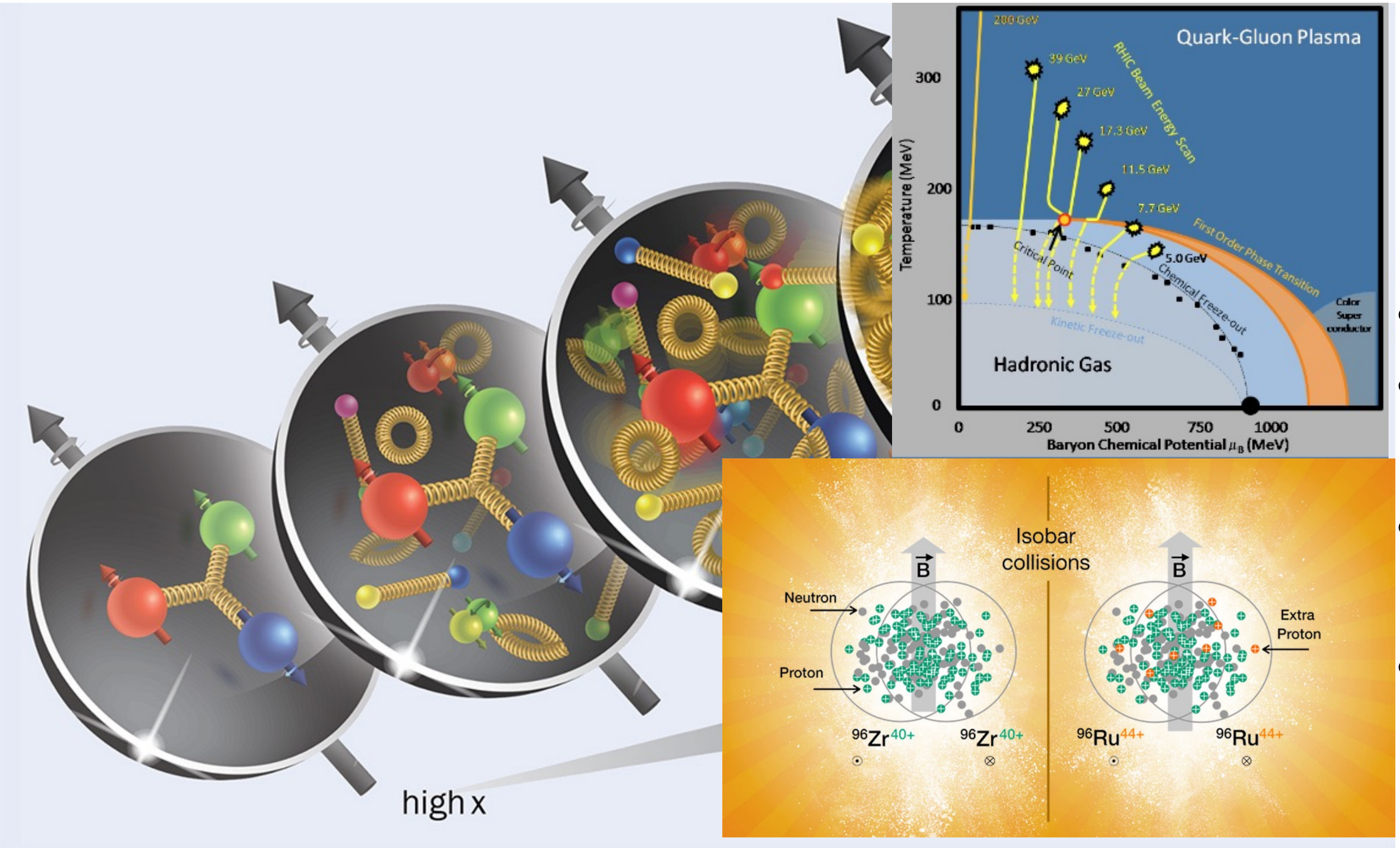
Experimental findings on the Gluon Topology from BES-I and Isobar data



Zhangbu Xu
(Brookhaven National Lab)

- baryon number carrier
- Three experimental approaches at RHIC
- Earlier theory and experiment work on pp and ep
- Implication for fluctuations and future perspectives

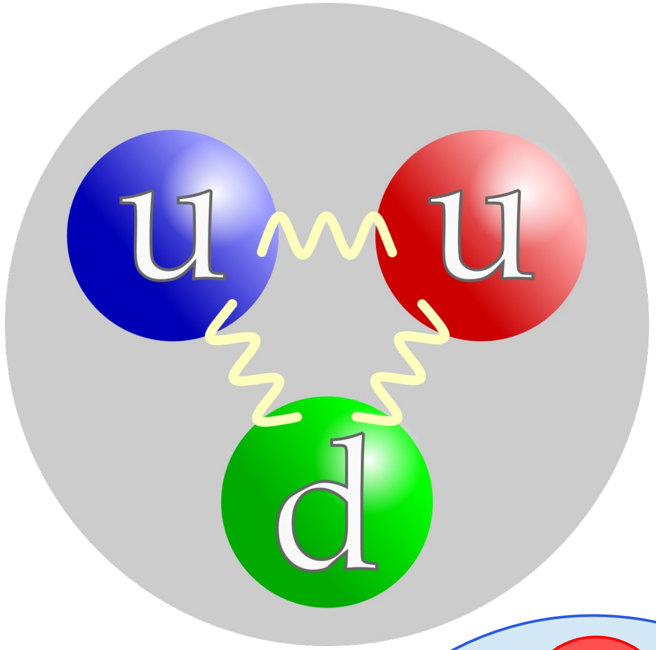
N. Lewis, T. Tsang, Y. Li, H. Klest, W.B. Zhao, N. Magdy, R.R. Ma, P. Tribedy, J.D. Brandenburg, Z.B. Tang, Z.W. Lin, C. Shen, B. Schenke, D. Kharzeev, *et al.*

INT 20r-1c Chirality and Criticality, 2023

In part supported by
Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY Office of Science

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

Baryon Number (B) Carrier



- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime $>10^{34}$ years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
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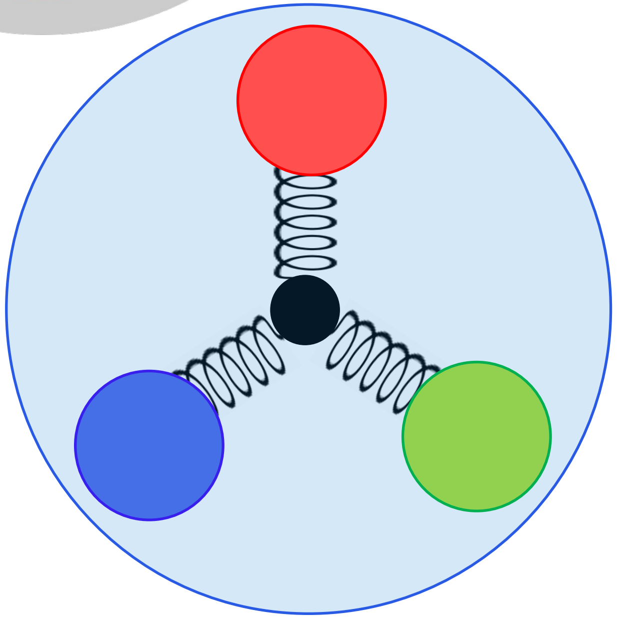

[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).
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Baryon Number (B) Carrier

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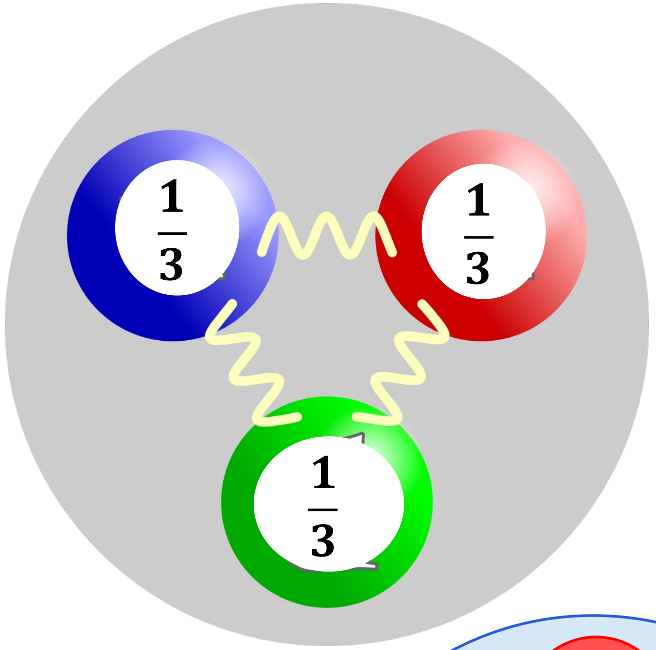

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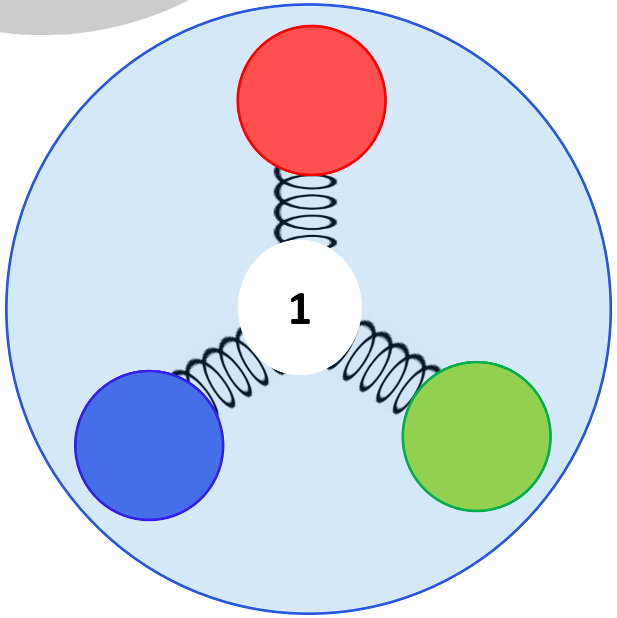

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Model implementations of baryons at RHIC

- Many of the models used for heavy-ion collisions at RHIC (HIJING, AMPT, UrQMD) have implemented a nonperturbative baryon stopping mechanism

V. Topor Pop, *et al,* Phys. Rev. C **70**, 064906 (2004)

Zi-Wei Lin, *et al*, Phys. Rev. C **72**, 064901 (2005)

M. Bleicher, *et al,* J.Phys.G **25,** 1859-1896 (1999)

- Baryon Stopping
  - Theorized to be an effective mechanism of stopping baryons in pp and AA

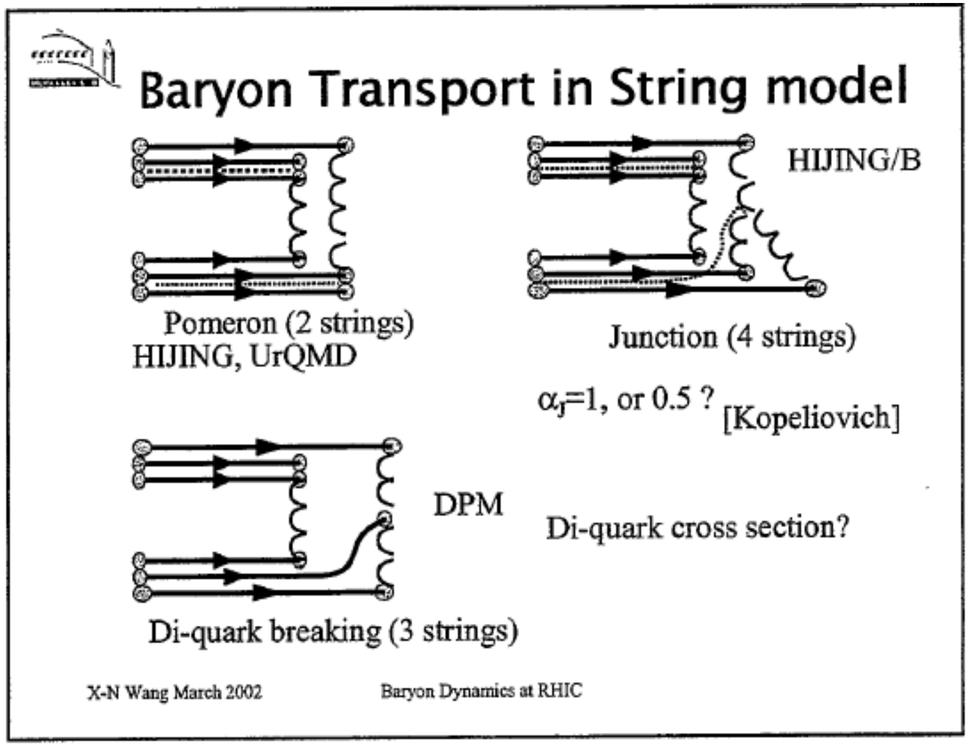
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- Specific rapidity dependence is predicted:

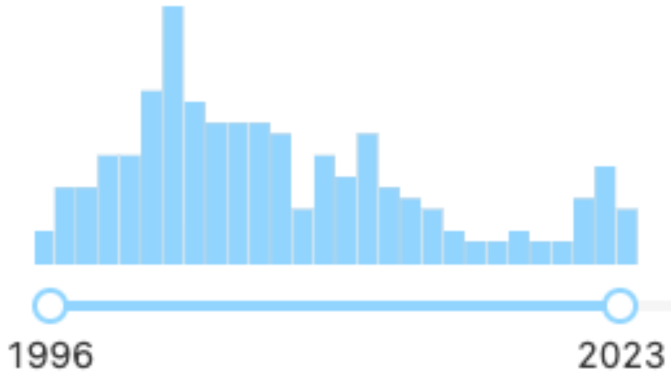
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

2003 RBRC Workshop on "Baryon Dynamics at RHIC"



D. Kharzeev, Physics Letters B **378**, 238-246 (1996)
"Can gluons trace baryon number?"



"Science, however, is never conducted as a popularity contest..." --- Michio Kaku

