A STRING JUNCTION MODEL-INSPIRED SOLUTION TO THE OBSERVED ANTIBARYON-TO-BARYON ASYMMETRY

Nur Hussain
Banajit Barman &
Prof. Buddhadeb Bhattacharjee

Madhab Choudhury College, Barpeta
Gauhati University, Guwahati

16th Regular Conference of Physics Academic of the North East (PANE-2026)

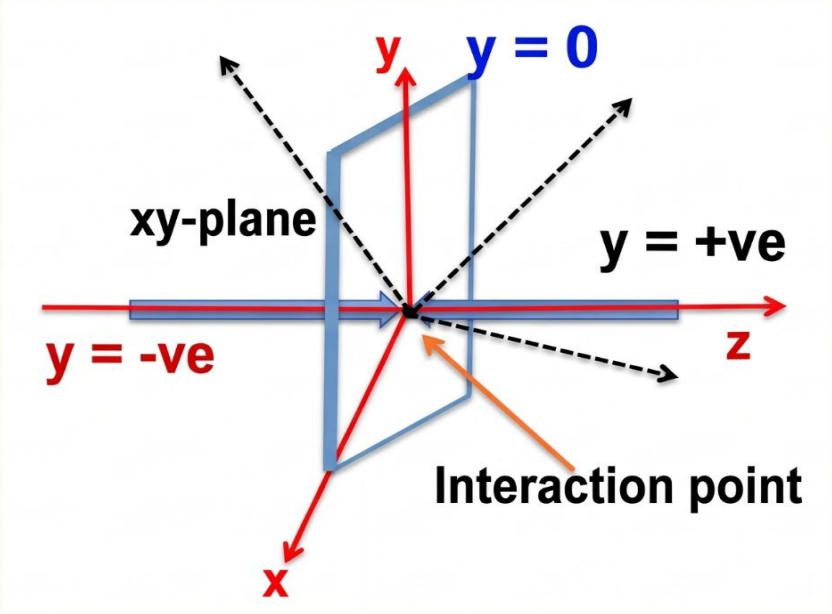
Roadmap

- Introduction
  - Baryon conservation & the mystery of proton stability.
  - Objective and motivation
- Results
  - anti-lambda/lambda ratio as a function of rapidity.
  - B/Q ratio in pp collision.
- Summary

Rapidity

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}, \qquad \text{(Rapidity)}$$

where E is the energy of the particle. The geometrical representation of the rapidity is shown in Fig.

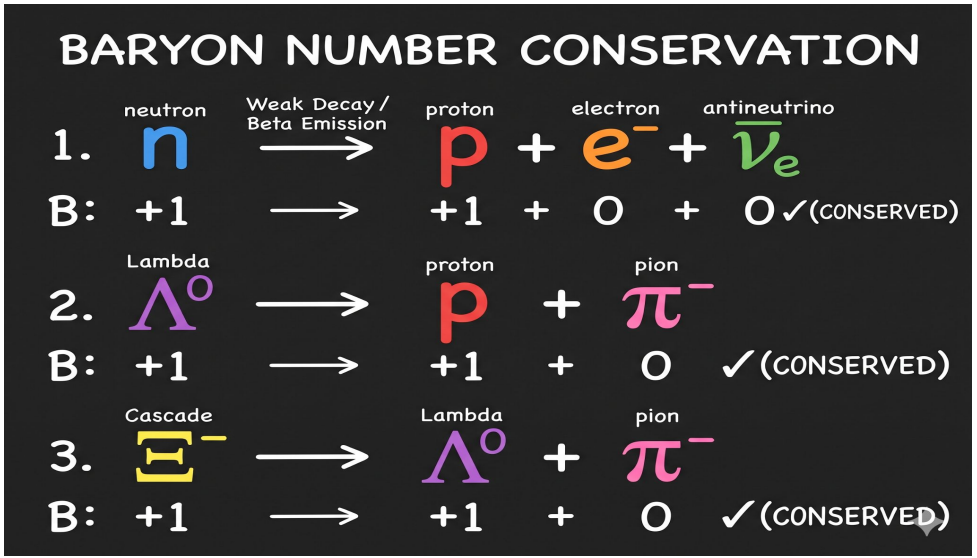


- If a particle is emitted along the xy-plane, the value of p_z will be very small and thus from figure it could be found that the rapidity of this particle will become zero.
- On the other hand, if the produced particle is predominantly emitted along the $+z$ and $-z$ axes, the corresponding rapidities will be $y \to \infty$ and $y \to -\infty$ respectively.
- Thus, physically rapidity is related to the angle between the *xy*-plane and the direction of the emission of the particle.

