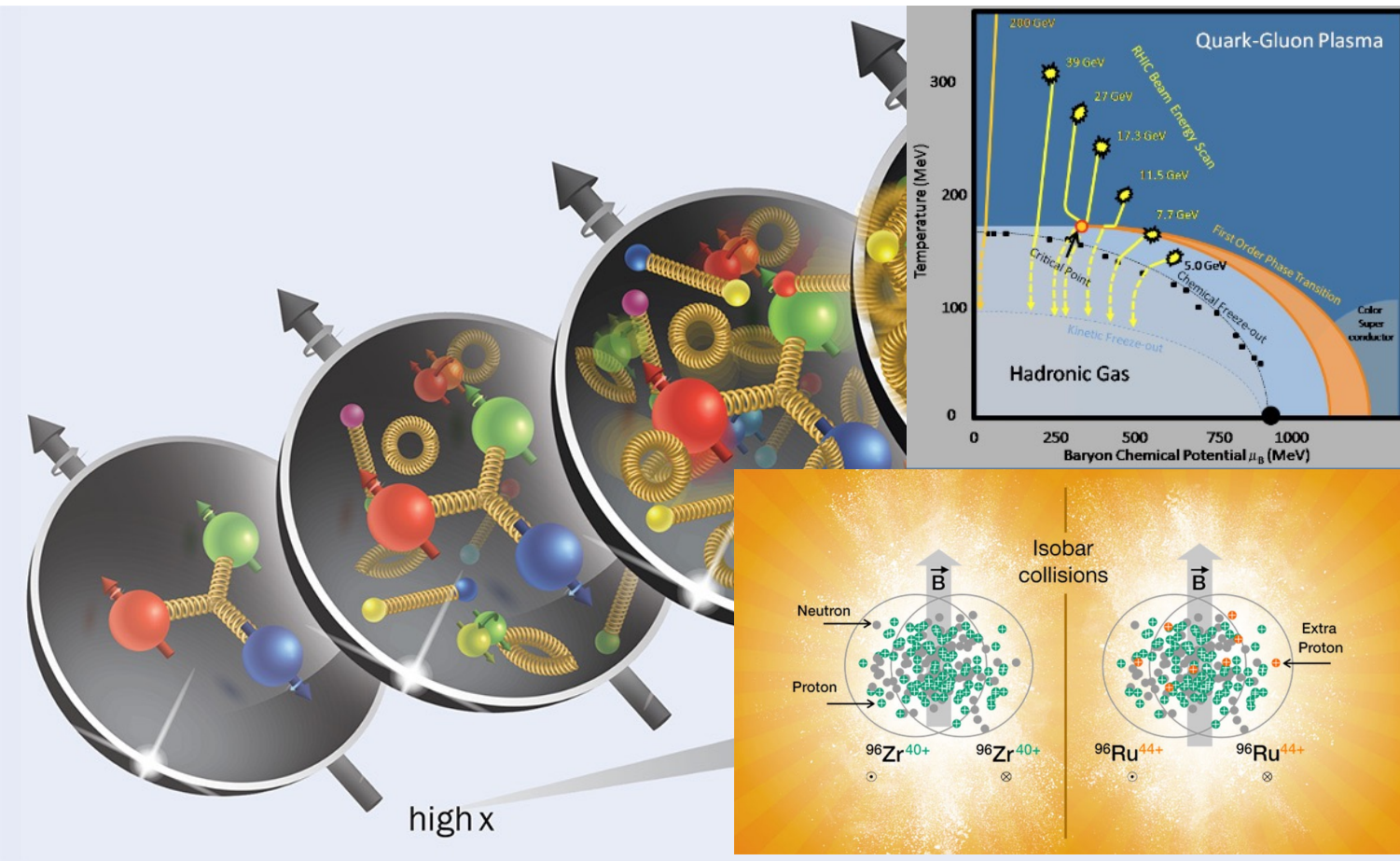


Experimental findings on the simplest QCD topology from BES-I and Isobar data

Zhangbu Xu
(Brookhaven National Lab)

- baryon number carrier
- Three experimental approaches at RHIC
- Earlier theory and experiment work on pp and ep
- EIC perspectives and requirements

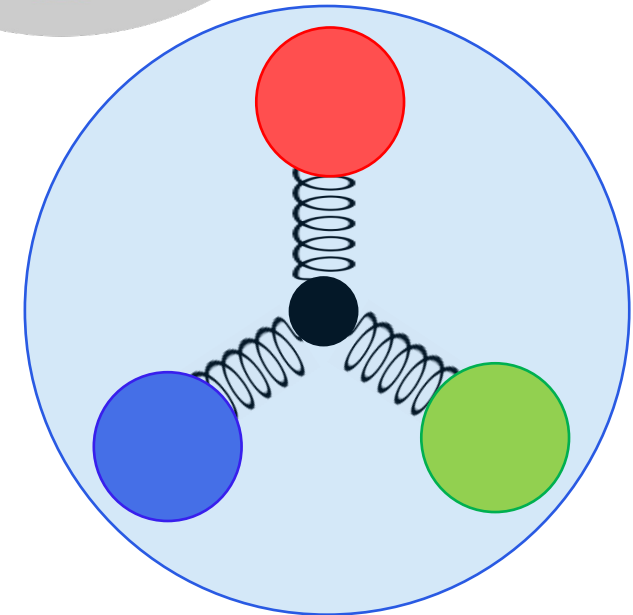
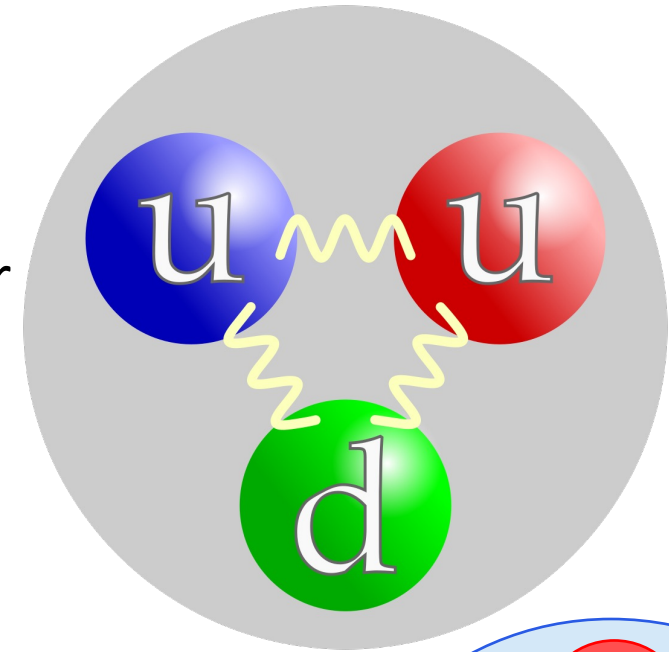


N. Lewis, T. Tsang, Y. Li, H. Klest, W.B. Zhao, N. Magdy, R.R. Ma, P. Tribedy, J.D. Brandenburg, Z.B. Tang, Z.W. Lin, C. Shen, B. Schenke, D. Kharzeev, *et al.*

In part supported by

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
 - A Y-shaped gluon junction topology carries baryon number ($B=1$)
 - The topology number is the strictly conserved number
 - Quarks do not carry baryon number
 - Valence quarks are connected to the end of the junction

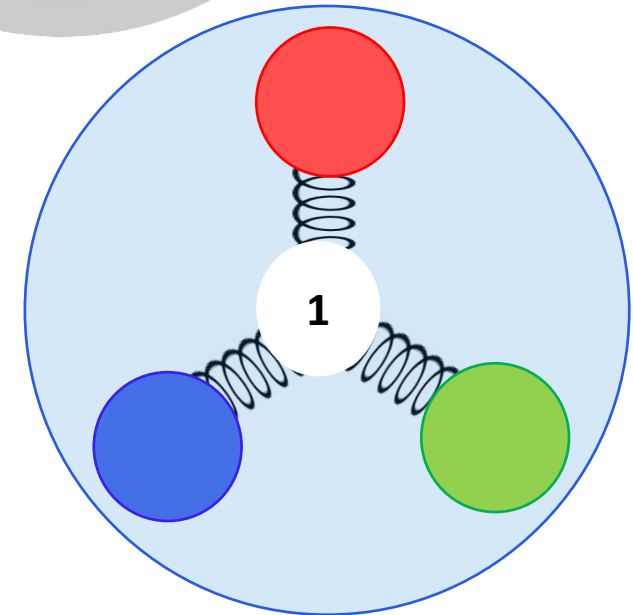
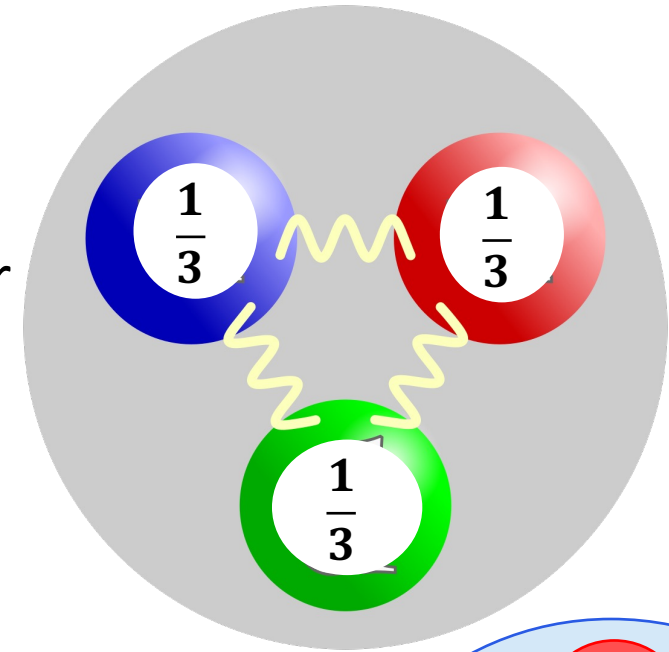


[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (1975).

[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (1977)

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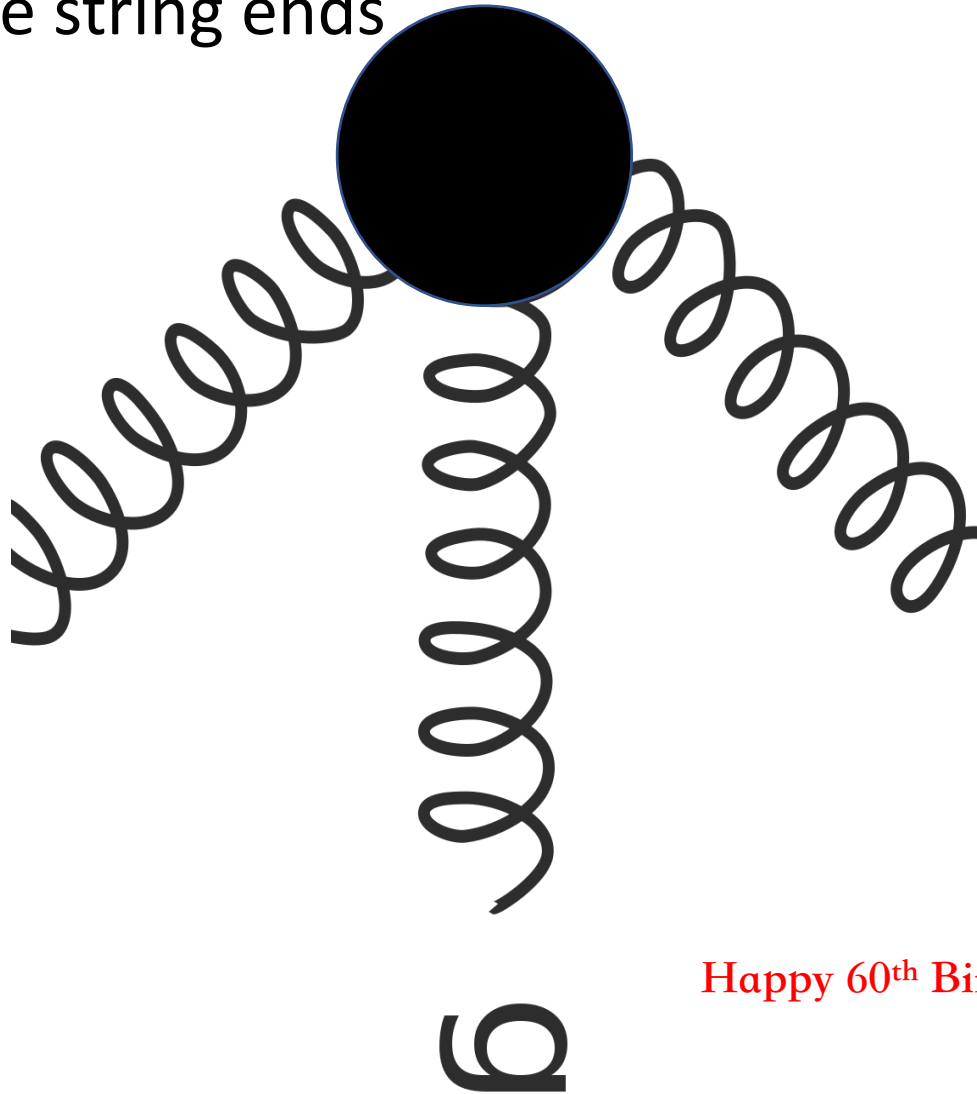
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[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (1977)

The important part of the idea is that the topology of three strings is the center of a baryon, not the objects (quarks) attached to the string ends



Happy 60th Birthday, Dima!



