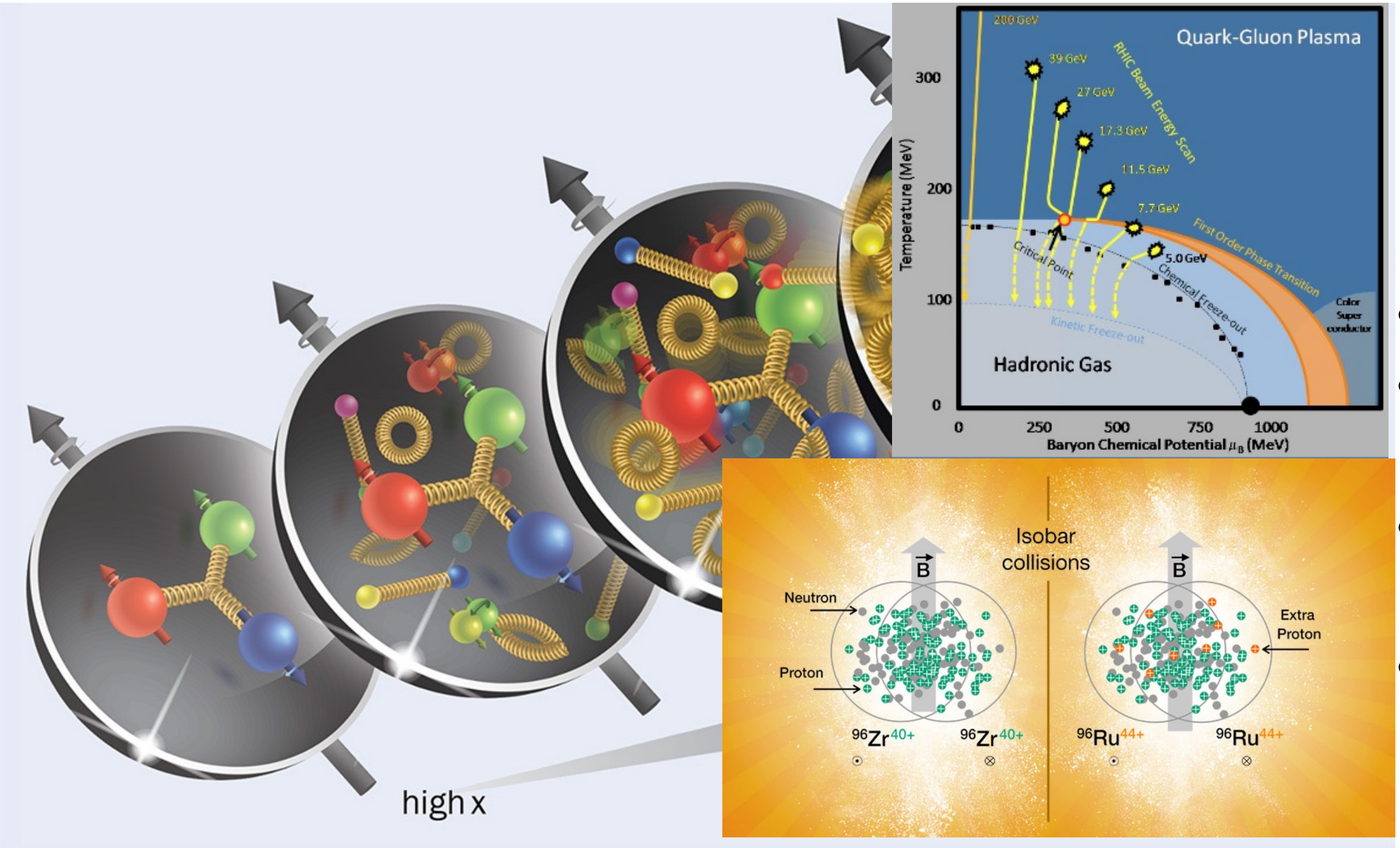
Tracking the baryon number at RHIC and EIC



Zhangbu Xu
(Brookhaven National Lab)

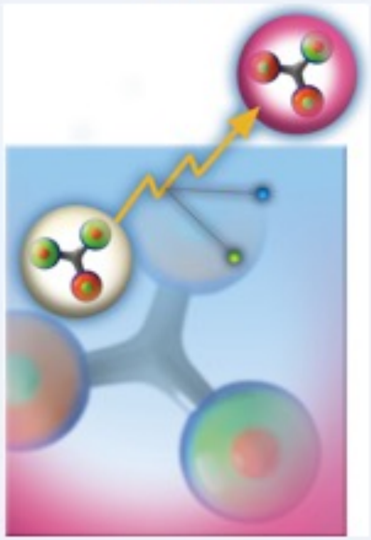
- baryon number carrier
- Three experimental approaches at RHIC (3+1)
- Earlier theory and experiment work on pp and ep
- EIC perspectives and requirements

STAR, 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,X.F. Luo, *et al.*

RHIC-BES Online Seminar 12/05/2023

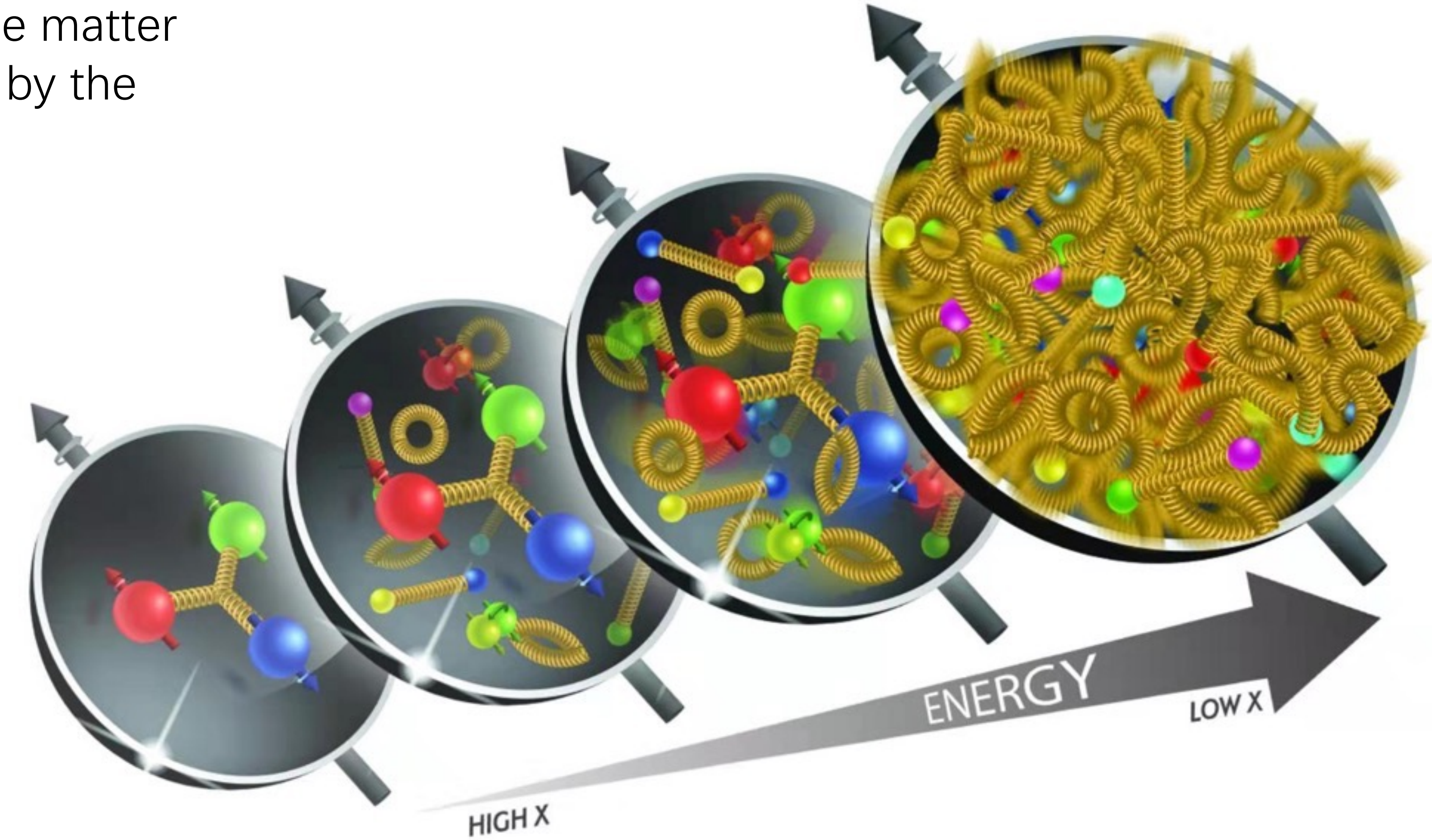
In part supported by
Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY Office of Science

The four fundamental interactions in Nature

Interaction	**Strong Interaction**	**Electromagnetism**	**Weak Interaction**	**Gravitation**
Year Formulated	**1970s**	1860s	1960s	1680s
				
Relative strength at 2 proton distance	**1**	**10^{-2}**	**10^{-6}**	**10^{-38}**
Interaction range (m)	10^{-15}	∞	10^{-18}	∞
Mediator	gluons	photon	Z/W Bosons	graviton

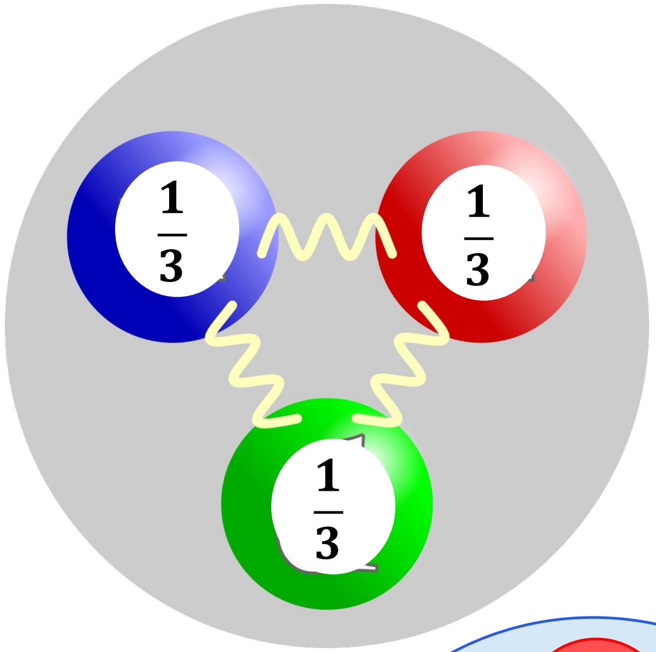
Quantum Chromodynamics (QCD)

In nuclei, 99% of the matter mass is generated by the strong interaction

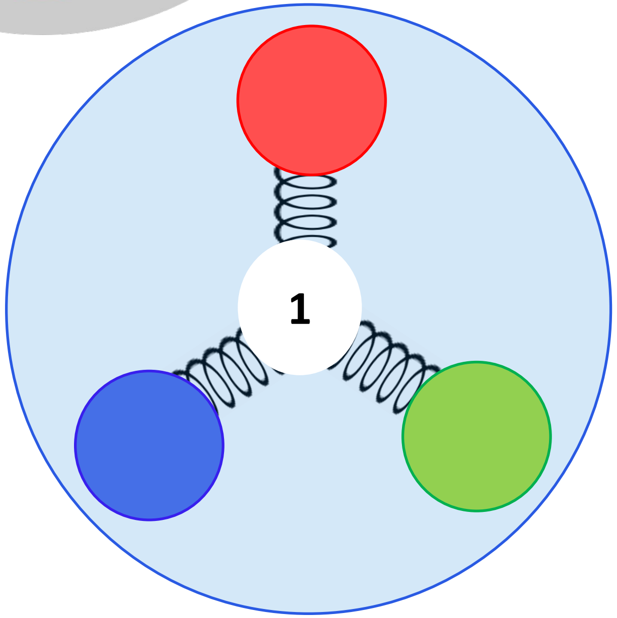


Baryon Number (B) Carrier

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



- 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 always
- Neither of these postulations has been verified experimentally



[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**)

20 June 1996

PHYSICS LETTERS B

Physics Letters B 378 (1996) 238–246

Can gluons trace baryon number?

D. Kharzeev

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Received 15 March 1996
Editor: R. Gatto

Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested experimentally, since it can lead to substantial baryon asymmetry in the central rapidity region of ultra-relativistic nucleus-nucleus collisions.

In QCD, quarks carry colour, flavour, electric charge and isospin. It seems only natural to assume that they also trace baryon number. However, this latter assumption is not dictated by the structure of QCD, and there-

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

which is ignored in most of the naive quark model formulations. This constraint turns out to be very severe; in fact, there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons [1] (note however that there is a large amount of freedom in choosing the paths connecting x to x_i):

$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_j \times \left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_k . \quad (1)$$

of gauge invariant operators representing a baryon in QCD. With properly optimised parameters it is used extensively in the first principle computations ... lattice Monte Carlo attempting to determine the nucleon mass. The purpose of this work is to study ... phenomenological impact on baryon number production in the central region of nucleus-nucleus collisions.

It is evident from the structure of (1) that the trace of baryon number should be associated not with the valence quarks, but with a non-perturbative configuration of gluon fields located at the point x – the "string junction" [1]. This can be nicely illustrated in the string picture: let us pull all of the quarks aw...

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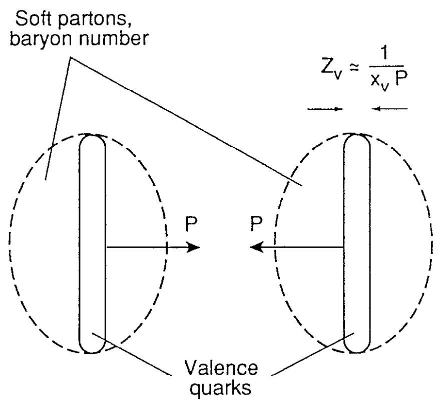


Fig. 2.

of the produced baryons will in general differ from the composition of colliding protons.

Why then is the leading baryon effect a gross feature of high-energy pp collisions? The reason may be the following. The string junction, connected to all three of the valence quarks, is confined inside the baryon, whereas pp collisions become on the average more and more peripheral at high energies. Therefore, in a typical high-energy collision, the string junctions of the colliding baryons pass far away from each other in the impact parameter plane and do not interact. One can however select only central events, triggering on high multiplicity of the produced hadrons. In this case, we expect that the string junctions will interact and may be stopped in the central rapidity region. This ... central rapidity region: even at very high energies, there should be more baryons than antibaryons there. ... the experimental study of baryon and an... associated hadron multiplicity has been already performed at ISR, at the ... collisions [3]. This study has revealed that in the central rapidity region, the multiplicities associated with a proton are higher ... that the number of baryons in the central rapidity re... number of antibaryons

[4]. These two observations combined indicate the existence of an appreciable baryon stopping in central pp collisions even at very high energies [3].

Where else do we encounter central baryon-baryon collisions? In a high energy nucleus-nucleus collision, the baryons in each of the colliding nuclei are densely packed in the impact parameter plane, with an average inter-baryon distance

$$r \simeq (\rho\, r_0)^{-1/2} A^{-1/6}, \quad (4)$$

where ρ is the nuclear density, $r_0 \simeq 1.1$ fm, and A is the atomic number. The impact parameter b in an individual baryon-baryon interaction in the nucleus-nucleus collision is therefore effectively cut off by the packing parameter: $b \le r$. In the case of a lead nucleus, for example, r appears to be very small: $r \simeq 0.4\ fm$, and a central lead-lead collision should therefore be accompanied by a large number of interactions among the string junctions. This may lead to substantial baryon stopping even at RHIC and LHC energies.

We shall now proceed to more quantitative considerations. In the topological expansion scheme [1], the separation of the baryon number flow from the flow of valence quarks in baryon-(anti)baryon interaction can be represented through a t-channel exchange of the quarkless junction-antijunction state with the wave function given by

$$M_0^J = \epsilon_{ijk}\epsilon^{i'j'k'}\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{i'}^{i} \times \left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{j'}^{j} \times \left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]_{k'}^{k}. \quad (5)$$

The structure of the wave function (5) is illustrated in Fig. 1b – it is a quarkless closed string configuration composed from a junction and an antijunction. In the topological expansion scheme, the states (5) lie on a Regge trajectory; its intercept can be related to the baryon and reggeon intercepts [1]:

$$\alpha_0^J(0) \simeq 2\alpha_B(0) - 1 + 3(1 - \alpha_R(0)) \simeq \frac{1}{2}, \quad (6)$$

Baryon Conservation in QCD

$U_V(1)$ global symmetry
of QCD Lagrangian results
in conserved baryon current

$$J^\mu_B(x) = \sum \bar\psi(x) B \gamma^\mu \psi(x)$$

Dima Kharzeev (SBU) at STAR Collaboration meeting, 10/17/2023

Baryon number in the Standard Model

$$B = \text{diag}\left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$$

The baryon number associated with a single quark

The baryon current in QCD is conserved:

$$\partial_\mu J^\mu_B = 0.$$

This conservation law is not spoiled by QCD instantons. Non-conservation of BN is possible however due to electroweak instantons that couple only to left-handed components of fermion fields and thus change the fermion number.

It is local and color-neutral

$$J^\mu_B(x) = \sum \bar\psi(x) B \gamma^\mu \psi(x)$$

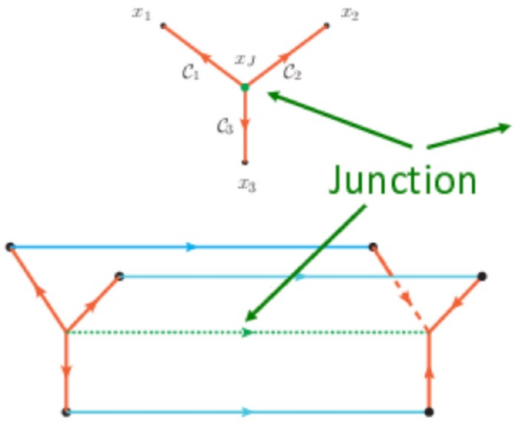
and thus invariant under non-Abelian gauge transformations

$$\psi(x) \to \exp\left(i\alpha^i(x)t^i\right)\ \psi(x)$$

So, where are the junctions?

Gauge invariance and baryon junction

For baryons, these factors have to be combined in a junction:



$$\text{Baryon} \to B(x_1,x_2,x_3) = \frac{\varepsilon^{i_1 i_2 i_3}}{\sqrt{3!}} q_{k_1}(x_1) C(x_1,x_J)^{k_1}_{i_1} q_{k_2}(x_2) C(x_2,x_J)^{k_2}_{i_2} q_{k_3}(x_3) C(x_3,x_J)^{k_3}_{i_3}$$

$$\text{Propagator} \to \langle B(x_1,x_2,x_3) B^+(y_1,y_2,y_3) \rangle$$

G. Rossi, G.Veneziano

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

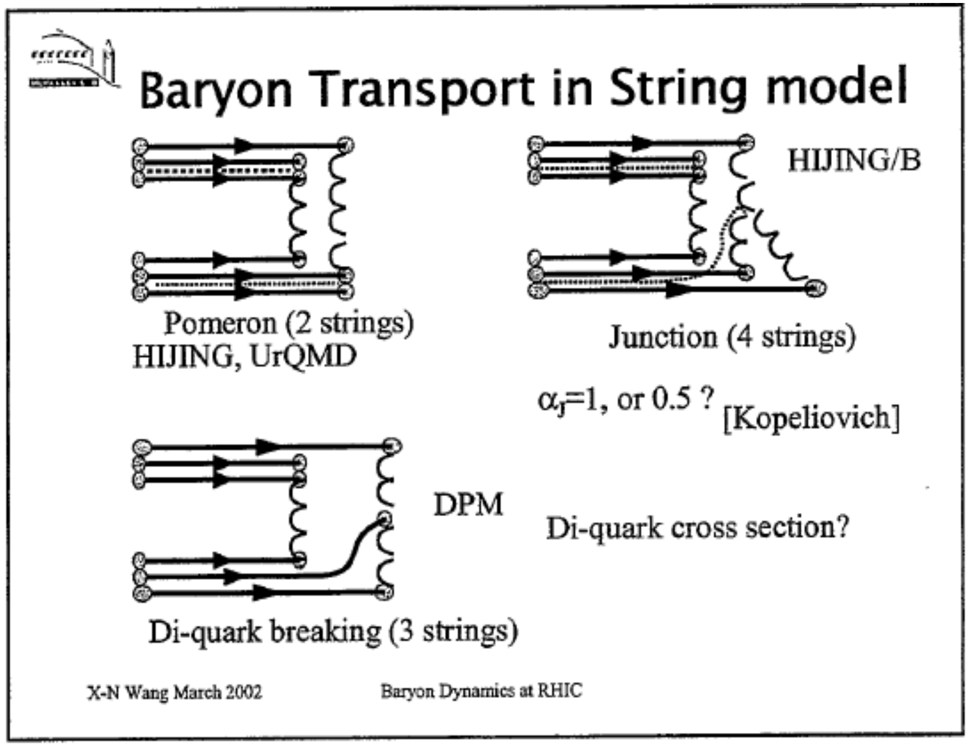
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- Specific rapidity dependence is predicted:

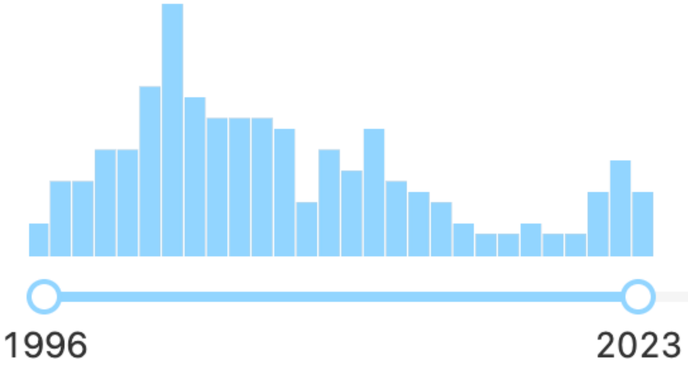
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

2003 RBRC Workshop on "Baryon Dynamics at RHIC"
Organized by D. Kharzeev, M. Gyulassy, N. Xu



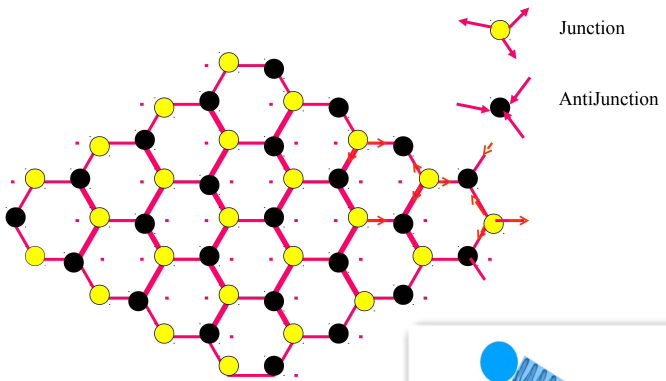
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)
"Can gluons trace baryon number?"