Baryon Number Conservation

- The age of the universe ~ 13.8 billion years,
- proton half-life ~10^24 billion years

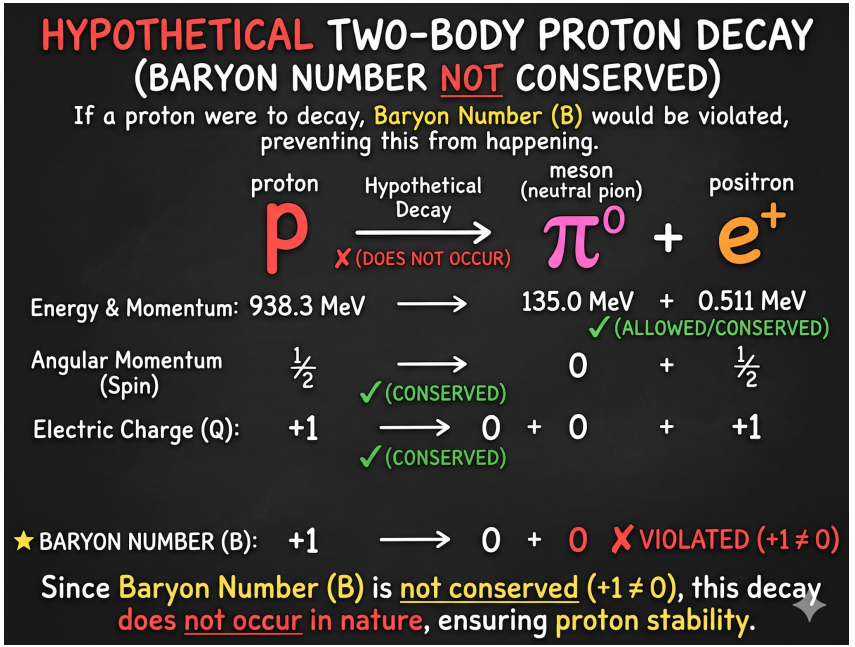
This extraordinary stability occurs because the proton does not decay, unlike other experimentally observed particles:



Baryon Number Conservation

- If a proton were to decay, the baryon number would **not** be conserved.

- This universal, extraordinary stability of the proton is the fundamental reason baryon number conservation was introduced in particle physics [H. Weyl, PNAS) **15 (1929), 323–334**.), E. Wigner, PAPS **93 (1949), 521–526**.]



Introduction

- Which physical observable probes baryon number conservation in heavy-ion and proton-proton collisions, and **how is that baryon number transported?**

The anti-lambda/lambda ratio serves as a-

- key observable for probing baryon-number transport

  [Ref.ALICE collaboration EPJC 73, 2496 (2013)]

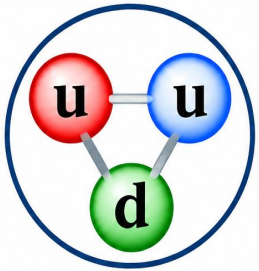
- sensitive tool to quantify **baryon–antibaryon asymmetry**
- and baryon-production mechanisms.

Introduction

In QCD, Valence quark is believed to carry->

- Electric & color charges
- Flavor
- Isospin
- Baryon no. etc.

The Valence Quark Model



Proton (uud)

$$B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$$

Baryon number, along with **electric charge** and **flavor,** is exclusively tracked by the fractional quantum numbers of valence quarks.

$$\pi^+ + p \longrightarrow \Omega^- + K^+ + 2K^o$$

$(u\bar{d})$ (uud) (sss) $(u\bar{s})$ $(d\bar{s})$

$B = 0$ $B = 1$ $B = 1$ $B = 0$ $B = 0$

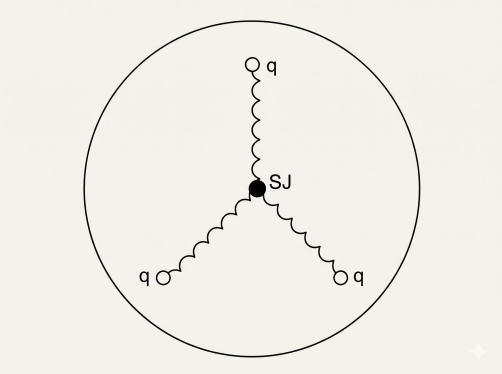
- Assignment of baryon number to a specific parton and its transportation is not straightforward!

Garvey et. al., *Comments on Modern Physics*, A2 (2001), 47–67.

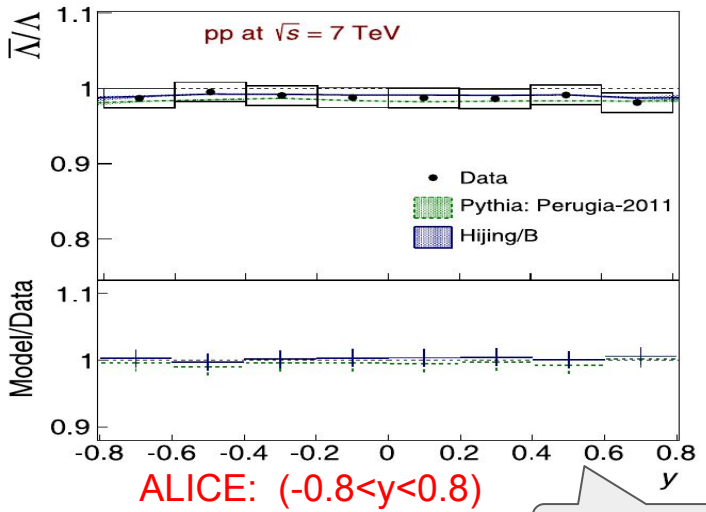
Q: Do valence quarks carry the baryon number, or is it actually carried by gluons and gluonic string junctions?