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

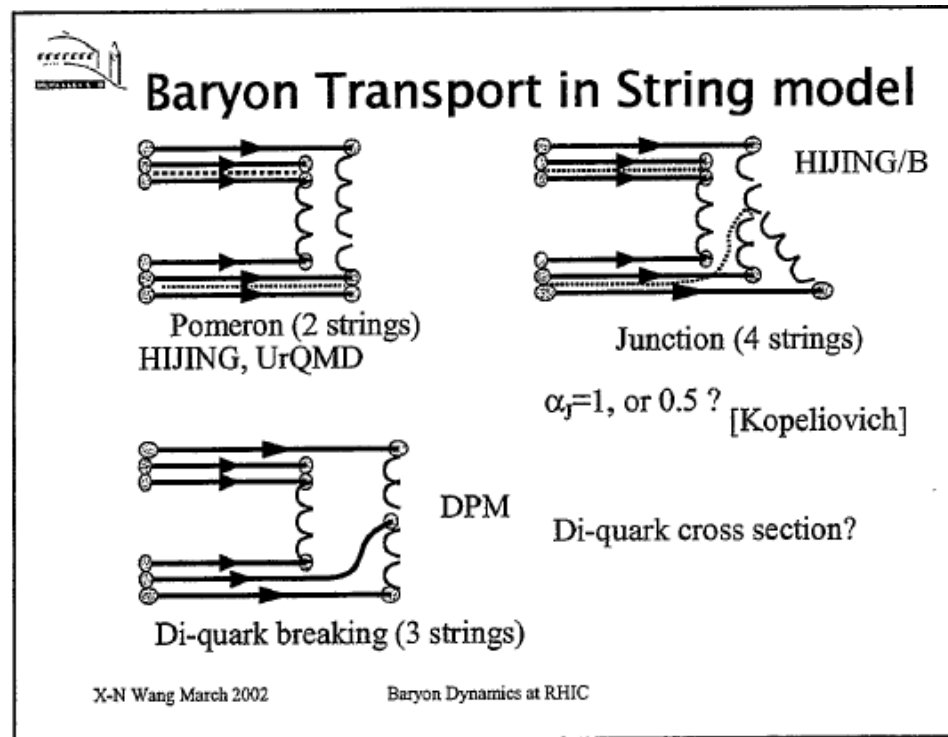
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- Specific rapidity dependence is predicted:

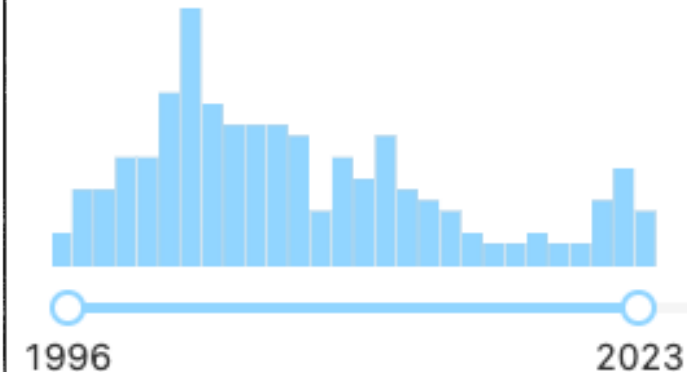
$$p = \sim e^{-\alpha_B y}$$

$$\alpha_B \sim 0.5$$

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 $\sigma \propto e_q^2$

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

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

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

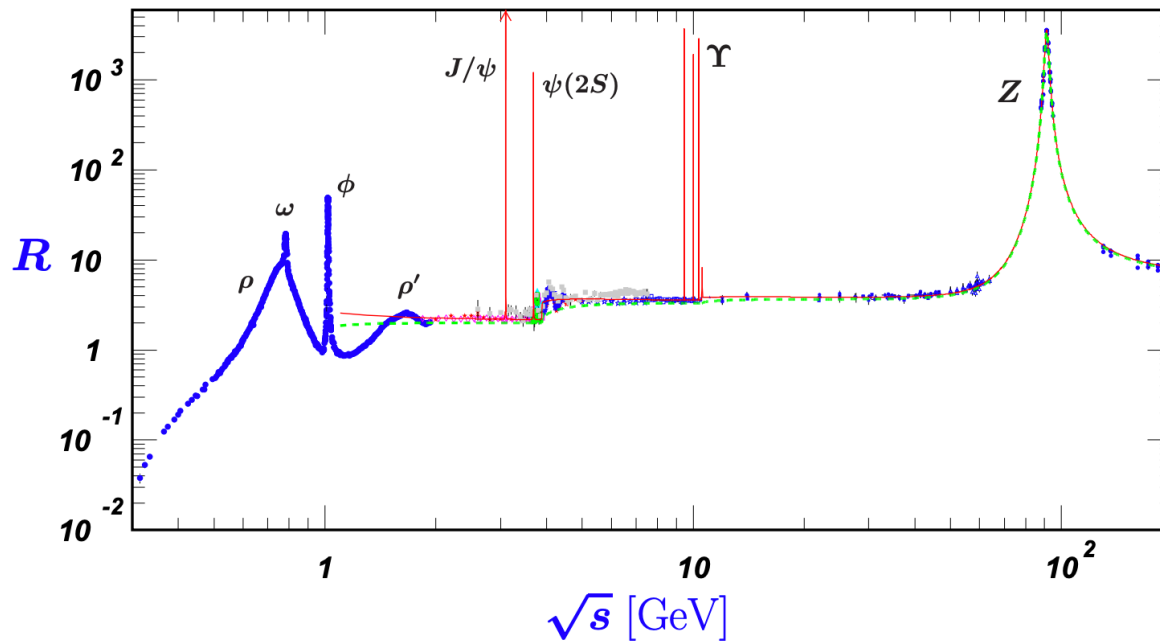


Figure 53.2: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons}, s) / \sigma(e^+e^- \rightarrow \mu^+\mu^-, s)$. $\sigma(e^+e^- \rightarrow \text{hadrons}, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \rightarrow \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. 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

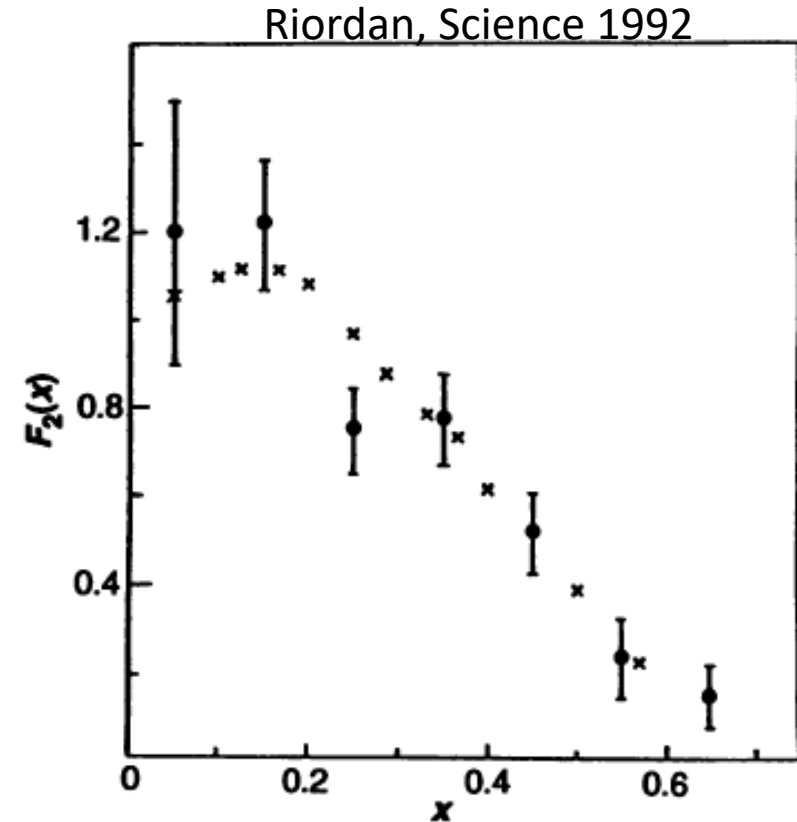
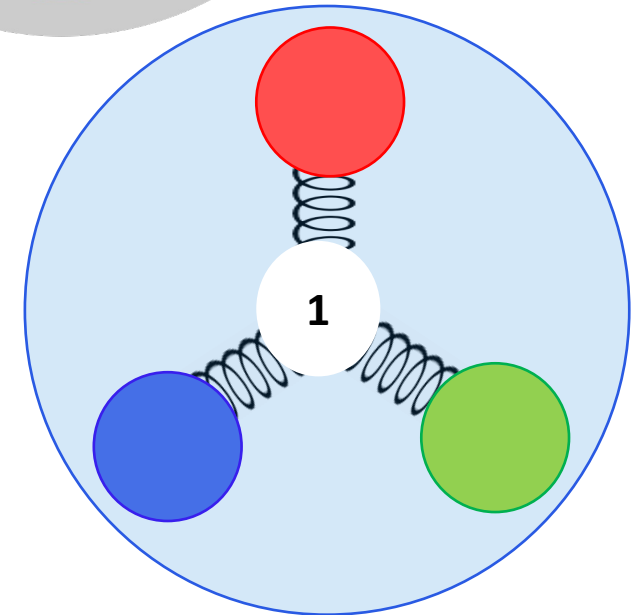
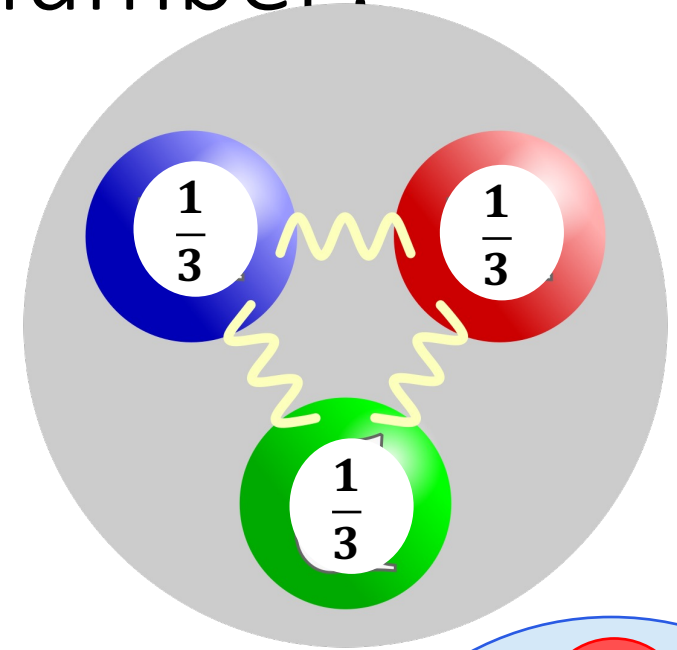


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, $(18/5)F_2^{\text{eN}}$]. When multiplied by 18/5, a number specified by the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

Measurements of quark baryon number?