BUT citations ARE

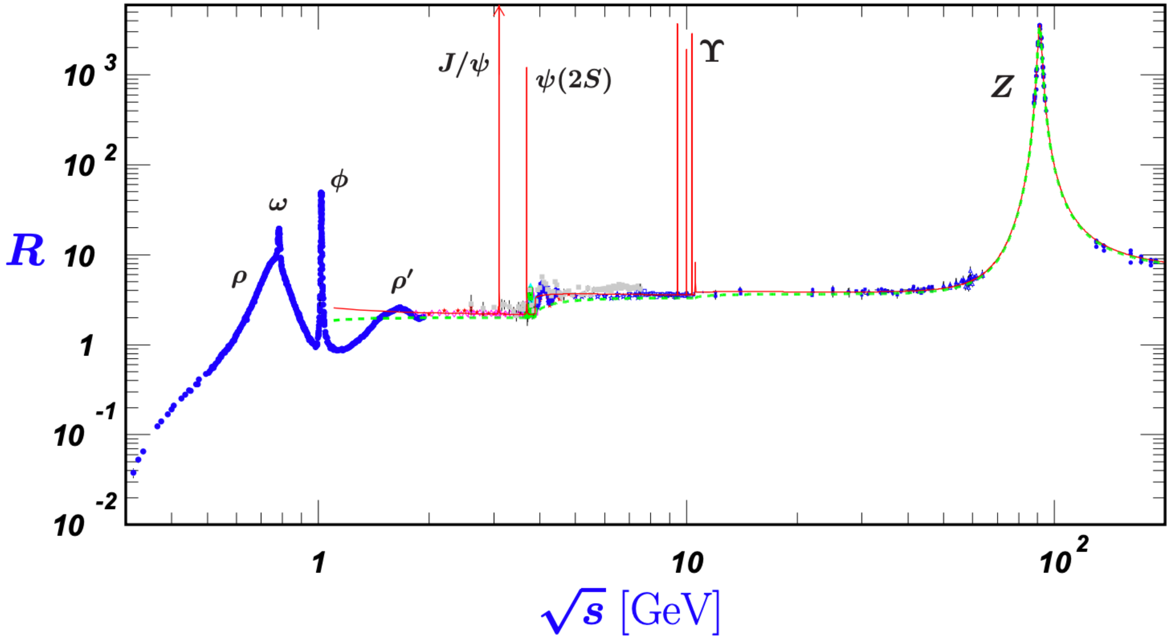
Measurements of quark electric charges

Scattering cross section $\sigma \propto e_q^2$

$(2/3)^2+(1/3)^2+(1/3)^2=2/3$

$(2/3)^2+(2/3)^2+(1/3)^2=1$

$(1/3)^2+(1/3)^2+(1/3)^2=1/3$



PDG

Figure 53.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model

Riordan, Science 1992

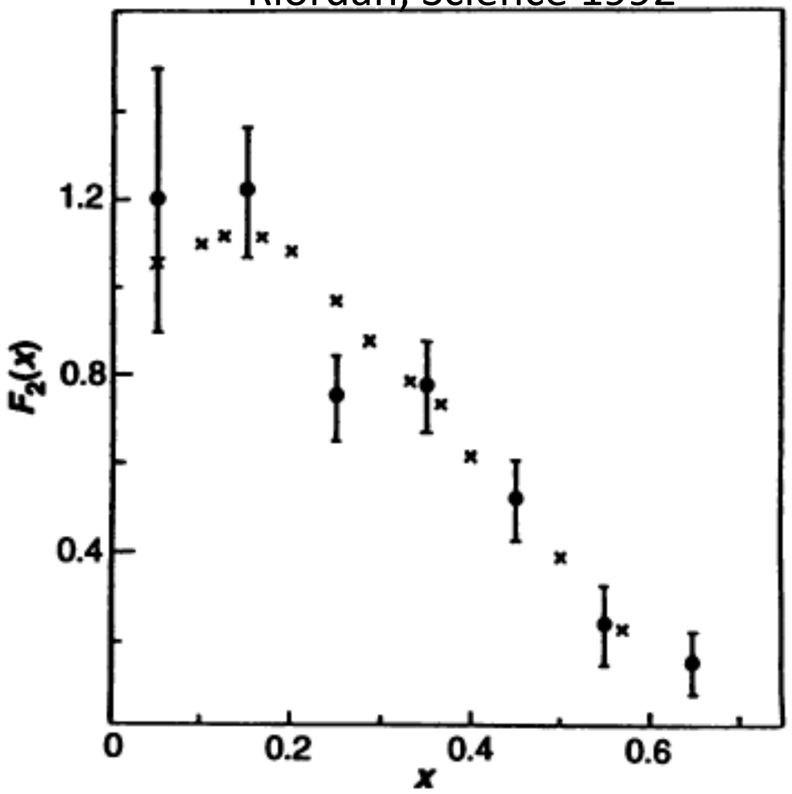
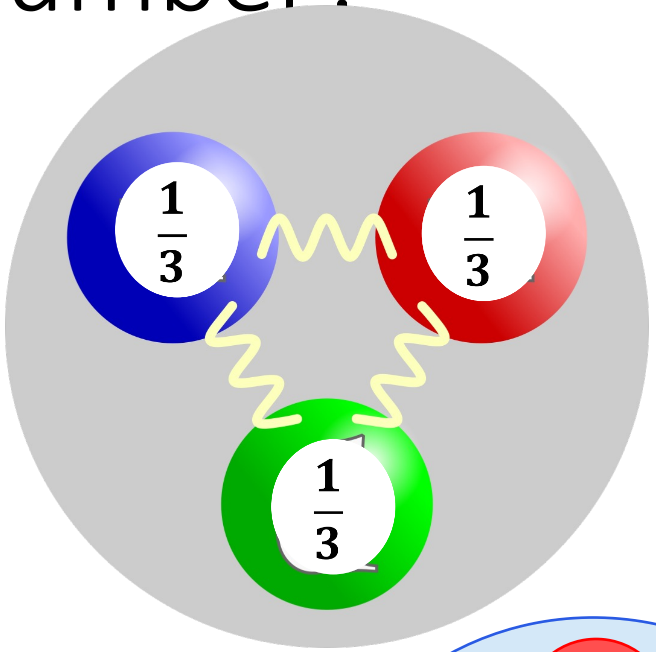


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, (18/5)F_2^{eN}]. When multiplied by 18/5, a number specified by the quark-parton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

Measurements of quark baryon number?



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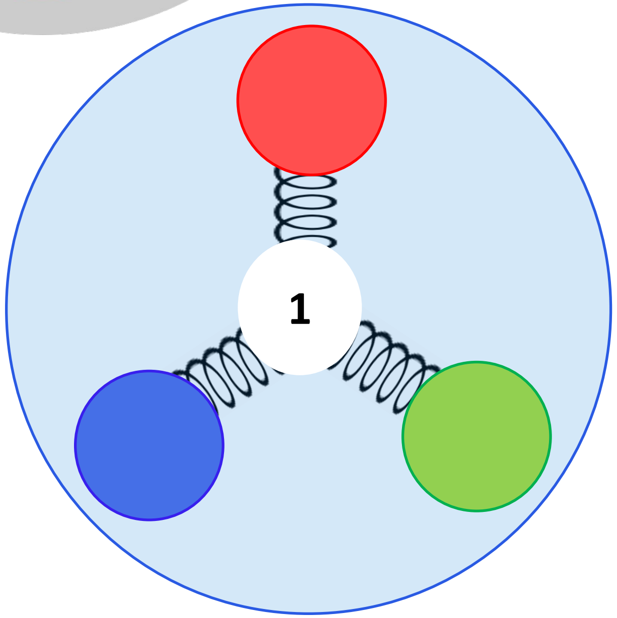

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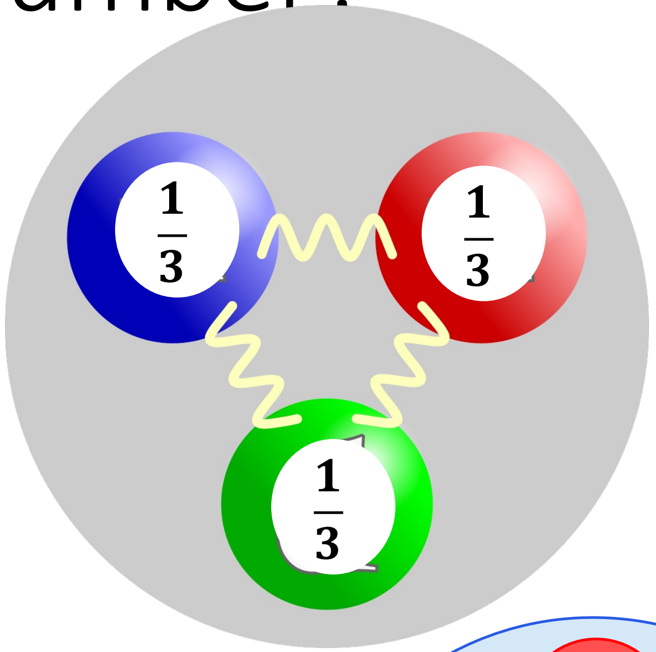
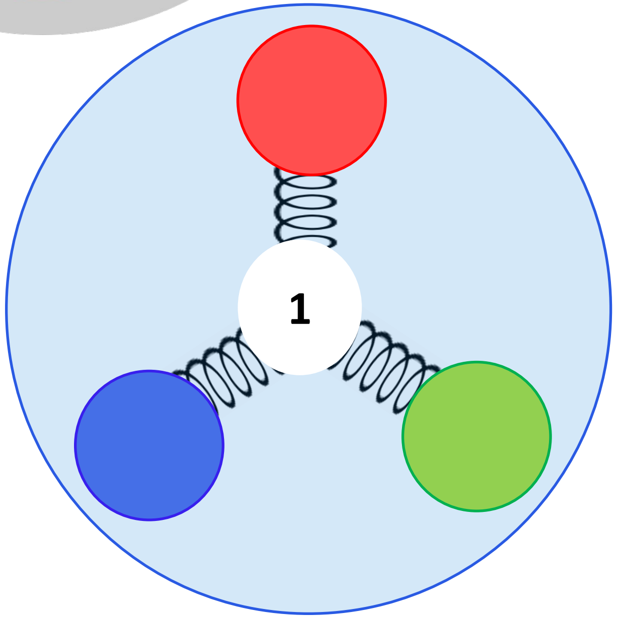
  - Valence quarks are connected to the end of the junction always
- **Neither of these postulations has been verified experimentally**





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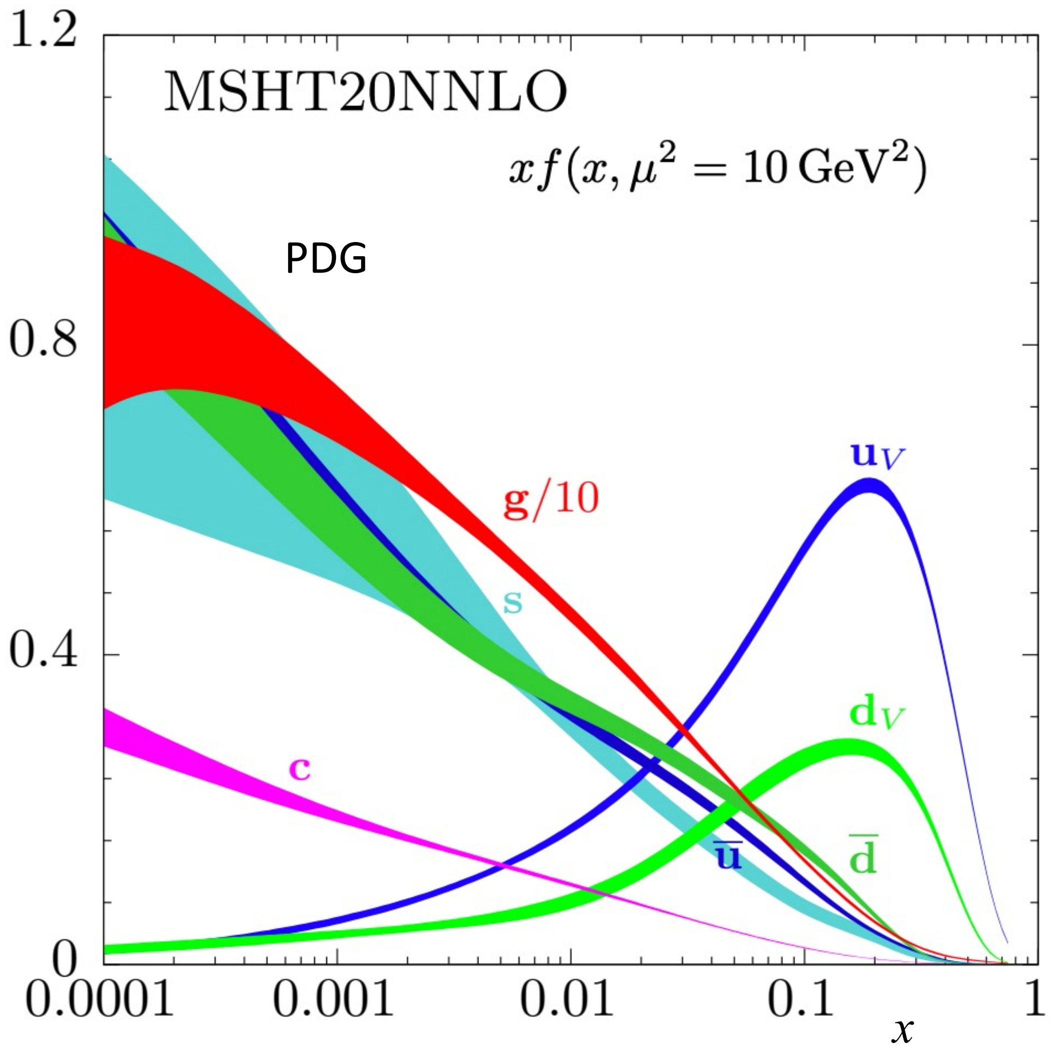
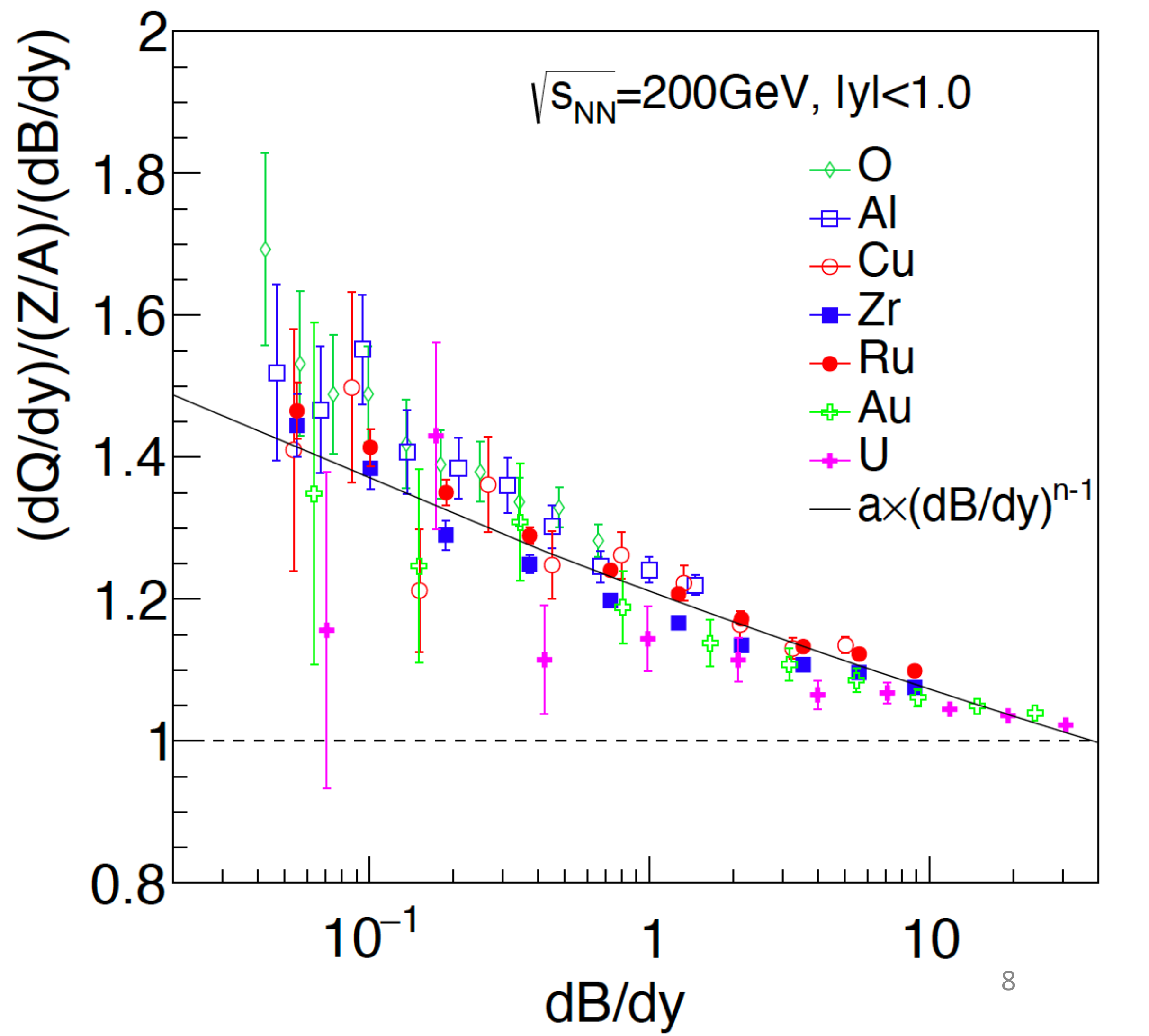
Quark Distribution and Charge Transport

