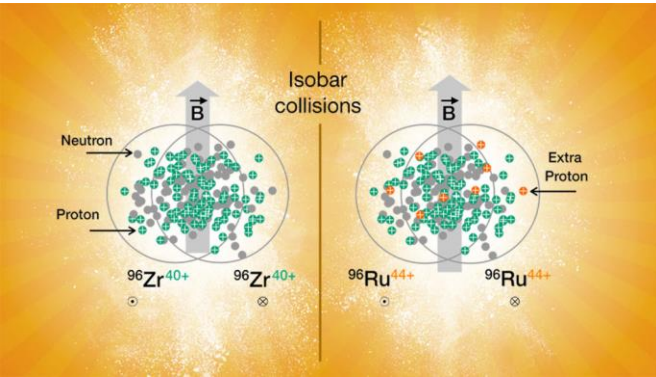
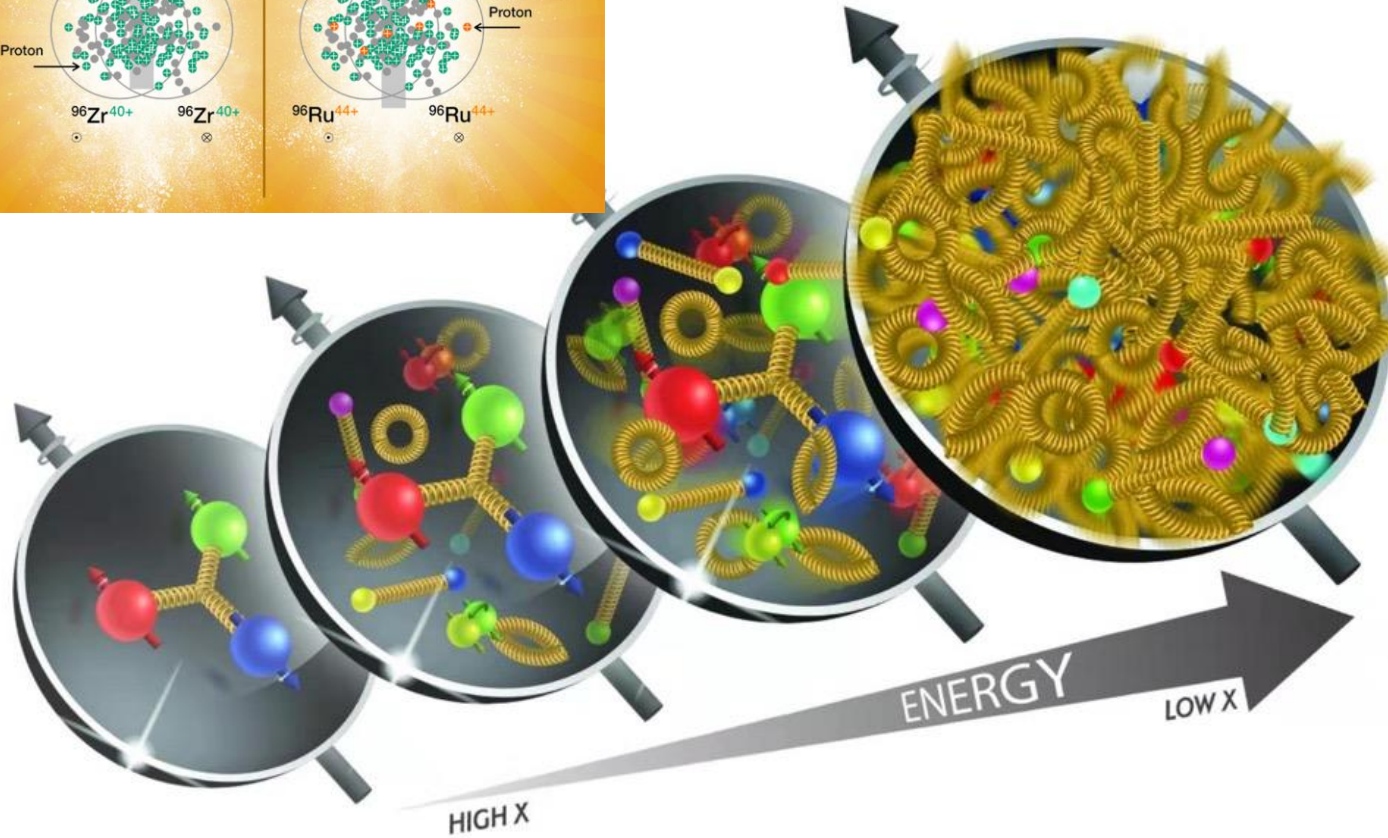


Flavor-Independent Baryon Transport



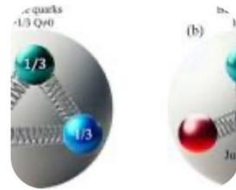
Zhangbu Xu
Kent State University
BNL



- baryon number carrier
- Three experimental approaches at RHIC (3+1)
- Flavor Independence of u,d
- Flavor Independence of u,d,s
- Flavor Independence of u,d,s,c,b
- Future Perspectives

Listen

A baryon junction is a point where three string operators merge in a baryon wave function. The baryon junction is a significant factor in the dynamics of baryon stopping at high energies.



Explanation

- The baryon junction is a result of the local gauge invariance of the baryon wave function.
- The baryon junction has been observed in data from the Relativistic Heavy Ion Collider (RHIC).
- The baryon junction can be tested in semi-inclusive deep inelastic scattering at the Jefferson Laboratory and the Electron Ion Collider.
- The baryon junction can be used to explain the baryon excess in the midrapidity region of ultra-relativistic nucleus-nucleus collisions.
- The transport of baryonic gluon junctions can lead to an exponential distribution of net-baryon density.

Google AI overview:

A Possible Description of Baryon Dynamics in Dual and Gauge Theories

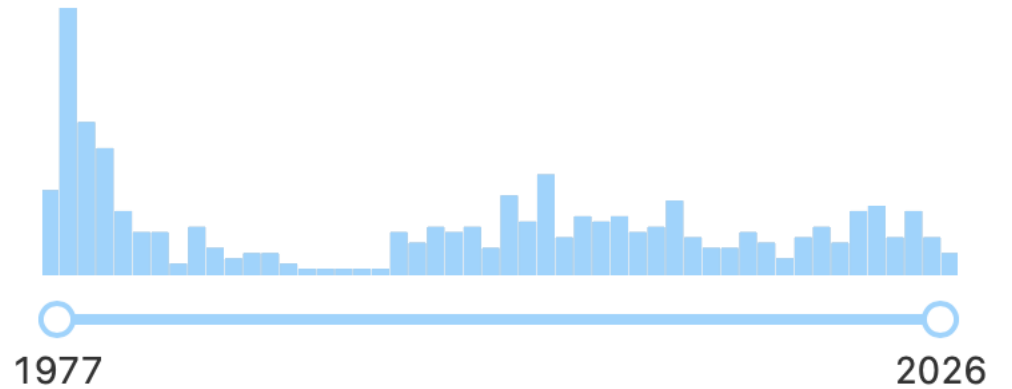
#18

G.C. Rossi (CERN), G. Veneziano (CERN) (Mar, 1977)

Published in: Nucl.Phys.B 123 (1977) 507-545

pdf DOI cite claim reference search 452 citations

Date of paper



Can gluons trace baryon number?

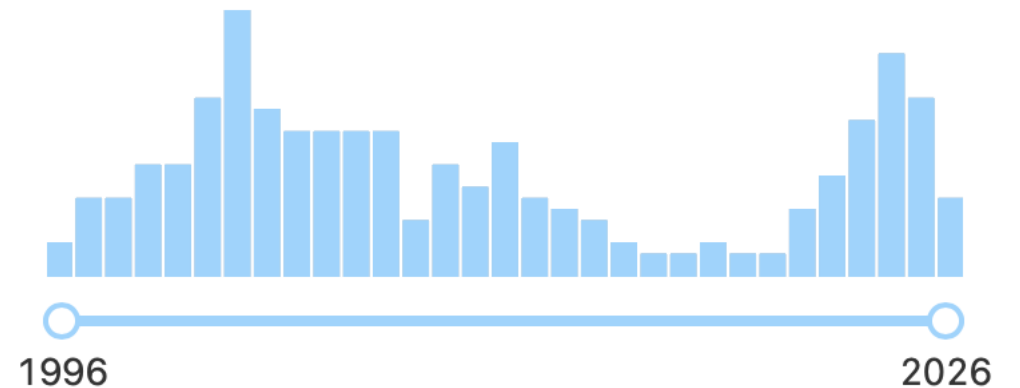
#1

D. Kharzeev (CERN and Bielefeld U.) (Feb, 1996)

Published in: Phys.Lett.B 378 (1996) 238-246 • e-Print: nucl-th/9602027 [nucl-th]

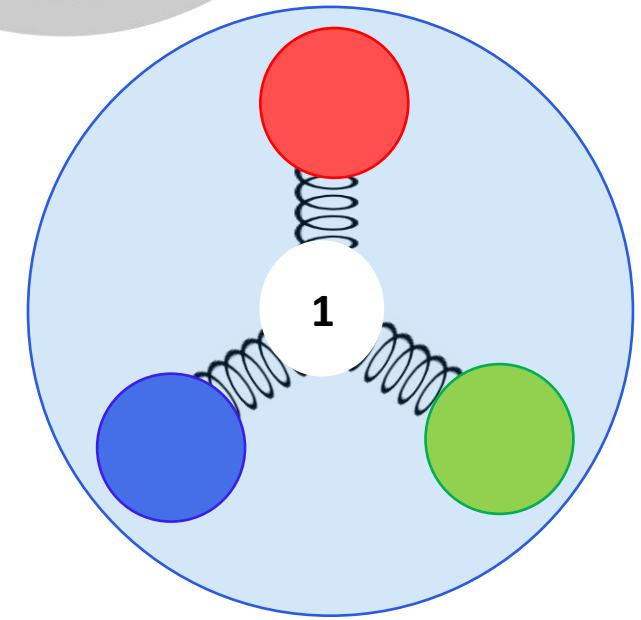
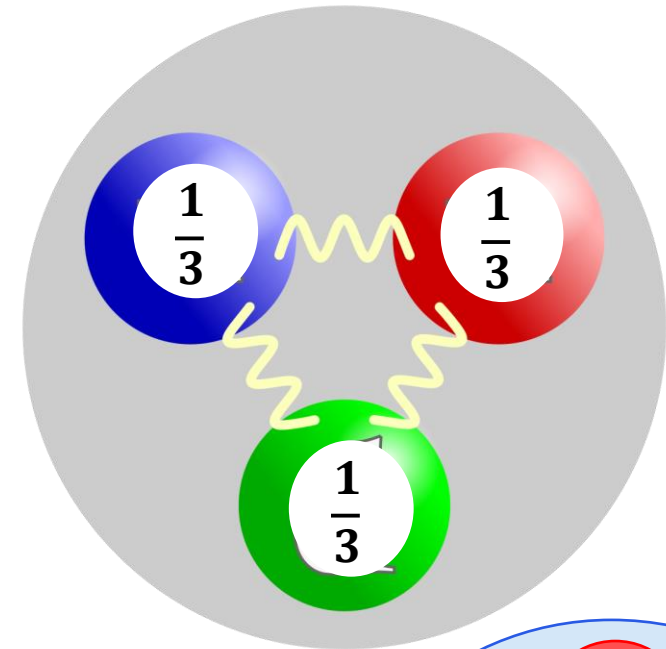
pdf DOI cite claim reference search 283 citations

Date of paper



Baryon Number (B) Carrier

- Textbook picture of a proton
 - Lightest baryon with strictly conserved baryon number
 - Each valence quark carries $\frac{1}{3}$ 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)

Measurements of quark electric charges

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

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

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

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

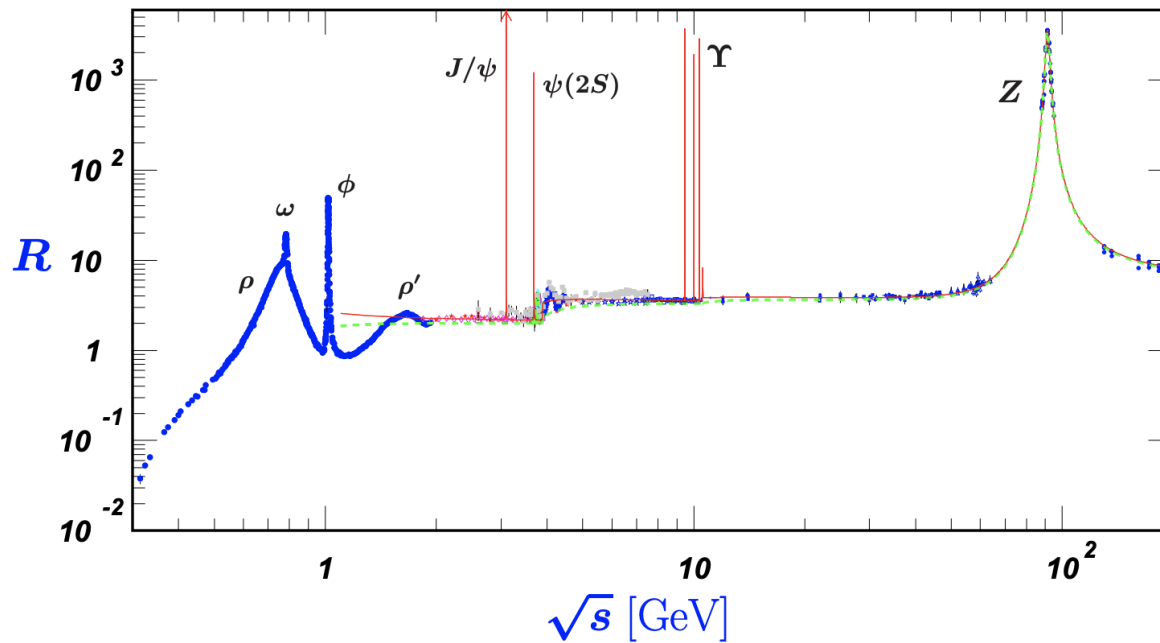


Figure 53.2: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons}, s) / \sigma(e^+e^- \rightarrow \mu^+\mu^-, s)$. $\sigma(e^+e^- \rightarrow \text{hadrons}, s)$ is the experimental cross section corrected for initial 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