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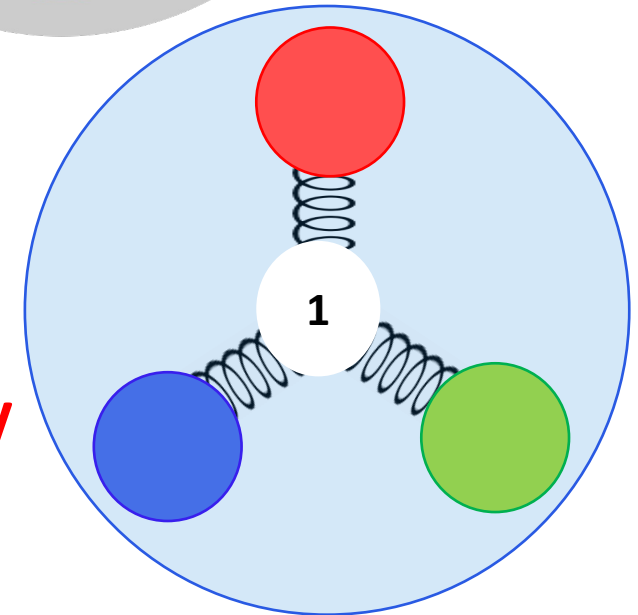
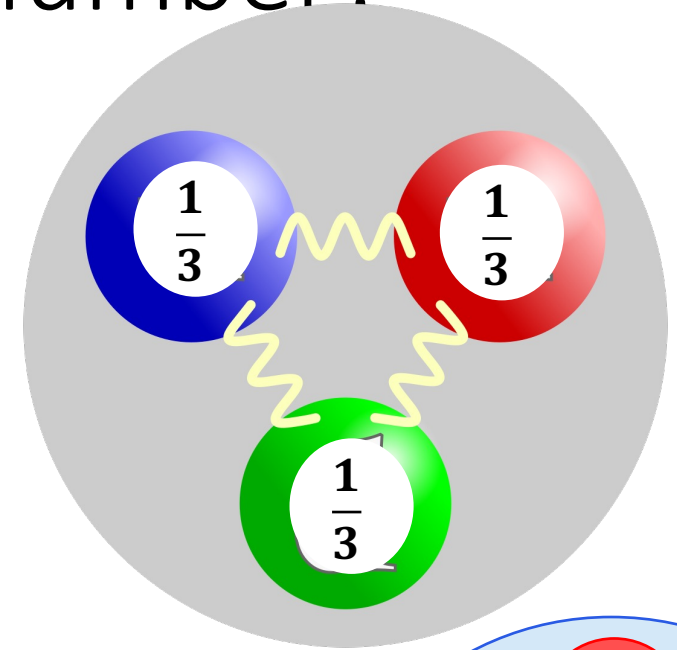


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 - Valence quarks are connected to the end of the junction always
- **Neither of these postulations has been verified experimentally**



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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

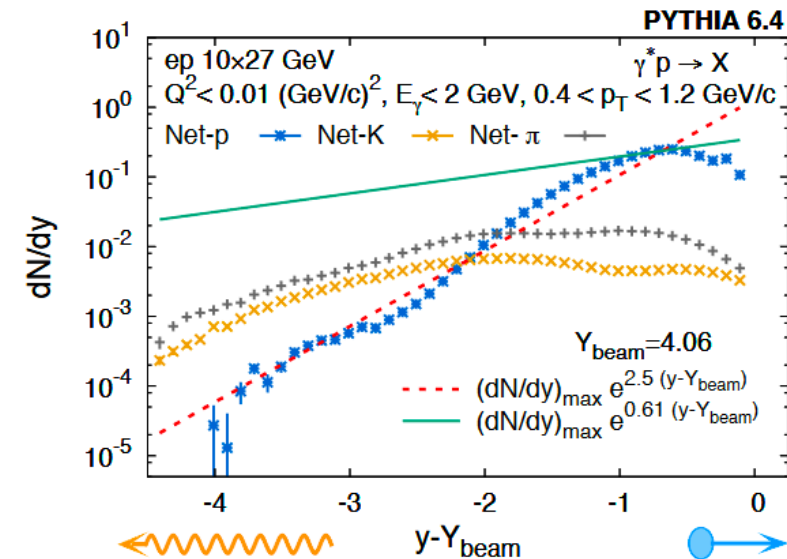
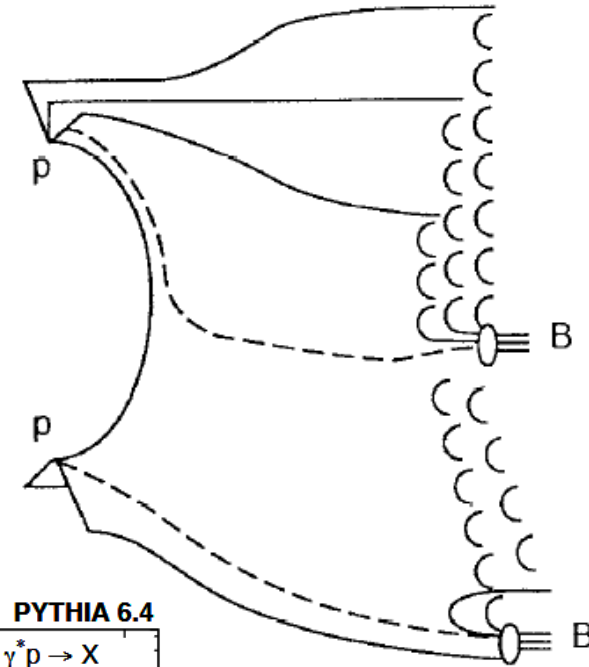
$$p = \sim e^{-\alpha_B Y}$$
$$\alpha_B \sim 0.5$$

3. Artru Method:

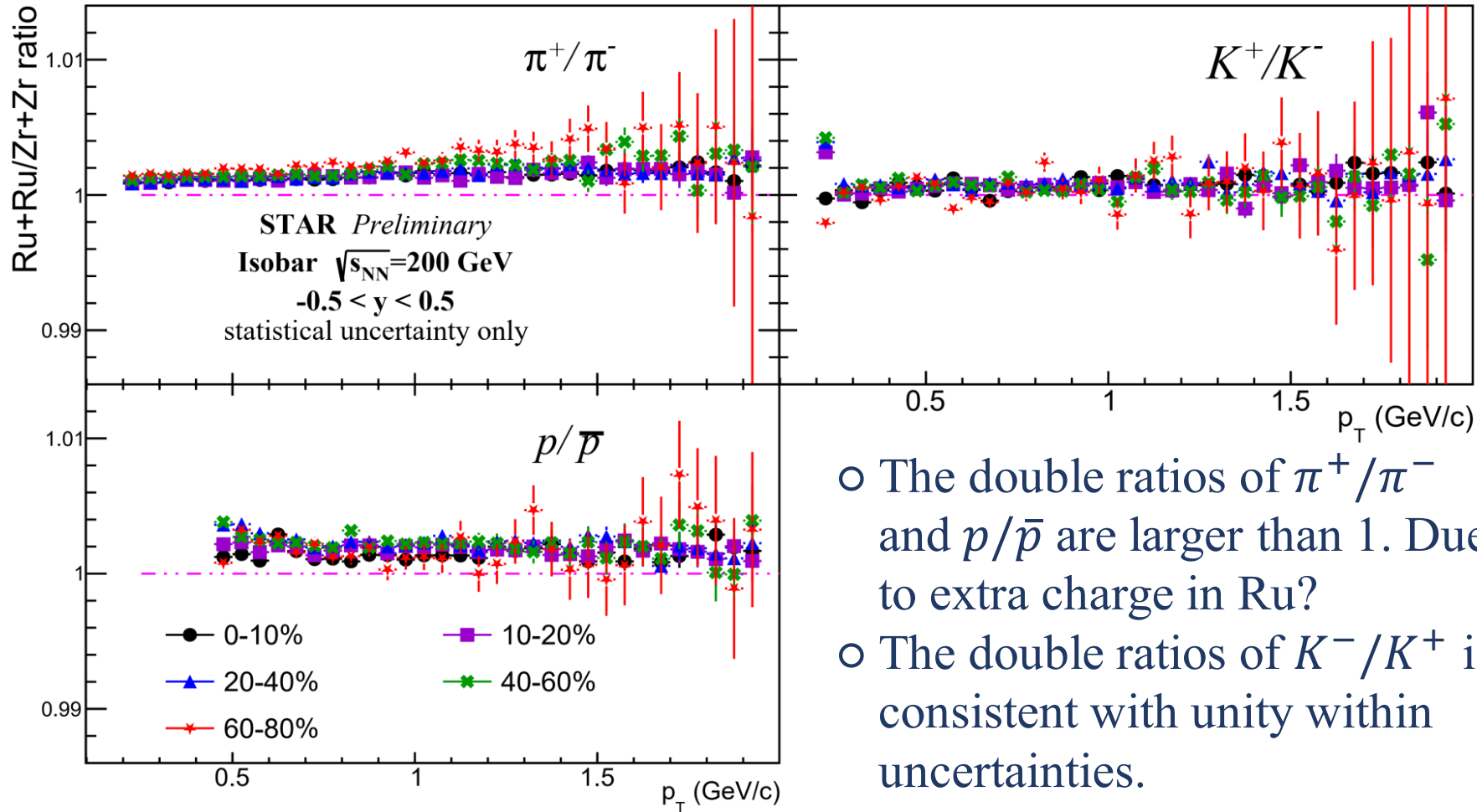
In γ +Au collision, rapidity asymmetry can reveal the origin

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 all the
detector effects, the signal
is at the level of 10^{-3}



Double ratios between Ru+Ru and Zr+Zr collisions



From baryon stopping:
 $B^*(\Delta Z/A) \sim 2 \times 10^{-3}$

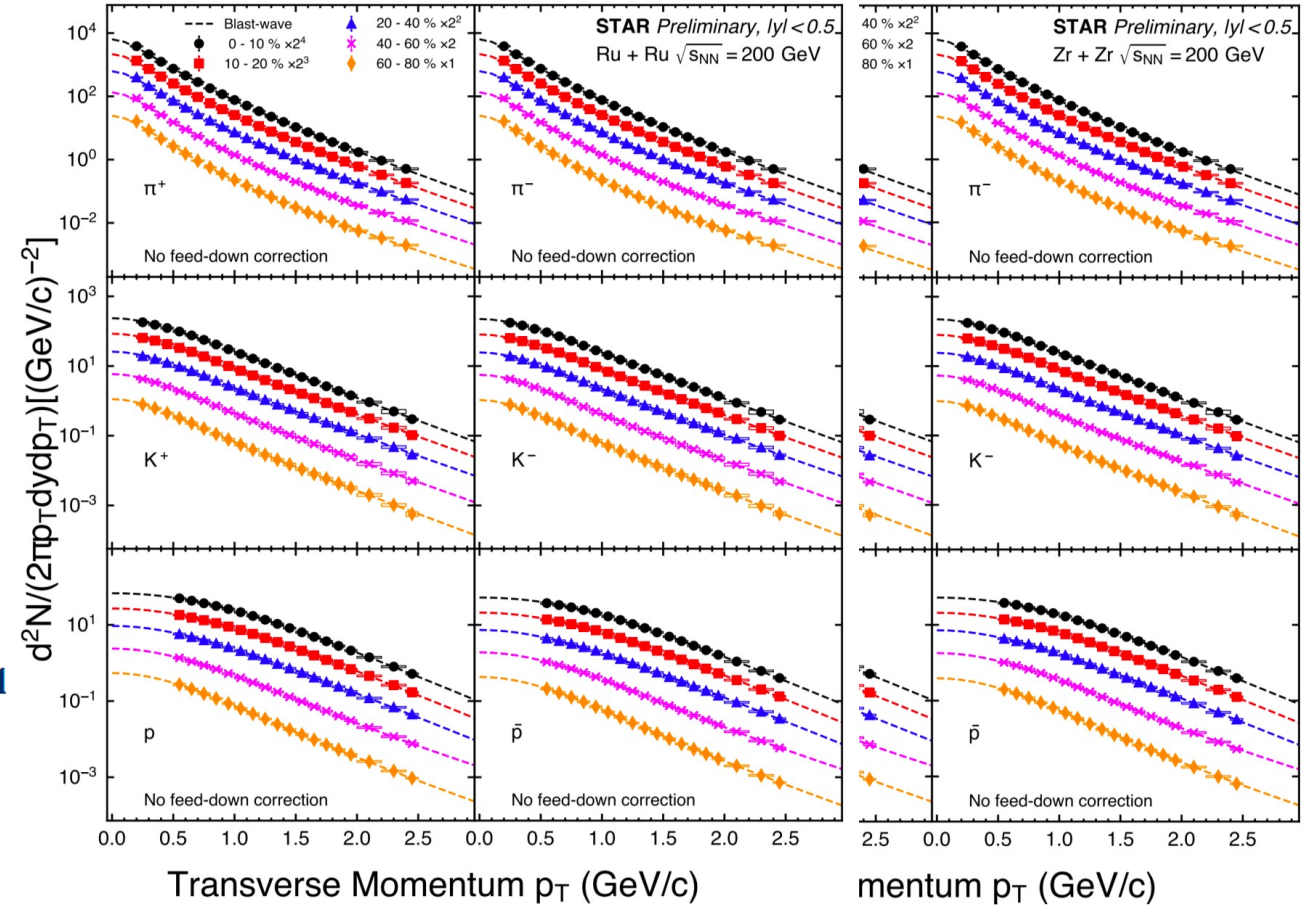
Charge stopping:
 $\Delta Q \sim 1 \times 10^{-3}$

- 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.

