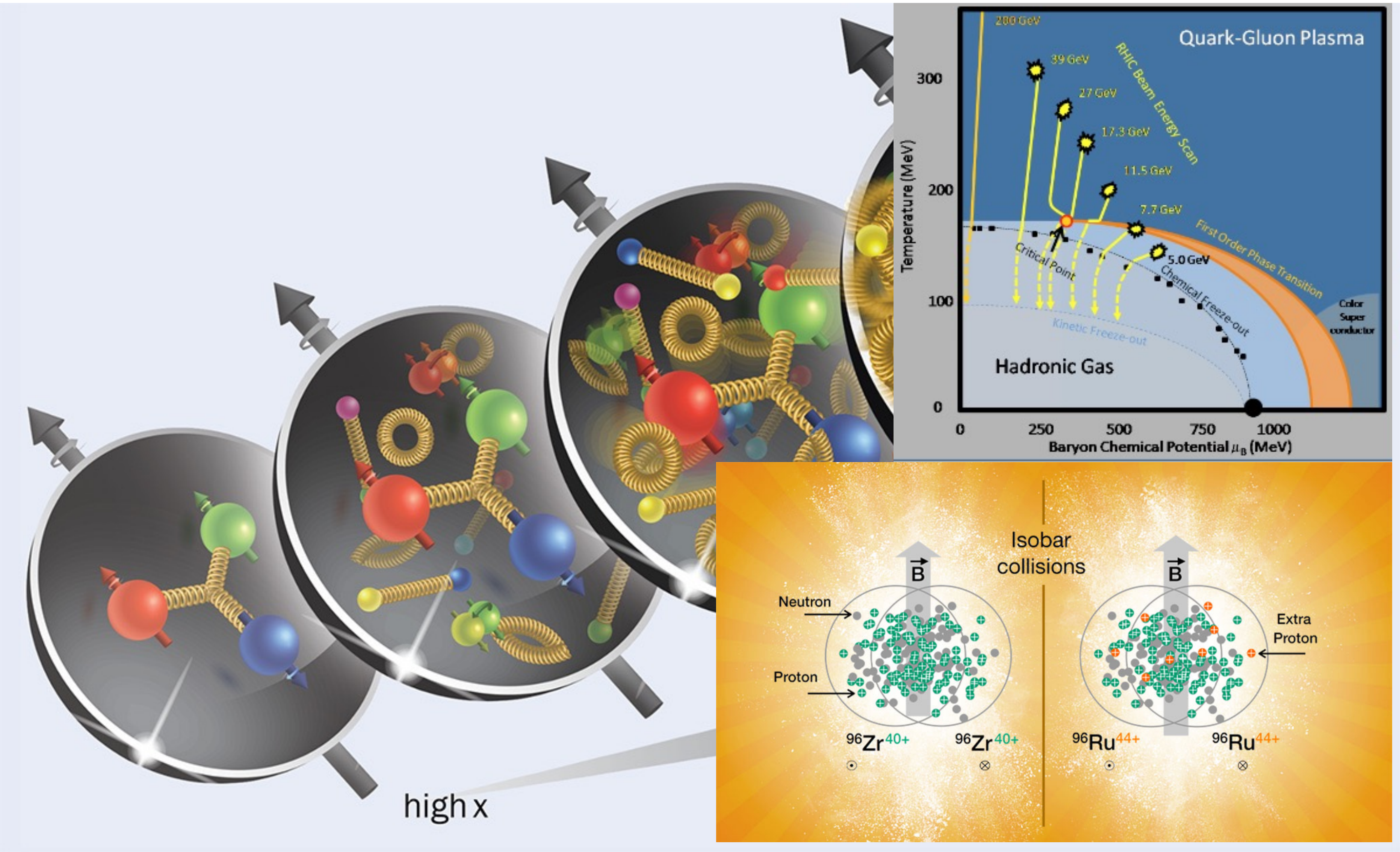
Tracking the Baryon Number in Heavy-ion Collisions



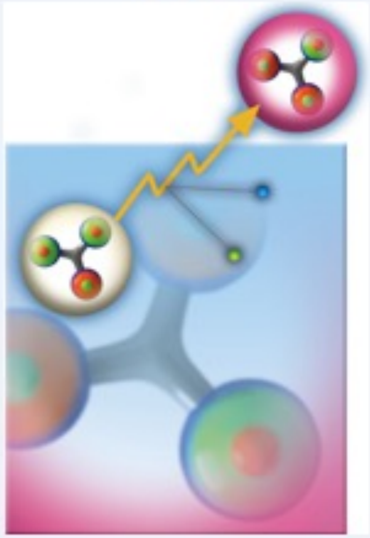
Zhangbu Xu
(Brookhaven National Lab)

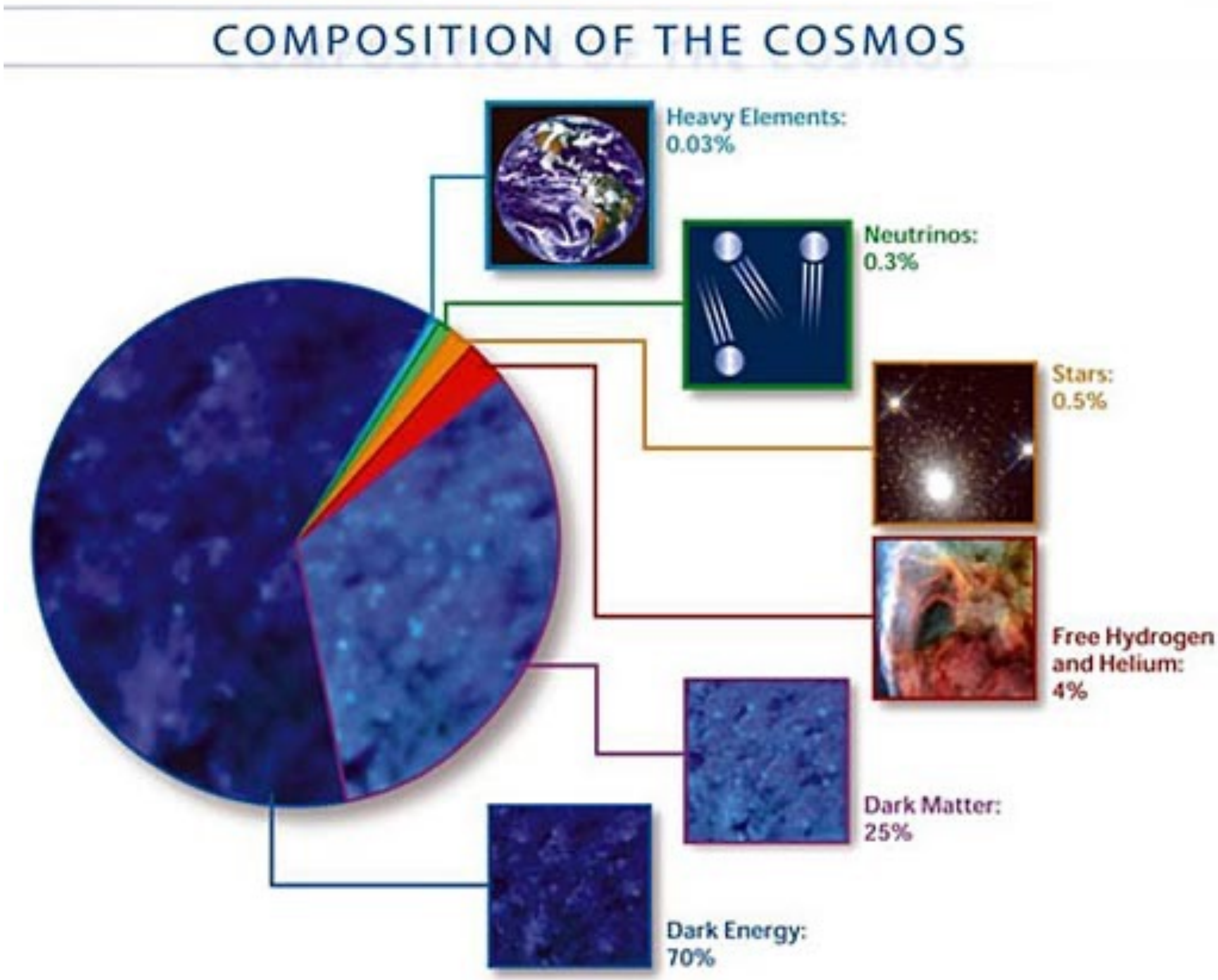
- Introduction to QCD at RHIC
- Three Measurements
- Previous Results and Future Perspectives

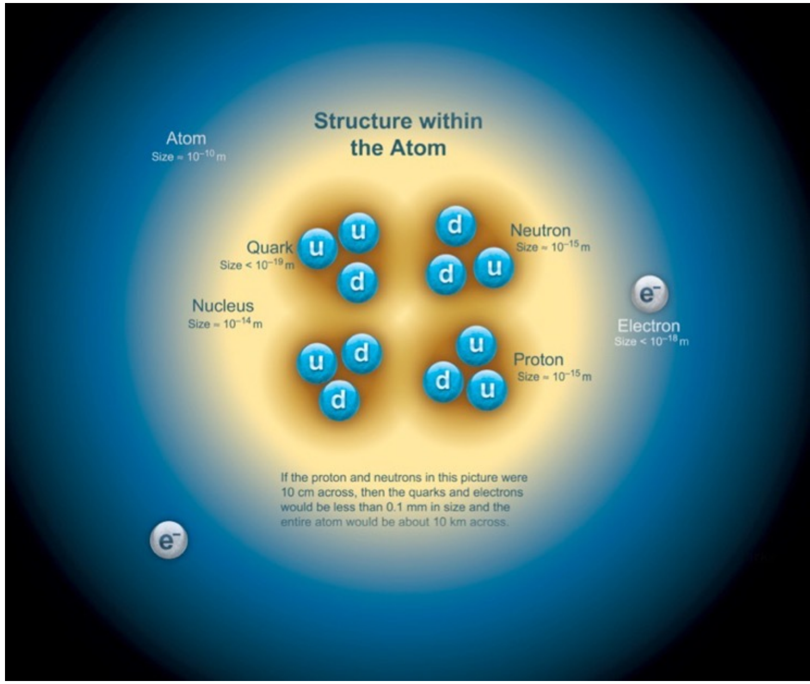
Zimanyi Winter School, 12/05/2023

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



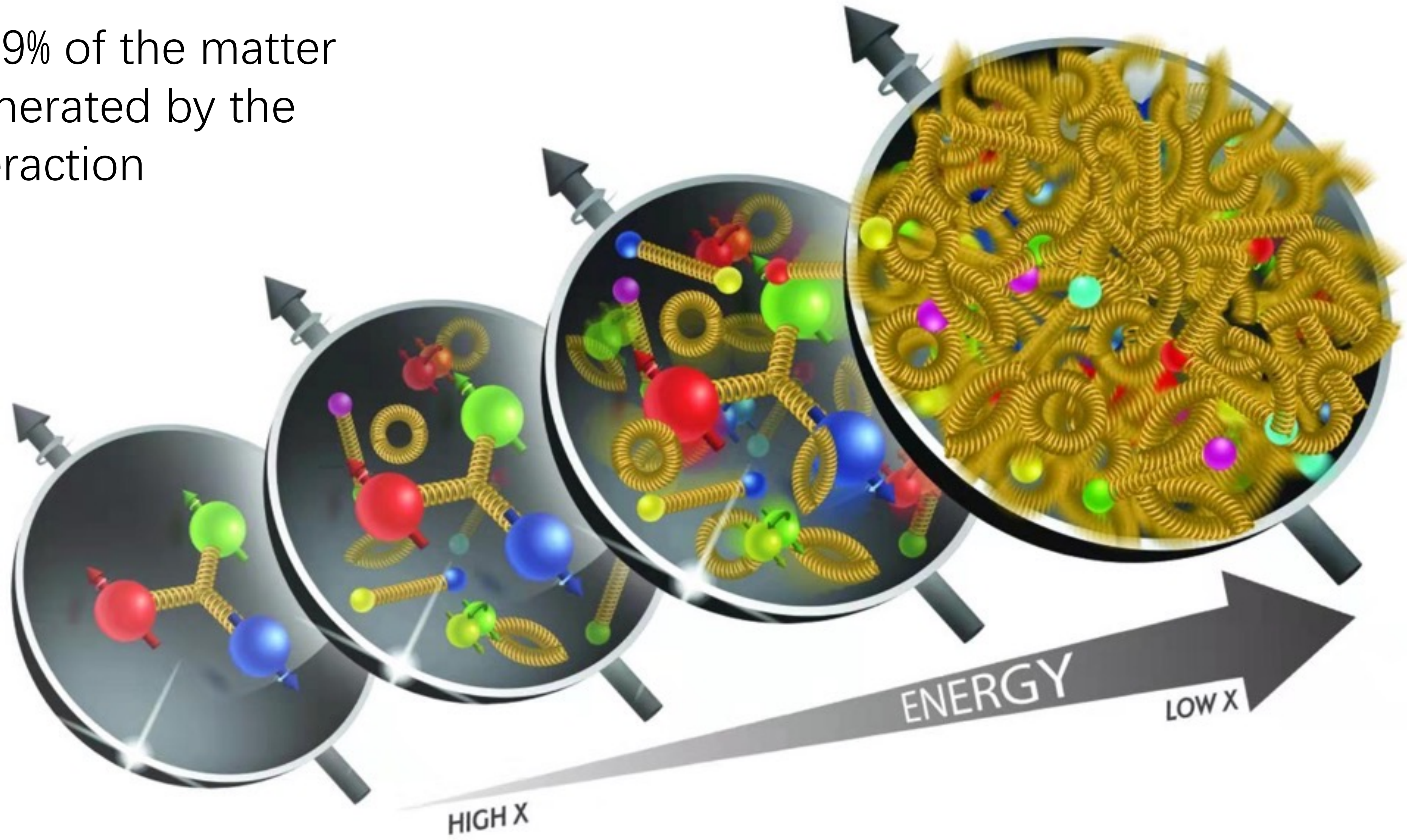


For the 4% of ordinal matter, they are mainly made of baryons: protons and neutrons

Quantum Chromodynamics (QCD)

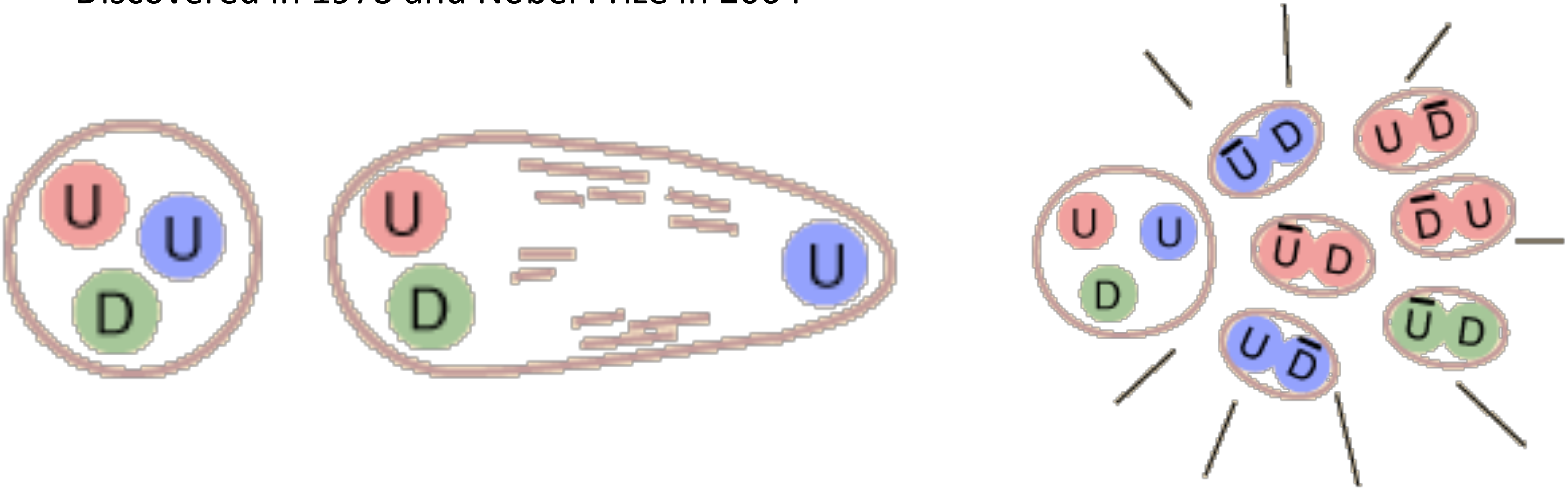
Using relativistic heavy-ion collisions to investigate the simplest QCD topology

