Tracking the baryon number with heavy-ion collisions

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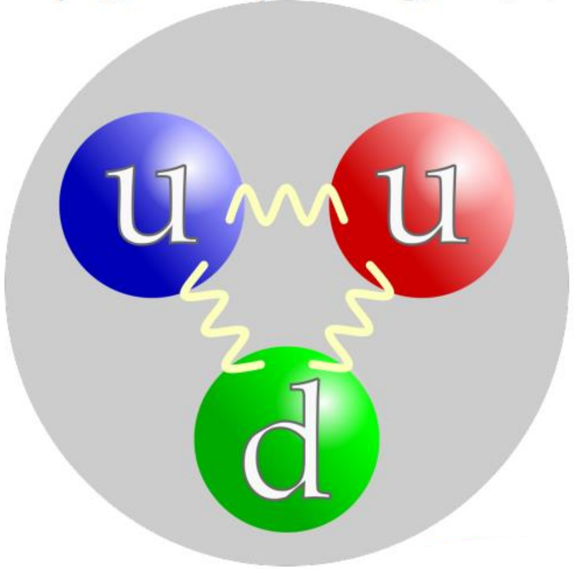
Supported in part by:

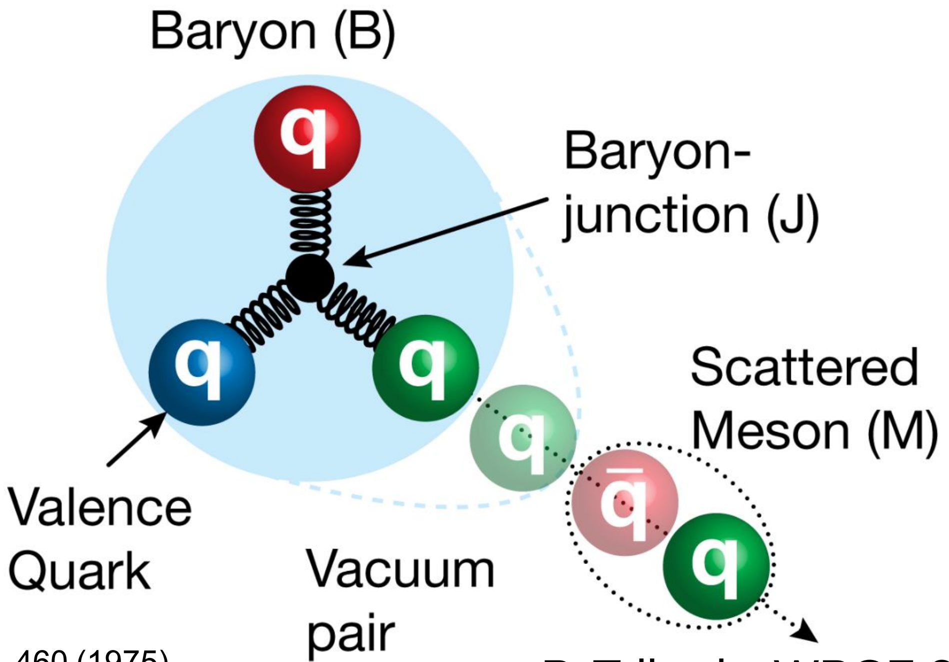
What carries baryon number, quark vs. baryon Junction?

Conventional picture



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

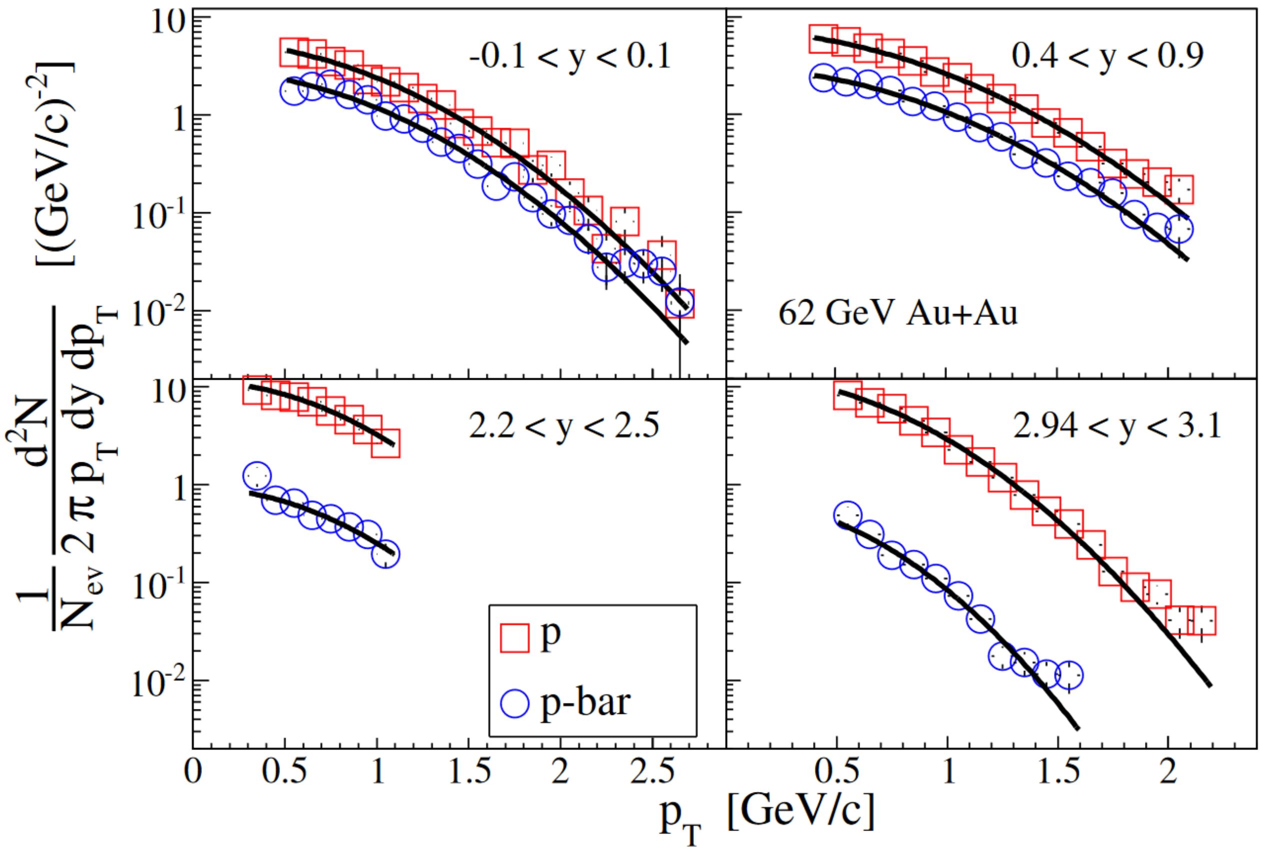
Baryon Junction [1, 2]



P. Tribedy, WPCF 2022

[1]: Artru, X. String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (1975).
[2]: Rossi, G. C. & Veneziano, G. A Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (1977)

Net-Baryon at mid-rapidity



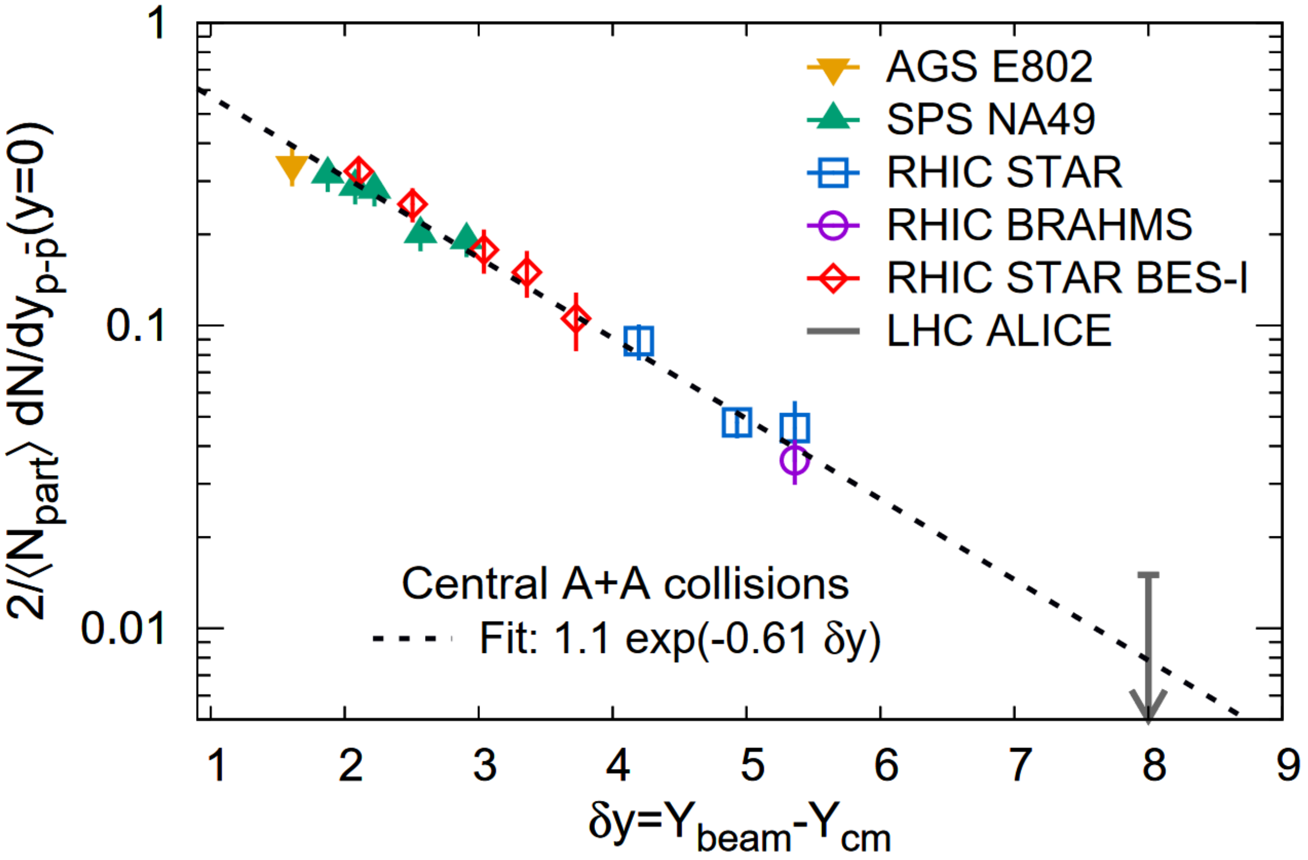
BRAHMS Collaboration, Phys. Lett. B **677,** 267-271 (2009)

- **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)

Baryon stopping from Junction

- **Quarks carry most momentum and are contracted into thin “pancakes” at high energy.**
  - Quarks have less time to interact due to contracted longitudinal length.

- **Junction carries lower momentum and is less contracted.**
  - Junction is made of low-x gluons.
  - More time to interact with other partons.
  - Enhanced baryon stopping at mid-rapidity.

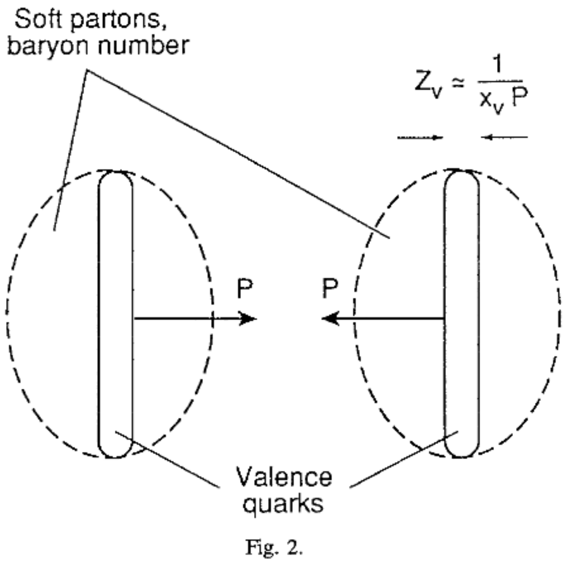
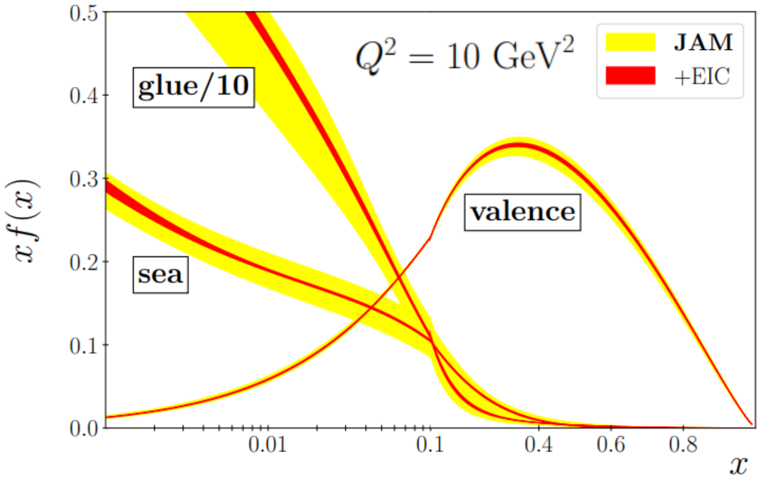


Figure from D. Kharzeev, Physics Letters B 378, 238 (1996)



R. Abdul Khalek et al, arXiv:2103.05419 [physics.ins-det]

Baryon stopping from Junction

- **Three methods to test the hypothesis:**
  - Net-proton yield as a function of rapidity in hadronic Au+Au collisions.
  - Net-Baryon vs. Net-Electric charge in Isobar collisions.
  - Net-Baryon in photonuclear collisions.

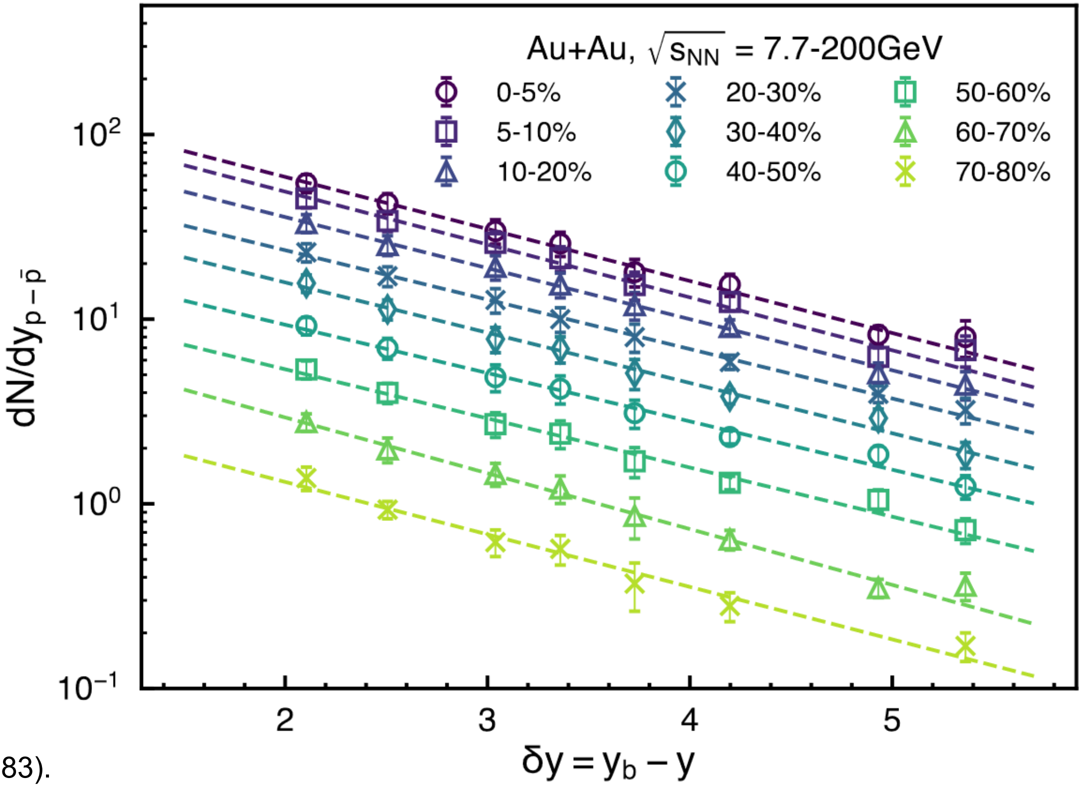
Beam energy dependence using Au+Au results from BES-I data

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

- **Regge theory predicts $dN/dy|_{y=0} \propto e^{-a y_{beam}}$.**
- **Measured $a \approx 0.65$.**
- **Expected $a \approx 2.5$ from PYTHIA 6.4 e + p simulation [1, 2, 3].**
- **Slope does not depend on centrality.**
  - Not caused by multiple scatterings.

Au + Au BES-I data

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



[1]: J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)
[2]: B. Andersson, G. Gustafson, G. Ingelman, and T. Sj¨ostrand, Physics Reports 97, 31–145 (1983).
[3]: Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands, JHEP 05, 026 (2006), arXiv:hep-ph/0603175.

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

Riordan, Science 1992

Electric charge of quarks

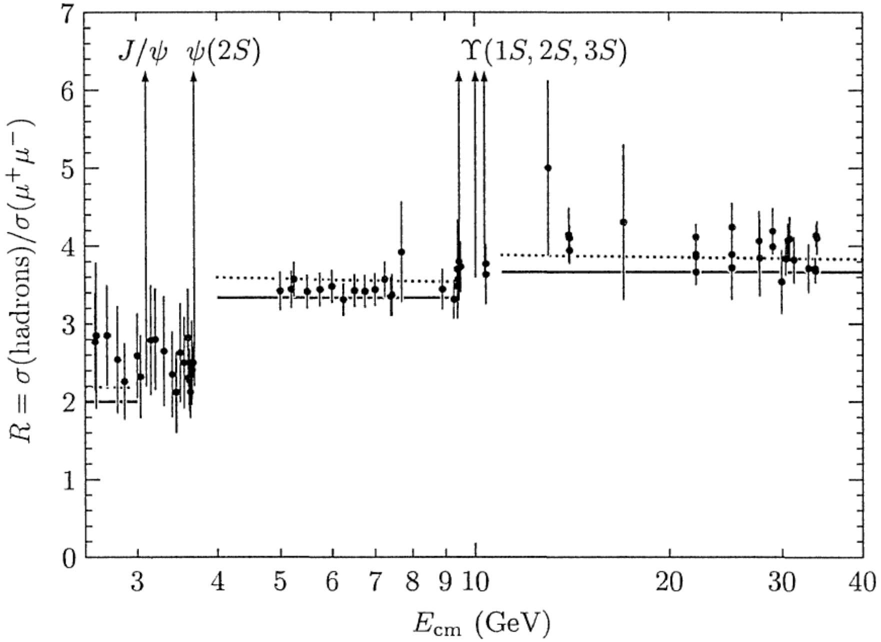
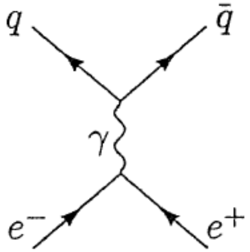


Figure 5.3. Experimental measurements of the total cross section for the reaction $e^+e^- \to$ hadrons, from the data compilation of M. Swartz, *Phys. Rev.* D (to appear). Complete references to the various experiments are given there. The measurements are compared to theoretical predictions from Quantum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