Identified hadron spectra to low momentum

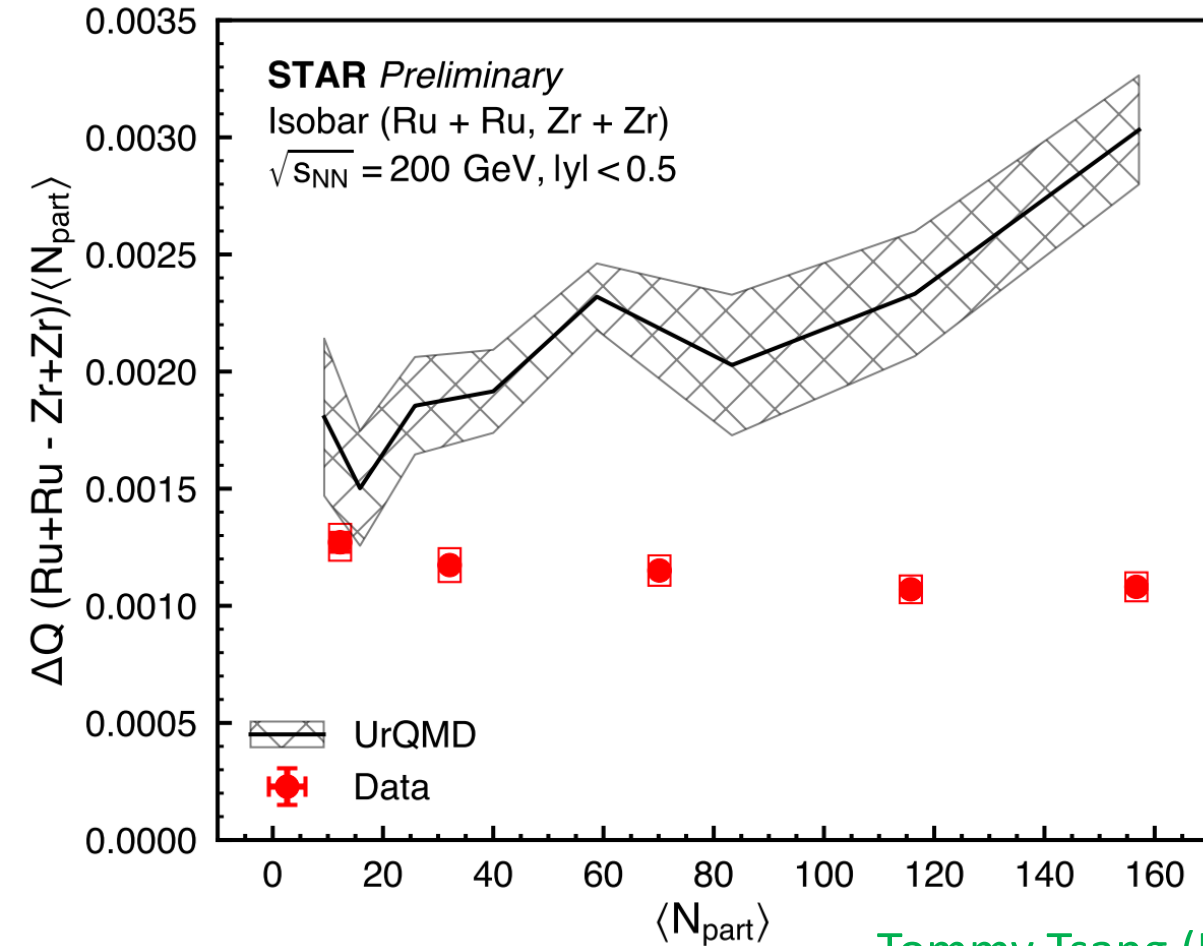
Net-charge difference (Ru+Ru – Zr+Zr)

- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta R_{Ru}}{1+\Delta R_{Zr}} \approx 1 + \Delta R_{Ru} - \Delta R_{Zr}$
- $\Delta Q = [(N_\pi^+ + N_K^+ + N_p) - (N_\pi^- + N_K^- + N_{\bar{p}})]_{Ru} - []_{Zr}$
- Focus on pion terms,
- $(N_\pi^+ - N_\pi^-)_{Ru} - (N_\pi^+ - N_\pi^-)_{Zr} = N_{\pi,Ru} \times \Delta R_{Ru} - N_{\pi,Zr} \times \Delta R_{Zr}$
- $\approx N_\pi(\Delta R_{Ru} - \Delta R_{Zr}) = N_\pi \times (R2_\pi - 1)$
- Where $N_\pi = 0.5 \times (N_\pi^+ + N_\pi^-)$
- Therefore, $\Delta Q = N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$

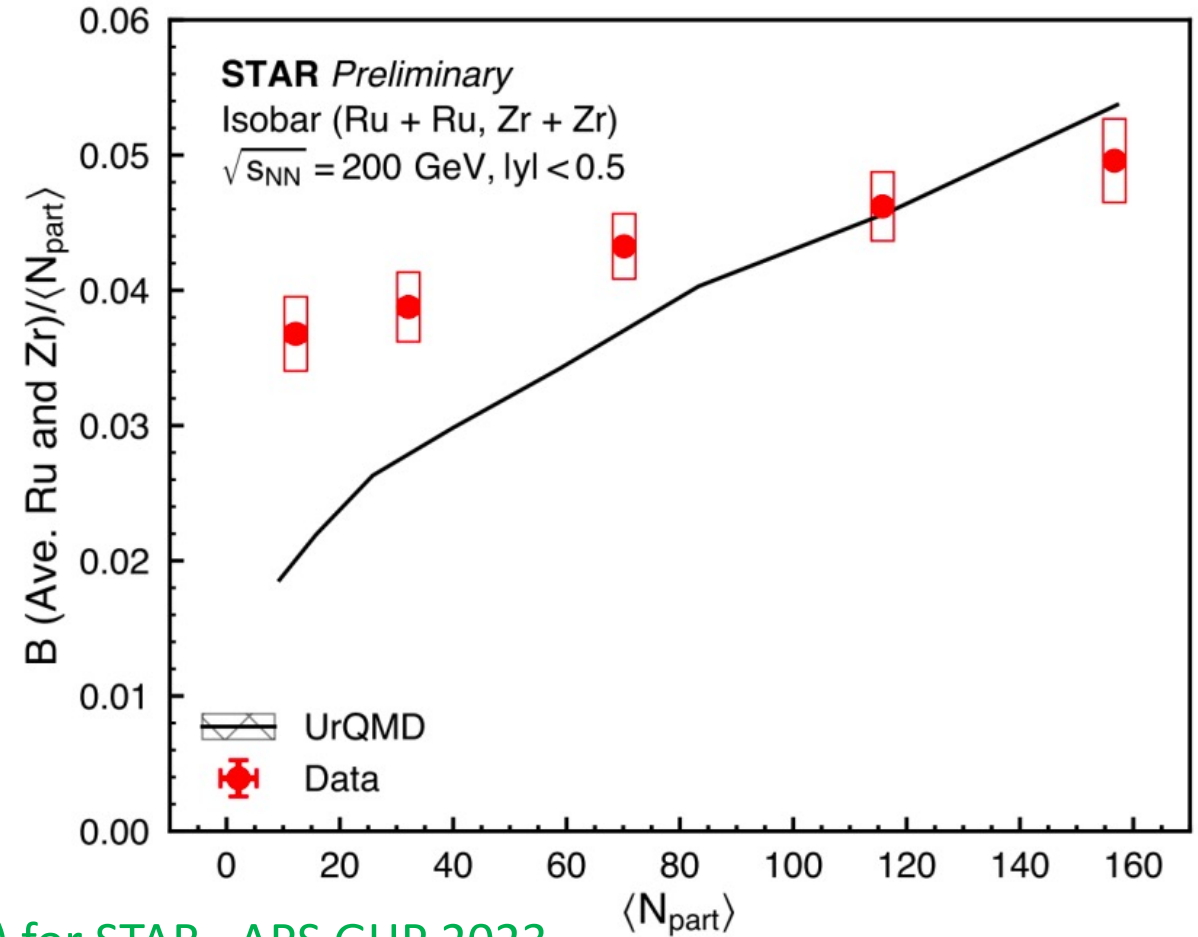


Separate charge and baryon transports

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

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

The light cone momentum p_{hadron}^\pm given to the newly produced hadron is:

$$p_{\text{hadron}}^\pm = z_{\text{fraction}}^\pm p_{\text{total}}^\pm \quad (34)$$

The fragmentation of a baryonic string reads:

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

The main input is the fragmentation function which yields the probability distribution $p(z_{\text{fraction}}^\pm, m_t)$. 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]:

$$p(z_{\text{fraction}}^\pm) = \text{constant} \times (1 - z_{\text{fraction}}^\pm)^2, \quad (36)$$

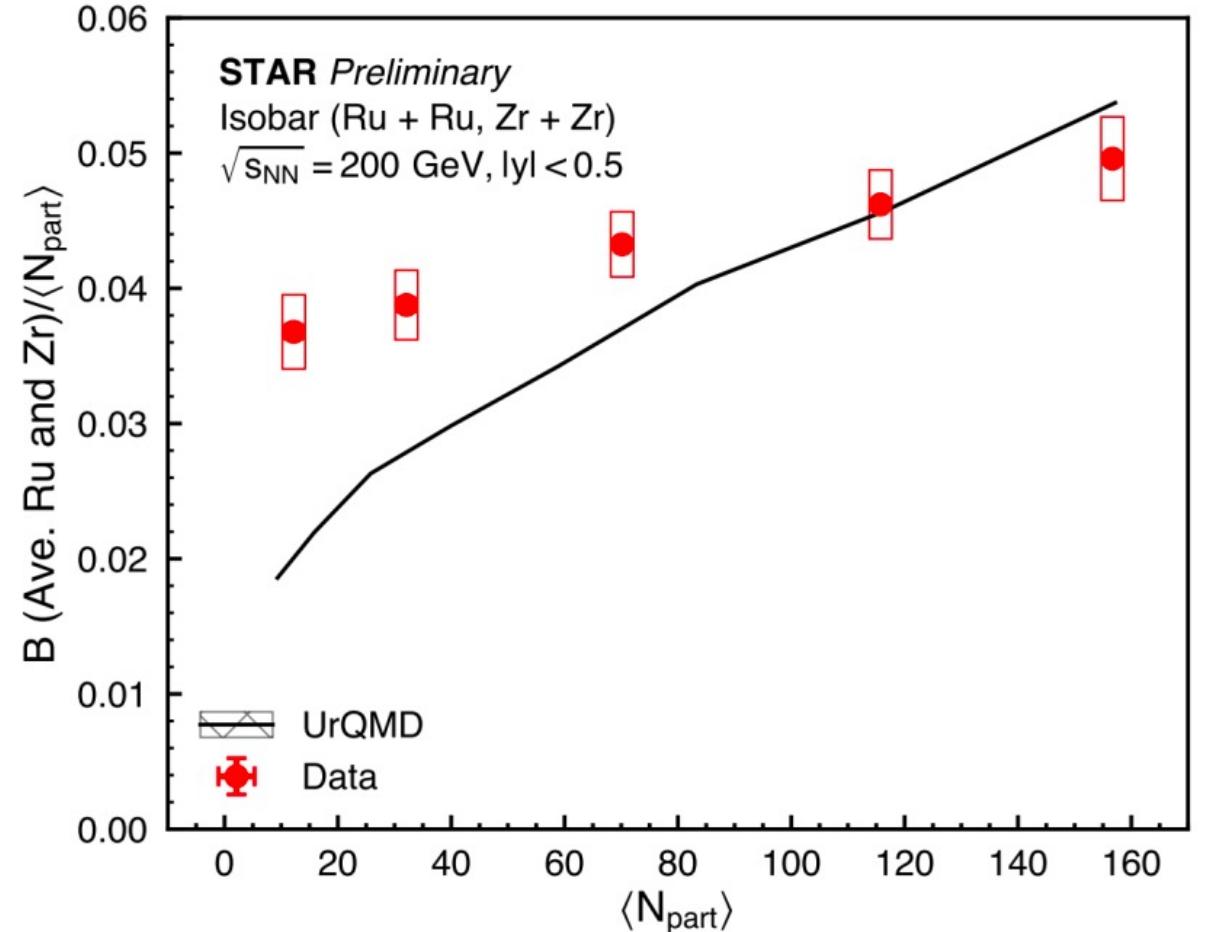
is used. $P(z)$ drops rapidly with increasing z (Fig. 29). Therefore, the longitudinal momenta of e.g. produced antibaryons (Fig. 30) and pions (Fig. 31) are small (they stick to central rapidities), in line with the experimental data. The rapidity spectra of these particles have a characteristic Gaussian-like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