Riordan, Science 1992

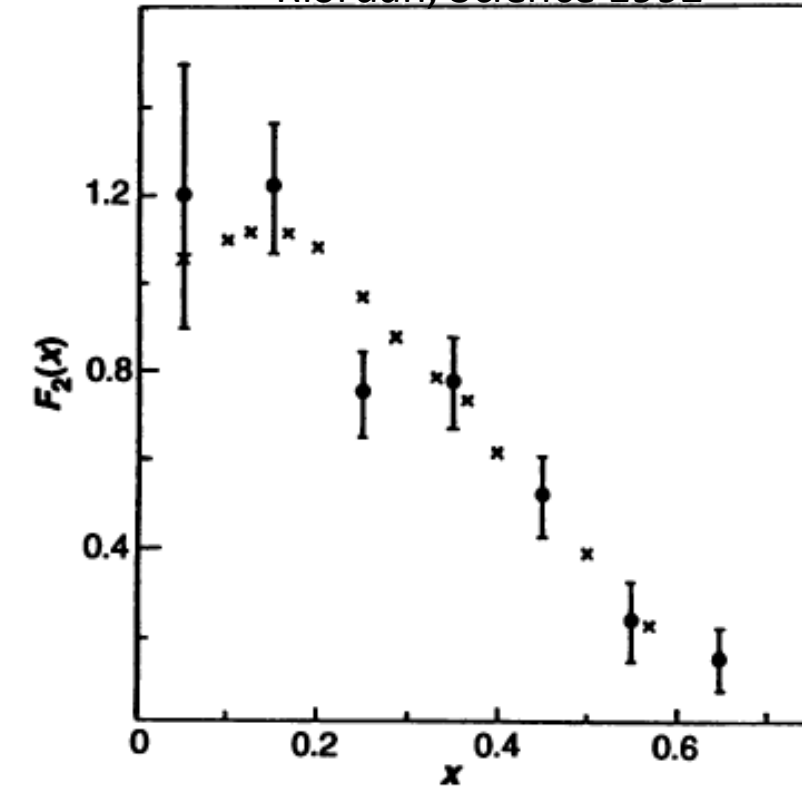
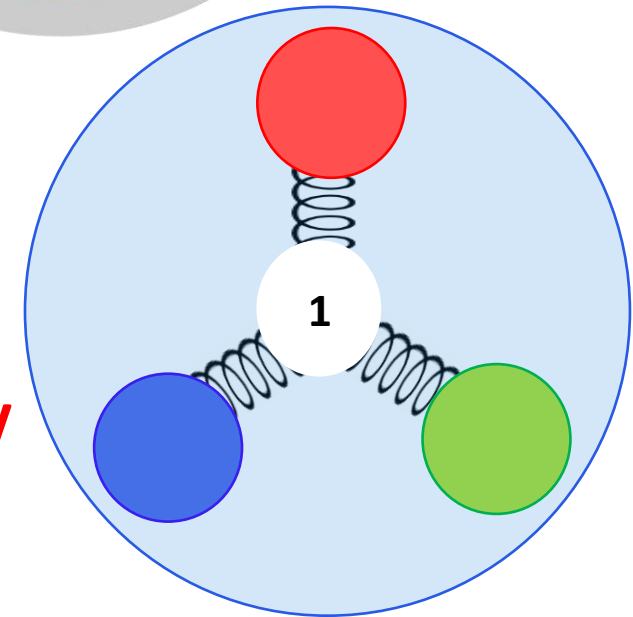
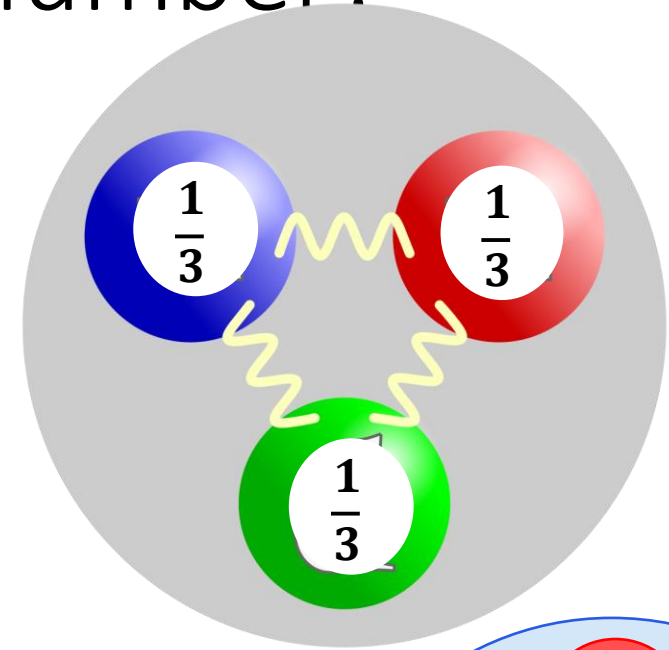


Fig. 8. Comparison of structure functions measured in deep inelastic neutrino-nucleon scattering experiments on the Gargamelle heavy-liquid bubble chamber with the MIT-SLAC data [(●), Gargamelle, $F_2^{\nu N}$; (x), MIT-SLAC, $(18/5)F_2^e$]. When multiplied by 18/5, a number specified by the quark-parton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

Measurements of quark baryon number?

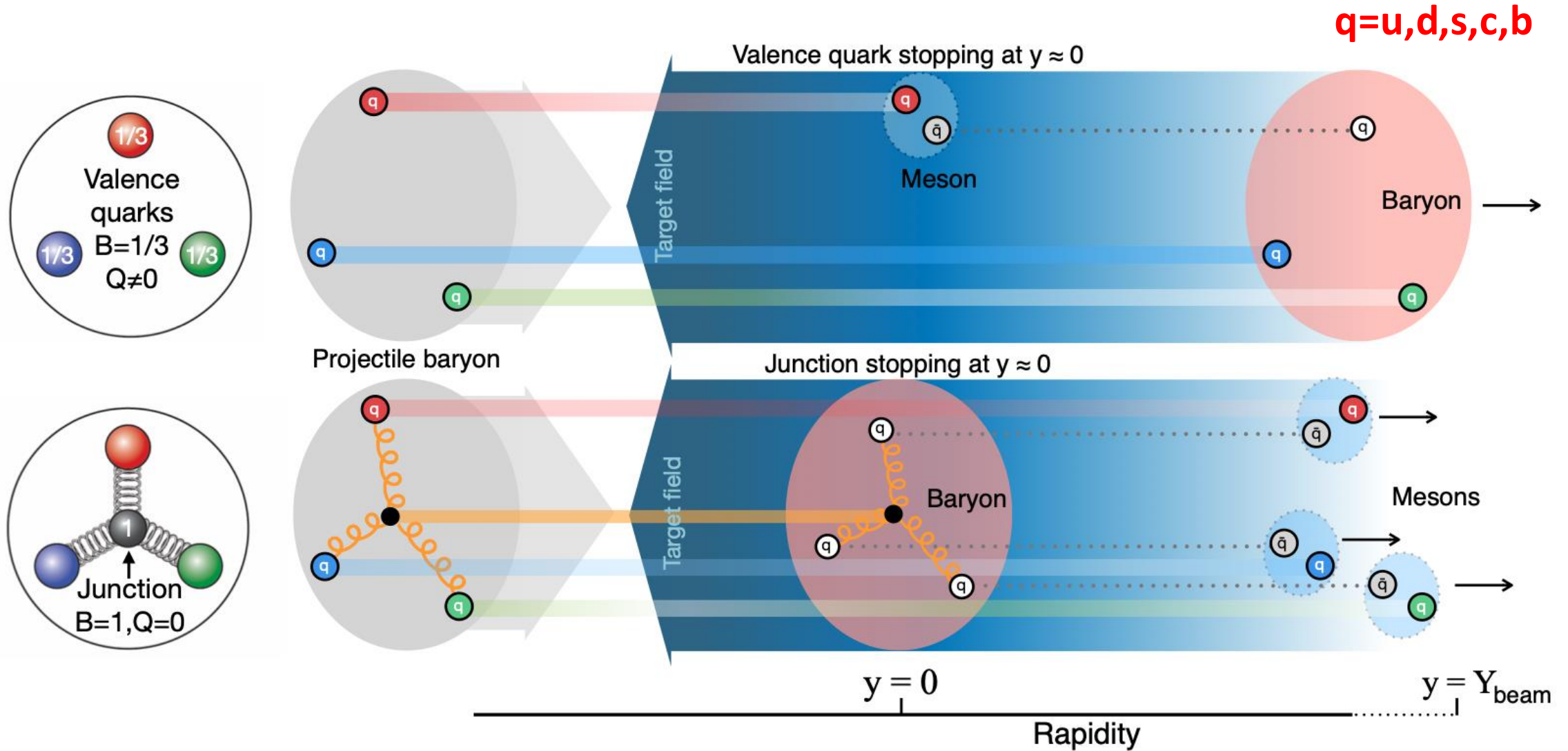
- Textbook picture of a proton
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Flavor Independent Baryon Transport



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

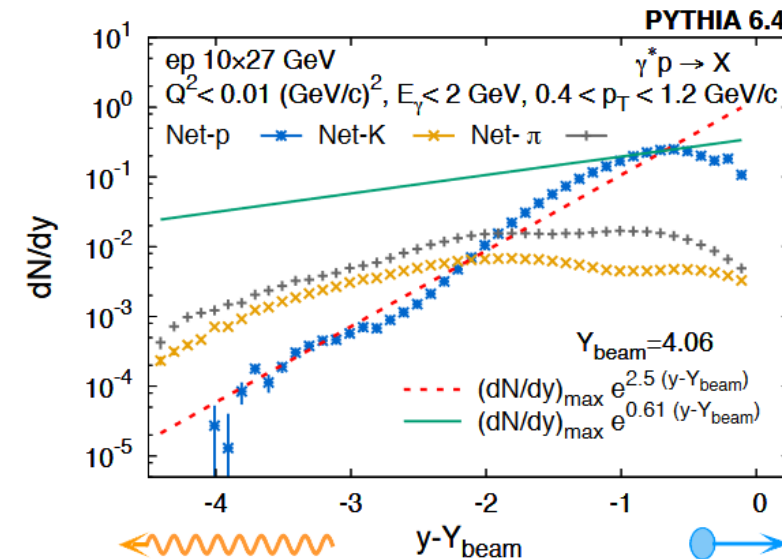
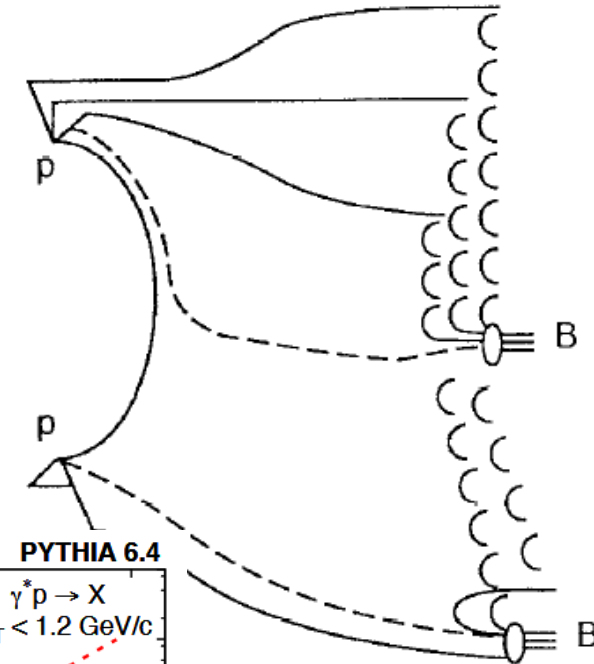
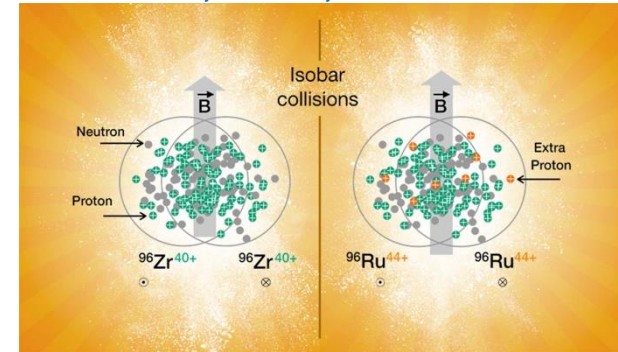
$$p = \sim e^{-\alpha_B Y}$$

$$\alpha_B \sim 0.5$$

3. Artru Method:

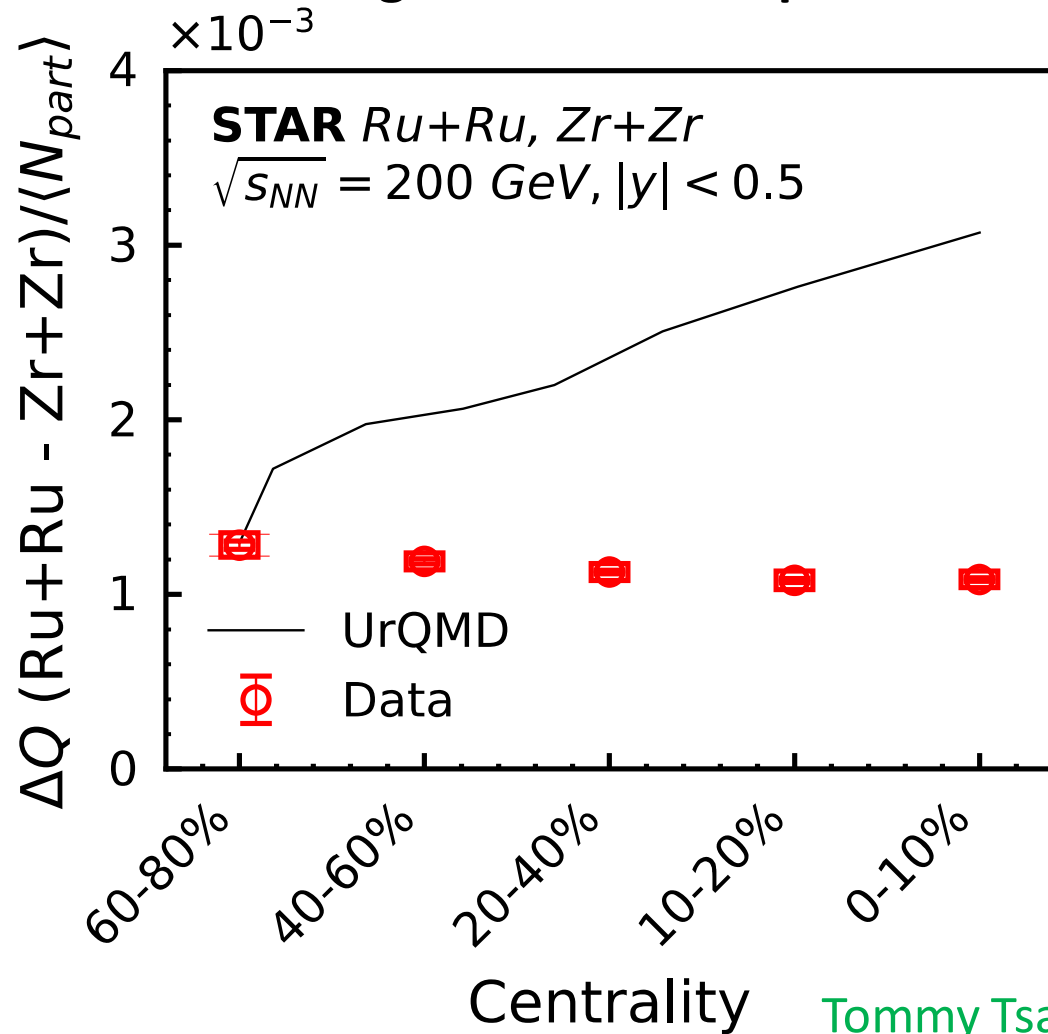
In γ +Au collision, rapidity asymmetry can reveal the origin