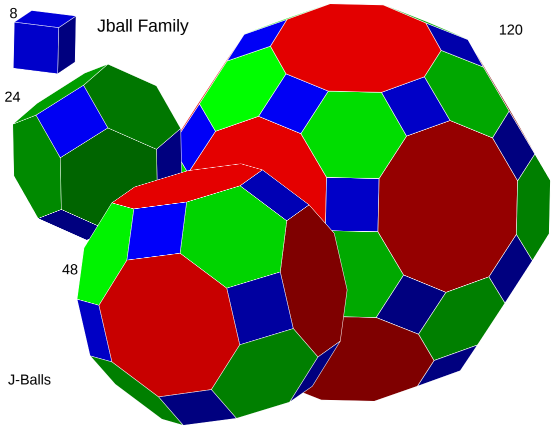


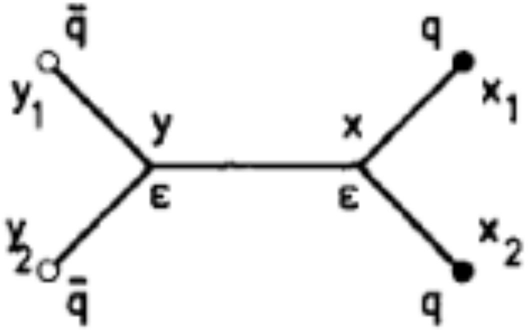
"Science, however, is never conducted as a popularity contest..." --- Michio Kaku

BUT citations ARE

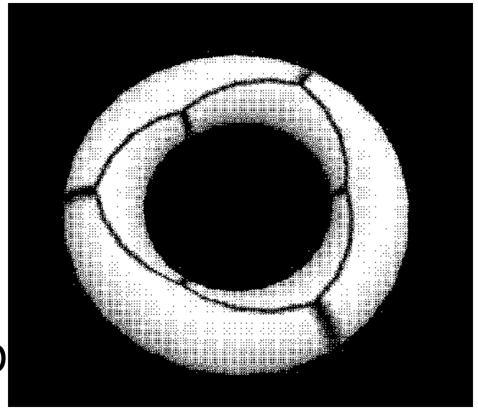
Junction anti Junction Gluon “Graphite”



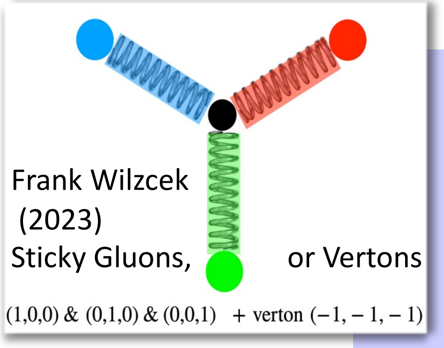




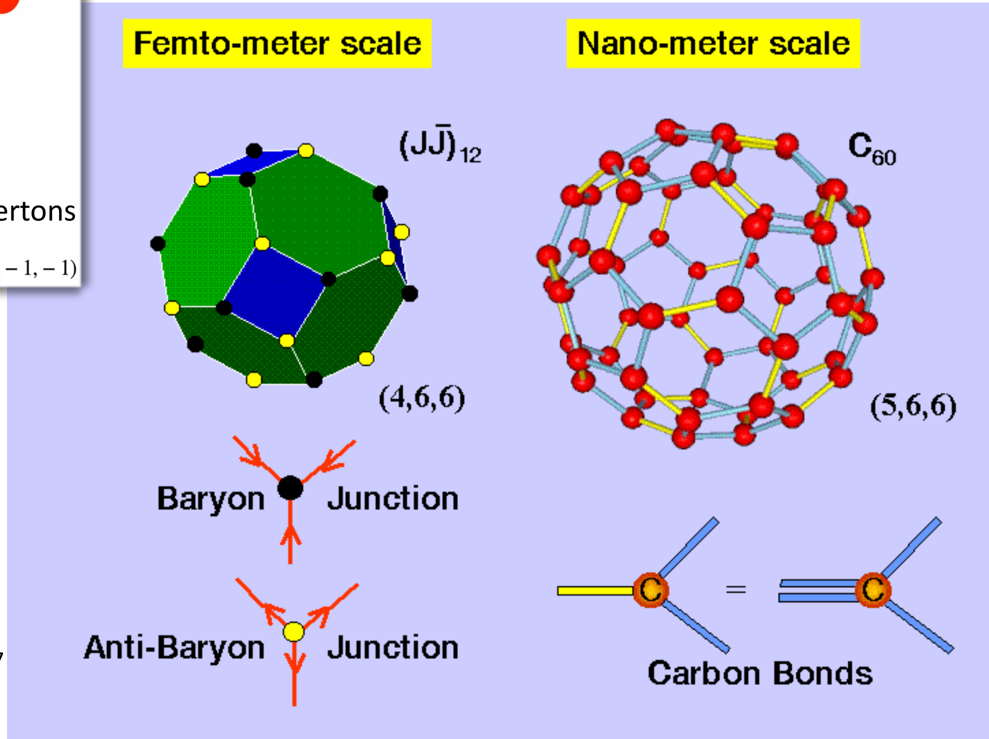
Veneziano, 50 years of QCD
arXiv:1603.05830

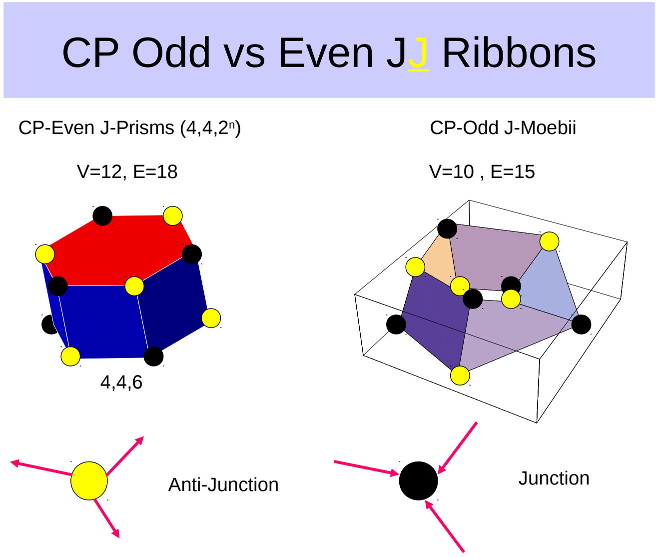


Baryonium Torus, O.I. Piskounova
hep-ph/1909.08536



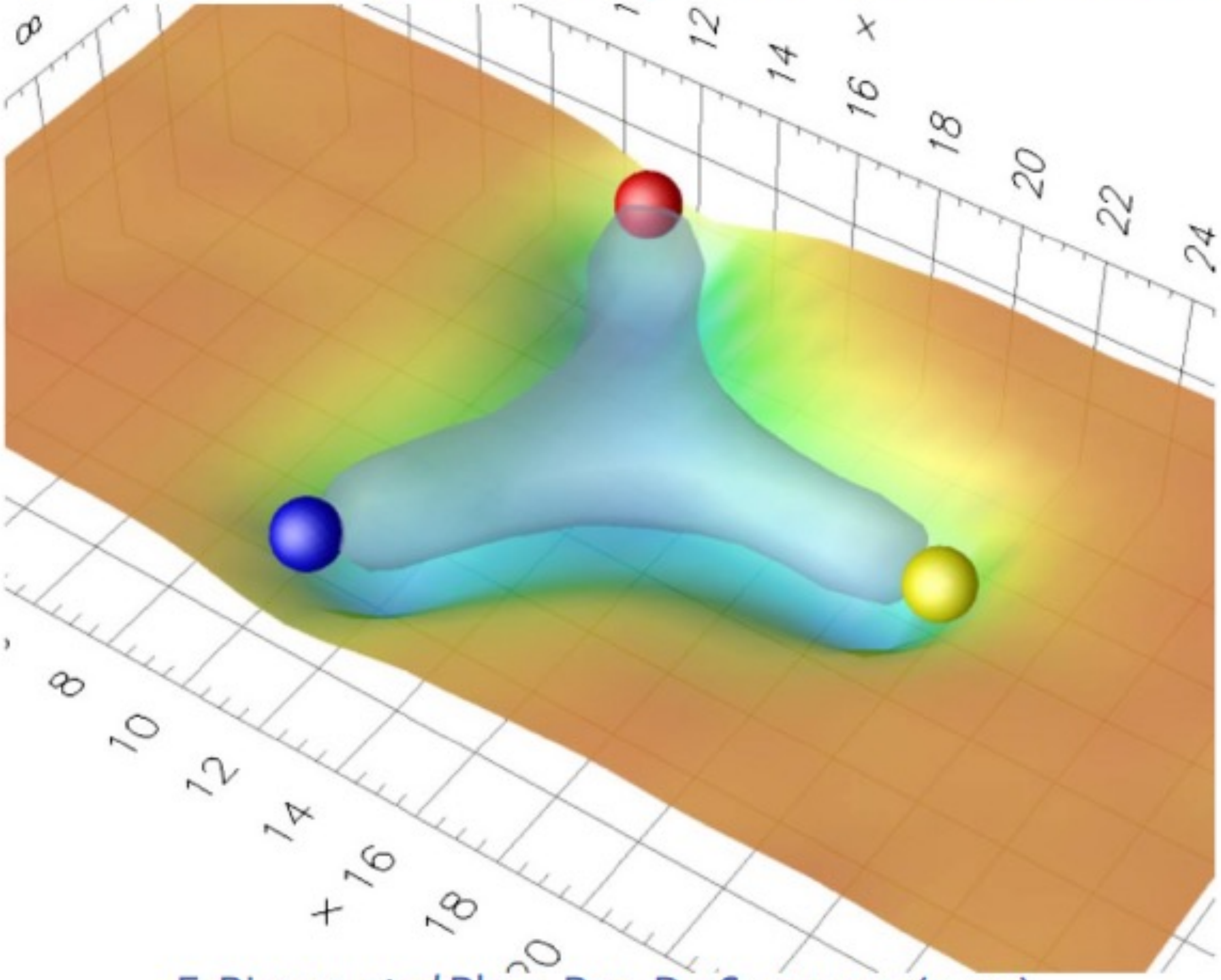
Buckyballs and gluon junction networks on the femtometre scale





D. Kharzeev, PLB 378 (96)
S. Vance, M. Gyulassy, XN Wang, PLB 443 (98)
T. Csorgo, M. Gyulassy, D. Kharzeev, JPG 30 (2004) L17

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)

  Takahashi, RBRC workshop 2003
- Still under investigation

Finite Temperature LQCD?

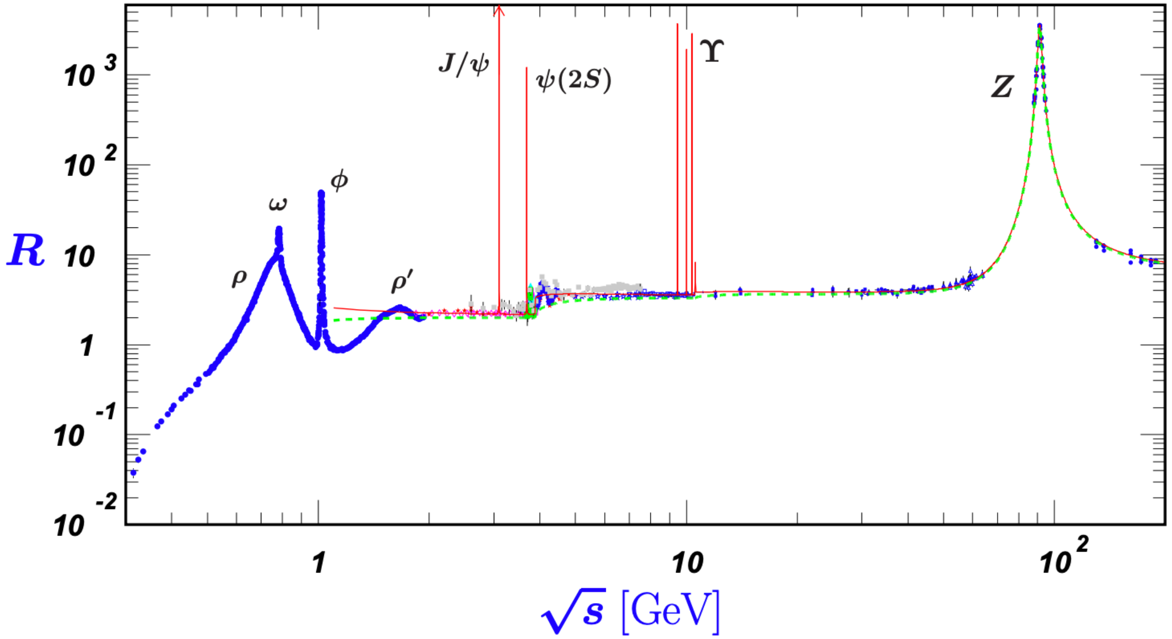
Measurements of quark electric charges

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

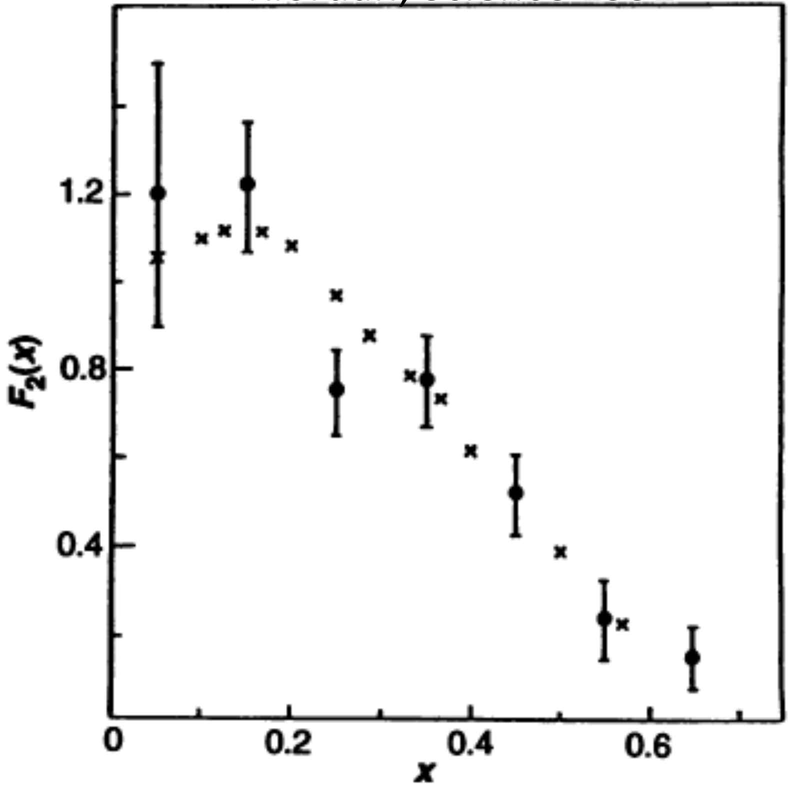
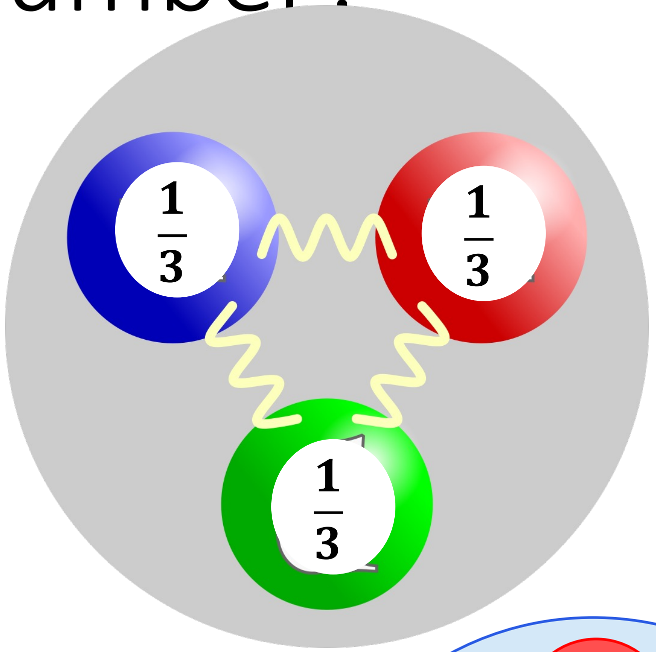


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, $(18/5)F_2^{eN}$]. When multiplied by 18/5, a number specified by the quark-parton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

Measurements of quark baryon number?



- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
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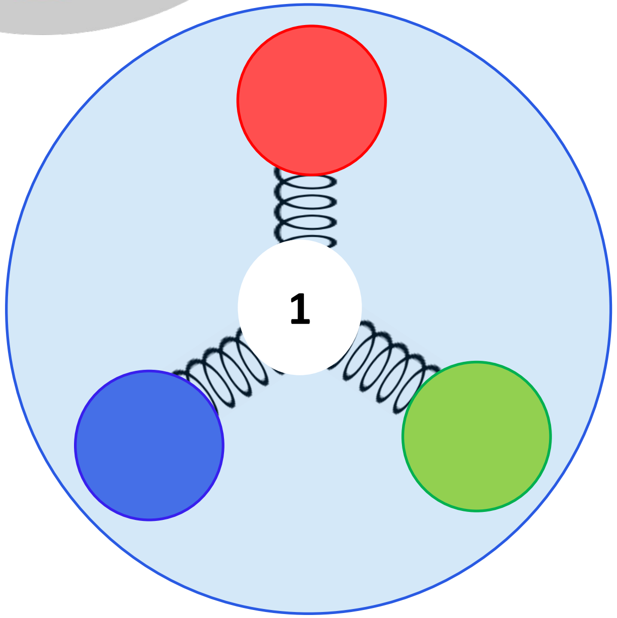
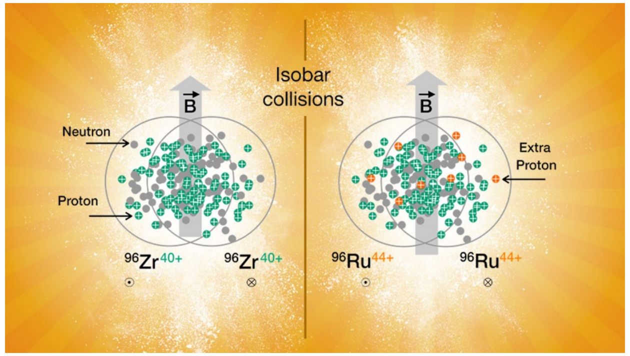


[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).

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

Three approaches toward tracking the origin of the baryon number

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



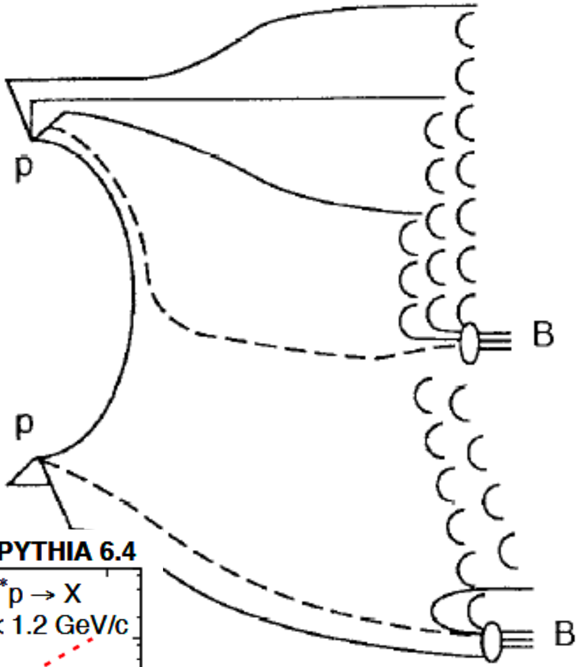
1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity

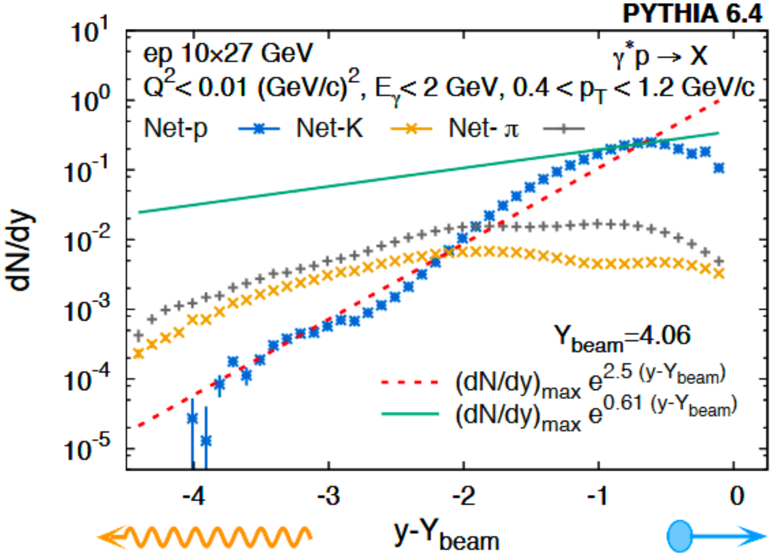
2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

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

α_B ~=0.5

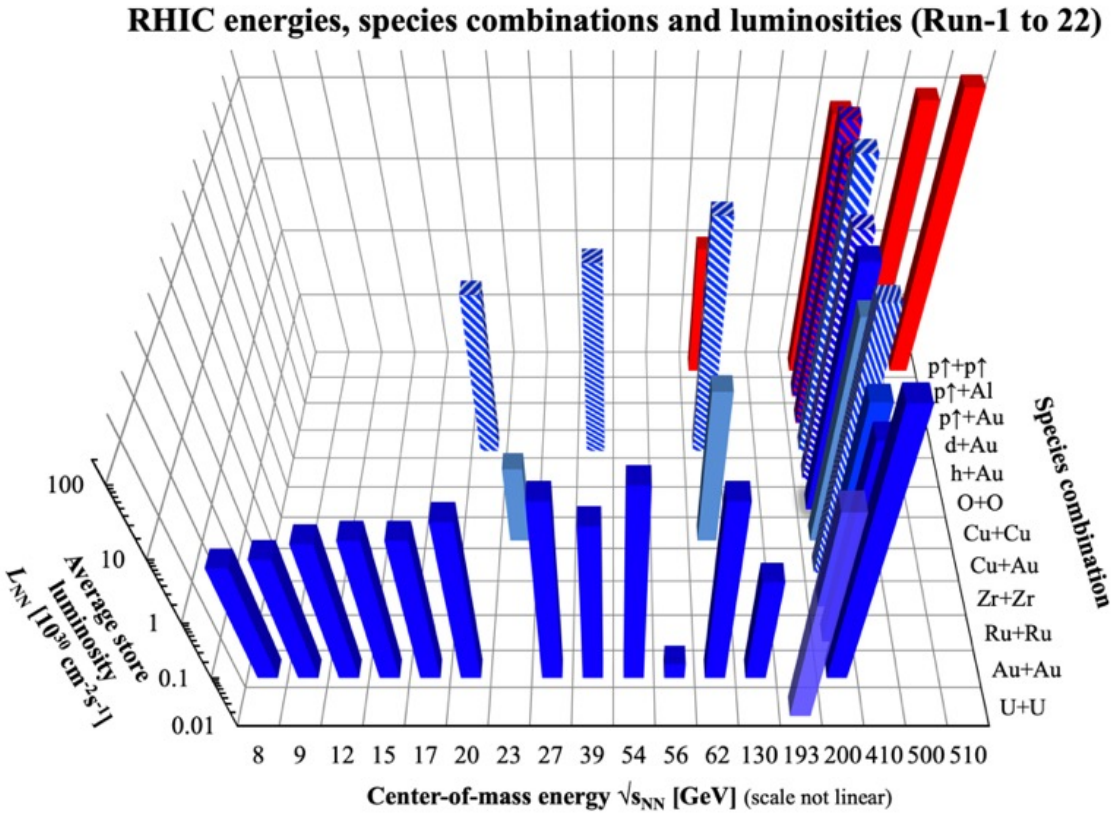
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin