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



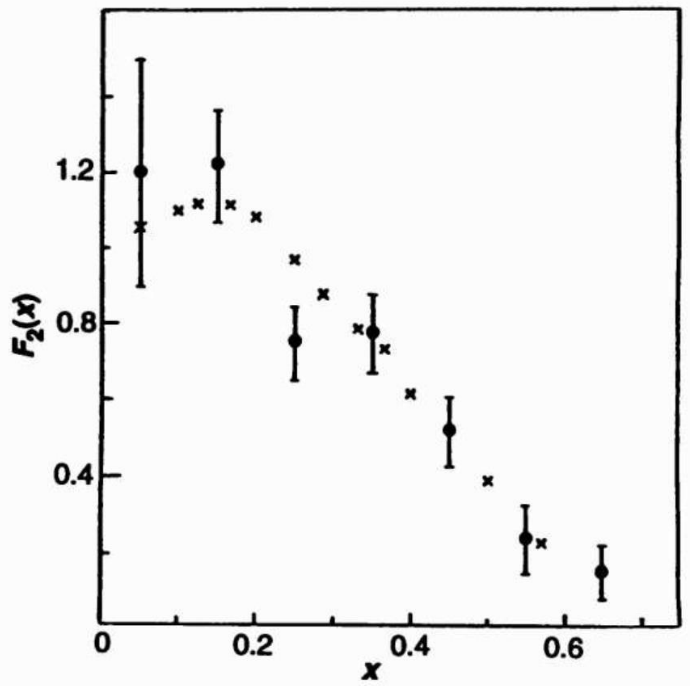
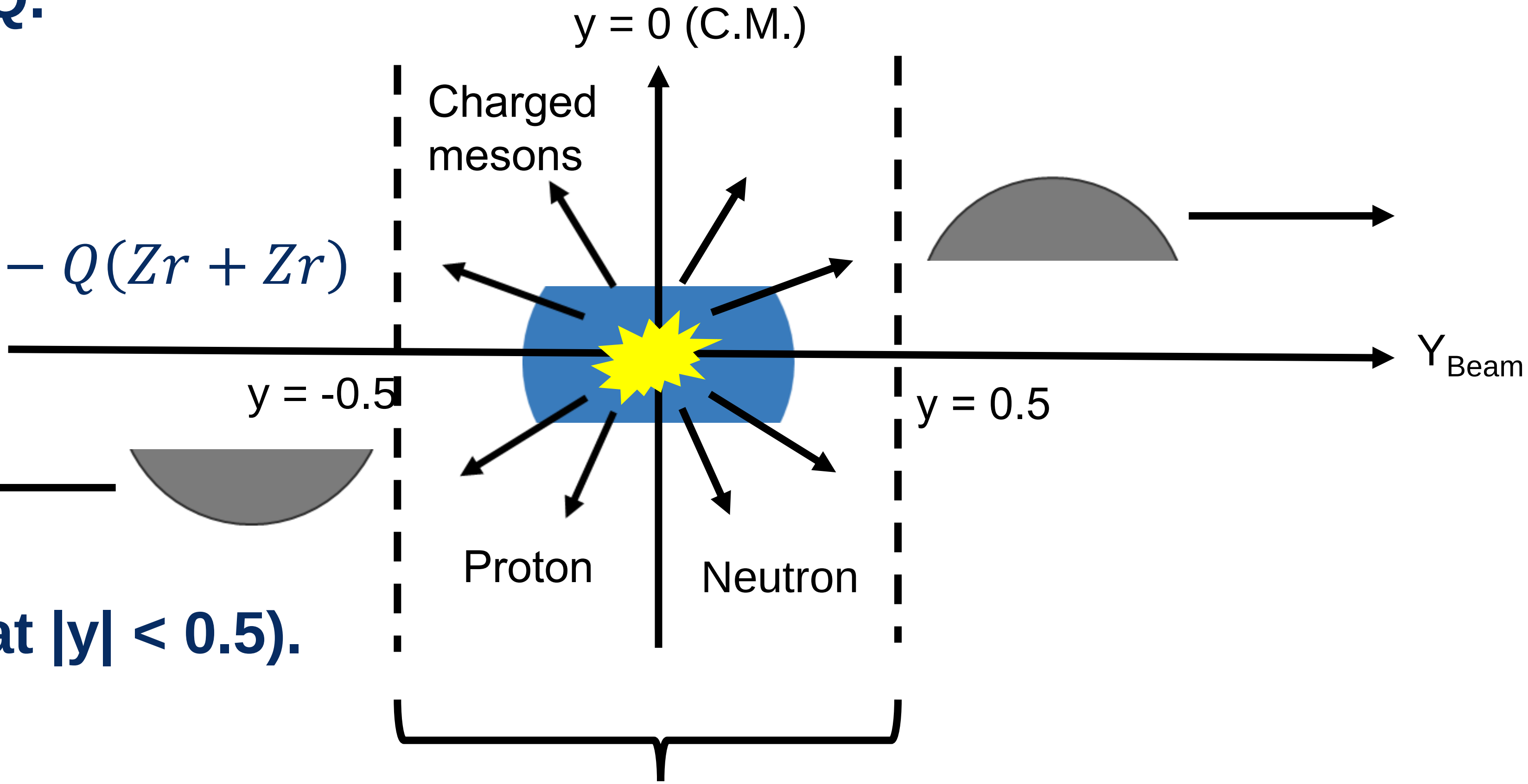


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, (18/5)F_2^{eN}]. When multiplied by 18/5, a number specified by the quark-parton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

Net-Baryon (B) vs. Net-Charge (Q)

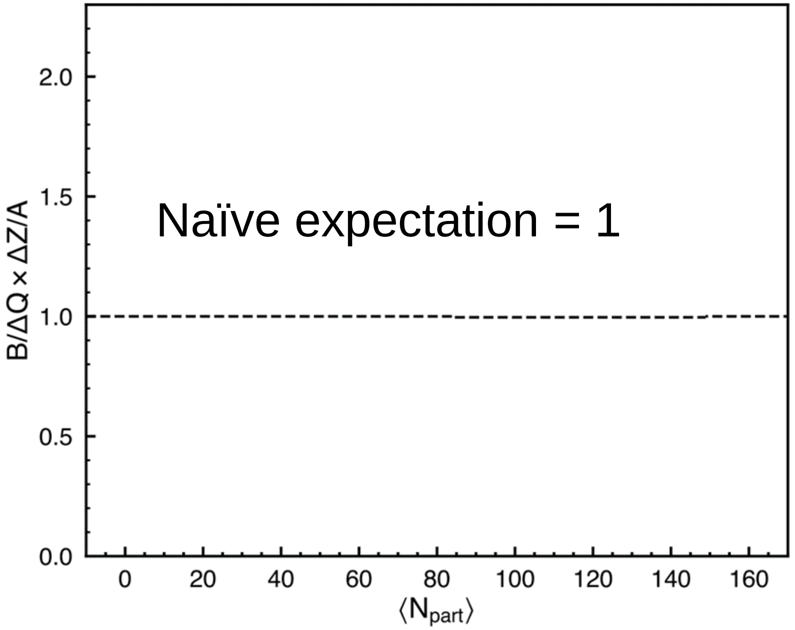
- **Charged meson: Carry Q.**
- **Proton: Carry B and Q.**
- **Neutron: Carry B.**
- **Define** $\Delta Q = Q(Ru+Ru) - Q(Zr+Zr)$



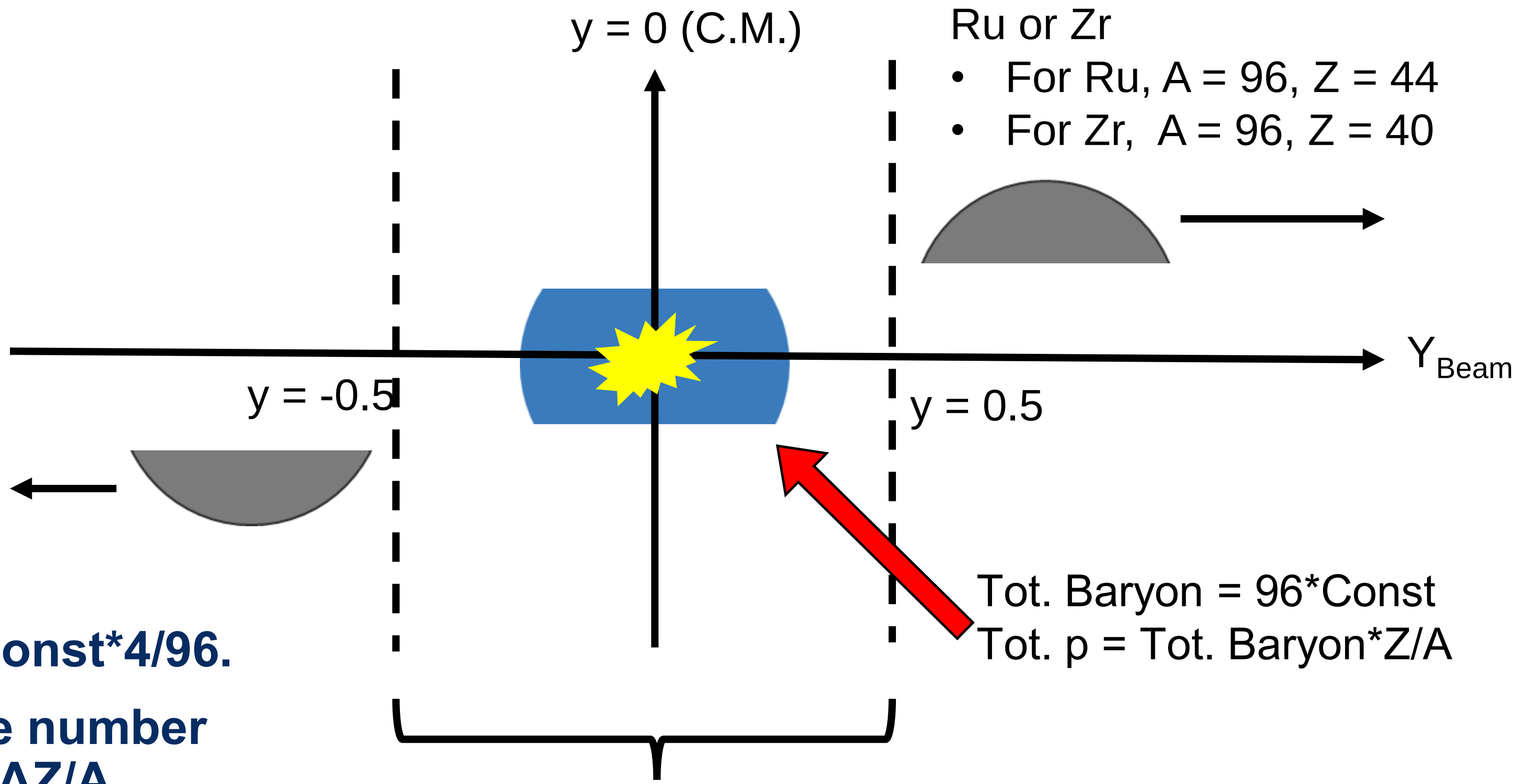
- **Question:** $\Delta Q = ???\frac{B\Delta Z}{A}$ **(at |y| < 0.5).**

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

If quarks carry the baryon number



- **B_{init}=96*Const.**
- **$\Delta Q_{init} = Q_{init}\,(Ru - Zr)$=96*Const*4/96.**
- **If baryon number and charge number are carried by quarks, B/ΔQ*ΔZ/A should be 1 throughout the collision evolution at mid-rapidity.**

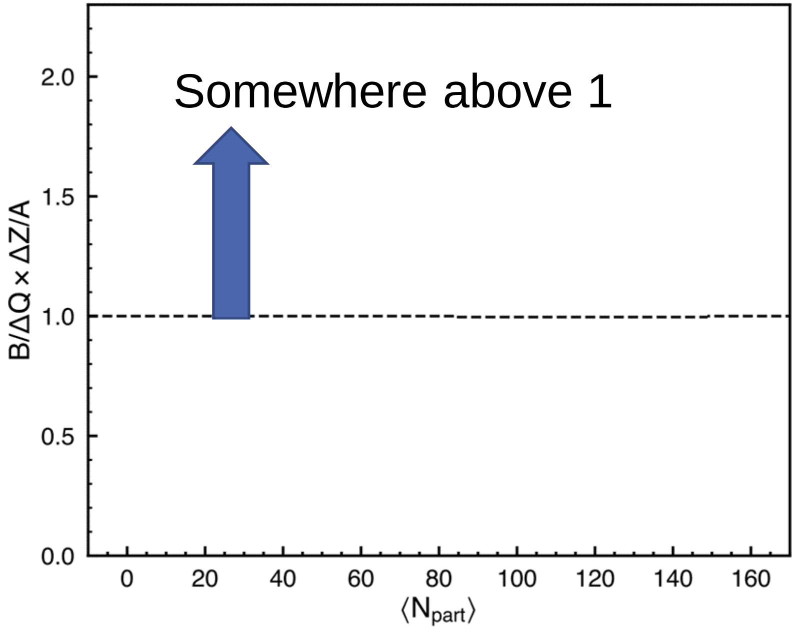


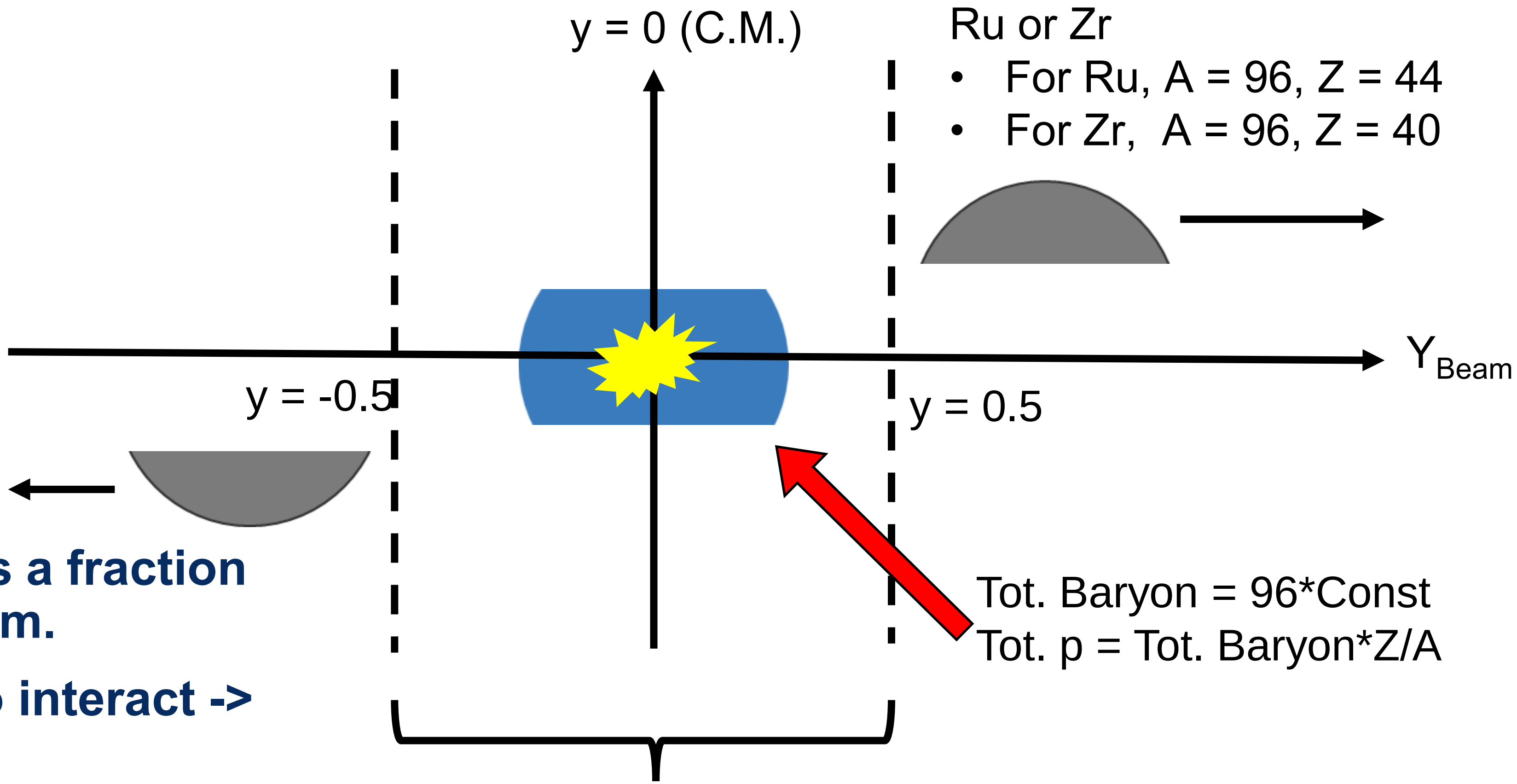
Ru or Zr
- For Ru, A = 96, Z = 44
- For Zr, A = 96, Z = 40

Tot. Baryon = 96*Const
Tot. p = Tot. Baryon*Z/A

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

If Baryon Junction carries the baryon number





Ru or Zr

- For Ru, A = 96, Z = 44
- For Zr, A = 96, Z = 40

Tot. Baryon = 96*Const
Tot. p = Tot. Baryon*Z/A

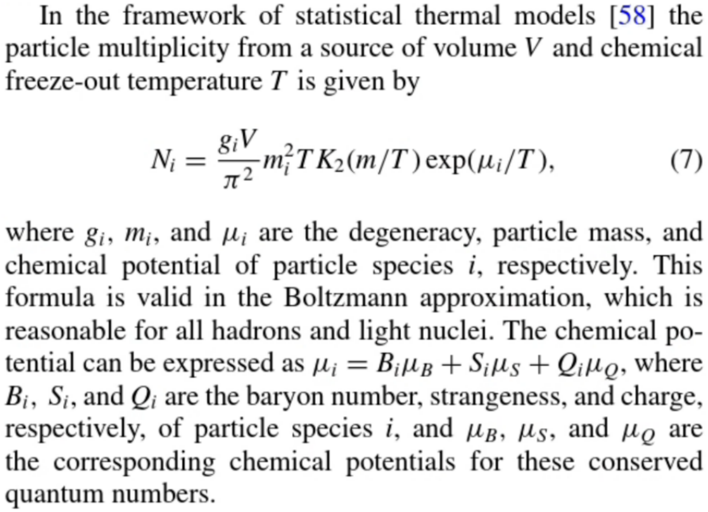
- **Baryon Junction only carries a fraction of valence quark’s momentum.**
- **Junction has enough time to interact -> More baryon stopping.**
- **Net-Baryon > Net-Charge.**

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

Net-Baryon number (B)

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$.
- **We don't measure (anti-)neutron spectrum. Approximated by thermal model assumption.**
- $B = (N_p - N_{\bar{p}}) + N_{\bar{p}}\sqrt{\frac{N_d}{N_{\bar{d}}}} - N_p\sqrt{\frac{N_{\bar{d}}}{N_d}}$.

Assumption



In the framework of statistical thermal models [58] the particle multiplicity from a source of volume V and chemical freeze-out temperature T is given by

$$N_i = \frac{g_i V}{\pi^2} m_i^2 T K_2(m/T) \exp(\mu_i/T), \tag{7}$$

where g_i, m_i, and μ_i are the degeneracy, particle mass, and chemical potential of particle species i, respectively. This formula is valid in the Boltzmann approximation, which is reasonable for all hadrons and light nuclei. The chemical potential can be expressed as $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$, where B_i, S_i, and Q_i are the baryon number, strangeness, and charge, respectively, of particle species i, and μ_B, μ_S, and μ_Q are the corresponding chemical potentials for these conserved quantum numbers.