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



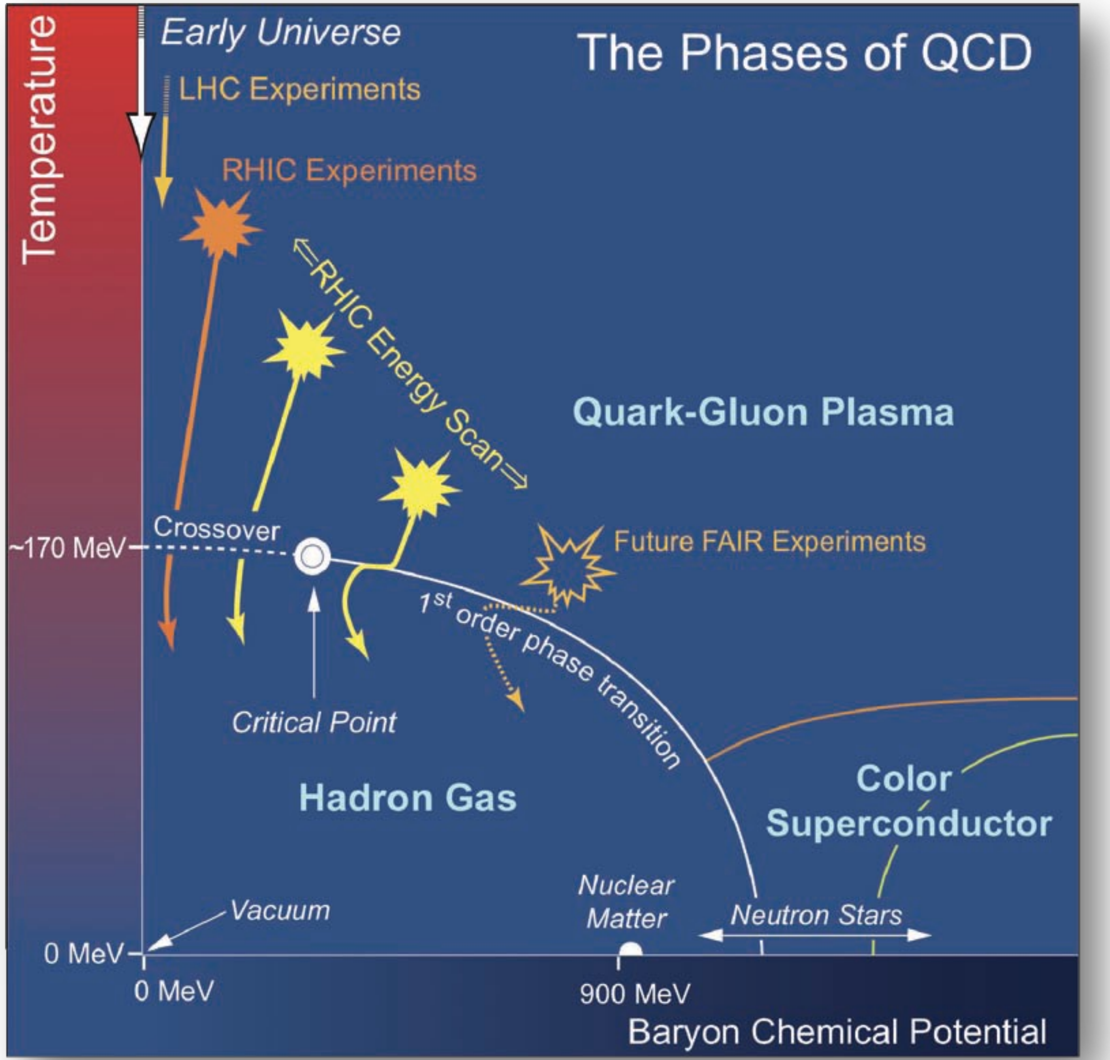
QCD strange behavior

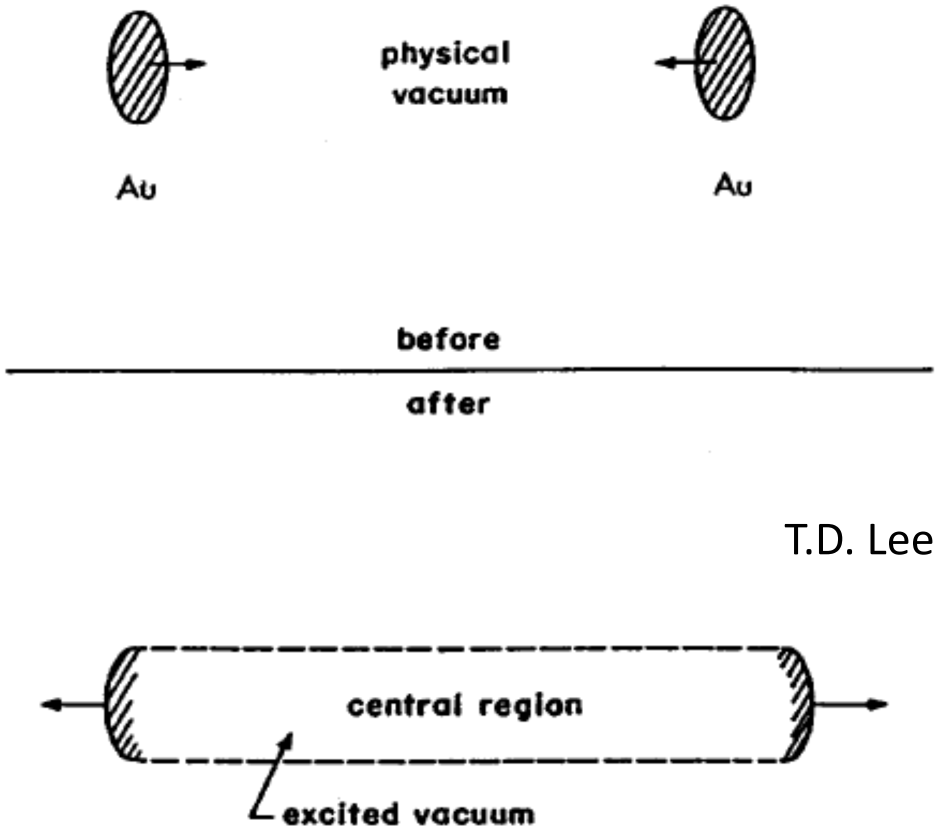
Confinement and Asymptotic freedom
Discovered in 1973 and Nobel Prize in 2004



Free quarks in excited vacuum

2007 NSAC Long Range Plan

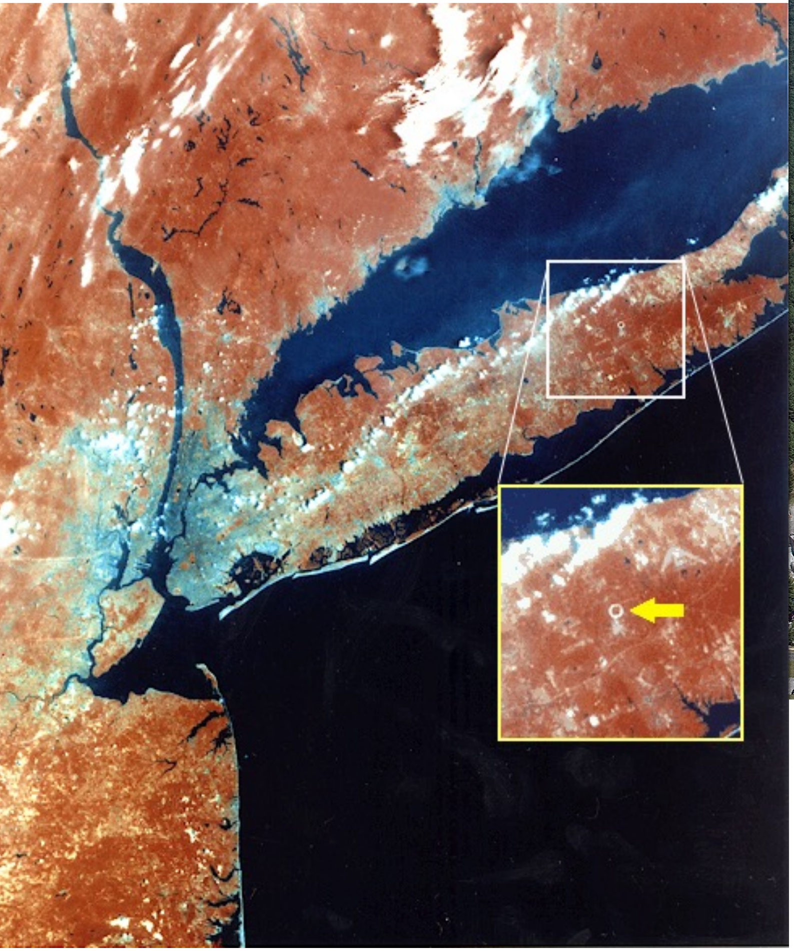


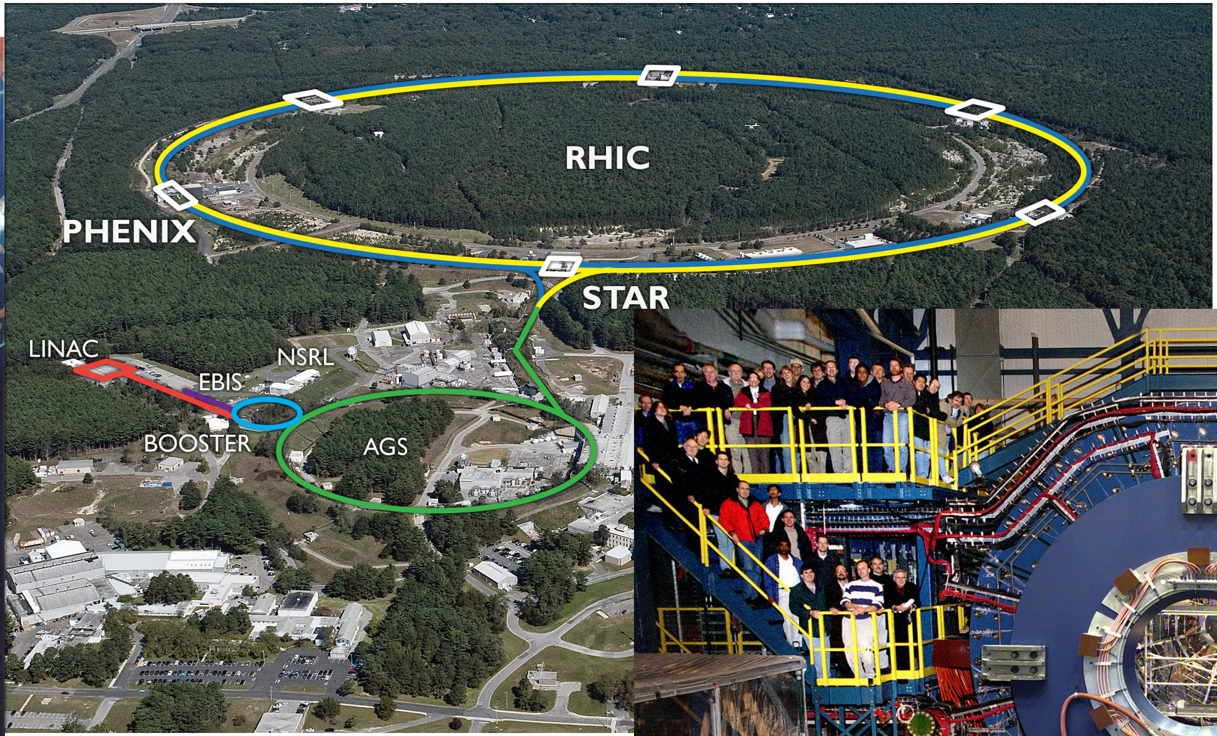


T.D. Lee (1970s)

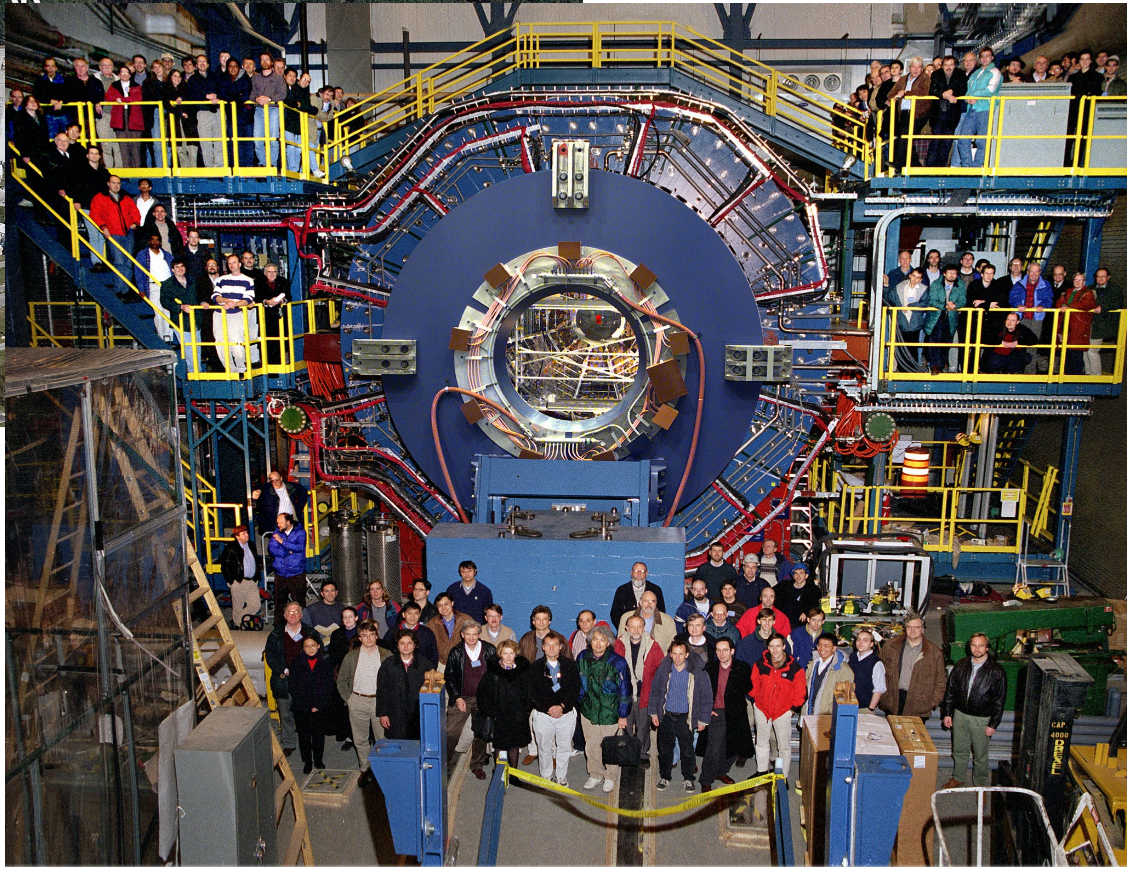
Figure 2. Vacuum excitation through relativistic heavy ion collisions.

Our Experiment: the STAR Collaboration at RHIC



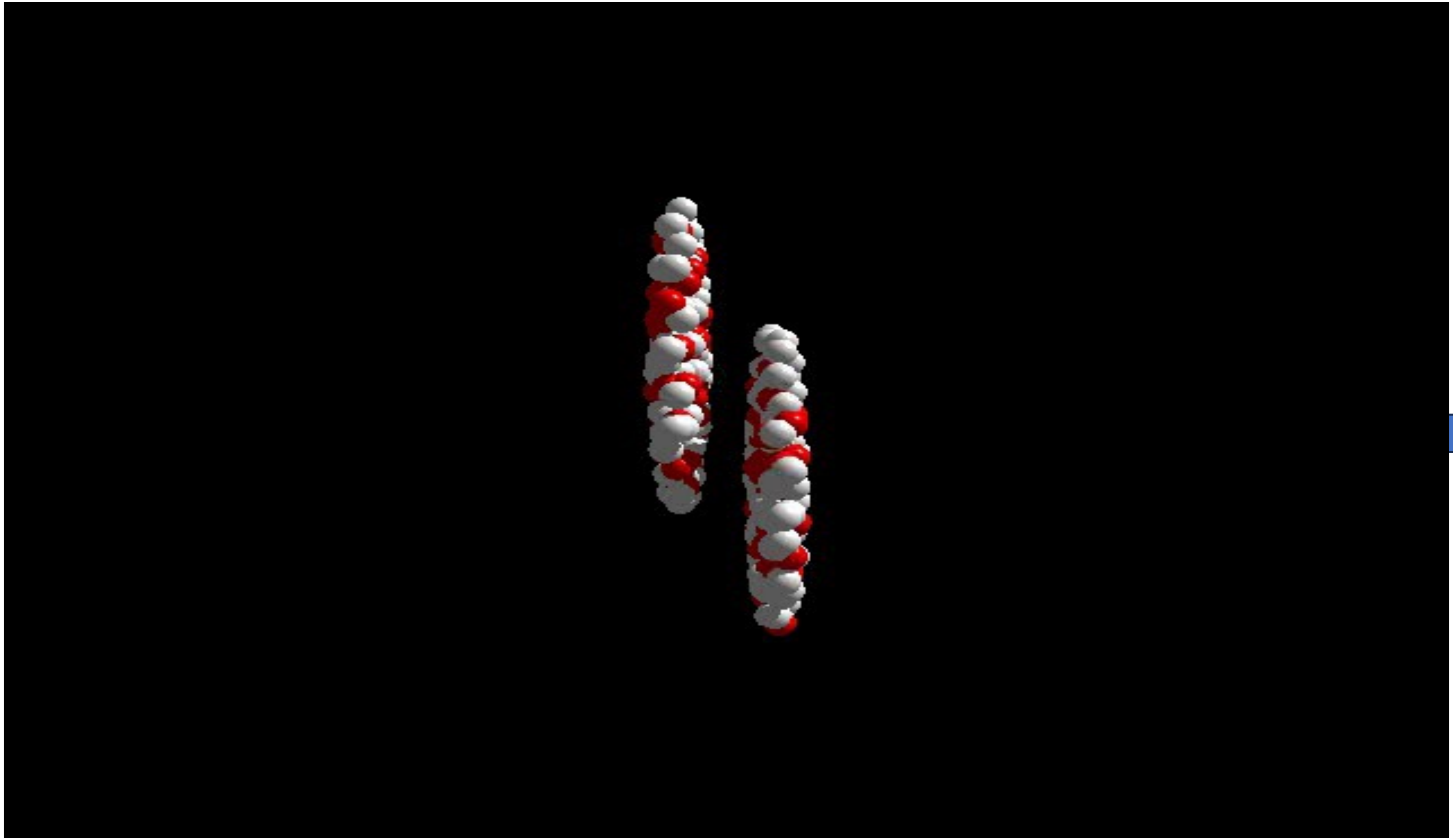


My term as spokesman (2014-17) ,
co-spokesperson (17-20),
institutions from 48-> 70



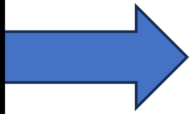
Relativistic Heavy Ion Collider (RHIC) is 3.8km in length
STAR Collaboration: 700+ scientists from 14 countries
Established in 1993, and operational since 2000
www.star.bnl.gov