Example of versatile colliders and detectors

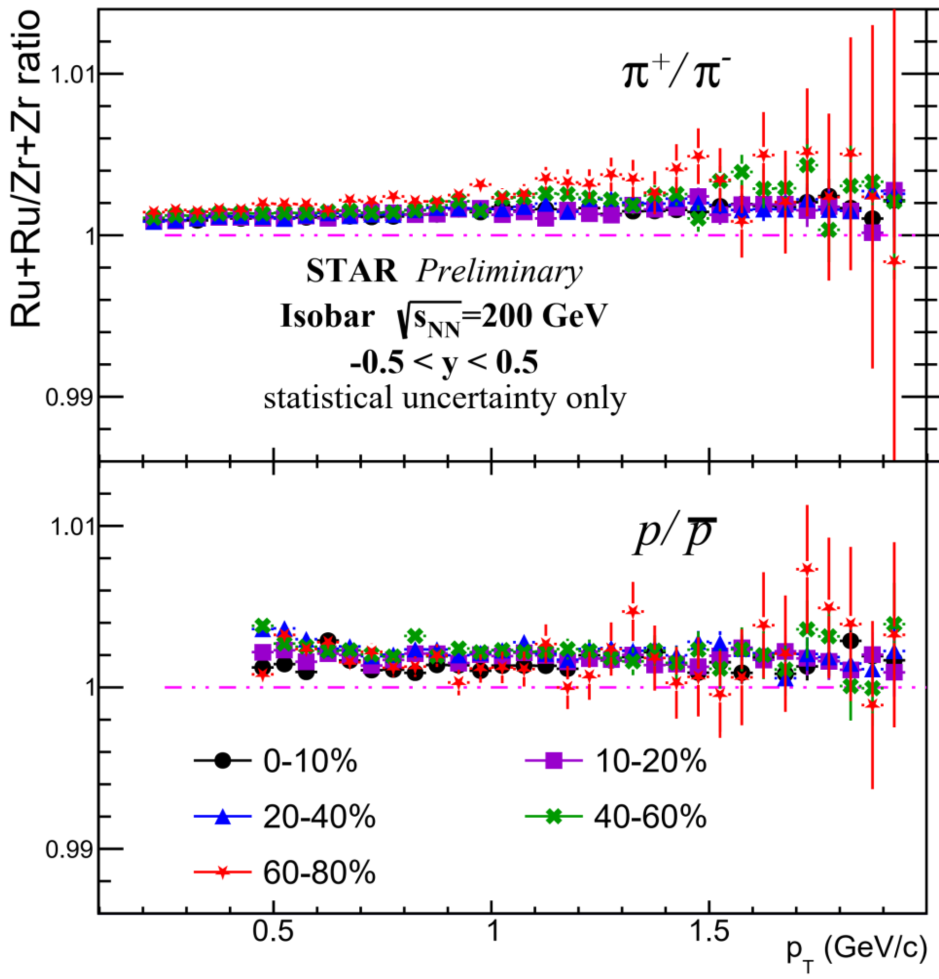
major upgrades over the last twenty years to improve particle identification and vertex reconstruction and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.

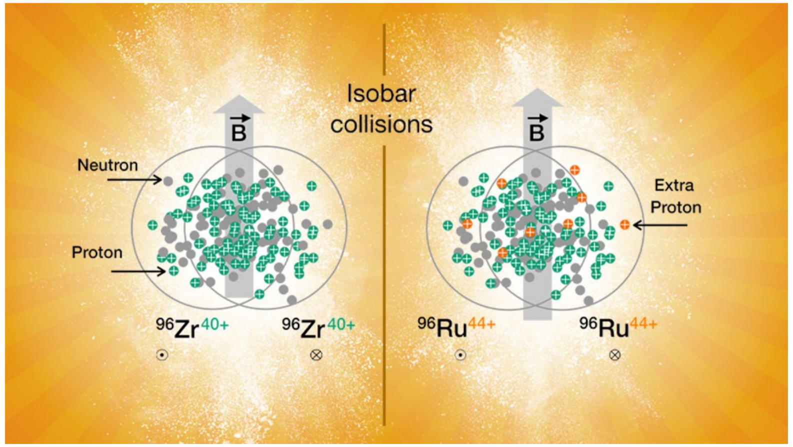


Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\| <1$ Tracking		1999-
Barrel EMC	$\|\eta\| <1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1< \eta <2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5< \eta <4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1< \eta <2$ $W^{\pm}$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta >5$ π^0	(Japan)	2017
iTPC	$\|\eta\| <1.5$ Tracking	(China)	2019-
eTOF	$-2< \eta <-1$ PID	(Germany/China)	2019-
FCS	$2.5< \eta <4$ calorimeter	(NSF)	2021-
FTS	$2.5< \eta <4$ Tracking	(NCKU/SDU)	2021-

8 new detectors added to STAR since 2014

Double ratios between Ru+Ru and Zr+Zr collisions



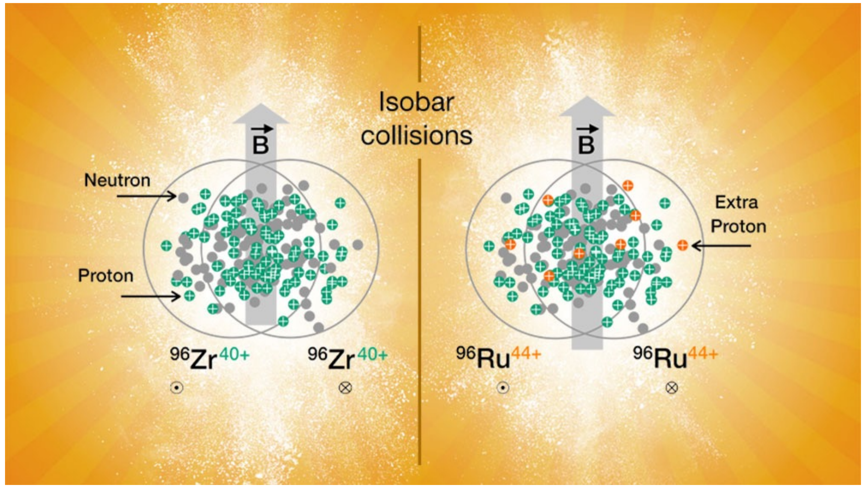


From baryon stopping: B*(ΔZ/A)~=2x10^{-3}

Charge stopping: ΔQ ~=1x10^{-3}

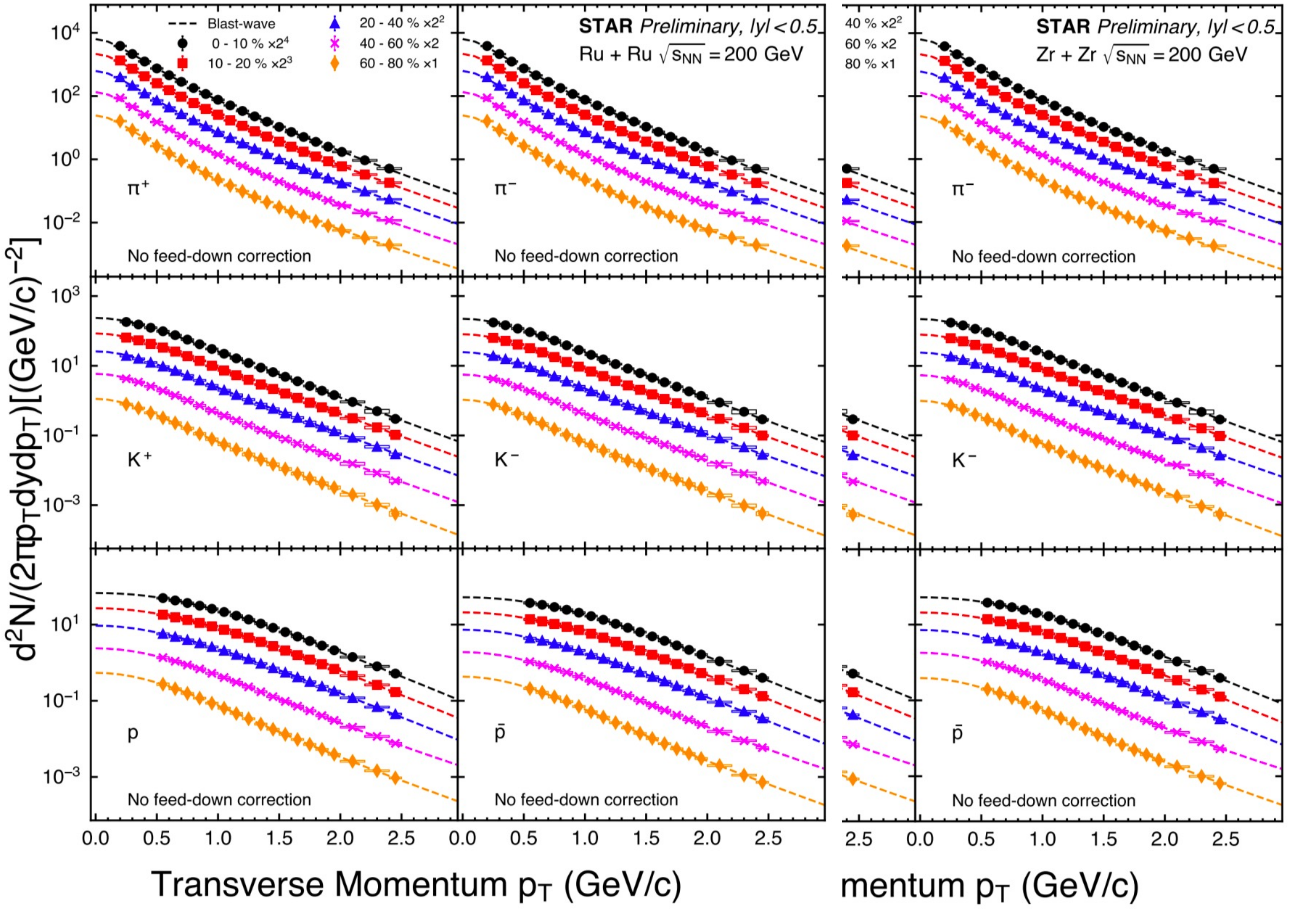
- The double ratios of π^+/π^- and $p/\bar{p}$ are larger than 1. Due to extra charge in Ru?
- The double ratios of K^-/K^+ is consistent with unity within uncertainties.

Identified hadron spectra to low momentum

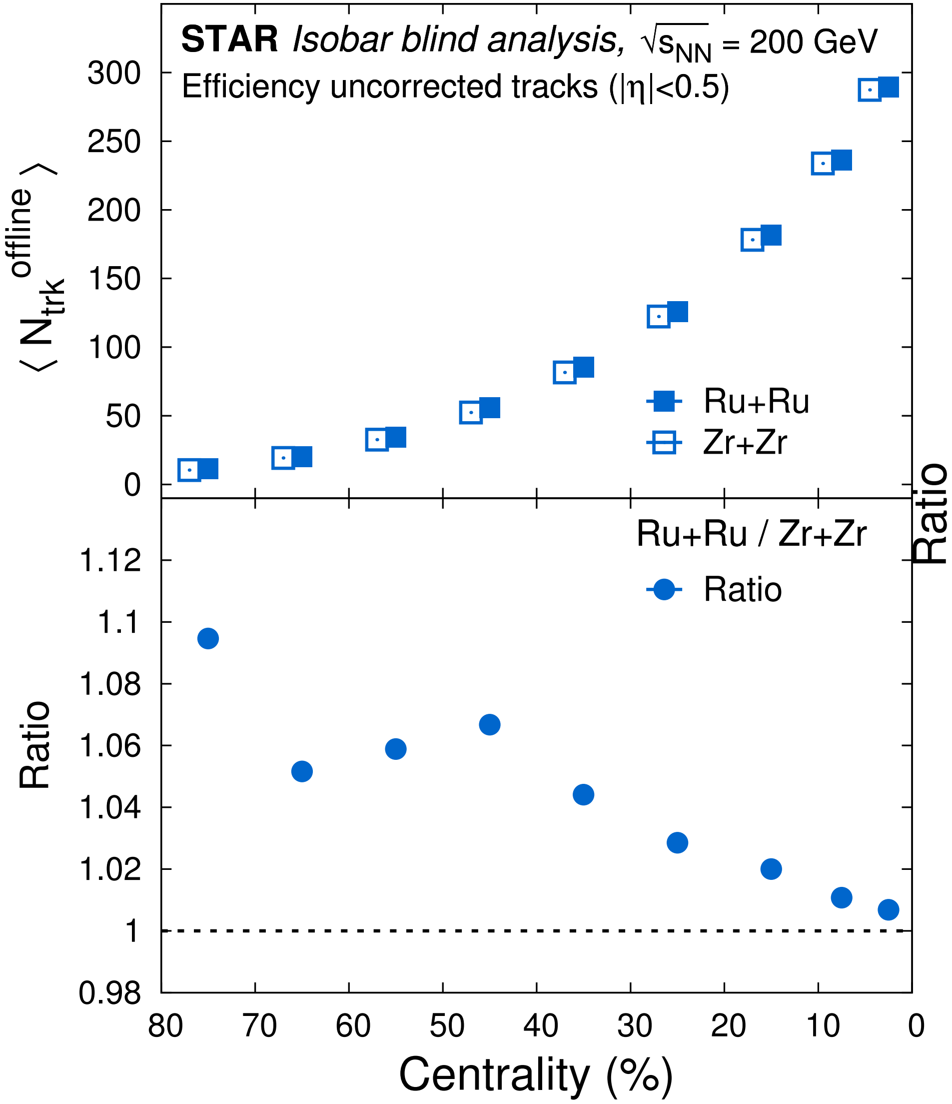


Net-charge difference (Ru+Ru – Zr+Zr)

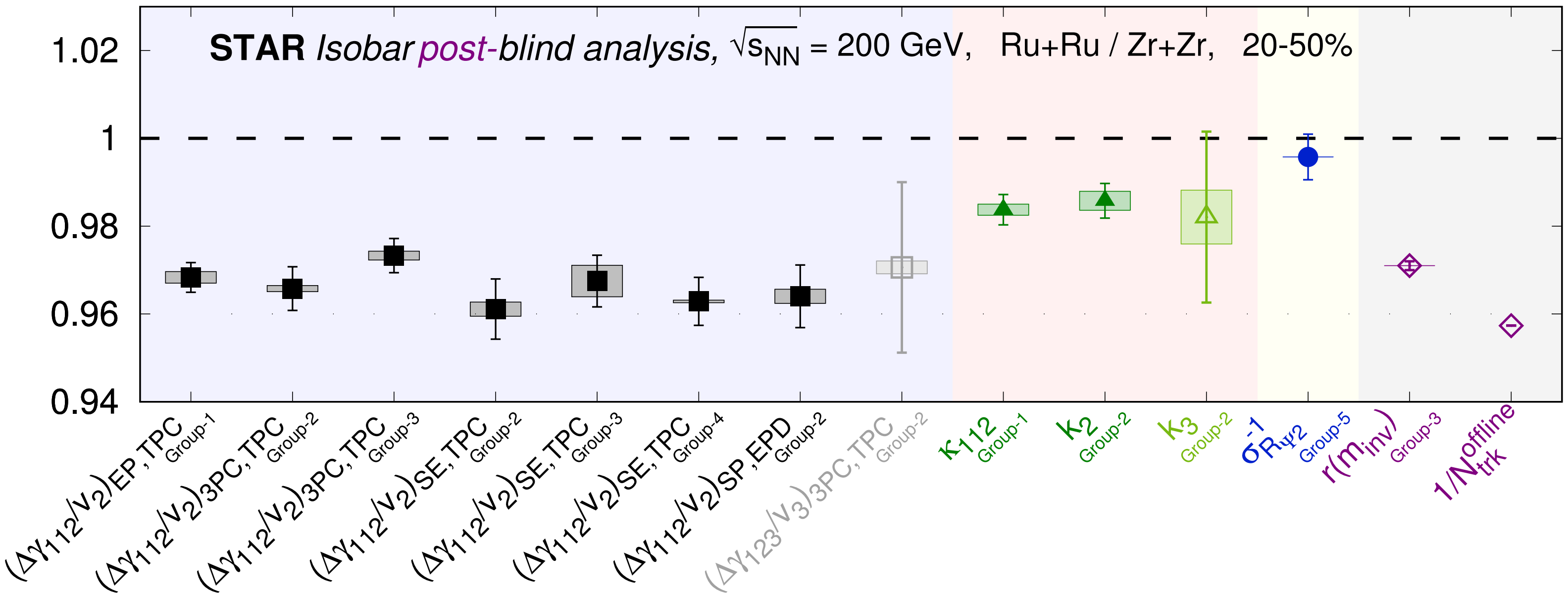
- $R2_\pi = \frac{(N_\pi^+/N_\pi^-)_{Ru}}{(N_\pi^+/N_\pi^-)_{Zr}} \approx \frac{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Ru}}{[1+(N_\pi^+-N_\pi^-)/N_\pi]_{Zr}} = \frac{1+\Delta R_{Ru}}{1+\Delta R_{Zr}} \approx 1 + \Delta R_{Ru} - \Delta R_{Zr}$
- $\Delta Q = [(N_\pi^+ + N_K^+ + N_p) - (N_\pi^- + N_K^- + N_{\bar{p}})]_{Ru}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



Small Multiplicity Mismatch, Big Physical Effect?



STAR Collaboration, Phys. Rev. C **105** (2022) 14901
"Search for CME with Isobar Collisions"



Multiplicity mismatch is from 0.5% (central) to 10% (peripheral)

Power and Simplicity of Double Ratio

3.3 Derive $\Delta Q_\pi = N_\pi(R2-1)$ in isobar

The relationship between ΔQ and the double ratios ($R2$) in isobar is purely algebra. Let's define

$$N^{Ru}_{\pi^+} = N^{Ru}_{\pi} + \delta_1$$
$$N^{Ru}_{\pi^-} = N^{Ru}_{\pi} - \delta_1$$
$$N^{Zr}_{\pi^+} = N^{Zr}_{\pi} + \delta_2$$
$$N^{Zr}_{\pi^-} = N^{Zr}_{\pi} - \delta_2$$

The multiplicity difference between Zr and Ru can be rewritten in terms of small excess of δ:

$$N^{Ru}_{\pi} = N_\pi + \delta$$
$$N^{Zr}_{\pi} = N_\pi - \delta$$

Effectively, we redefine the four pion measurements into four other variables (N_π, δ, δ_1 and δ_2). Therefore,

$$N^{Ru}_{\pi^+} = N_\pi + \delta + \delta_1$$
$$N^{Ru}_{\pi^-} = N_\pi + \delta - \delta_1$$
$$N^{Zr}_{\pi^+} = N_\pi - \delta + \delta_2$$
$$N^{Zr}_{\pi^-} = N_\pi - \delta - \delta_2$$

Since the multiplicity of the two isobar collisions are different in the above equations, it is incorrect to calculate the charge difference directly:

$$\Delta Q_\pi = (N^{Ru}_{\pi^+} - N^{Ru}_{\pi^-}) - (N^{Zr}_{\pi^+} - N^{Zr}_{\pi^-})$$
$$= 2(\delta_1 - \delta_2)$$

The correct charge difference is:

$$\Delta Q_\pi = (N^{Ru}_{\pi^+} - N^{Ru}_{\pi^-})\frac{N_\pi}{N_\pi+\delta} - (N^{Zr}_{\pi^+} - N^{Zr}_{\pi^-})\frac{N_\pi}{N_\pi-\delta}$$

$$= \frac{2N_\pi}{N_\pi^2-\delta^2}(N_\pi(\delta_1-\delta2) - \delta(\delta_1+\delta_2))$$
$$\simeq 2(\delta_1-\delta_2) - \frac{2\delta}{N_\pi}(\delta_1+\delta_2)$$
$$-2(\frac{\delta}{N_\pi})^3(\delta_1+\delta_2) + [...]$$

And:

$$R2_\pi = \frac{(N^{Ru}_{\pi^+}/N^{Ru}_{\pi^-})}{(N^{Zr}_{\pi^+}/N^{Zr}_{\pi^-})}$$
$$= \frac{(N^{Ru}_{\pi^+}\times N^{Zr}_{\pi^-})}{(N^{Zr}_{\pi^+}\times N^{Ru}_{\pi^-})}$$
$$= \frac{(N_\pi+\delta+\delta_1)(N_\pi-\delta-\delta_2)}{(N_\pi-\delta+\delta_2)(N_\pi+\delta-\delta_1)}$$
$$= \frac{N_\pi^2 + N_\pi(\delta_1-\delta_2) - (\delta+\delta_1)(\delta+\delta_2)}{N_\pi^2 - N_\pi(\delta_1-\delta_2) - (\delta-\delta_1)(\delta-\delta_2)}$$

Here comes the approximation with the assumption of $\delta << N_\pi$, $\delta_1 << N_\pi$ and $\delta_2 << N_\pi$, we omit any higher-order terms of $(\delta_{,1,2}/N_\pi)^3$ (order of 10^{-6}) and get:

$$R2_\pi \simeq 1 + \frac{2}{N_\pi}(\delta_1-\delta_2) - \frac{2\delta}{N_\pi^2}(\delta_1+\delta_2)$$
$$+\frac{2}{N_\pi^2}(\delta_1-\delta_2)^2 + (1/N_\pi)^3[...] + [...]$$

One can see from the above equation and the ΔQ equation that $R2$ and ΔQ are sensitive to the multiplicity difference δ at the second order ($\delta(\delta_1+\delta_2)$) between the two isobar collision systems. More importantly, the second and third terms in $R2_\pi$ coincide with the first and second terms of ΔQ_π, and the relationship between $R2$ and ΔQ does not depend on how well the centralities match between the two isobar collision systems. It becomes evident that:

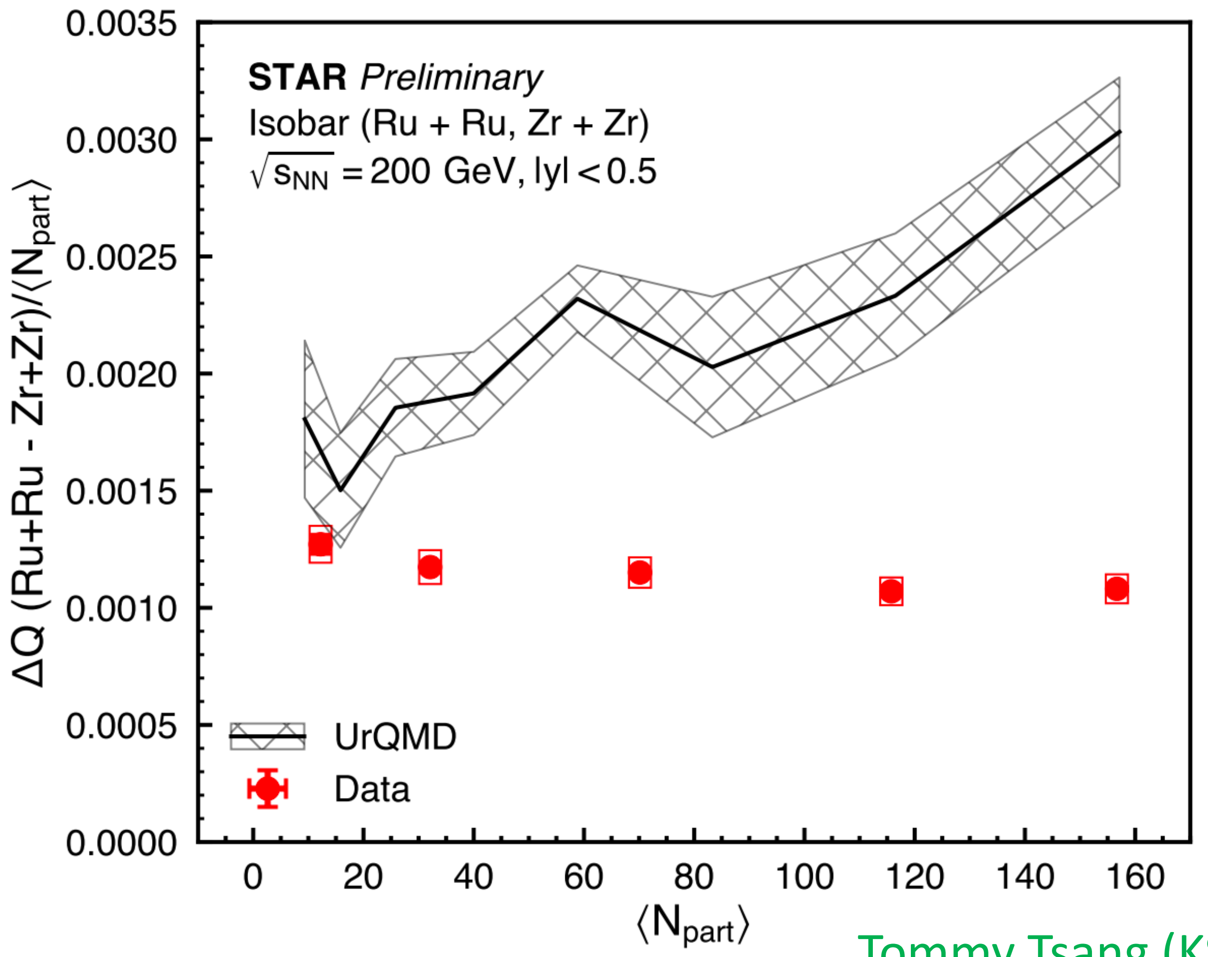
$$R2_\pi = 1 + \Delta Q_\pi / N_\pi$$

This approximation ignores higher order contribution at the level $< 1\%$ of ΔQ_π. Finally:

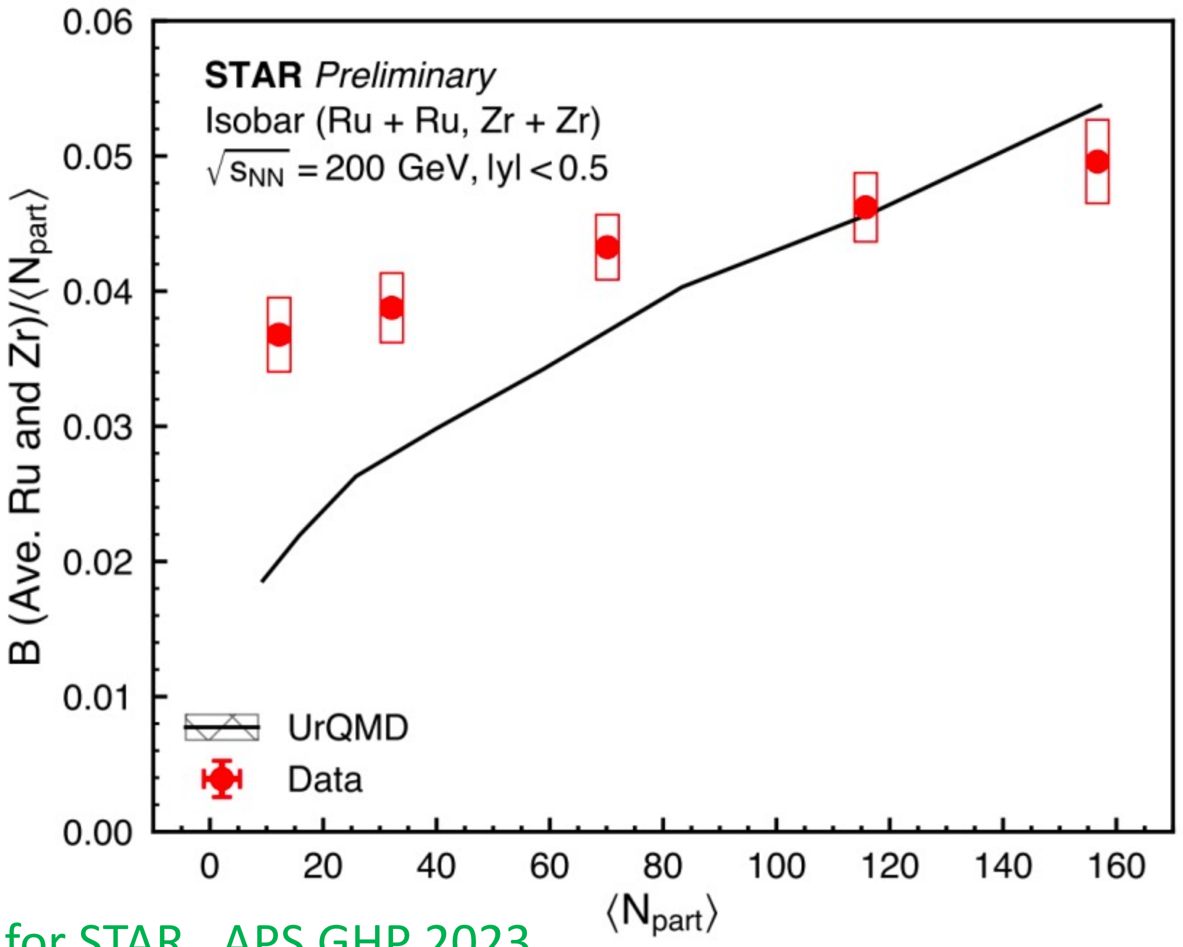
$$\Delta Q_\pi = N_\pi(R2_\pi - 1)$$

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

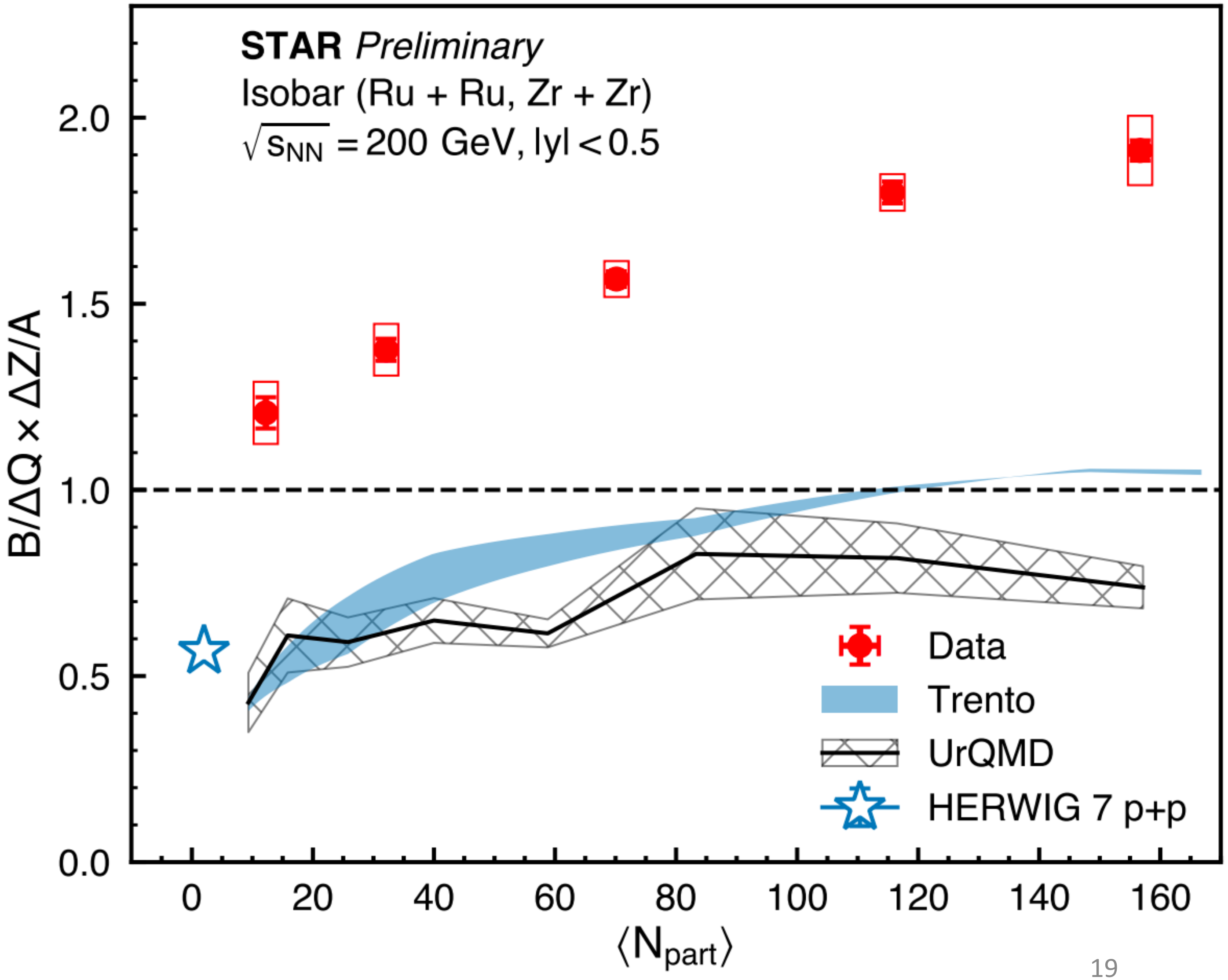
Ratio of baryon over charge transports

- **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)

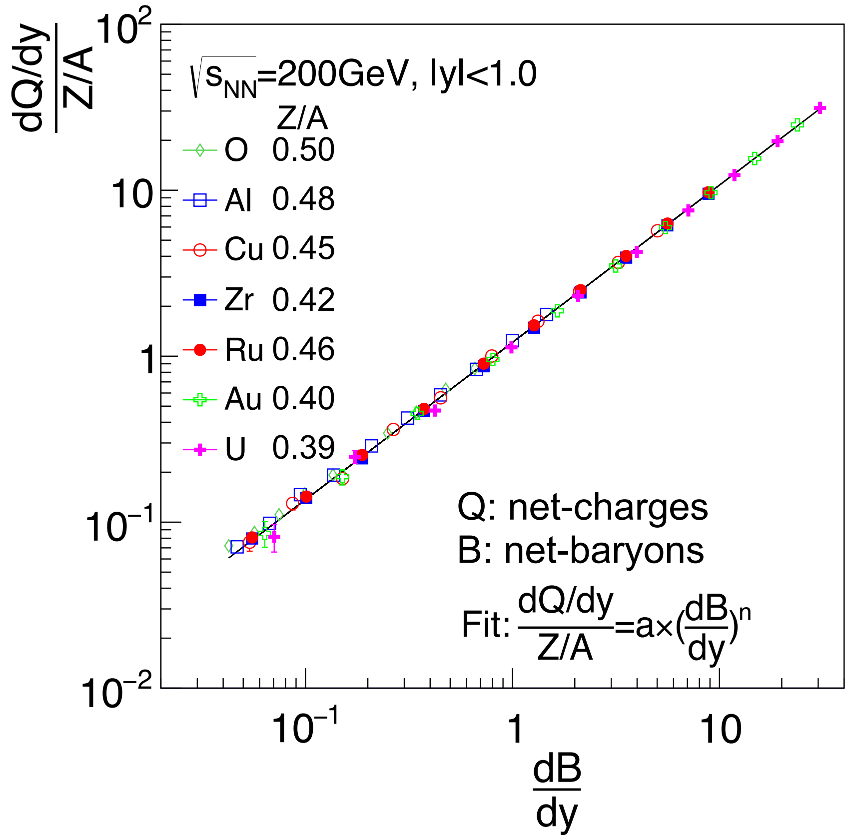
Tommy Tsang (KSU) for STAR, QM, APS GHP 2023

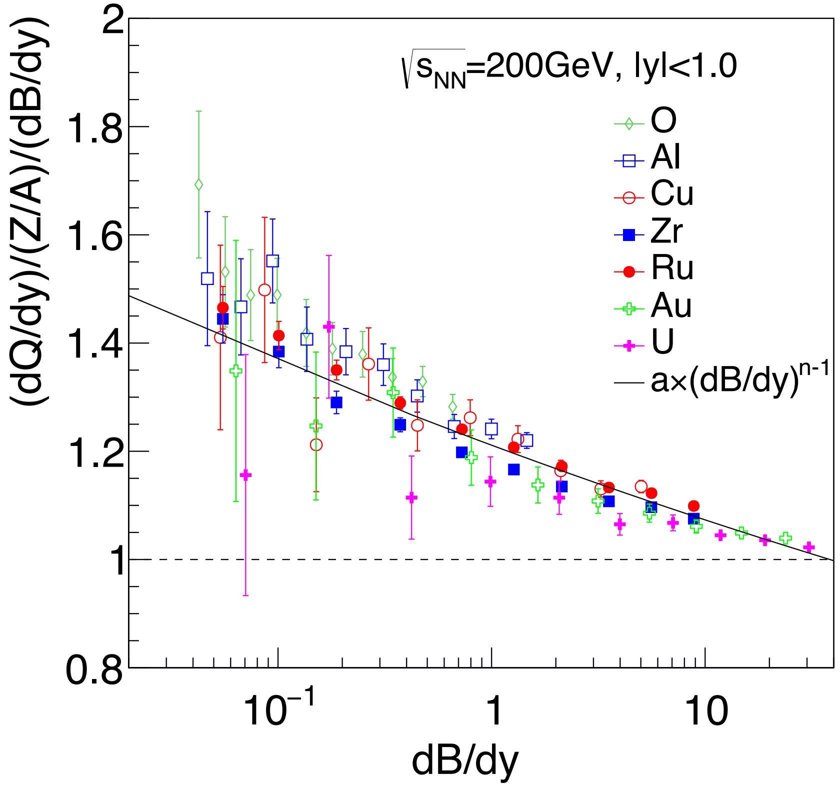


endi Lv, et al.
Xiv:2309.06445

Net–Charge vs. Net–Baryon from UrQMD

Baryon stopping in UrQMD: valence quark stopping + multiple scattering





- Net–charges at mid–y scale with Z/A in O+O to U+U collisions at 200 GeV
- Q/B x A/Z approaches 1 for large A
- Expect 25% difference of Q/B in O+O and Au+Au collisions

Low-energy baryon rapidity loss

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

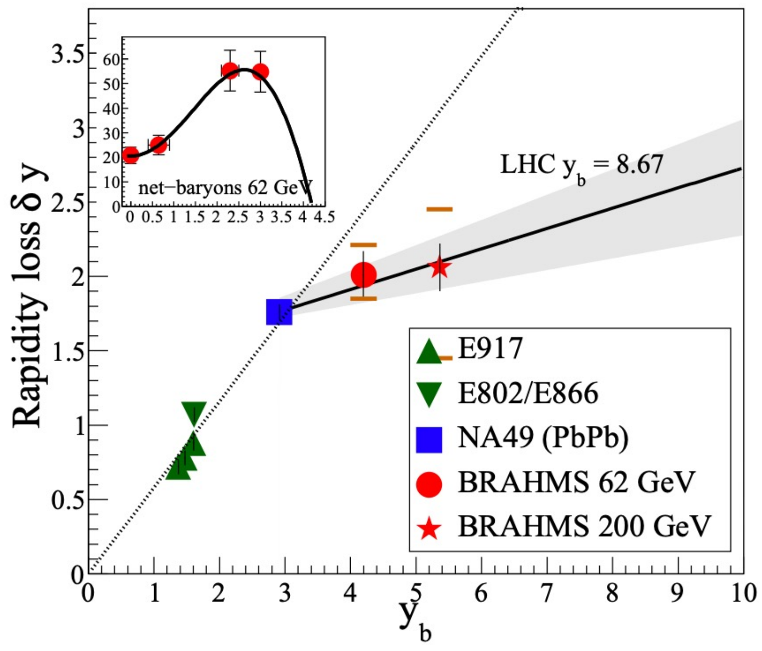


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS 2009

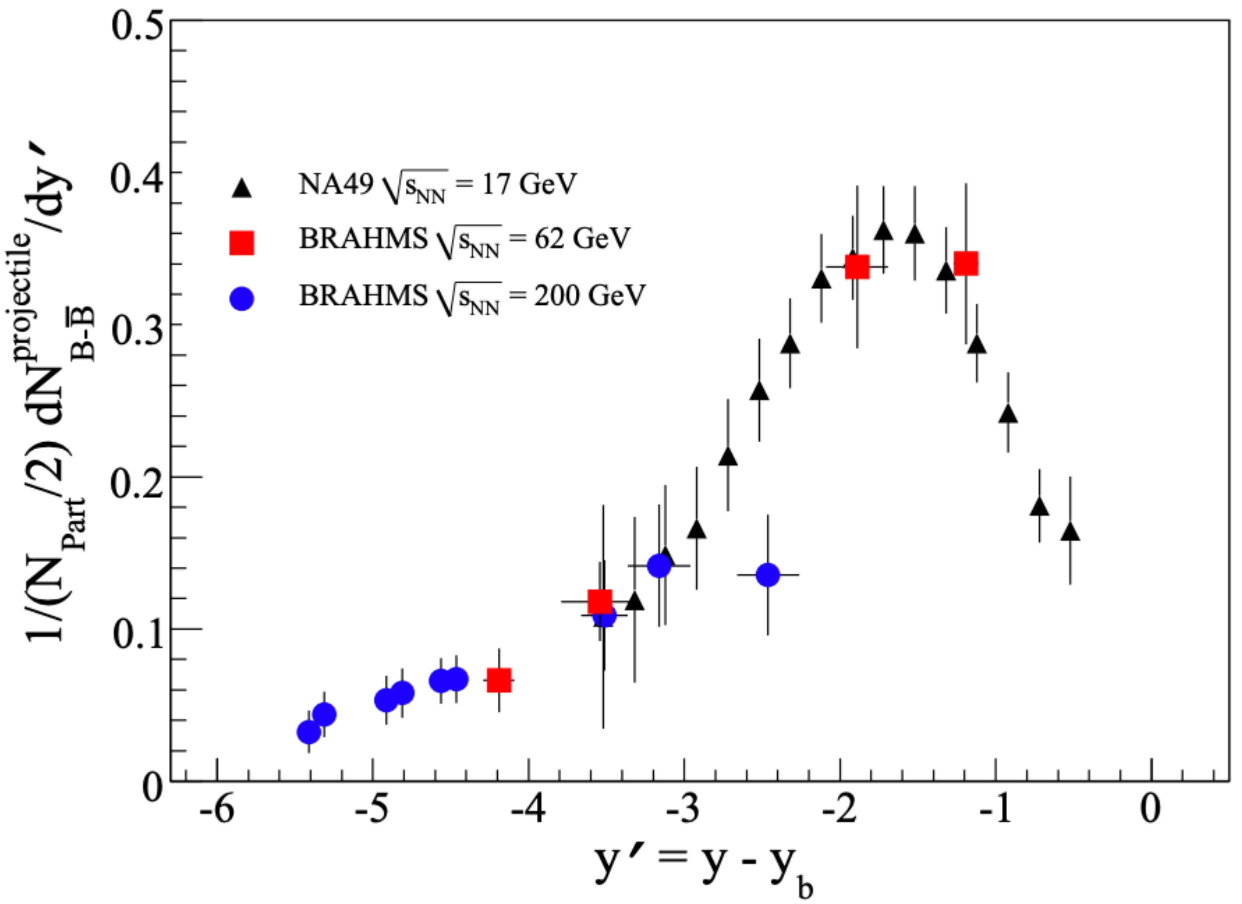


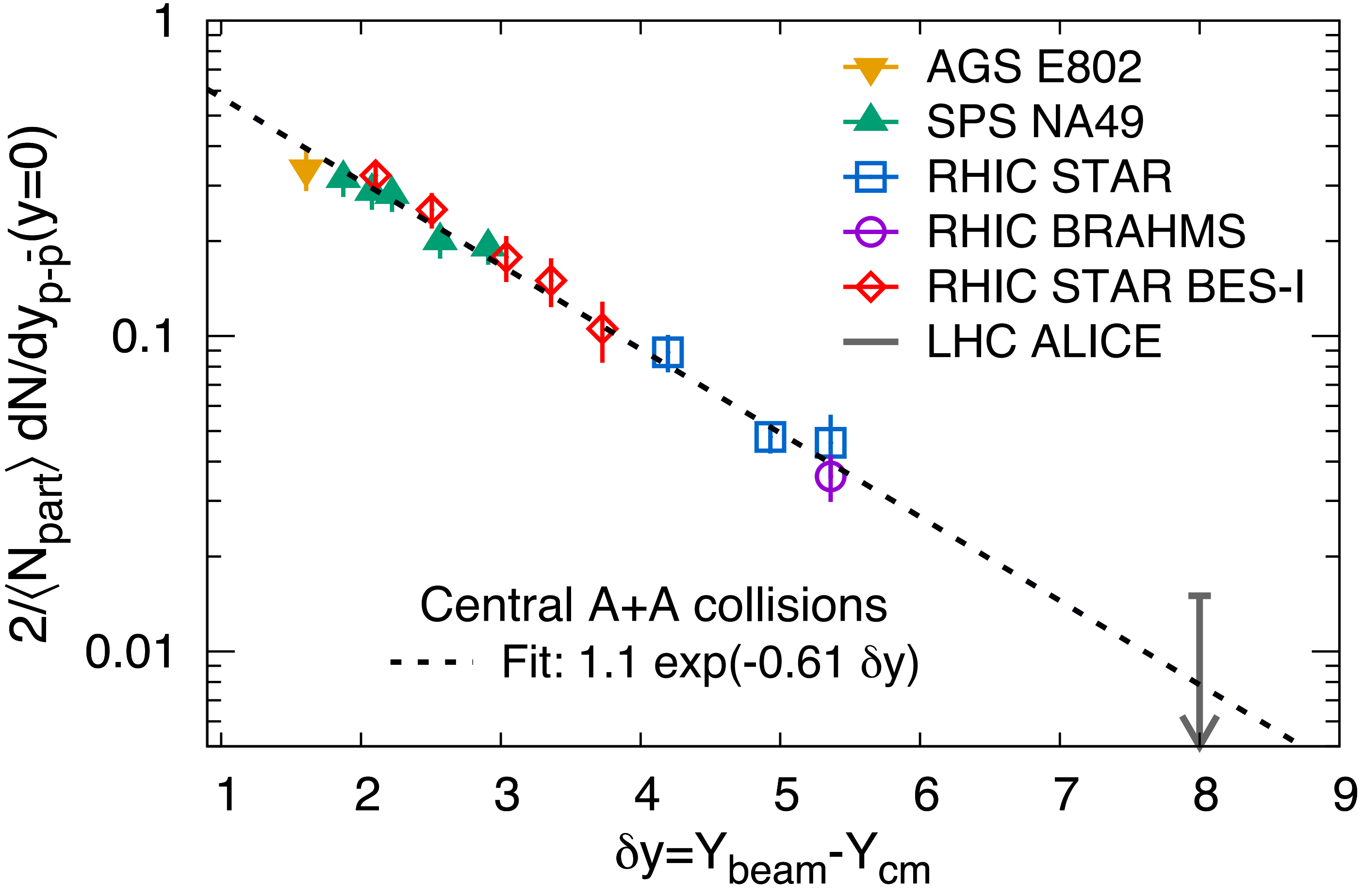
Figure 5: Projectile net-baryon rapidity density $(1/N_{part}/2)dN^{projectile}_{B-\bar{B}}/dy'$ from SPS and RHIC after subtraction of the target net-baryon contribution (see Fig. 4).