N. Lewis, et al., arXiv:2205.05685, *Eur.Phys.J.C* 84 (2024) 6, 590



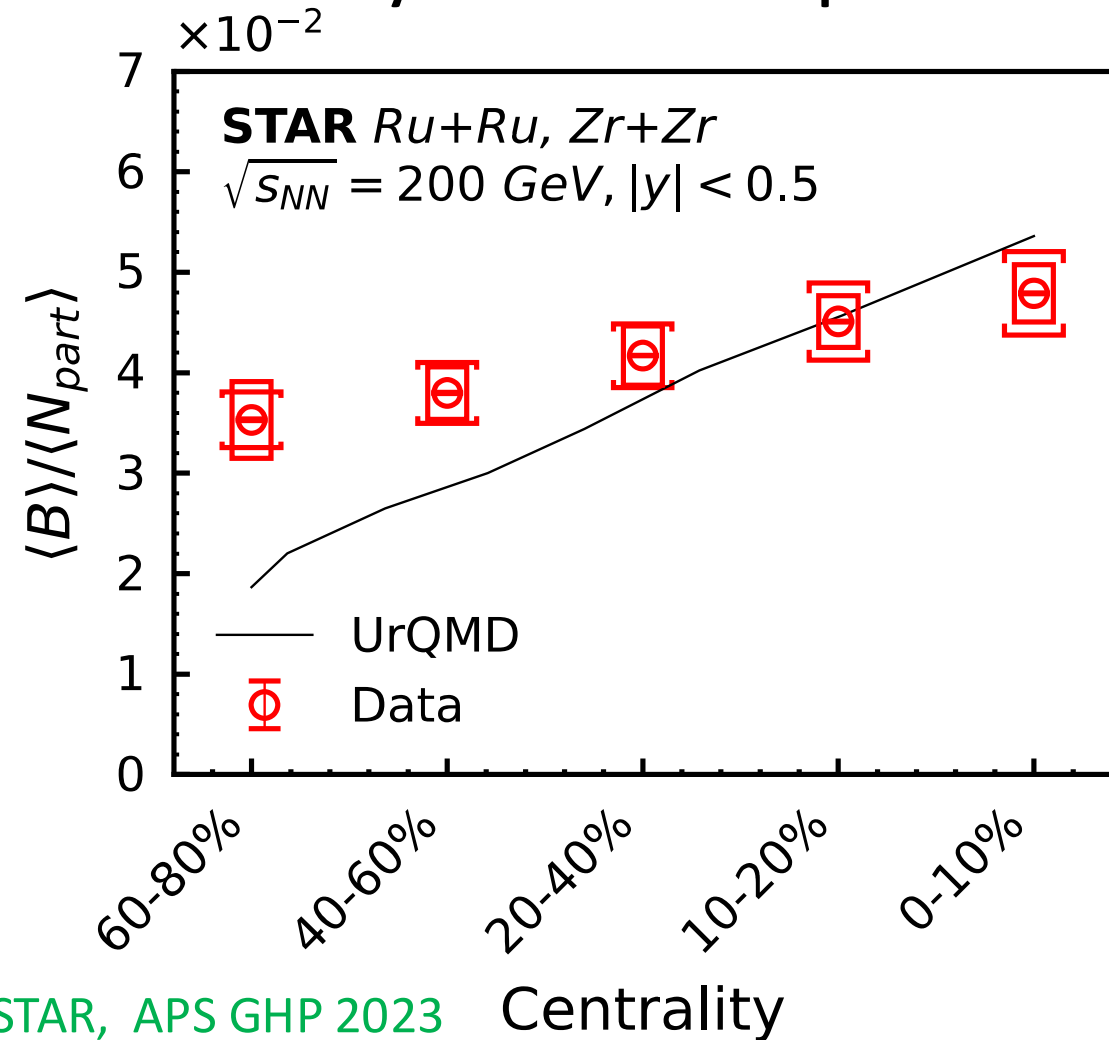
Separate charge and baryon transports

Charge number transport



STAR, arXiv:2408.15441

Baryon number transport



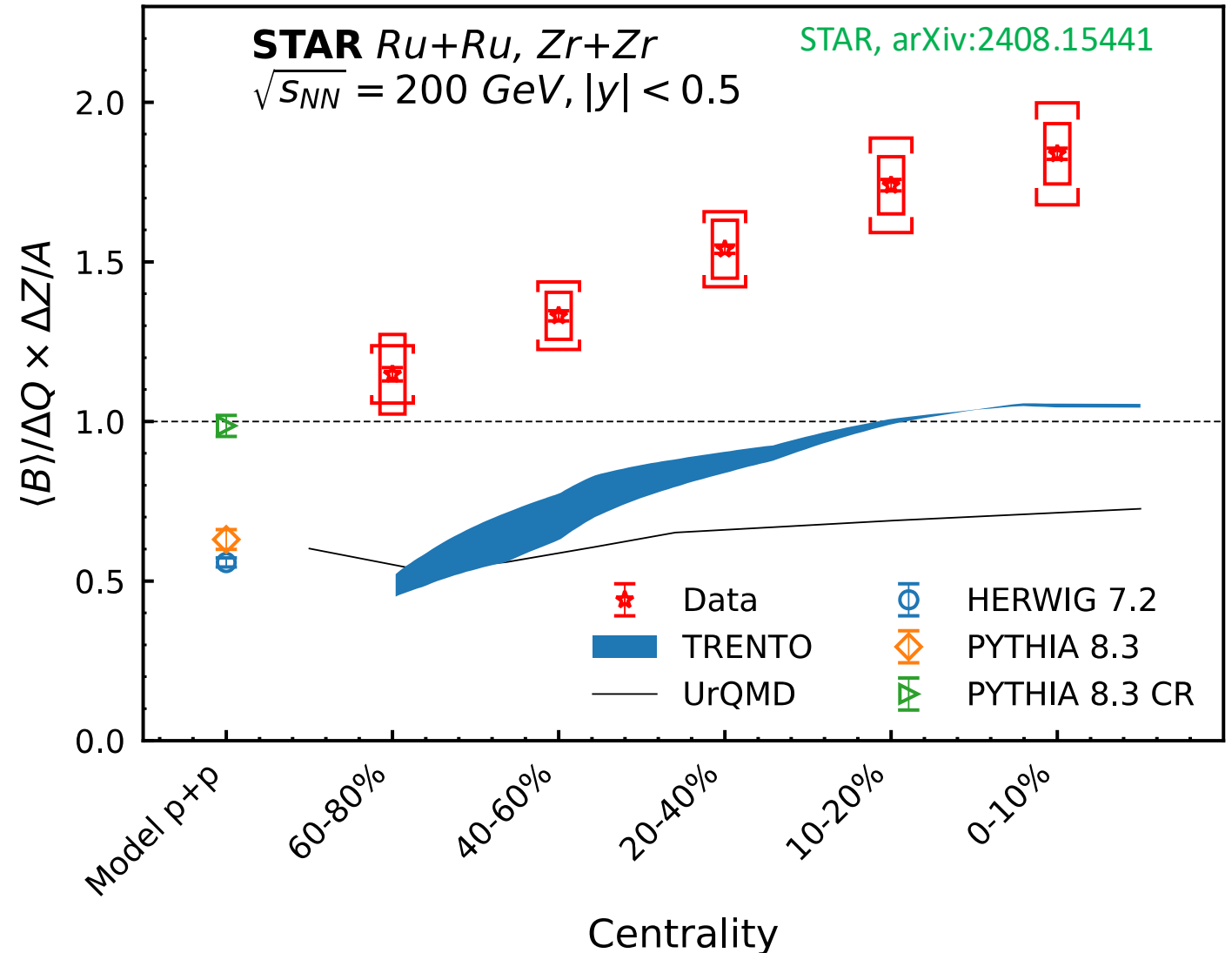
Tommy Tsang (KSU) for STAR, APS GHP 2023

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

Tommy Tsang (KSU) for STAR, QM, 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)

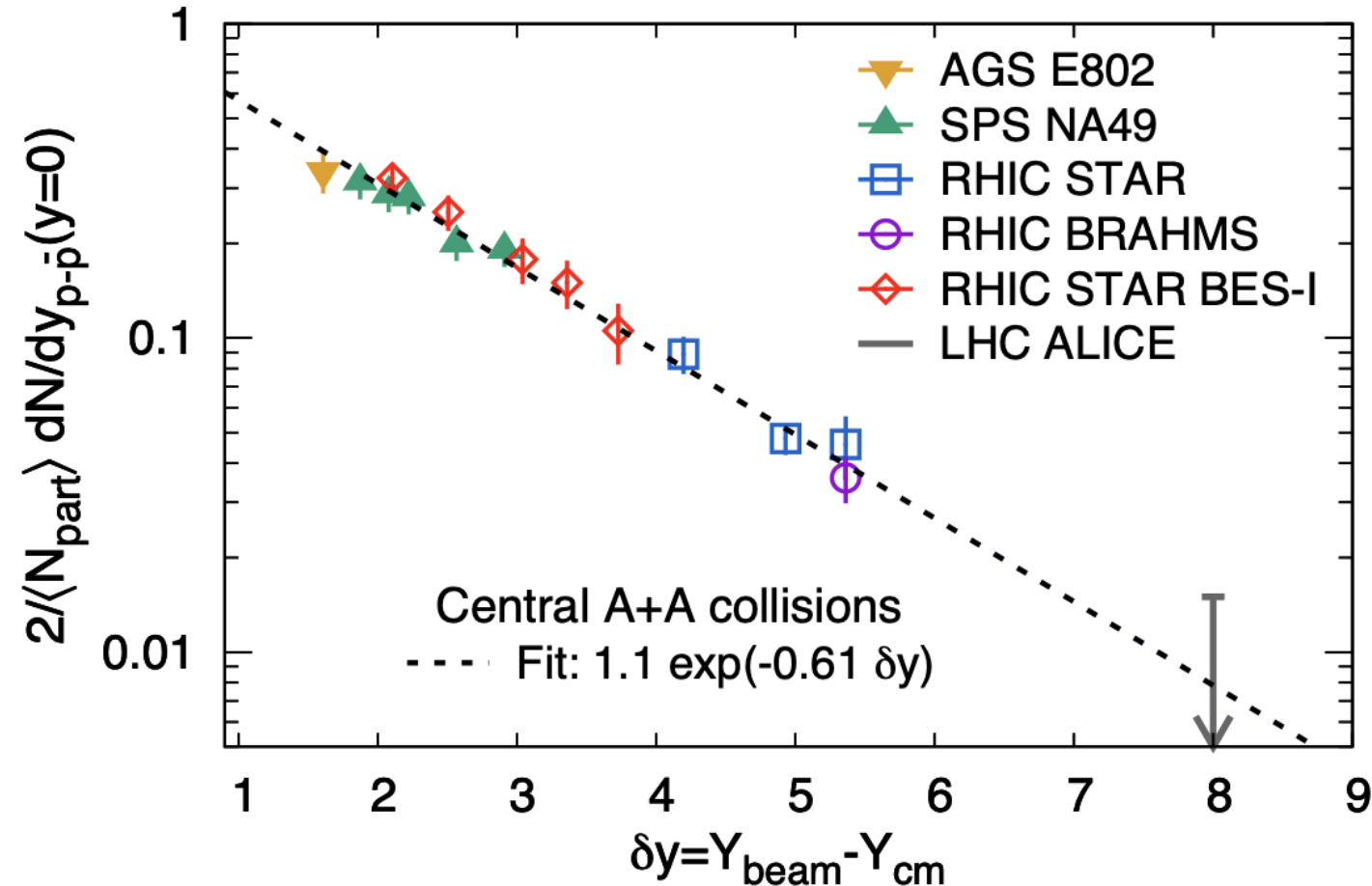


Quantifying baryon number transport

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

N. Lewis, et al., arXiv:2205.05685, *Eur.Phys.J.C* **84** (2024) 6, 590

- 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:
 $\alpha_B \sim 0.5 + \Delta$
 $\Delta \sim 0.1$



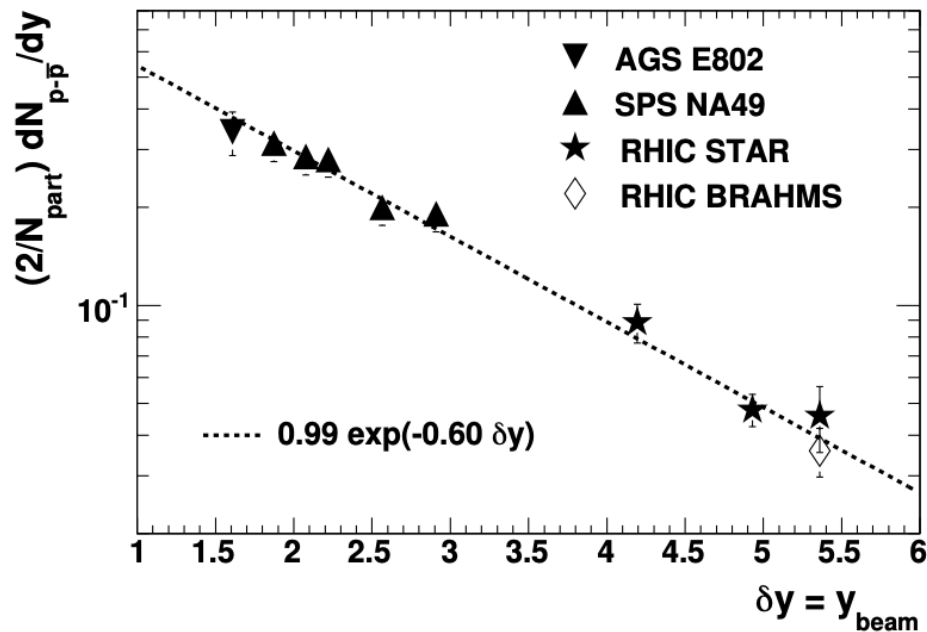


FIG. 29: The ratio of mid-rapidity inclusive net-protons to half of the number of participants in central heavy-ion collisions as a function of the rapidity shift. The AGS data is taken from Refs. [75, 86], SPS data from Refs. [87, 88, 89], and BRAHMS data from Ref. [90]. The published SPS data have already been corrected for weak-decays, the size of which is of the order 20-25% [88], so we have added 25% to the published net-proton yields to obtain the inclusive ones. Errors shown are total statistical and systematic uncertainties. The dashed line is an exponential fit to the data.

shift, obtained from central collisions at different energies, as a “measure” of the rapidity distribution of net-protons in central Au+Au collisions at the top RHIC energy. Since the net-protons shown in Fig. 29 contain equal contributions from the two colliding nuclei, the net-proton rapidity distribution in Au+Au collisions at the top RHIC energy is the data points in Fig. 29 multiplied by a factor varying between 1/2 and 1. At small $\delta y \sim 0$ the net-proton density should be close to 1/2 of those shown in Fig. 29, and at large δy (i.e. nearly mid-rapidity) the factor should be close to 1. Assuming an exponential variation in this factor between 1/2 and 1, i.e. a net-proton rapidity distribution of $\frac{dN_{p-\bar{p}}/dy}{N_{\text{part}}/2} = 2^{\delta y/5.36-1} \times 0.99 \exp(-0.60\delta y) = 0.50 \exp(-0.47\delta y)$ in 200 GeV Au+Au collisions (where 5.36 is the beam rapidity for 100 GeV beams), we estimate a rapidity shift of $\langle \delta y \rangle = 1/0.47 \approx 2.1$. It is interesting to note that the integral of the above rapidity distribution between 0 and 5.36 comes out to be rather close to unity as required by proper normalization. Clearly the exponential form we used is a simplification. BRAHMS has measured the rapidity distribution of net-protons in the range $0 < y < 3$ in central Au+Au collisions at 200 GeV, and used a more sophisticated functional form to estimate the average rapidity shift to be approximately 2.06 ± 0.16 [90].