What we know

Quark components at low-x is proportional to valence quarks

Q/B*Z/A ratio in UrQMD → 1 for large A





Three approaches toward tracking the origin of the baryon number

1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity

2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

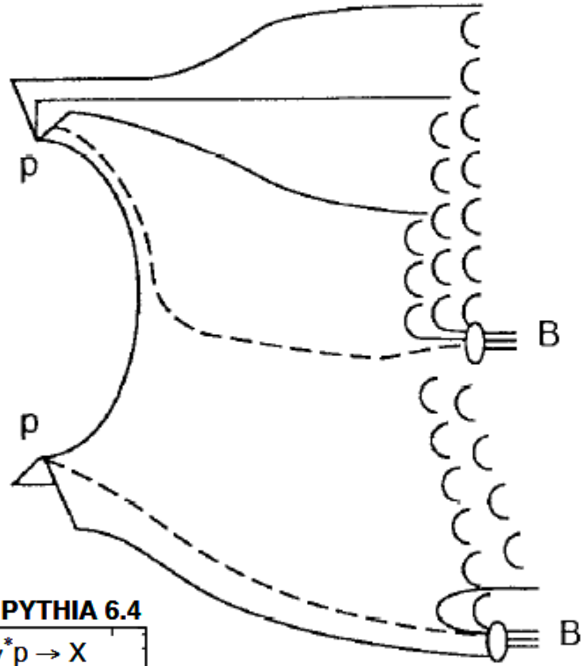
$$p = \sim e^{-\alpha_B y}$$

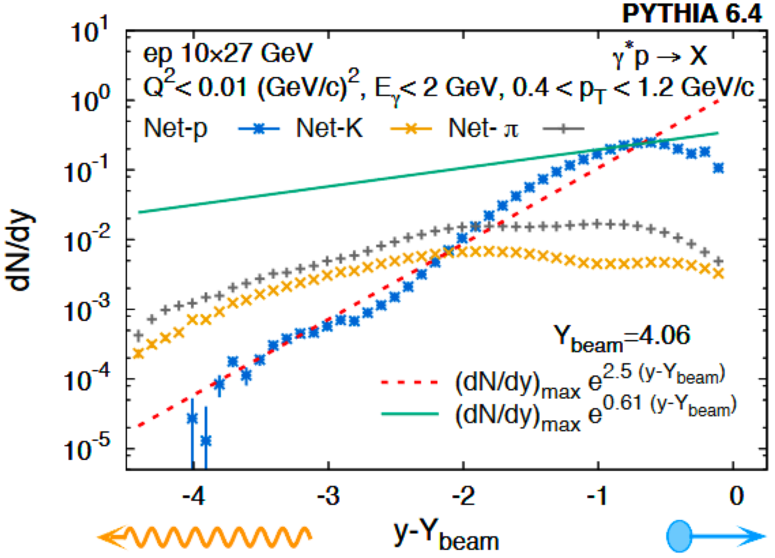
α_B ~=0.5

3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin

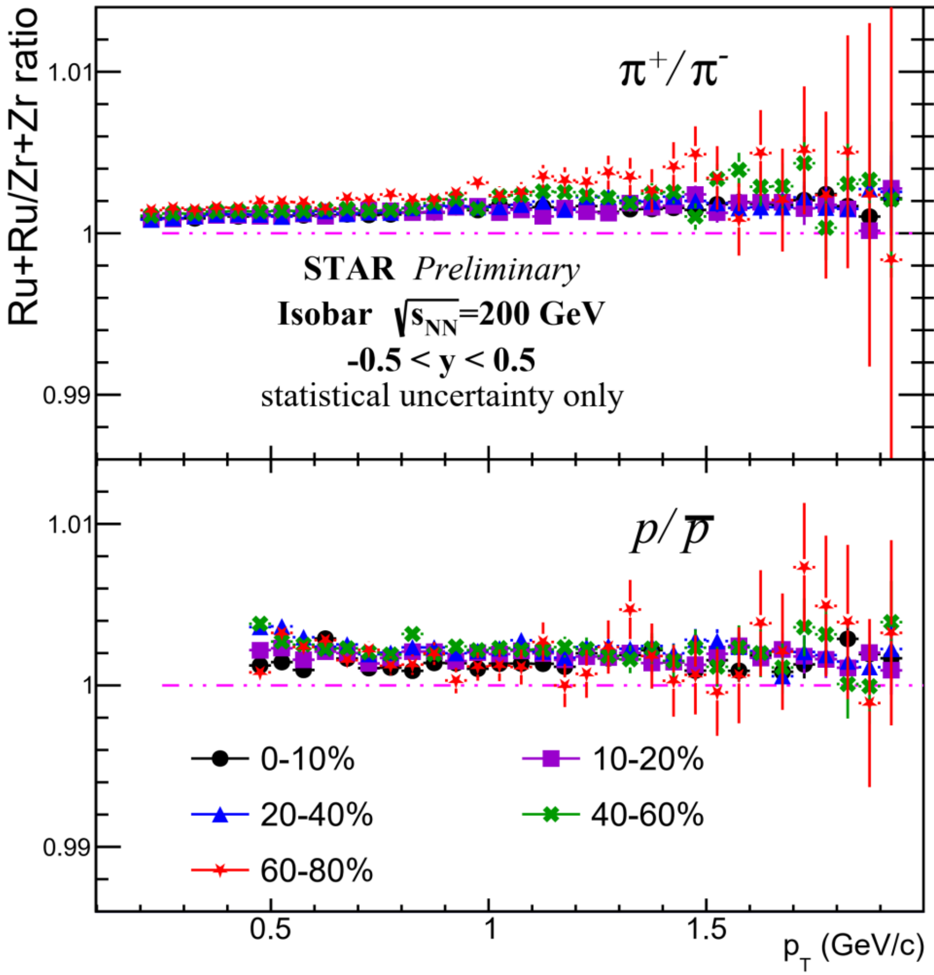
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685

Proposed to use double ratio in Zr+Zr and Ru+Ru isobar collisions to cancel al the detector effects, the signal is at the level of 10^{-3}





Double ratios between Ru+Ru and Zr+Zr collisions



- The double ratios of π^+/π^- and $p/\bar{p}$ are larger than 1. Due to extra charge in Ru?
- The double ratios of K^-/K^+ is consistent with unity within uncertainties.

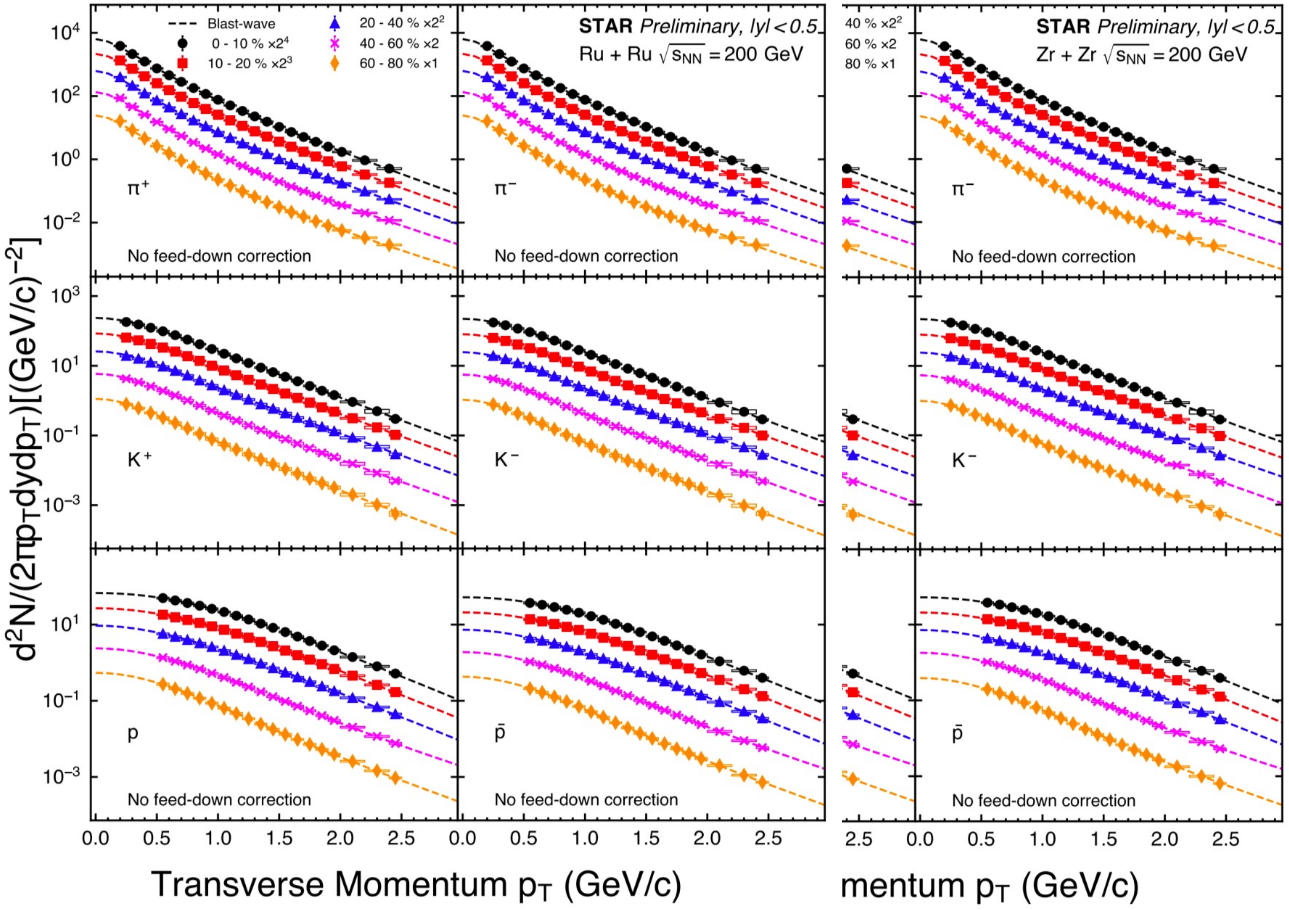
From baryon stopping: $B*(\Delta Z/A)$~=2x10^{-3}

Charge stopping: ΔQ ~=1x10^{-3}

Identified hadron spectra to low momentum

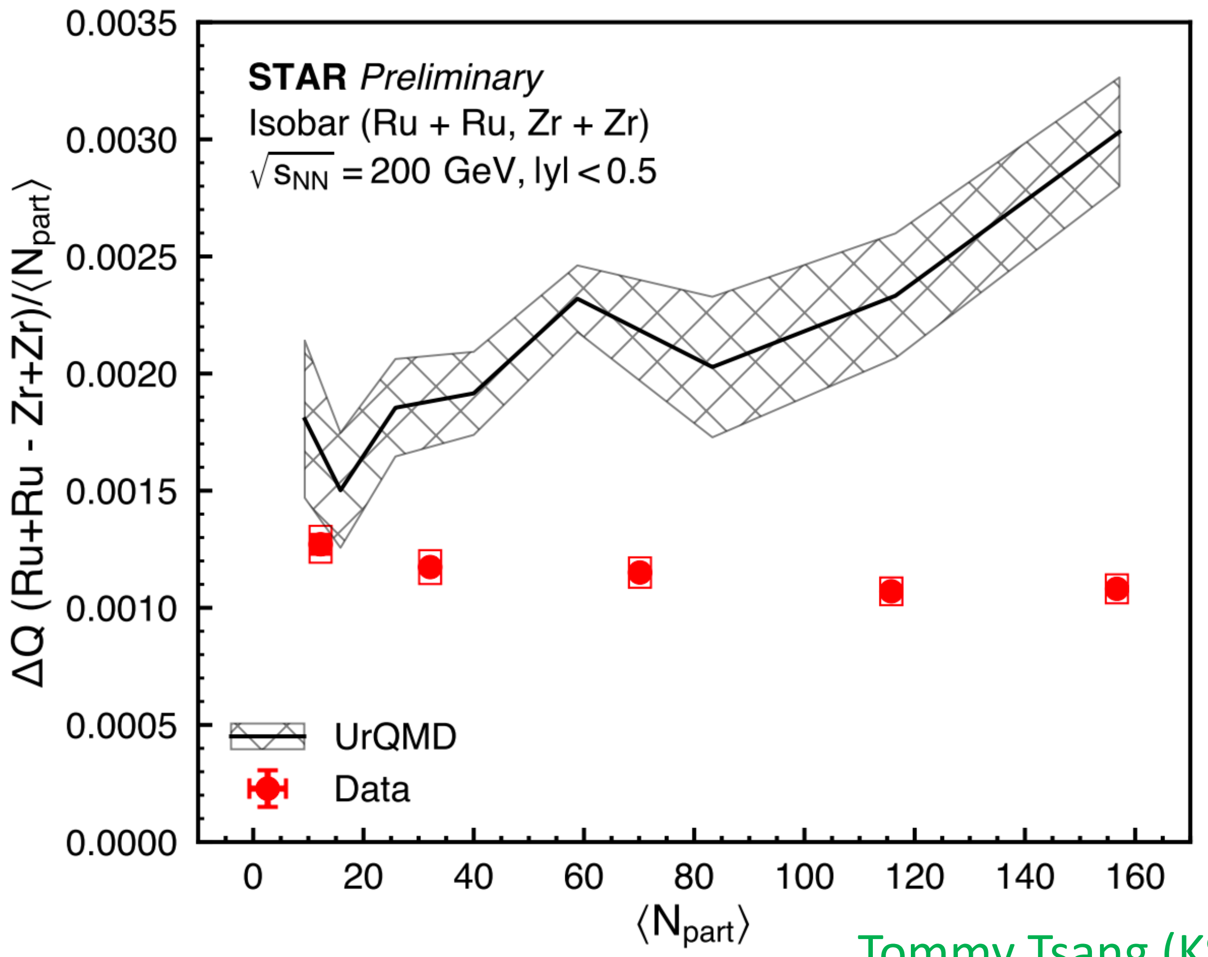
Net-charge difference (Ru+Ru – Zr+Zr)