Ultra-relativistic heavy-ion collisions



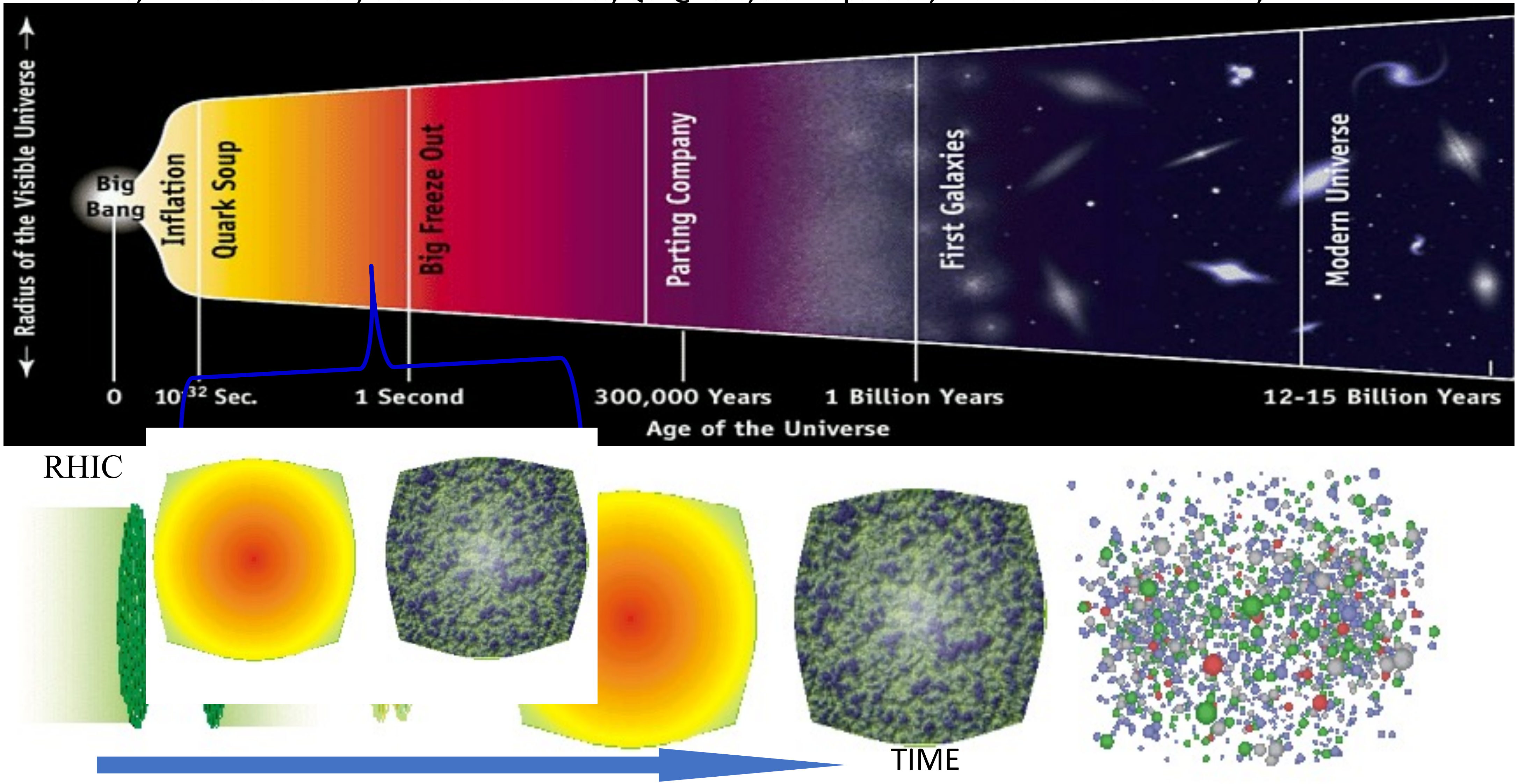
UrQMD event

Rapidity = +-5



Little Big Bang

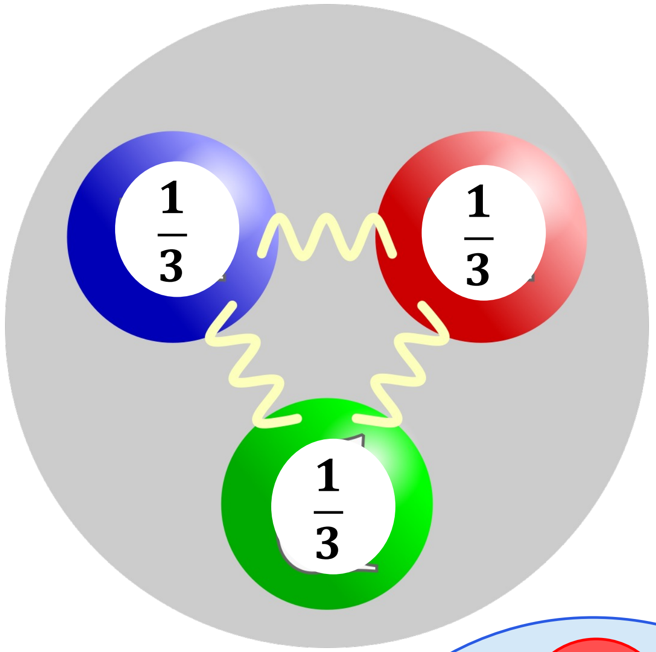
BIG; All 4 forces at work; Gravitation dominates; QGP@10^{-6}s; Slow expansion; Antimatter-matter annihilate;



Little; Strong force at work; QGP@10^{-23}s; Fast expansion; Antimatter-matter decouple; repeat trillion times

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
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  - Quarks are connected by gluons
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  - A Y-shaped gluon junction topology carries baryon number (B=1)
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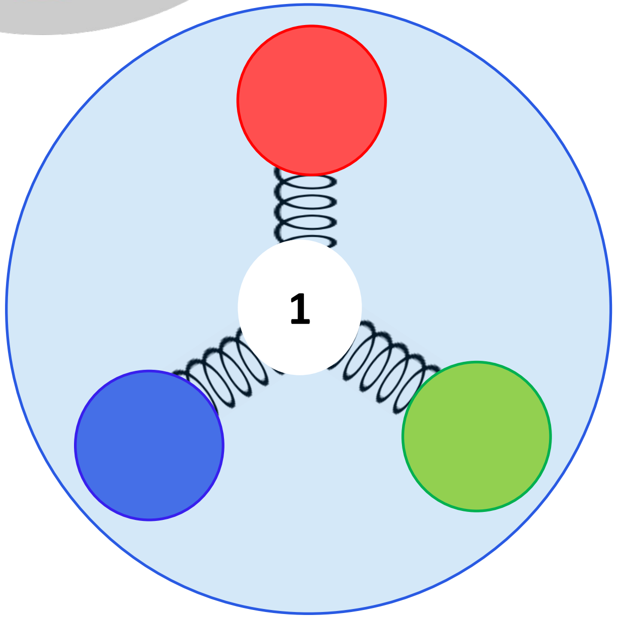
  - Valence quarks are connected to the end of the junction always
-



[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**)

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

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" .

20 June 1996

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 378 (1996) 238–246

Can gluons trace baryon number?

D. Kharzeev

Theory Division, CERN, CH-1211 Geneva, Switzerland
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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- …

… state vector which is gauge-invariant – the constraint 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):

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

… quark fields (see Fig. 1a). The B in Eq. (1) is a set of gauge invariant operators representing a baryon in QCD. With properly optimised parameters … extensively in the first principle computation… tice Monte Carlo attempting to determine th… mass. The purpose of this work is to study … nomenological impact on baryon number … in the central region of nucleus-nucleus coll…

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

PII S0370-2693(96)00435-2

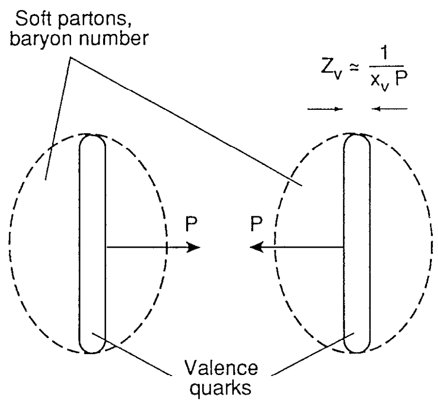


Fig. 2.

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 …

[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.

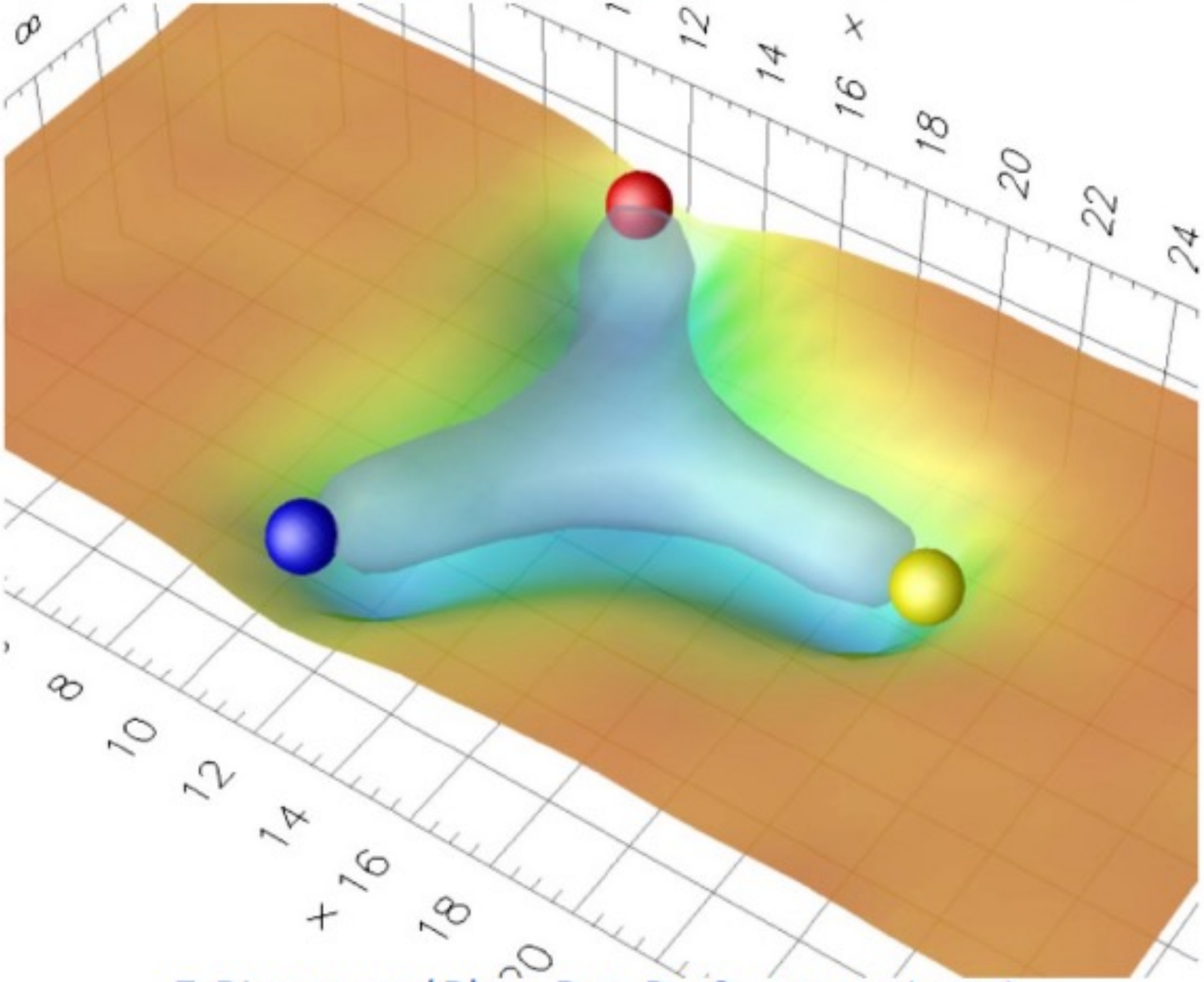
We shall now proceed to more quantitative considerations. In the topological expansion scheme [1], the separation of the baryon number flow from the flow of valence quarks in baryon-(anti)baryon interaction can be represented through a t-channel exchange of the quarkless junction-antijunction state with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

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

Y-Shaped Baryon Flux-Tube in Lattice QCD



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

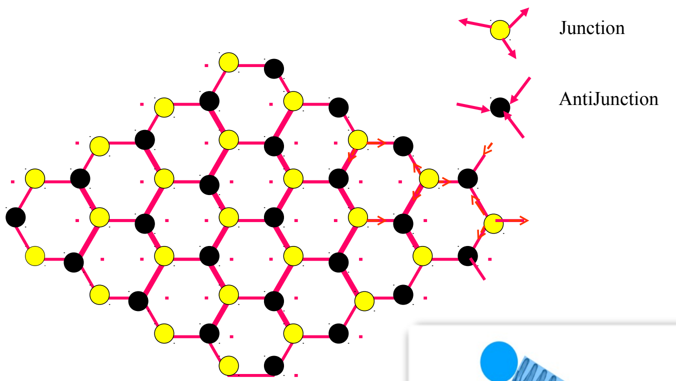
- Some lattice calculations have suggested the formation of a Y-shaped color flux tube among the three quarks at long distances

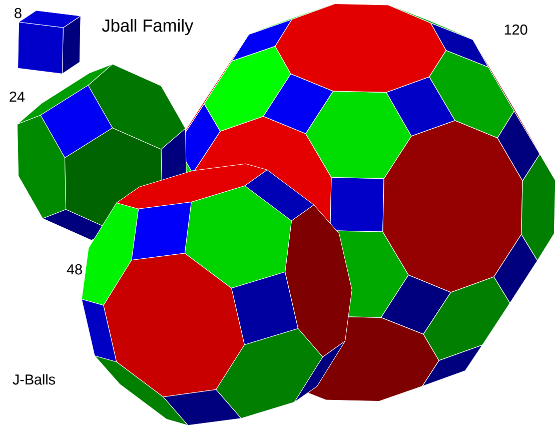
  T. T. Takahashi, *et al* Phys. Rev. Lett. **86**, 18 (2001).

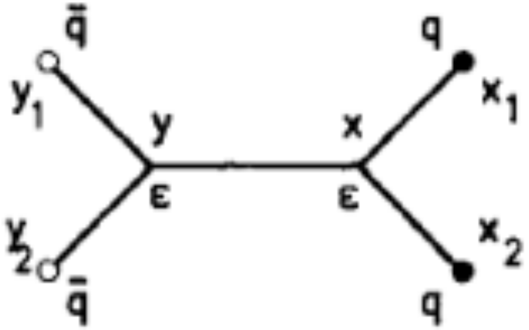
  T. Takahashi, *et al*, Phys. Rev. D **65**, 114509 (2002)

- Still under investigation

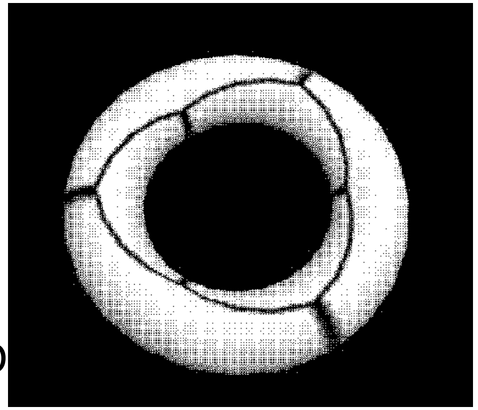
Junction anti Junction Gluon "Graphite"



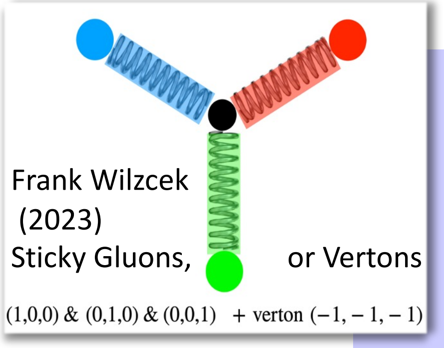




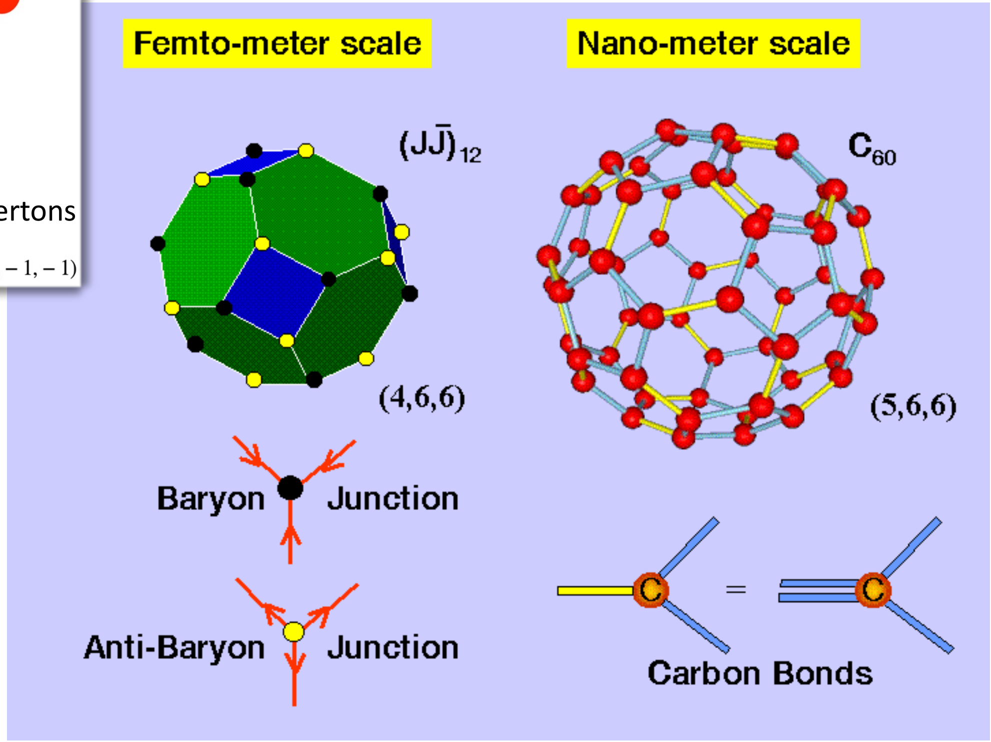
Veneziano, 50 years of QCD
arXiv:1603.05830