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

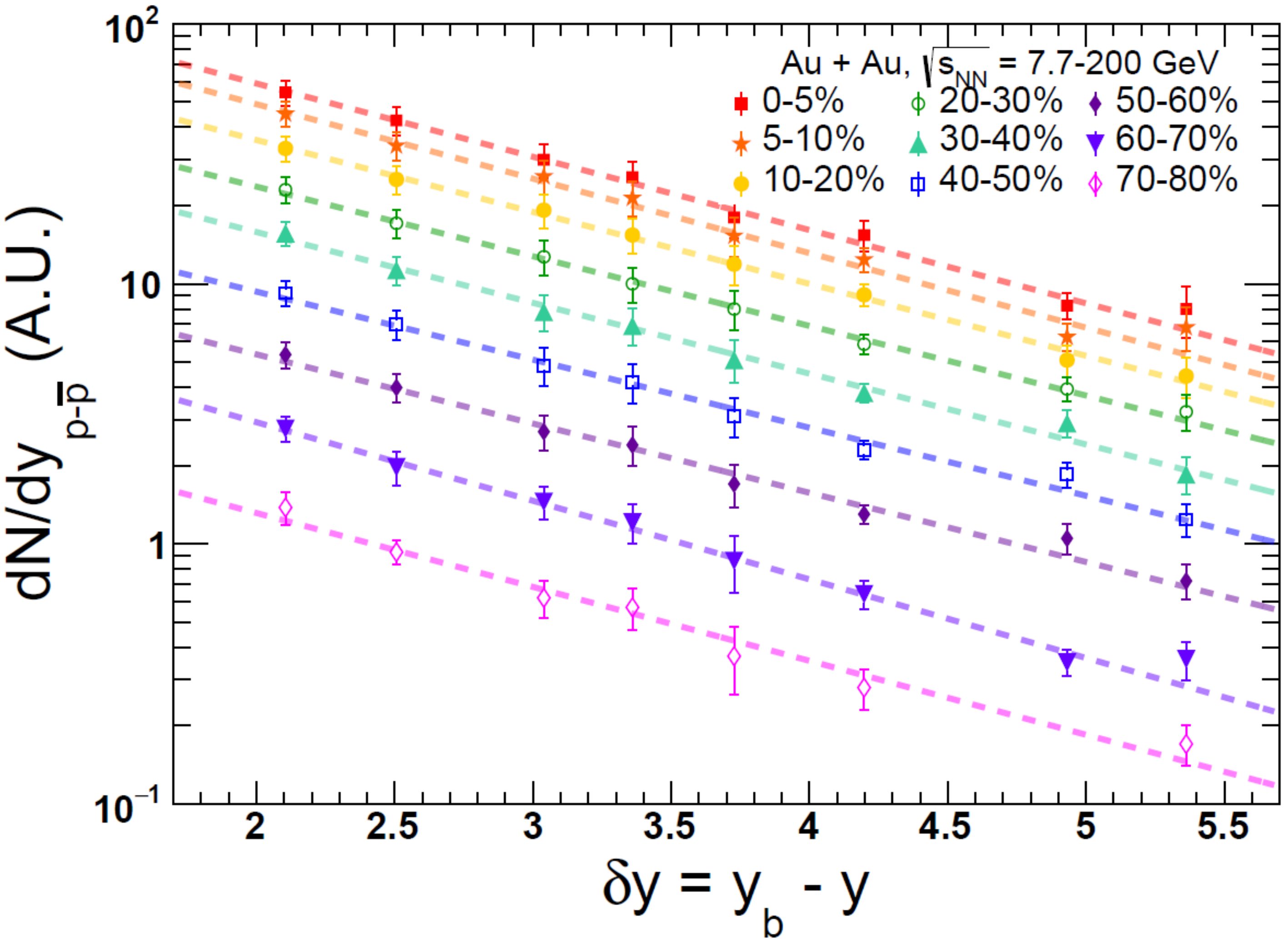
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685



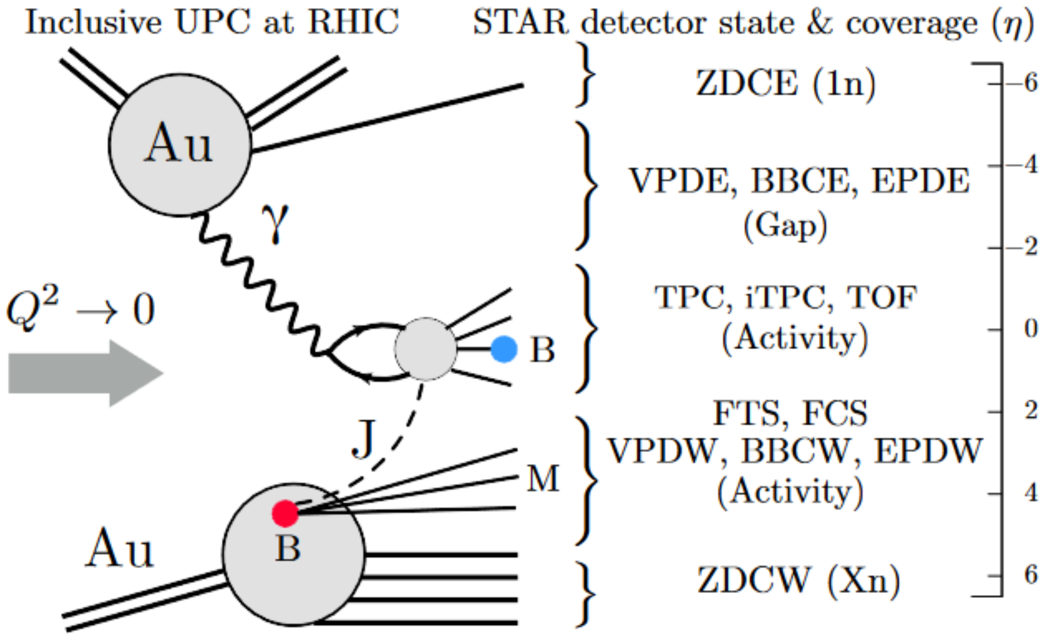
Quantifying baryon number transport

- 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

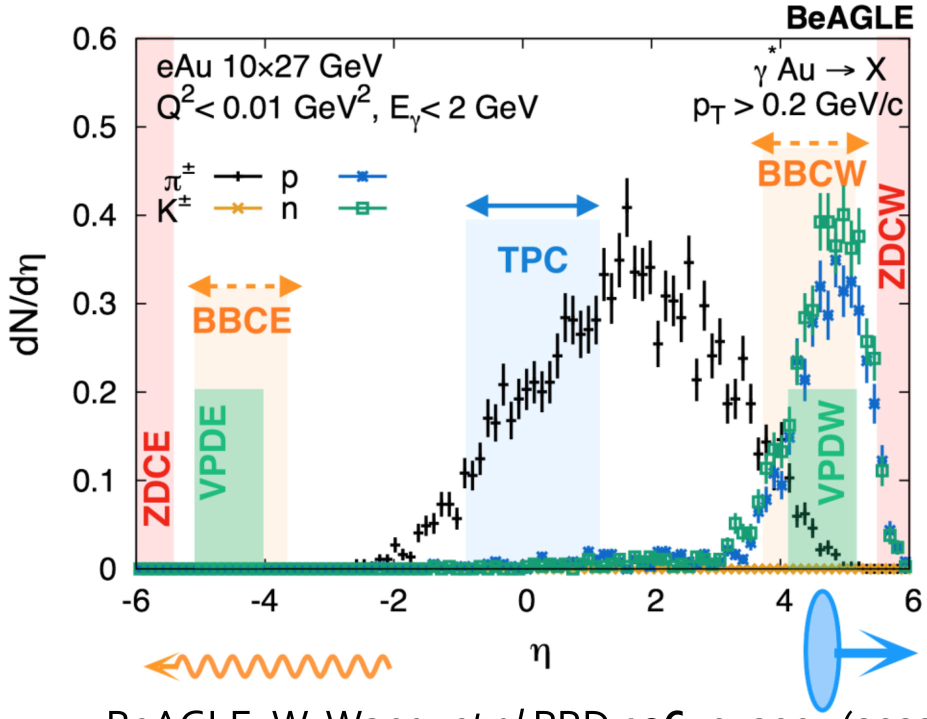
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.



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:

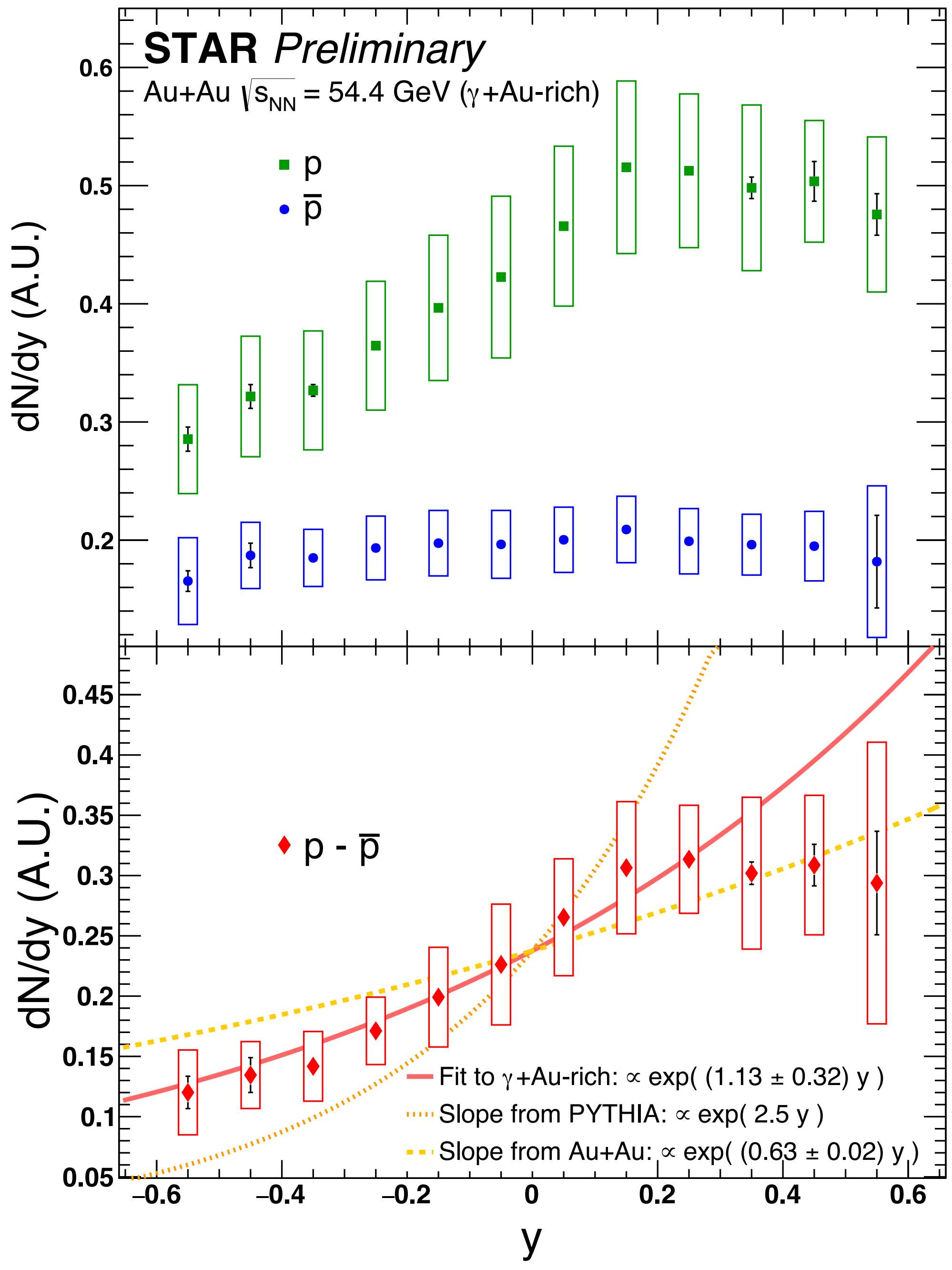
ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021) and CMS Collaboration, arXiv:2204.13486 (2022)

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

Rapidity asymmetry in photon-nucleus collision

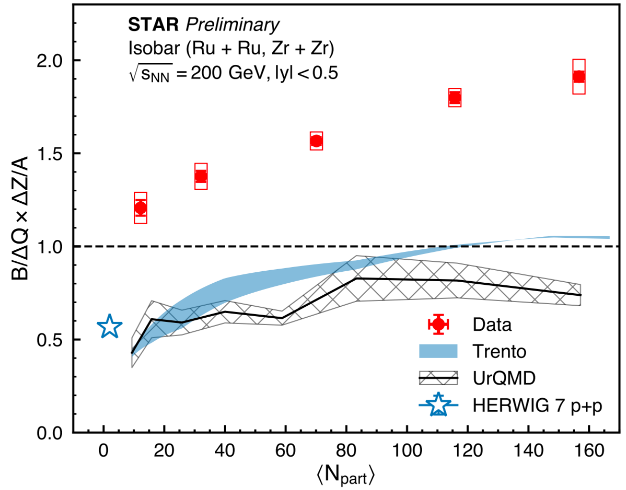
Nicole Lewis (BNL) for STAR, DIS2023

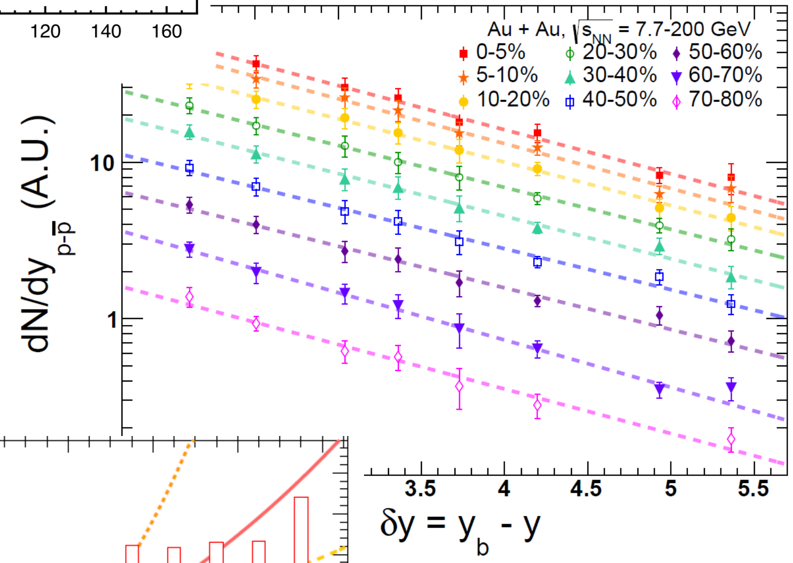
- Selection of photon+Au collisions from Au+Au at 54.4GeV ultra-peripheral collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic asymmetry increase toward nucleus side
- Slope is closer to the slope of the beam energy dependence
- PYTHIA shows much larger slope



Three approaches toward tracking the origin of the baryon number

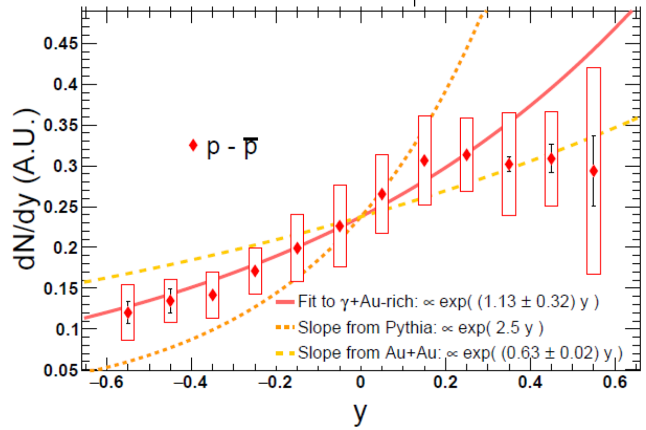
1. **STAR Method:**
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. **Kharzeev-STAR Method:**
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. **Artru Method:**
   In γ+Au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



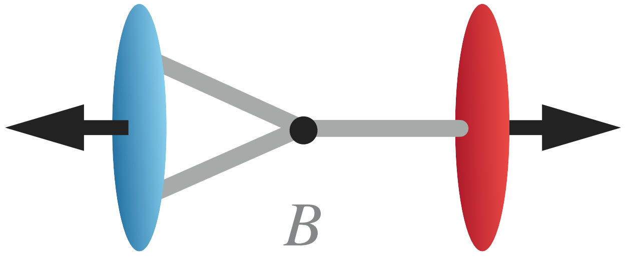


$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5



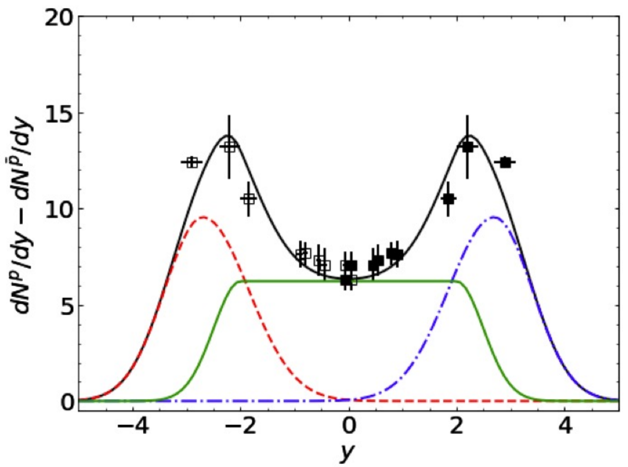
Baryon Junction reduces directed flow

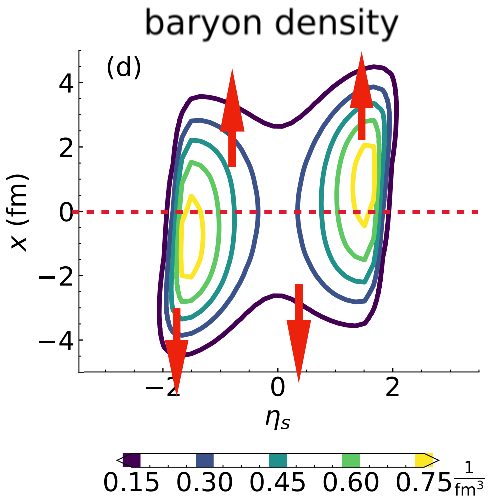


DIRECTED FLOW OF BARYONS AT 19.6 GEV

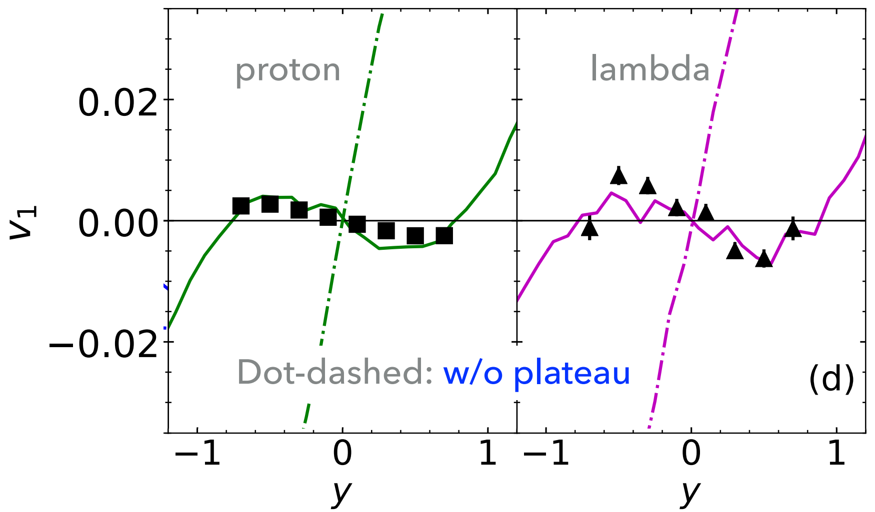
L.P. Du, et al., arXiv:2211.6408;
Du, RHIC/AGS June, INT 20r-1c, August 2023