- $R2_{\pi} = \frac{(N_{\pi}^{+}/N_{\pi}^{-})_{Ru}}{(N_{\pi}^{+}/N_{\pi}^{-})_{Zr}} \approx \frac{[1+(N_{\pi}^{+}-N_{\pi}^{-})/N_{\pi}]_{Ru}}{[1+(N_{\pi}^{+}-N_{\pi}^{-})/N_{\pi}]_{Zr}} = \frac{1+\Delta\mathrm{R_{Ru}}}{1+\Delta\mathrm{R_{Zr}}} \approx 1 + \Delta\mathrm{R_{Ru}} - \Delta\mathrm{R_{Zr}}$
- $\Delta Q = \left[\left(N_{\pi}^{+} + N_{K}^{+} + N_{p}\right) - \left(N_{\pi}^{-} + N_{K}^{-} + N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$
- Focus on pion terms,
- $(N_{\pi}^{+} - N_{\pi}^{-})_{Ru} - (N_{\pi}^{+} - N_{\pi}^{-})_{Zr} = N_{\pi,Ru} \times \Delta\mathrm{R_{Ru}} - \mathrm{N}_{\pi,Zr} \times \Delta\mathrm{R_{Zr}}$
- $\approx N_{\pi}(\Delta\mathrm{R_{Ru}} - \Delta\mathrm{R_{Zr}}) = \mathrm{N}_{\pi} \times (R2_{\pi} - 1$
- Where $N_{\pi} = 0.5 \times (N_{\pi}^{+} + N_{\pi}^{-})$
- Therefore, $\Delta Q = \mathrm{N}_{\pi}(\mathrm{R2}_{\pi} - 1) + N_{K}(R2_{K} - 1) + N_{p}(R2_{p} - 1)$

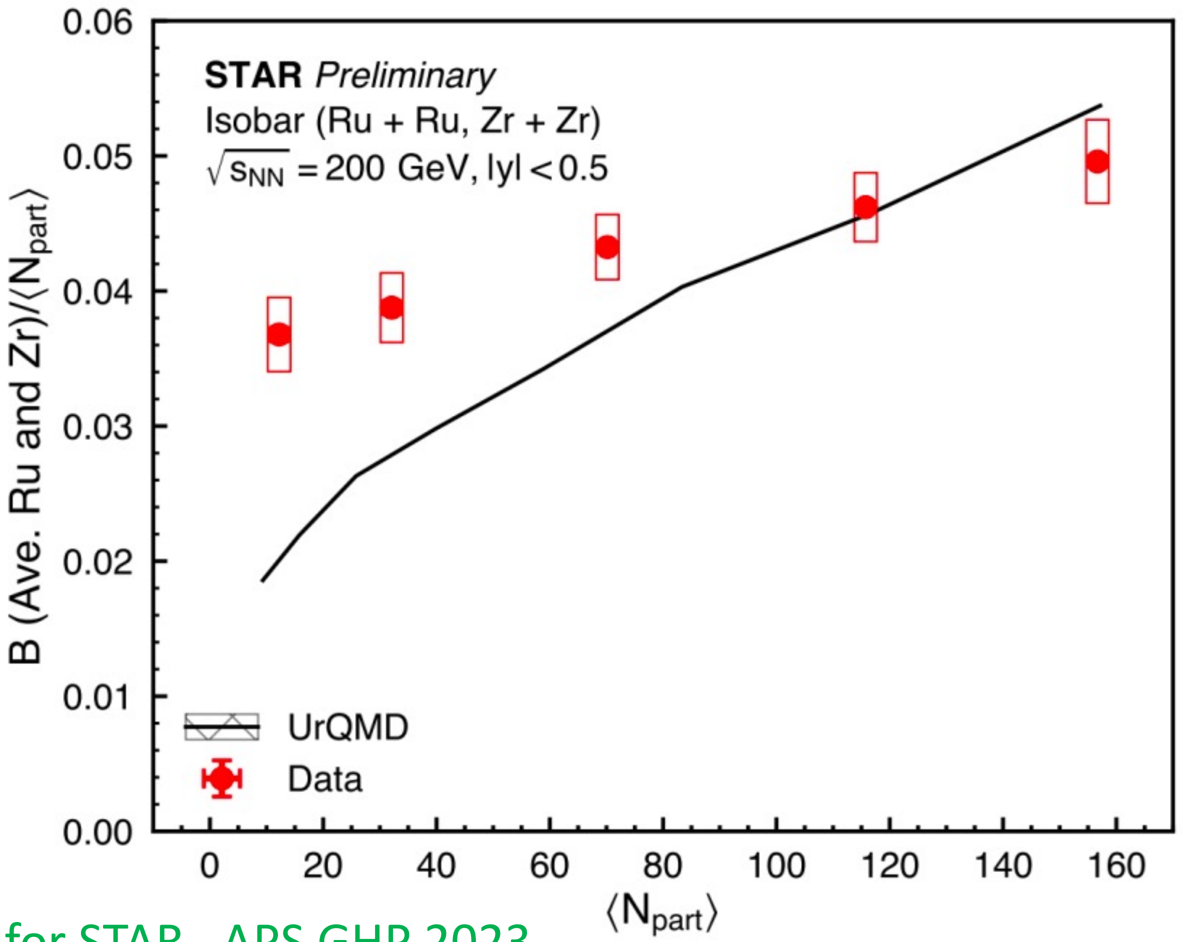


Separate charge and baryon transports

Charge number transport



Baryon number transport



Tommy Tsang (KSU) for STAR, APS GHP 2023

UrQMD matches data on charge stopping better in peripheral; better on baryon stopping in central
overpredicts charge stopping in central; underpredicts baryon stopping in peripheral

Baryon stopping in UrQMD

M. Bleicher, *et al.*, JPG 25 (1999); hep-ph/9909407

$$z^{\pm} = t \pm z \quad \text{and} \quad p^{\pm} = E \pm p \quad . \tag{33}$$

The light cone momentum $p^{\pm}_{\text{hadron}}$ given to the newly produced hadron is:

$$p^{\pm}_{\text{hadron}} = z^{\pm}_{\text{fraction}}\, p^{\pm}_{\text{total}} \tag{34}$$

The fragmentation of a baryonic string reads:

$$p^{-}\underbrace{(qq\,q\bar{q}\,q)}_{\text{String}} = z^{-}_{\text{fraction}}p^{-}\underbrace{(qqq)}_{\text{Baryon}} + (p^{-} - z^{-}_{\text{fraction}}p^{-})\underbrace{\bar{q}q}_{\text{String}} \quad . \tag{35}$$

The main input is the fragmentation function which yields the probability distribution $p(z^{\pm}_{\text{fraction}}, m_t)$. This function regulates the fraction of energy and momentum given to the produced hadron in the stochastic fragmentation of the color string. For newly produced particles the Field-Feynman function [41]:

$$p(z^{\pm}_{\text{fraction}}) = \text{constant} \times (1 - z^{\pm}_{\text{fraction}})^2, \tag{36}$$

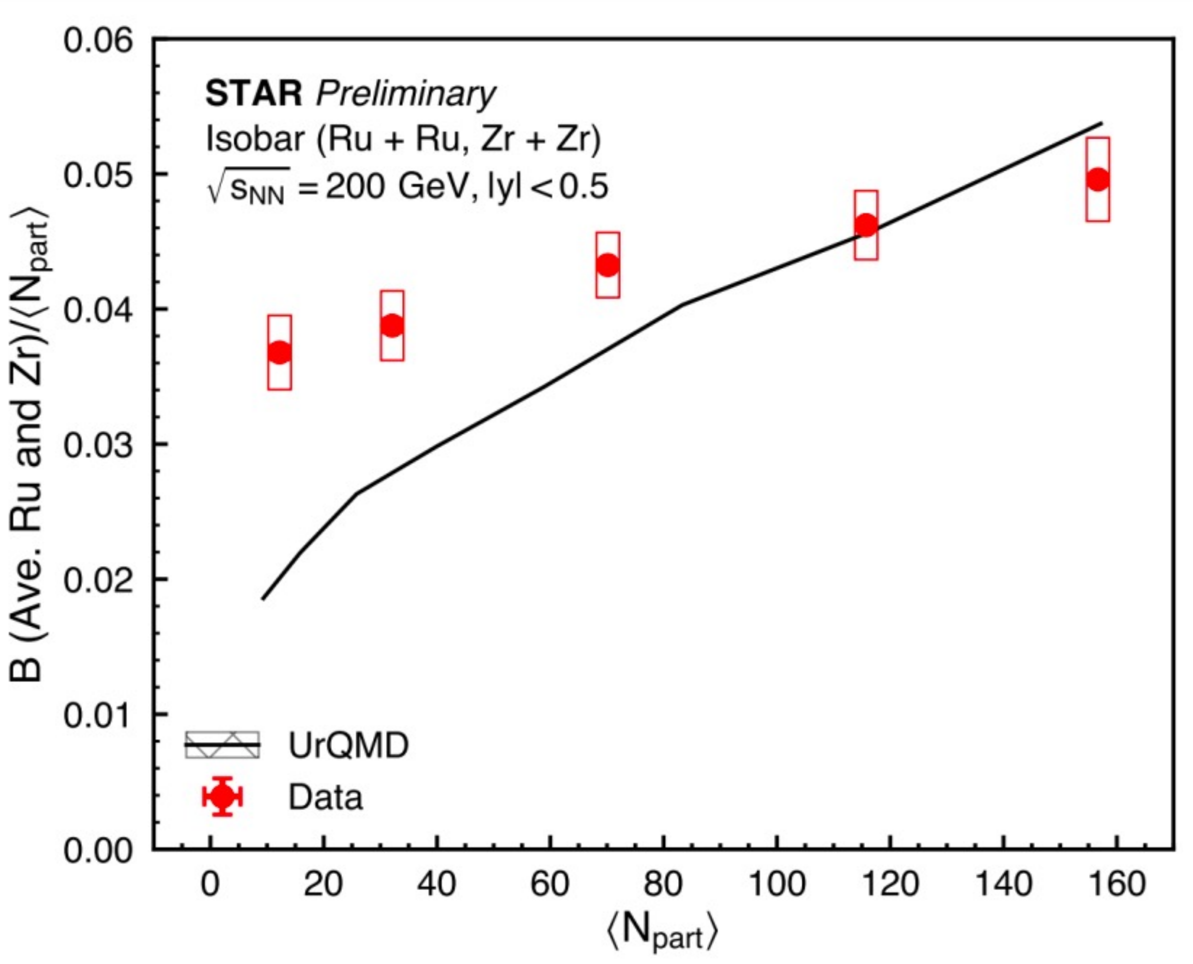
is used. $P(z)$ drops rapidly with increasing z (Fig. 29). Therefore, the longitudinal momenta of e.g. produced antibaryons (Fig. 30) and pions (Fig. 31) are small (they stick to central rapidities), in line with the experimental data. The rapidity spectra of these particles have a characteristic Gaussian-like shape, in contrast to the baryon spectra in pp, as it is clearly seen in Figure 30.

The proton is on average less stopped, since it is build up from the leading diquark in the string (leading particle effect). Fig. 32 compares the x_F distribution of protons and Λ's for the Feynman scaling variable $x_F = 2p_{||}/\sqrt{s}$ measured in pp reactions at 205 GeV/c. The data on leading baryons can only be reproduced when a modified fragmentation function is used for the leading baryons (cf. Fig. 29, dashed curve). This leading baryon fragmentation function is of Gaussian form:

$$p(z^{\pm}_{\text{fraction}}) = \text{constant} \times \exp\left[-\frac{(z^{\pm}_{\text{fraction}} - b)^2}{2a^2}\right] \quad , \tag{37}$$

with parameters $a = 0.275$ and $b = 0.42$.