>>Driven by QCD gauge-invariance constraints, the baryon number is believed to reside in the central gluon field (string junction) rather than individual quarks. Kharzeev et. al, Phys. Lett. B 378, 238-246 (1996).

>> SJ:: Y-shaped gluonic vertex connecting three gluon flux tubes



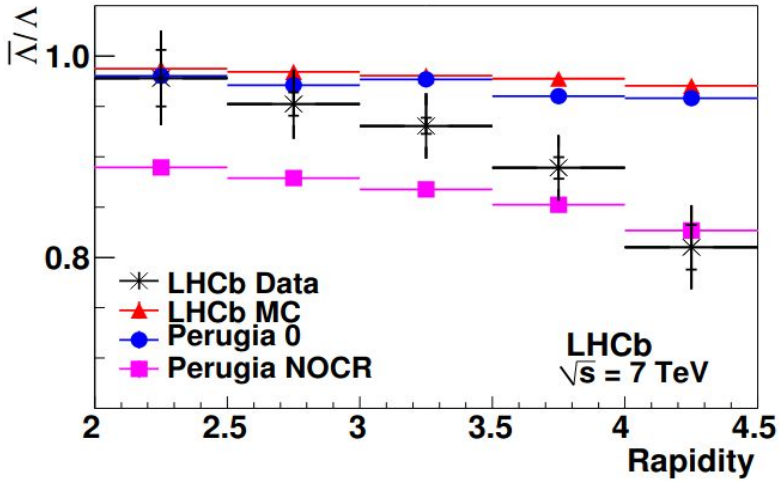
Anti-lambda/lambda =1→ Pair production



ALICE: (-0.8<y<0.8)

Fig-1

Anti-lambda/lambda<1 → Baryon stopping



LHCb: (2.0<y<4.5)

Fig-2

Eur. Phys. J. C (2013) 73:2496

JHEP08(2011)034

>>Model/data ratio:: ALICE → Good agreement (~1)

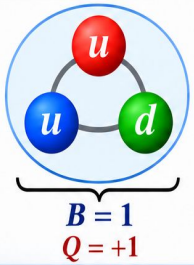
>>LHCb→ Significant disagreement

Baryon Transport vs. Charge Transport (B/Q)

Valence Quark Model

$$\frac{B}{A} \simeq \frac{Q}{Z} \Rightarrow \frac{B}{Q}\frac{Z}{A} \approx 1$$

In this model, the baryon number is carried by **valence quarks**. Thus each valence quark carries **both charge and baryon number.**



Key Point

Valence quarks:

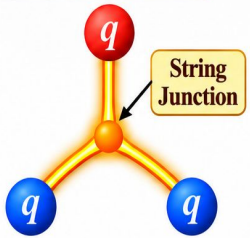
$B = \frac{1}{3}$, $Q = \frac{+2}{3}(u)$

or $Q = -\frac{1}{3}(d, s)$

String Junction Model

$$\frac{B}{A} > \frac{Q}{Z} \Rightarrow \frac{B}{Q}\frac{Z}{A} > 1$$

In this model, baryon number is carried by a **string junction** (a Y-shaped configuration of color strings), which can stop more easily in mid-rapidity, leading to $B/A > Q/Z$.



Key Point

String junction:

$B = 1,\ Q = 0$

(carries baryon number but no charge)

Science, 393, 727-731 (2026)

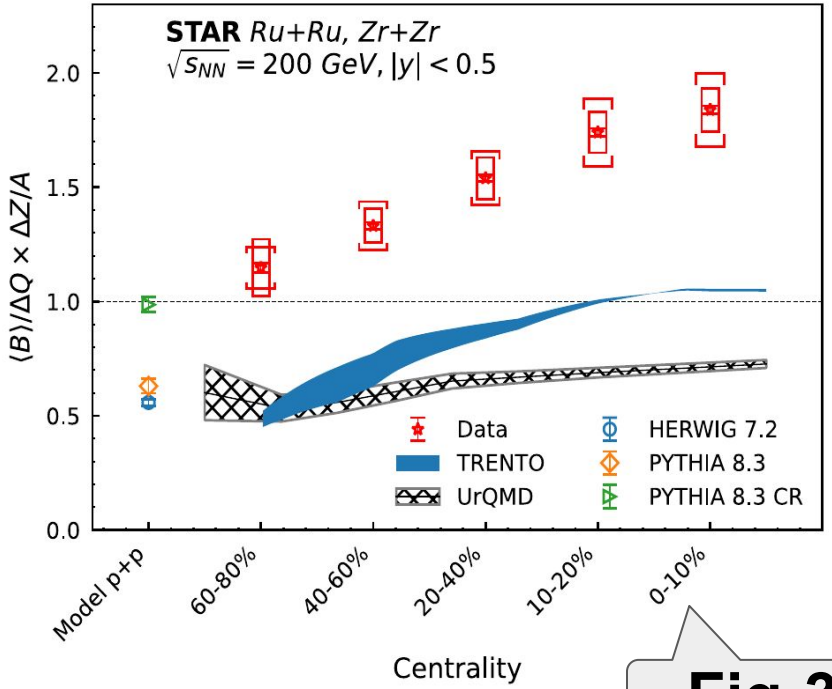
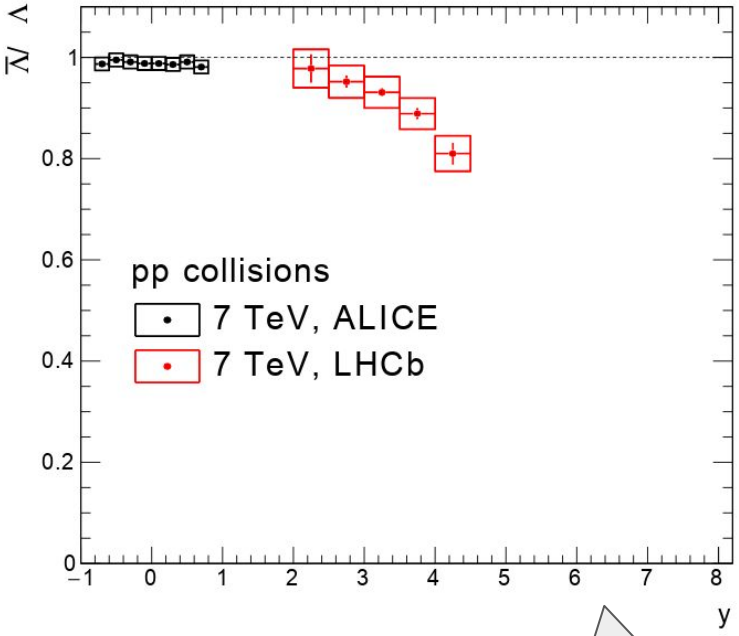