Baryons get distributed in rapidity through string junction breaking





Initial distributions in reaction plane for 10-40% Au+Au@19.6 GeV

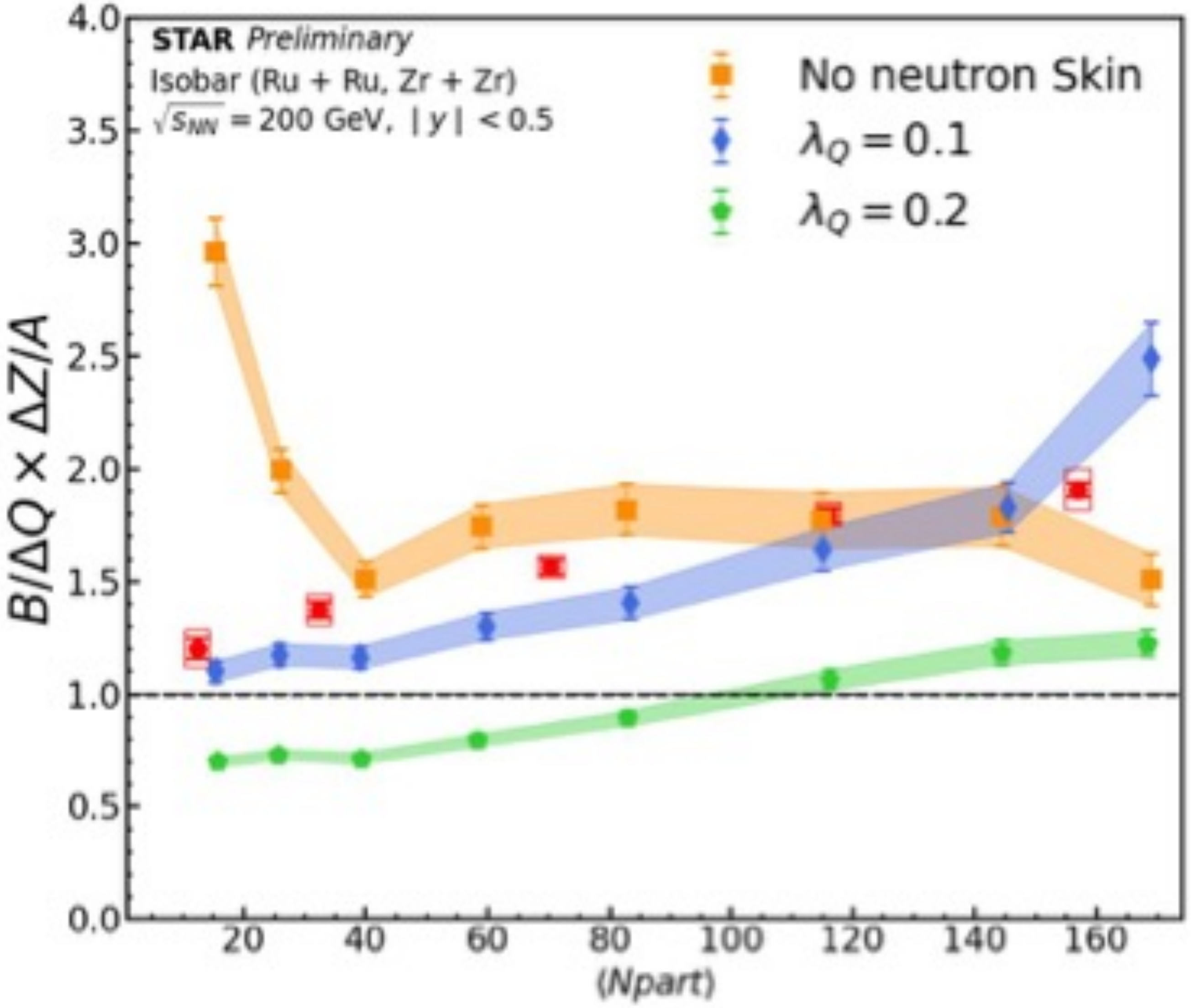


- Initial baryon distribution: central plateau + tilted peaks
- Transverse expansion + asymmetric distribution of baryon density along x $\Longrightarrow$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV

Ratio at initial stage

QM2023, September

The iEBE-MUSIC framework



Grégoire **Pihan**[1], Akihiko **Monnai**[2], Bjoern **Schenke**[3], Chun **Shen**[1,3]

[1]*Wayne state University*, Detroit, USA, [2]*Osaka Institute of technology*, Osaka, Japan, [3]*Brookhaven National Lab*, Upton, USA

At initial stage

➢ Equal stopping $\lambda_Q = \lambda_B = 0.2$

- Largely underestimate the experimental ratio
- ratio < 1 for smaller Npart.
- Overall increase with Npart: **Neutron skin**

➢ Half stopping $\lambda_Q = \lambda_B/2 = 0.1$

- Closer to experimental data
- Overall increase with Npart: **Neutron skin**

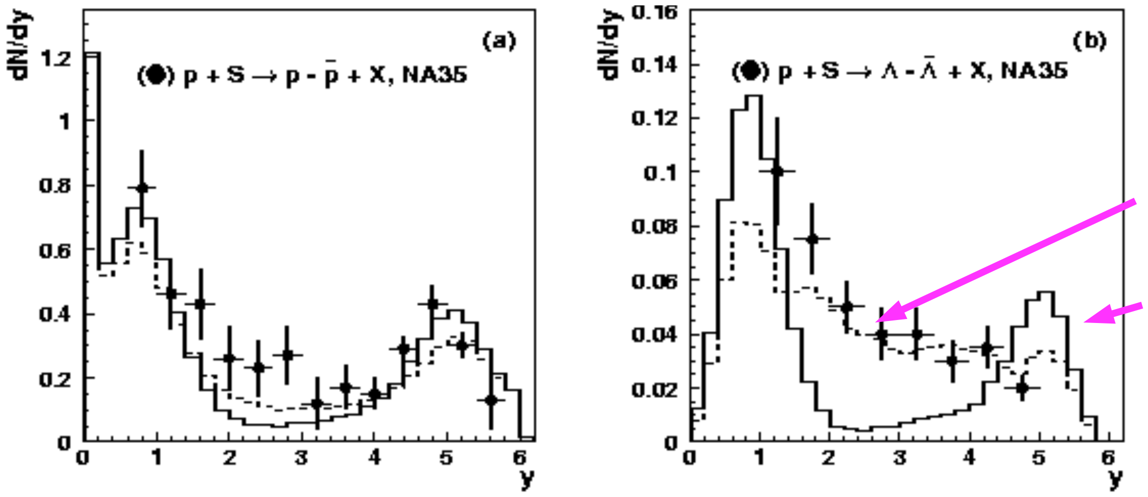
➢ No neutron skin $\lambda_Q = 0.1$

- Flat for a large range of Npart
- Cannot account for increasing behavior of the data

Comparison with STAR data at initial stage advocates for a difference in baryon to electric charge stopping ratio!

NET BARYON NUMBER TRANSPORT VIA GLUONIC JUNCTIONS vs SPS data

S Vance, MG, XN Wang Phys.Lett.B443:45-50,1998



HIJING/B dashed

HIJING   solid

Distribution of final Y=rapidity of proton = $\tanh^{-1}(v_z)$

Miklos Gyulassy

Prepared in 08/18/2022

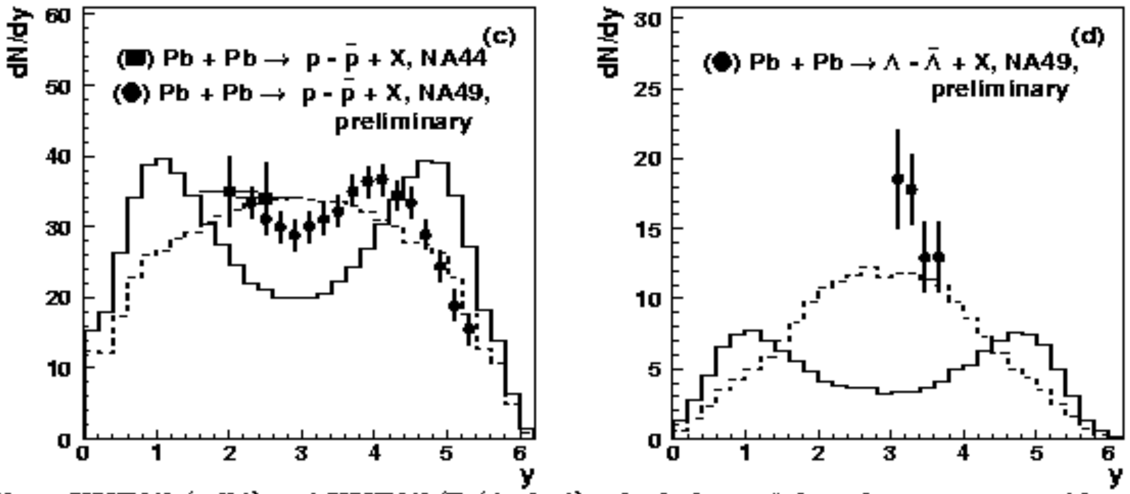
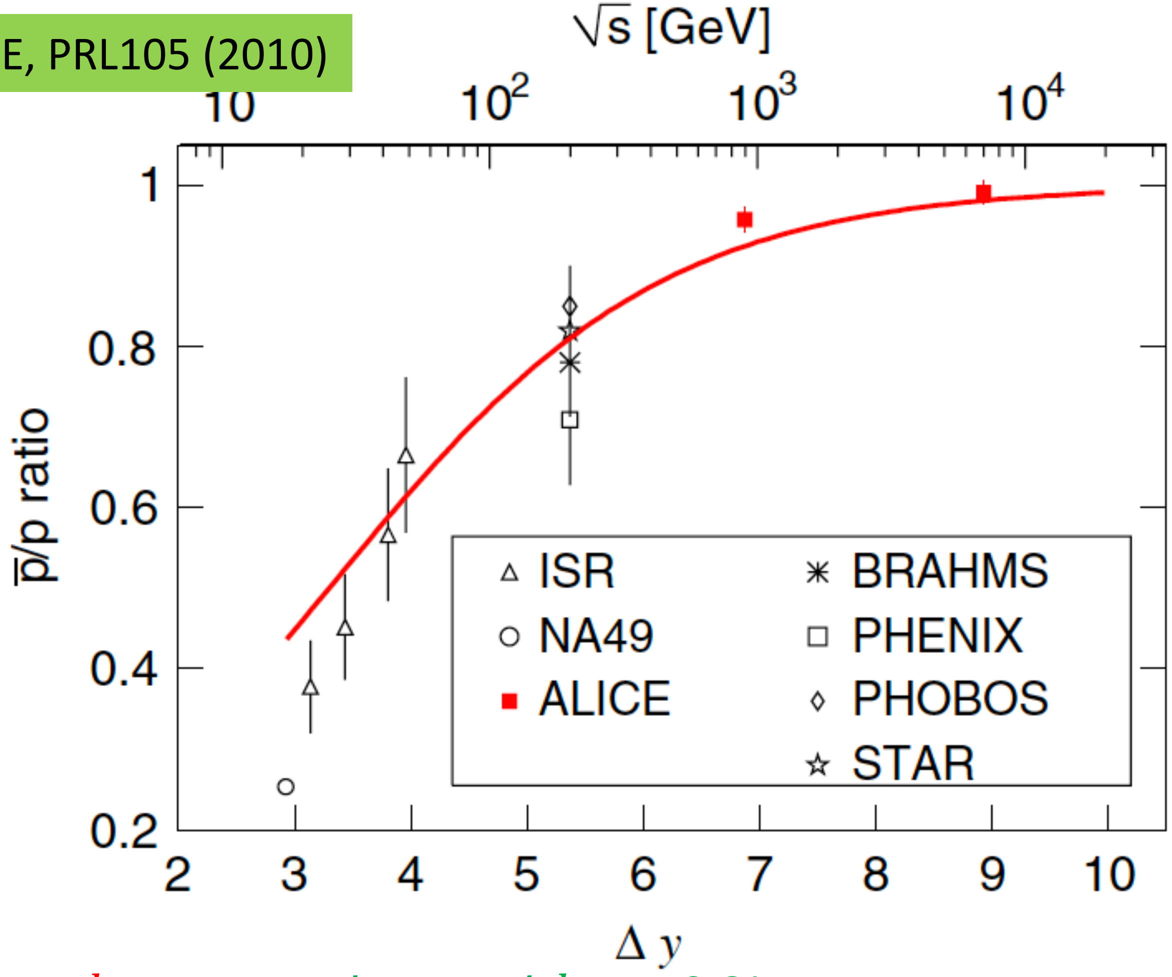


FIG. 1. HIJING (solid) and HIJING/B (dashed) calculations of the valence proton and hyperon rapidity distributions are shown for minimum bias $p+S$ collisions at 200 AGeV and central $Pb+Pb$ collisions at 160 AGeV. The data are from measurements made by the NA35 [1,2], NA44 [3] and NA49 [5] collaborations.

What do we know about pp collisions?

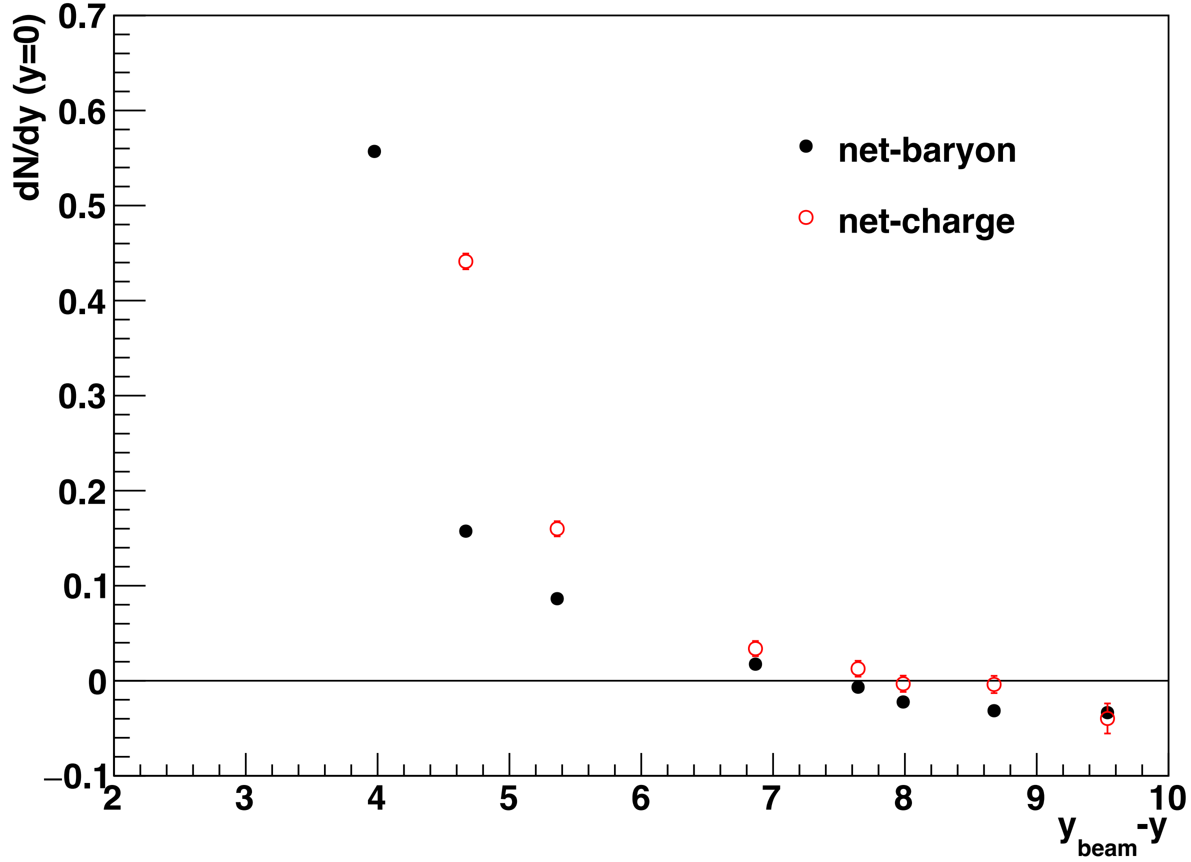
"These results are consistent with standard models of baryon-number transport and set tight limits on any additional contributions to baryon-number transfer over very large rapidity intervals in pp collisions."

ALICE, PRL105 (2010)



red curve consistent with α_B =0.61

Rongrong Ma (BNL)



HERWIG and PYTHIA 6: α_B ~=1.6-2.5

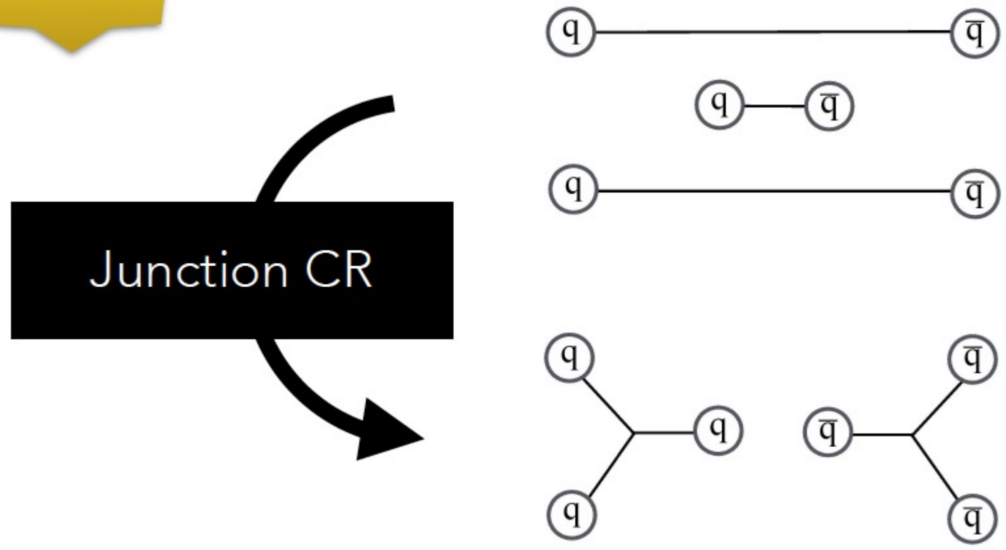
Negative (pbar>p) at LHC energy

new!

Peter Skands, 2021

“Final-State” baryon junction in PYTHIA 8.x

Illustrations by J. Altmann



Junction treatment (PYTHIA MANUAL 8.x)

A junction topology corresponds to an Y arrangement of strings i.e. where three string pieces have to be joined up in a junction. Such topologies can arise if several valence quarks are kicked out from a proton beam, or in baryon-number-violating SUSY decays. Special attention is necessary to handle the region just around the junction, where the baryon number topologically is located. The junction fragmentation scheme is described in [Sjo03, 2003]. The parameters in this section should not be touched except by experts.

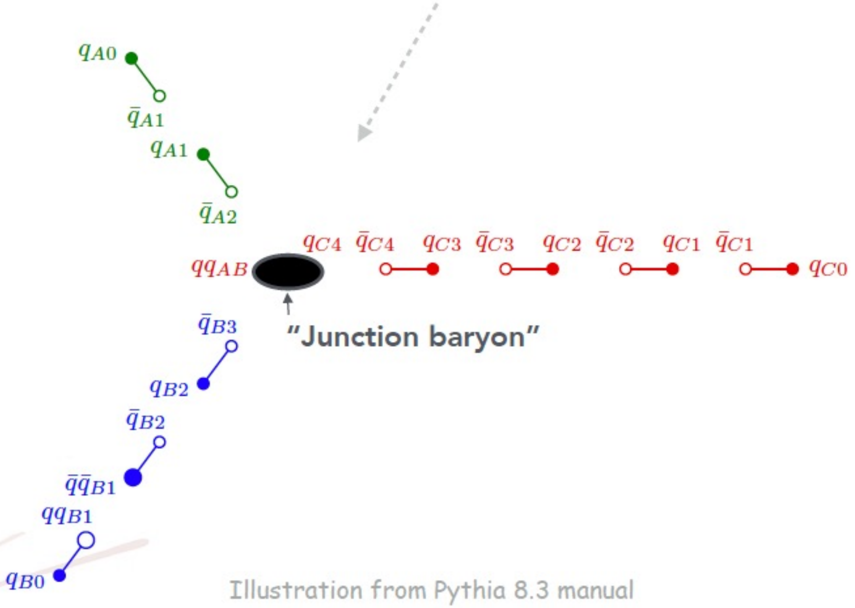


Illustration from Pythia 8.3 manual

MCnet

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

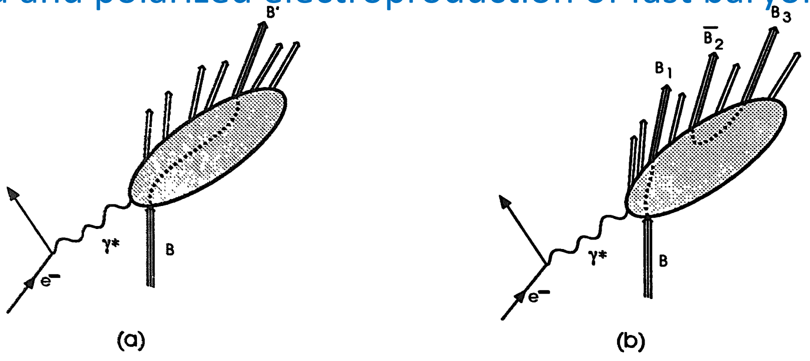


Figure 1. Main mechanisms of electroproduction of fast baryons.

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

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

(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).

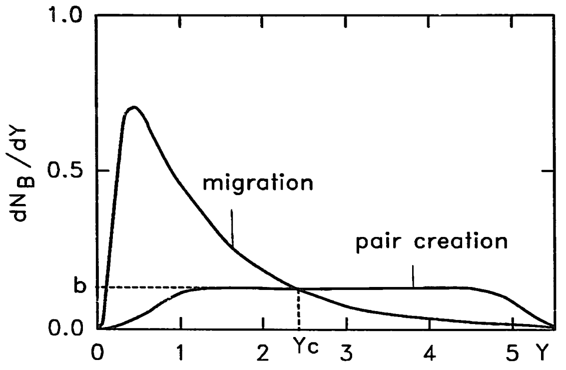
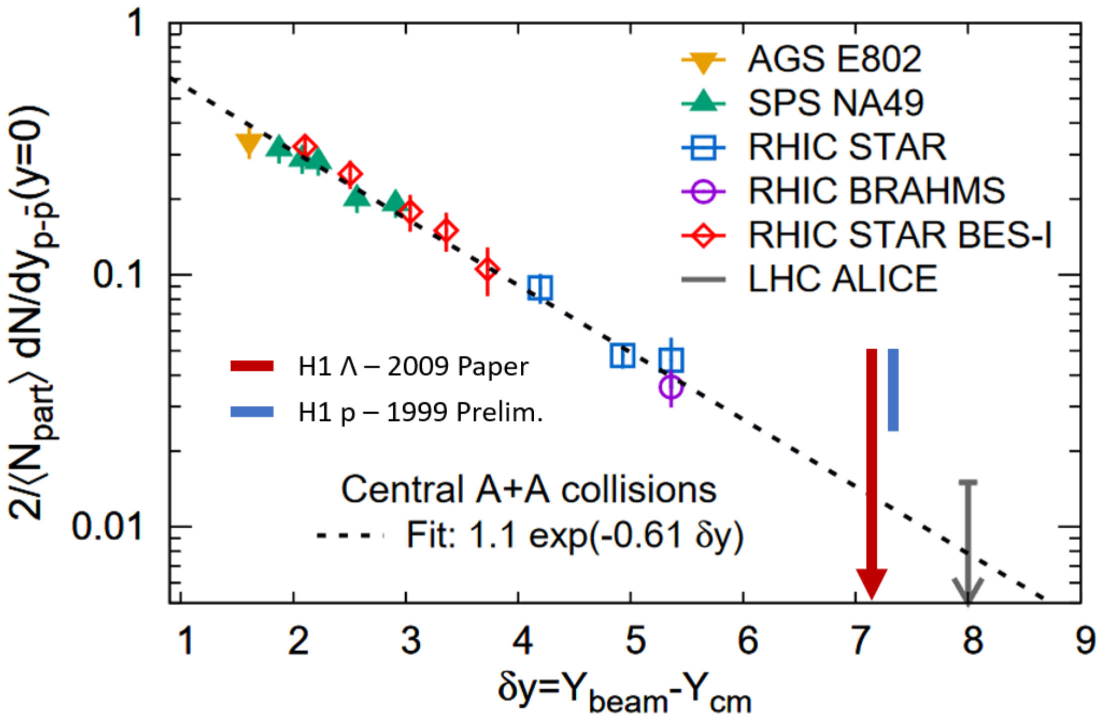


Figure 2. Rapidity spectrum: (a) of the migration mechanism, (b) of the pair creation mechanism.

