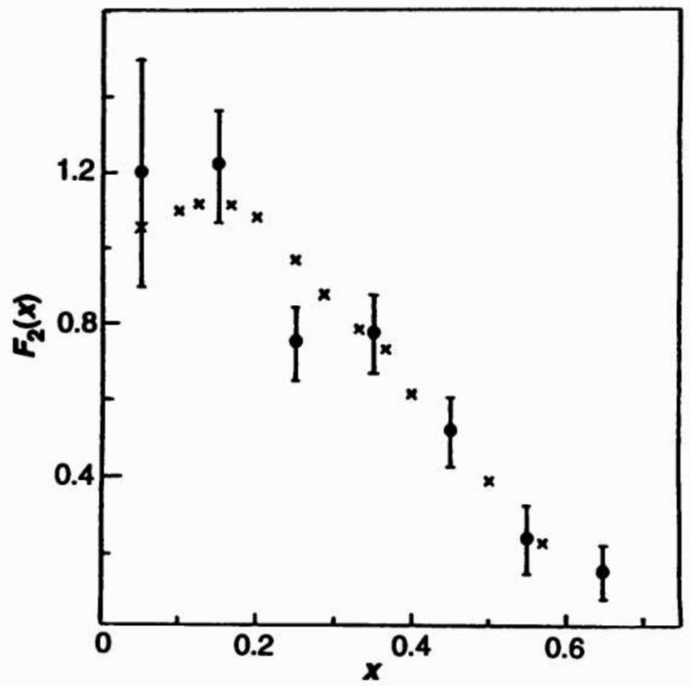


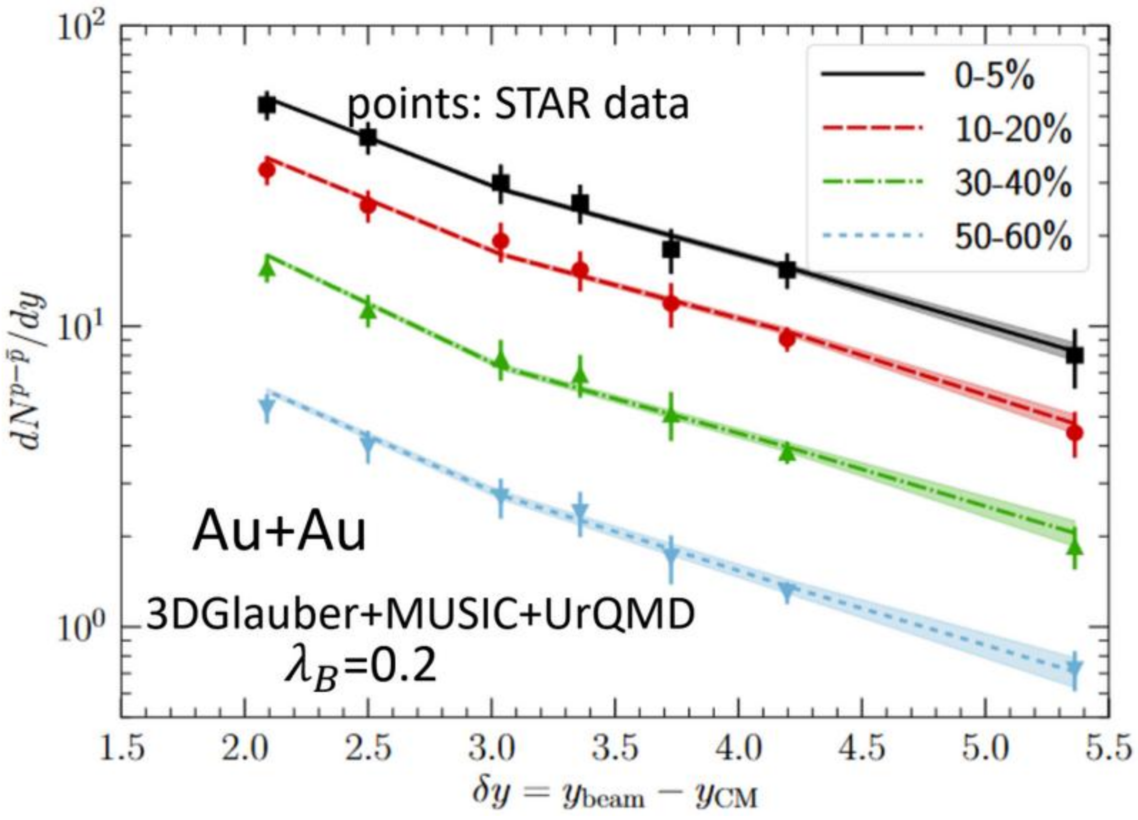
Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, (18/5)F_2^{eN}]. When multiplied by 18/5, a number specified by the quark-parton model, the electron scattering data coincide with the neutrino data.