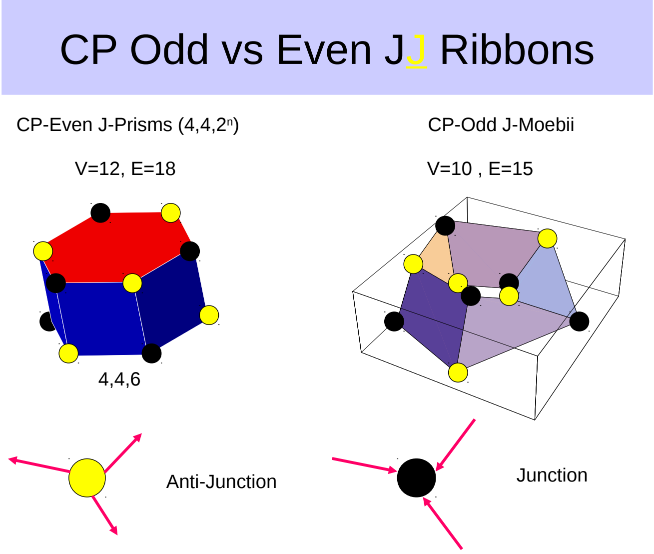


Baryonium Torus, O.I. Piskounova
hep-ph/1909.08536



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

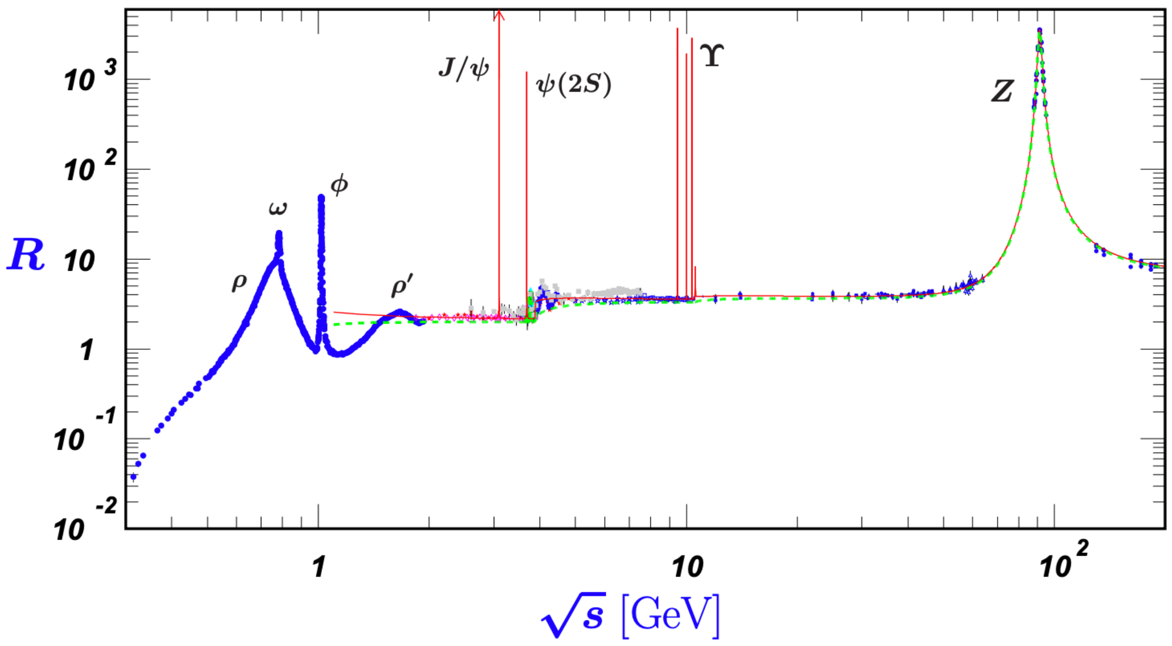
Measurements of quark electric charges

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

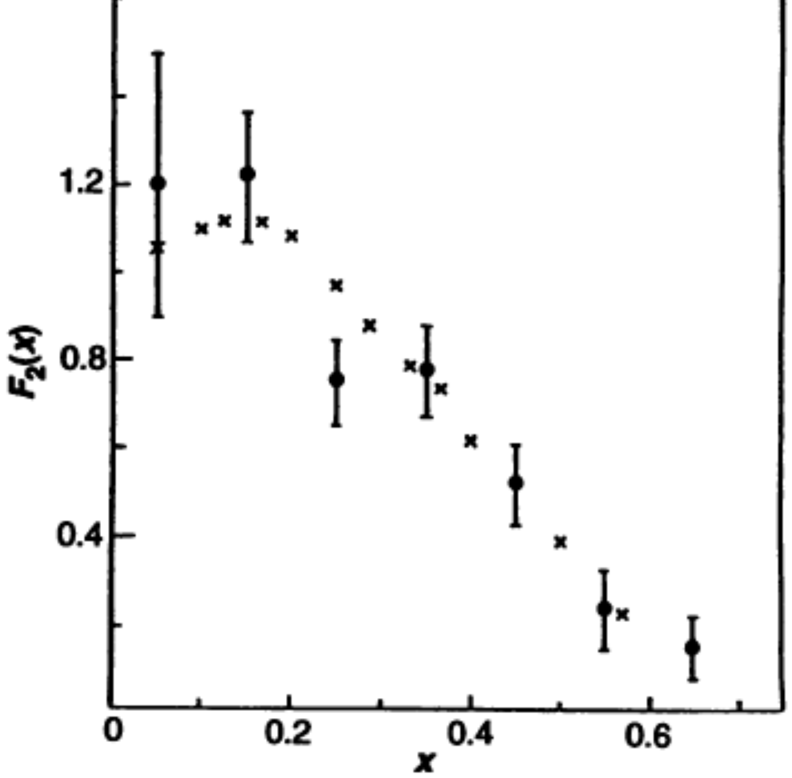
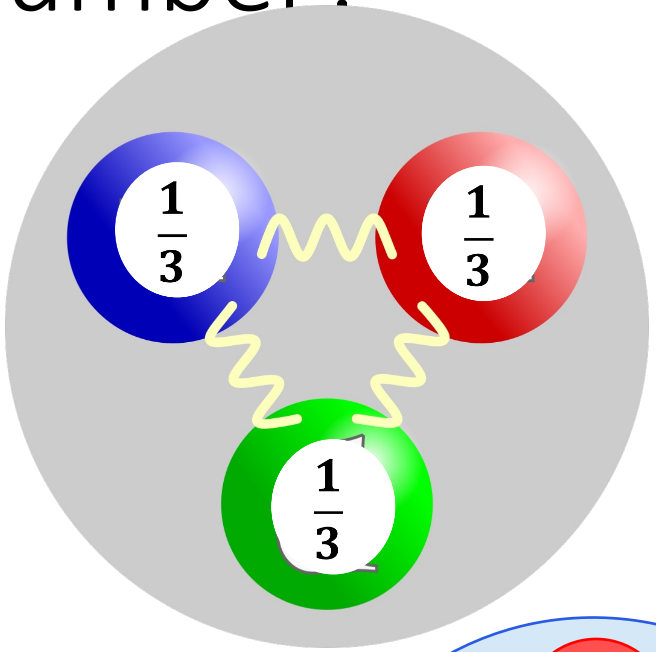


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (×), MIT-SLAC, $(18/5)F_2^{eN}$]. When multiplied by 18/5, a number specified by the quark-parton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

Measurements of quark baryon number?



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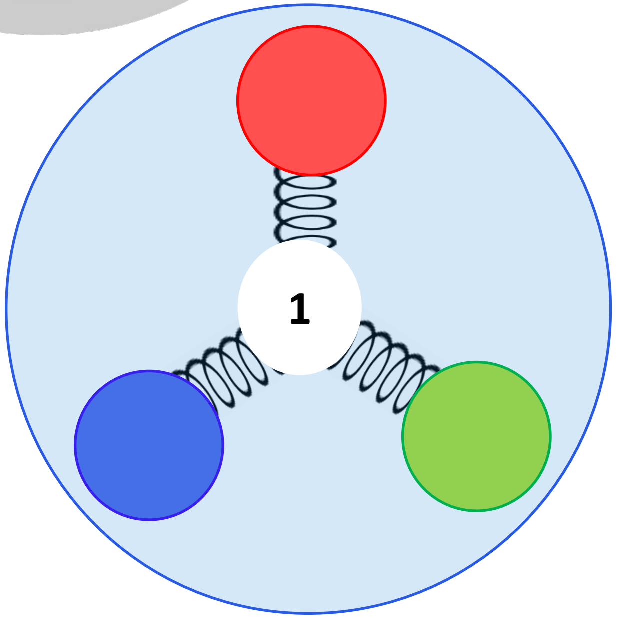
  - A Y-shaped gluon junction topology carries baryon number (B=1)
  - The topology number is the strictly conserved number
  - Quarks do not carry baryon number
  - Valence quarks are connected to the end of the junction always
- **Neither of these postulations has been verified experimentally**



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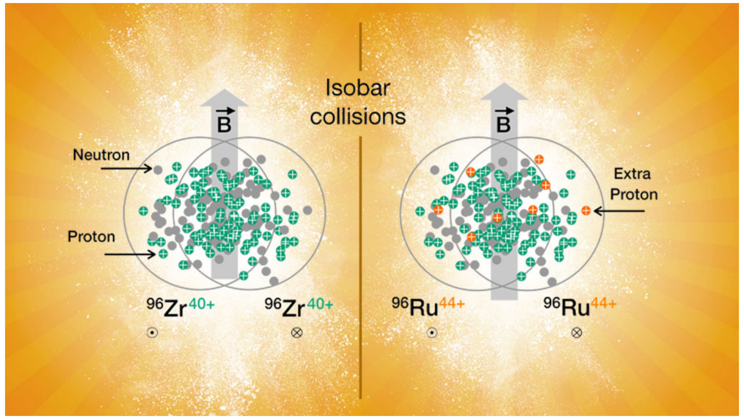
[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

Three approaches toward tracking the origin of the baryon number

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

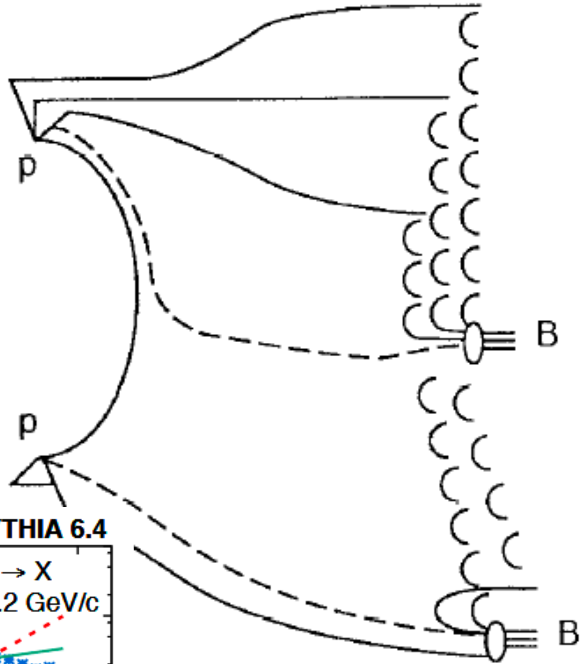
1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity



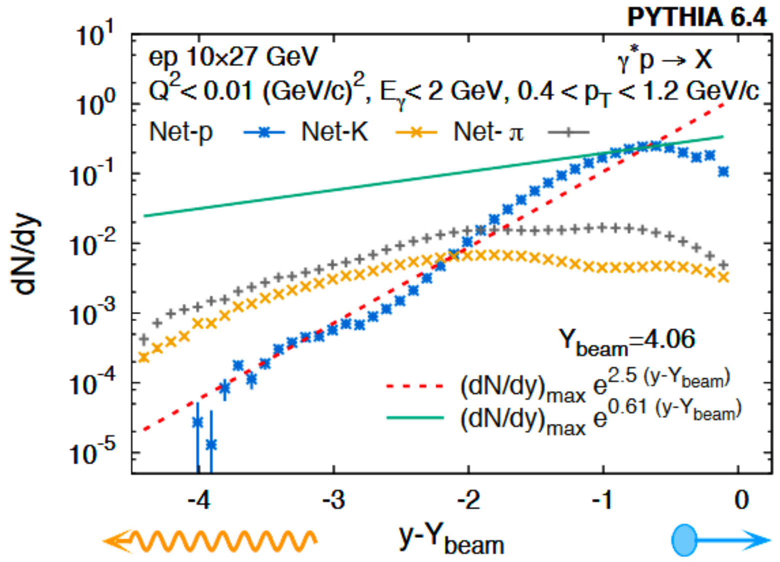
2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

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

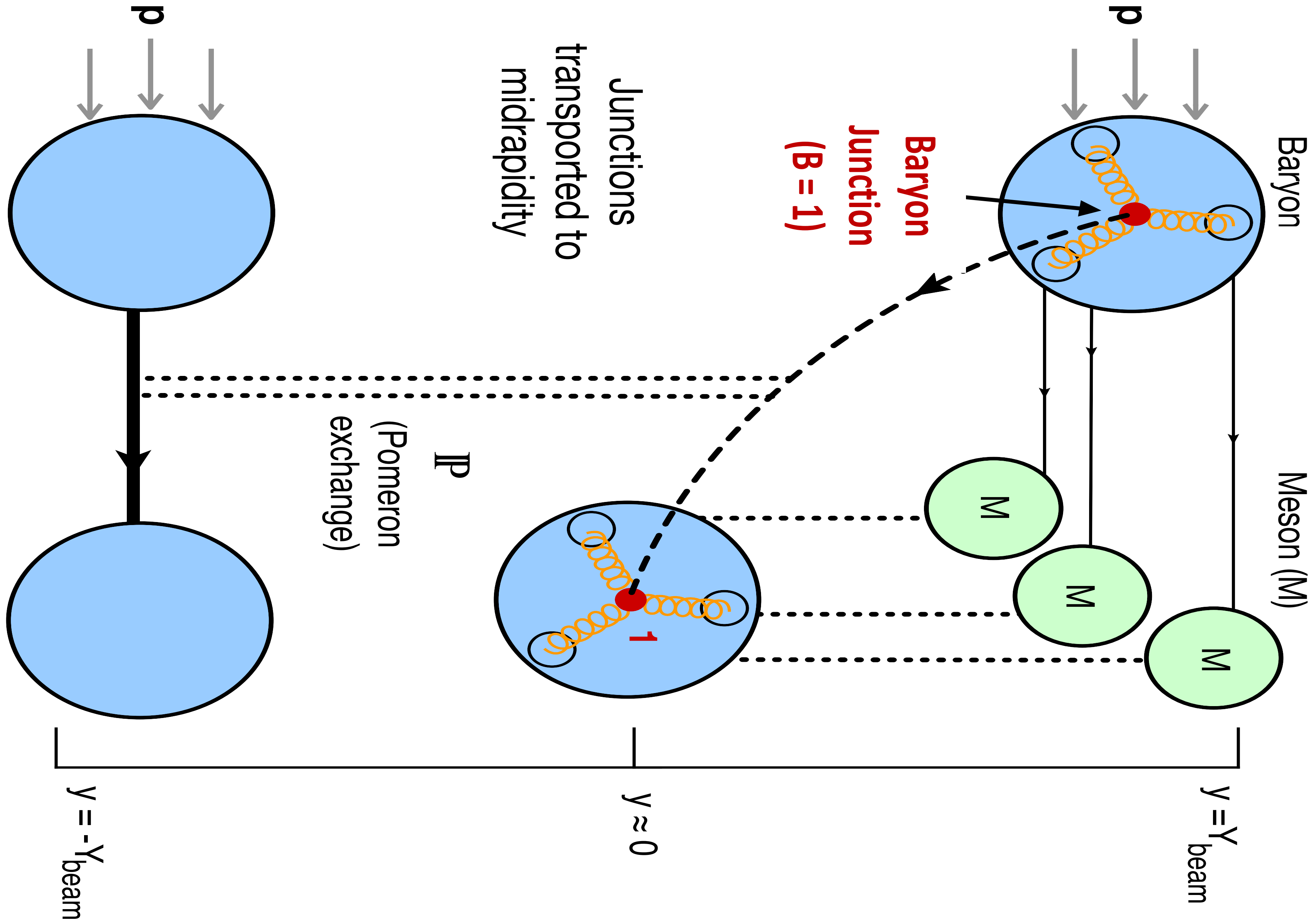
α_B ~=0.5



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



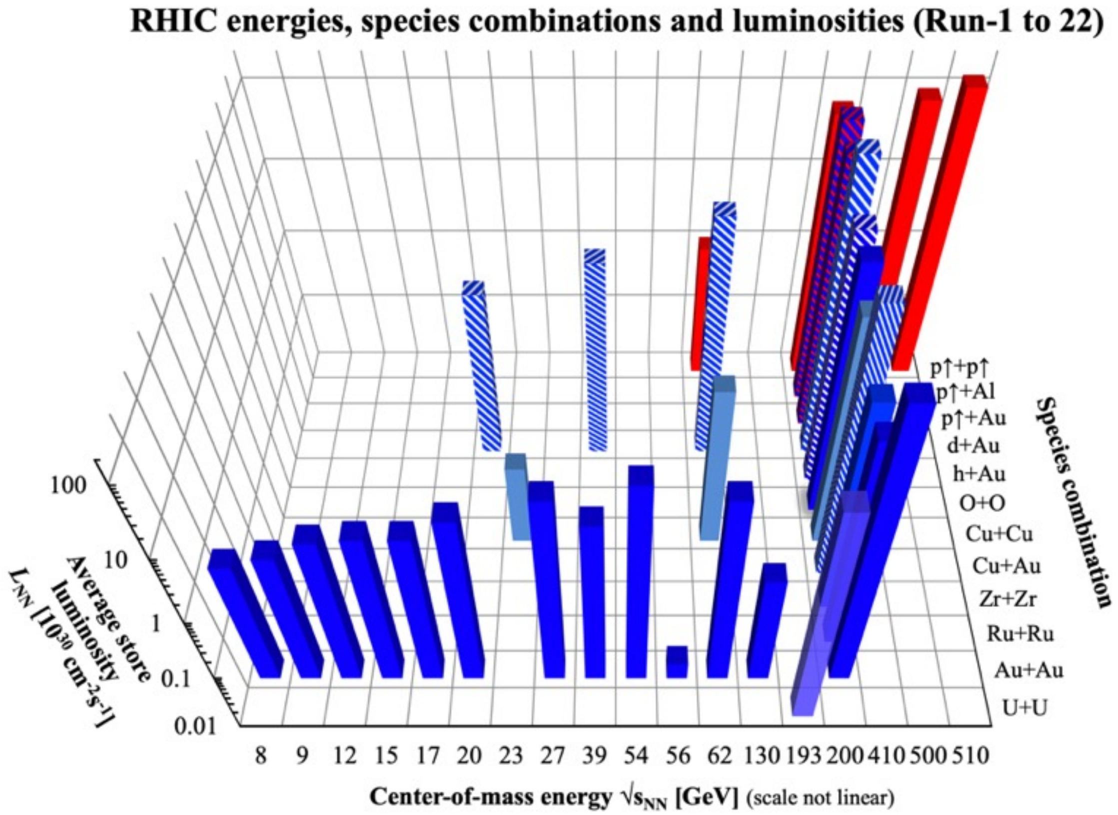
Baryons from target to midrapidity



Rapidity = +-5

Example of versatile colliders and detectors

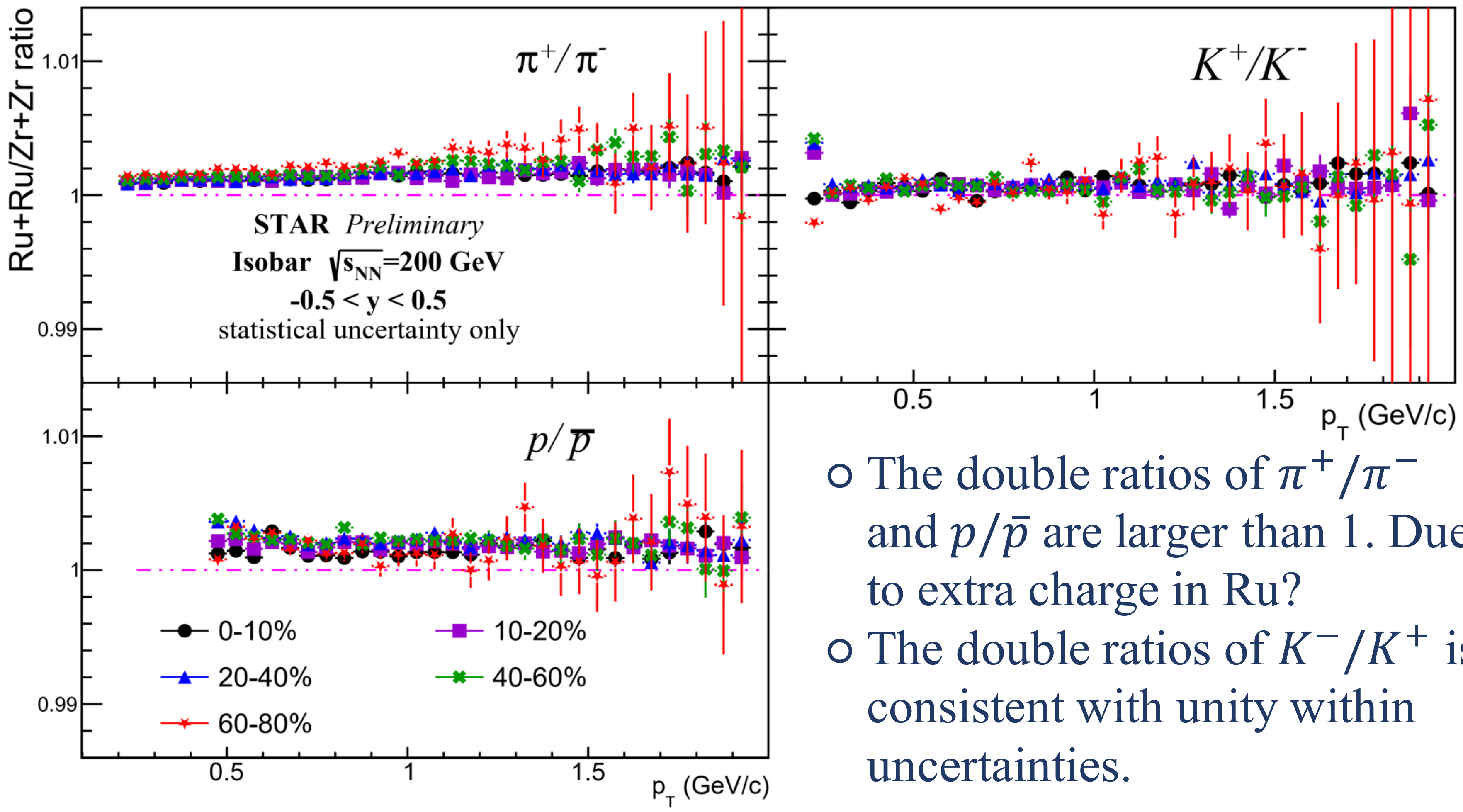
major upgrades over the last twenty years to improve particle identification and vertex reconstruction and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.