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

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]

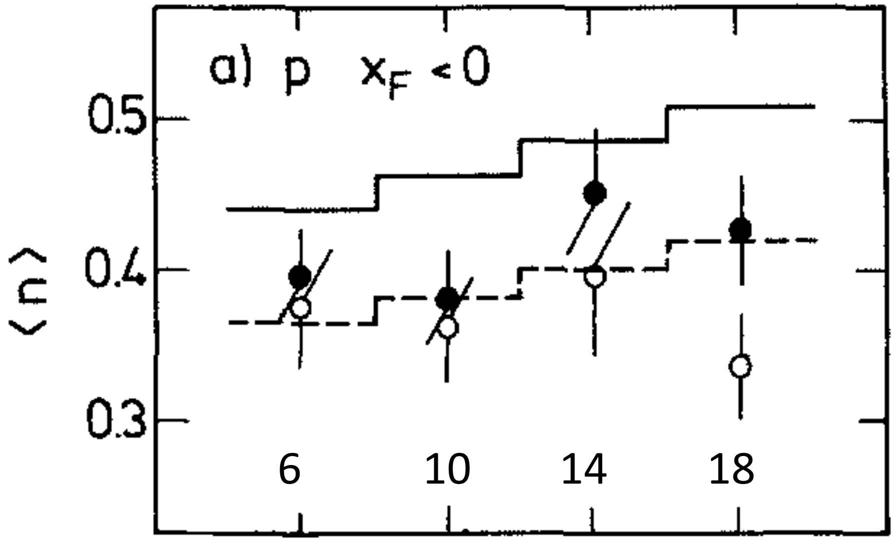
What do we know about μ+p (d) collisions

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

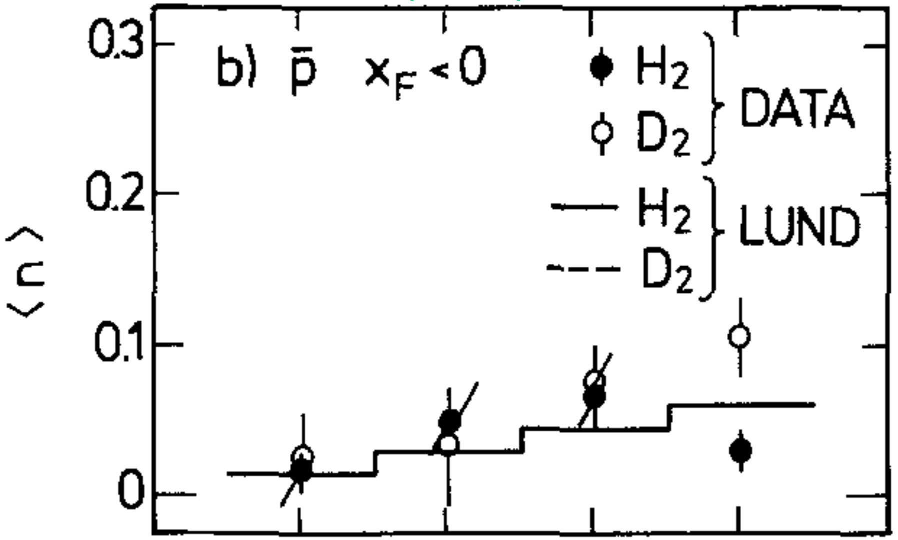
Fig. 5a-d. Average multiplicities from the H_2 (full circles) and the D_2 target (open circles) vs. W for backward protons a, backward antiprotons b. The histograms show the Lund model predictions (full line: H_2 target, dashed line: D_2 target, full line only where both are the same)

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



EMC, ZPC 35 (1987) 433



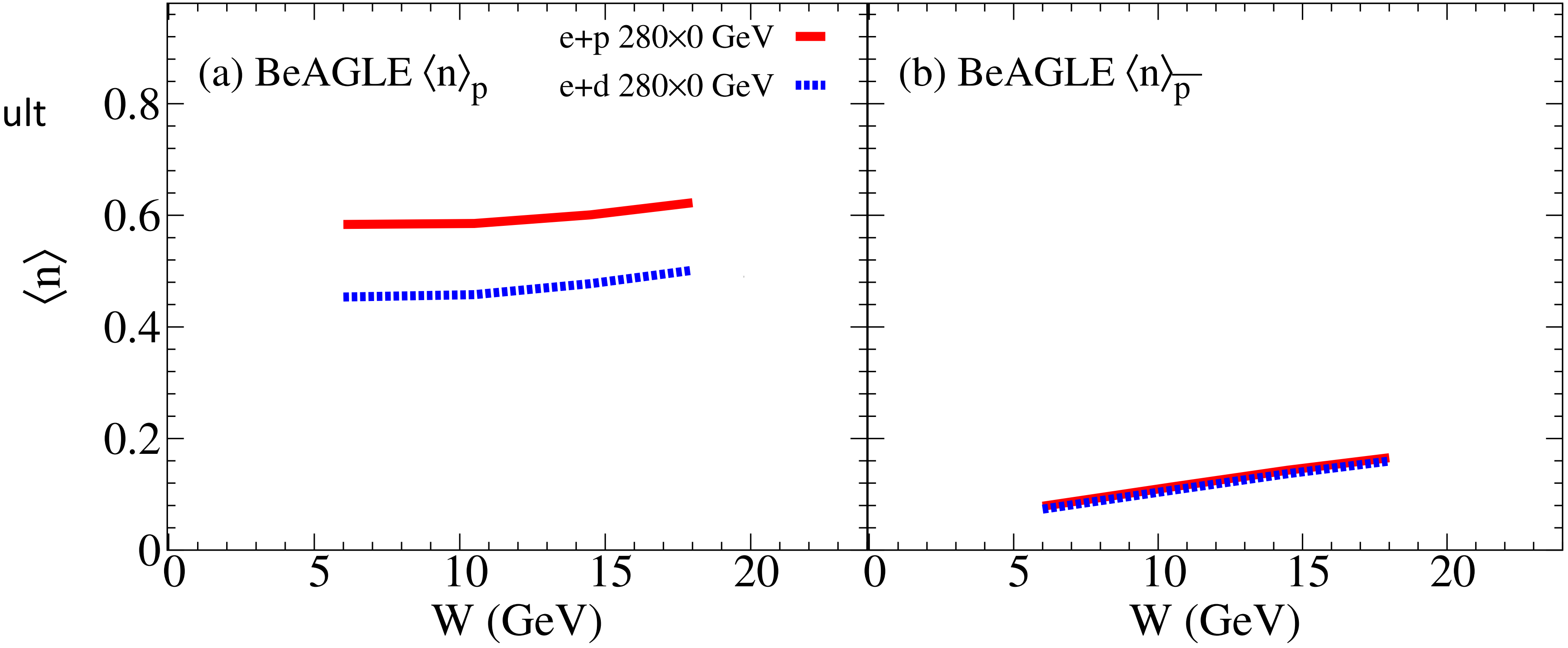
W² (GeV²)

Simulation at present day

Niseem Magdy (SBU)

Same kinematics as EMC, reproduce the simulation result

Next, using EIC kinematics,



EIC simulation of baryon vs charge transports

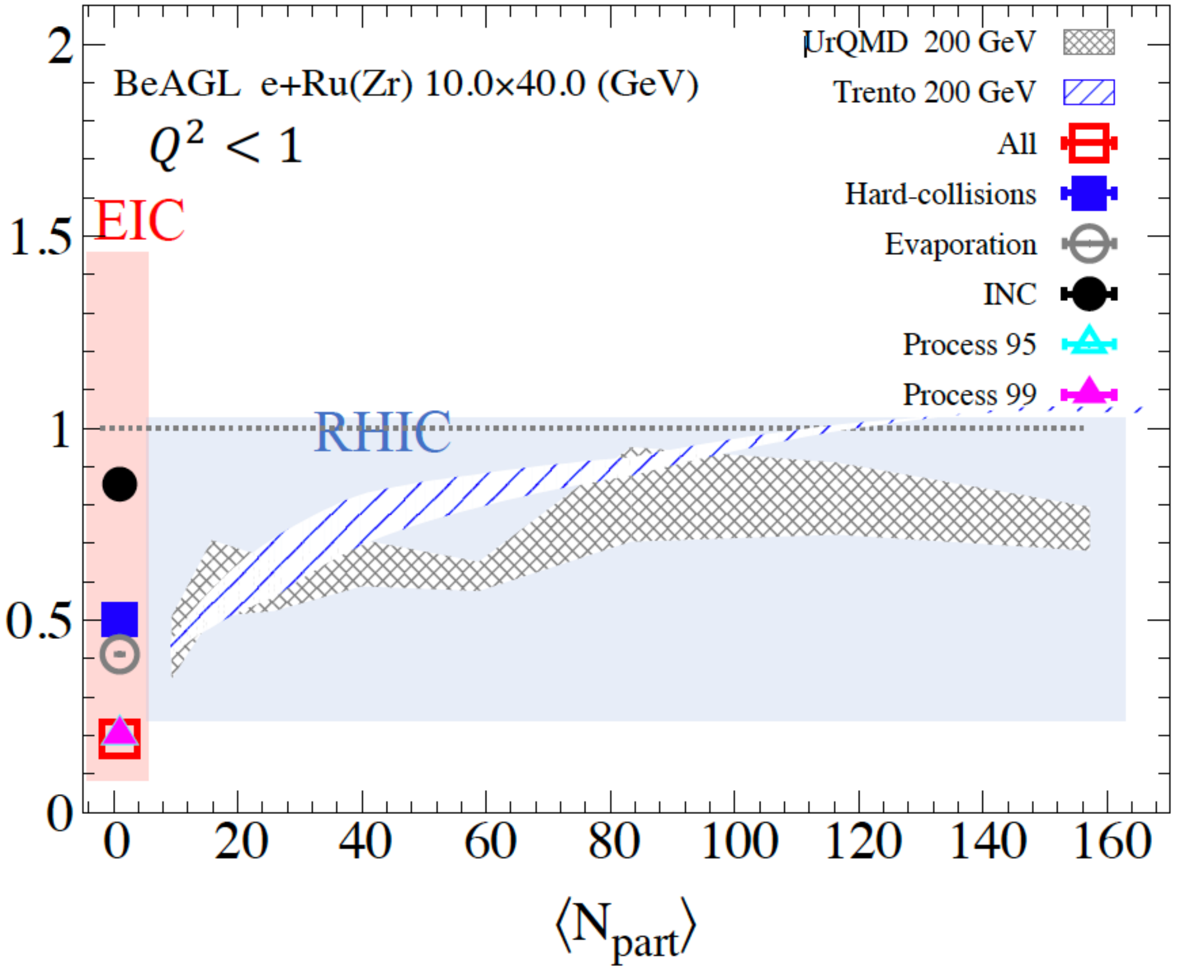
Niseem Magdy (SBU)

Summary of the 1st workshop on 2nd EIC detector (05/15/23)

Golden Channels Strawman

CHANNEL	PHYSICS	DETECTOR II OPPORTUNITY
Diffractive dijet	Wigner Distribution	detection of forward scattered proton/nucleus + detection of low p_T particles
DVCS on nuclei	Nuclear GPDs	High resolution photon + detection of forward scattered proton/nucleus
Baryon/Charge Stopping	Origin of Baryon # in QCD	PID and detection for low p_T pi/K/p
F_2 at low x and Q^2	Probes transition from partonic to color dipole regime	Maximize Q^2 tagger down to 0.1 GeV and integrate into IR.
Coherent VM Production	Nuclear shadowing and saturation	High resolution tracking for precision t reconstruction

These channels are just a starting point, a way to initially focus activities within the group. Additional ideas and efforts are welcome!



Topology and entanglement in the baryon structure at small x

Adrien Florio[1], **David Frenklakh**[2] and Dmitri Kharzeev[1,2,3]

[1]Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[2]Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
[3]Co-design Center for Quantum Advantage, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

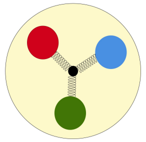
Introduction: baryon junctions

It has been suggested [1] that baryon number is carried by a gluonic string junction. It ensures gauge invariance of the operator containing three quark fields at different points.

Gauge-invariant baryon operator:

$$B(x_1,x_2,x_3) \sim q(x_1)q(x_2)q(x_3) \xrightarrow{\text{Gauge inv.}} B(x_1,x_2,x_3,x) = \epsilon^{ijk}[P\exp(ig\int_x^{x_1} A_\mu dx^\mu)q(x_1)]_i[P\exp(ig\int_x^{x_2} A_\nu dx^\nu)q(x_2)]_j[P\exp(ig\int_x^{x_3} A_\rho dx^\rho)q(x_3)]_k$$

If a string breaks, the baryon is restored around the junction. **Does the junction carry the baryon number?**



A schematic illustration of the baryon junction structure

Theory

Phenomenology

(1+1)-dimensional QCD

QCD in (1+1) is similar to (3+1): confinement, chiral symmetry breaking and mass gap in meson and baryon spectrum **and** is exactly solvable in the large N_c limit.

Bosonization → sine-Gordon model:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^2 - m'^2\cos\left(2\sqrt{\frac{\pi}{N_c}}\phi\right)$$

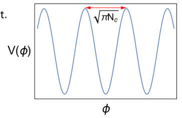


Fig.1 Potential of the sine-Gordon field

Baryon is represented by a topological kink (see Figure 2).

Baryon number is naturally topological charge.

Quantum state of a baryon is a particular coherent state [2]:

$$|B\rangle = \bigotimes_k |\alpha_k\rangle, \quad |\alpha_k\rangle = e^{-|\alpha_k|^2/2}\sum_{n=0}^{\infty}\frac{\alpha_k^n}{n!}(a_k^\dagger)^n|0\rangle$$

where $a_k^\dagger$ create soliton constituents, not free quanta.

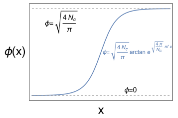


Fig. 2 Sine-Gordon kink field profile

α_k are Fourier coefficients of the classical kink profile:

$$\alpha_k = t_k c_k, \quad t_k = -\frac{i}{2k}, \quad c_k = \sqrt{2\sqrt{2}\pi N_c|k|}\frac{1}{\cosh\left(\sqrt{\frac{N_c}{4\pi}}\frac{\pi k}{2m'}\right)}$$

leading to a natural decomposition of the coherent state into topology and "energy":

$$|\alpha_k\rangle = e^{-\frac{1}{2}|t_k|^2|c_k|^2}\sum_{n_k=0}^{\infty}\frac{t_k^{n_k}c_k^{n_k}}{\sqrt{n_k!}}|n_k\rangle_t\otimes|n_k\rangle_c$$

Reduced density matrix after tracing over the topological degrees of freedom:

$$\rho_{red} = \bigotimes_k \rho_k = \bigotimes_k e^{-|\alpha_k|^2}\sum_{n_k=0}^{\infty}\frac{|\alpha_k|^{2n_k}}{n_k!}|n_k\rangle_c\langle n_k|_c$$

Compute the entanglement entropy:

$$S_k = -\mathrm{Tr}(\rho_k\log\rho_k) = |\alpha_k|^2(1-\log|\alpha_k|^2) + e^{-|\alpha_k|^2}\sum_{n=2}^{\infty}|\alpha_k|^2\frac{\log n!}{n!}$$

Estimate the asymptotic behavior at small and large *k* analytically; the rest can be computed numerically. Results are shown on Fig. 3

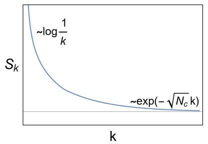


Fig. 3 Entanglement entropy as a function of momentum. Most entanglement is concentrated near zero momentum which corresponds to small x.

- We find entanglement between topological degrees of freedom (carrying the baryon number) and the rest of the baryon wavefunction.
- Entanglement is strongly enhanced at small momentum (fraction).

Proposal: semi-inclusive *ep*-collision tagging a forward baryon

A mature idea: junctions should lead to baryon stopping at heavy ion collisions [1].

Has been tested several times including by STAR with isobars recently: see e.g. the talk by C.Y. Tsang

A new idea: can we study junctions in ep-collisions? Yes!

- Tag a baryon in the virtual photon fragmentation region.
- Junction goes forward along with 2, 1 or 0 valence quarks (as shown on Fig. 4a-6a).
- The rest of the valence quarks break away from the junction producing unobserved mesons.
- The asymptotic *s*-dependence of the cross-sections estimated using optical theorem and Regge theory:

  $$\sigma \propto s^{\alpha(0)-1}$$

  where $\alpha(0)$ is the intercept of the state exchanged in the *t*-channel of squared diagram.
- For the states M_4^J, M_2^J, M_0^J (shown on Fig. 4b-6b) the intercepts are estimated as [3]:

  $$\alpha_{2k}^J = 2\alpha_B(0) - 1 + (3-k)(1-\alpha_R(0))$$

  for *k*=0, 1, 2. $\alpha_B(0)$ and $\alpha_R(0)$ are the baryon and reggeon intercepts respectively.
- M_0^J has the largest intercept so the corresponding process dominates at large *s*.
- Rapidity dependence estimated (see Fig. 7)

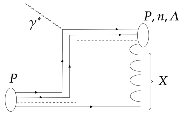


Fig. 4a The junction and two valence quarks in the forward direction. One string breaks producing unobserved X.

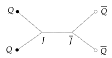


Fig. 4b M_4^J state exchanged in the t-channel of squared amplitude of Fig. 4a.

$$\alpha_4^J \approx -\frac{1}{2}$$

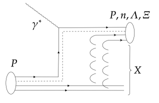


Fig. 5a The junction and one valence quark in the forward direction. Two strings break producing unobserved X.

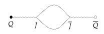


Fig. 5b M_2^J state exchanged in the t-channel of squared amplitude of Fig. 5a.

$$\alpha_2^J \approx 0$$

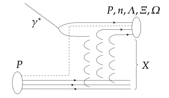


Fig. 6a Only the junction without valence quarks in the forward direction. Three strings break producing unobserved X.

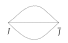


Fig. 6b M_0^J state exchanged in the t-channel of squared amplitude of Fig. 6a.

$$\alpha_0^J \approx \frac{1}{2}$$

- Flavor-independent forward baryon production rate since no valence quarks remain with the junction
- Large flavor-independent meson multiplicity
- Characteristic rapidity dependence (see Figure 7), decreasing in the forward direction slower than naively expected

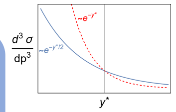


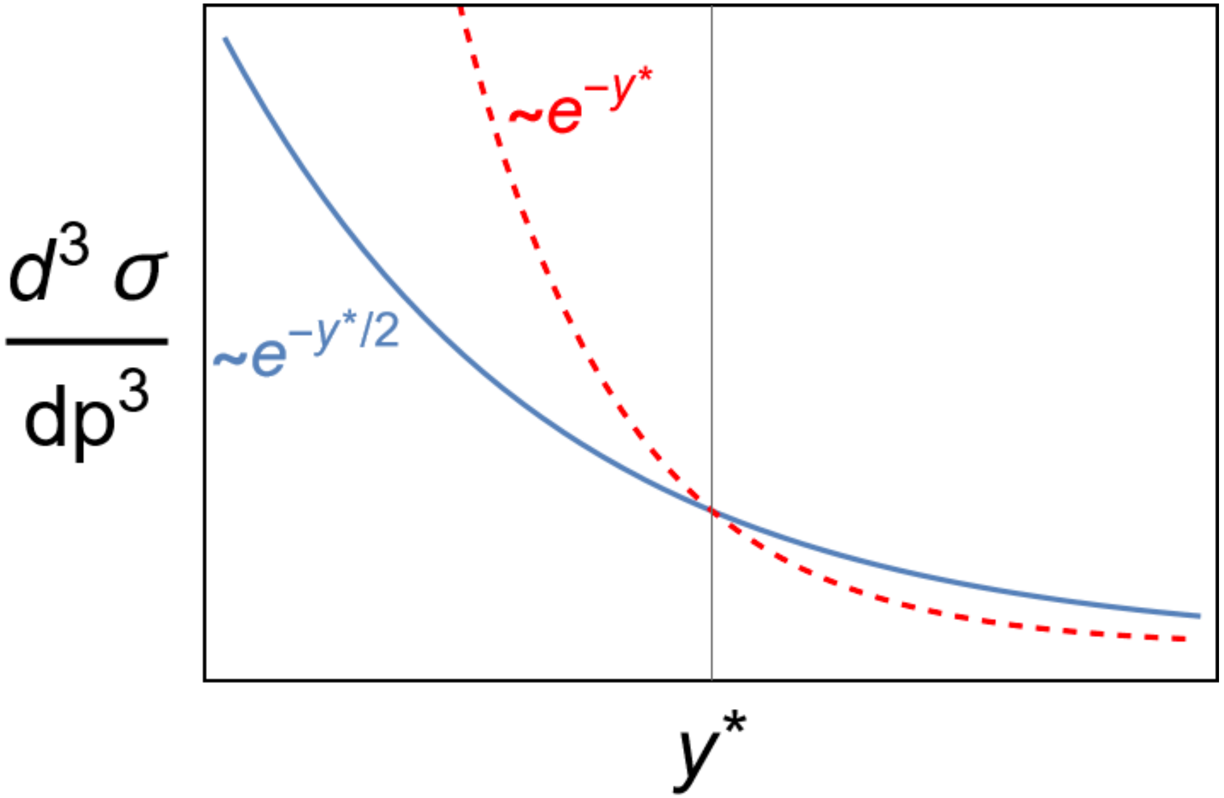
Fig. 7 Differential cross-section as a function of produced baryon COM rapidity y^*. Solid blue line: leading M_0^J exchange. Dashed red: subleading exchange or a naive expectation with baryon exchange.