Fig-3

String Junction (SJ) model is an important prospect in Particle production.

Motivation

- **A single model (& hence mechanism) that can explain th experimentally estimated values of anti-Λ / Λ ratio of both ALICE and LHCb collaborations.**
- **Study the microscopic carrier of baryon number by comparing net-baryon to electric-charge transport (B/Q)**



Eur. Phys. J. C (2013) 73:2496

JHEP08(2011)034

Fig-4

PYTHIA

PYTHIA MODEL→to generate realistic, high-energy pp and heavy-ion data.

It includes→

- Soft and hard QCD processes.
- Initial and final state parton showers.
- Multiple parton-parton interactions (MPI).
- String fragmentation and hadronization.
- Particle decays.
- Beam remnants, color reconnection, string junctions, etc.

>>Angantyr → For Heavy-ion collisions.

EVENT statistics and model tuning

- Number of events: 57 million
- Track cut – “ParticleDecays:limitTau0 = on” and “ParticleDecays:tau0Max =10” ---to select only primary particle

- To include new color reconnection scheme – “ColourReconnection:mode = 1” (default 0)

- To include the junction from beam remnant – “BeamRemnants:beamJunction = on”

Results

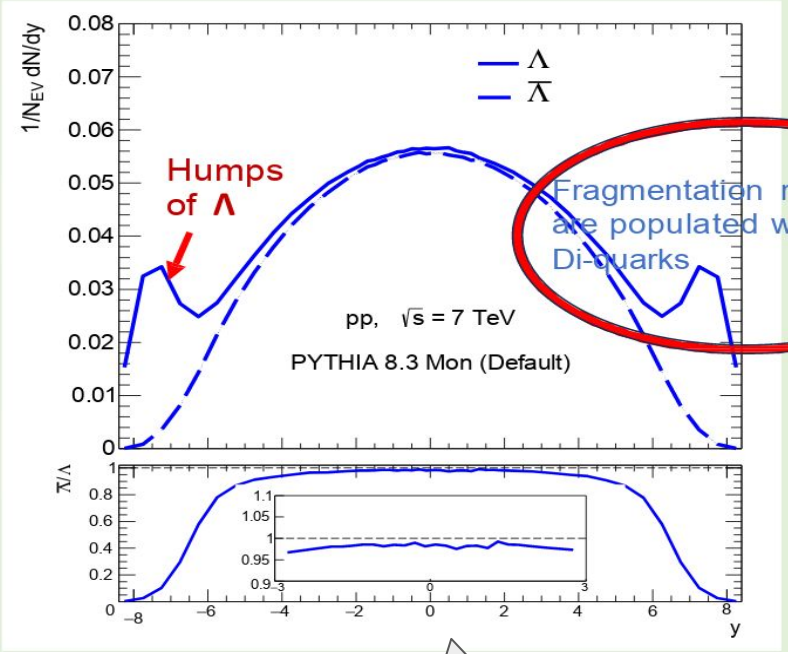
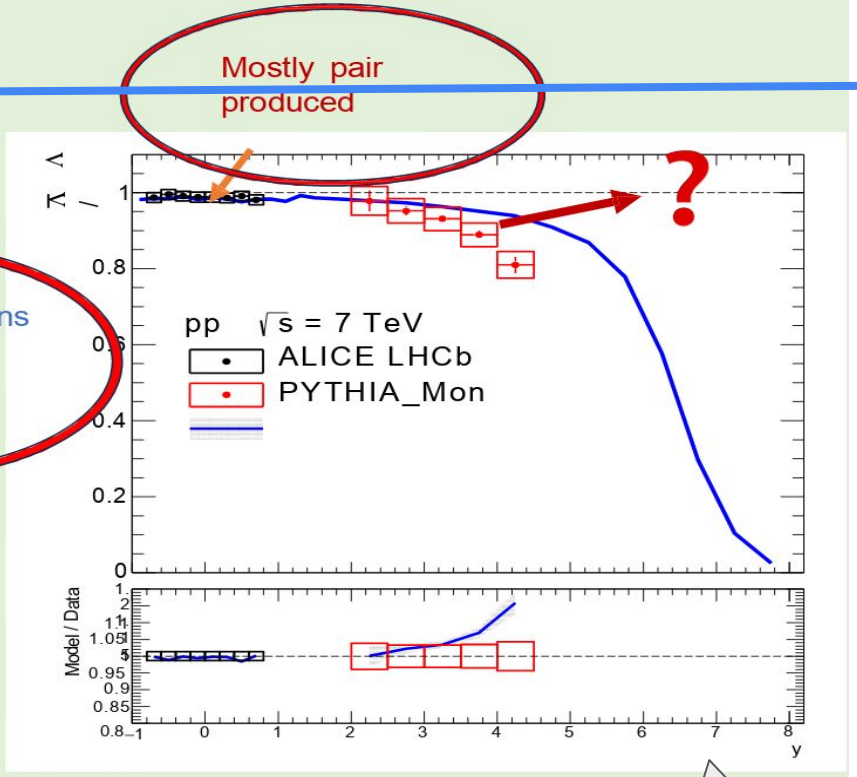