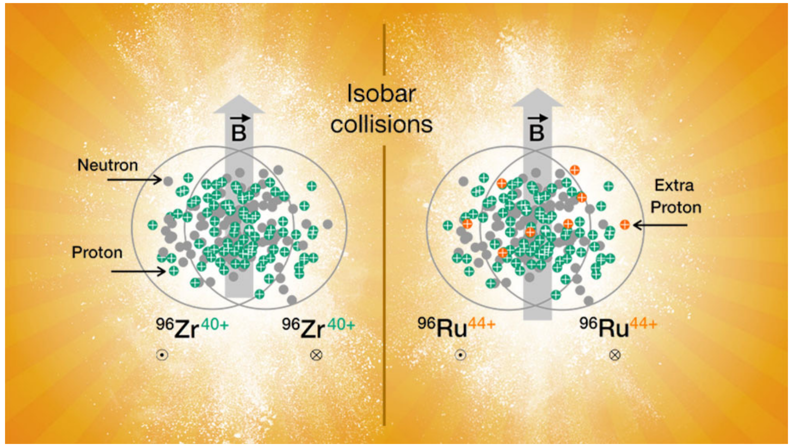


Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\| <1$ Tracking		1999-
Barrel EMC	$\|\eta\| <1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1< \eta <2$ 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



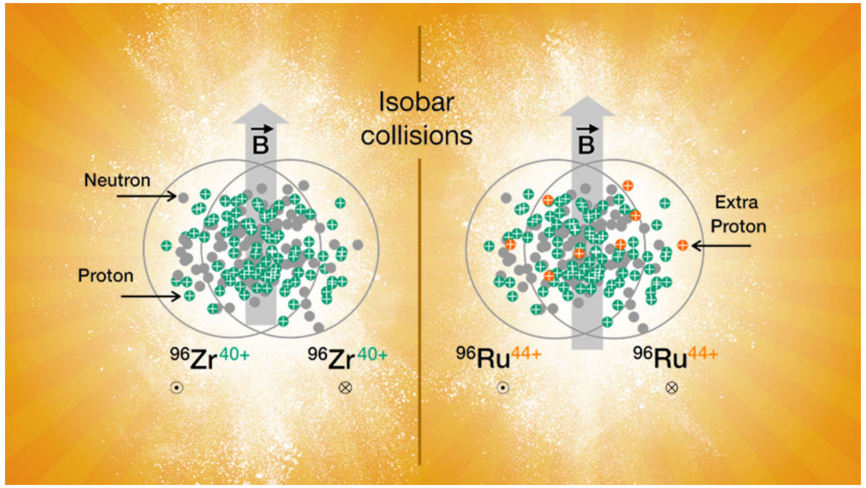


- The double ratios of π^+/π^- and $p/\bar{p}$ are larger than 1. Due to extra charge in Ru?
- The double ratios of K^-/K^+ is consistent with unity within uncertainties.

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

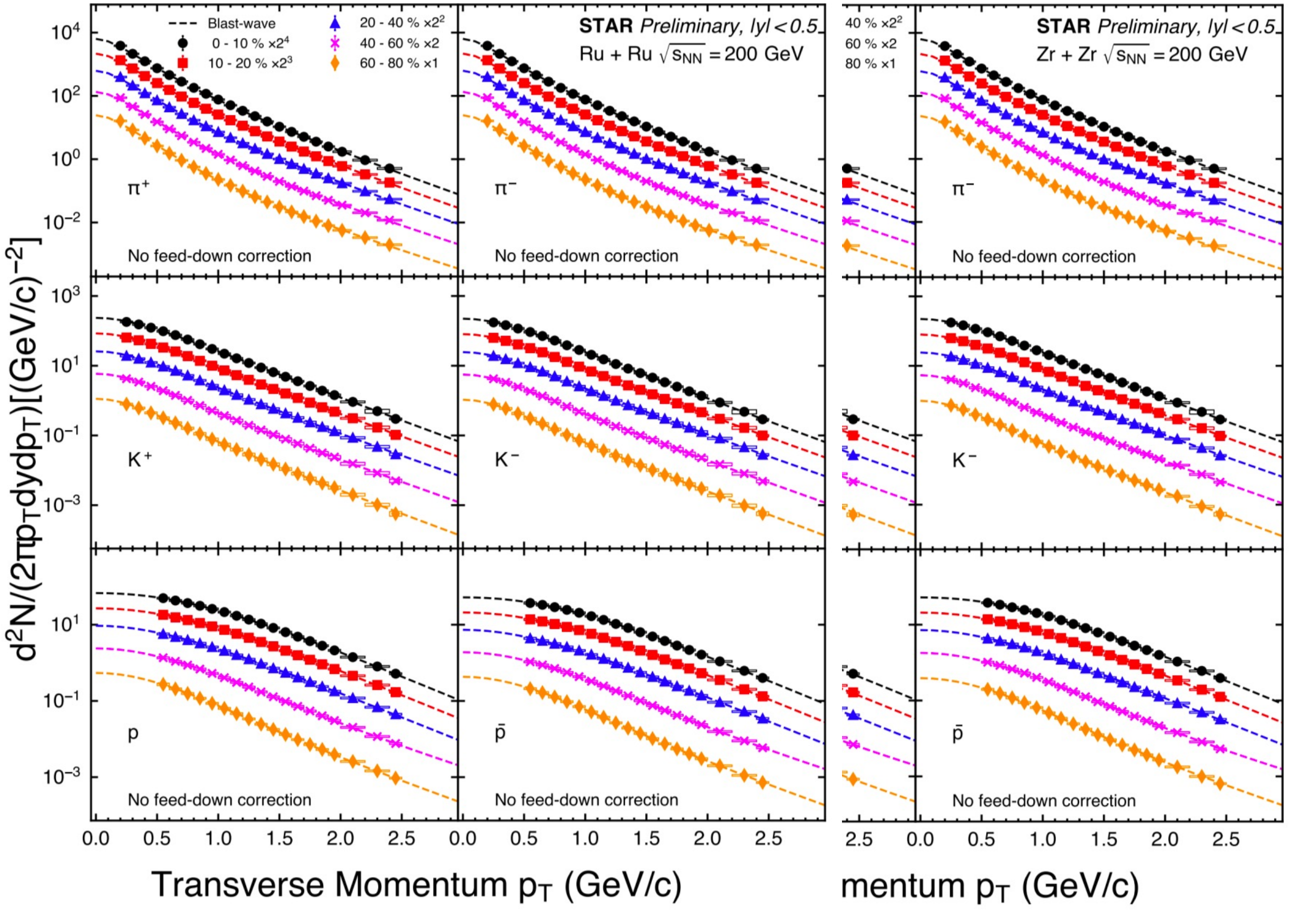
Charge stopping: ΔQ ~=1x10^{-3}

Identified hadron spectra to low momentum



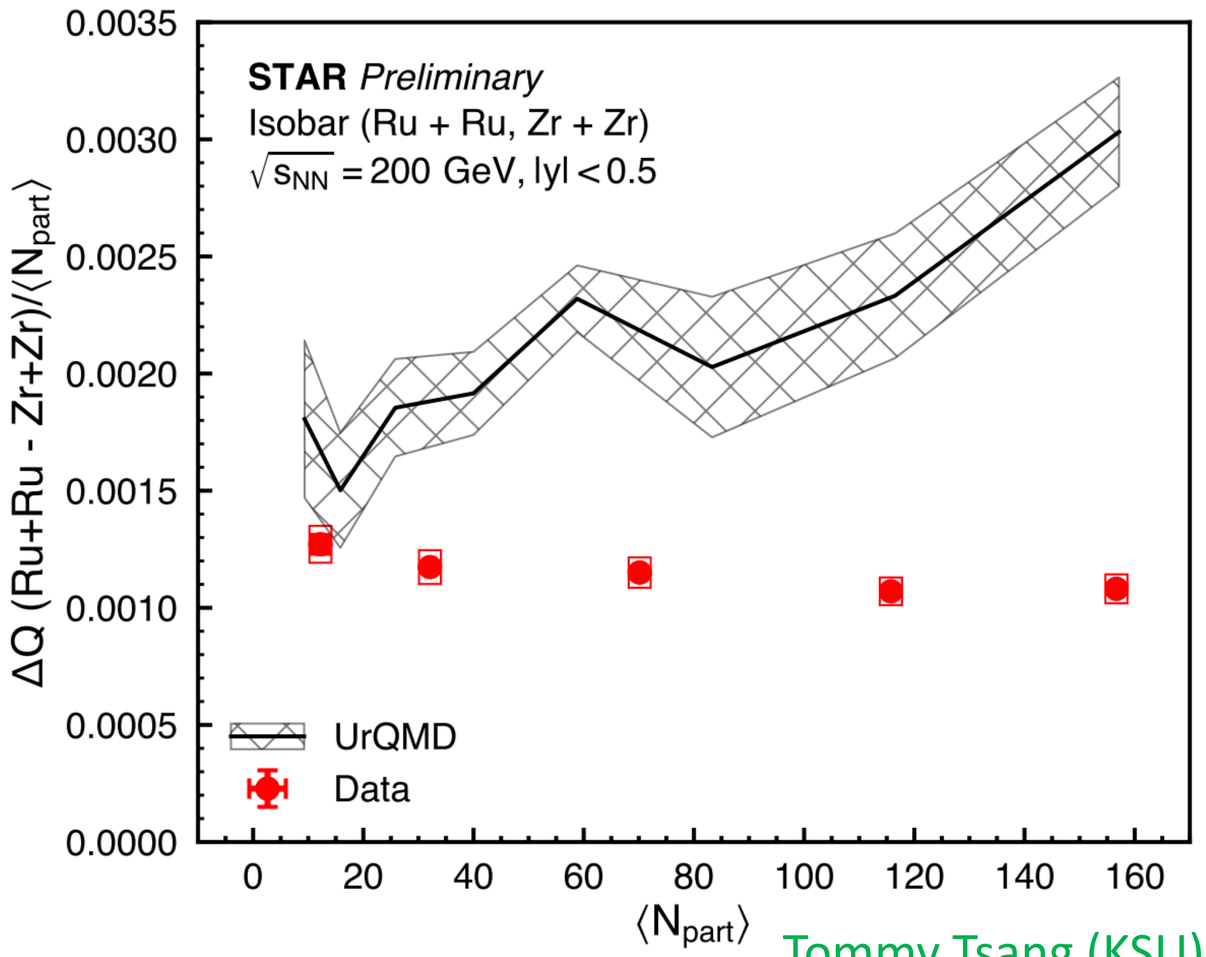
Net-charge difference (Ru+Ru – Zr+Zr)

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

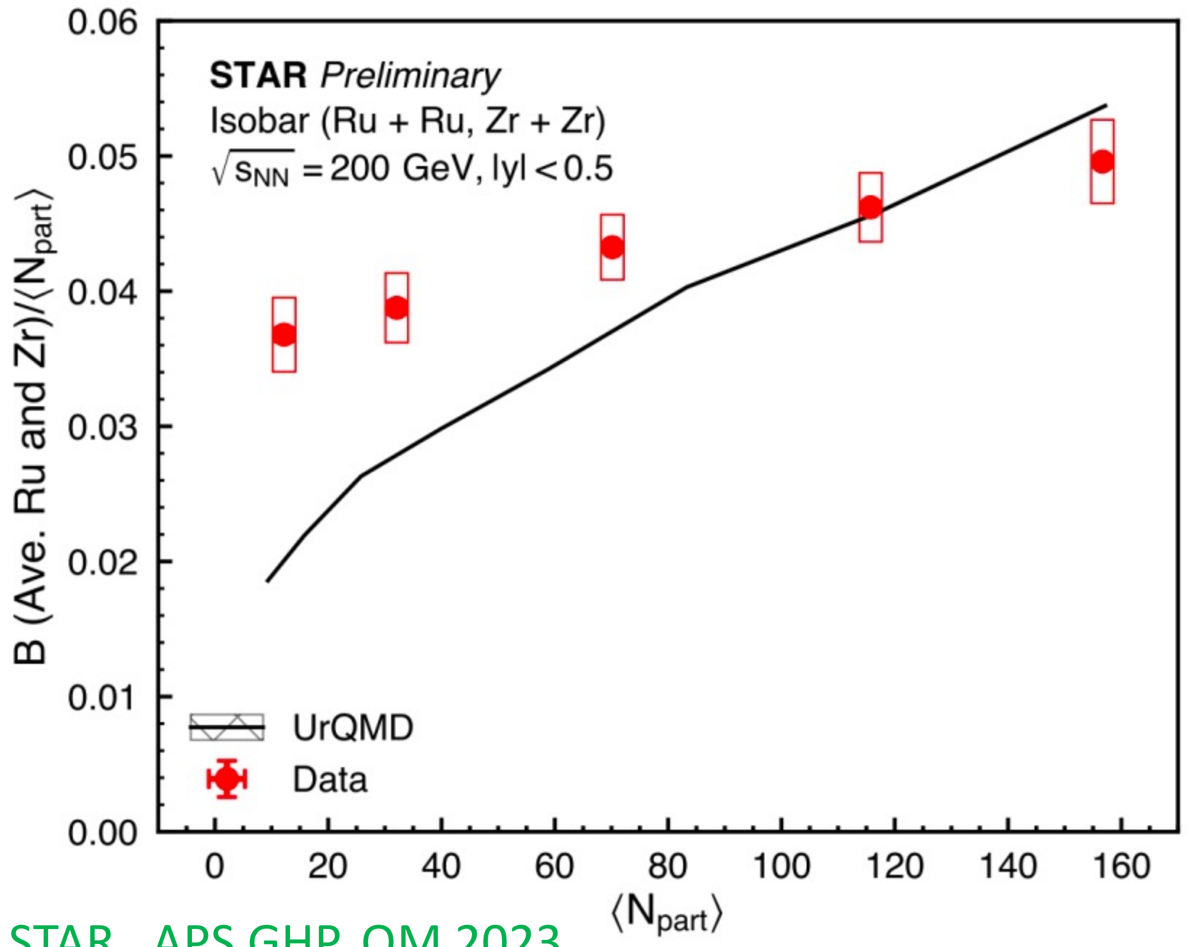


Separate charge and baryon transports

Charge number transport



Baryon number transport



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

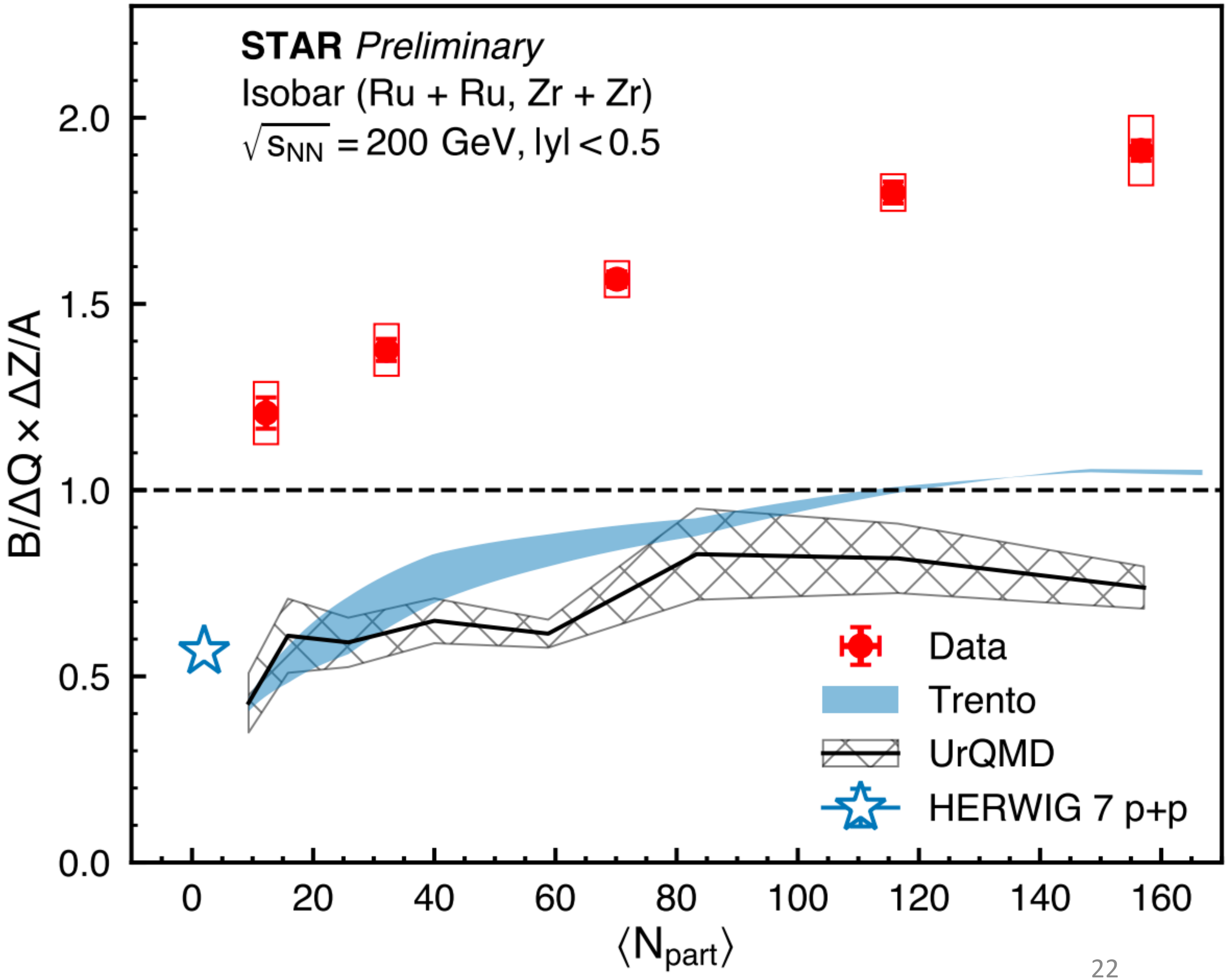
Ratio of baryon over charge transports

- **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, APS GHP, QM 2023



Low-energy baryon rapidity loss

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

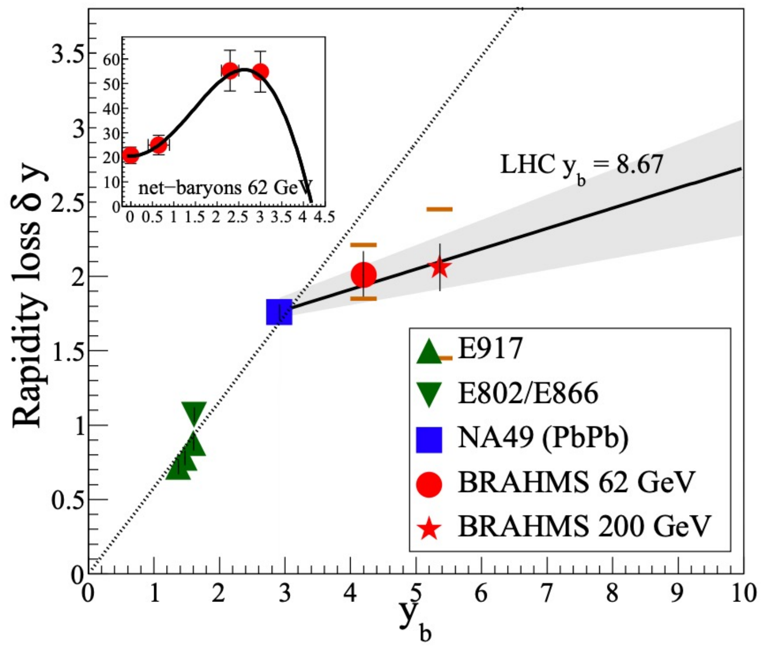


Figure 3: Rapidity losses from AGS, SPS and RHIC as a function of beam rapidity. The solid line is a fit to SPS and RHIC data, and the band is the statistical uncertainty of this fit. The dashed line is a linear fit to AGS and SPS data from [15].