Conclusion

Bibliography

[1] D. Kharzeev, Phys. Lett. B 378, 238 (1996)
[2] A. Florio, D. Frenklakh, D. Kharzeev, Phys.Rev.D 106 (2022)
[3] G.C. Rossi, G. Veneziano Nucl.Phys.B 123 (1977)

EIC

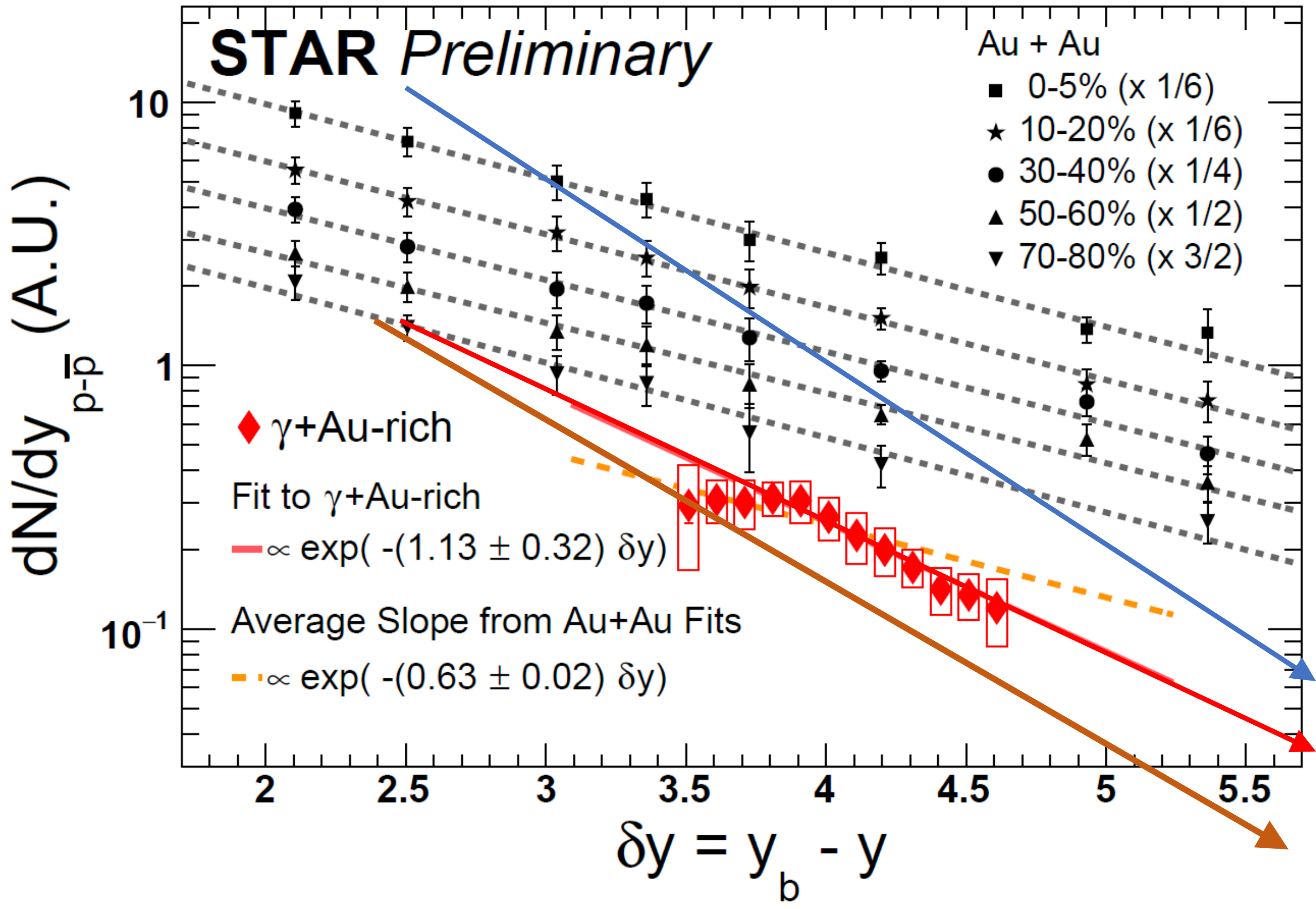


Similar to γ+Au collisions?

Tracking the origin of baryon number at EIC

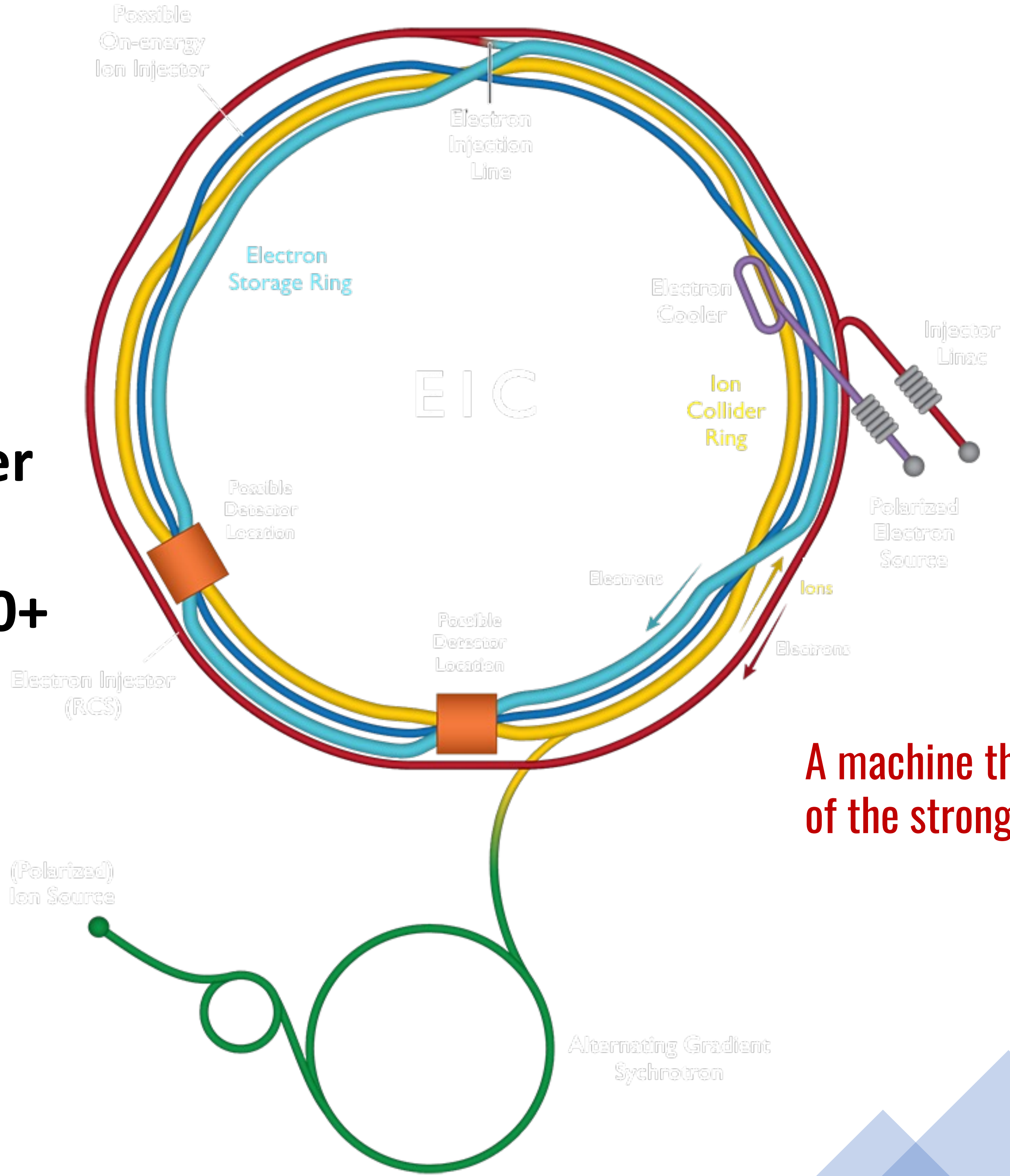
- RHIC nuclear energy is at a sweet spot
  - U+U, Au+Au, O+O, Cu+Au, Cu+Cu, He3+Au, d+Au,p+Au, p+p
- LHC and HERA energy are too high with small baryon excess (<1%)
- Isobar collisions at EIC with low Q^2 and low-p_t PID to study the charge and baryon transports
- EIC: extend to large range of rapidity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



Electron-ion Collider

Operational in 2030+



A machine that will unlock the secrets of the strongest force in Nature

Tracking the origin of baryon number at EIC

- RHIC nuclear energy is at a sweet spot
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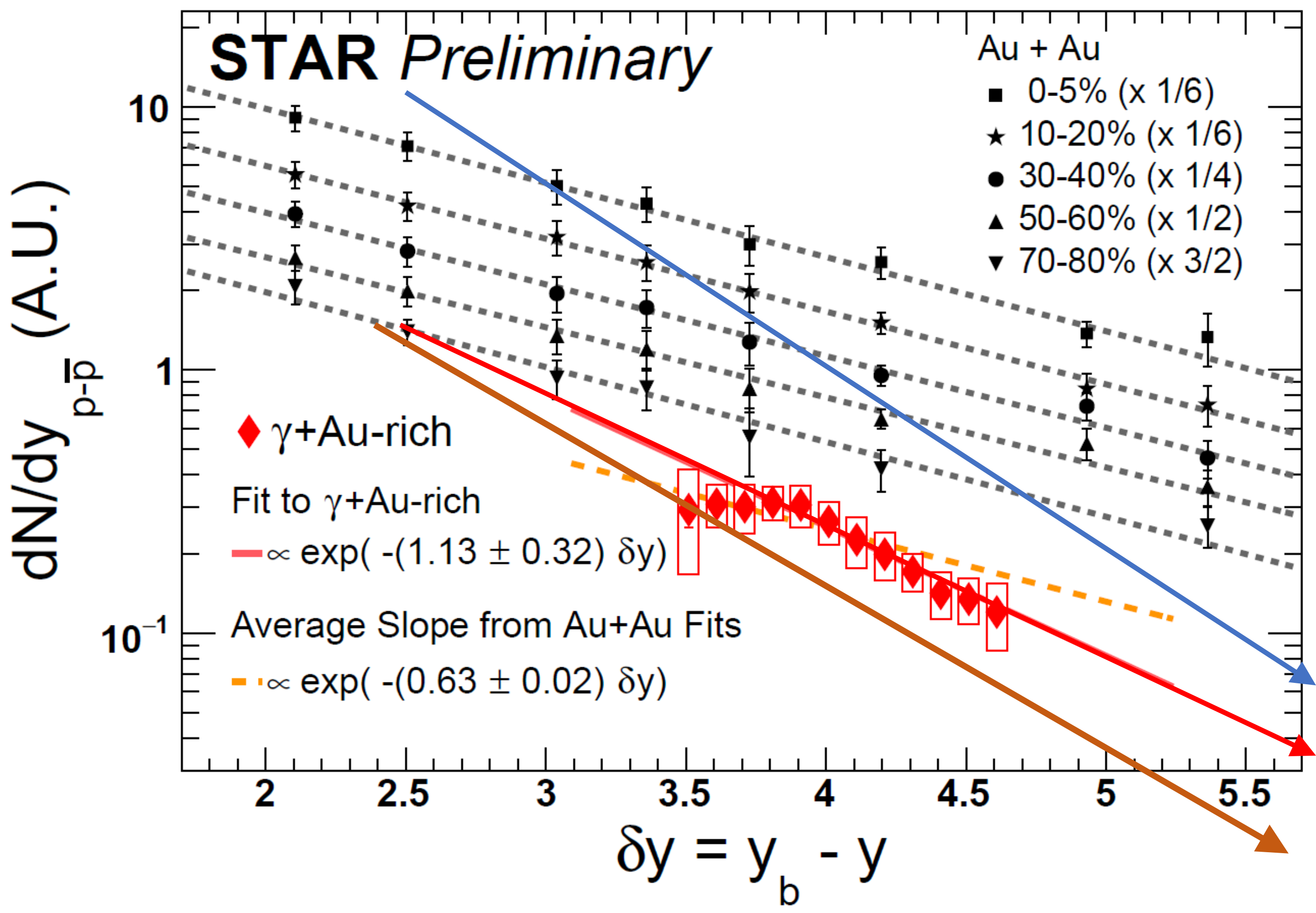

1st Workshop on Baryon Dynamics from RHIC to EIC

Jan 22 – 24, 2024
CFNS
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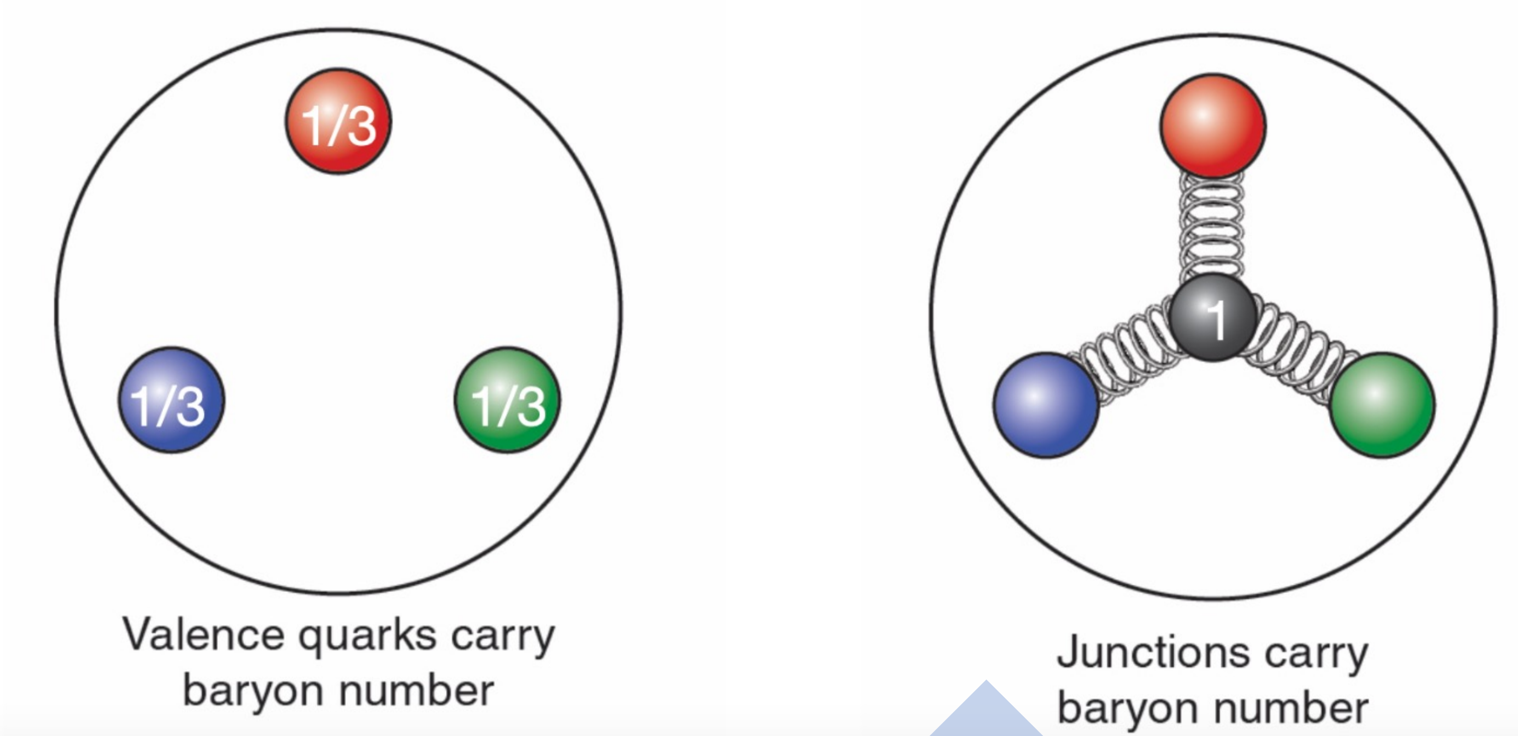
Contact Person

The 1st workshop on Baryon Dynamics from RHIC to EIC will be held at Center for Frontiers in Nuclear Science (CFNS), Stony Brook University, on Jan 22-24, 2024.

This workshop aims to address fundamental questions such as what carries the baryon quantum number and how a baryon is stopped in high-energy collisions.



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, large rapidity coverage and low-momentum hadron particle identification

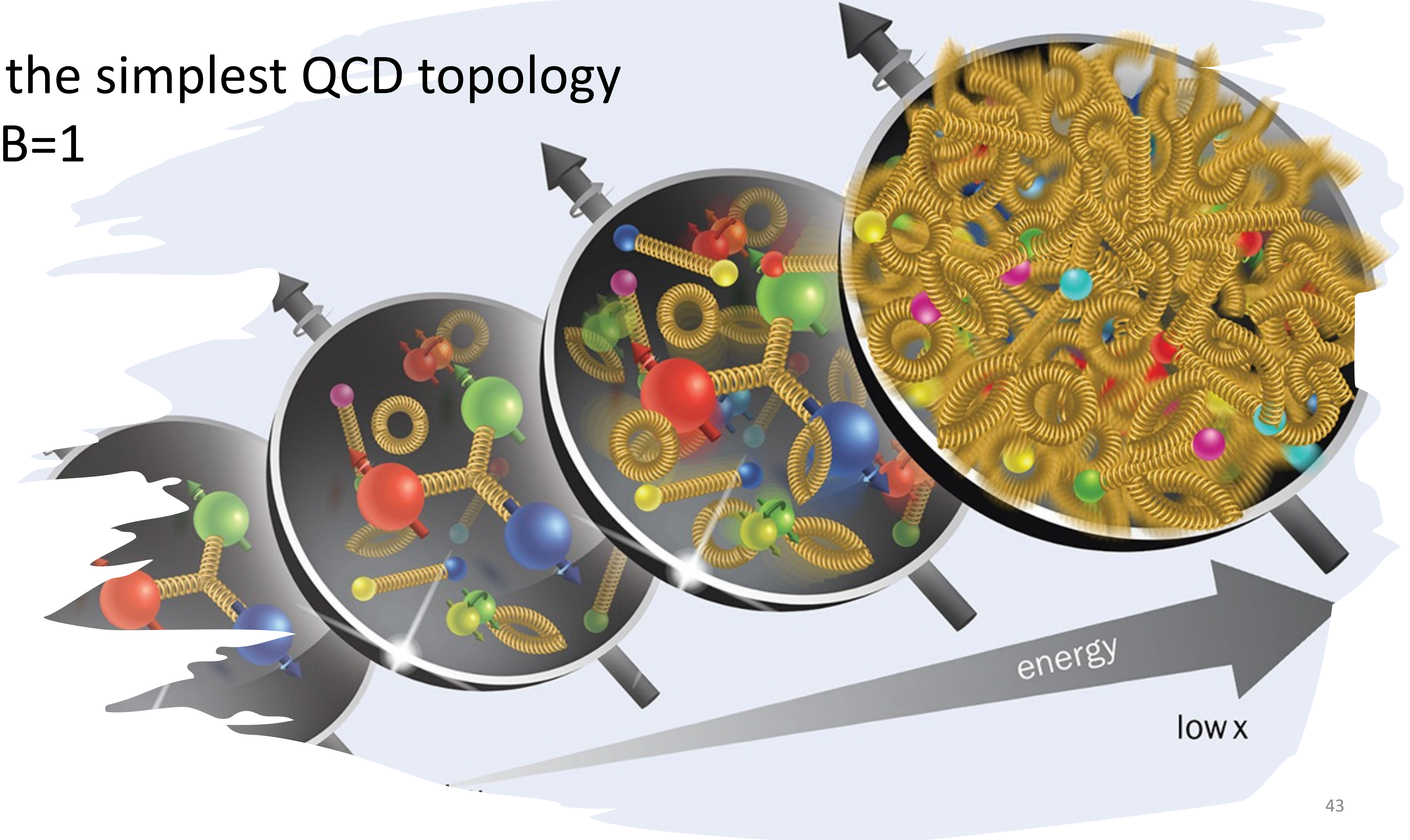
$$Q^2 \leq 1\ GeV^2$$

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

- Isobar collisions to measure charge transport (quark transports),
  Zr/Ru; $^{7}Li/^{7}Be$
- EIC can measure the baryon junction distribution function
- Explore other signatures at EIC

the simplest QCD topology

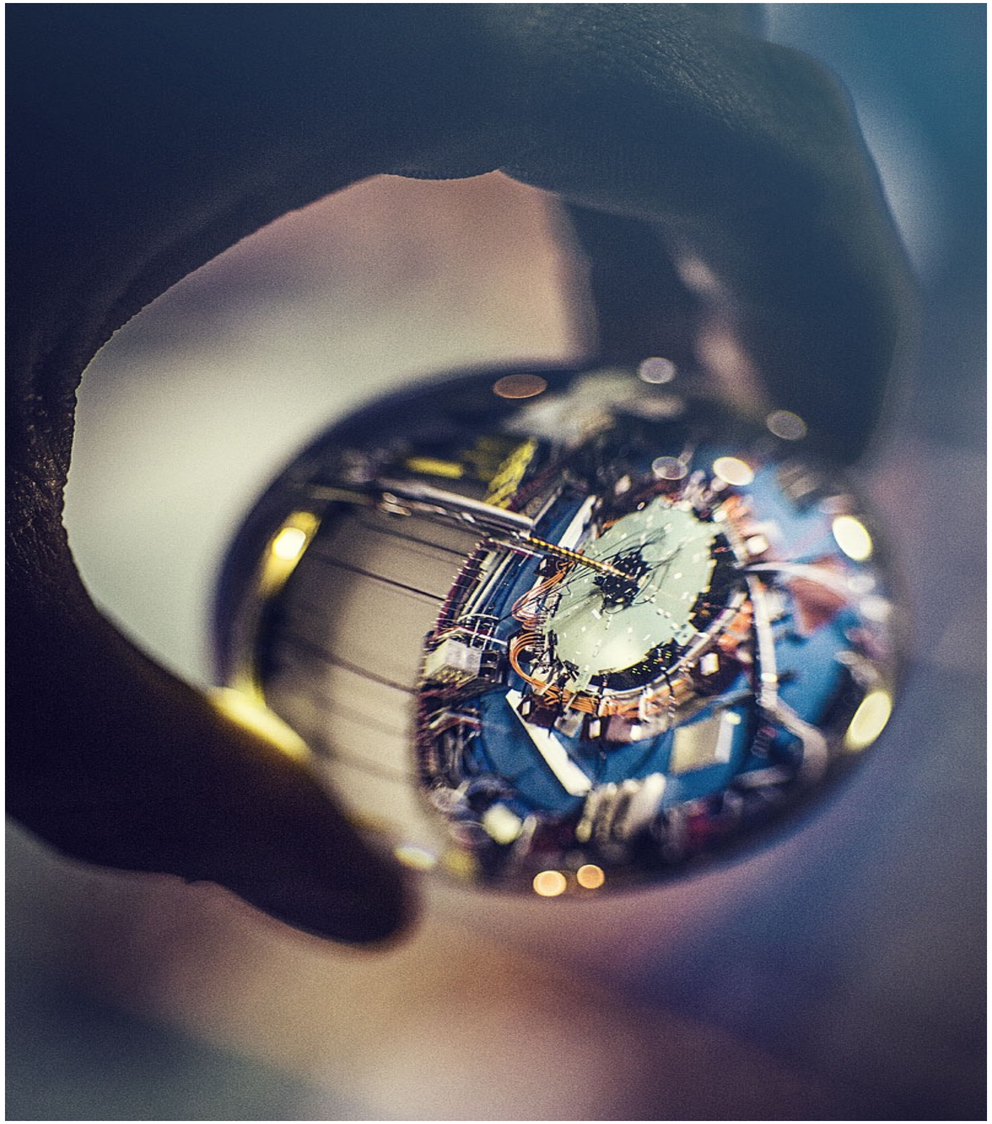
B=1



Solenoidal Tracker at RHIC

Artistic rusty representation of past and present

Crystal Ball prediction of future (literately)



Still an indispensable discovery detector
Exciting time with all the new facilities!