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

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

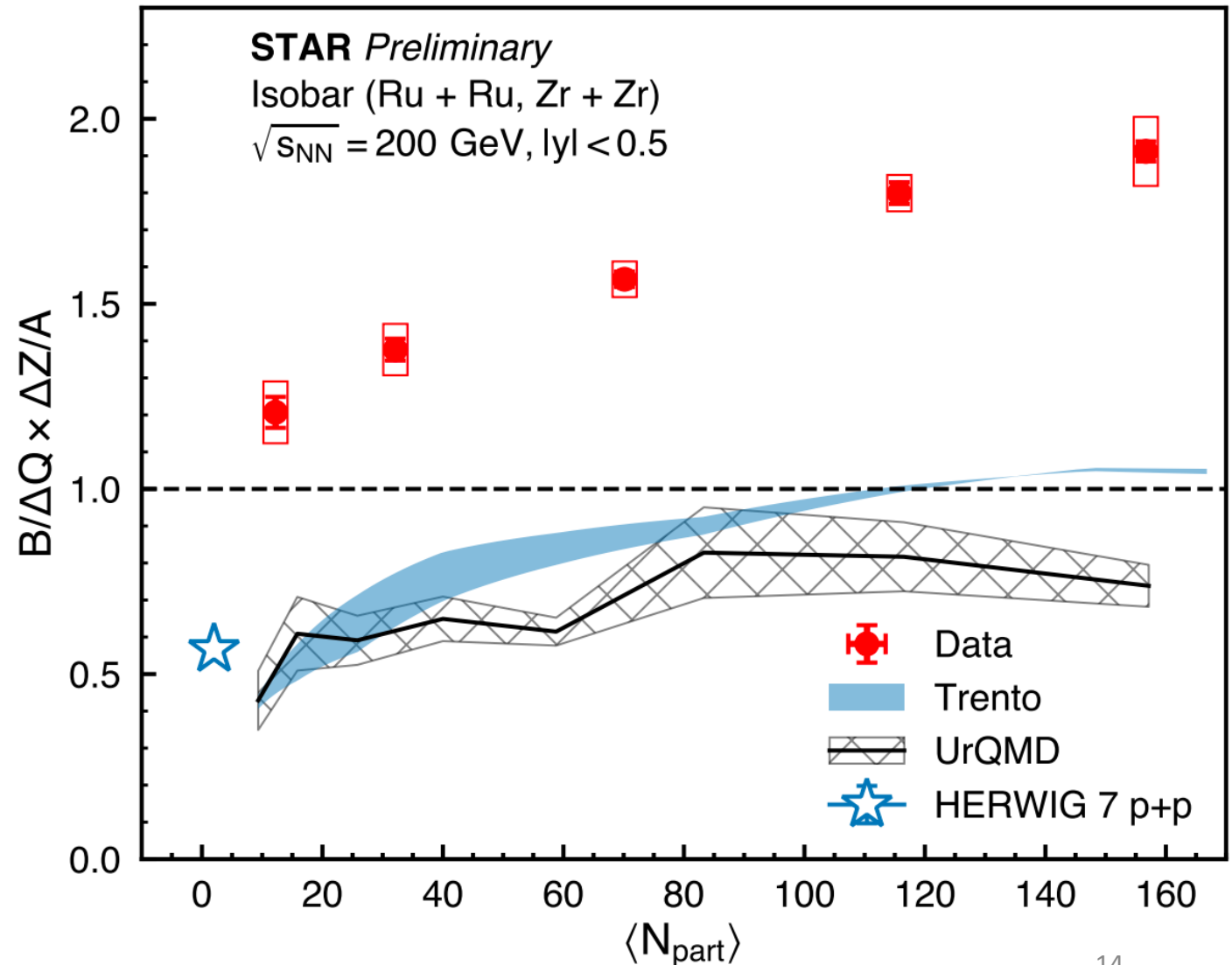
Baryon number transport



Ratio of baryon over charge transports

Tommy Tsang (KSU) for STAR, APS GHP 2023

- **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)



Low-energy baryon rapidity loss

The average close to beam rapidity does not reflect the “tail” at high rapidity

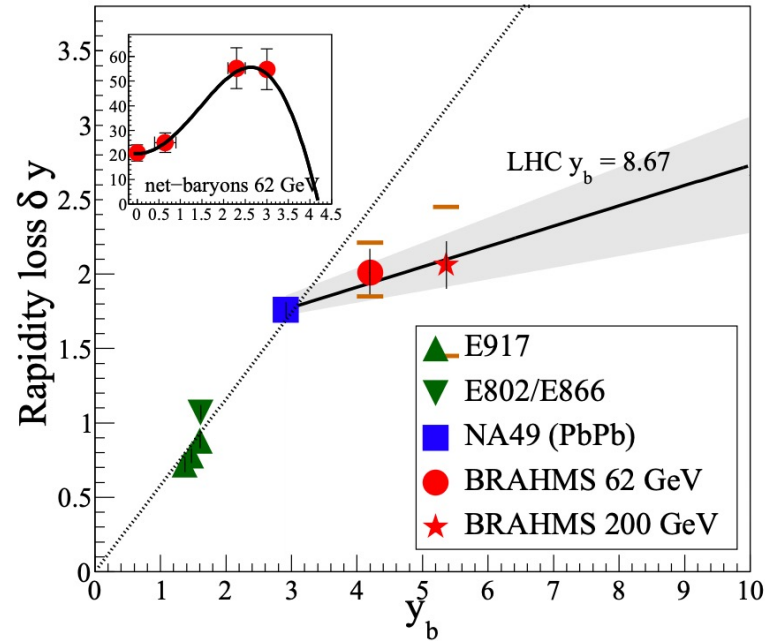


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS 2009

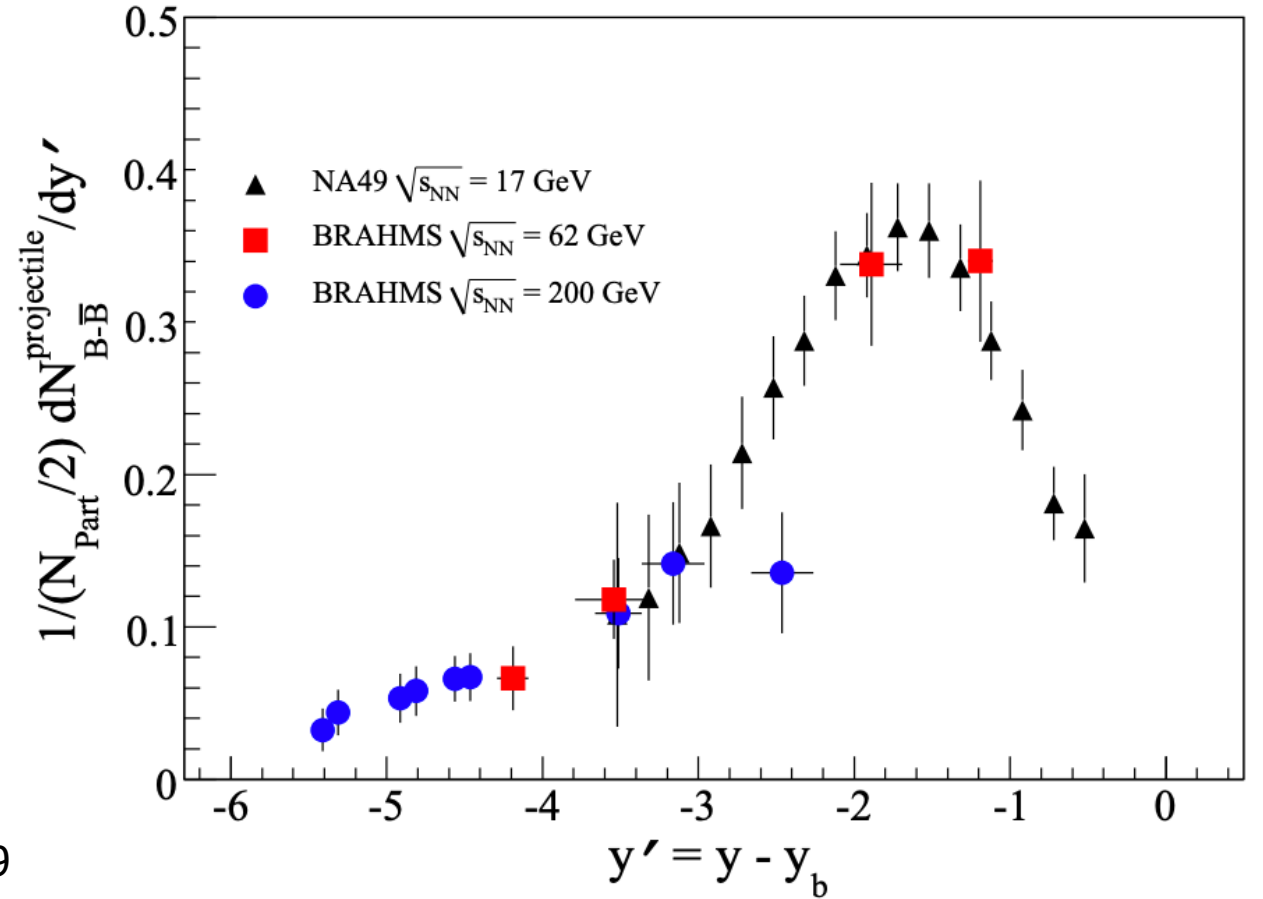


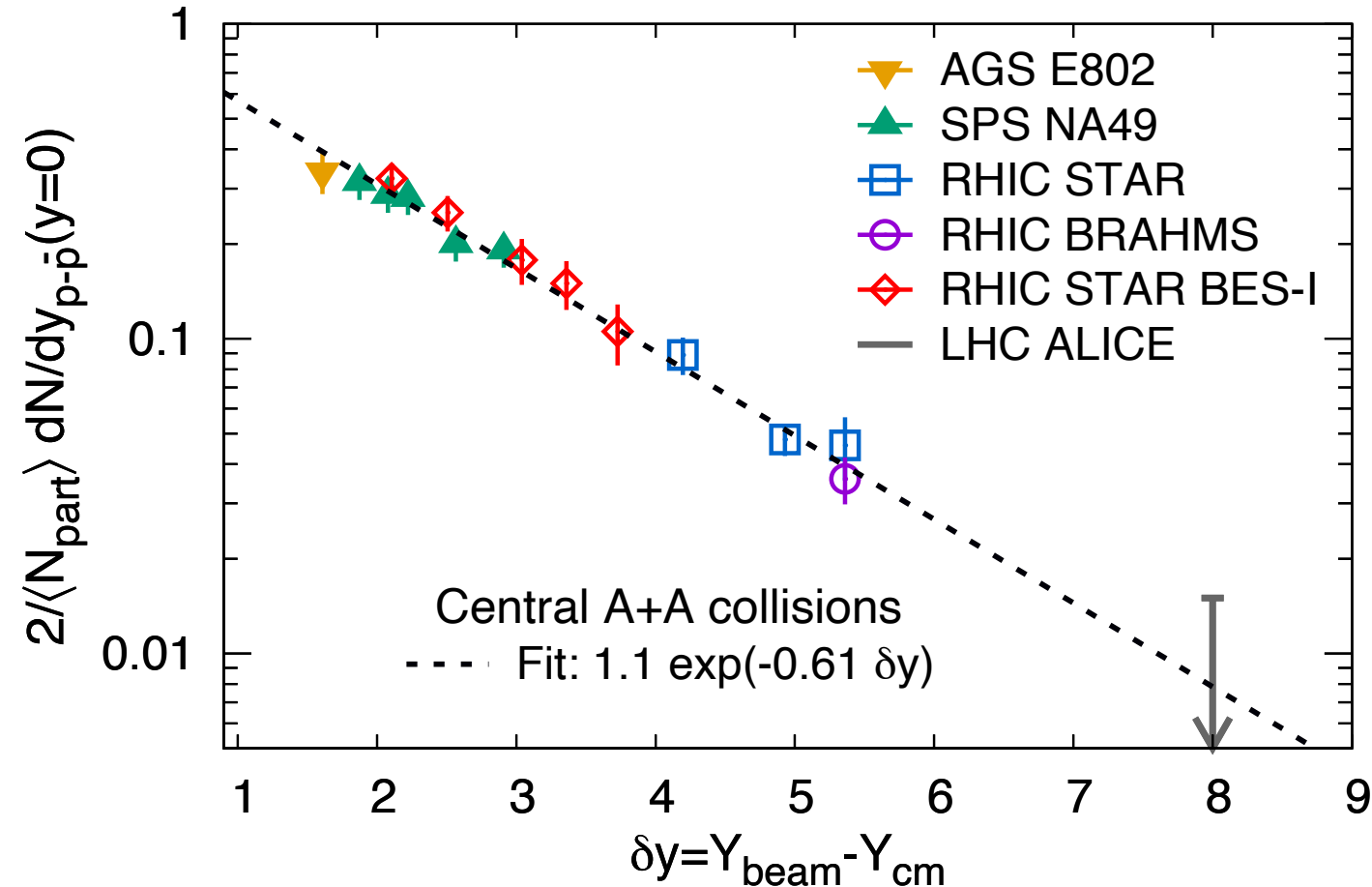
Figure 5: Projectile net-baryon rapidity density $(1/N_{part}/2)dN_{B-\bar{B}}^{projectile}/dy'$ from SPS and RHIC after subtraction of the target net-baryon contribution (see Fig. 4).