BRAHMS 2009

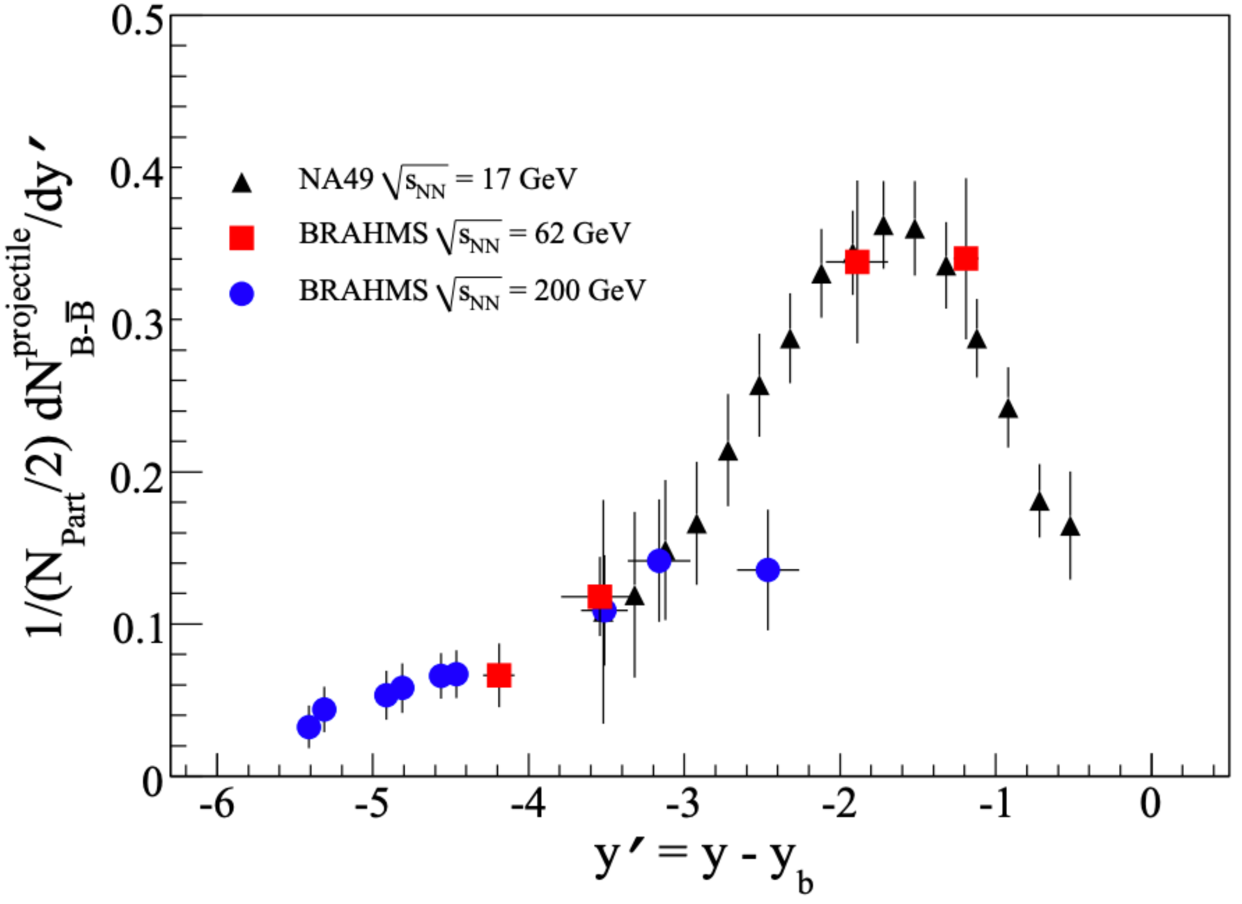


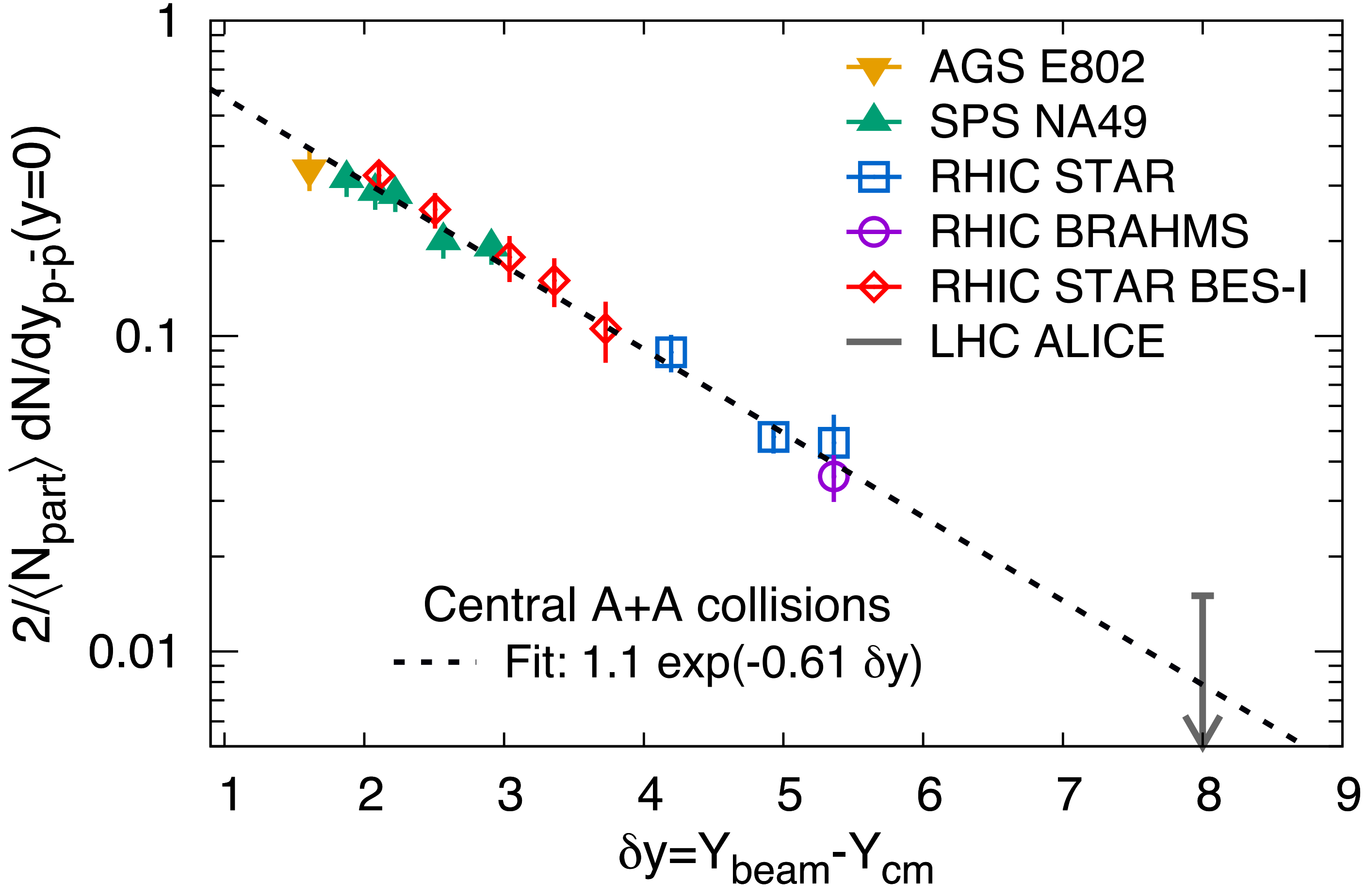
Figure 5: Projectile net-baryon rapidity density $(1/N_{part}/2)dN^{projectile}_{B-\bar{B}}/dy'$ from SPS and RHIC after subtraction of the target net-baryon contribution (see Fig. 4).

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

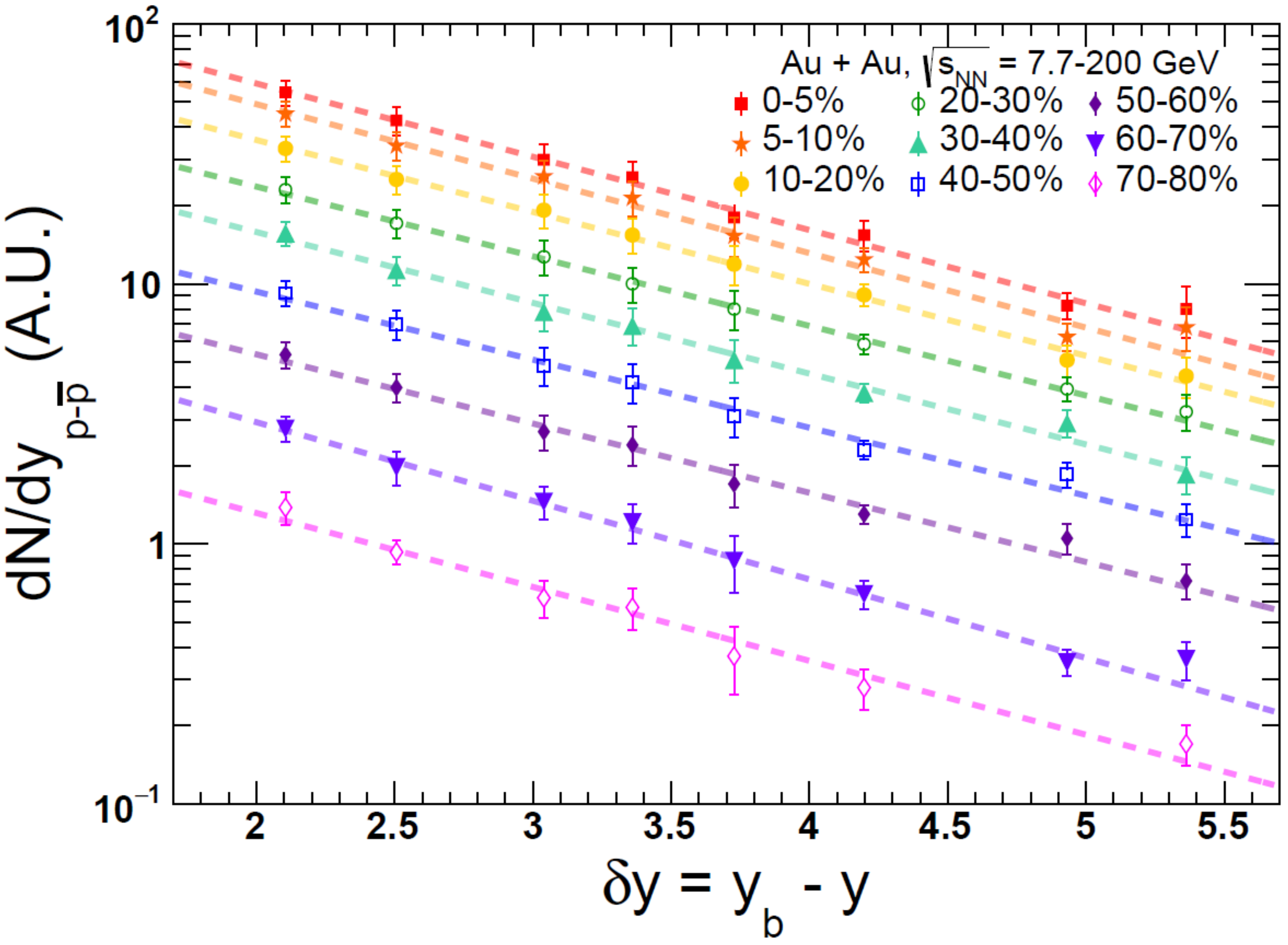
D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685



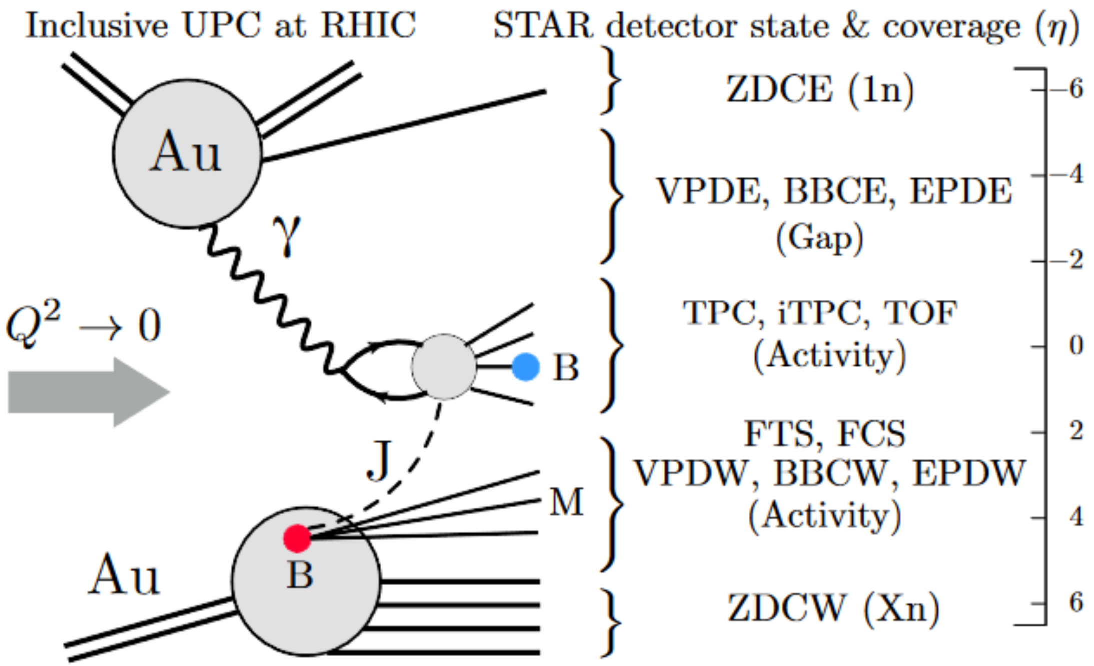
Quantifying baryon number transport

- 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

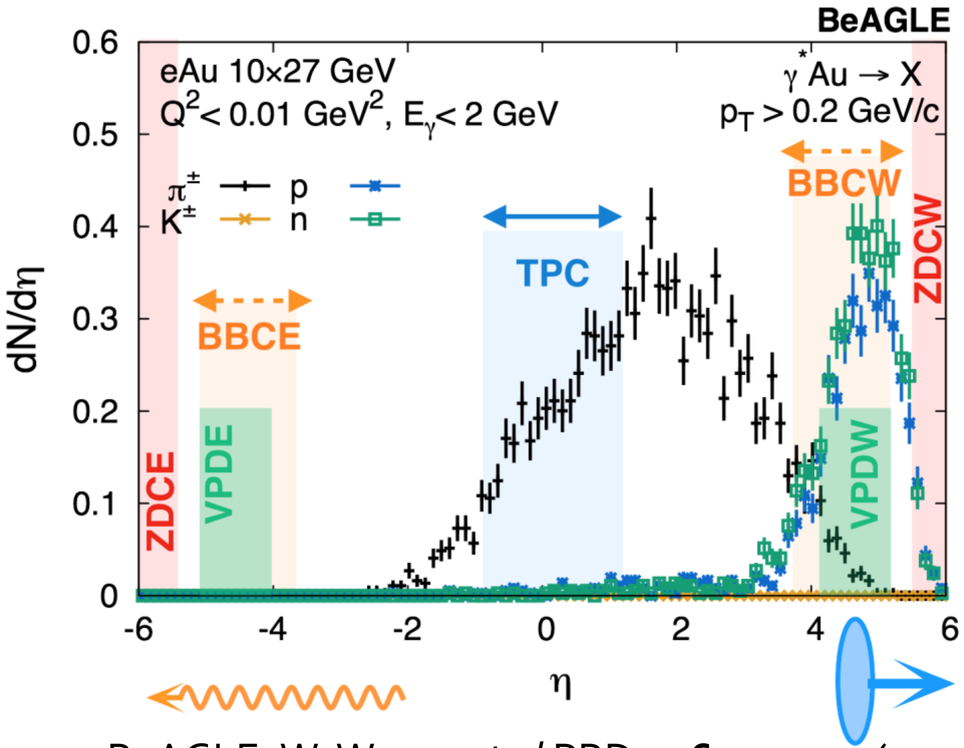
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.