Fig-5



Phy. Rev. C 111, 014905 (2025)

Fig-6

Results

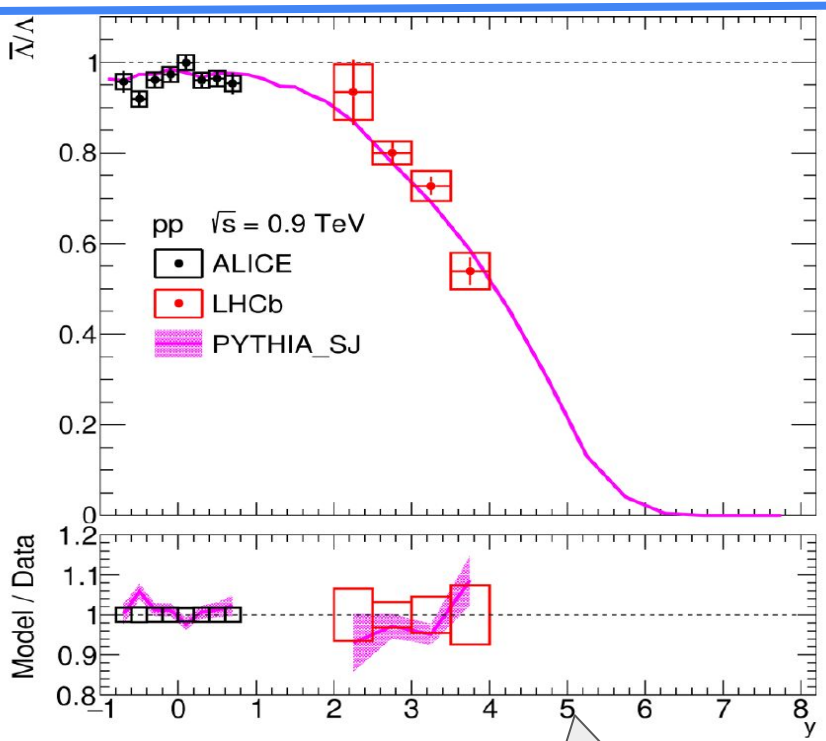
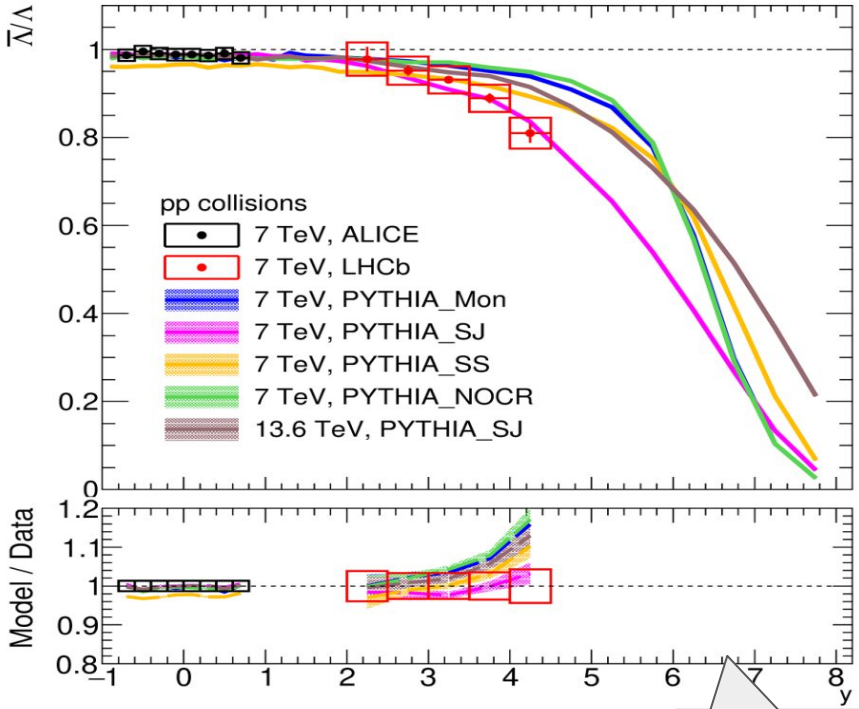