Quantifying baryon number transport

- RHIC Beam Energy Scan (BES-I) span large range of rapidity shift
- Exponential with slope of $\alpha_B = 0.61 \pm 0.03$
- Consistent with the baryon junction transport by gluons:
 $\alpha_B \sim 0.5 + \Delta$
 $\Delta \sim 0.1$

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

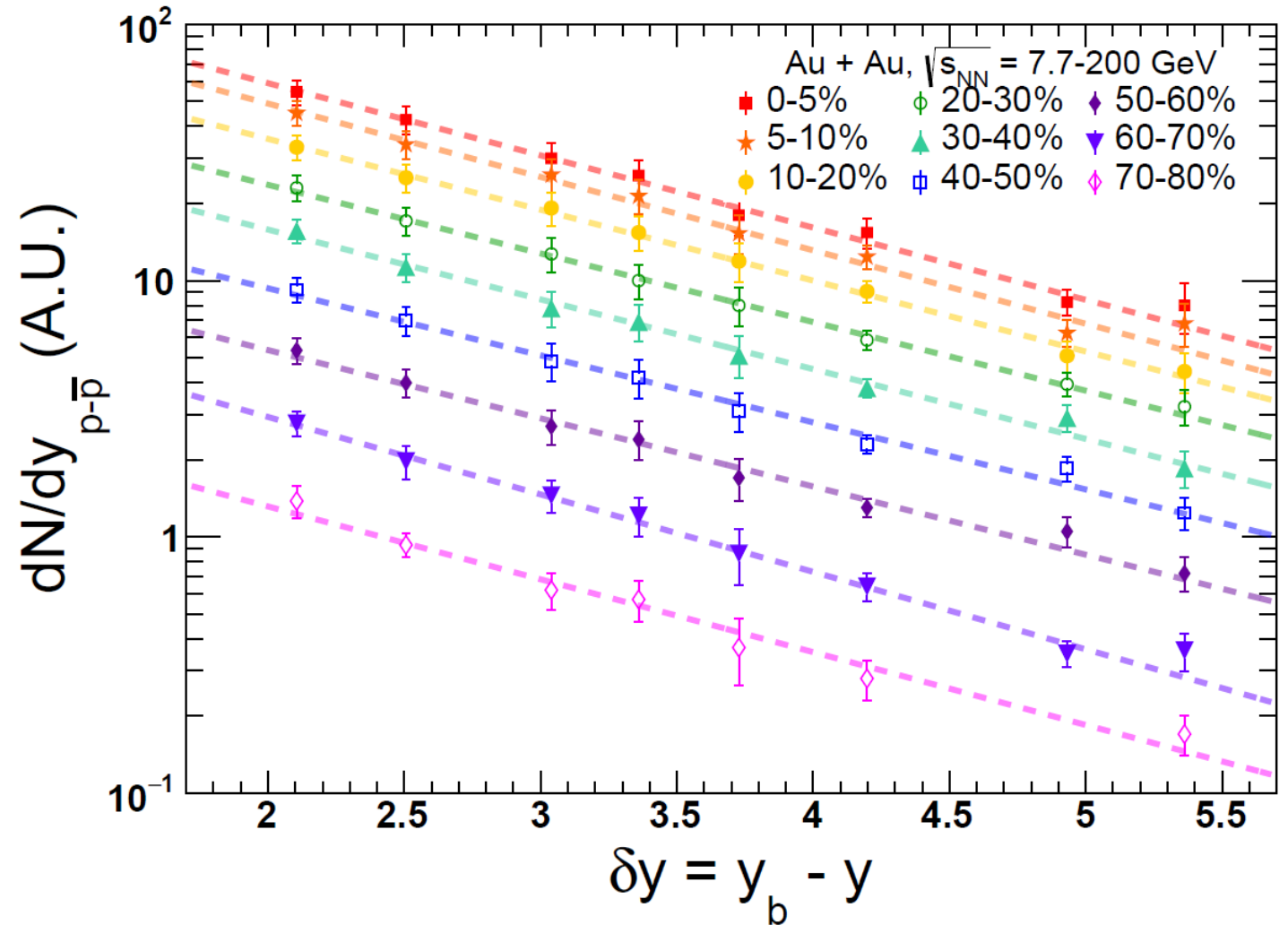
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, [arXiv:2205.05685](https://arxiv.org/abs/2205.05685)



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

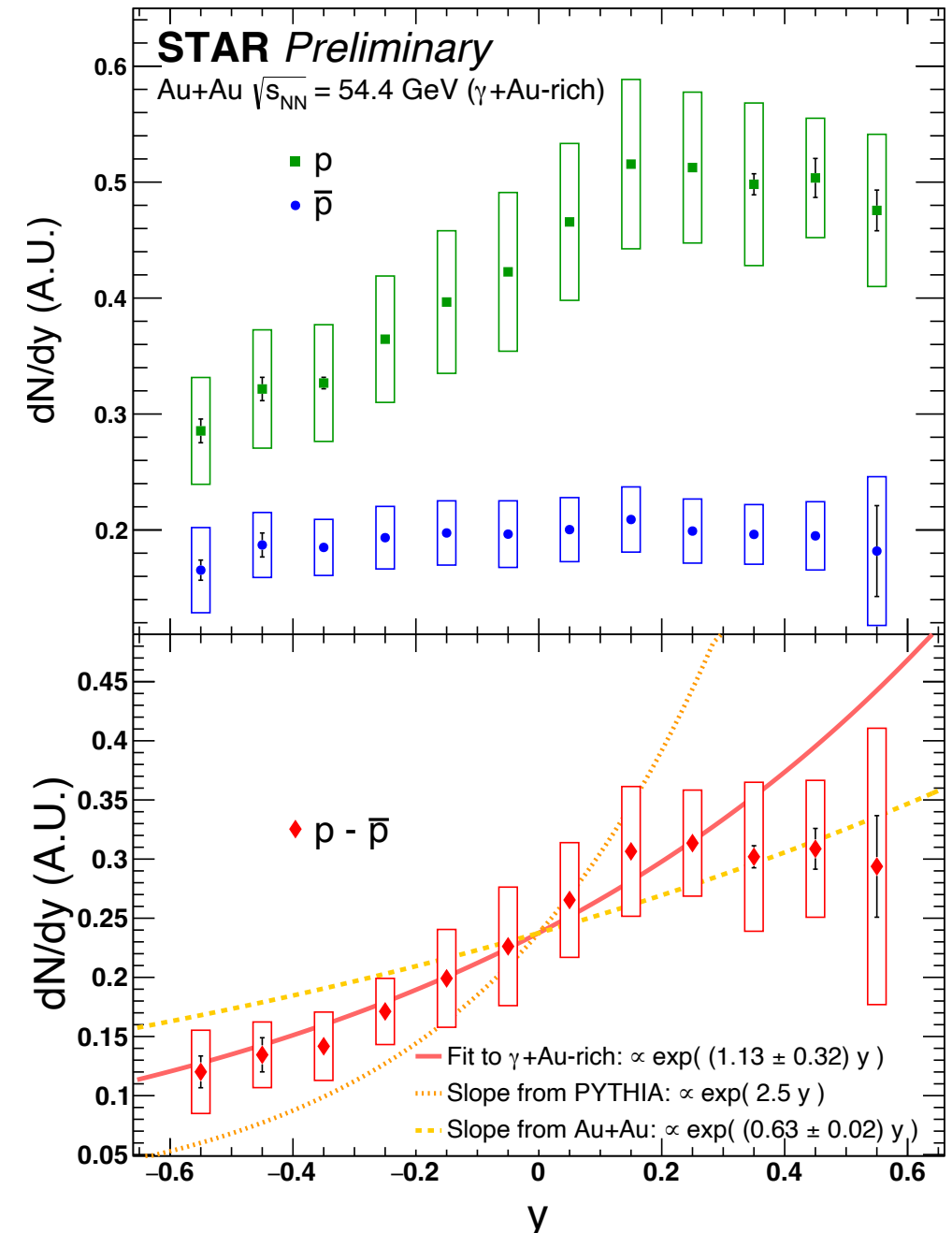
C. Shen and B. Schenke, Phys. Rev. C, 105 (2022), 064905.



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

Nicole Lewis (BNL) for STAR, DIS2023



Three approaches toward tracking the origin of the baryon number

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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