Baryon number transport



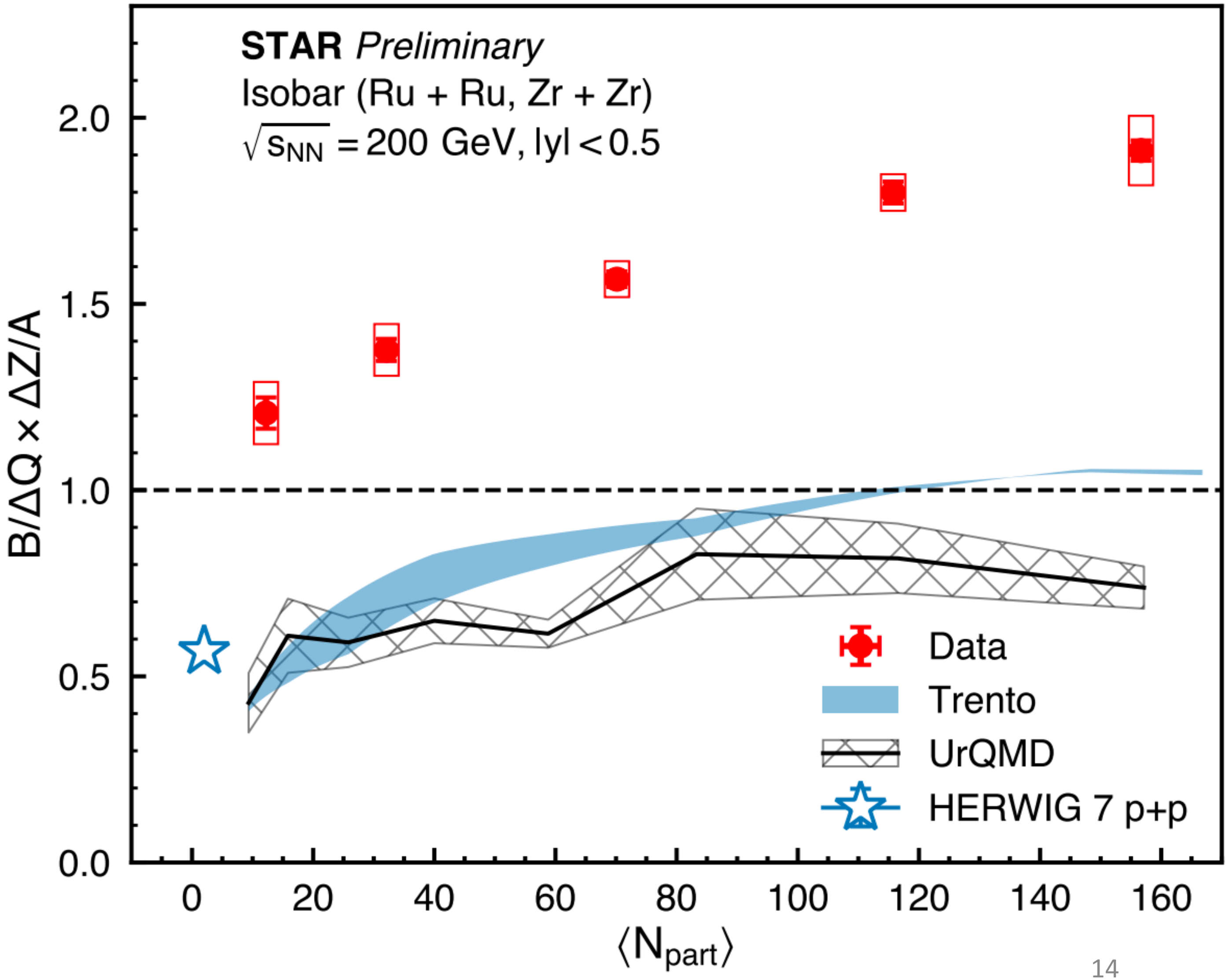
Ratio of baryon over charge transports

- **Experimental data**:
  More baryon transported to C.O.M than charge by about a factor of 2

- **Model simulations**:
  Less baryon transported to C.O.M frame than charge

- Pure geometry:
  with neutron skin predicts the right centrality dependence (Trento)

Tommy Tsang (KSU) for STAR, APS GHP 2023



Low-energy baryon rapidity loss

The average close to beam rapidity
(limiting Fragmentation)
does not reflect the "tail" at high rapidity

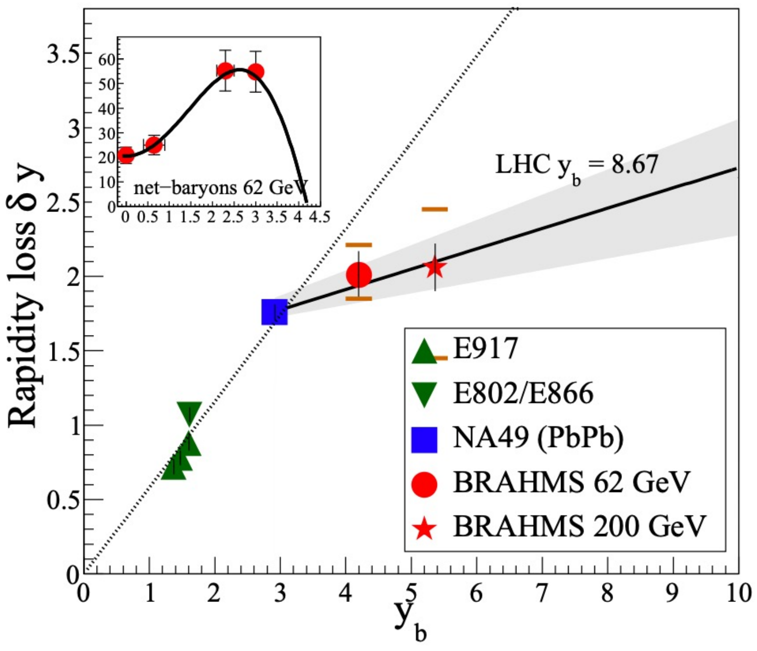


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS 2009

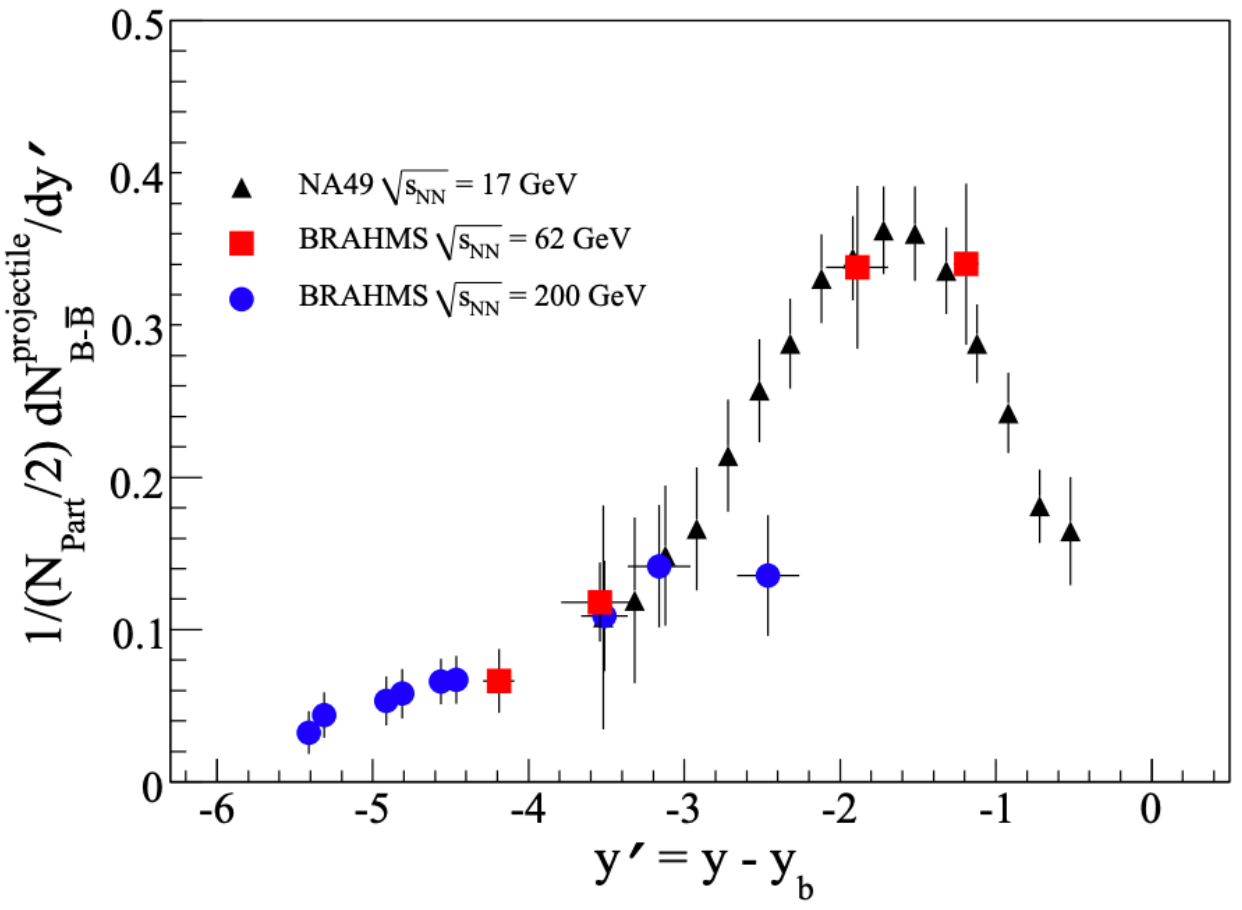


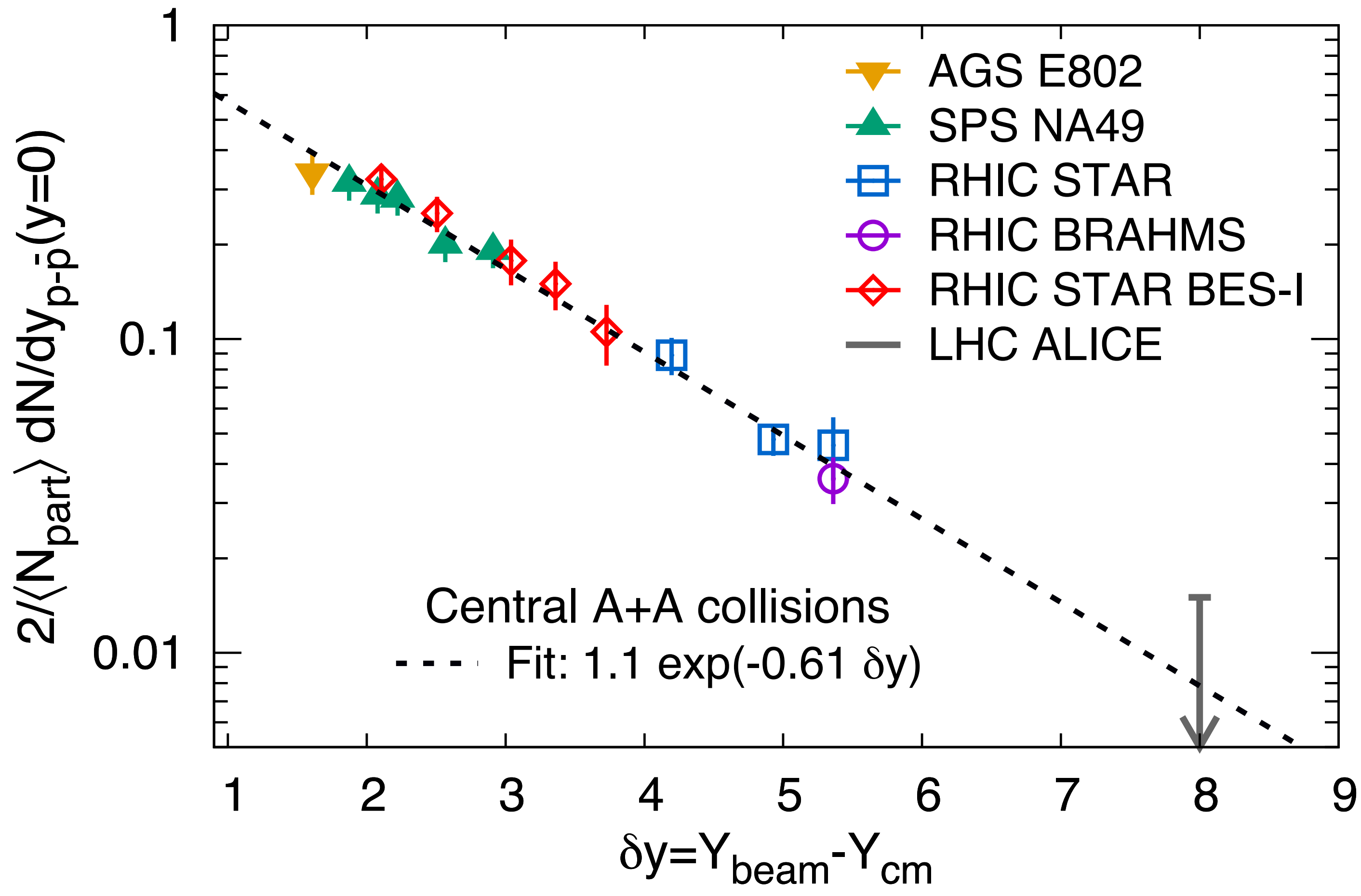
Figure 5: Projectile net-baryon rapidity density $(1/N_{part}/2)dN^{projectile}_{B-\bar{B}}/dy'$ from SPS and RHIC after subtraction of the target net-baryon contribution (see Fig. 4).

Quantifying baryon number transport

- RHIC Beam Energy Scan (BES-I) span large range of rapidity shift
- Exponential with slope of α_B =0.61±0.03
- Consistent with the baryon junction transport by gluons:
  α_B~=0.5+Δ
  Δ~=0.1

STAR, Phys. Rev. C **79** (2009) 34909; **96** (2017) 44904

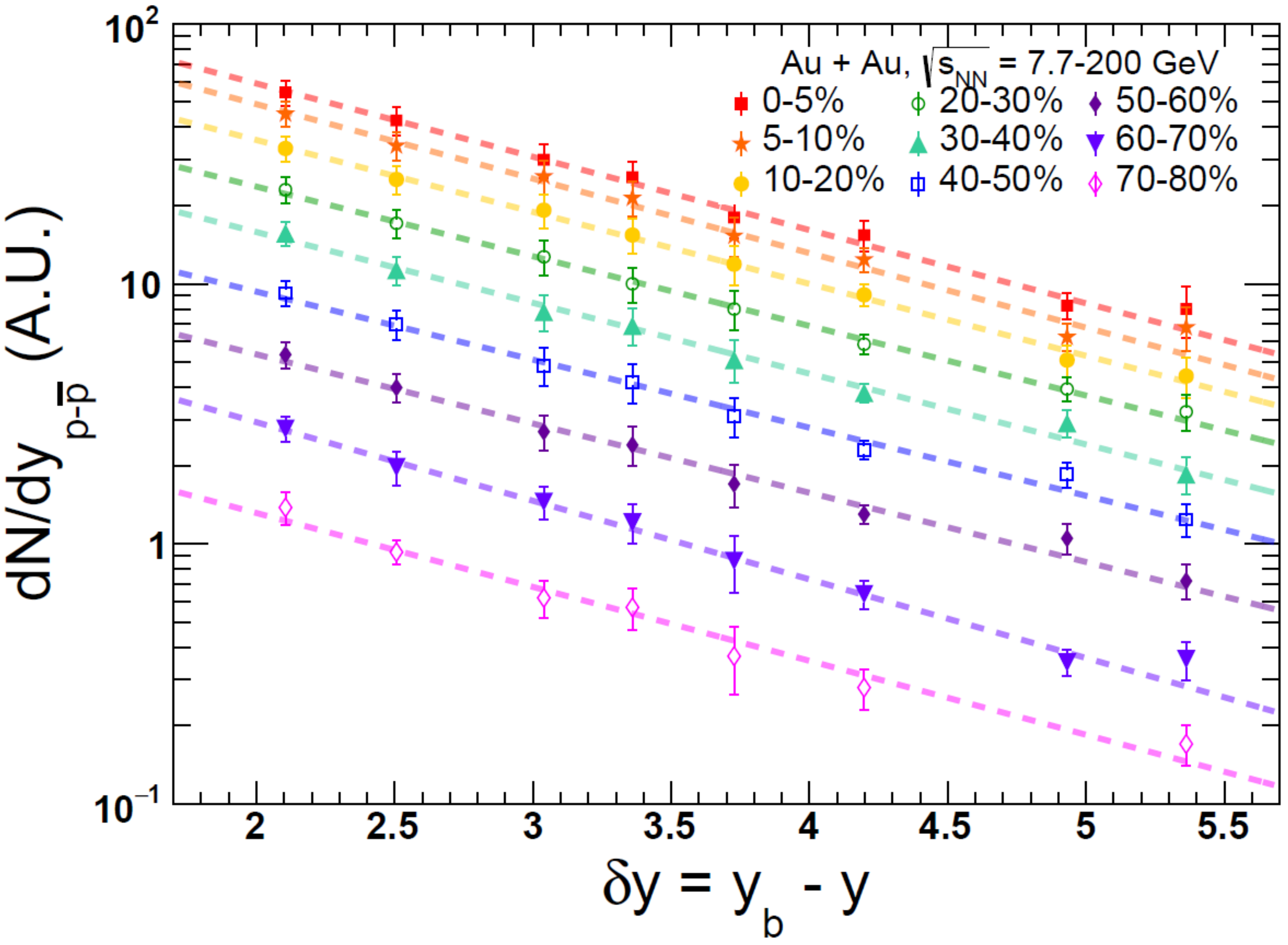
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685



Quantifying baryon number transport

- Striking scaling for all centralities and collision beam energies from central A+A to p+p
- Expect slope to change if stopping is through multiple scattering of quarks
- New heavy-ion simulation require baryon junction to match data

C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.