Fig-7



Phy. Rev. C 111, 014905 (2025)

Fig-8

SJ is the only model that successfully describes both ALICE and LHCb data.

>>In PYTHIA_Mon, and all tunings other than SJ, initial diquarks remain intact, trapping net-baryon density in the beam fragmentation regions (6 < |y| < 8) → preventing baryon migration to intermediate rapidities.

>>In PYTHIA_SJ, color exchanges between partons fragment the beam diquarks, freeing the non-perturbative gluonic string junction (B=1, Q=0).

→ **migrates smoothly from the fragmentation region toward mid-rapidity.**

Phy. Rev. C 111, 014905 (2025)

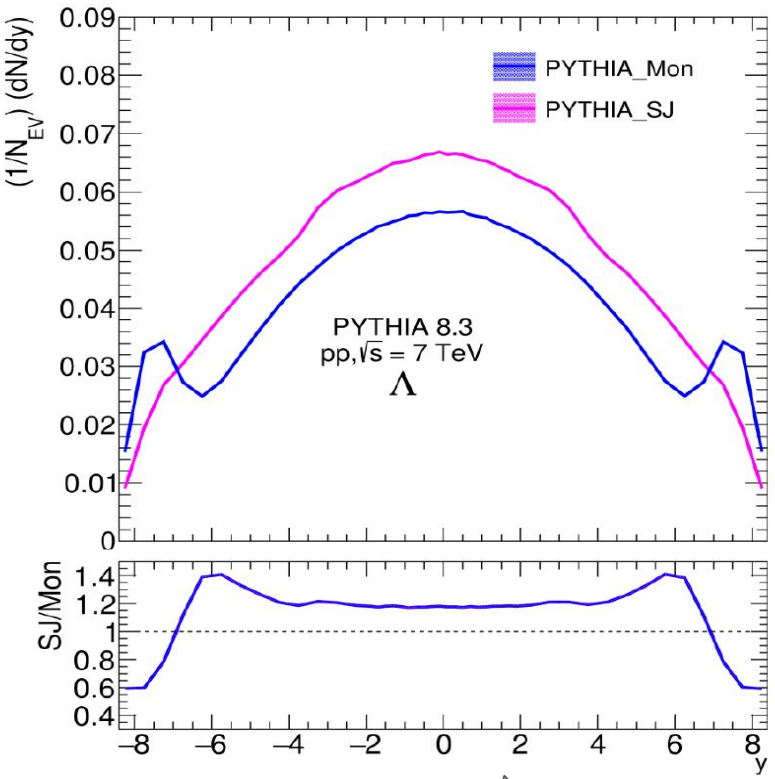


Fig-9

Phy. Rev. C 111, 014905 (2025)