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

Therefore,

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

Therefore,

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

Extracted from STAR Collaboration, PRC 99, 064905 (2019)

Net-Charge difference (Ru+Ru – Zr+Zr)

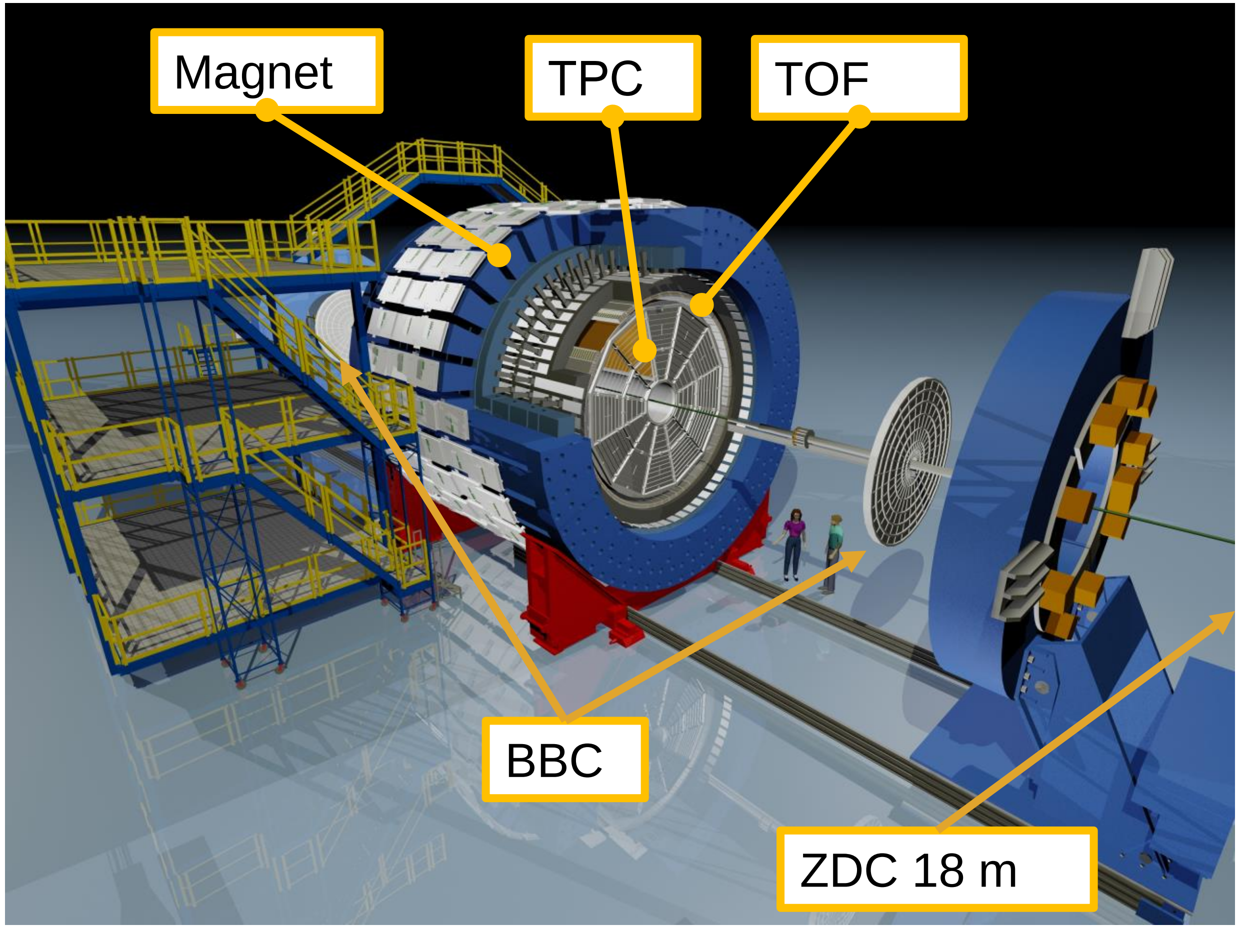
- **Define** $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}}$,
- **Define** $\Delta Q = \left[\left(N_\pi^+ + N_K^+ + N_p\right) - \left(N_\pi^- + N_K^- + N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$,
- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta \mathrm{R}_{\mathrm{Ru}}}{1+\Delta \mathrm{R}_{\mathrm{Zr}}} \approx 1 + \Delta \mathrm{R}_{\mathrm{Ru}} - \Delta \mathrm{R}_{\mathrm{Zr}}$.
- Focus on pion terms,
- $(N_\pi^+ - N_\pi^-)_{Ru} - (N_\pi^+ - N_\pi^-)_{Zr} = N_{\pi,Ru} \times \Delta \mathrm{R}_{\mathrm{Ru}} - \mathrm{N}_{\pi,Zr} \times \Delta \mathrm{R}_{\mathrm{Zr}}$
- $\approx N_\pi(\Delta \mathrm{R}_{\mathrm{Ru}} - \Delta \mathrm{R}_{\mathrm{Zr}}) = \mathrm{N}_\pi \times (R2_\pi - 1)$.
- Where $N_\pi = 0.5 \times (N_\pi^+ + N_\pi^-)$.
- Therefore, $\Delta Q = \mathrm{N}_\pi(\mathrm{R2}_\pi - 1) + N_K(R2_K - 1) + N_p\left(R2_p - 1\right)$.
- Double ratio reduces systematics uncertainty.

Recap what are needed.

- **For baryon stopping B,**
  - $N_p, N_{\bar{p}}, N_d, N_{\bar{d}}$ for Ru+Ru and Zr+Zr.

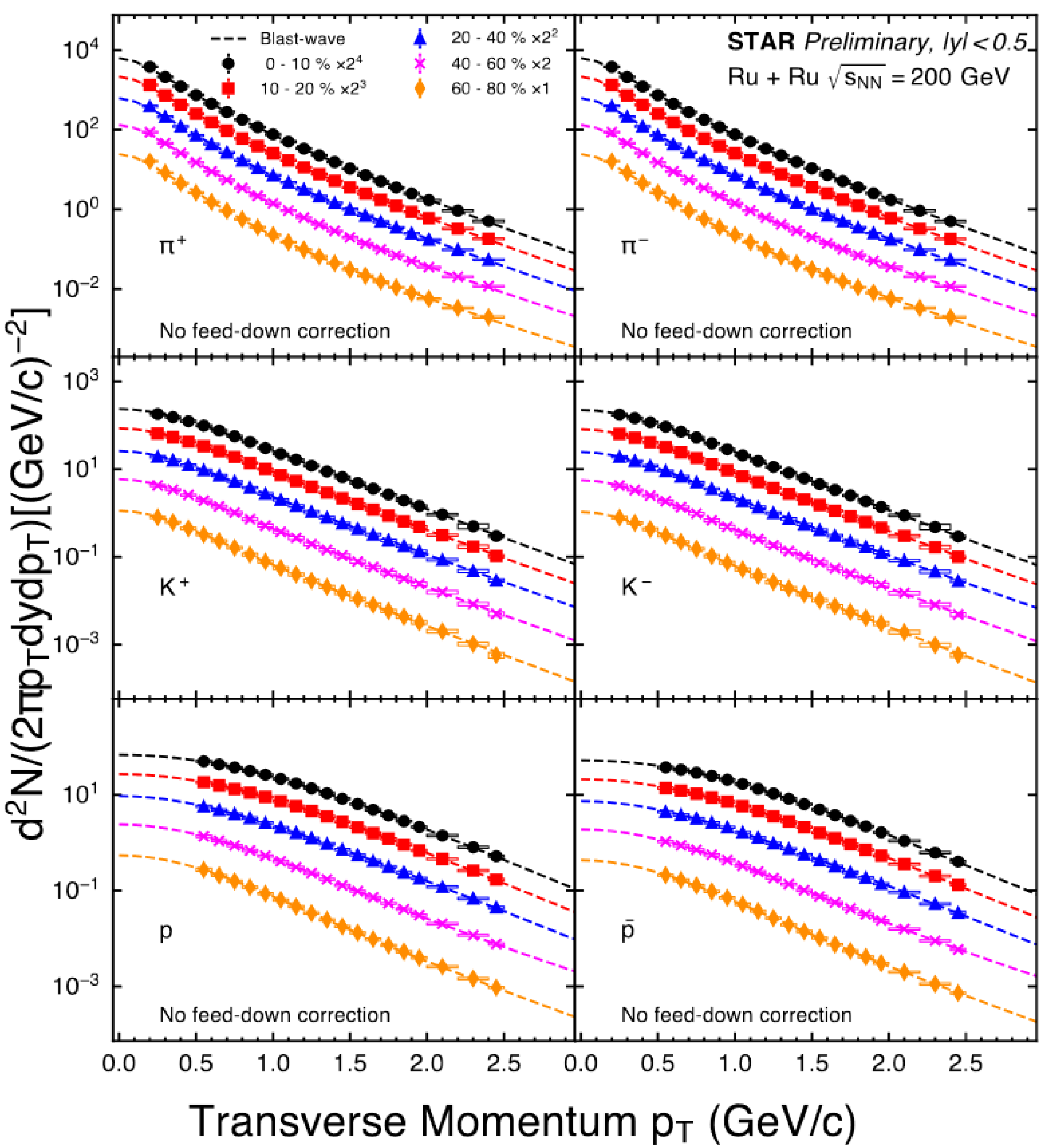
- **For charge stopping difference ΔQ,**
  - $N_\pi^+,\ N_K^+,\ N_p,\ N_\pi^-,\ N_K^-,\ N_{\bar{p}}$ for Ru+Ru and Zr+Zr.
  - $R2_\pi, R2_K, R2_p$.

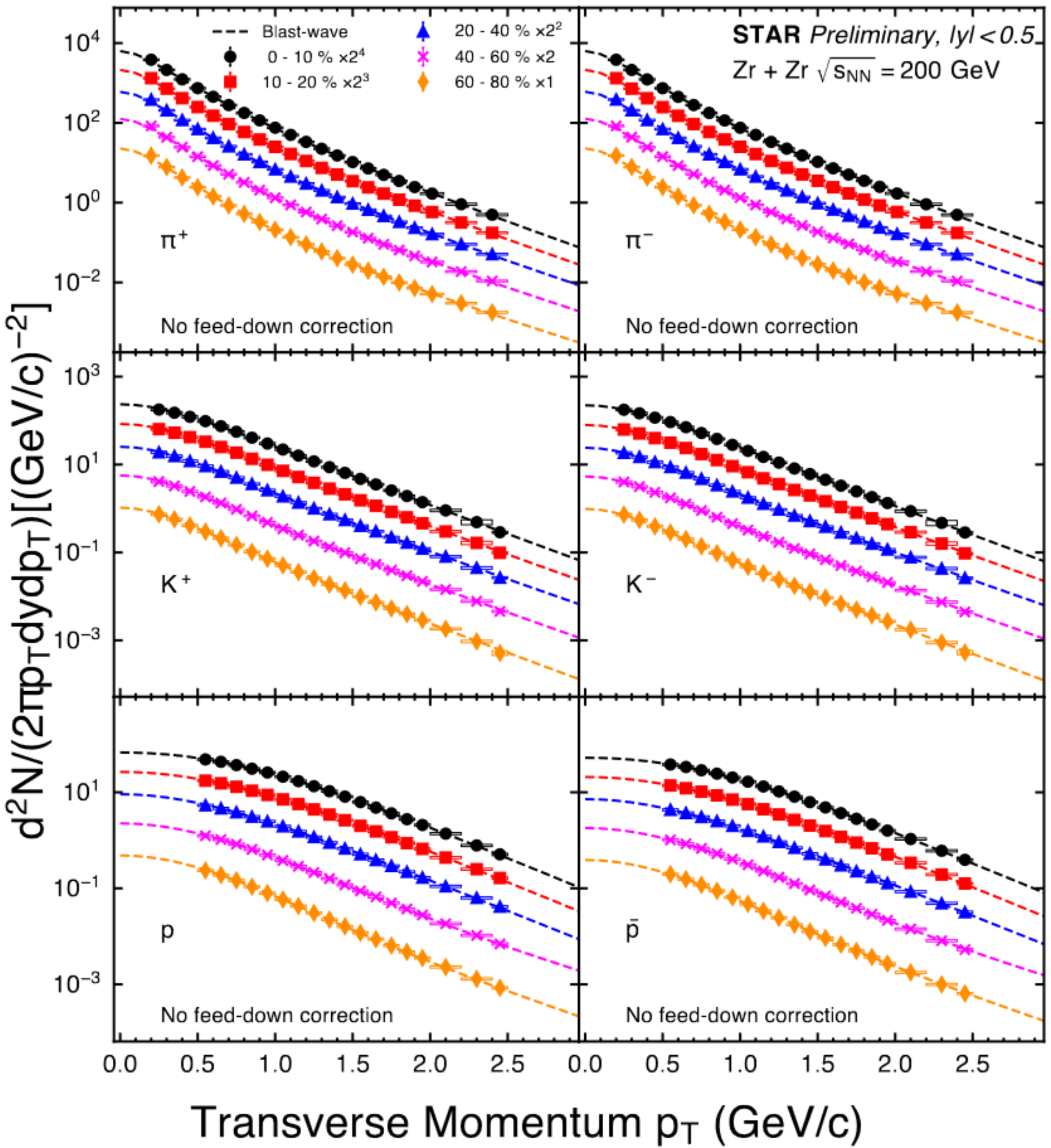
STAR detector



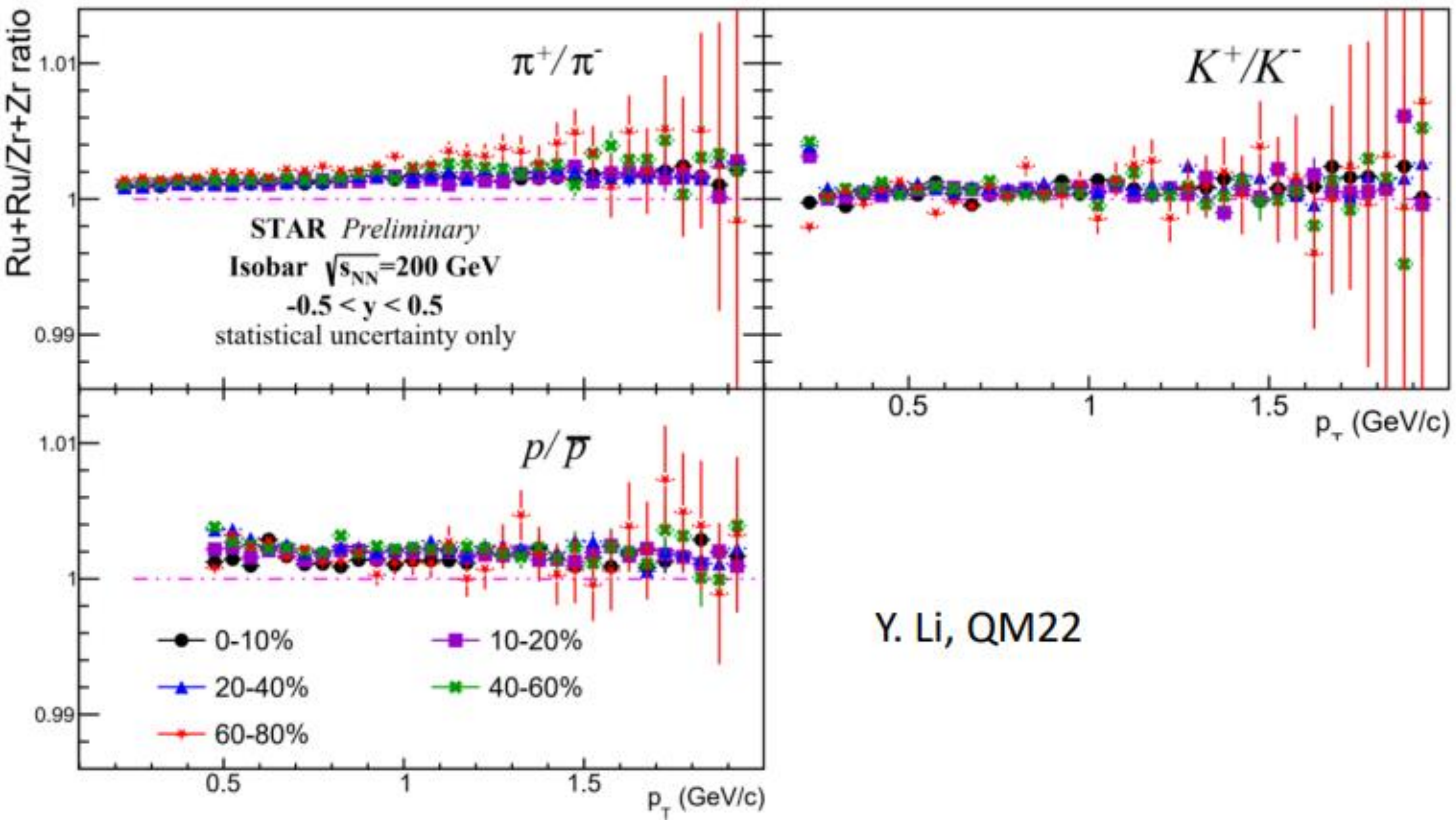
- **Time Projection Chamber (TPC)**
  - Measures charged particle momentum with track curvature under B-field.
  - Identifies particle with energy loss per unit length (dE/dx).
- **Time-Of-Flight (TOF)**
  - Extends momentum range for particle identification.
  - Pile-up rejection.
- **Zero Degree Calorimeter (ZDC)**
  - Detect forward neutrons for event selection.
- **Beam-Beam counter (BBC)**

Spectra from Isobar



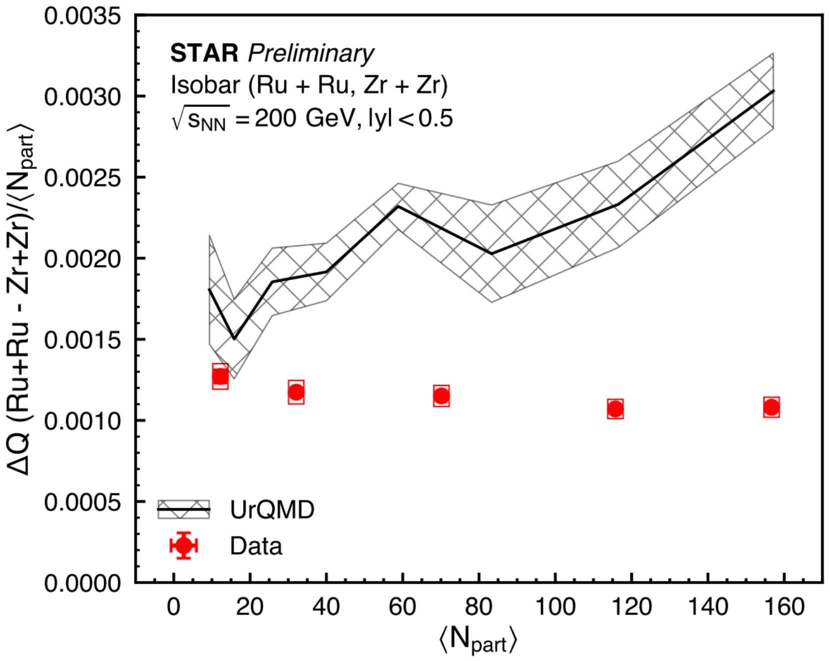


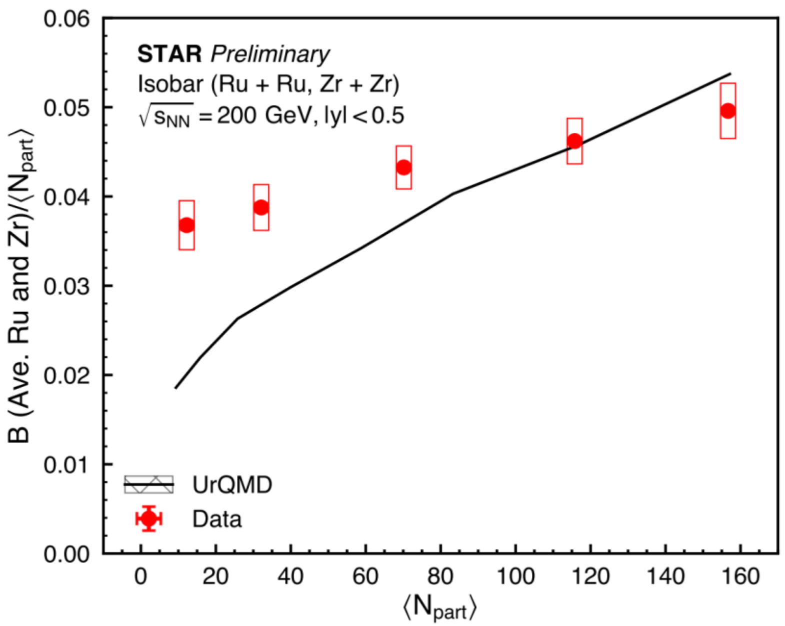
Double ratio R2s



Y. Li, QM22

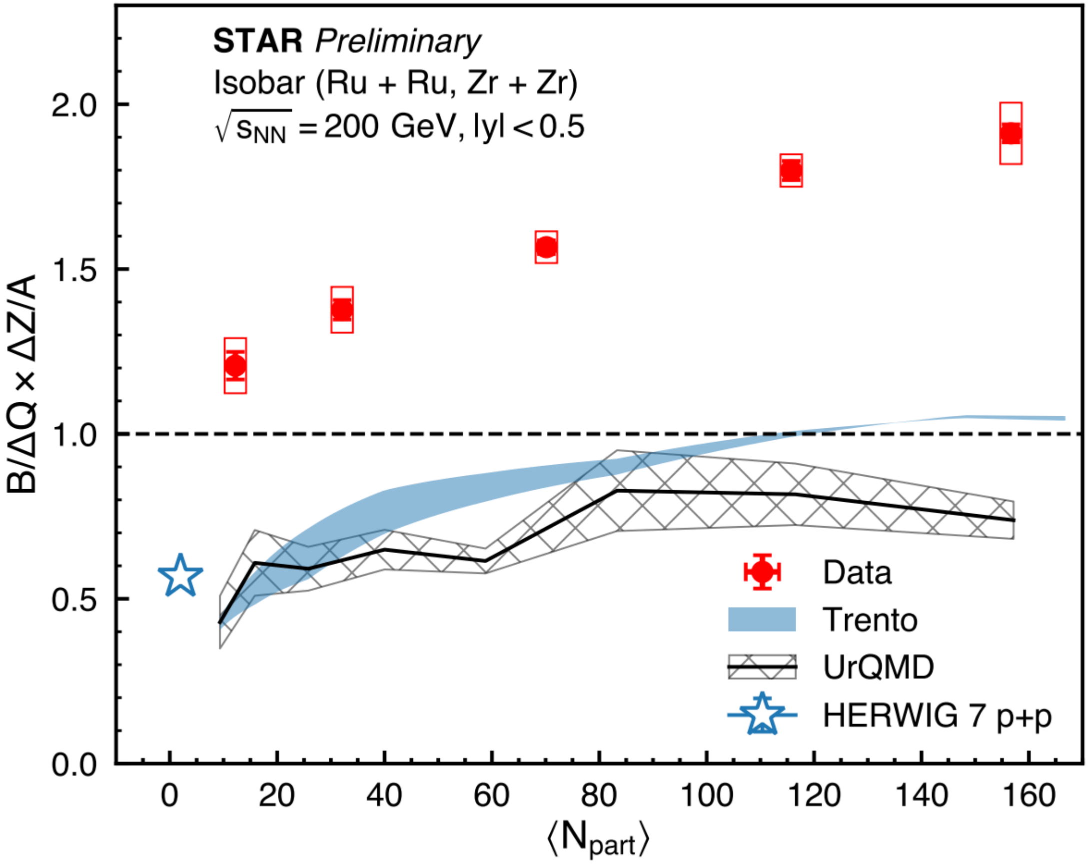
Net-Charge and Net-Baryon compared to UrQMD separately