$$\alpha_B=0.61$$

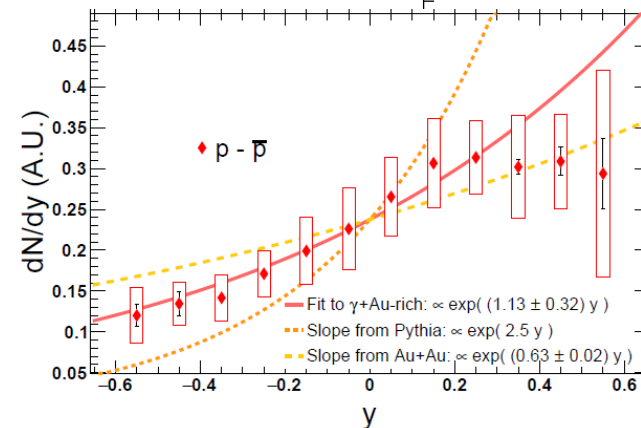
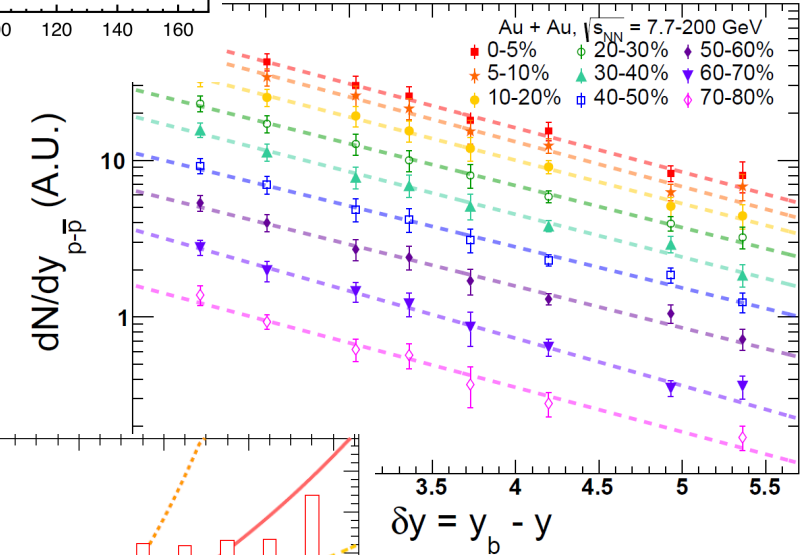
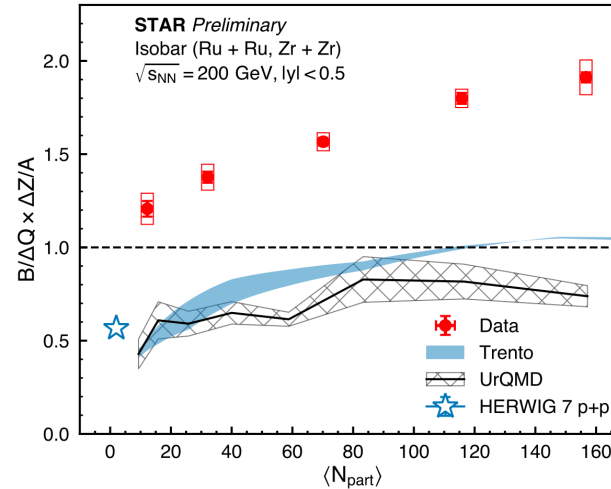
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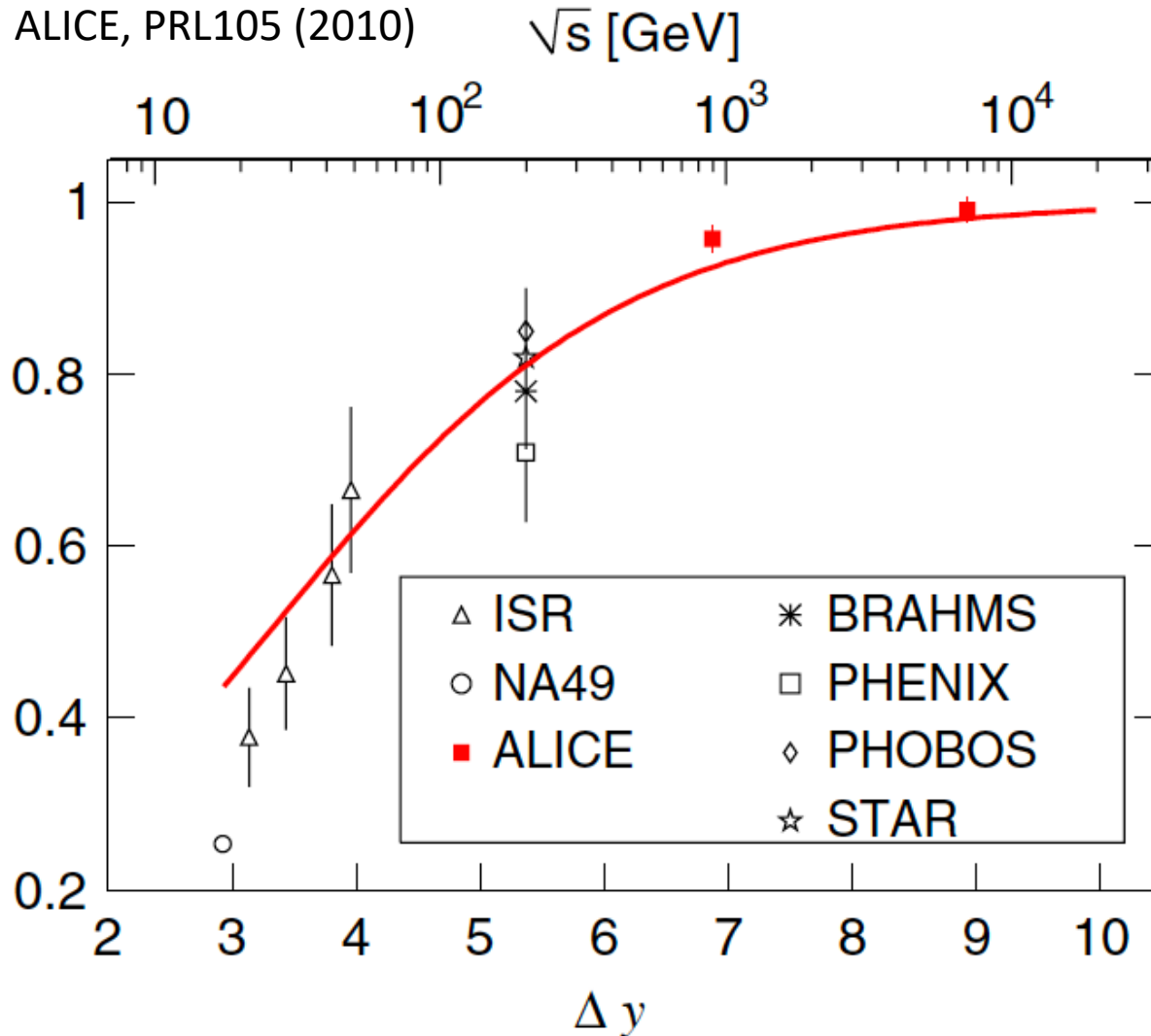
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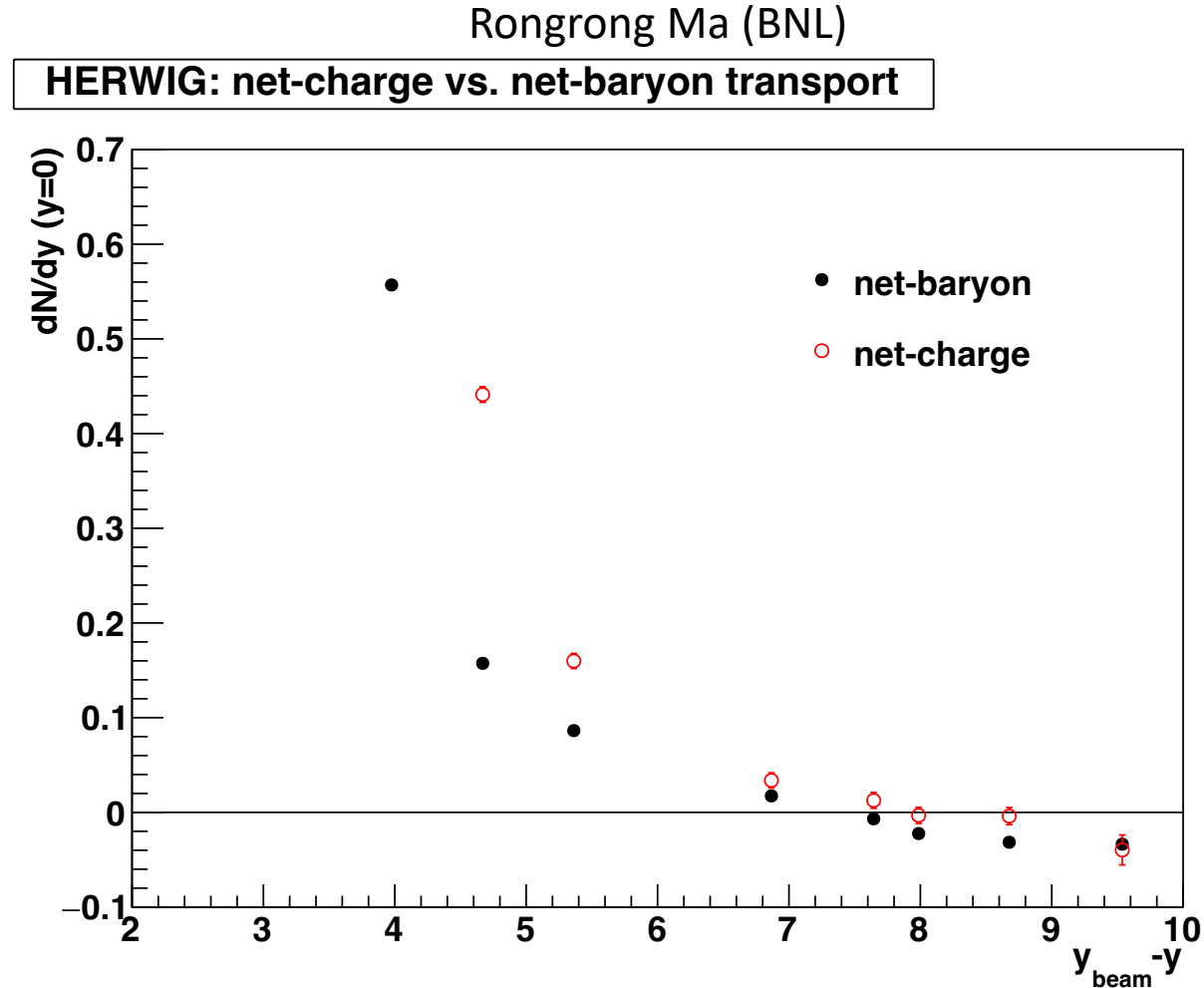
$$\alpha_B(A+A)=0.61 < \alpha_B(\gamma+A)=1.1 < \alpha_B(\text{PYTHIA})$$



What do we know about pp collisions?



red curve consistent with $\alpha_B = 0.6$



HERWIG and PYTHIA: $\alpha_B \sim 1.6-2.5$
Negative ($\bar{p} > p$) at LHC energy

What do we know about e+p collisions?

Artru & Mekhfi, NPA 1991

“unpolarized and polarized electroproduction of fast baryons

- 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

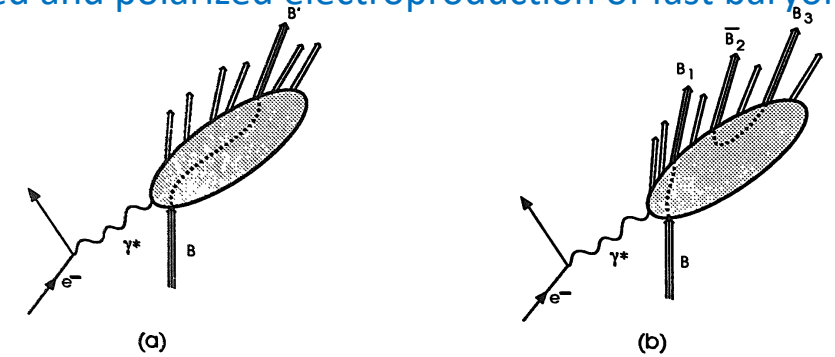


Figure 1. Main mechanisms of electroproduction of fast baryons.

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

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

(Y_G corresponds to Δ_1 in Ref.1). The second one dominates for $Y > Y_G$. 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).

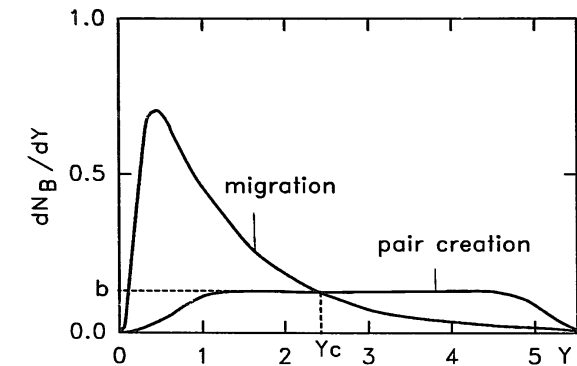


Figure 2. Rapidity spectrum: (a) of the migration mechanism, (b) of the pair creation mechanism.

What do we know about e+p collisions

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Measurement of the Baryon-Antibaryon Asymmetry in Photoproduction at HERA

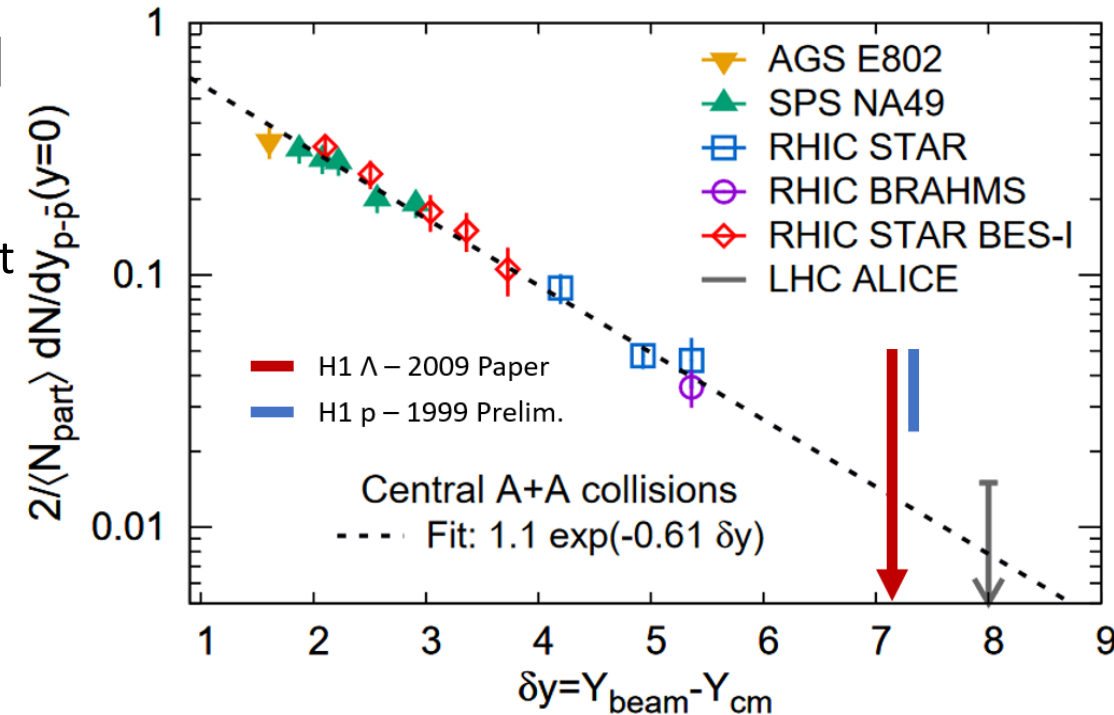
C. Adloff et al. (H1 Collaboration), ICHEP 1998