What do we know about e+p collisions?

- RHIC nuclear energy is at a sweet spot
  - U+U, Au+Au, O+O, Cu+Au, Cu+Cu, He3+Au, d+Au,p+Au, p+p
- LHC and HERA energy are too high with small baryon excess (<1%)
- Isobar collisions at EIC with low Q^2 and low-p_t PID to study the charge and baryon transports

Artru & Mekhfi, NPA 1991

“unpolarized and polarized electroproduction of fast baryons

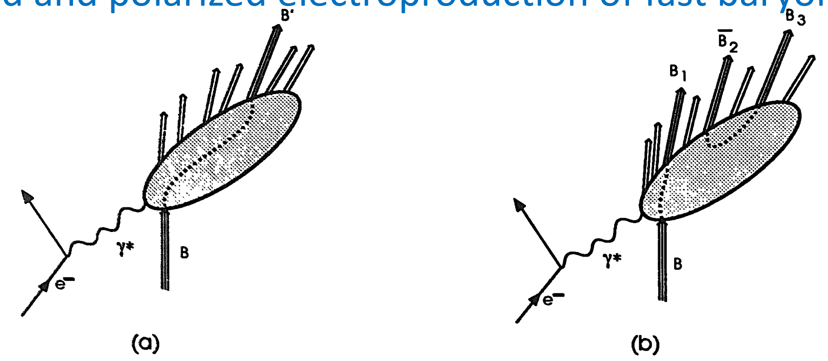


Figure 1. Main mechanisms of electroproduction of fast baryons.

The first mechanism dominates in the region (see Fig. 2)

$$Y < Y_C \simeq \beta^{-1} \ln(\beta/b) \quad (3)$$

(Y_C corresponds to Δ_1 in Ref.1). The second one dominates for $Y > Y_C$. In this talk I will show that both mechanisms can reveal interesting features of hadronic physics (I shall consider only events with low transverse momenta).

Slope β~=1 at y=2.5

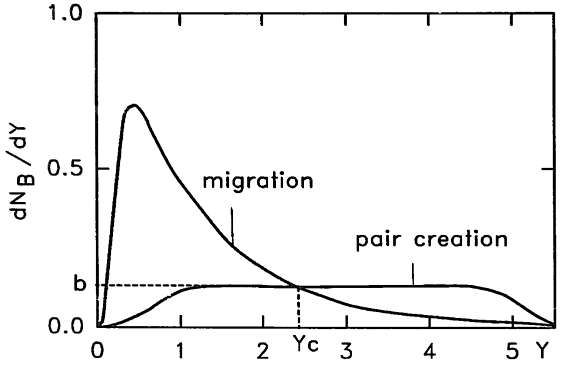


Figure 2. Rapidity spectrum: (a) of the migration mechanism, (b) of the pair creation mechanism.

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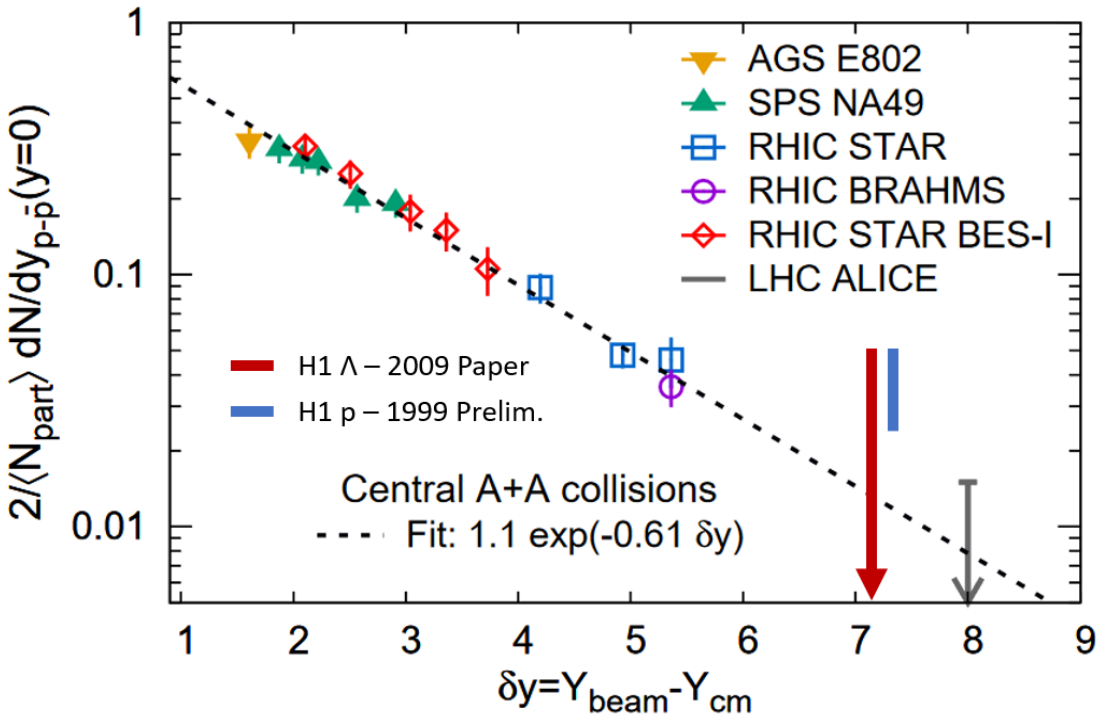
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685; Henry Klest (SBU) HERA data



Measurement of the Baryon-Antibaryon Asymmetry in Photoproduction at HERA

C. Adloff et al. (H1 Collaboration), ICHEP 1998

Baryon stopping at HERA: Evidence for gluonic mechanism

Boris Kopeliovich (Heidelberg, Max Planck Inst. and Dubna, JINR), Bogdan Povh (Heidelberg, Max Planck Inst.)

Published in: *Phys.Lett.B* 446 (1999) 321-325 • e-Print: hep-ph/9810530 [hep-ph]

What do we know about μ+p collisions

Same plot, opposite conclusion!

Benchouk (EMC), ISMD1984

At this point it should be noted that, if they were significantly contributing, protons coming from scattering on diquark clusters (higher twist)[10] would also present such behaviours as those of Figs. 2 and 3d. However those protons must exhibit a strong decrease with Q^2, which is obviously not the case as shown by Fig. 4 and their contribution to our sample can be excluded.

EMC, PLB 103 (1981) 388;
last cited in 1992

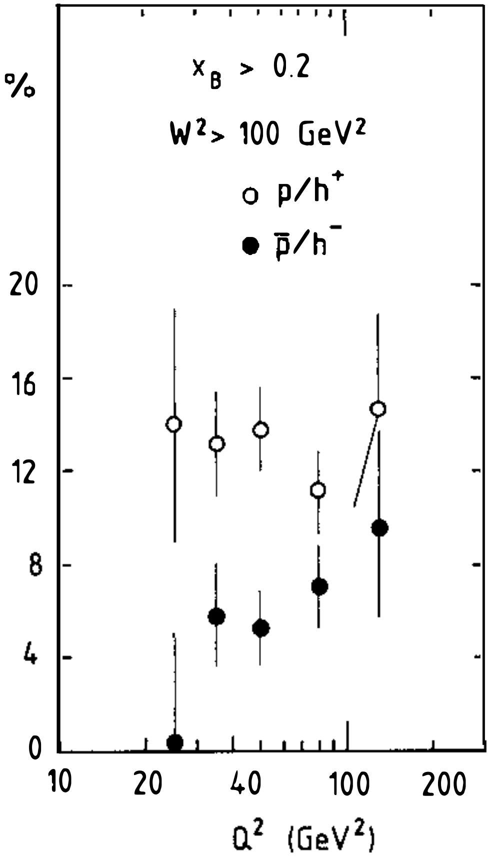
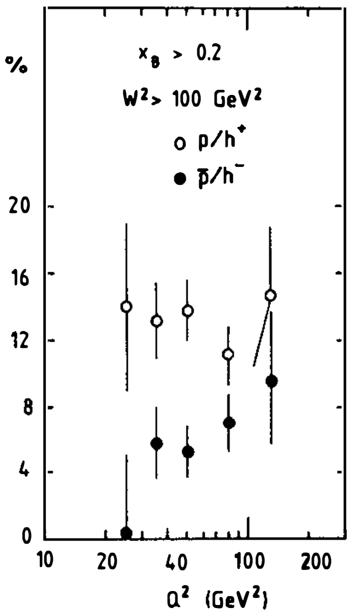
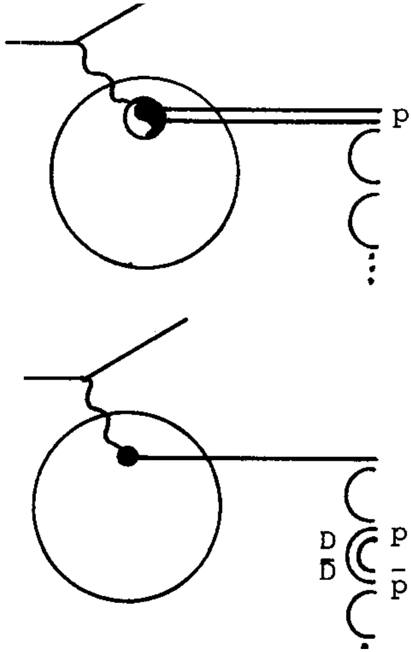


Fig. 4 – The ratio of the proton (antiproton) multiplicity to the overall positive (negative) hadron multiplicity as a function of Q^2 for $W^2 > 100$ GeV^2 and $x_B > 0.2$.

Fredriksson, "Hello Diquark, Goodbye Gluon!", Moriond 1984

Fig.3 Ratio of proton (antiproton) multiplicity to the overall positive (negative) multiplicity in μp scattering according to Ref.7 (EMC). Part of the difference between p and $\bar{p}$ might be explained by the diquark process in the upper reaction, while large-Q^2 events come from knocked-out quarks, as shown in the lower reaction. The two processes give rise to completely different p-$\bar{p}$ correlations.





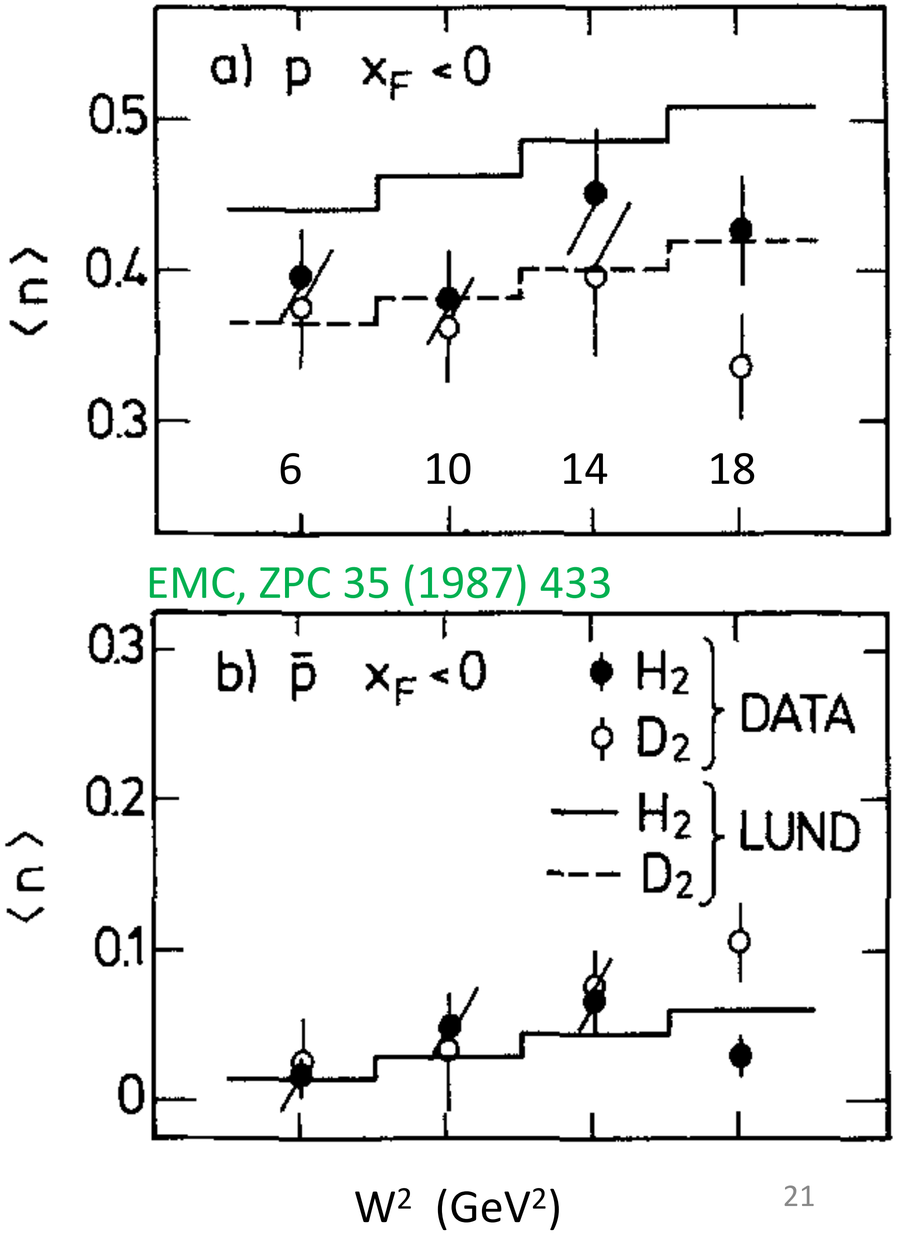
What do we know about μ+p (d) collisions