- **UrQMD accurately reproduces baryon stopping at mid-rapidity in central collisions but not ΔQ, probably because UrQMD has been tuned to net-proton measurements.**
- **Accurate measurement of charge stopping can be used for model tuning.**

Experimental result on Net-Charge and Net-Baryon



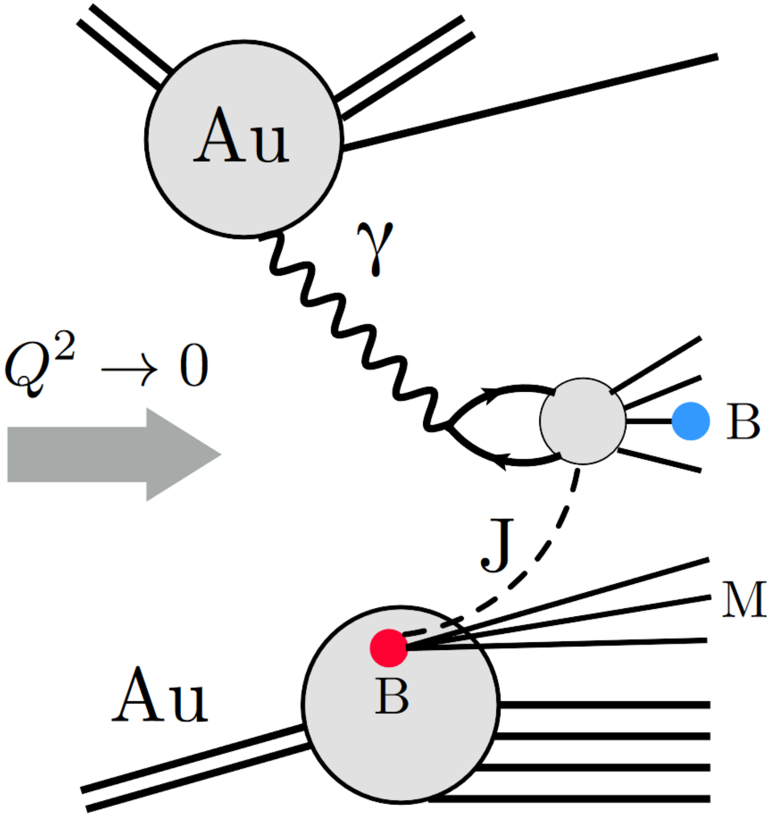
- B/ΔQ∗ΔZ/A > 1.
- Model calculations (Herwig $p + p$ (B/Q*Z/A, Z=A=1) [1] and UrQMD [2]) cannot describe our data.
- Decrease with decreasing $\langle N_{part} \rangle$.
  - Similar trend seen in Trento model [3].
  - Trento model accounts for initial conditions only.
  - Consistent with change in neutron skin thickness differences.

[1]:J. Bellm et al, Eur. Phys. J.C. 80 5, 452 (2020)
[2]: M. Bleicher et al, J. Phys. G. 25, 1859 (1999)
[3]: H. Xu et al, PRC 105, L011901 (2022)

Net-Baryon in photonuclear collisions

Net-Baryon in photonuclear collisions

- **Inclusive particle production in photonuclear collisions.**
  - Large flux of quasi-real photons produced by ultra-relativistic large-Z nuclei.
  - Similar to eA collisions except that the photon has almost zero virtuality.
  - Probes the nucleus at low-x.



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

Net-Baryon in photonuclear collisions

If Junction hypothesis is true:

- **Quasi-real $\gamma \to q\bar{q}$.**
- **Interact with a Junction in target Au nucleus.**
- **Enhanced creation of mid-rapidity baryons.**
  - Junction interaction time > quark interaction time.
  - More baryons are stopped in Junction picture.
- **Regge theory: $dN/dy \propto e^{-\alpha_B(y-y_{beam})}$ in the direction of the target.**
  - α_B is related to Regge intercept of Junctions (J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)).

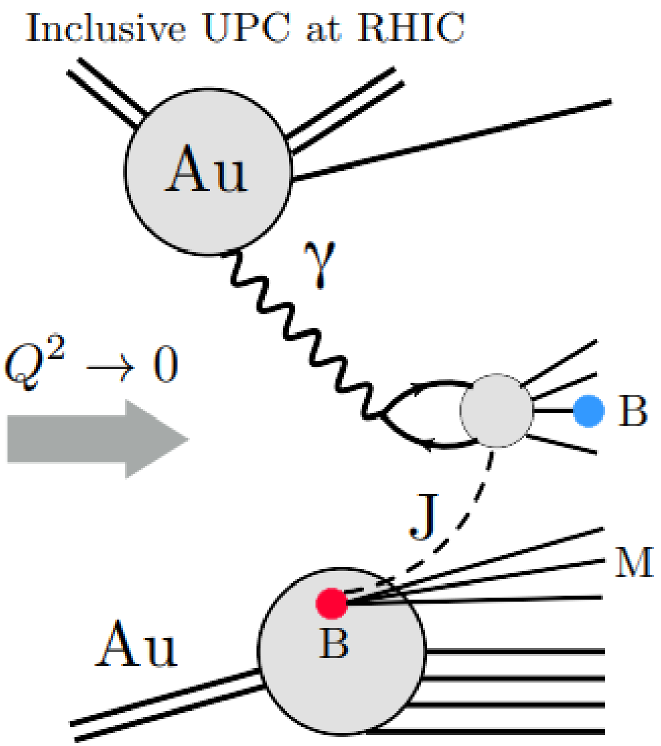
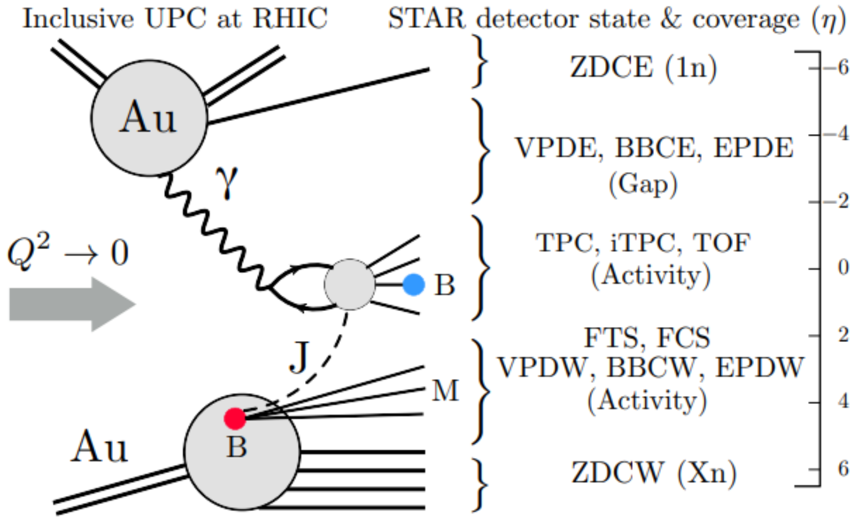


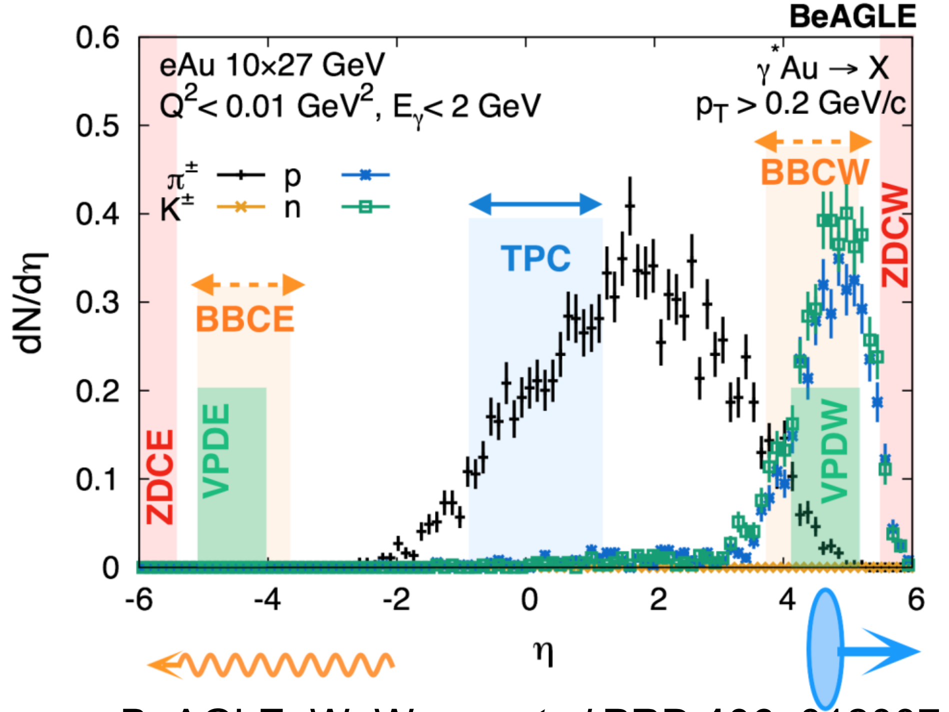
Figure from J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

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.
  - $|V_z(\text{VPD}) - V_z(\text{TPC})| > 10$ cm.
  - vice versa (east ⇔ west).

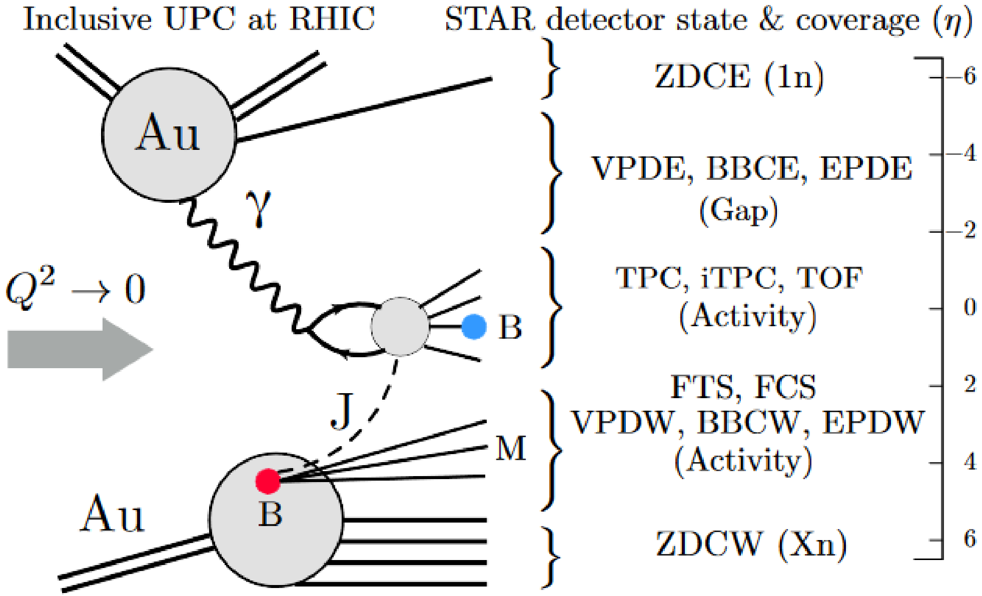
Figures from J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)



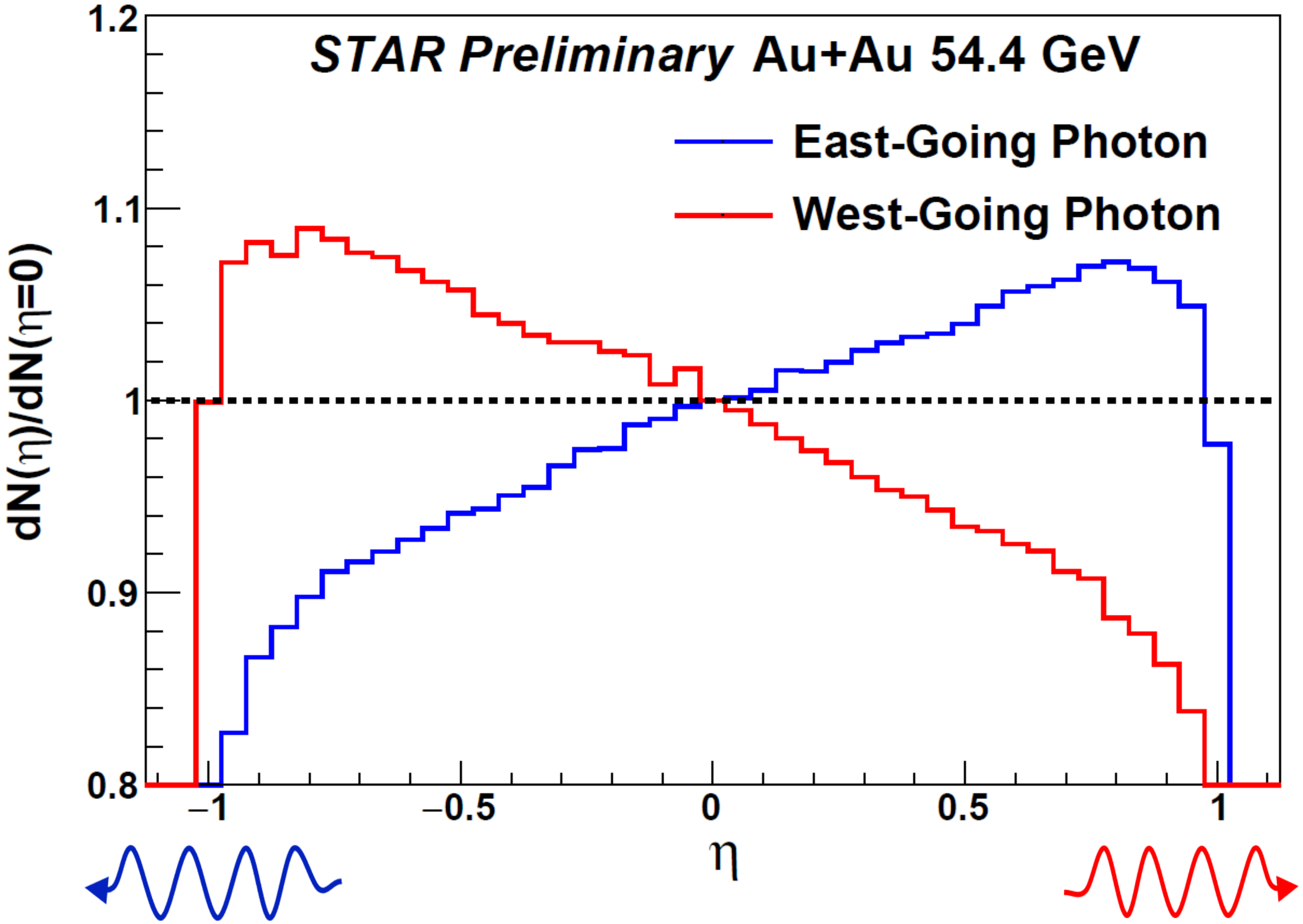


BeAGLE: W. Wang, *et al* PRD **106,** 012007 (2022)

Rapidity asymmetry in γA-rich events

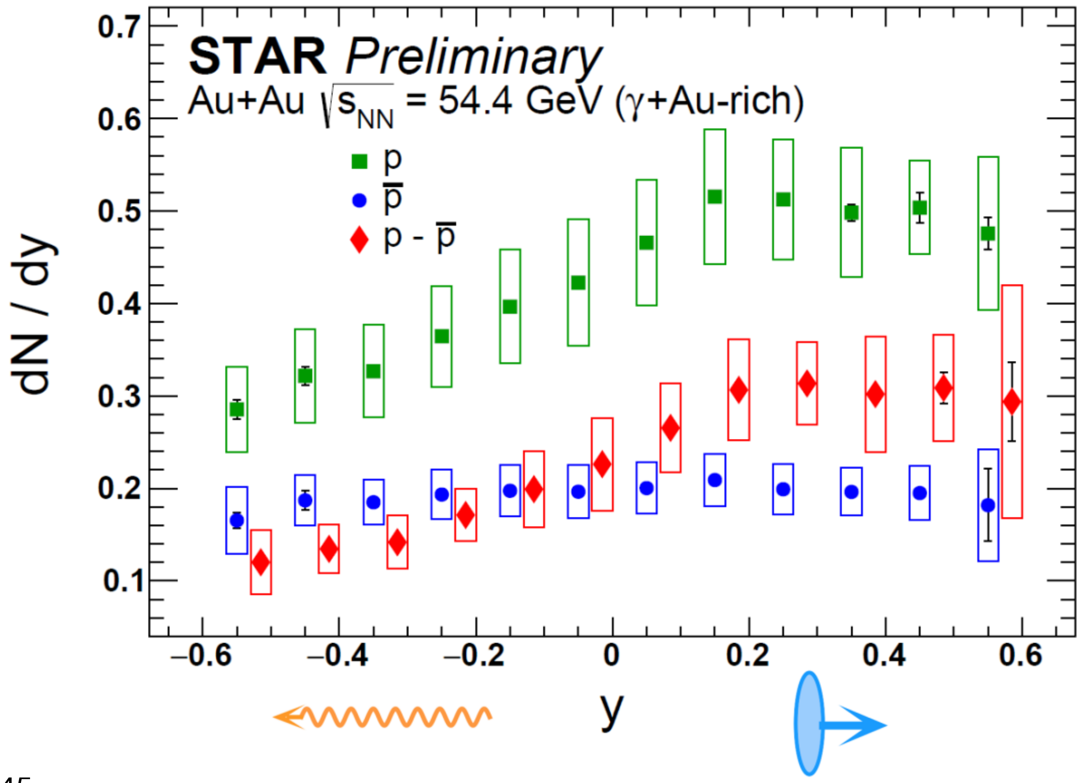


J. D. Brandenburg, N. Lewis,
P. Tribedy, Z. Xu, arXiv:2205.05685
(2022)



Net-proton yield as a proxy for Net-Baryon

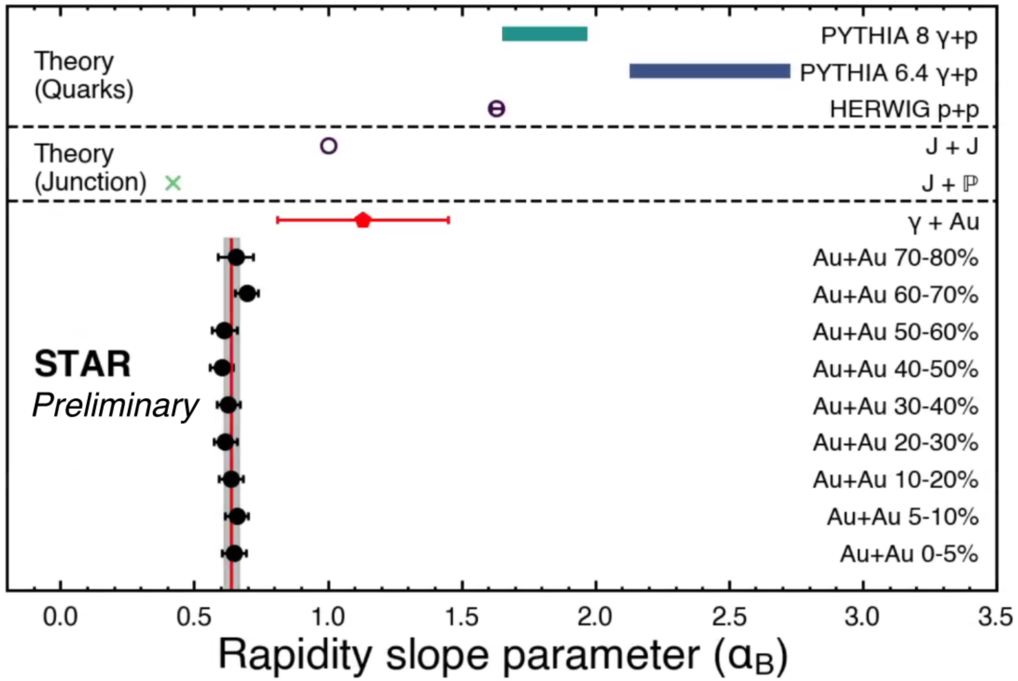
- Net-proton yield is described by $exp(-(1.06 \pm 0.05)y)$.
- PYTHIA-6, which has valence quarks as baryon number carrier, predicts a dependence of $exp(-2.43y)$[1, 2, 3].