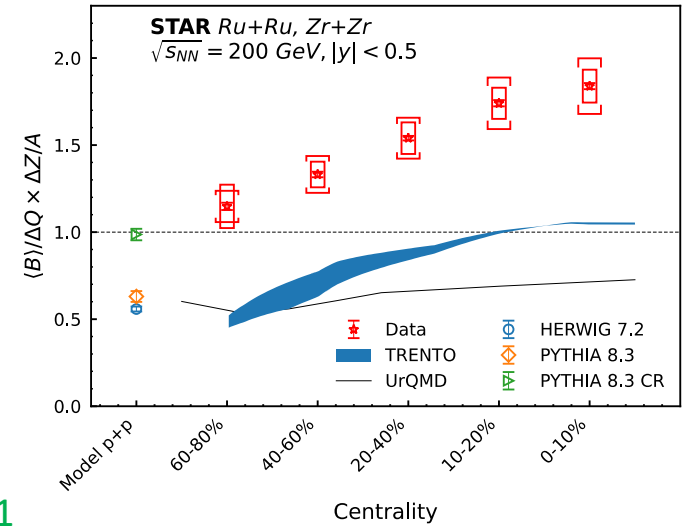
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STAR, <https://arxiv.org/pdf/2408.15441>

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Q=B at middle rapidity

$$B/Q=2$$



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If gluon topology (J) carries B as one unit,
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Regge theory

$$\alpha_B=0.61$$

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

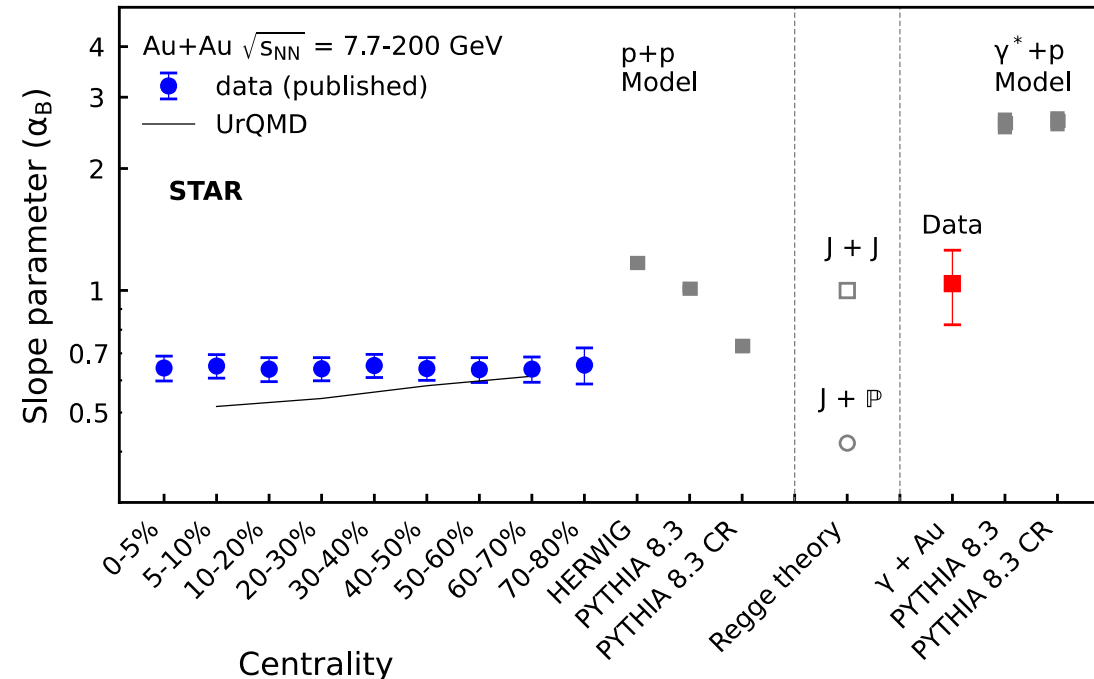
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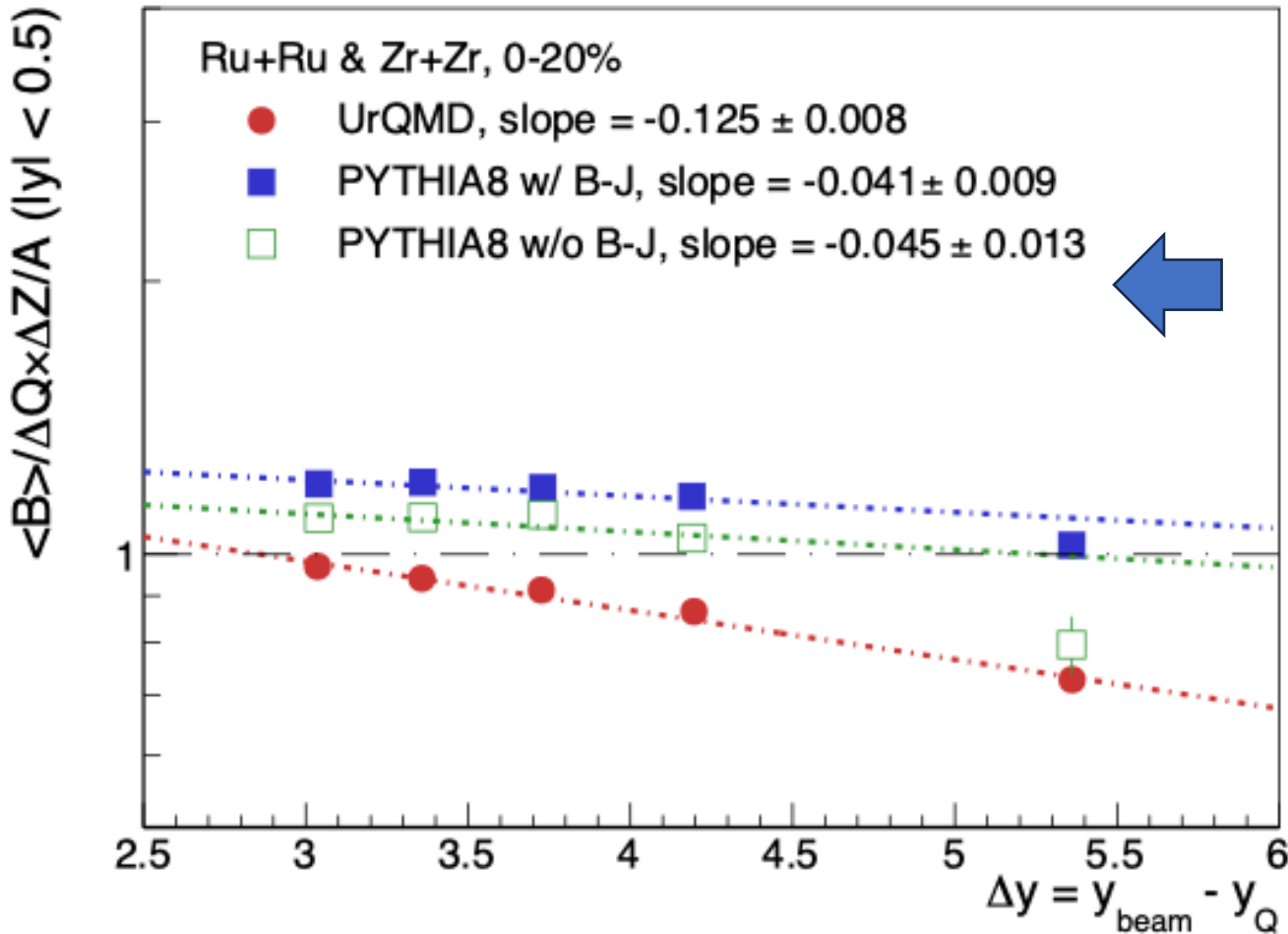
$$\alpha_B(A+A)=0.61 < \alpha_B(\gamma+A)=1.1 < \alpha_B(\text{PYTHIA})$$

STAR, arXiv:2408.15441



Charge vs baryon rapidity slope

STAR BUR 2025



$q=u,d$

Measure charge transport in high-energy nuclear collisions with an energy scan of isobaric collisions

Wendi Lv, Niseem Magdy, Rongrong Ma, Zebo Tang, Prithwish Tribedy, Chun Yuen Tsang, Zhangbu Xu

We present a method to measure electric-charge transport in high-energy nuclear collisions using a beam-energy scan of isobaric systems. Comparing collisions of nuclei with identical mass number but different atomic number allows the charge difference (ΔQ) to be extracted with a double-ratio technique that suppresses most experimental systematic uncertainties. By varying the beam energy, the rapidity gap (Δy) over which electric charge is transported can be systematically scanned. Simulations of Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 19.6\text{--}200\text{GeV}$ with UrQMD and PYTHIA Angantyr show that midrapidity ΔQ decreases exponentially with increasing Δy , with the slope parameter exhibiting strong model dependence. Comparisons with the baryon number transport reveal distinct patterns. In both UrQMD and PYTHIA Angantyr (with and without final-state baryon junctions), where baryon number is carried solely by valence quarks, the rapidity slope for baryon transport is larger than that for electric-charge transport. In contrast, scenarios that include baryon junctions in the initial state are expected to produce the opposite trend. This demonstrates that an isobar beam-energy scan provides a sensitive probe of electric-charge transport and offers new constraints on the microscopic mechanisms governing conserved-charge redistribution in QCD matter.

Comments: 8 pages, 7 figures

Subjects: Nuclear Experiment (nucl-ex); High Energy Physics - Experiment (hep-ex)

Cite as: arXiv:2604.02825 [nucl-ex]

RHIC top energy data and baryon junction would predict a positive slope difference

Unfortunately, RHIC decided to pass on the opportunity

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

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.**



Junction CR

Illustrations by J. Altmann

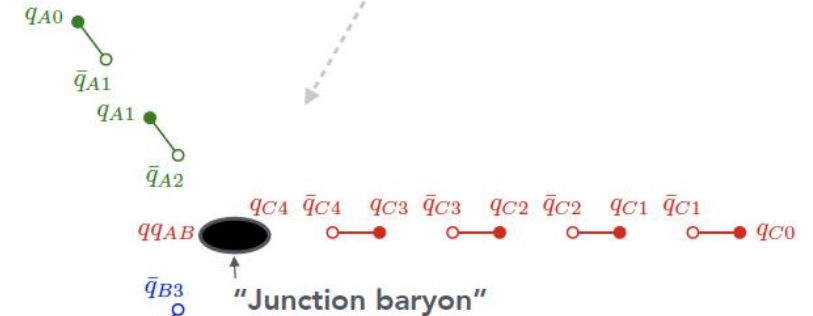
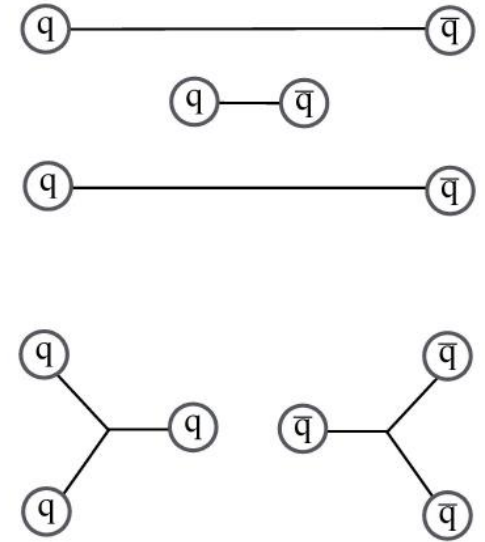


Illustration from Pythia 8.3 manual

What do we know about e+p collisions?

Artru & Mekhfi, NPA 1991

“unpolarized and polarized electroproduction of fast baryons

- 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
- JLab Electron beam at exponential slope of baryon transport in baryon junction model

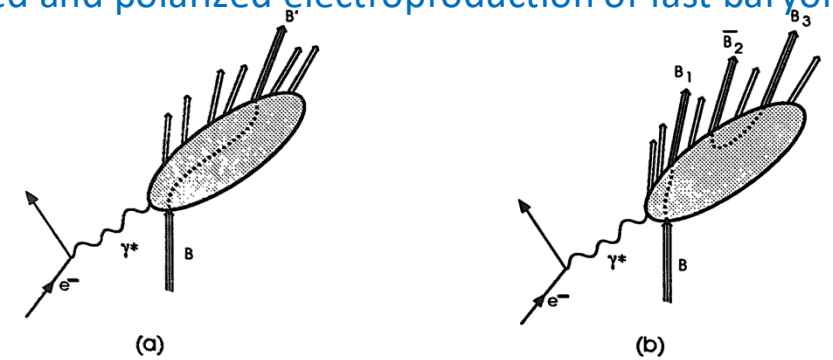


Figure 1. Main mechanisms of electroproduction of fast baryons.

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

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

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

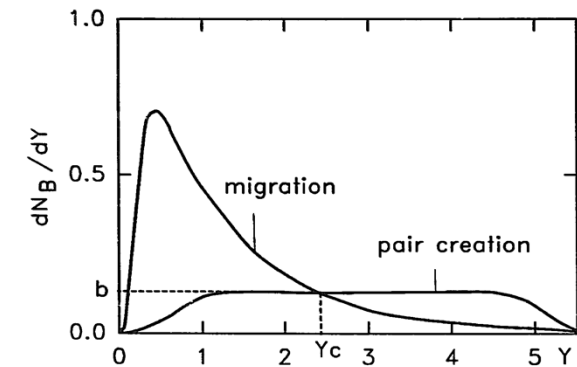


Figure 2. Rapidity spectrum: (a) of the migration mechanism, (b) of the pair creation mechanism.

What do we know about e+p collisions

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Measurement of the Baryon-Antibaryon Asymmetry in Photoproduction at HERA

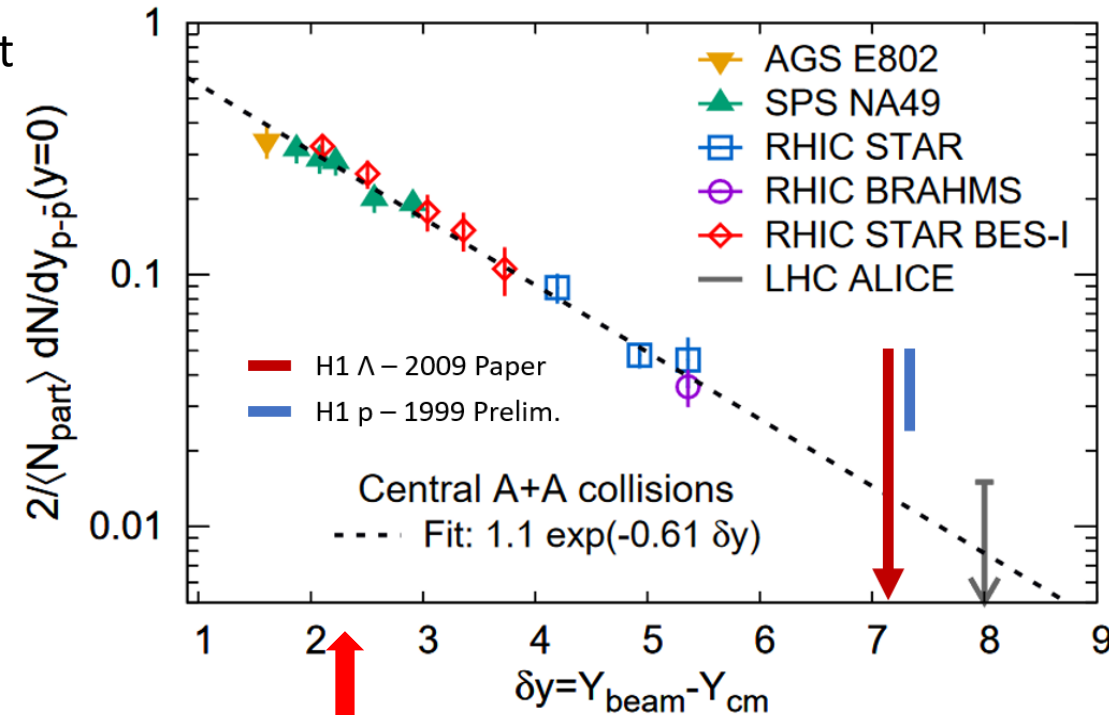
C. Adloff et al. (H1 Collaboration), ICHEP 1998

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]