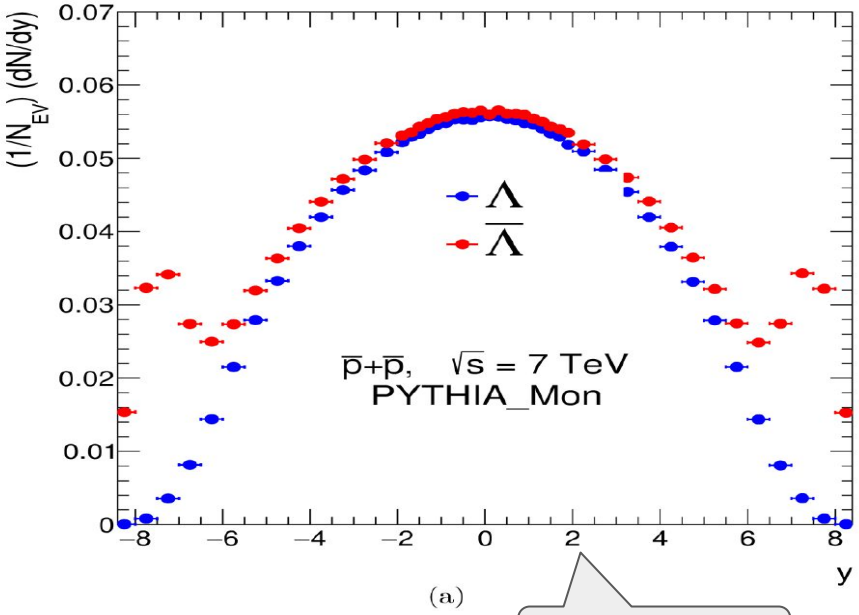


Fig-10

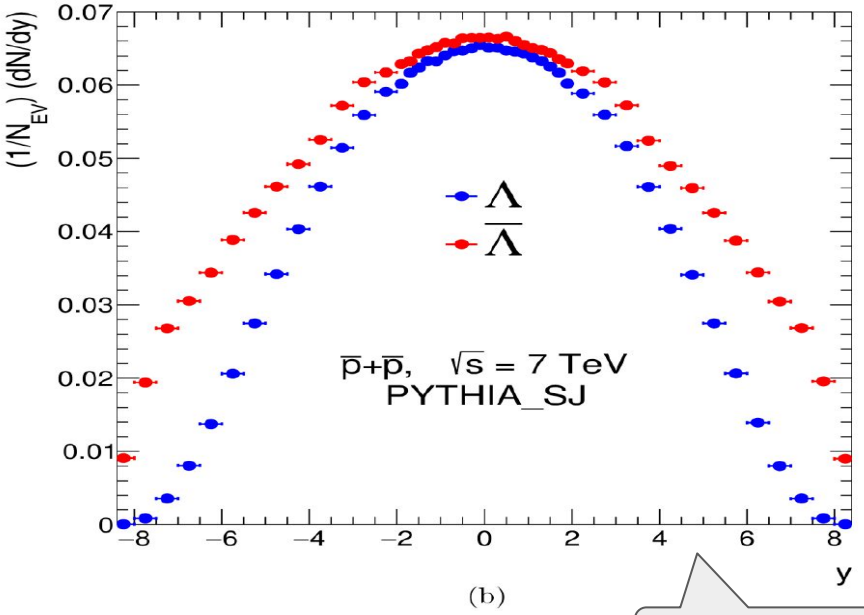
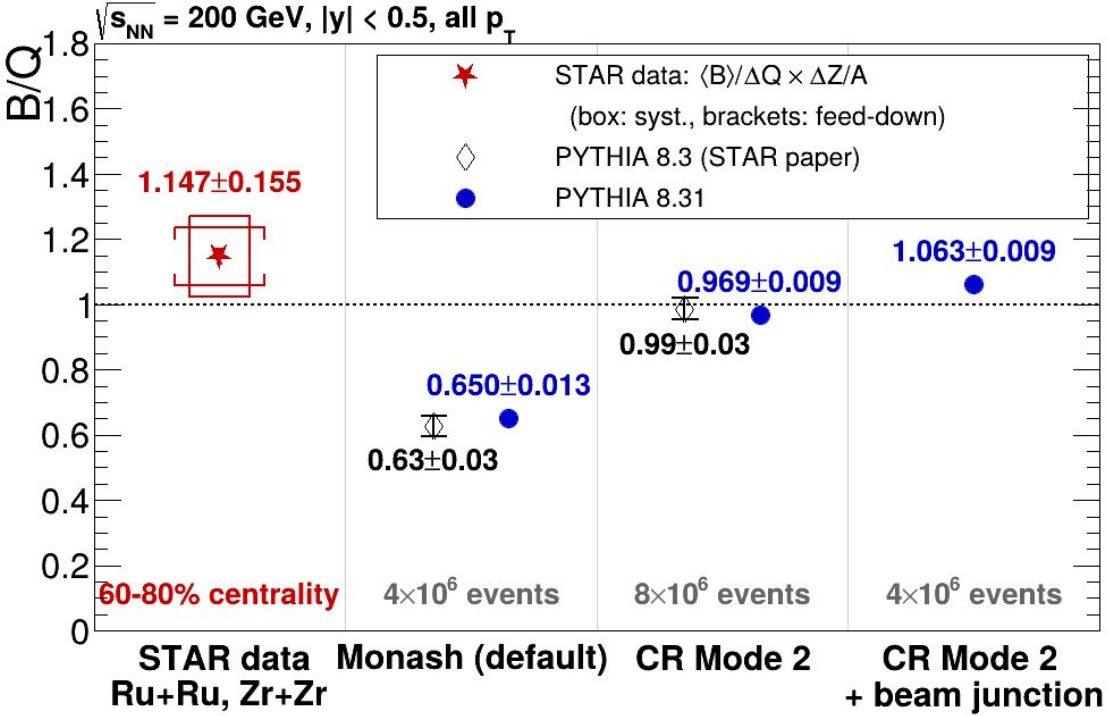


Fig-11

>>In the case of anti-p+anti-p collision, the humps are observed in anti-lambda in PYTHIA_monash as expected.