Diquark Lund model predicts a flavor dependence of backward proton production (20%) while data shows little-to-no dependence

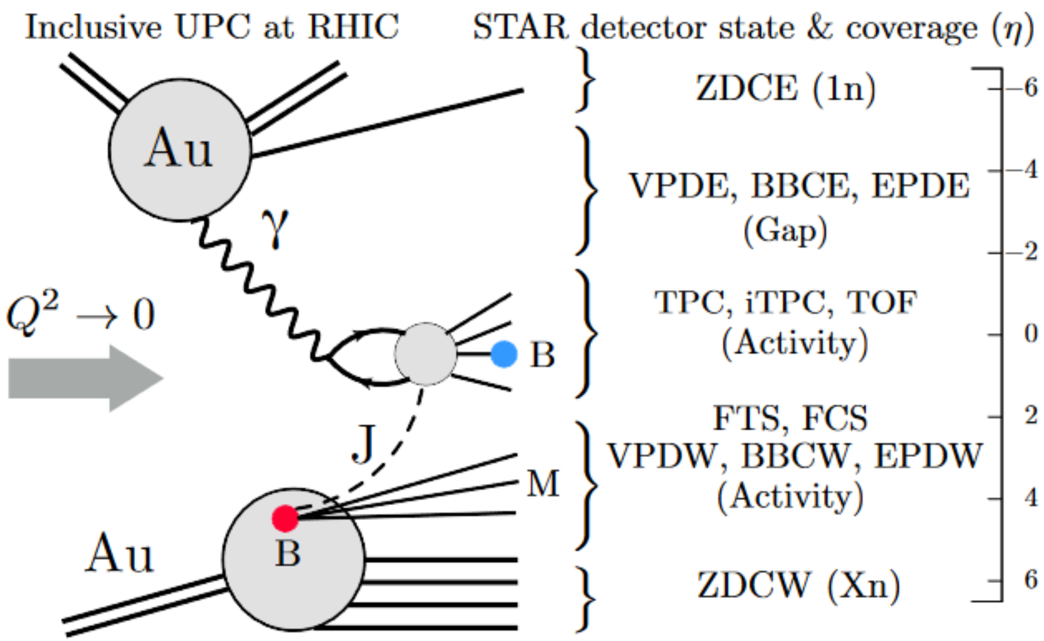
Fig. 5a-d. Average multiplicities from the H_2 (full circles) and the D_2 target (open circles) vs. W for backward protons a, backward antiprotons b. The histograms show the Lund model predictions (full line: H_2 target, dashed line: D_2 target, full line only where both are the same)

the Lund model (JETSET62) predicts a higher yield of backward going protons from hydrogen than from deuterium, an effect which is less pronounced in the data.

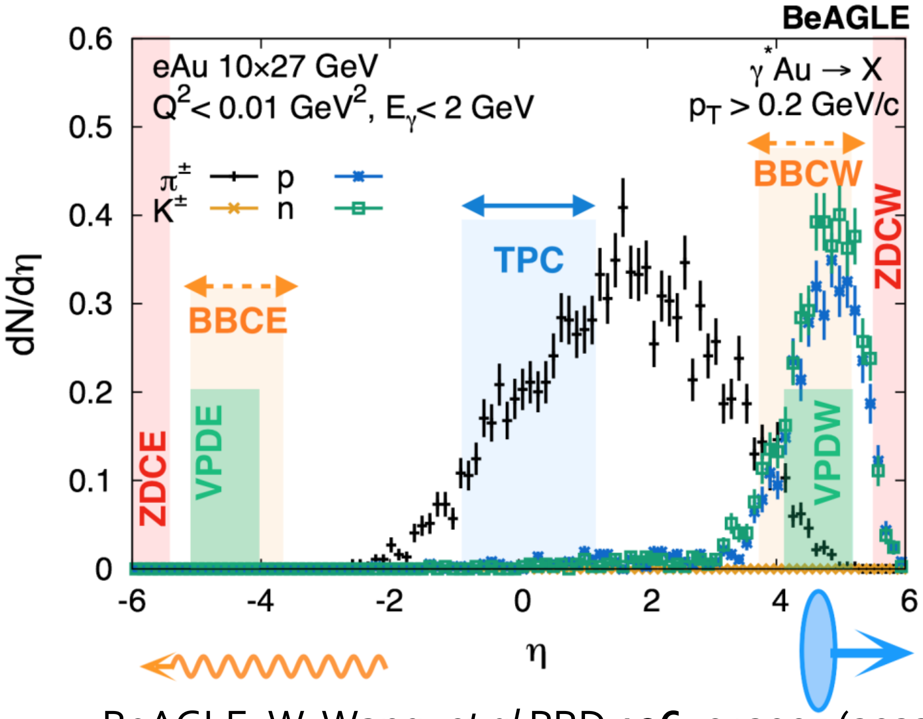
Total citations: 19



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:

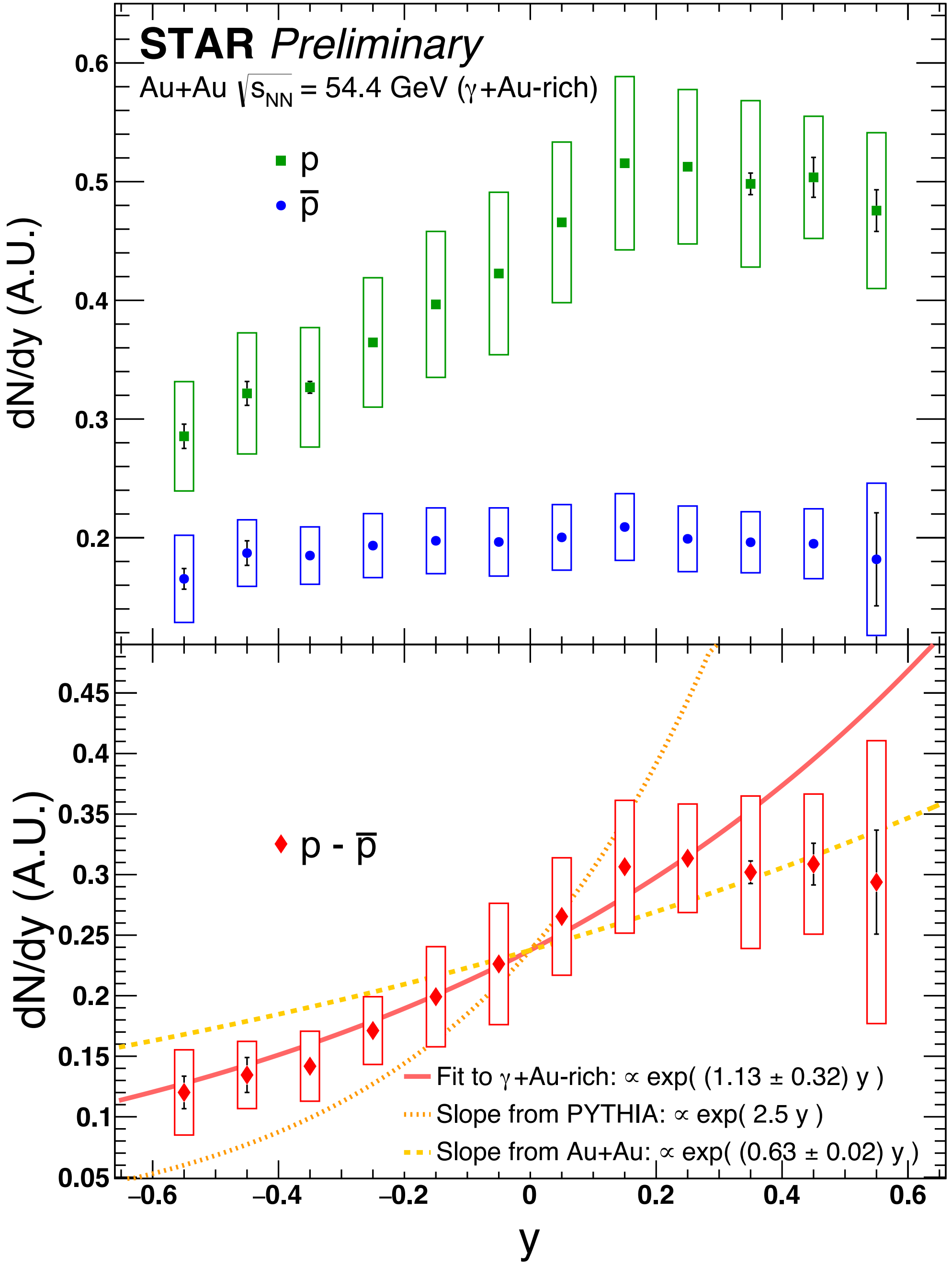
ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021) and CMS Collaboration, arXiv:2204.13486 (2022)

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

Nicole Lewis (BNL) for STAR, DIS2023

Rapidity asymmetry in photon-nucleus collision

- Selection of photon+Au collisions from Au+Au at 54.4GeV ultra-peripheral collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic asymmetry increase toward nucleus side
- Slope is closer to the slope of the beam energy dependence
- PYTHIA shows much larger slope

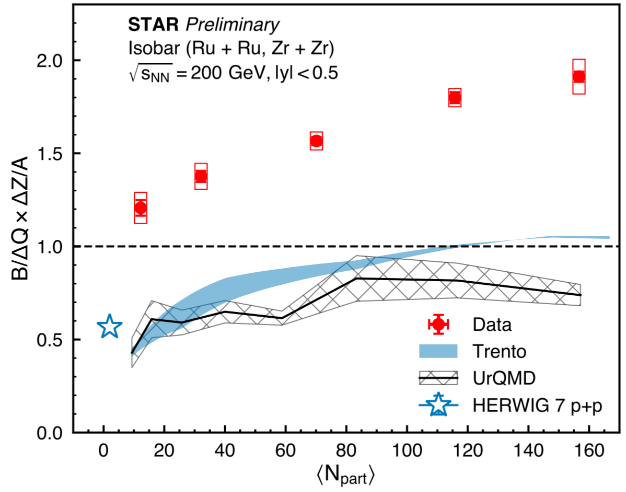


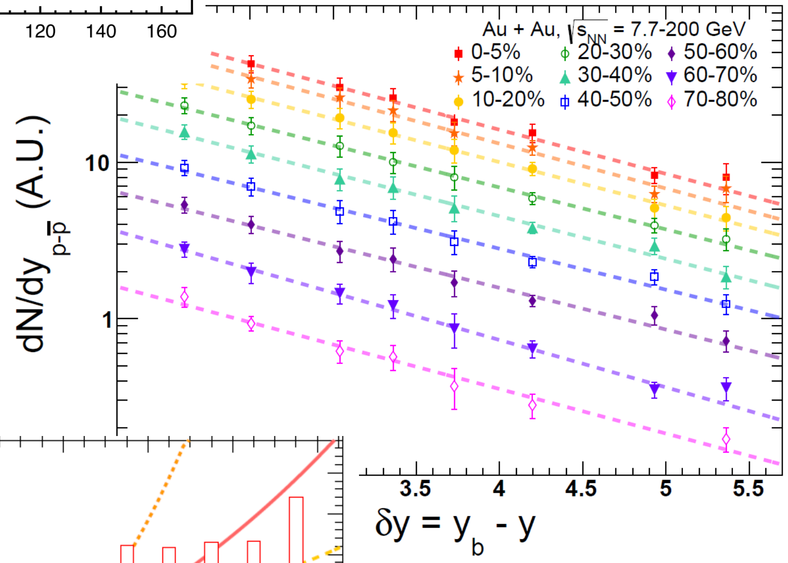
Three approaches toward tracking the origin of the baryon number

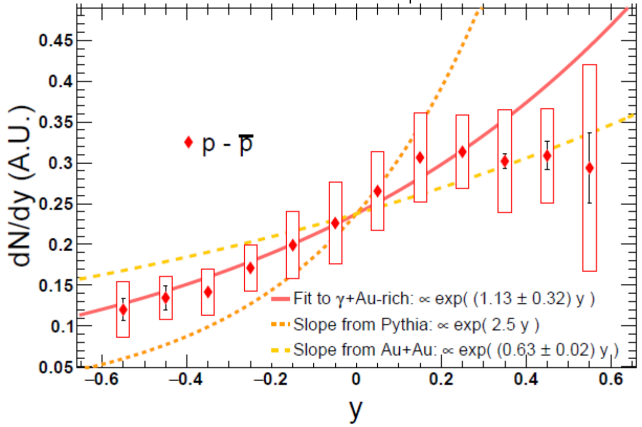
1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin
   α_B(A+A)=0.61< α_B(γ+A)=1.1< α_B(PYTHIA)