N. Lewis, et al., arXiv:2205.05685;
Henry Klest (SBU) HERA data



CLAS12 Kinematics
Li's talk

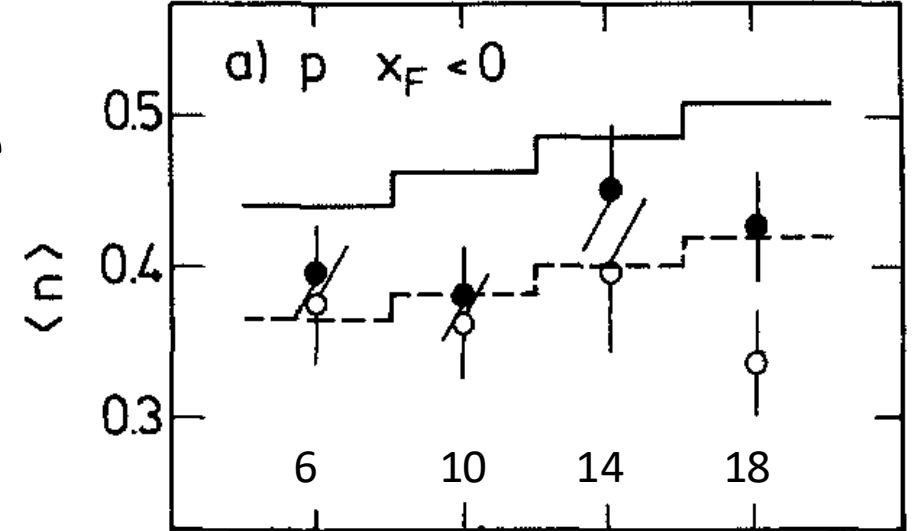
What do we know about $\mu+p$ (d) collisions

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

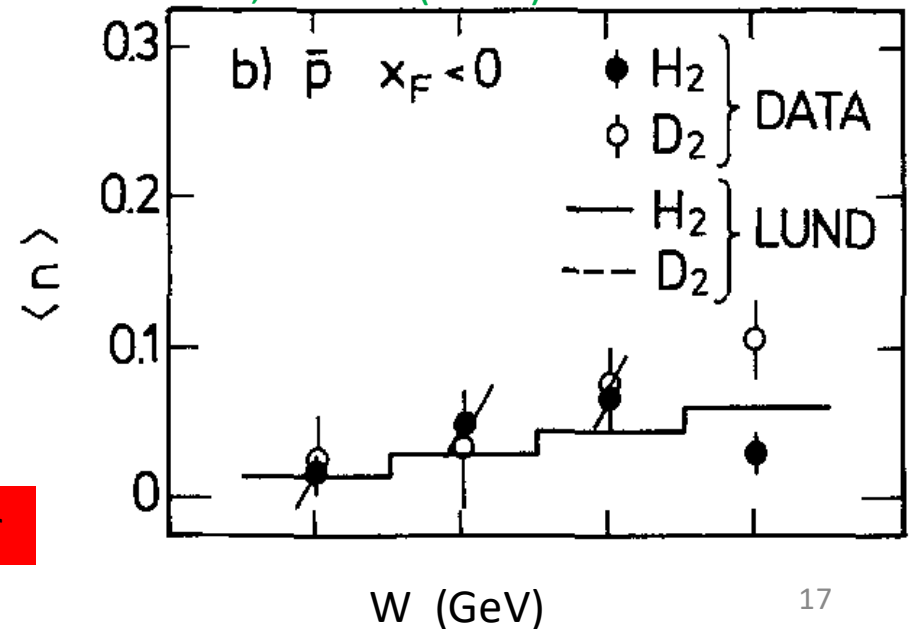
Total citations: 19

Fig. 5a-d. Average multiplicities from the H₂ (full circles) and the D₂ target (open circles) vs. W for backward protons a, backward antiprotons b. The histograms show the Lund model predictions (full line: H₂ target, dashed line: D₂ 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.



EMC, ZPC 35 (1987) 433



Both proton and antiproton yields show independent on target flavor

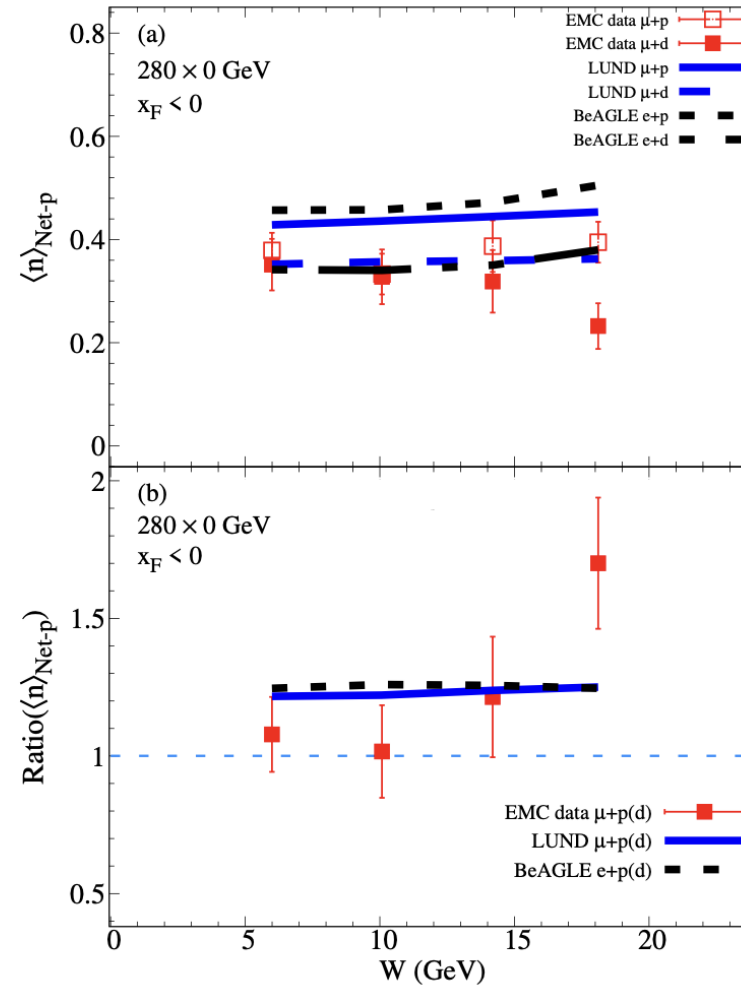
Simulation at present day

Niseem Magdy (SBU), arXiv:2408.08713

Same kinematics as EMC,
reproduce the simulation result

Next, using EIC kinematics,

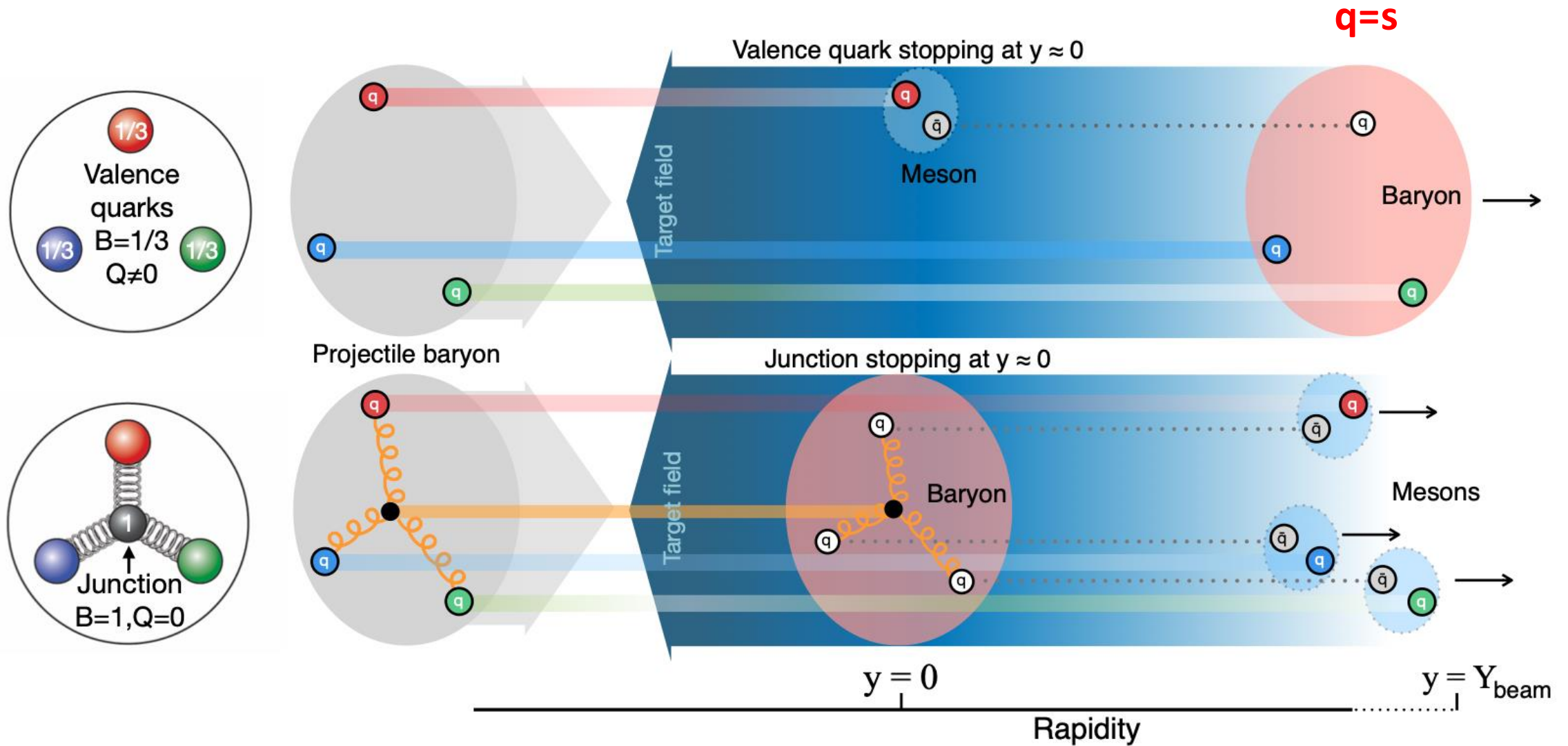
Does proton transport
independent of target flavor



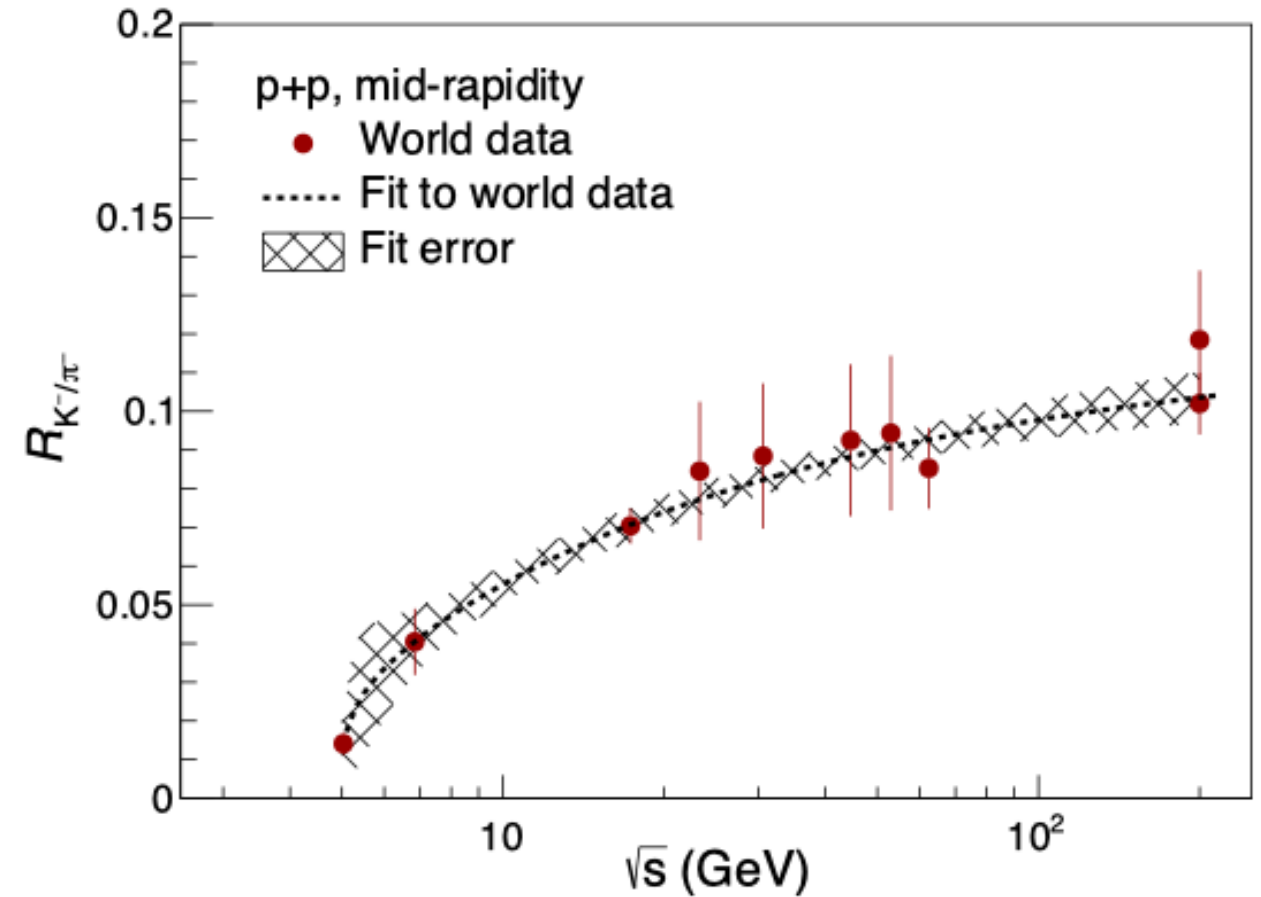
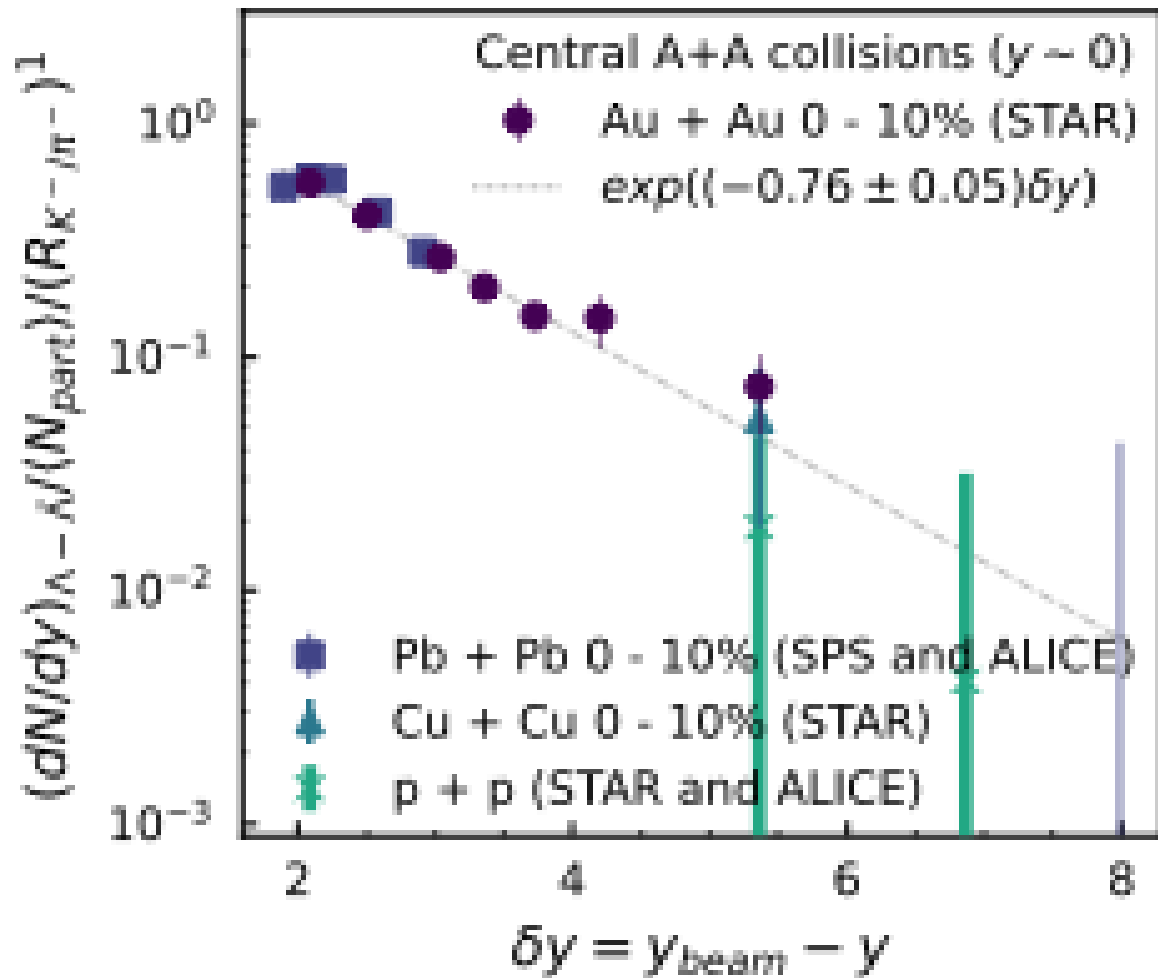
Xiaqing Li (SDU), Bill Li (MSU), Zhihong Ye (THU)

FIG. 7. The W dependence of the net-proton for $\mu+p$ and $\mu+d$ at 280-GeV muon on fixed targets are shown in panel (a). The ratios between $\mu+p$ and $\mu+d$ are presented in panel (b). Data and LUND model calculations are extracted from Ref. [15].