Baryon stopping at HERA: Evidence for gluonic mechanism

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

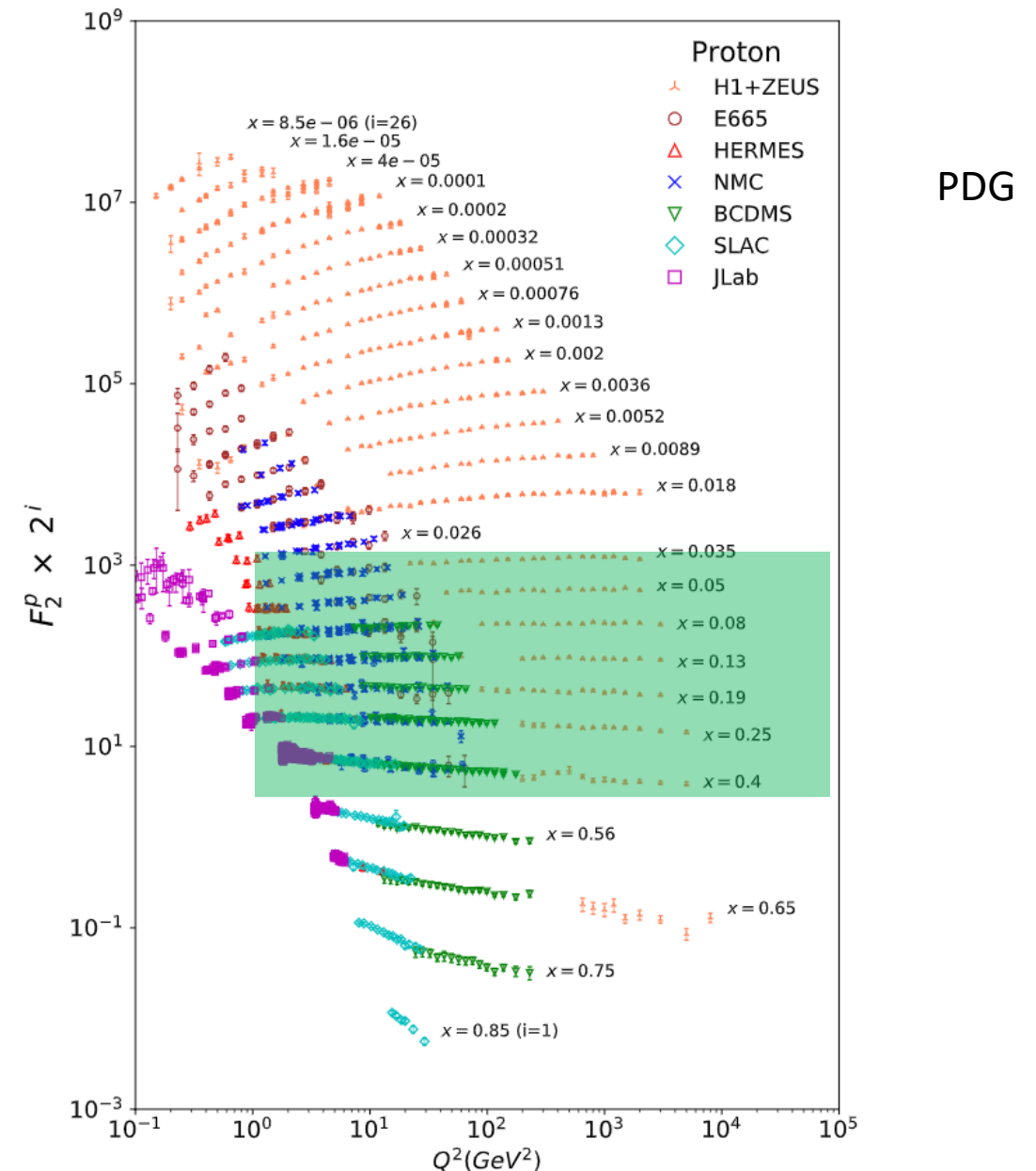
Published in: *Phys.Lett.B* 446 (1999) 321-325 • e-Print: [hep-ph/9810530](#) [hep-ph]

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



Bjorken Scaling for quarks

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



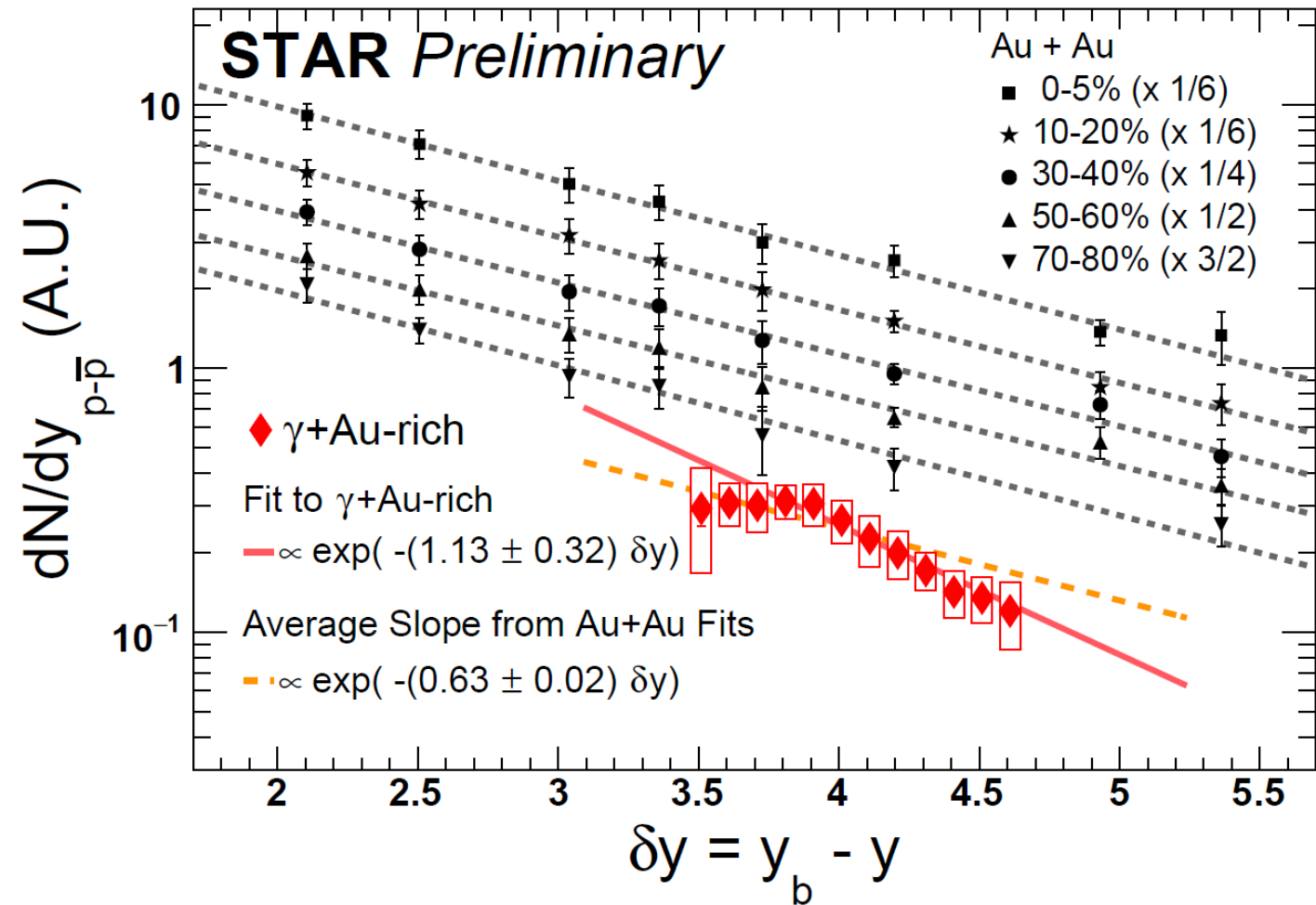
PDG

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

Tracking the origin of baryon number at RHIC

- 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 with a beam-energy scan at RHIC to study the charge and baryon transports

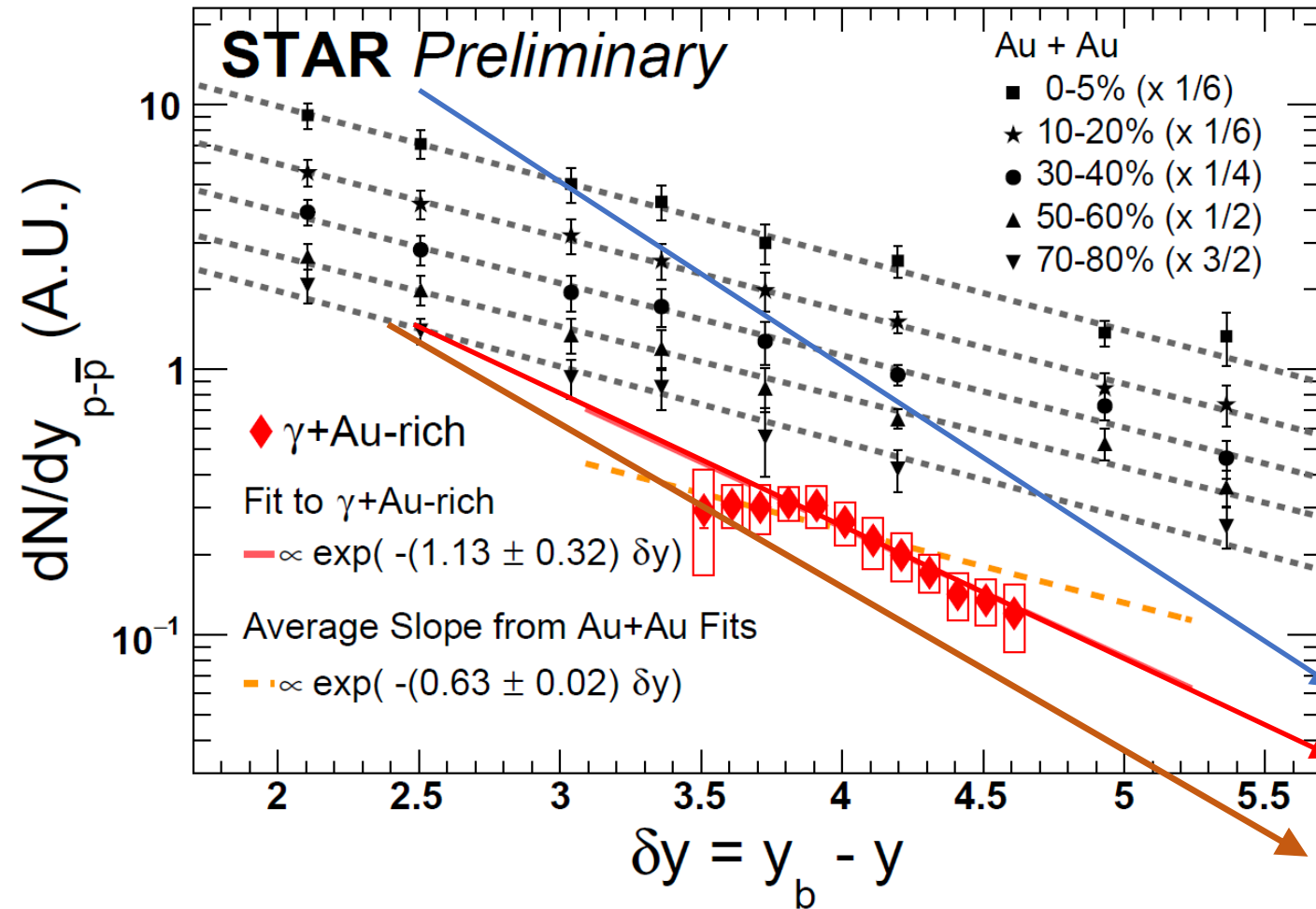
Nicole Lewis (BNL) for STAR, DIS2023



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- 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
- EIC: extend to large range of rapidity shift from 2.5 to 6 at the same time, measure the **charge** (model, RHIC) transport as well as **baryon** transport (BeAGLE $B/Q=0.2$, Niseem)

Nicole Lewis (BNL) for STAR, DIS2023



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

$$Q^2 \leq 1 \text{ GeV}^2$$

$$\pi/k/p \text{ PID } p_t \geq \sim 100 \text{ MeV}$$

- Isobar collisions to measure charge transport (quark transports),
Zr/Ru; Li7/Be7
- EIC can measure the baryon junction distribution function
- Explore other signatures at EIC

the simplest QCD topology
 $B=1$