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)

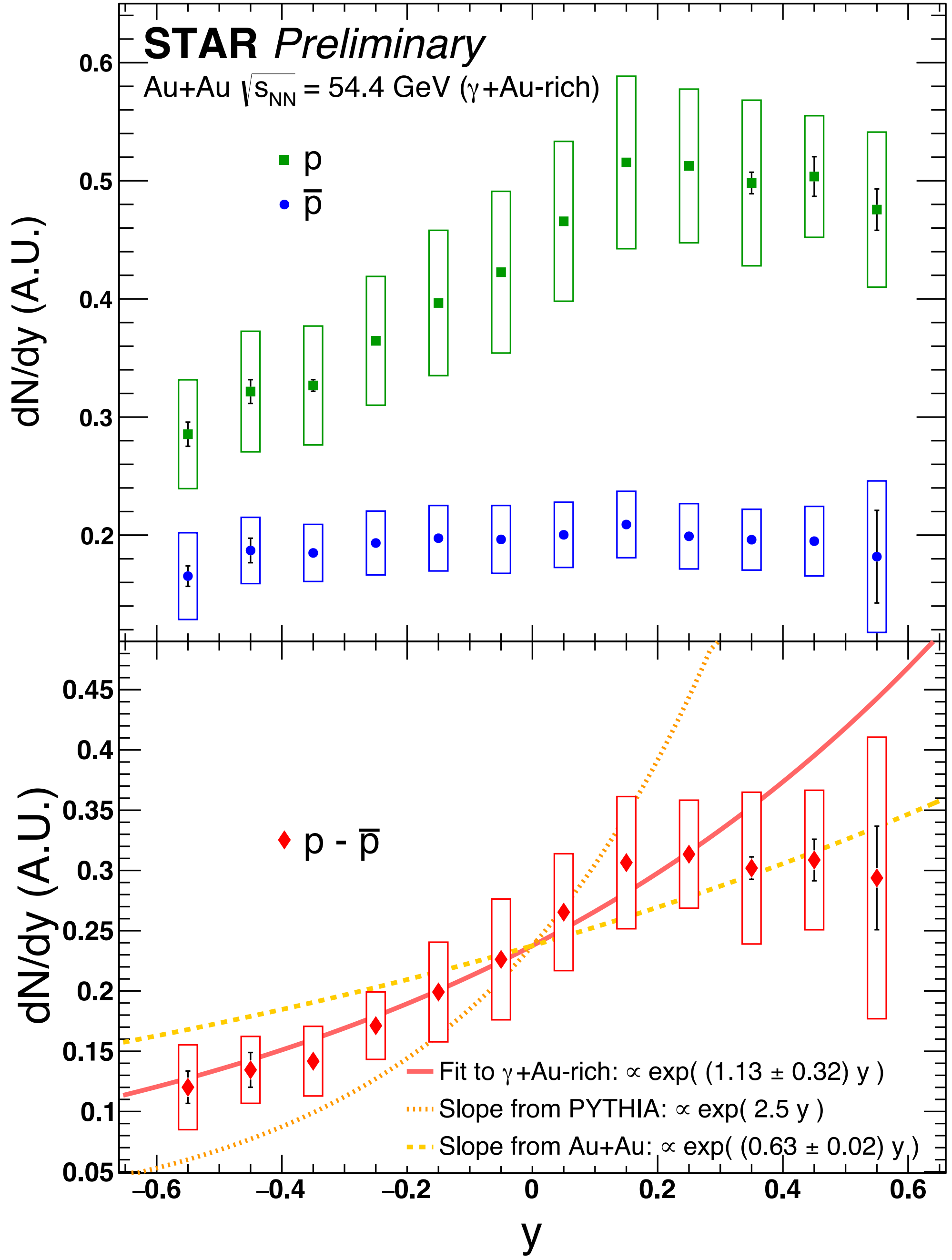
Similar technique used by LHC photonuclear measurements:
ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021) and CMS Collaboration, arXiv:2204.13486 (2022)

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

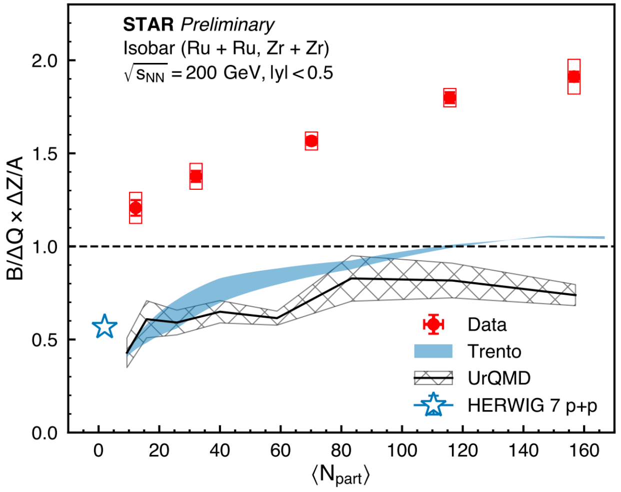


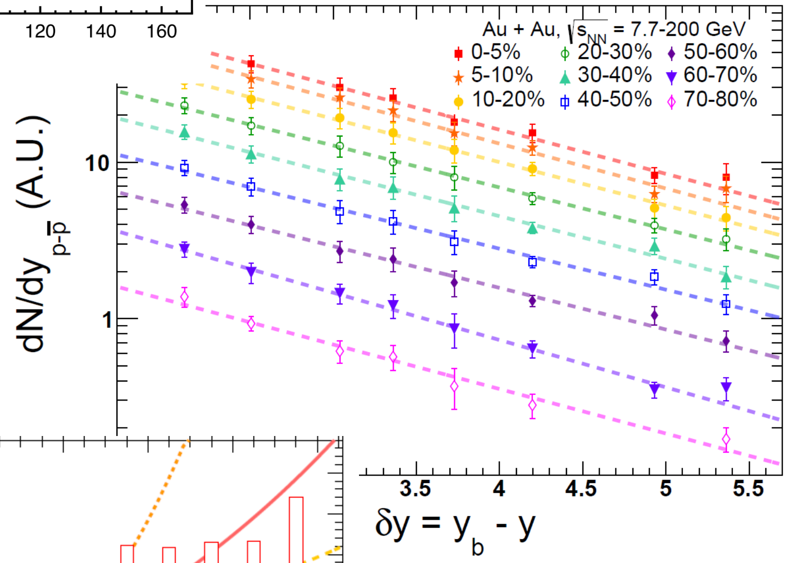
Three approaches toward tracking the origin of the baryon number

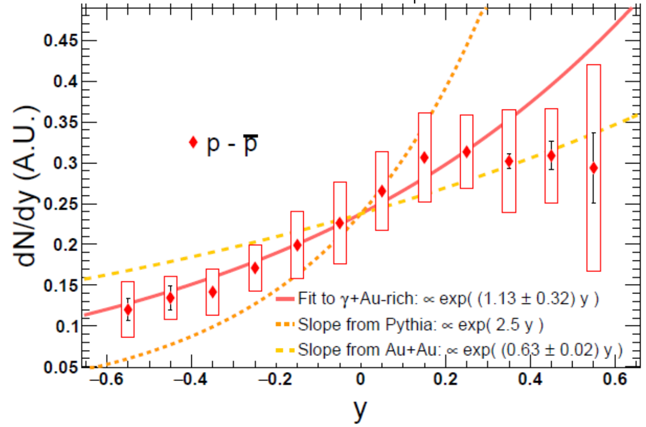
1. **STAR Method:**
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. **Kharzeev-STAR Method:**
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. **Artru Method:**
   In γ+Au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

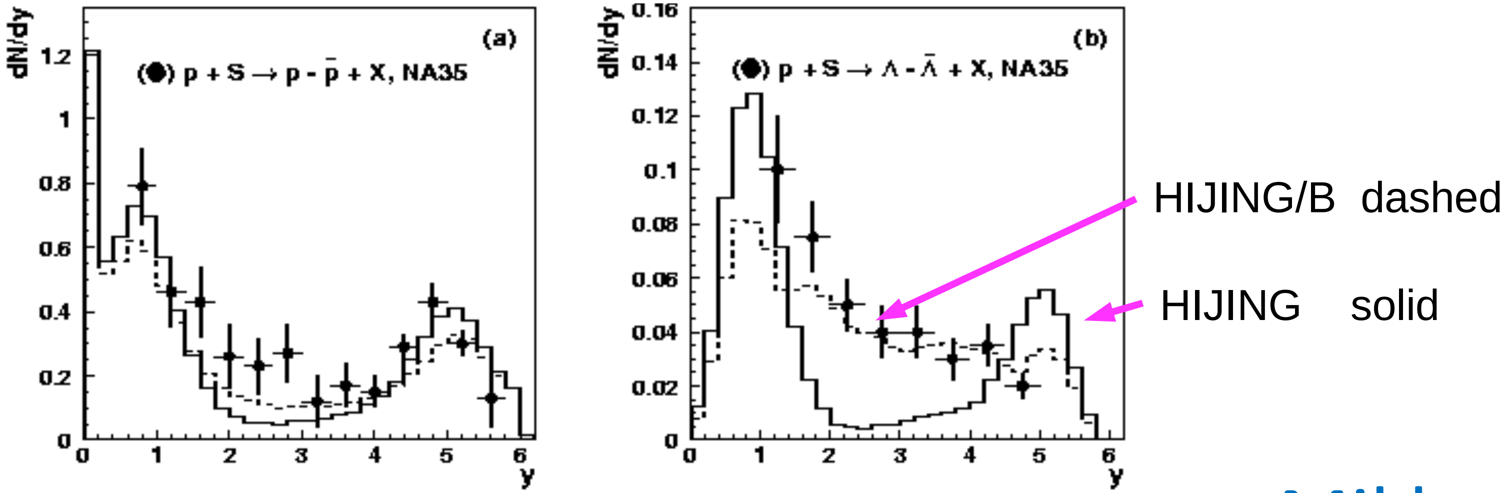






NET BARYON NUMBER TRANSPORT VIA GLUONIC JUNCTIONS vs SPS data

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



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

Miklos Gyulassy
Prepared in 08/18/2022

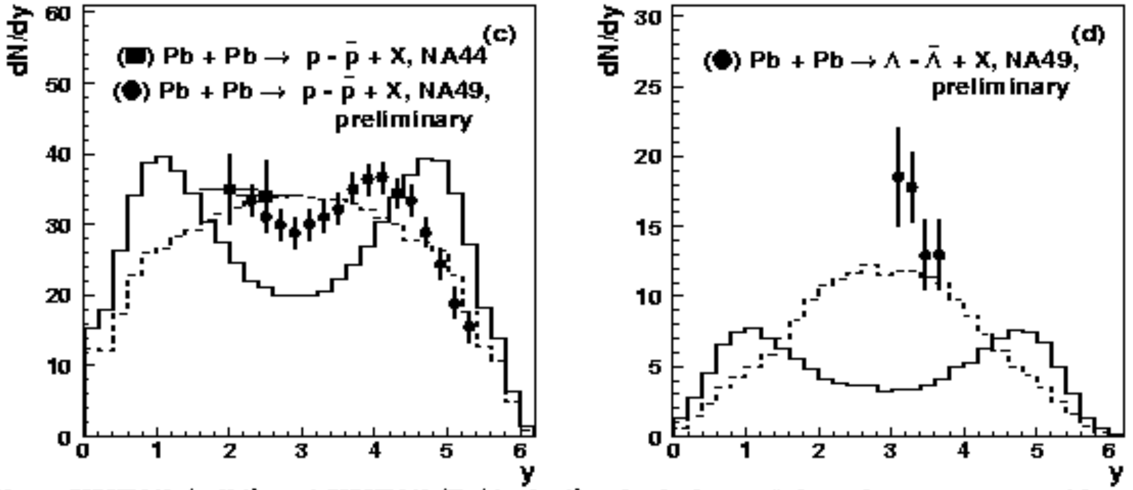
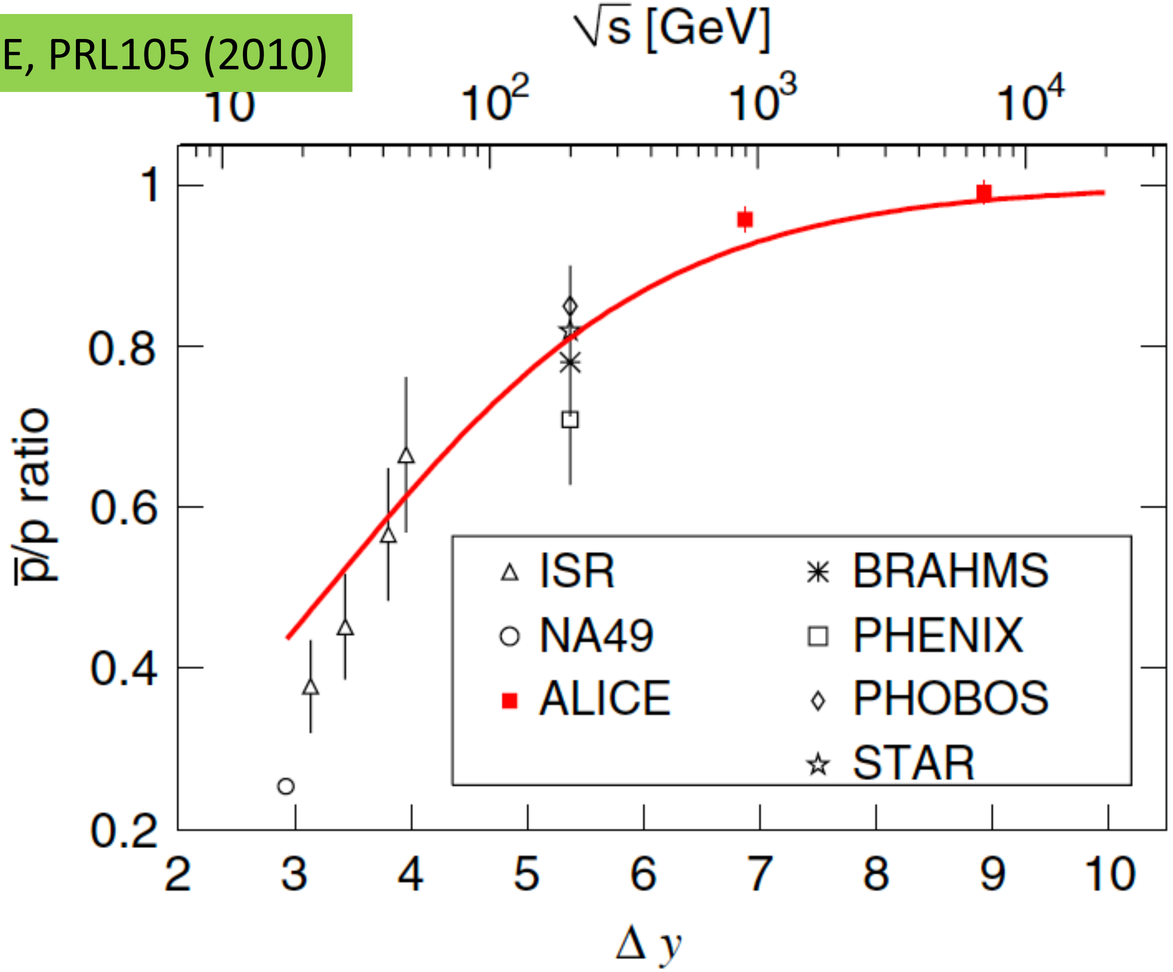


FIG. 1. HIJING (solid) and HIJING/B (dashed) calculations of the valence proton and hyperon rapidity distributions are shown for minimum bias $p+S$ collisions at 200 AGeV and central $Pb+Pb$ collisions at 160 AGeV. The data are from measurements made by the NA35 [1,2], NA44 [3] and NA49 [5] collaborations.

What do we know about pp collisions?

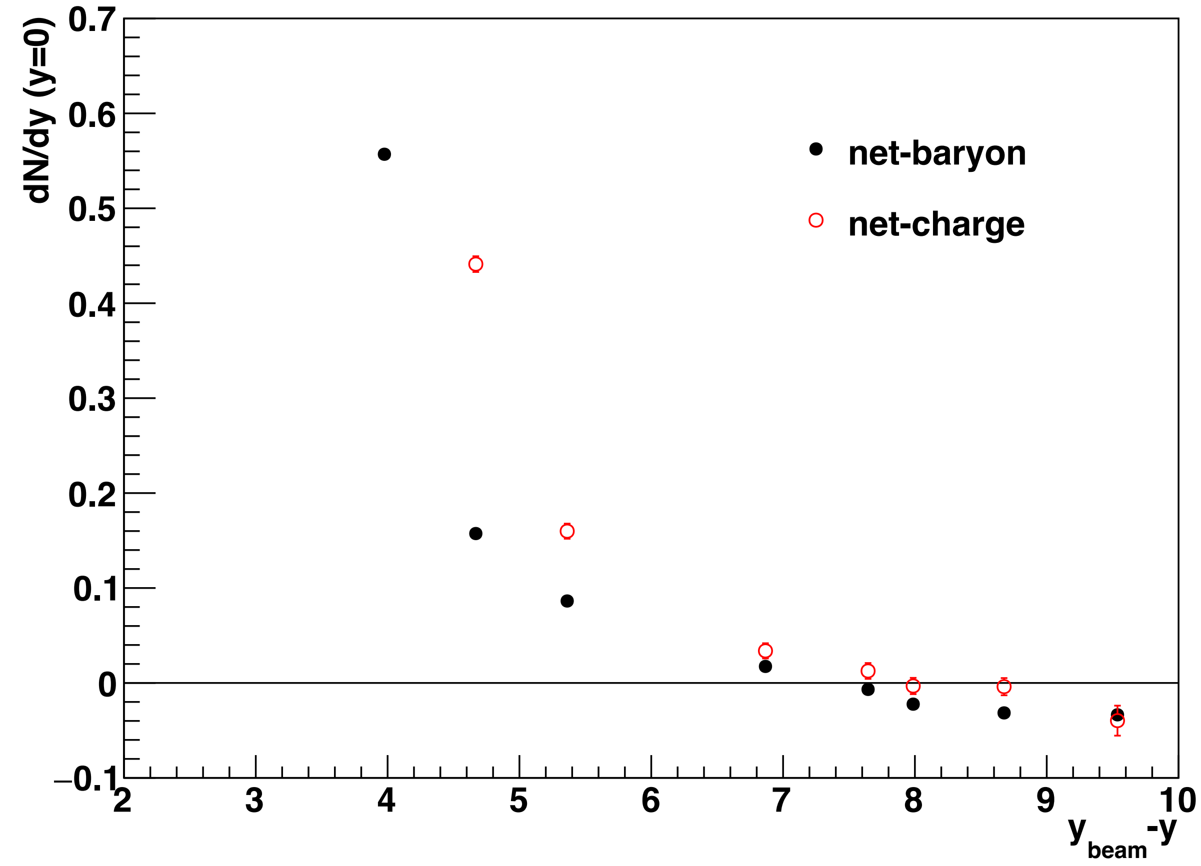
“These results are consistent with standard models of baryon-number transport and set tight limits on any additional contributions to baryon-number transfer over very large rapidity intervals in pp collisions.”