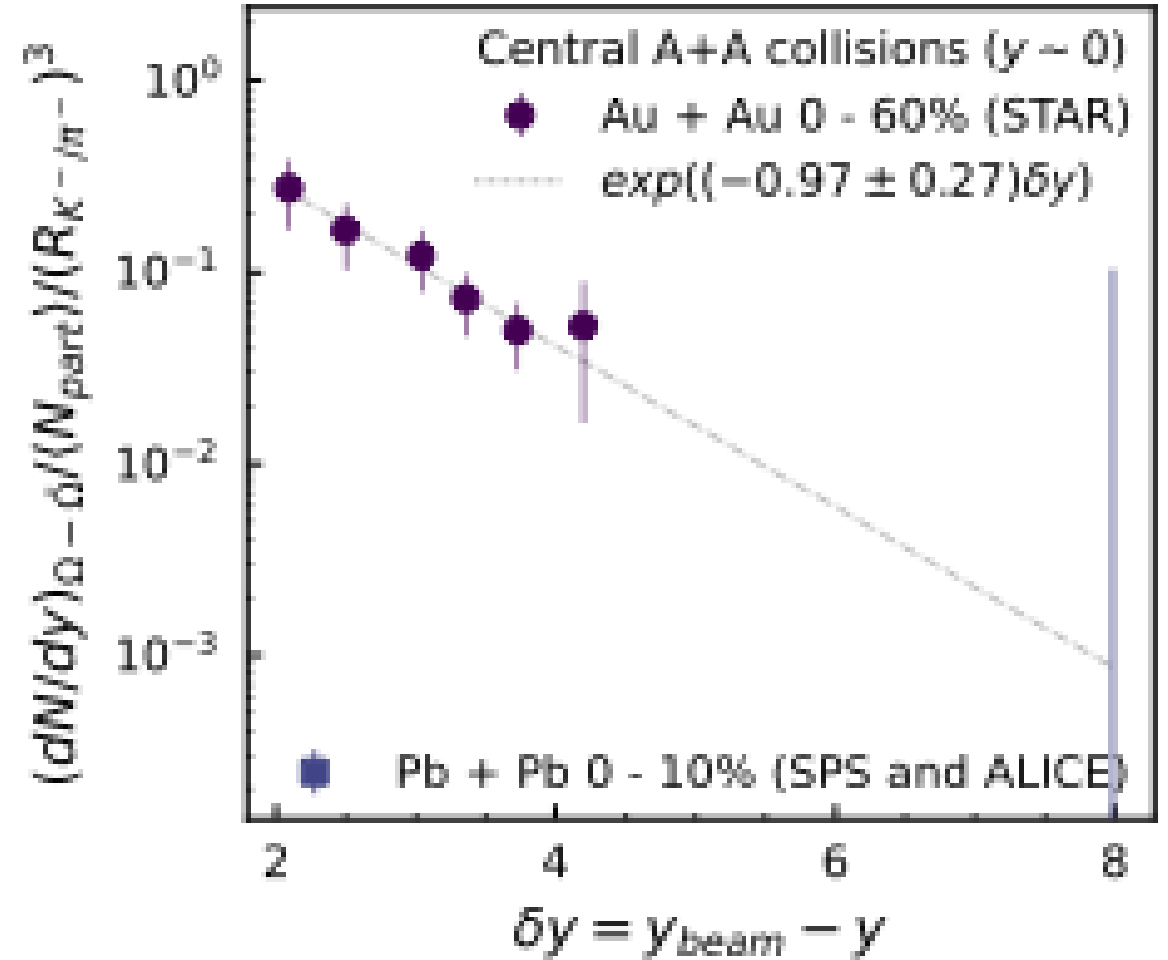
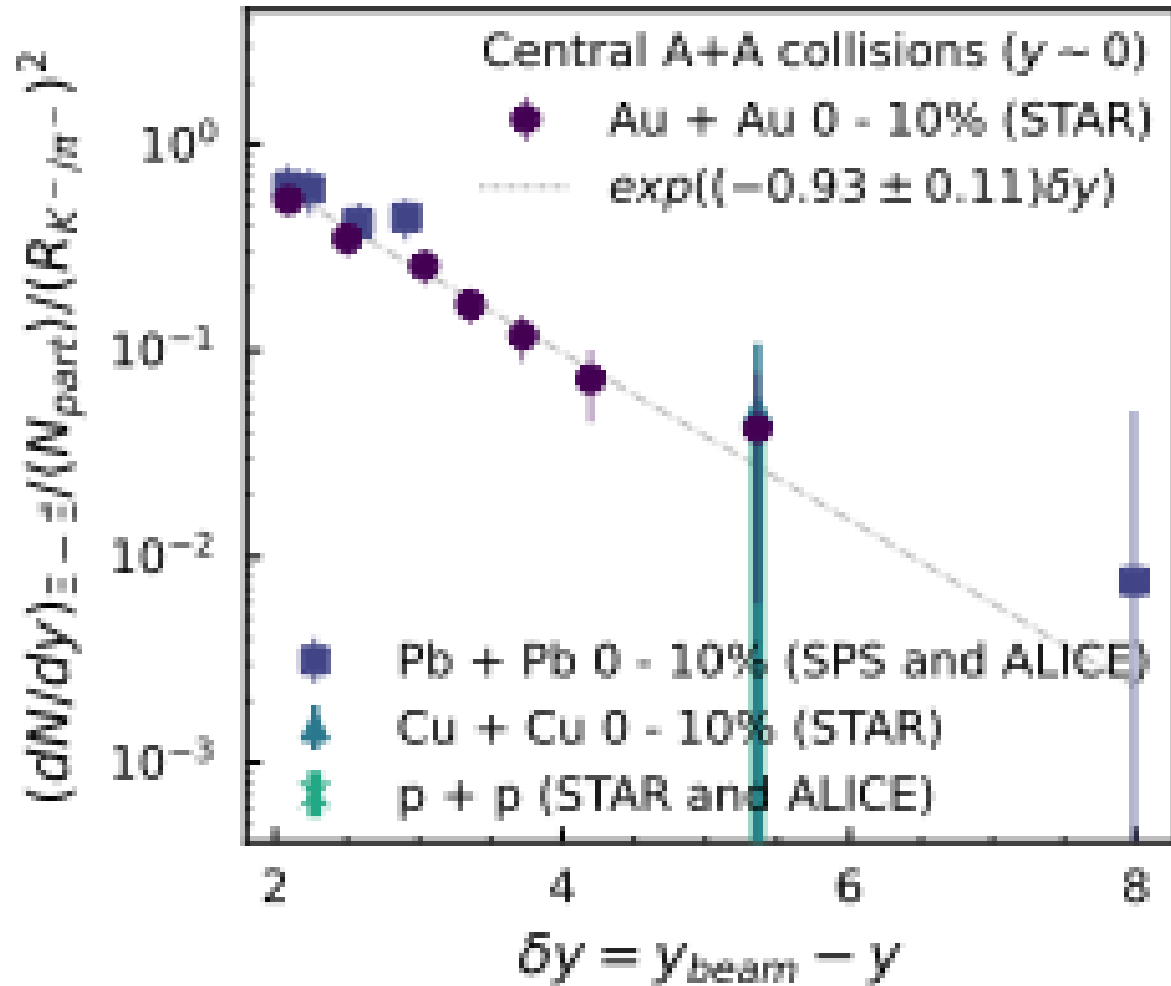
Flavor Independent Baryon Transport