[1]: J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)
[2]: B. Andersson, G. Gustafson, G. Ingelman, and T. Sj ̈ostrand, Physics Reports 97, 31–145 (1983).
[3]: Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands, JHEP 05, 026 (2006), arXiv:hep-ph/0603175.

Net-proton exponential slope (α_B)

- $\alpha_B \sim 0.6$ **for Au+Au [1, 2].**
- $\alpha_B \sim$ **1 for** $\gamma + \mathrm{Au}$**.**
- **Predicted values from HERWIG and PYTHIA (both versions) disagree with data.**
  - PYTHIA 8 includes a Junction-like mechanism in final-state hadronization [3].
- **Slopes for Junction-Junction (J+J) and Junction-Pomeron (J+P) predictions are more compatible with data [4].**



[1] STAR, PRC **79**, 034909 (2009)
[2] STAR, PRC **96,** 044904 (2017)
[3] Christiansen, J. R. & Skands, P. Z. String Formation Beyond Leading Colour. JHEP 08, 003 (2015). 1505.01681.
[4] Kharzeev, D. Can gluons trace baryon number? Phys. Lett. B 378, 238–246 (1996).nucl-th/9602027.

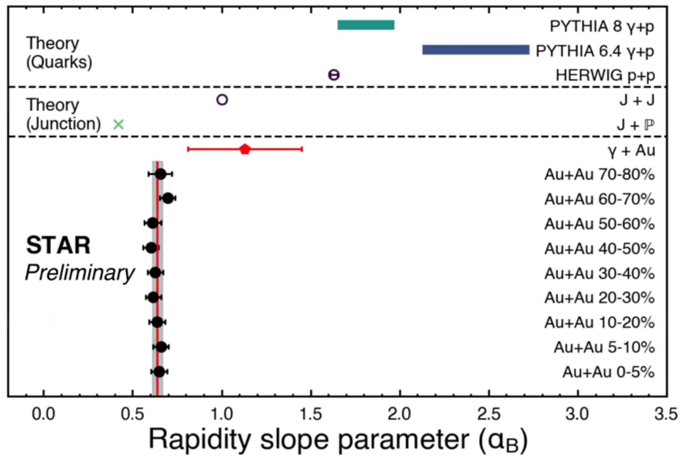
Conclusion

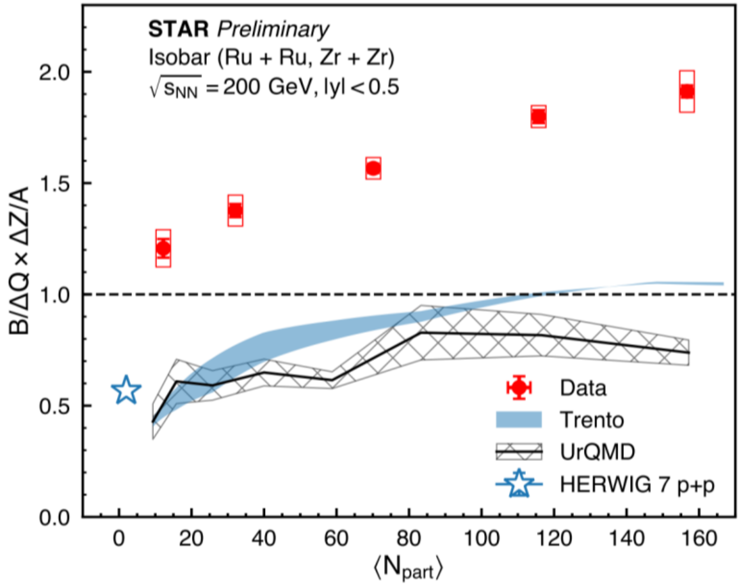
- **Exponential slope of mid-rapidity net-proton yield in hadronic Au+Au from BES-I < theoretical predictions.**

- **Observed significant net-proton yield $\gamma + Au$ collisions, whose slope against rapidity is smaller than that from PYTHIA and HERWIG without baryon junction.**

- **Ratio of baryon to charge number difference is observed to be larger than 1 using Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV.**

- **Our results disfavor the assertion that valence quarks carry the baryon number.**





Backup slides

Photon interactions in ultra-peripheral heavy ion collisions

- Ultra-relativistic, high-Z nuclei produce highly Lorentz-contracted EM fields.
- Equivalent Photon Approximation (EPA): EM fields can be quantized as a flux of quasi-real photons.
  - C. F. von Weizsacker, Z. Phys. 88, 612 (1934)
  - E. J. Williams, Phys. Rev. 45, 729 (1934)
  - X. Wang, et al, PRC 107, 044906 (2023)

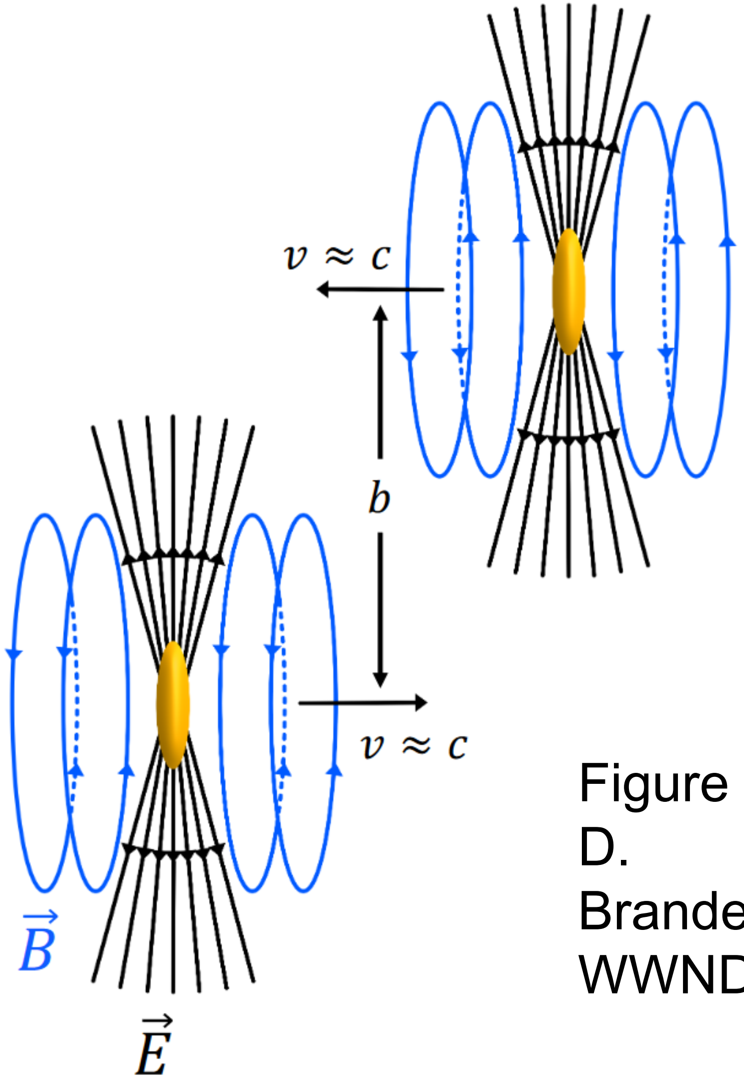
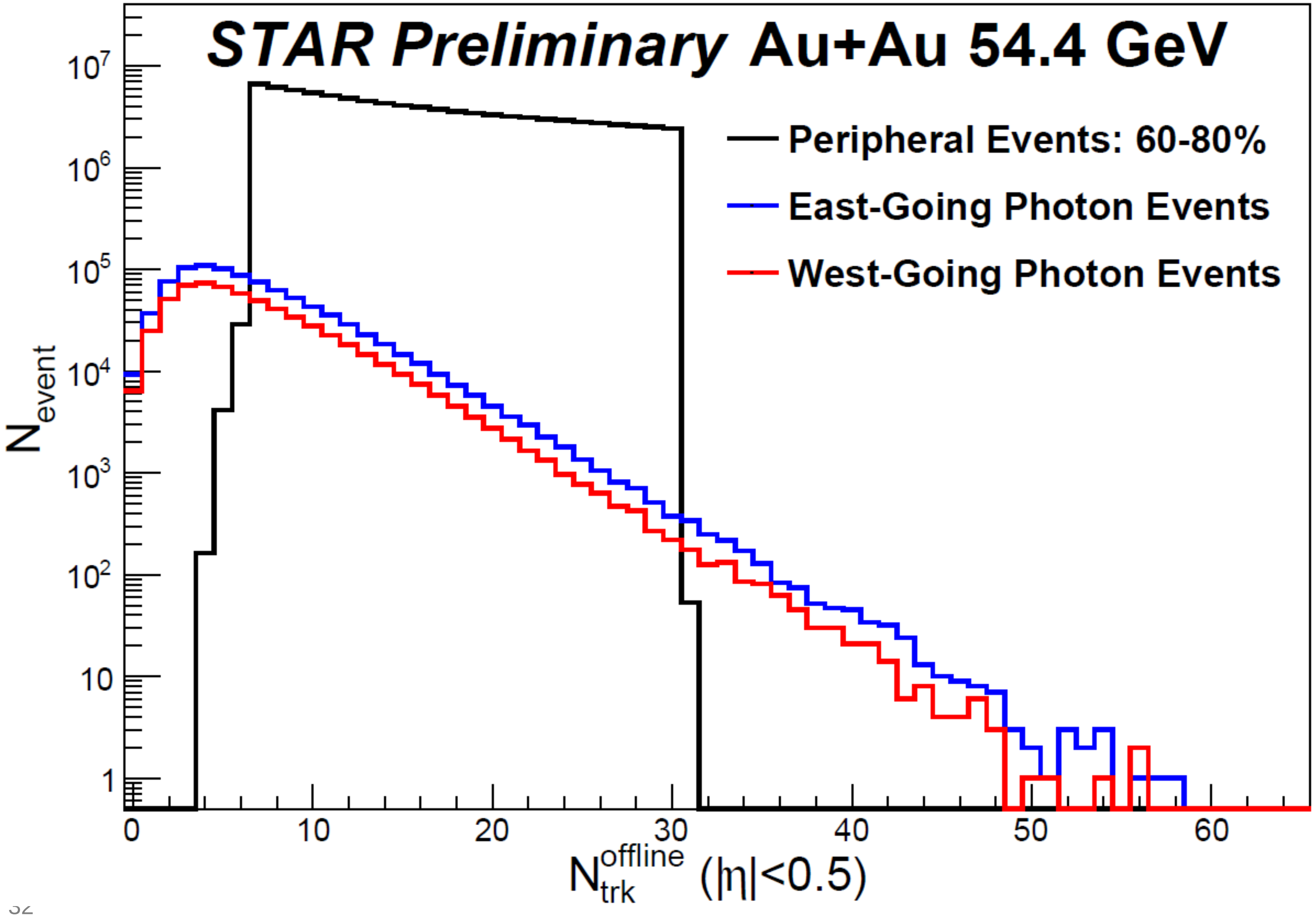


Figure from D. Brandenburg WWND 2020

Defining γA and AA event classes

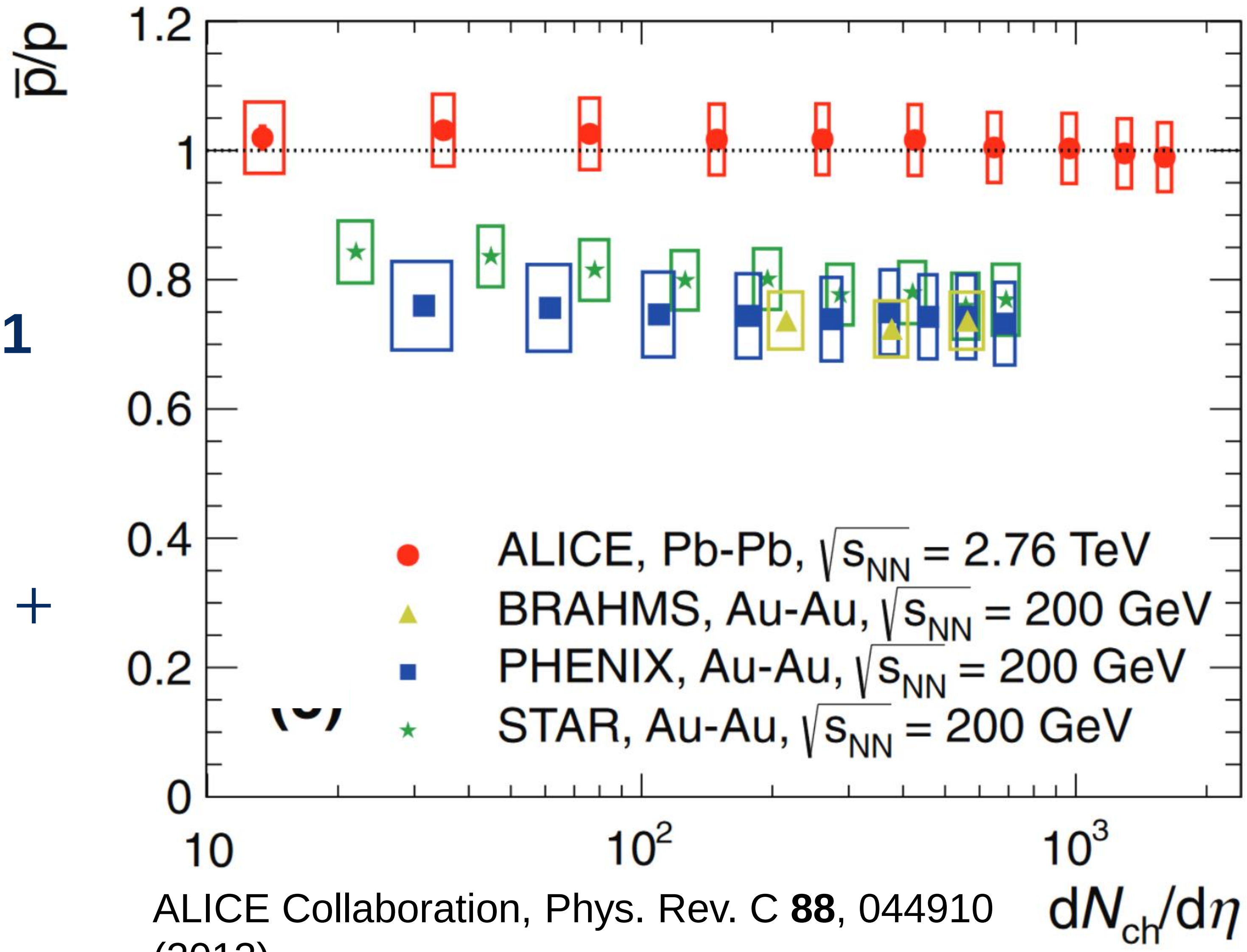


Most photonuclear events have low multiplicity, consistent with very peripheral $\mathrm{Au} + \mathrm{Au}$ **collisions.**

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

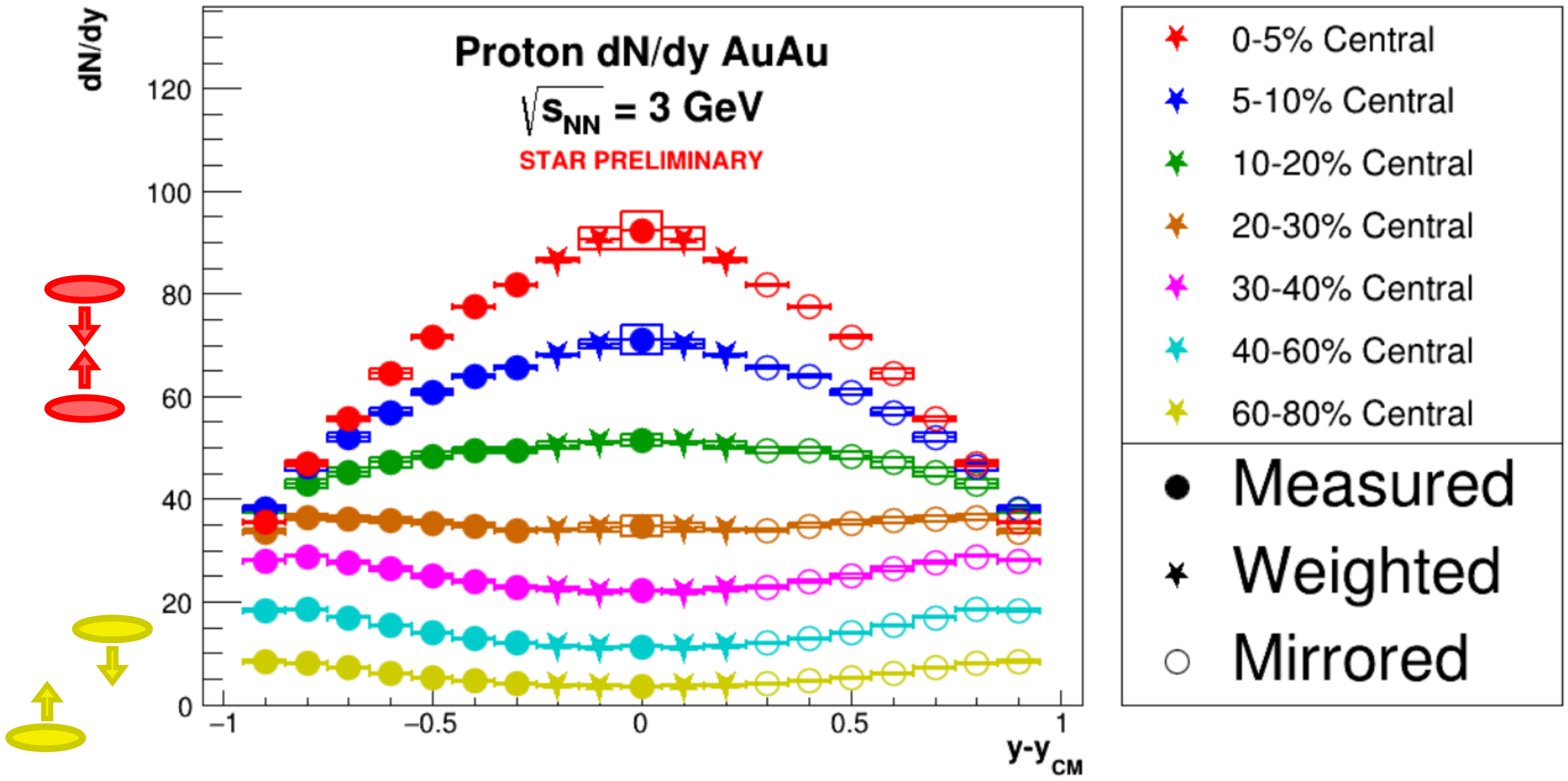
Vanishing baryon stopping at LHC energies

- $\bar{p}/p$ **ratio is consistent with 1 for midrapidity** $\mathrm{Pb+Pb}$**,** $\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$.
- **About** 0.8 **for** $\mathrm{Au+Au}$**,** $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$**.**