$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

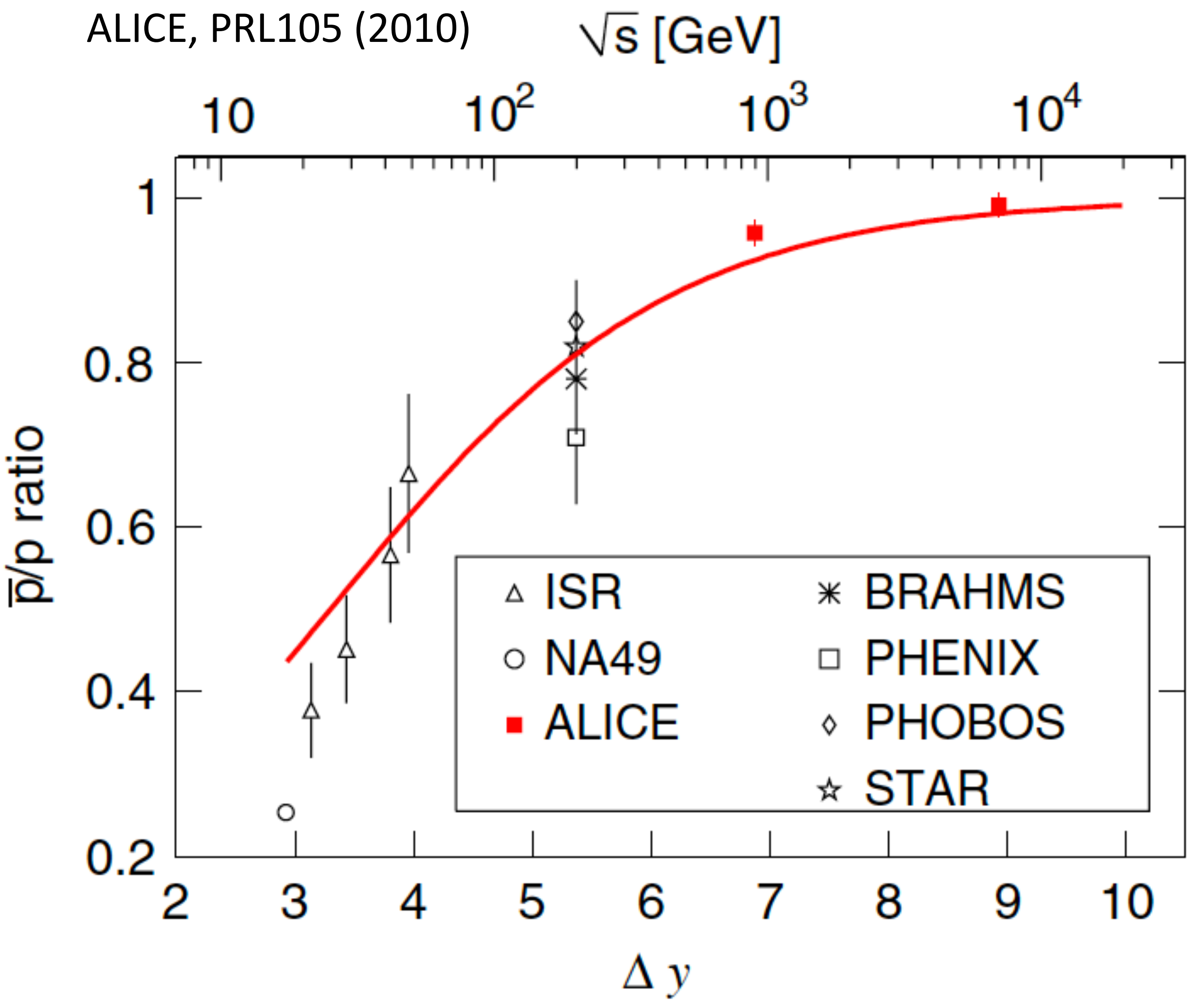






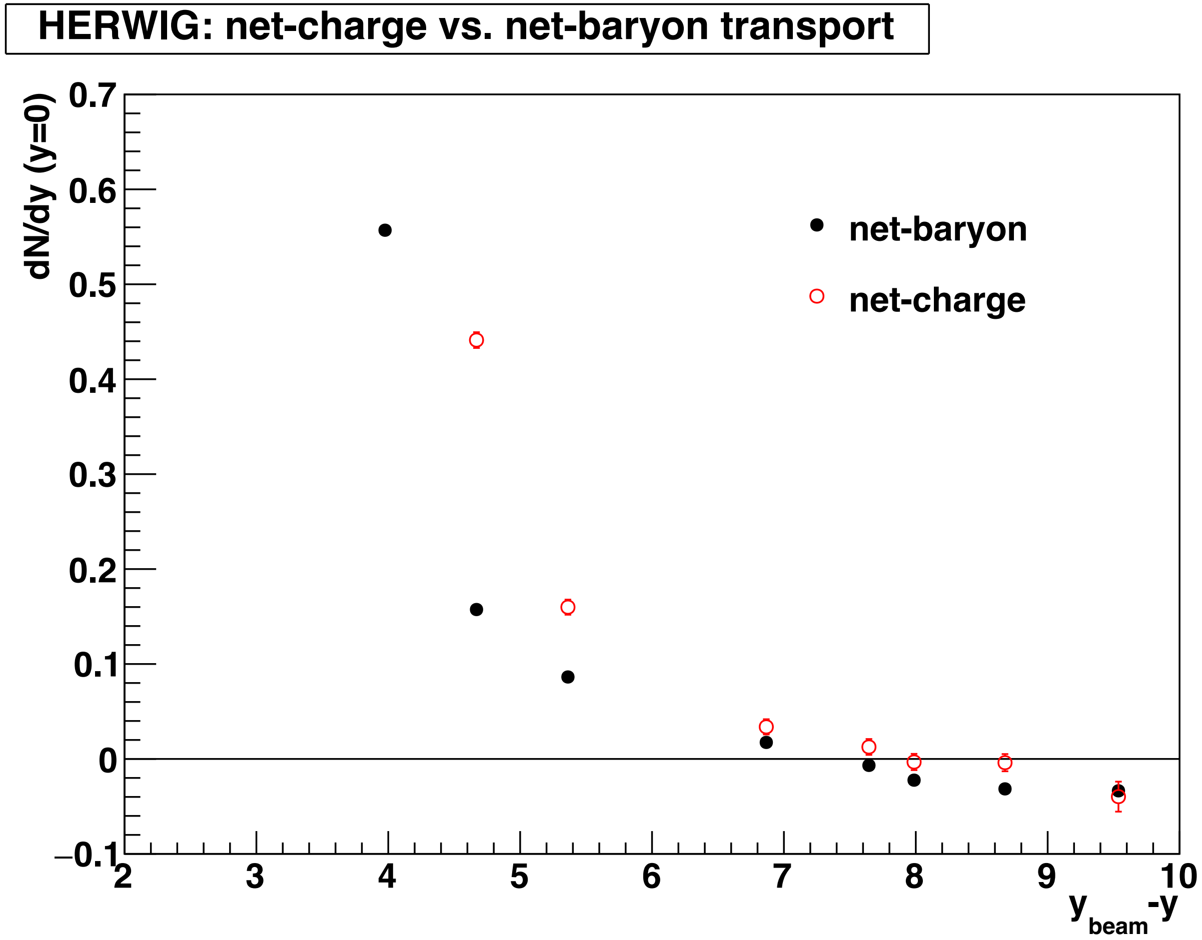
What do we know about pp collisions?

ALICE, PRL105 (2010)



red curve consistent with α_B =0.6

Rongrong Ma (BNL)

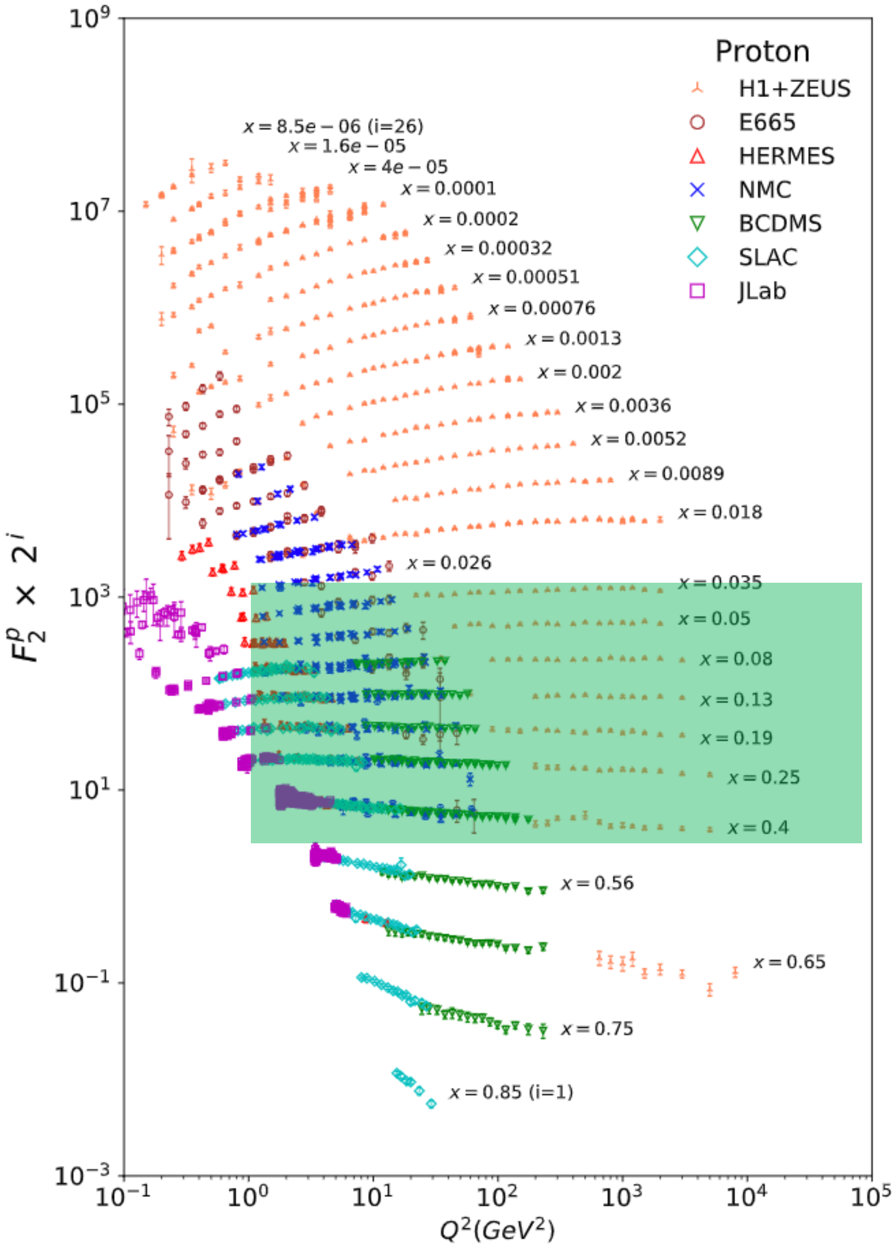


HERWIG and PYTHIA: α_B ~=1.6-2.5

Negative (pbar>p) at LHC energy

Bjorken Scaling for quarks

- Scaling at certain x range, quarks behave as point-like particles
- Evolution with x due to gluons
- At DIS (high Q^2>1 GeV^2)



PDG

Figure 18.10: The proton structure function F_2^p measured in electromagnetic scattering of electrons and positrons on protons, and for electrons/positrons (SLAC,HERMES,JLAB) and muons (BCDMS, E665, NMC) on a fixed target. Statistical and systematic errors added in quadrature are shown. The H1+ZEUS

Conclusions and Perspectives

- Baryon number is a strictly conserved quantum number,
  keeps the Universe as is

- We did not know what its carrier is;
  It has not been experimentally verified one way or the other until now

- RHIC Beam Energy Scans provide unique opportunity in studying baryon number transport over large unit of rapidity

- RHIC Isobar collisions provide unique opportunity in studying charge and baryon transport

- Experimental verification of the simplest QCD topology

- Baryon junction (if exists) is a non-perturbative object

- Need small Q^2 and low-momentum hadron particle identification

$$Q^2 \leq 1\ GeV^2$$

π/k/p PID $p_t \geq \sim 100\ MeV$

- Isobar collisions to measure baryon and charge transport (quark transports), EMC 1987

Zr/Ru; Li^7/Be^7

- EIC can measure the baryon junction distribution function

- Explore other signatures at EIC

Questions for discussion: what about fluctuations?

Brought up by a student at Chirality workshop in Beijing in 07/2023

Asakawa, Heinz, Muller, PRL 85 (2000) 2072

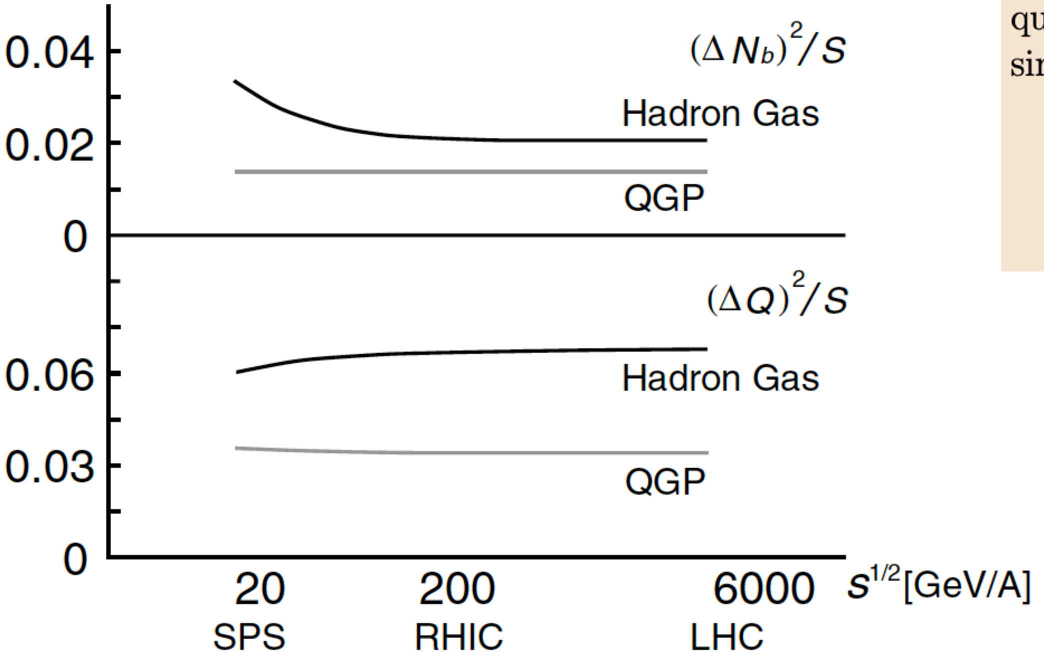


FIG. 1. Schematic drawing of the beam energy dependence of the net baryon number and charge fluctuations per unit entropy for a hadronic gas and a quark-gluon plasma.

V. Koch, arXiv:0810.2520

and since all baryons in the hadronic phase have baryon number $|B_{hadronic}| = 1$ and all quarks have baryon number $|B_{quark}| = 1/3$ we get for the the ratio of the cumulants the simple results

$$R^B_{4,2} = 1; \text{ hadron phase} \quad (40)$$

$$R^B_{4,2} = \frac{1}{9}; \text{ QGP} \quad (41)$$

Is the statement confirmed by LQCD?
If YES, does it rule out gluon junction
or can both scenarios co-exist?
Is this confirmed by experiments?
If YES,
how do we reconcile all experimental results?

the simplest QCD topology

B=1