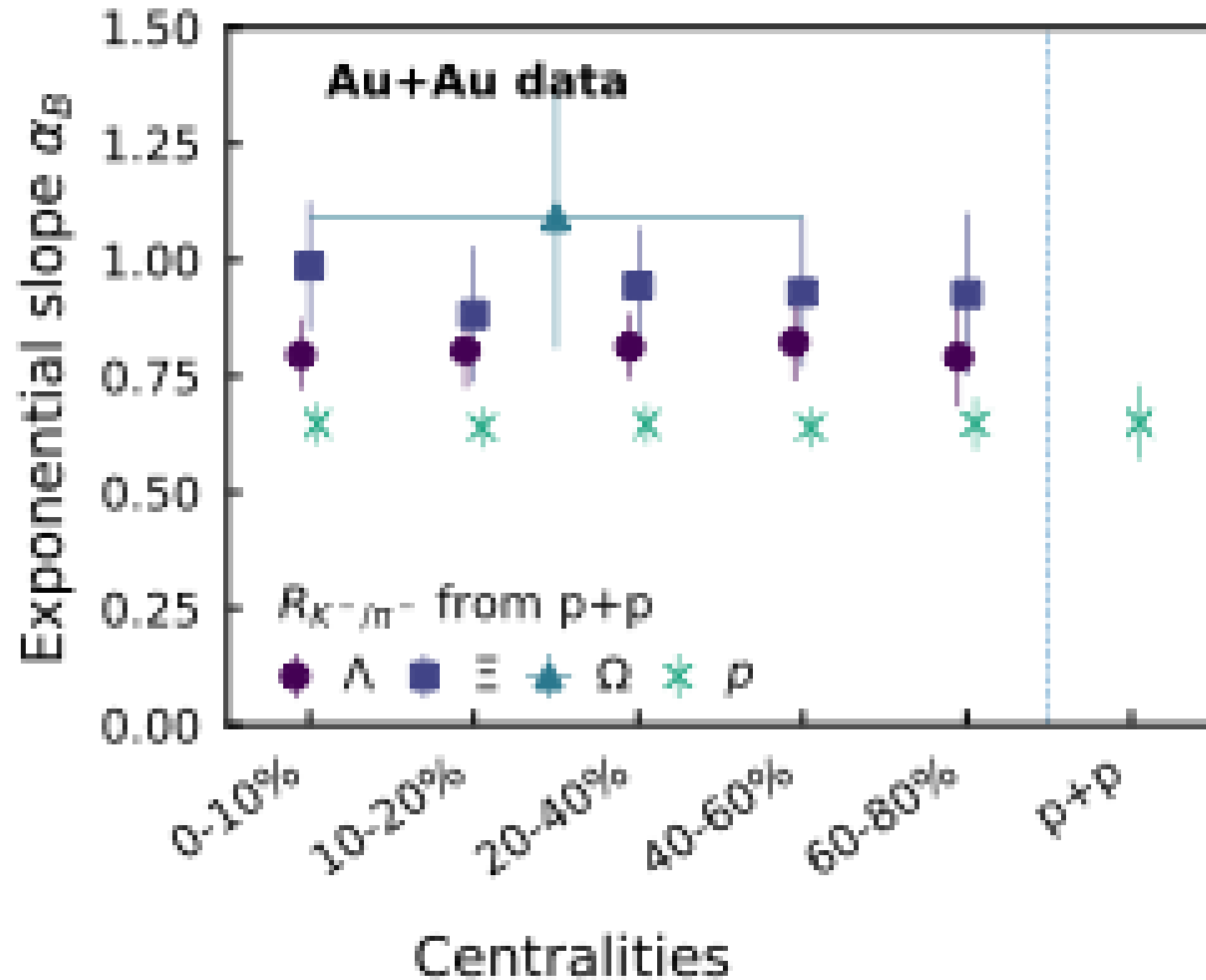
Hyperon Rapidity Slopes



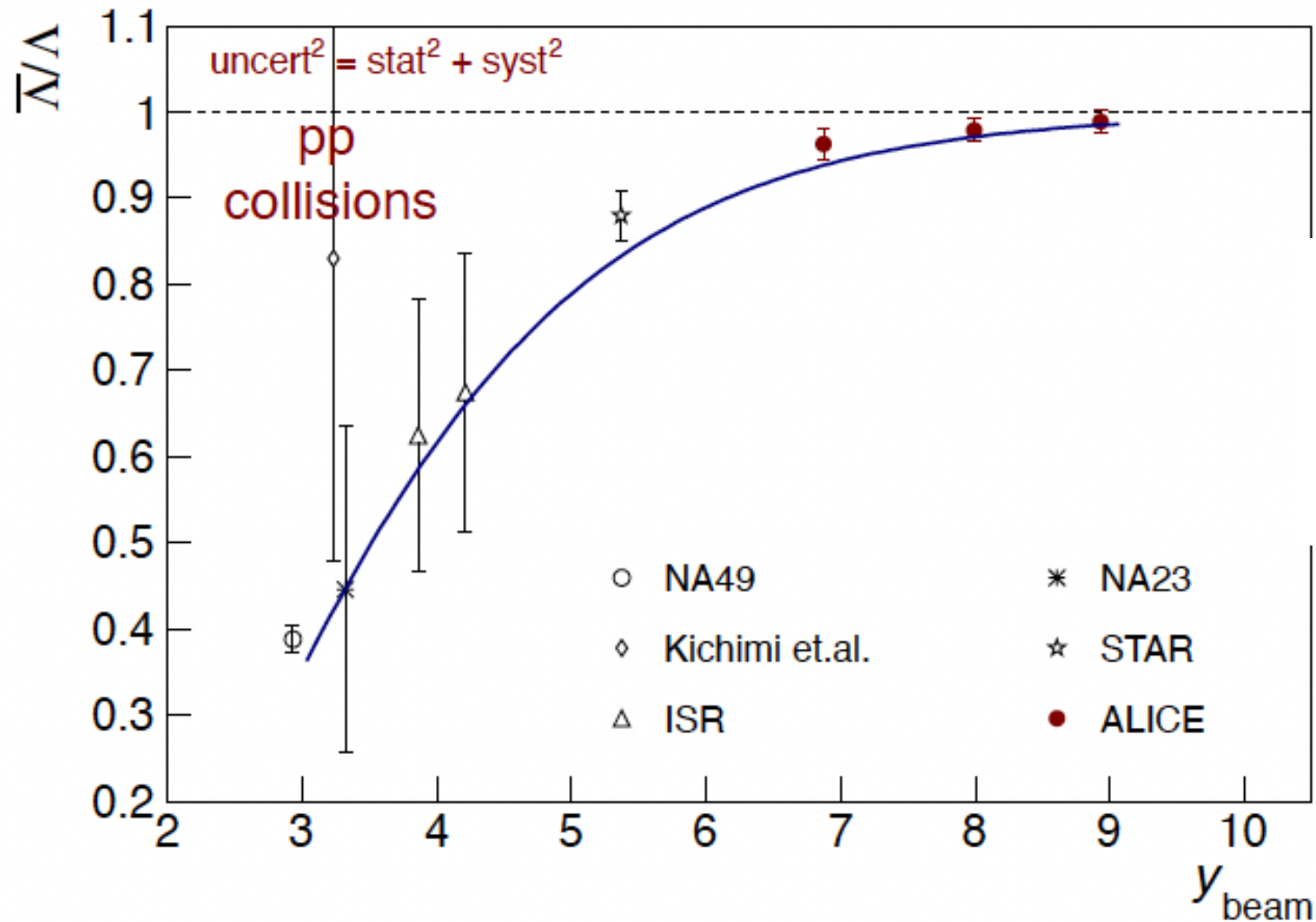
$S=-2,-3$



Flavor independence of baryon transport



ALICE@LHC $\bar{\Lambda}/\Lambda$



Eur. Phys. J. C (2013) 73:2496
DOI 10.1140/epjc/s10052-013-2496-5

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Experimental Physics

**Mid-rapidity anti-baryon to baryon ratios in pp collisions
at $\sqrt{s} = 0.9, 2.76$ and 7 TeV measured by ALICE**

The ALICE Collaboration*

CERN, 1211 Geneva 23, Switzerland

LHCb@LHC $\bar{\Lambda}/\Lambda$

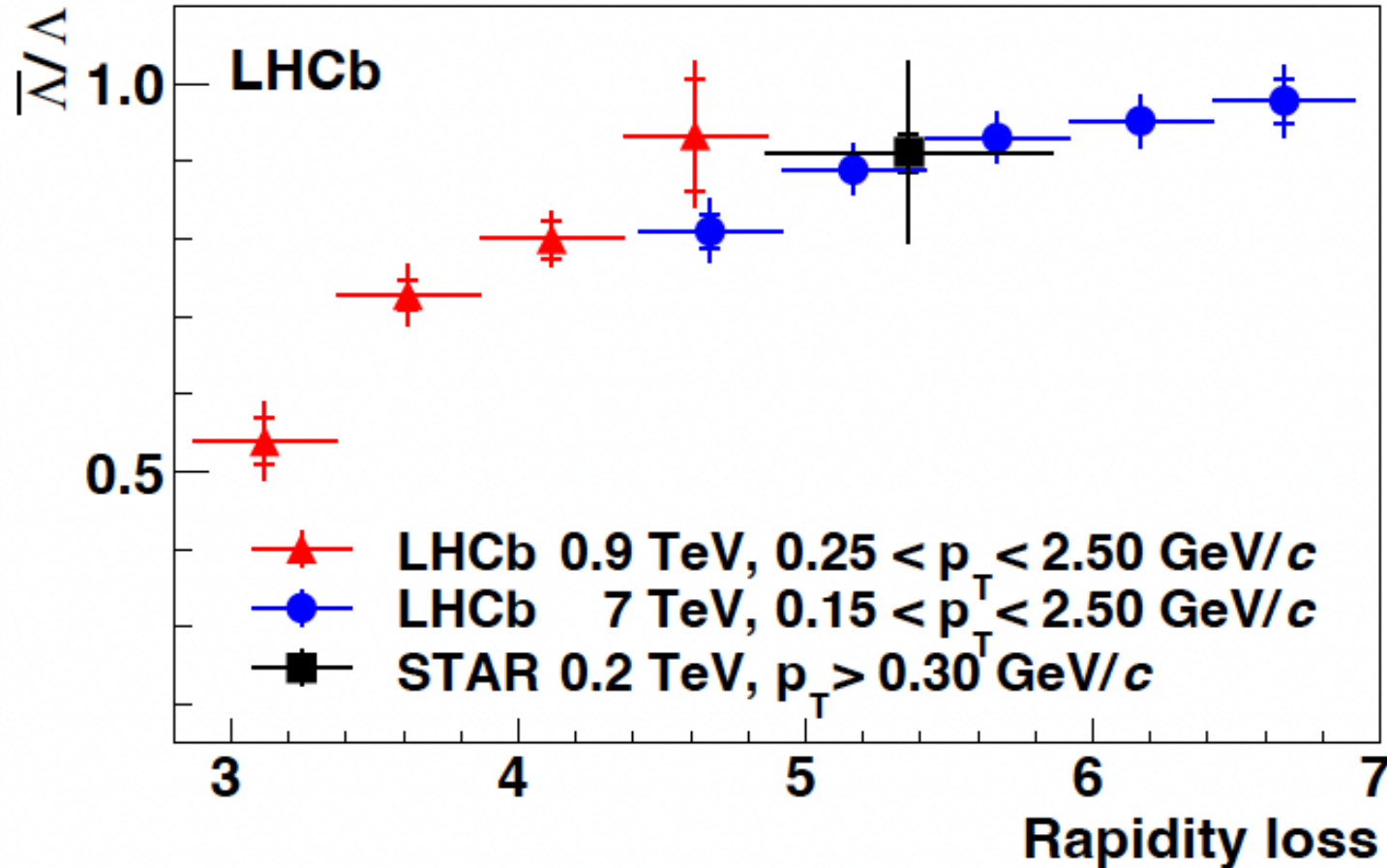


PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: July 6, 2011

ACCEPTED: July 13, 2011

PUBLISHED: August 8, 2011



Measurement of V^0 production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV



The LHCb collaboration

ABSTRACT: The $\bar{\Lambda}/\Lambda$ and $\bar{\Lambda}/K_S^0$ production ratios are measured by the LHCb detector from 0.3 nb^{-1} of pp collisions delivered by the LHC at $\sqrt{s} = 0.9 \text{ TeV}$ and 1.8 nb^{-1} at $\sqrt{s} = 7 \text{ TeV}$. Both ratios are presented as a function of transverse momentum, p_T , and rapidity, y , in the ranges $0.15 < p_T < 2.50 \text{ GeV}/c$ and $2.0 < y < 4.5$. Results at the two energies are in good agreement as a function of rapidity loss, $\Delta y = y_{\text{beam}} - y$, and are consistent with previous measurements. The ratio $\bar{\Lambda}/\Lambda$, measuring the transport of baryon number from the collision into the detector, is smaller in data than predicted in simulation, particularly at high rapidity. The ratio $\bar{\Lambda}/K_S^0$, measuring the baryon-to-meson suppression in strange quark hadronisation, is significantly larger than expected.

KEYWORDS: Hadron-Hadron Scattering

ARXIV EPRINT: [1107.0882](https://arxiv.org/abs/1107.0882)

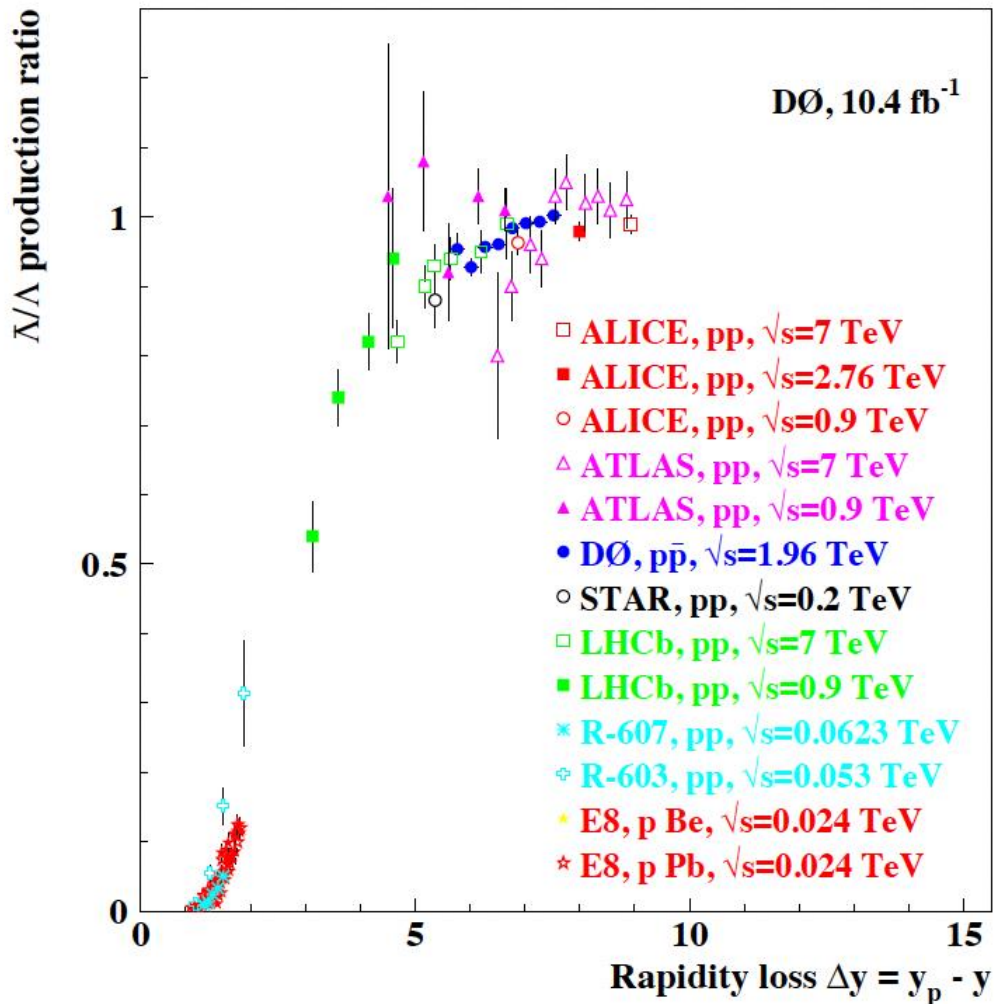


FIG. 6: $\bar{\Lambda}/\Lambda$ production ratio as a function of the rapidity loss $\Delta y \equiv y_p - y$ for several experiments that study reactions $pZ \rightarrow \Lambda(\bar{\Lambda})X$ for targets $Z = p, \bar{p}, \text{Be}$ and Pb . The experiments are ALICE [13], ATLAS [14], DØ (this analysis), STAR [15], LHCb [16], ISR R-607 [17], ISR R-603 [18], and the fixed target experiment Fermilab E8 studying $p\text{-Be}$ and $p\text{-Pb}$ collisions at a beam energy of 300 GeV [19].

DØ@Tevatron $\bar{\Lambda}/\Lambda$

Measurement of the forward-backward asymmetry of Λ and $\bar{\Lambda}$ production in $p\bar{p}$ collisions

DØ Collaboration · Victor Mukhamedovich Abazov (Dubna, JINR) [Show All\(368\)](#)

Nov 16, 2015

10 pages

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Published: Feb 9, 2016

e-Print: [1511.05113](#) [hep-ex]

DOI: [10.1103/PhysRevD.93.032002](#)

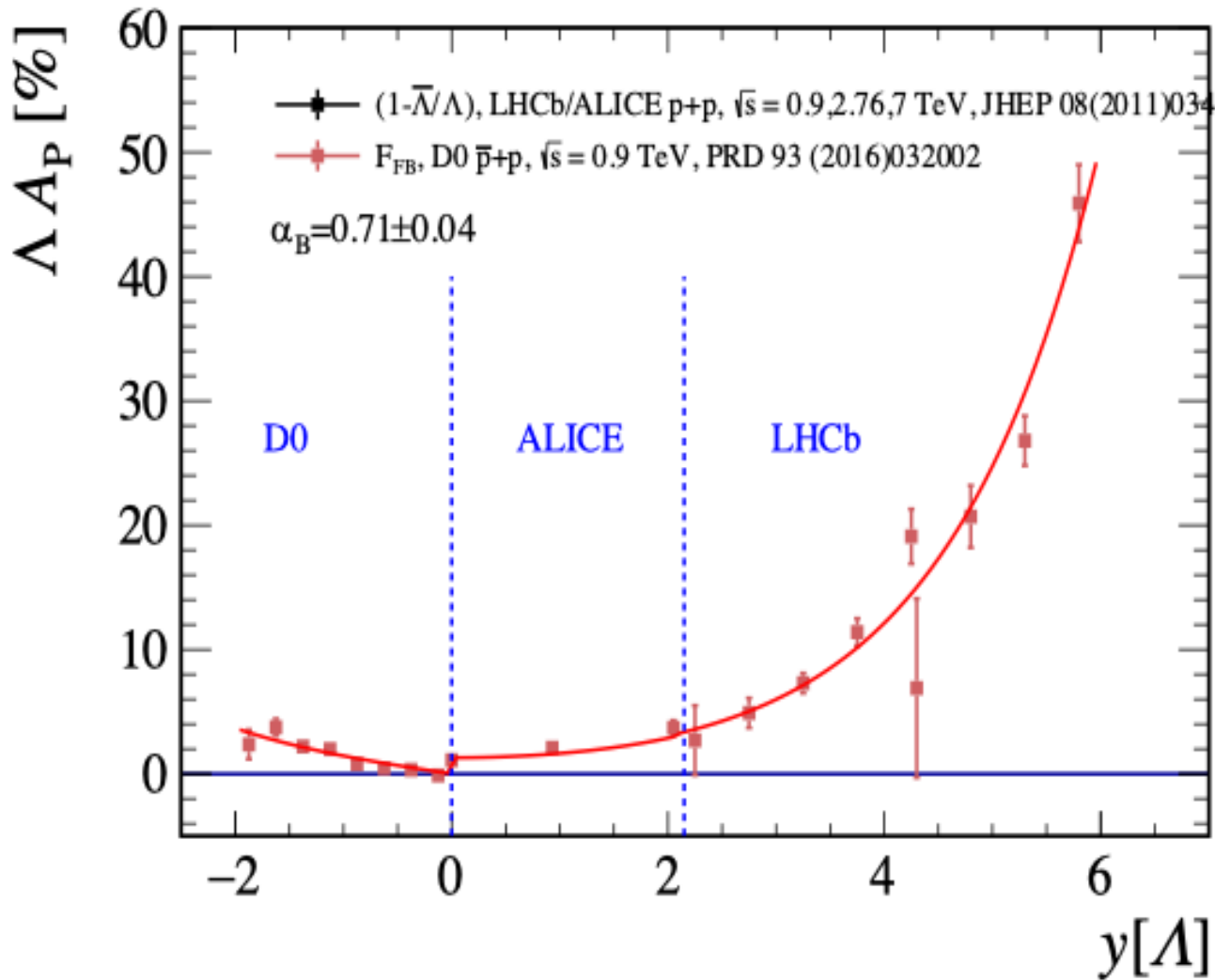
Report number: FERMILAB-PUB-15-496-E

Experiments: [FNAL-E-0823](#)