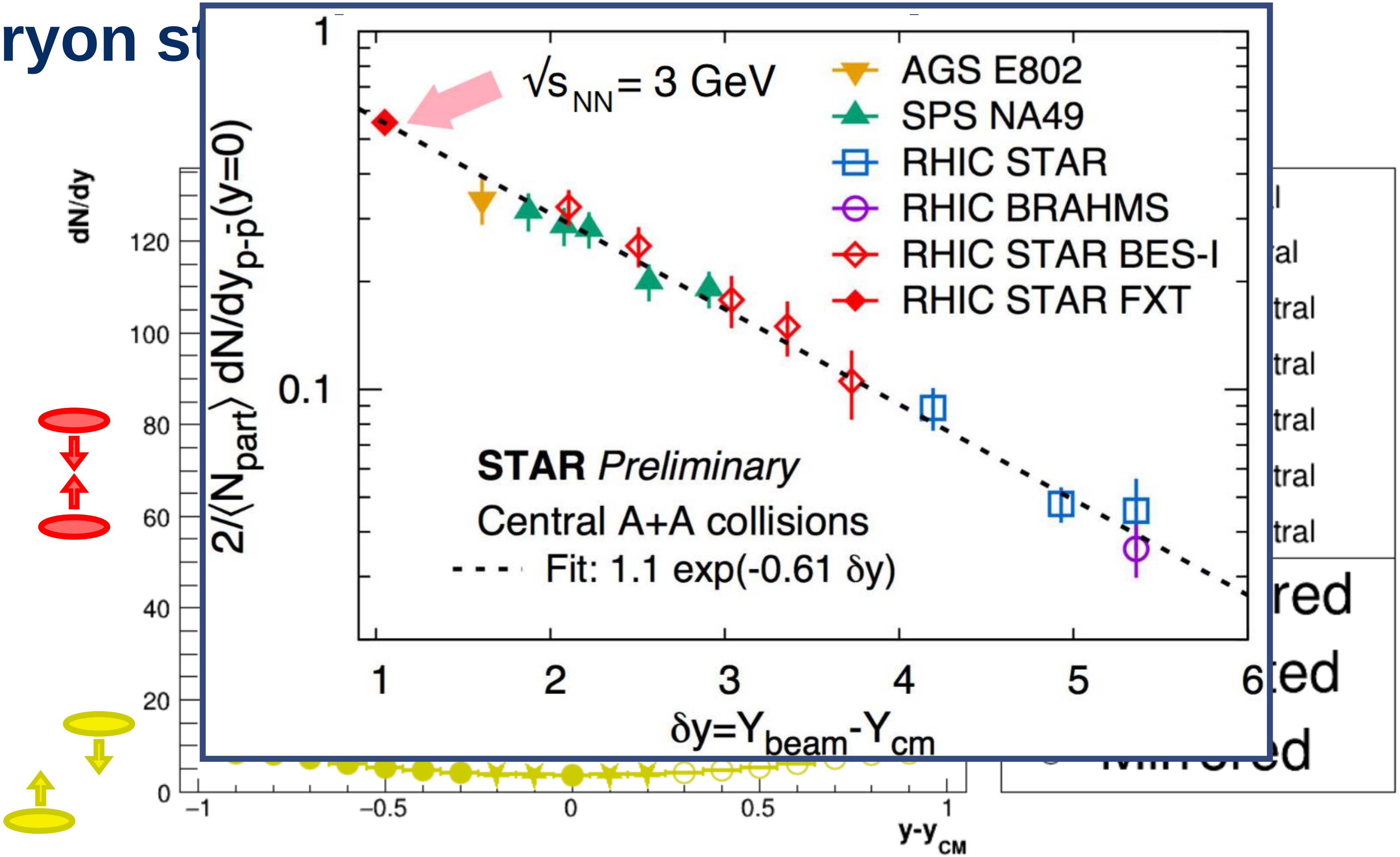
ALICE Collaboration, Phys. Rev. C **88**, 044910 (2013)

Baryon stopping at lower energies



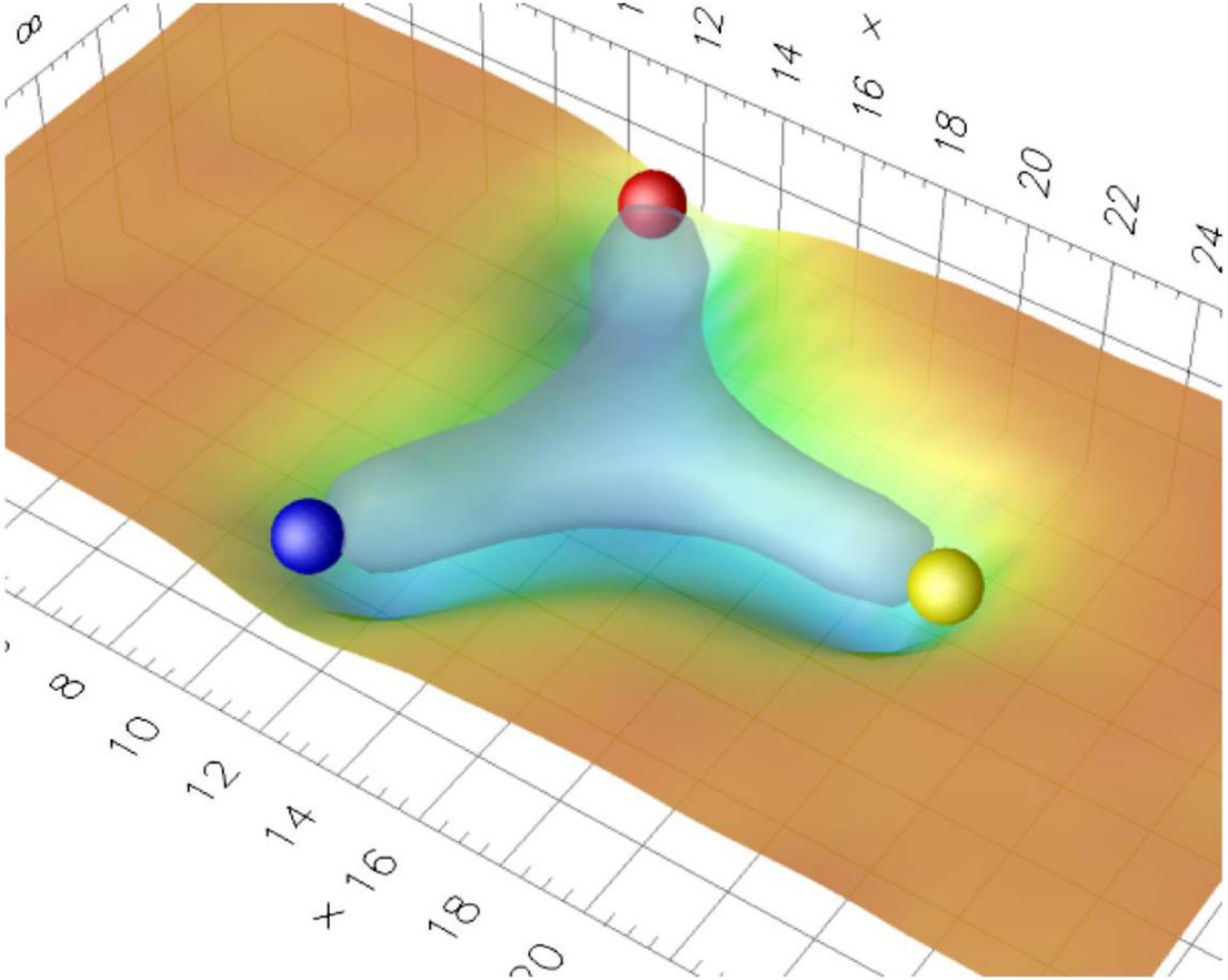
Chun Yuen Tsang, 2023 Annual RHIC and AGS Users' Meeting 2023

Baryon st



1
0.1
$\sqrt{s_{NN}}$ = 3 GeV
AGS E802
SPS NA49
RHIC STAR
RHIC BRAHMS
RHIC STAR BES-I
RHIC STAR FXT
STAR *Preliminary*
Central A+A collisions
Fit: 1.1 exp(-0.61 δy)
$2/\langle N_{part}\rangle\, dN/dy_{p-\bar{p}}(y=0)$
1
2
3
4
5
6
$\delta y = Y_{beam} - Y_{cm}$
dN/dy
120
100
80
60
40
20
0
−1
−0.5
0
0.5
1
$y-y_{CM}$

Y-Shaped baryon flux-tube in lattice QCD



F. Bissey, *et al* Phys. Rev. D **76**, 114512 (2007)

- **Some lattice calculations have suggested the formation of a Y-shaped color flux tube among the three quarks at long distances**

  T. T. Takahashi, *et al* Phys. Rev. Lett. **86**, 18 (2001)

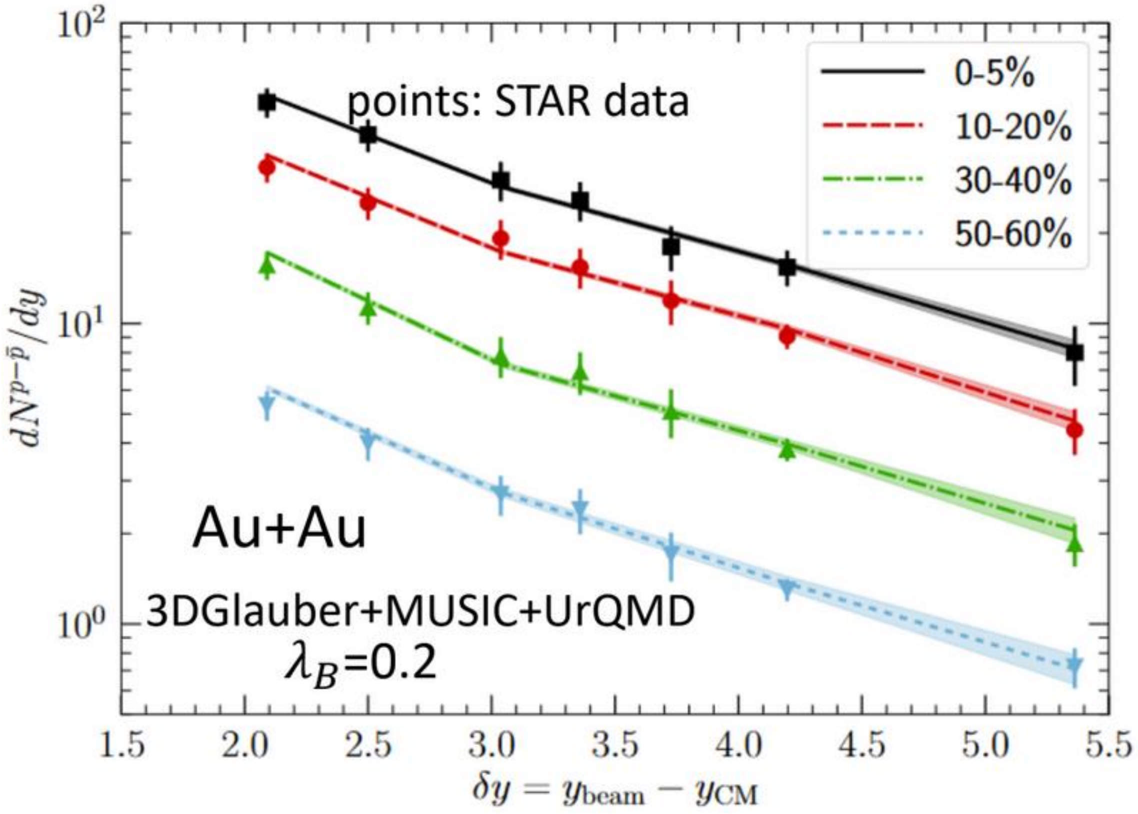
  T. Takahashi, *et al*, Phys. Rev. D **65**, 114509 (2002)

- **Still under investigation**

String Junction model

- **3D hybrid model:** $\text{GLAUBER} + \text{MUSIC} + \text{URQMD}$ **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

Systematic uncertainties for isobar analysis

Signal extraction for pions, Kaons and protons

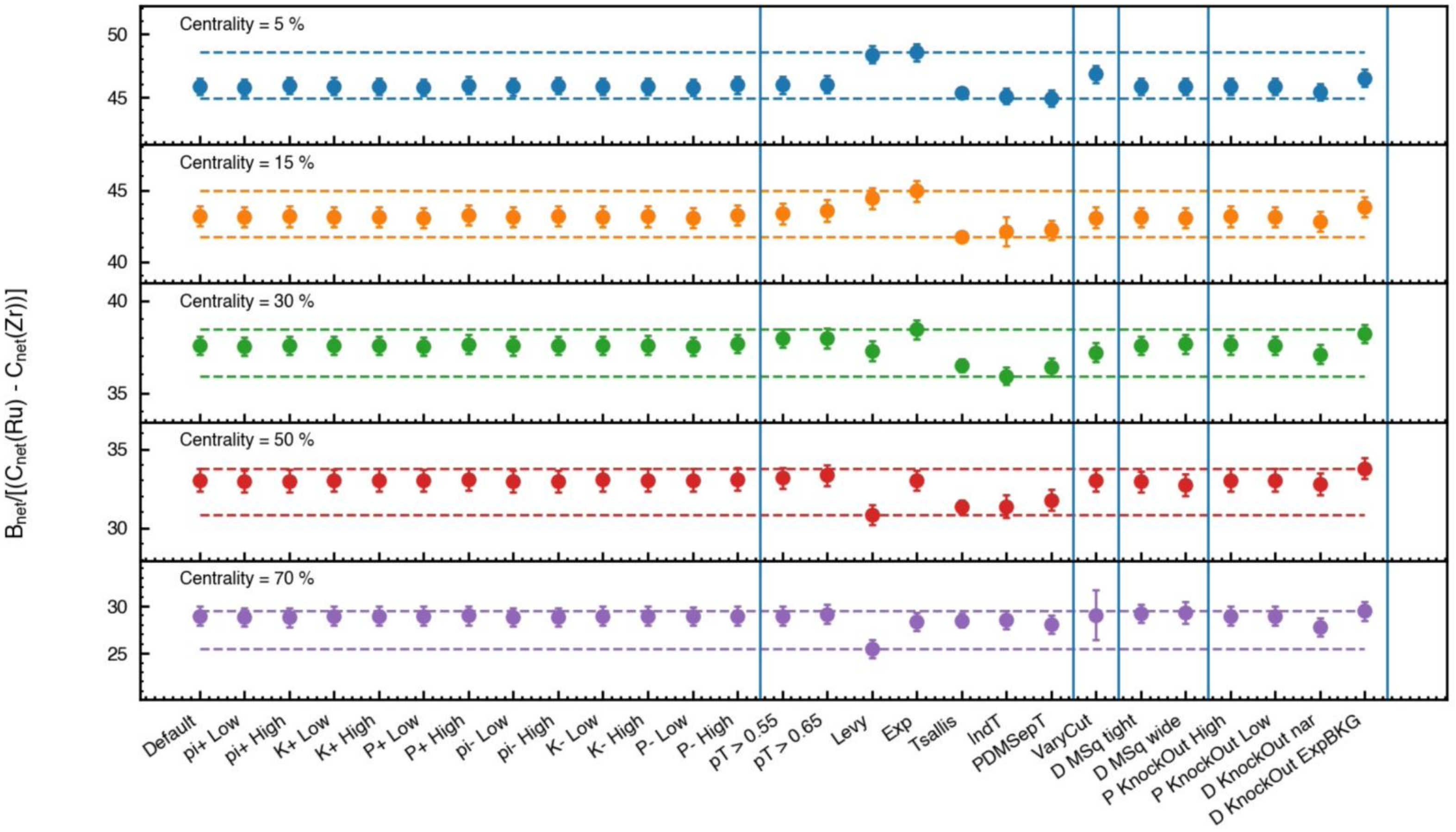
Extrapolation

Vary M-

square fit for deuteron

Varying nHitFits/nHitDeDx

Knock out

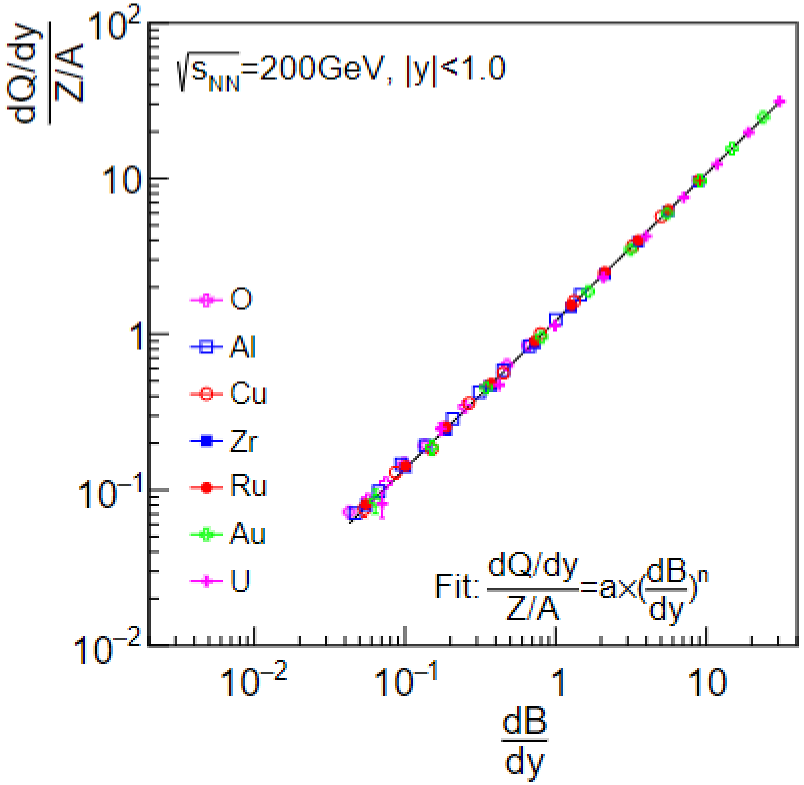


- Pions, Kaons and proton High and Low:
  - High: spectrum*(1 + err) from Yang.
  - Log: spectrum*(1-err).
- pT > 0.55 or 0.56:
  - Change pT/A threshold for extrapolation.
- Levy, Exp and Tsallis:
  - Function used for extrapolation.
- IndT, PDMSepT:
  - Default setting on Blast-wave requires particle anti-particle pair to have same temperature.
  - IndT: each particle can have different temperature.
  - PDMSepT: mesons (Kaons and Pions) need to have identical T.
- VaryCut:
  - nHitsFit >= 20, nHitsDeDx >= 15.
- D MSq tight/wide:
  - Fit range for D mass-square changes.
  - Tight: $2.5 < M^2 < 4.5$.
  - Wide: $2.1 < M^2 < 4.9$.
  - Default: $2.3 < M^2 < 4.7$.
- P KnockOut High/Low: err from Yang.
- D KnockOut nar: PID with $\left|\frac{1}{\beta_{TPC}} - \frac{1}{\beta_{TOF}}\right| < 0.03.$
- D KnockOut ExpBKG: use exponential instead of Log-Gaus background.

Percentage systematic uncertainty by source

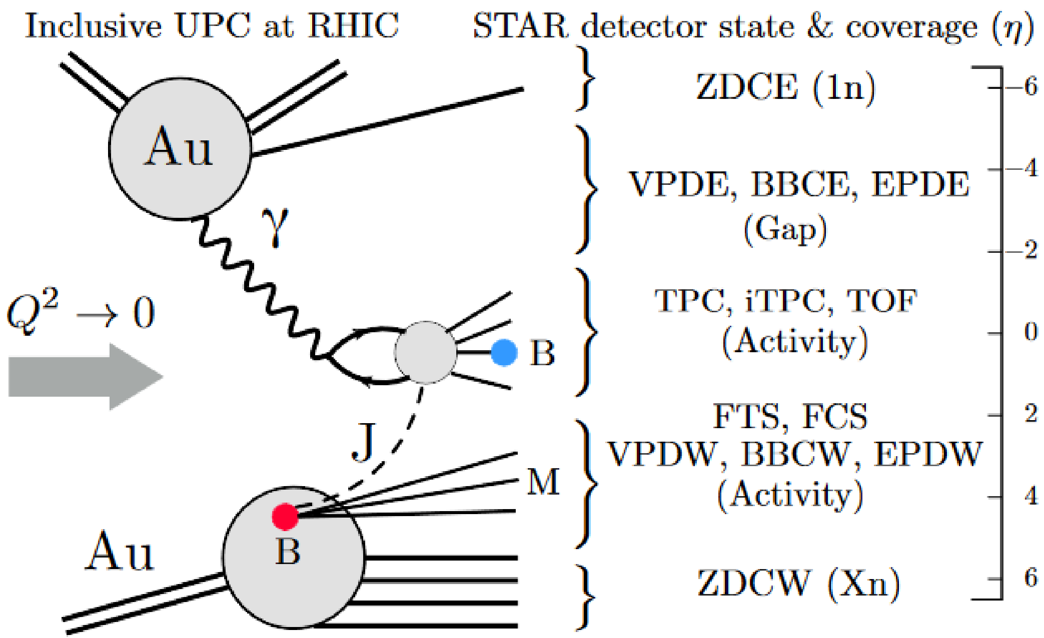
Source\Centrality	0 - 10 %	10 - 20 %	20 - 40%	40 - 60 %	60 - 80 %
Signal Extraction	0.17	0.01	0.17	0	0.23
Extrapolation	4.21	2.46	2.49	4.55	6.25
Vary nHits	2.11	0	1.01	0	0
D MSq fit	0	0	0	0.52	0.26
Knock-out variation	1.22	1.19	1.47	2.1	2.97
All	4.87	2.73	3.07	5.04	6.92