ALICE, PRL105 (2010)



red curve consistent with α_B =0.61

Rongrong Ma (BNL)



HERWIG and PYTHIA 6: α_B ~=1.6-2.5

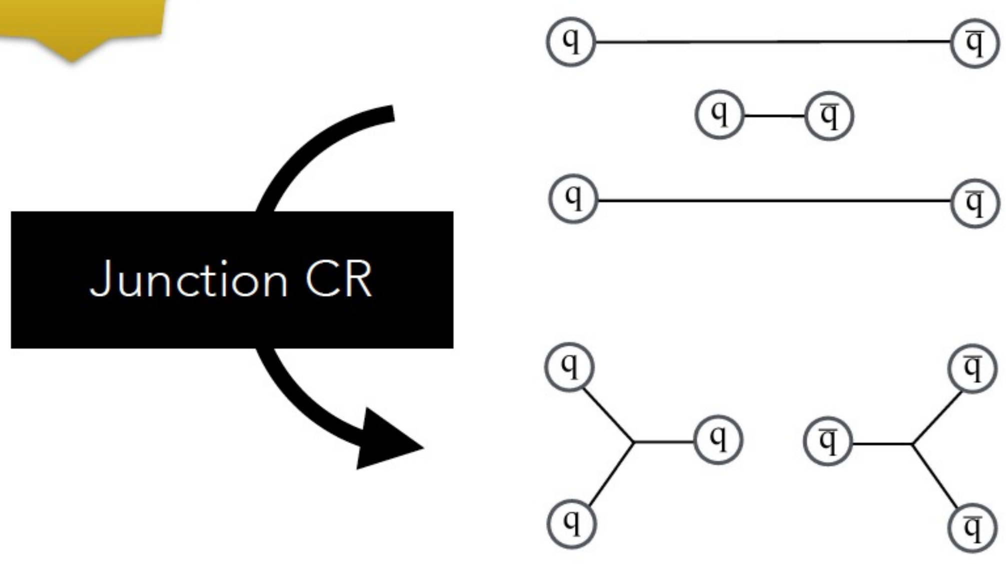
Negative (pbar>p) at LHC energy

Peter Skands, 2021

new!

“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.

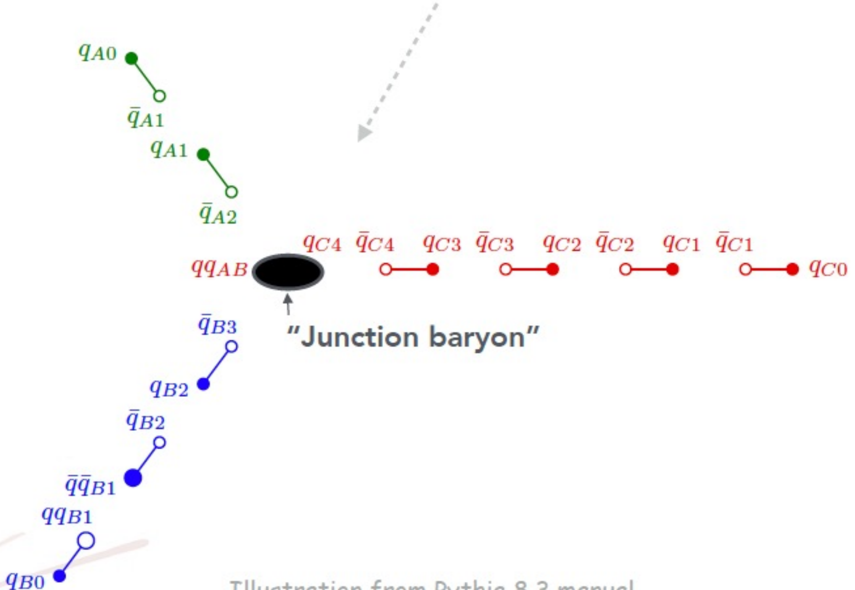


Illustration from Pythia 8.3 manual

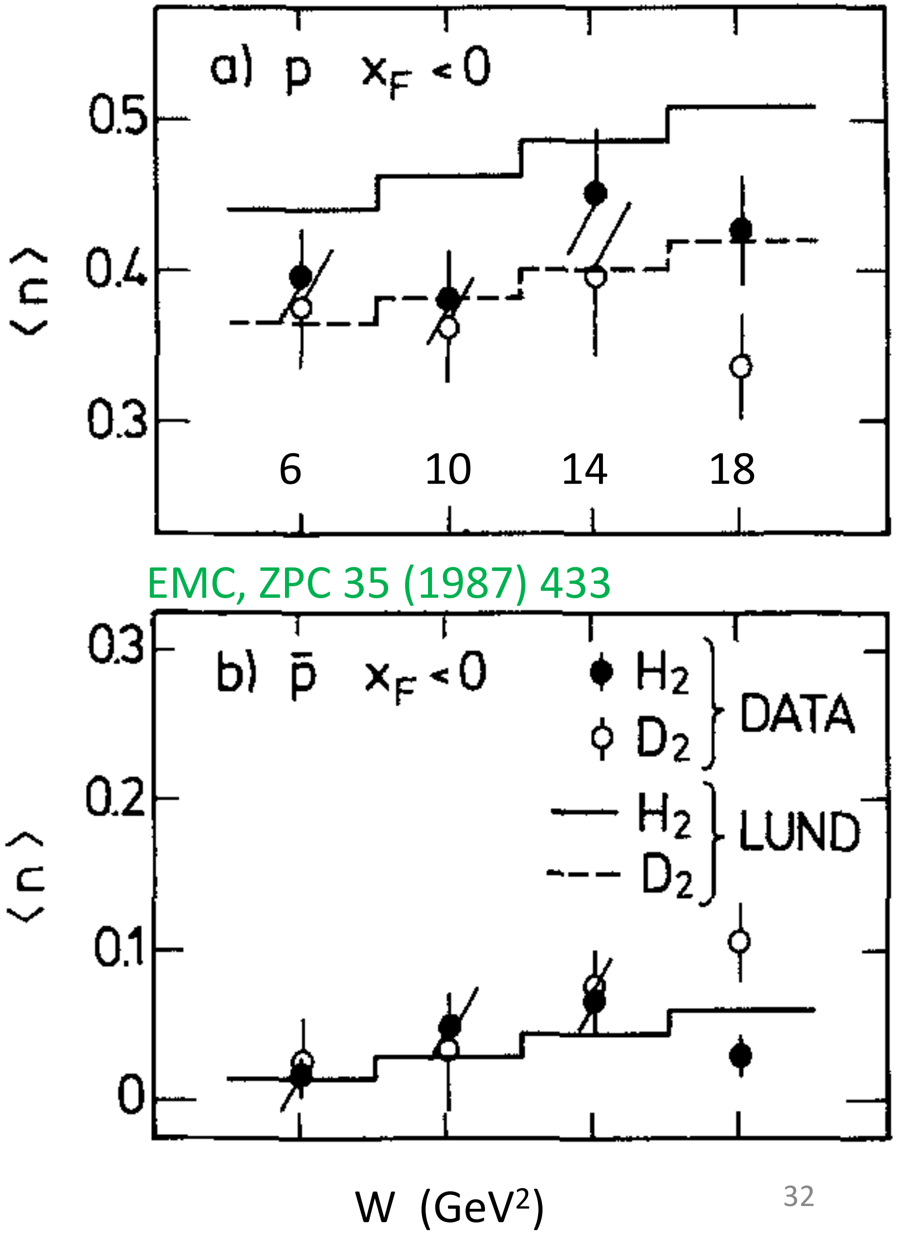
What do we know about μ+p (d) collisions

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)

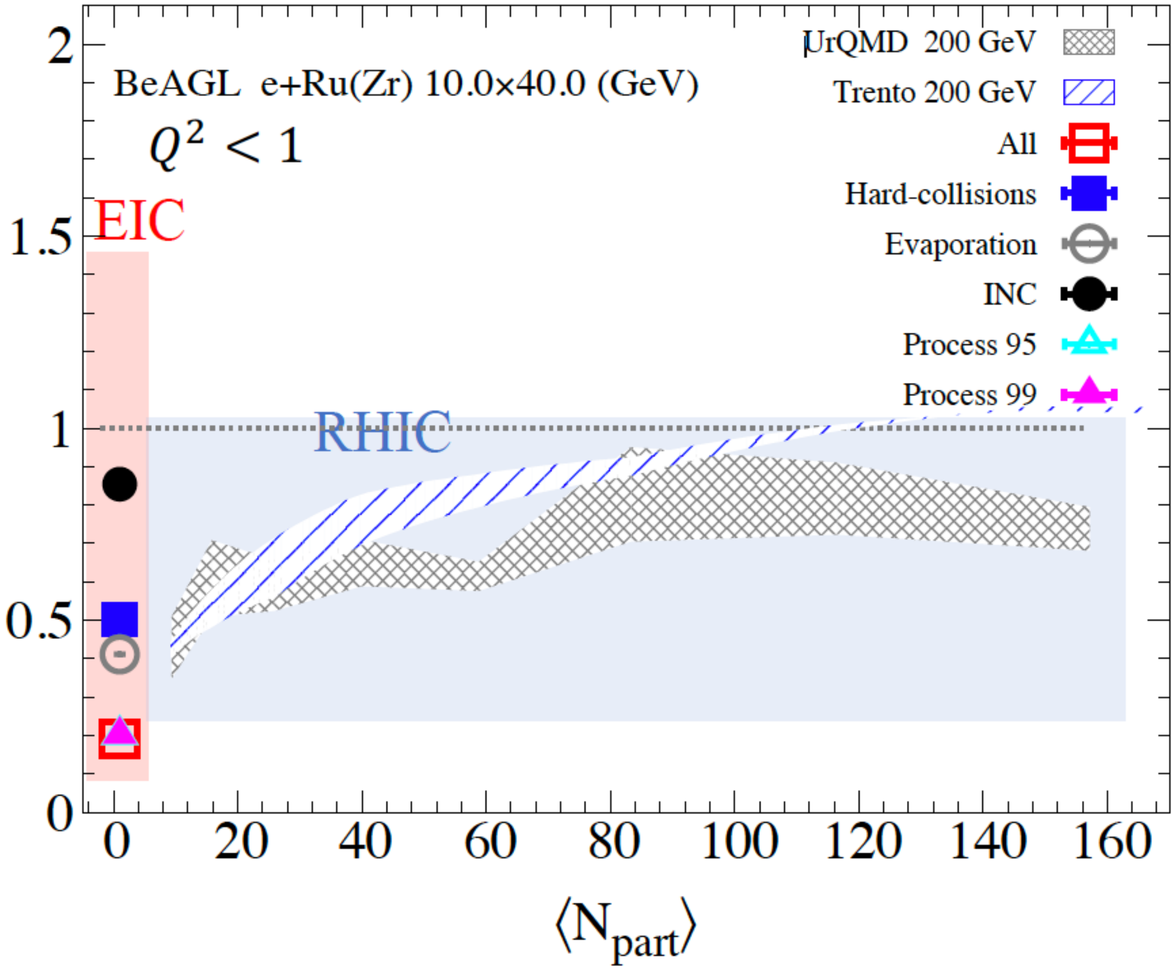
the Lund model (JETSET62) predicts a higher yield of backward going protons from hydrogen than from deuterium, an effect which is less pronounced in the data.

Total citations: 19



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

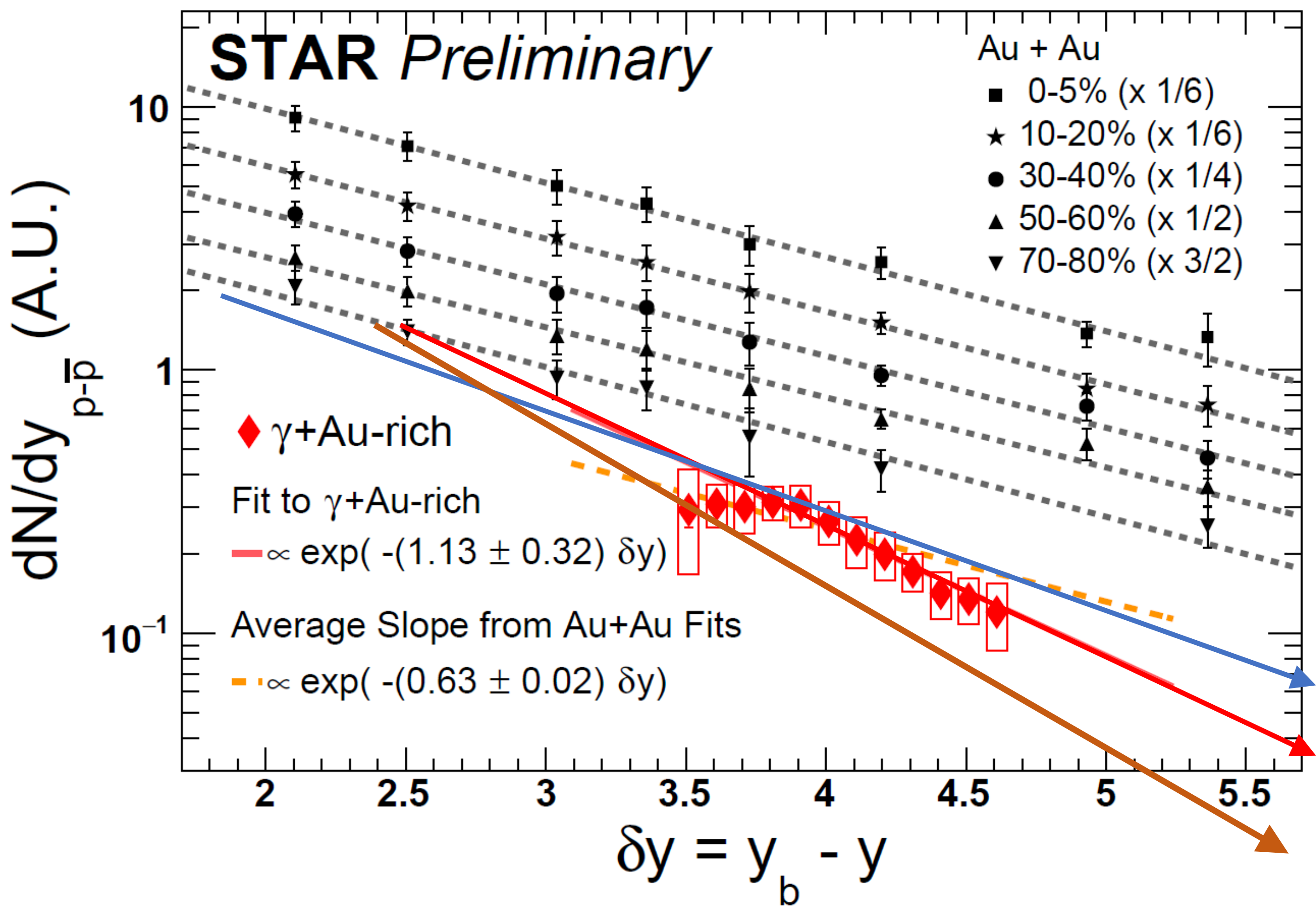
CHANNEL	PHYSICS	DETECTOR II OPPORTUNITY
Diffractive dijet	Wigner Distribution	detection of forward scattered proton/nucleus + detection of low p_T particles
DVCS on nuclei	Nuclear GPDs	High resolution photon + detection of forward scattered proton/nucleus
Baryon/Charge Stopping	Origin of Baryon # in 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!

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



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

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

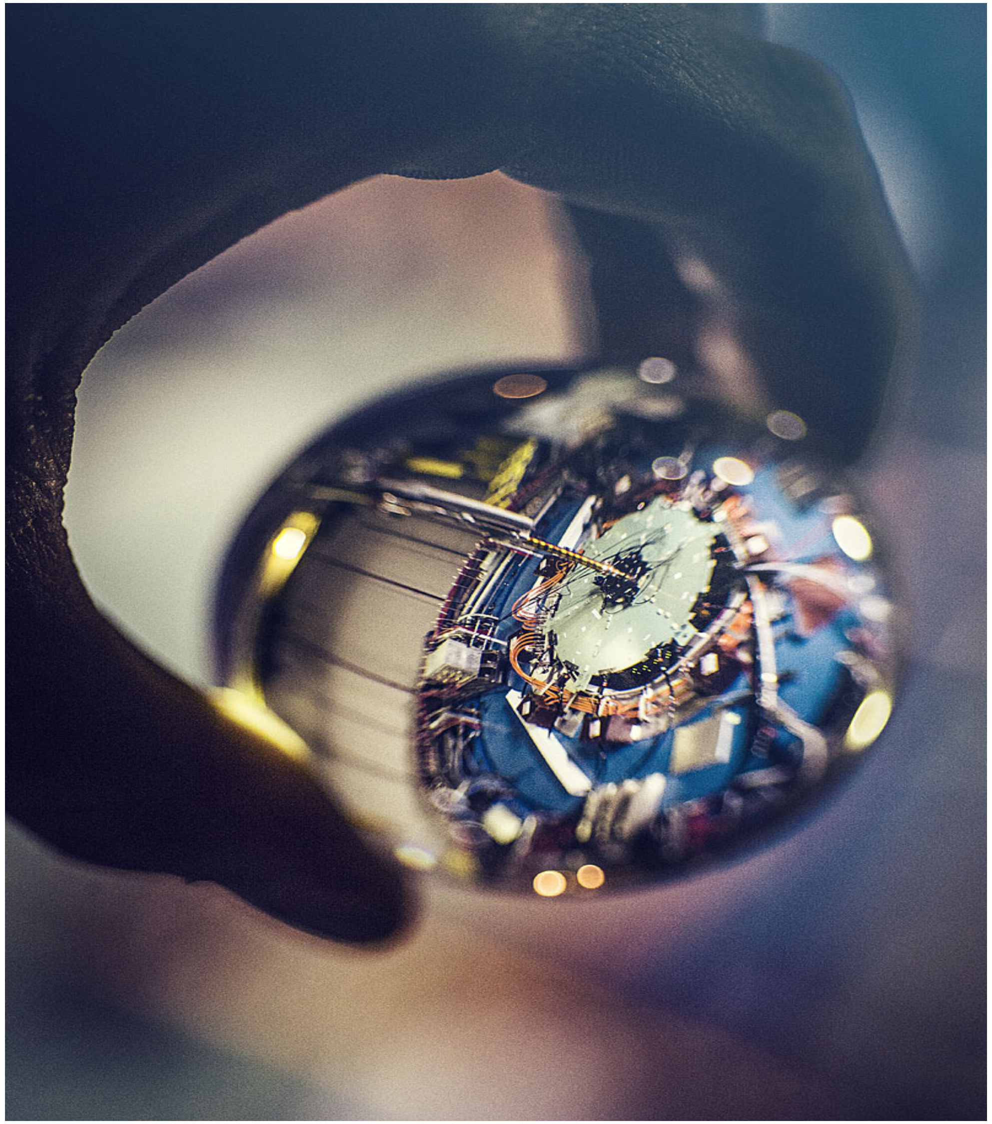
$$\pi/k/p \text{ PID } p_t \geq \sim 100\ MeV$$

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

Solenoidal Tracker at RHIC (25 years of Operation)

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!

the simplest QCD topology

B=1