M. E. Peskin, D. V. Schroeder, An Introduction to Quantum Field Theory, Addison-Wesley Publishing Company, 1995

String junction model

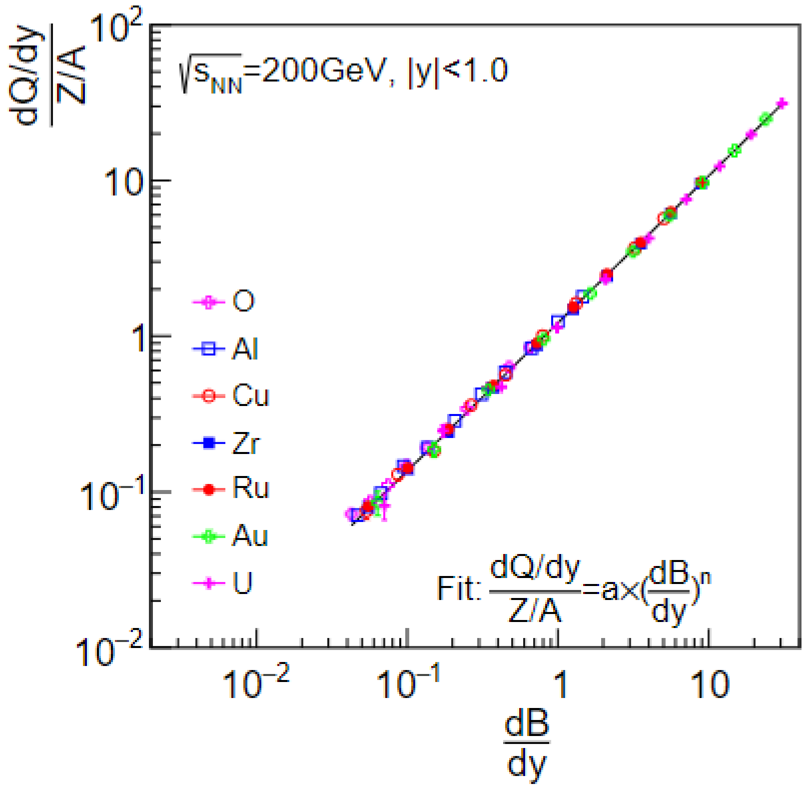
- **3D hybrid model:** $\mathrm{GLAUBER + MUSIC + URQMD}$ **Model**
- **String junction where the baryon charge of the string can fluctuate towards the center of the string with tuning parameter λ_B**
  - $\lambda_B = 0.2$ reproduces the dN/dy of net-protons at STAR

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



Plot from Wenbin Zhao, BES-Tea Seminar 2022

Net-Charge and Net-Baryon at $|y| < 1.0$, Predicted by UrQMD



Courtesy: Z. Tang

Virtuality of ultra-peripheral Au + Au

$\sqrt{s_{NN}} = 54$ and 200 GeV. In UPCs the gold ions are the source of quasi-real photons. The size ($R_A \sim 1.2\,A^{1/3}$) and charge ($Z = 79$) of gold ions (mass number $A = 197$) and the Lorentz boost $\gamma_L = 27 - 100$ at RHIC determines the energy of the quasi-real photons $E_\gamma = \gamma_L(\hbar c/R_A) = 0.8 - 2.8$ GeV. The virtuality and transverse momentum are $Q^2 \lesssim (E_\gamma/\gamma_L)^2 \simeq (\hbar c/R_A)^2 = 0.0008\ \mathrm{GeV}^2$. The typical range of the center of mass energy of the photon-nucleon system is $W_{\gamma N} = \sqrt{4E_\gamma E_A} \approx 9 - 34$ GeV for $\sqrt{s_{NN}} = 2\,E_A = 54 - 200$ GeV. These numbers are close to what are quoted in Ref [36]. However, it is

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

Thank you