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

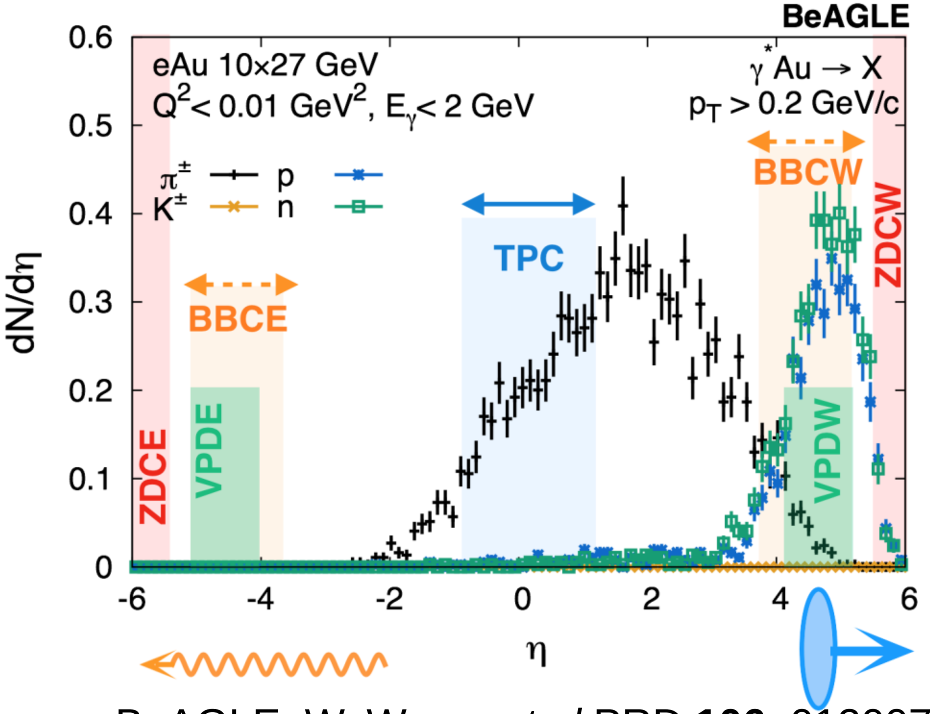


Courtesy: Z. Tang

Photonuclear event selection: using rapidity gaps



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

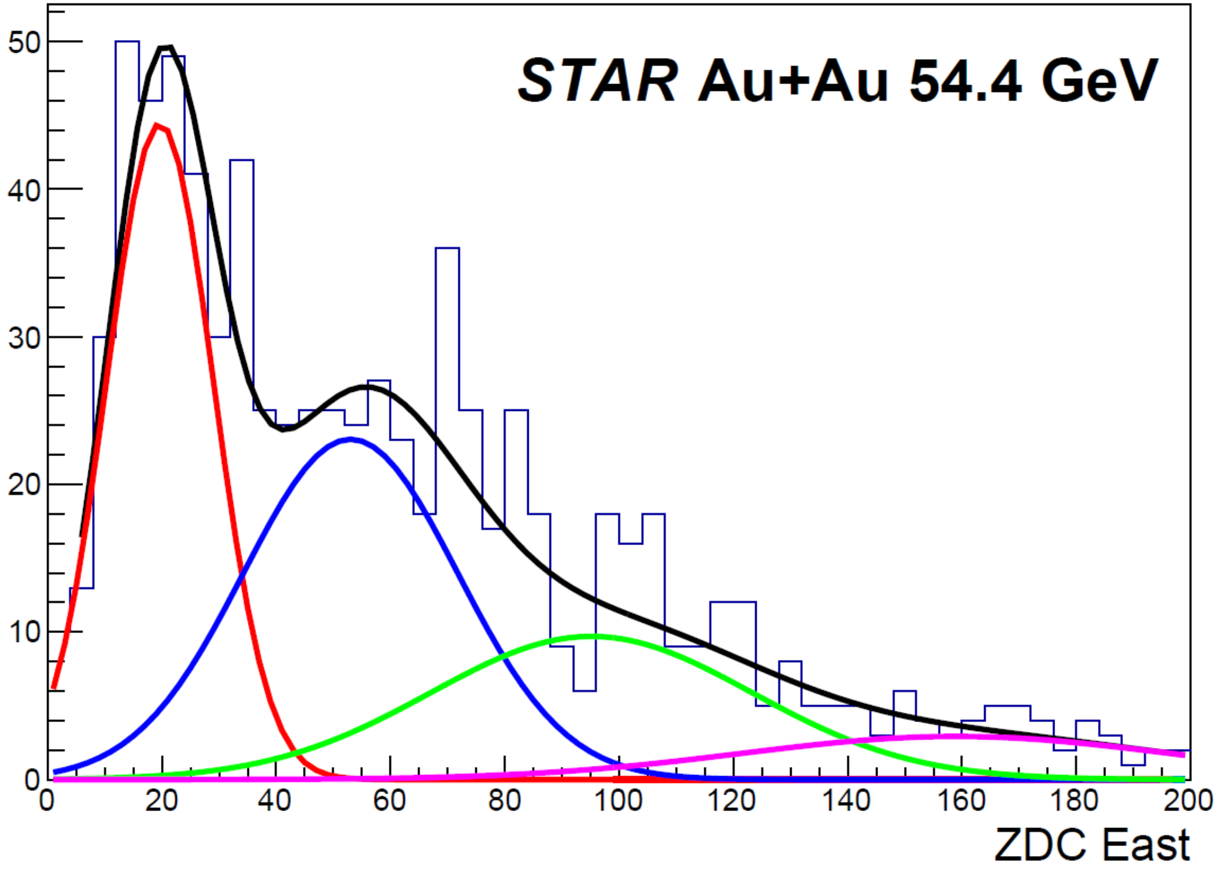


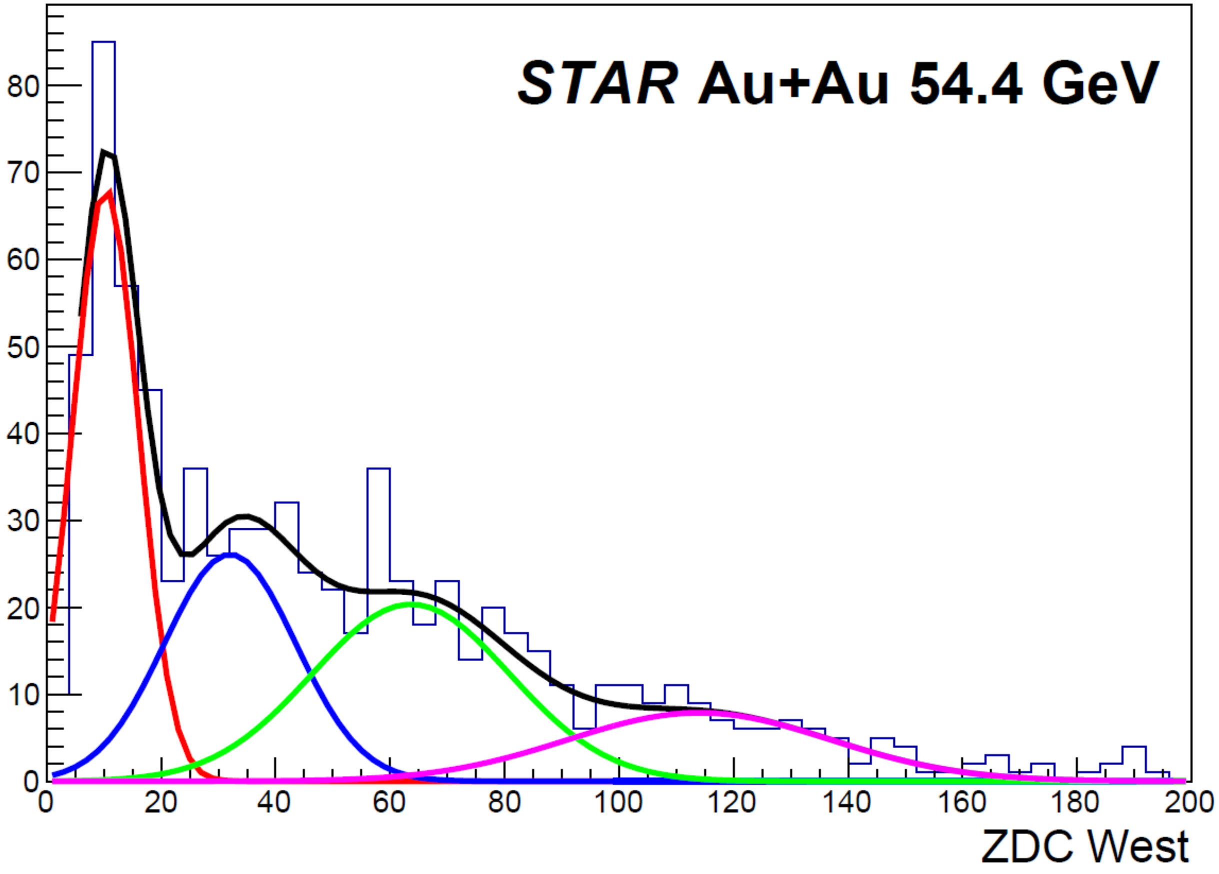
BeAGLE: W. Wang, *et al* PRD **106,** 012007 (2022)

Similar technique used by LHC for inclusive photonuclear measurements:
ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021) and CMS Collaboration, arXiv:2204.13486 (2022).

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

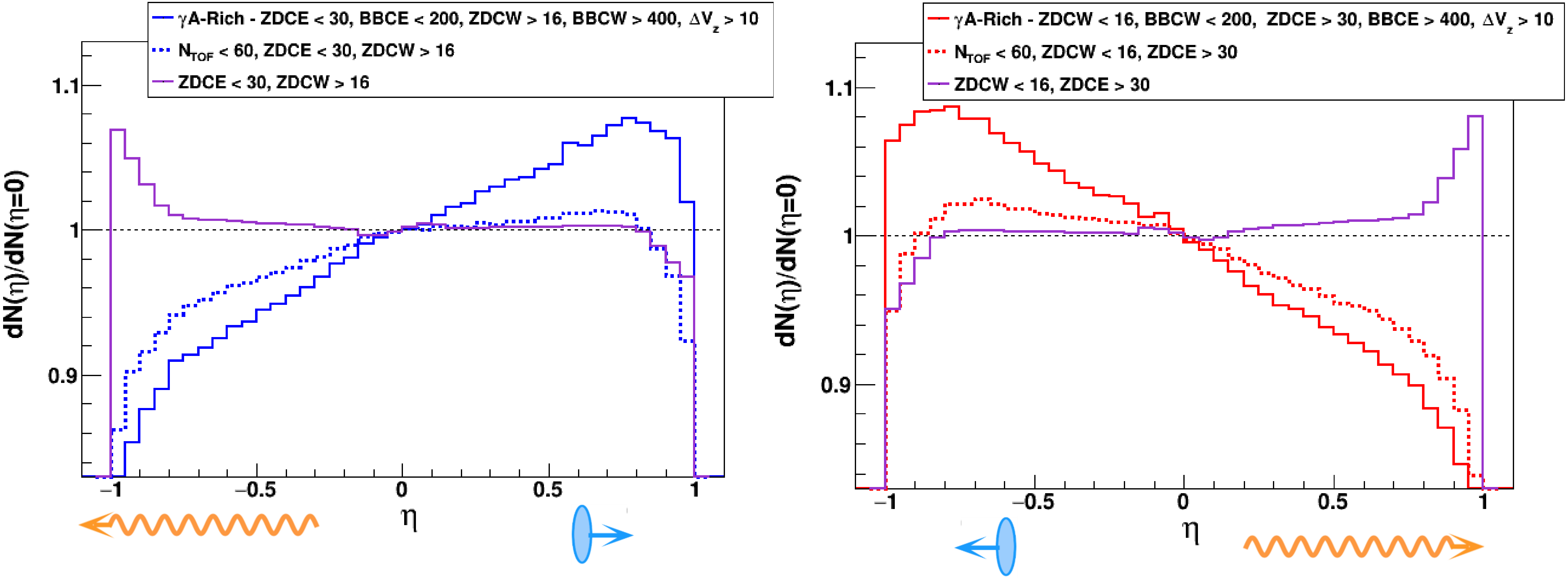
Photonuclear event selection: identifying the single neutron peak





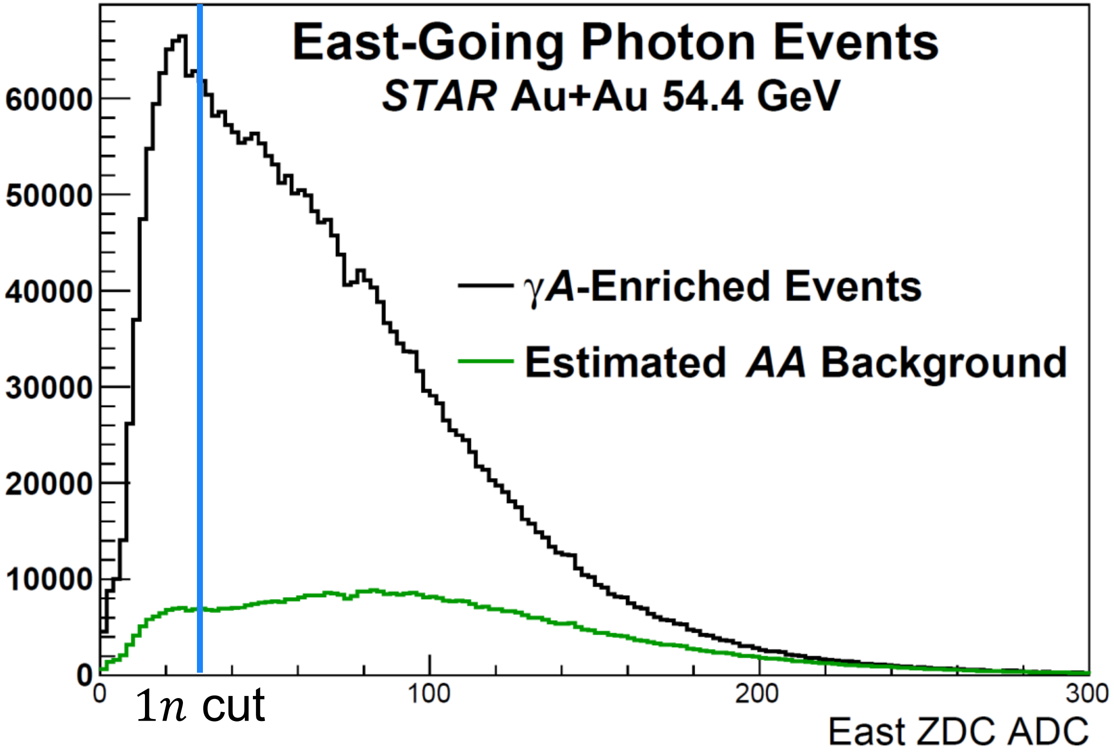
Low multiplicity events collected with ZDC triggers.
Cutting on single neutron peak, dominated by $\gamma + A$ events.

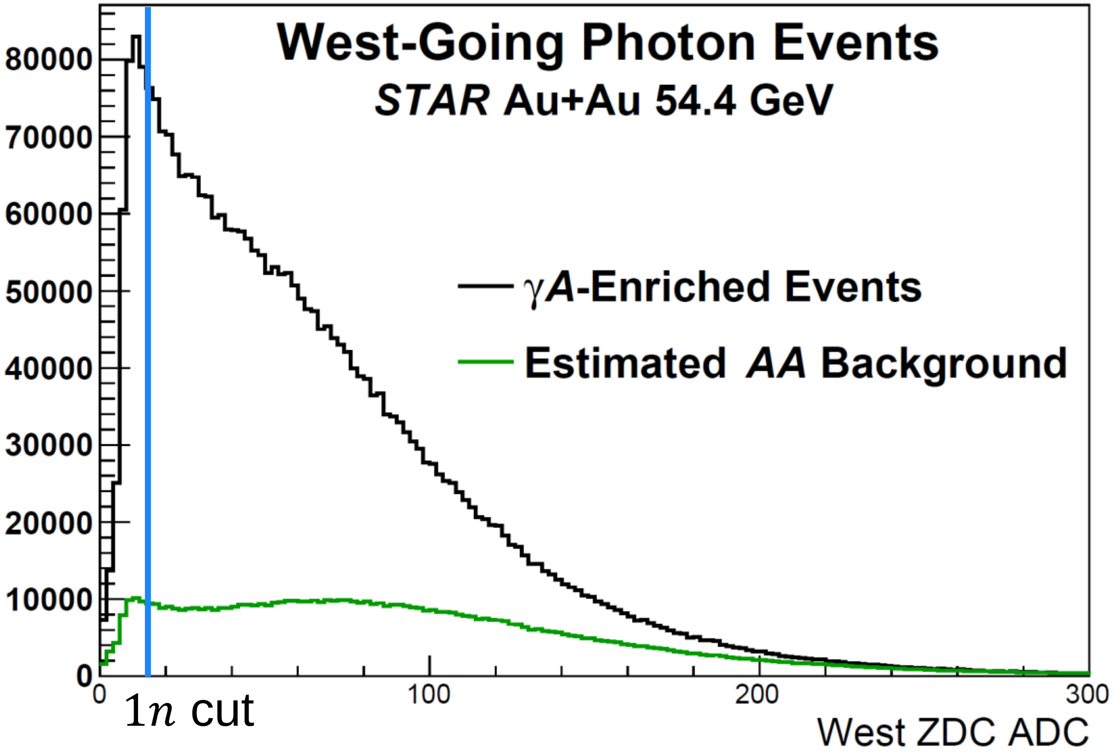
Photonuclear event selection: $dN/d\eta$ with and without BBC and VPD Cuts



Normalized by the total amount of tracks per η bin

Photonuclear analysis
Estimating background contamination from peripheral collisions



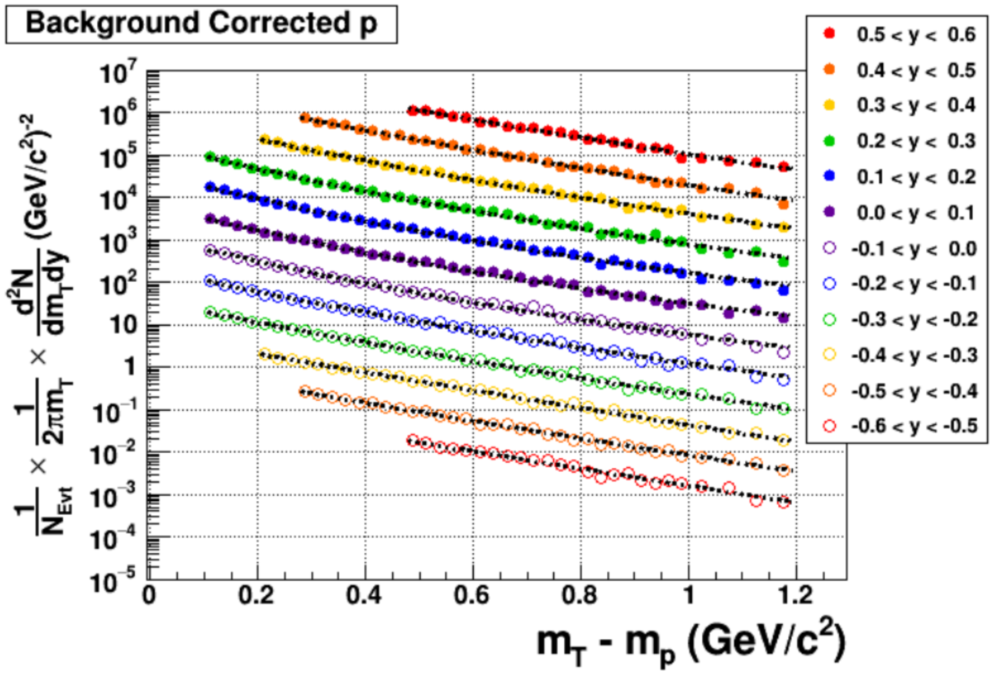


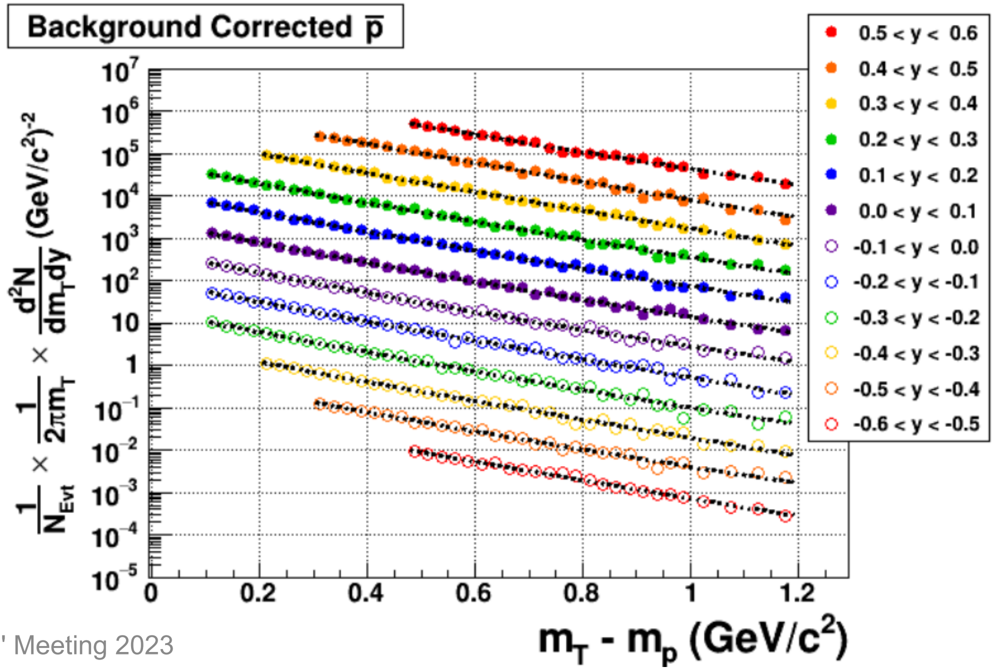
Estimate background contribution utilizing ZDC ADC distributions of peripheral events, 80-100% Centrality.