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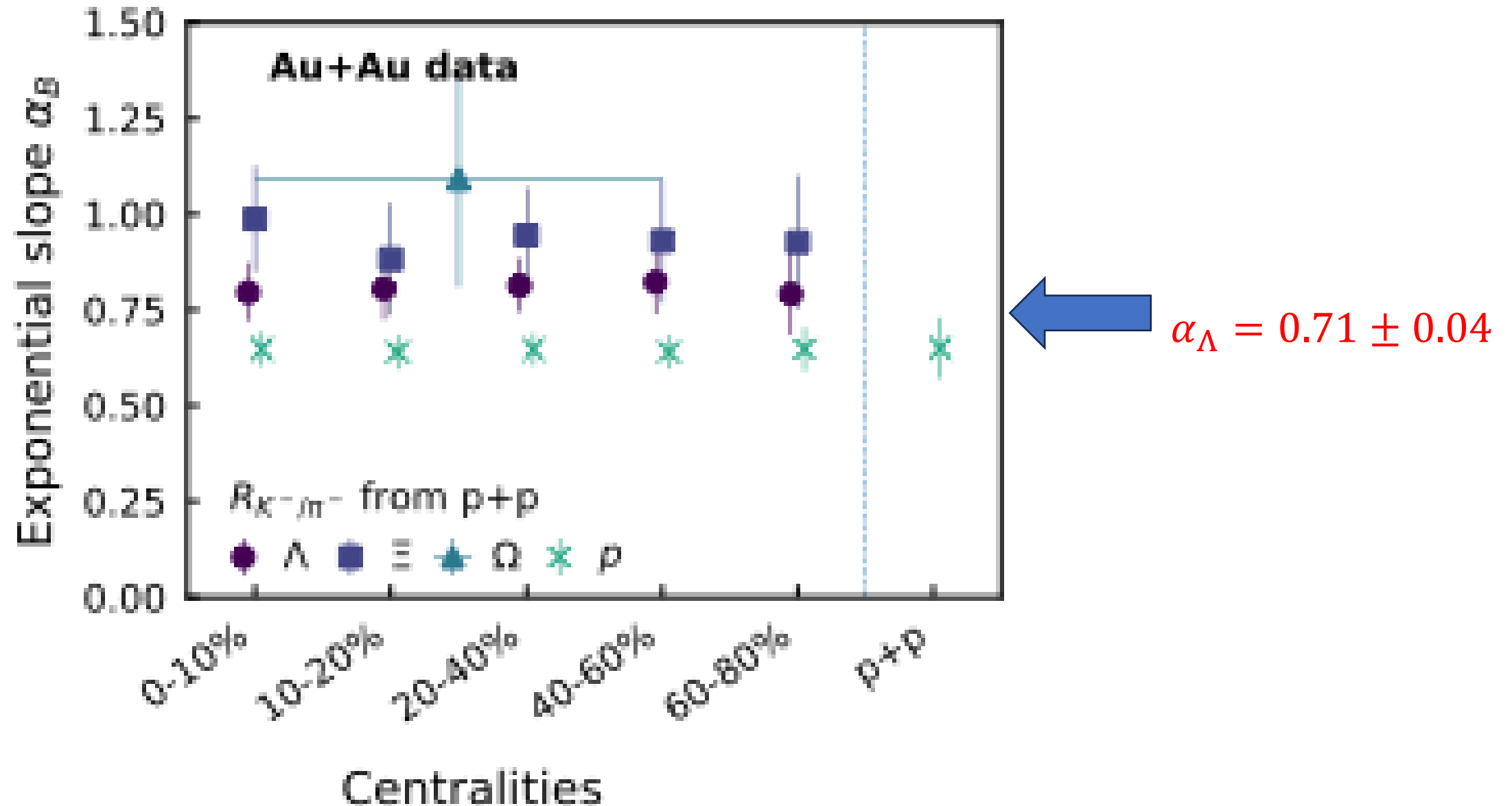
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Combined ALICE/LHCb/D0 $\bar{\Lambda}/\Lambda$

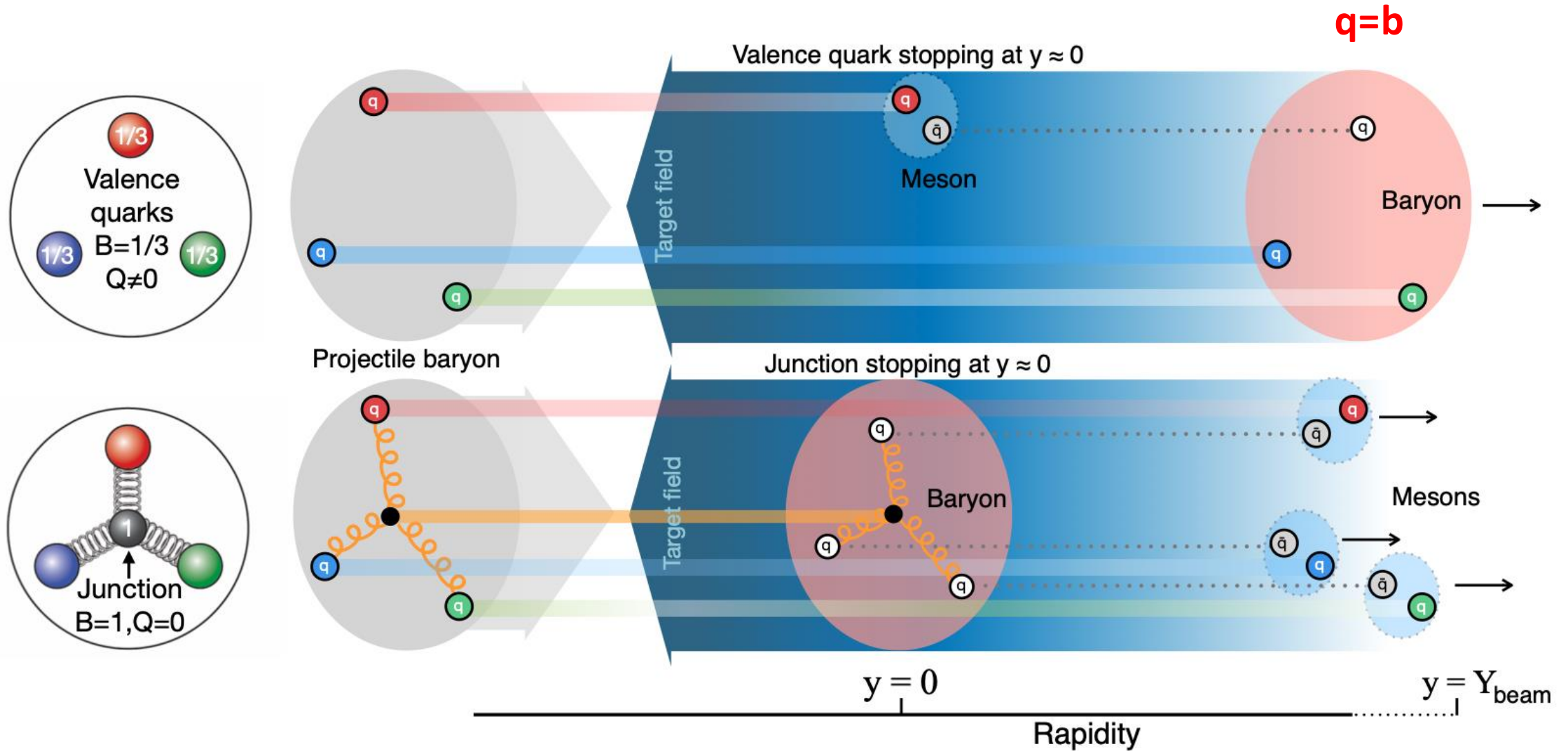


- LHC p+p: $\frac{\bar{\Lambda}}{\Lambda} \propto (e^{-\alpha_B y} + e^{\alpha_B y})$
- Tevatron $\bar{p}+p$: $\frac{\bar{\Lambda}}{\Lambda} \propto (e^{-\alpha_B y} - e^{\alpha_B y})$

Flavor independence of baryon transport



Flavor Independent Baryon Transport



Observation of a $\Lambda_b^0 - \bar{\Lambda}_b^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV



The LHCb collaboration

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ABSTRACT: This article presents differential measurements of the asymmetry between Λ_b^0 and $\bar{\Lambda}_b^0$ baryon production rates in proton-proton collisions at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV collected with the LHCb experiment, corresponding to an integrated luminosity of 3 fb^{-1} . The Λ_b^0 baryons are reconstructed through the inclusive semileptonic decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu X$. The production asymmetry is measured both in intervals of rapidity in the range $2.15 < y < 4.10$ and transverse momentum in $2 < p_T < 27 \text{ GeV}/c$. The results are found to be incompatible with symmetric production with a significance of 5.8 standard deviations for both $\sqrt{s} = 7$ and 8 TeV data, assuming no CP violation in the decay. There is evidence for a trend as a function of rapidity with a significance of 4 standard deviations. Comparisons to predictions from hadronisation models in PYTHIA and heavy-quark recombination are provided. This result constitutes the first observation of a particle-antiparticle asymmetry in b -hadron production at LHC energies.

KEYWORDS: Hadron-Hadron scattering (experiments), Heavy quark production, proton-proton scattering, Hard scattering, B physics

ARXIV EPRINT: [2107.09593](https://arxiv.org/abs/2107.09593)

Study of the production of Λ_b^0 and \bar{B}^0 hadrons in pp collisions and first measurement of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ branching fraction

The LHCb collaboration[†]

Abstract

The product of the Λ_b^0 (\bar{B}^0) differential production cross-section and the branching fraction of the decay $\Lambda_b^0 \rightarrow J/\psi p K^-$ ($\bar{B}^0 \rightarrow J/\psi \bar{K}^*(892)^0$) is measured as a function of the beauty hadron transverse momentum, p_T , and rapidity, y . The kinematic region of the measurements is $p_T < 20 \text{ GeV}/c$ and $2.0 < y < 4.5$. The measurements use a data sample corresponding to an integrated luminosity of 3 fb^{-1} collected by the LHCb detector in pp collisions at centre-of-mass energies $\sqrt{s} = 7 \text{ TeV}$ in 2011 and $\sqrt{s} = 8 \text{ TeV}$ in 2012. Based on previous LHCb results of the fragmentation fraction ratio, $f_{\Lambda_b^0}/f_d$, the branching fraction of the decay $\Lambda_b^0 \rightarrow J/\psi p K^-$ is measured to be

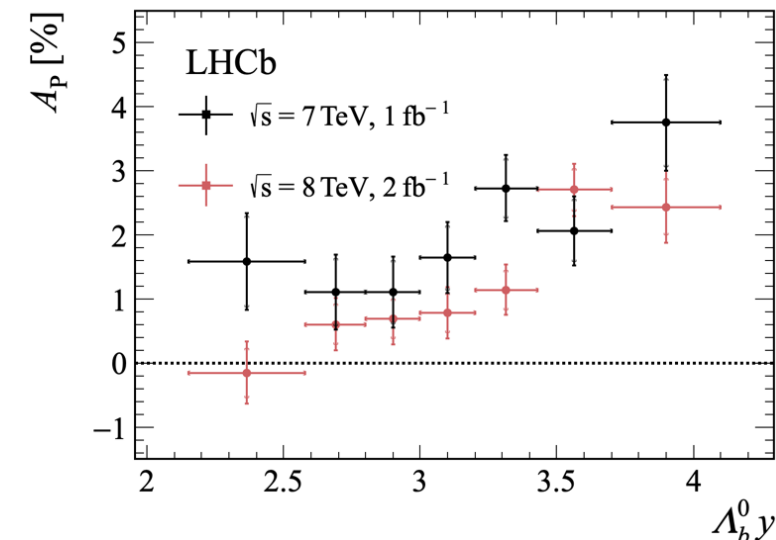
$$\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-) = (3.17 \pm 0.04 \pm 0.07 \pm 0.34_{-0.28}^{+0.45}) \times 10^{-4},$$

where the first uncertainty is statistical, the second is systematic, the third is due to the uncertainty on the branching fraction of the decay $\bar{B}^0 \rightarrow J/\psi \bar{K}^*(892)^0$, and the fourth is due to the knowledge of $f_{\Lambda_b^0}/f_d$. The sum of the asymmetries in the production and decay between Λ_b^0 and $\bar{\Lambda}_b^0$ is also measured as a function of p_T and y . The previously published branching fraction of $\Lambda_b^0 \rightarrow J/\psi p \pi^-$, relative to that of $\Lambda_b^0 \rightarrow J/\psi p K^-$, is updated. The branching fractions of $\Lambda_b^0 \rightarrow P_c^+(\rightarrow J/\psi p) K^-$ are determined.

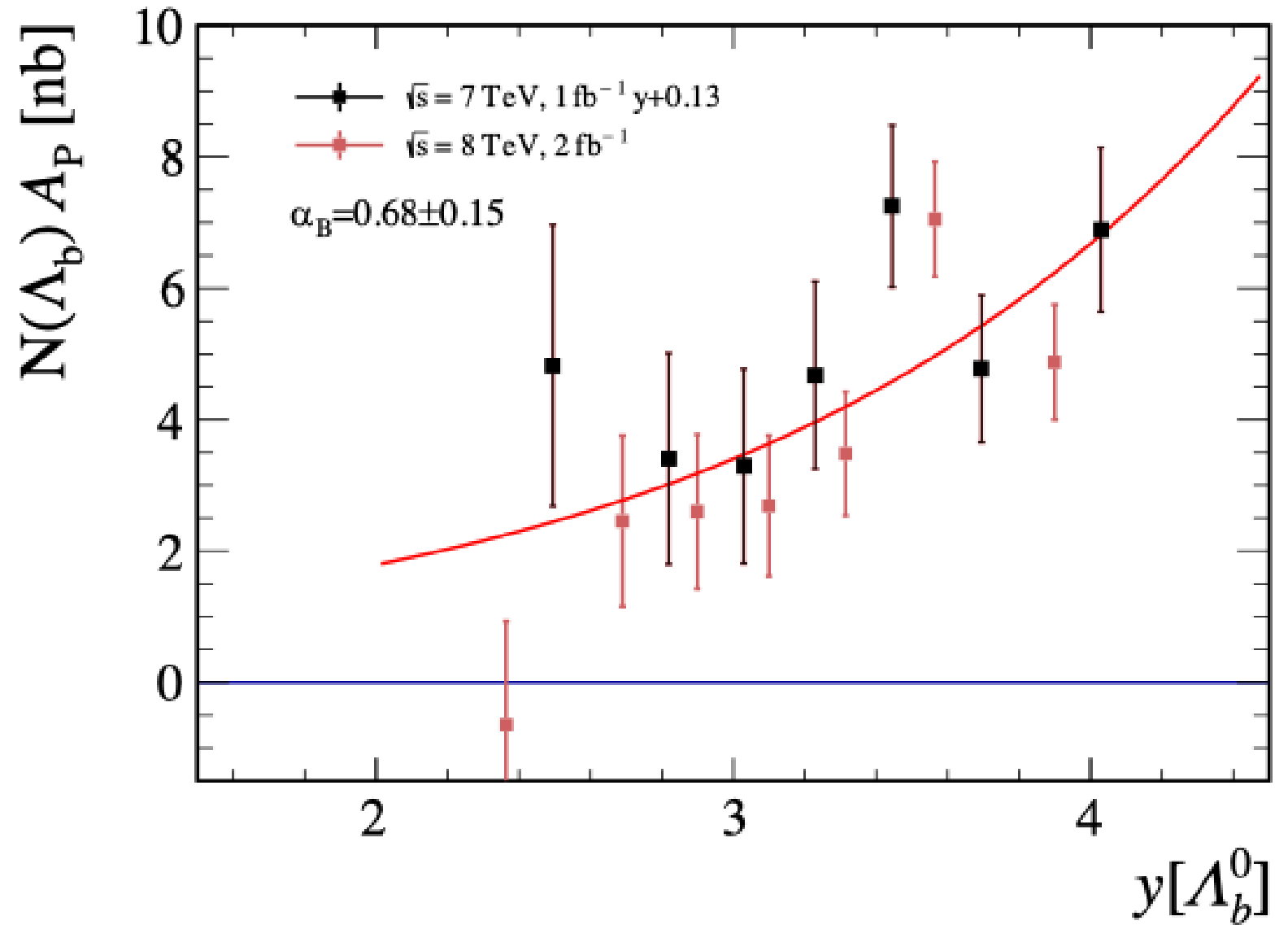
Published in Chin. Phys. C40 (2016) 011001

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[†]Authors are listed at the end of this paper.



LHCb Λ_b



Anantha Nair (KSU)
Existing high-statistic data at 13TeV

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 is a non-perturbative object
- First measurement of Flavor Independence at JLab (Bill Li's talk)
- Future Isobar collisions to measure charge transport (quark transports),
Unfortunately, RHIC decided to pass on the opportunity
Zr/Ru; $^7\text{Li}/^7\text{Be}$
- JLab and EIC can measure the baryon junction distribution function
- LHC has a unique position to measure Flavor-independent baryon transport
 $q=u,d,s,c,b$

the simplest QCD topology

$B=1$