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

Analysis procedures for photonuclear events

- **Track cuts:**
  - Must be primary tracks.
  - Must be TOF matched.
  - $\text{nHitsFit} > 15$.
  - $\text{DCA} < 3\ \text{cm}$.
  - $|\eta| < 0.75$.
  - $p_T > 0.2\ \text{GeV}/c$.
  - Proton PID: $0.7 < m^2 < 1.06\ \text{GeV}/c^{2}$.
- **Apply event and track cuts and measure spectra as a function of $m_\text{T} - m_\text{p}$ and y for:**
  - Photonuclear events.
  - Peripheral AA events with centrality 60-80% to estimate behavior of hadronic peripheral event contamination.
    - Centrality Determination for this dataset: https://drupal.star.bnl.gov/STAR/system/files/20181017_Centrality.pdf





Analysis procedures for photonuclear events

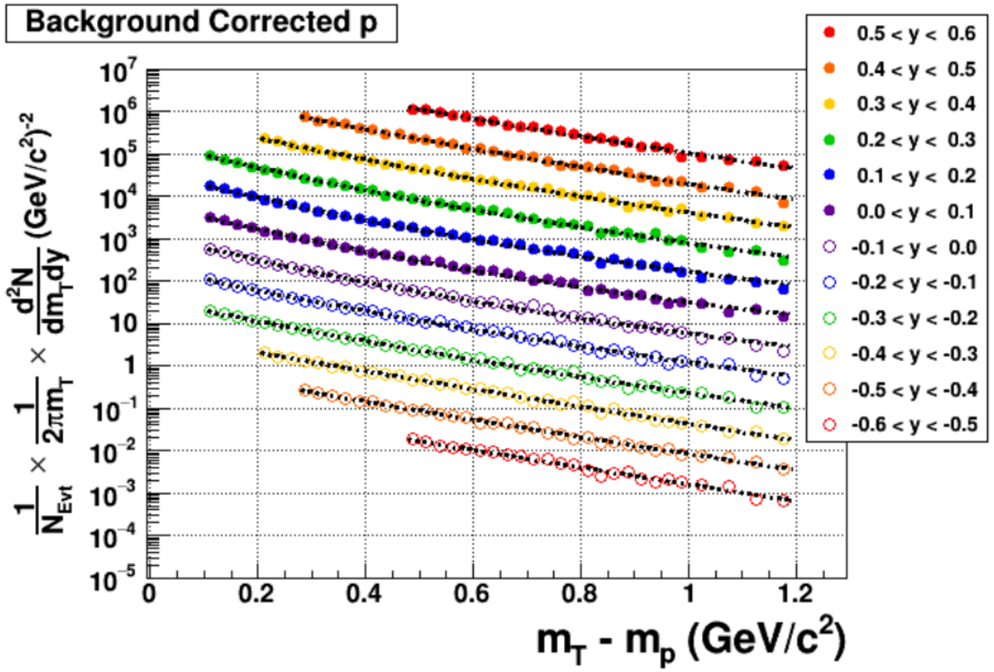
- **Correct for:**
  - Energy loss.
  - Tracking efficiency.
  - TOF matching efficiency.
  - Knock out protons.
  - Incorrectly reconstructed tracks by fitting m^2 distribution with student-t function.
  - Contamination from peripheral events.

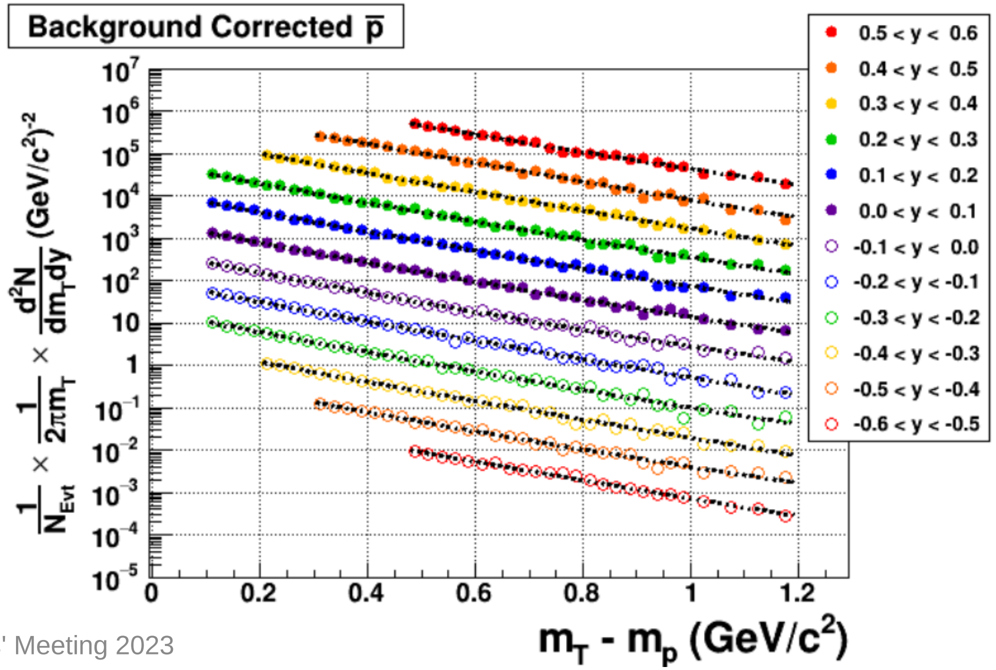
$$Y_p^{\gamma A-\text{rich}} = \frac{Y_p^{\gamma A+AA} - rf\ Y_p^{AA}}{1-rf}$$

r – Peripheral event contamination

f – Multiplicity factor

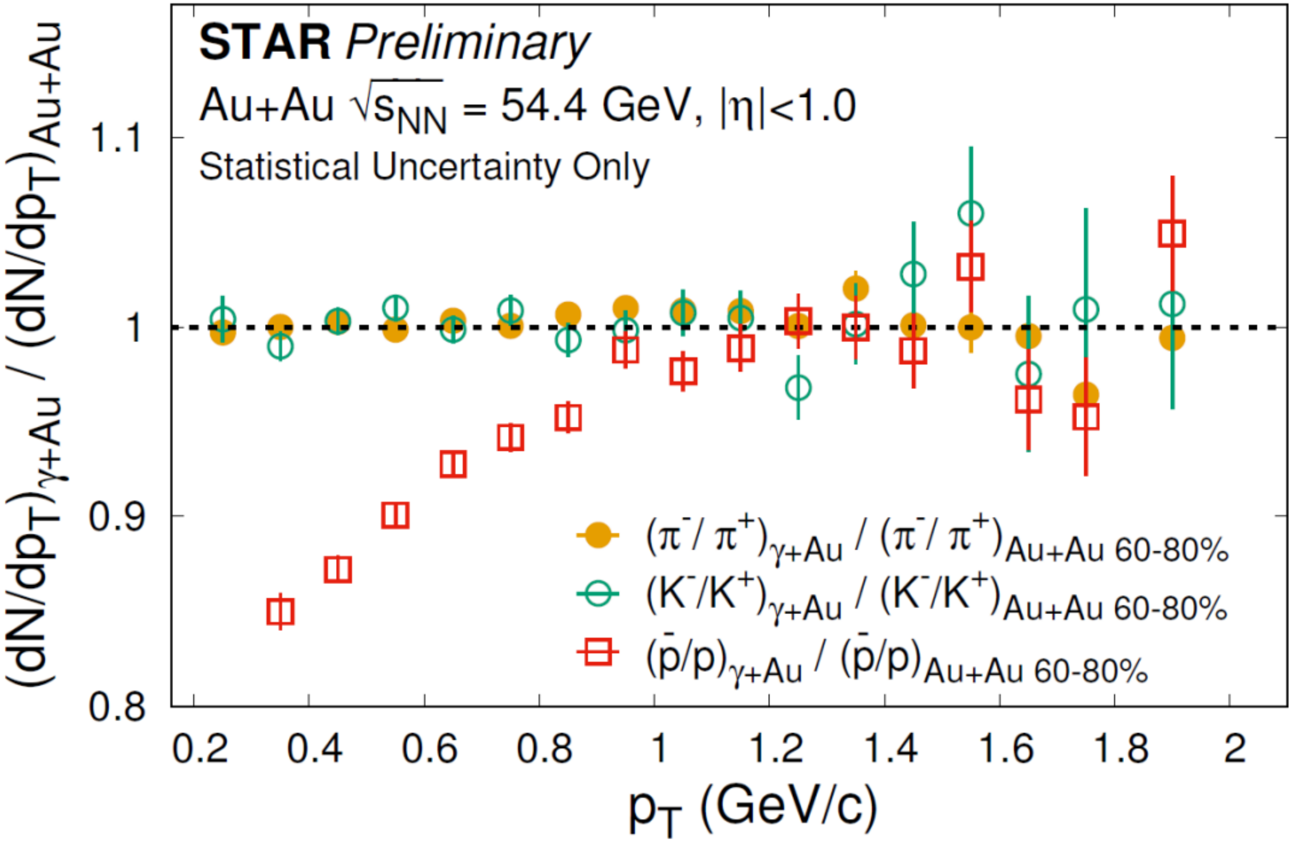
- **Fit spectra with a Levi fit function to extract dN/dy.**





Low p_T baryon enhancement in γA

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



Fitting to PYTHIA data

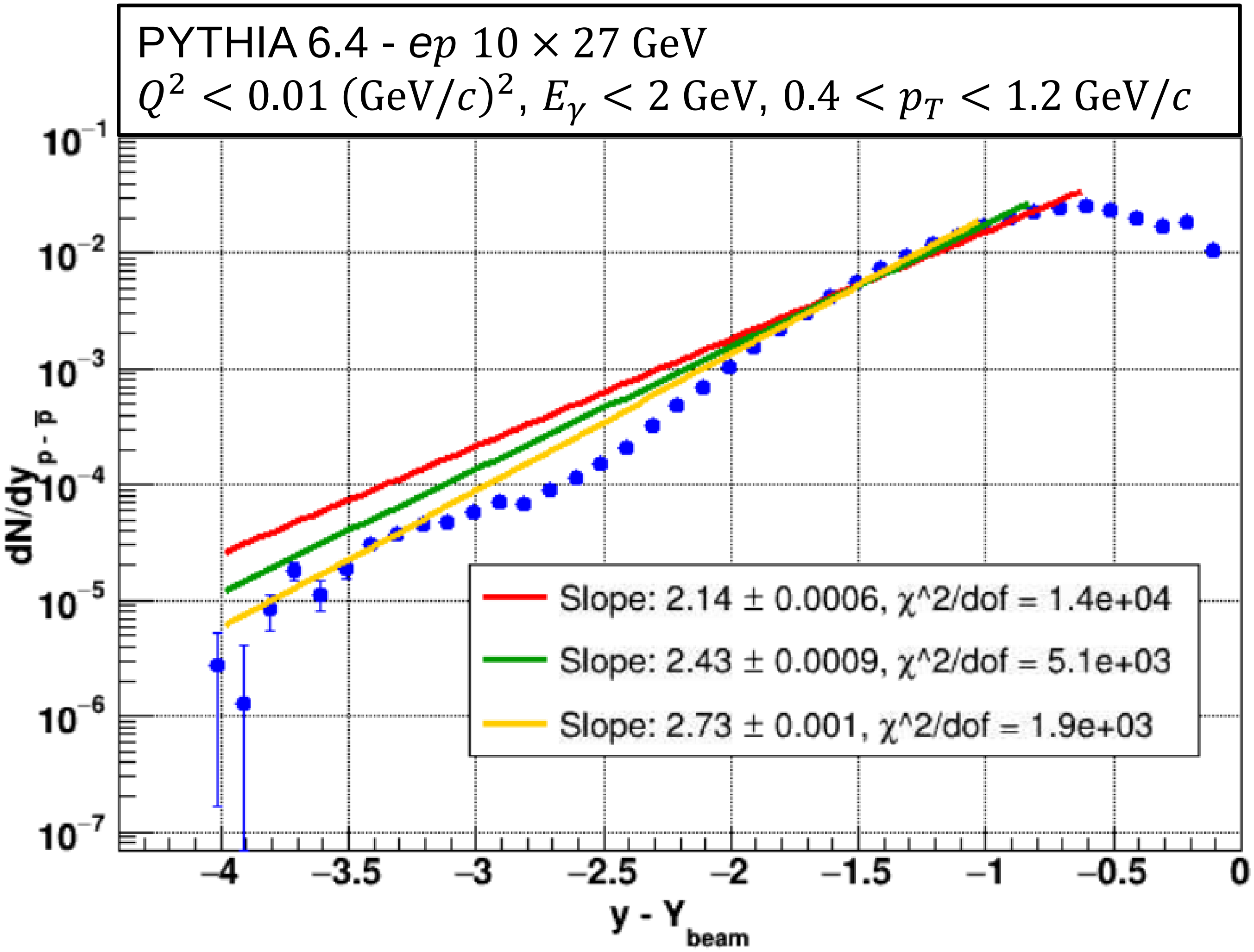
Exponential Slope: $f(y - Y_{\text{beam}}) = A\exp(b \times (y - Y_{\text{beam}}))$

- $\gamma + \text{Au}$**-rich points acceptance:** $-4.6 \lesssim y - Y_{\text{beam}} \lesssim -3.4$
- **Central value fit range:**

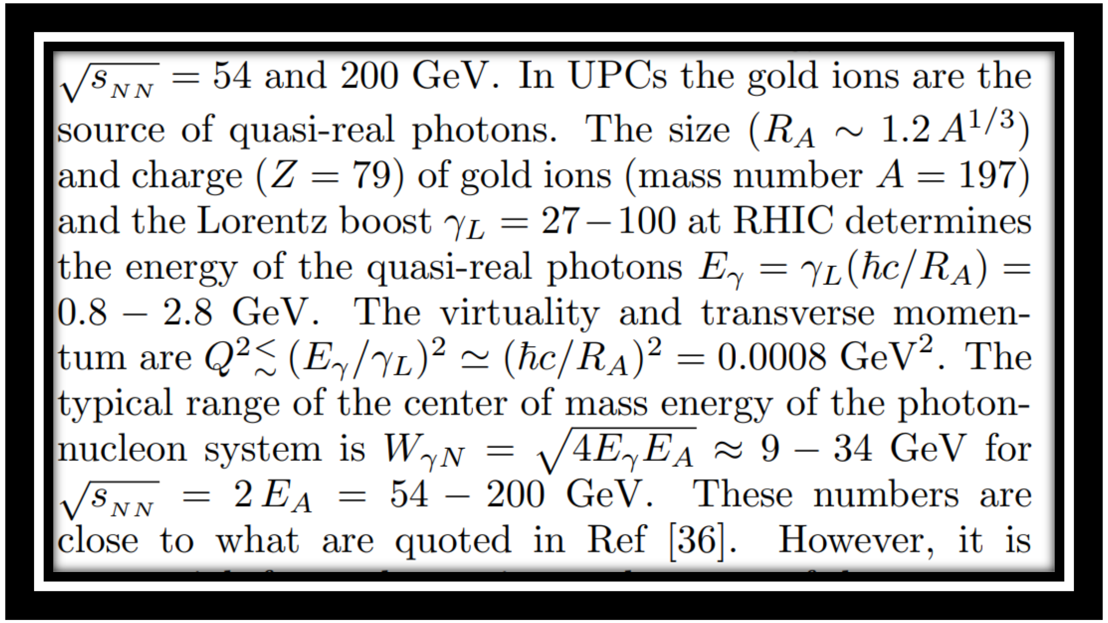
  $-4.0 < y - Y_{\text{beam}} < -0.81$
- **Estimate Uncertainty by adjusting fit range:**

  $-4.0 < y - Y_{\text{beam}} < -0.61$

  $-4.0 < y - Y_{\text{beam}} < -1.01$
- **Slope:** 2.43 ± 0.30.
- **Going to run more events in PYTHIA to have better coverage over our data acceptance.**



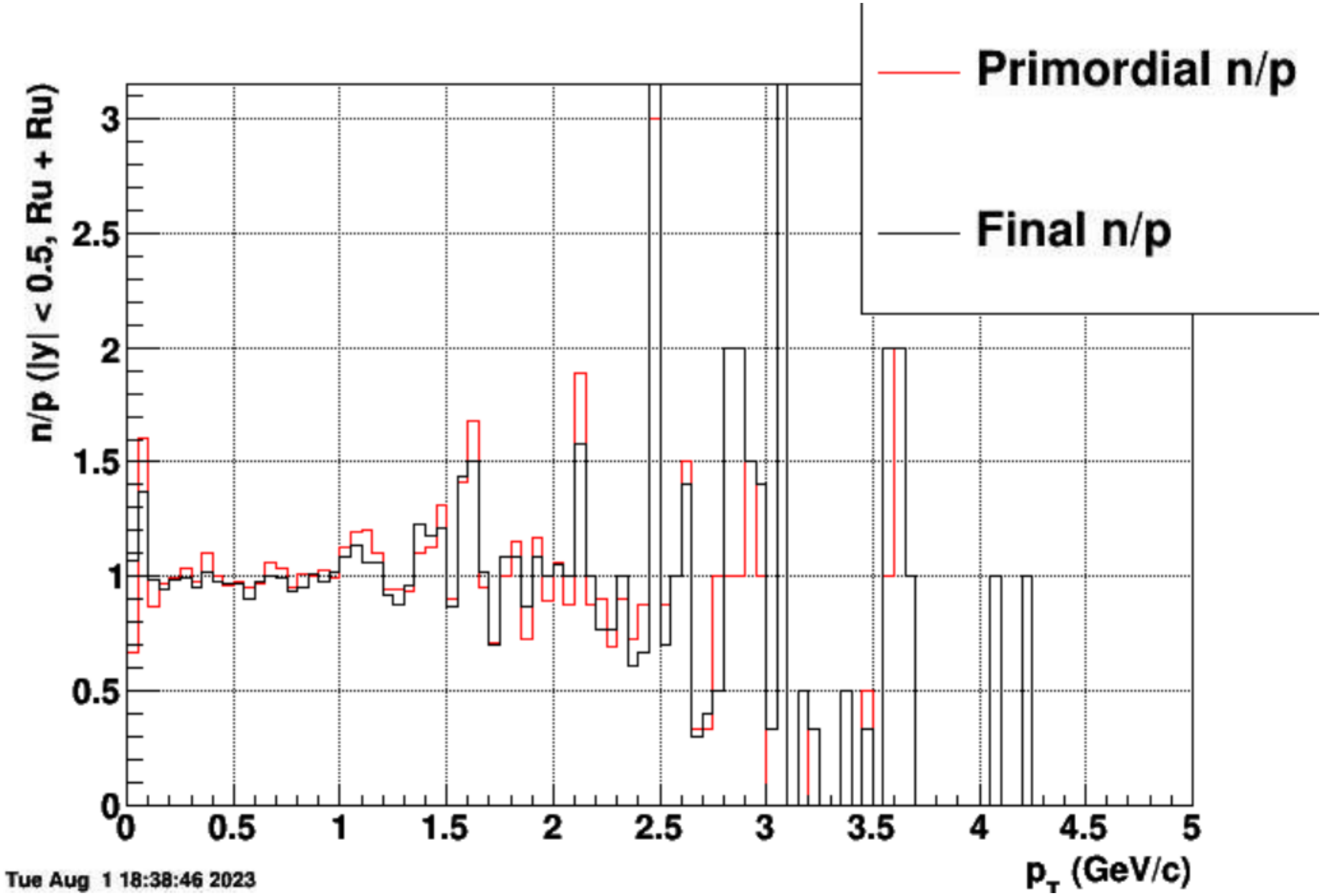
Virtuality of ultra-peripheral Au + Au



$\sqrt{s_{NN}} = 54$ 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 $Q^2 \lesssim (E_\gamma/\gamma_L)^2 \simeq (\hbar c/R_A)^2 = 0.0008$ 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)

n/p ratio from Hijing all centralities



Thank you