NEW prediction with PYTHIA_SJ model



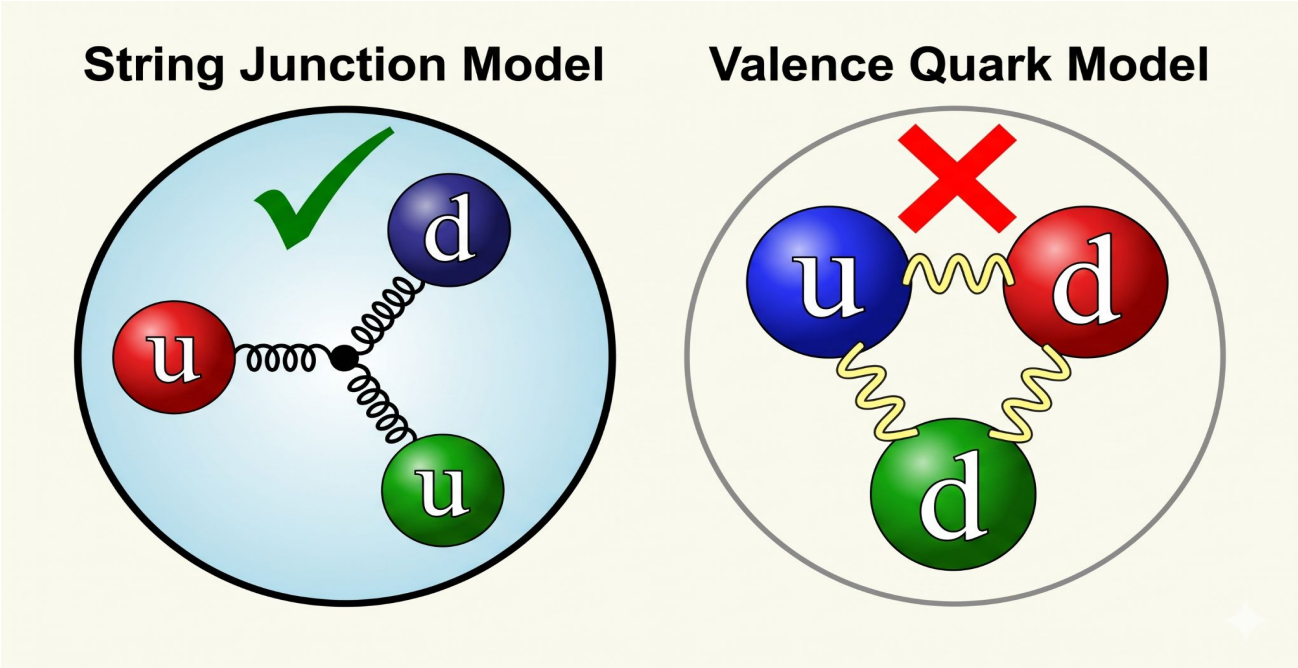
Science, 393, 727-731 (2026)

Fig-12

>> string junction configuration breaks the valence boundary to yield B/Q > 1.

>> Clear indication of baryon number is transported by gluonic string junctions rather than valence quarks.

Carrier of Baryon Number



Evidence Favors the String Junction Model over Valence Quark Transport

Summary

- ➔ **PYTHIA_SJ is the only model that simultaneously reproduces the measured** anti-lambda/lambda **ratios from both ALICE and LHCb at** 0.9 **and** 7 TeV.
- ➔ **In** pp **collisions at** 200 GeV **only the string junction configuration breaks the valence boundary to yield** B/Q > 1**.**
- ➔ **Together, the forward** anti-lambda/lambda **asymmetry result and** B/Q > 1 **provide definitive evidence that baryon number is transported by gluonic string junctions rather than valence quarks.**

Thank you

Backup slides

Baryon number transportation over full rapidity space in *pp* collisions at energies available at the CERN Large Hadron Collider

Banajit Barman [1,*] Nur Hussain [1,2,†] and Buddhadeb Bhattacharjee [1,‡]

[1]*Nuclear and Radiation Physics Research Laboratory, Department of Physics, Gauhati University, Guwahati 781014, Assam, India*

[2]*Department of Physics, MC College, Barpeta 781301, Assam, India*

(Received 16 July 2024; revised 8 November 2024; accepted 20 December 2024; published 8 January 2025)

The estimation of the antibaryon to baryon ratio is considered to be a useful tool for studying baryon number transport in *pp*, *pA*, and *AA* collisions. For this paper, the PYTHIA event generator with various tunes is used to measure the $\bar{\Lambda}/\Lambda$ ratio as a function of rapidity (y), transverse momentum (p_{T}), and multiplicity within both ALICE and LHCb acceptances. The results obtained using various Monte Carlo data for *pp* collisions at $\sqrt{s} = 0.9$ and 7 TeV are compared with the experimentally measured values of $\bar{\Lambda}/\Lambda$ ratio of ALICE and LHCb experiments. Out of the various studied tunes of PYTHIA 8.3, the string junction model is found to be the most successful to describe the experimentally observed results. Evidence of a considerable amount of baryon number transportation from the beam fragmentation to the ALICE and LHCb acceptances could be recognized.

DOI: 10.1103/PhysRevC.111.014905

Definition of Primary Particles

In relativistic collision experiments (ALICE, LHCb, STAR), a **primary particle** is defined as

1. A particle produced directly from the collision (primordial production from string fragmentation)
2. A particle originating from the **strong or electromagnetic decays** of resonances with $c\tau_0 < 10$ mm (e.g., $\Sigma^0 \rightarrow \Lambda + \gamma$)

.

Number of events: 5.7 x 107

- Track cut – “ParticleDecays:limitTau0 = on” and “ParticleDecays:tau0max =10” ---for considering only primary particle
- To include new color reconnection scheme – ColourReconnection:mode = 1” (default 0)--> It allows color strings from different multi-parton interactions to reconnect into complex multijunction configurations
- To include the junction from beam remnant – “BeamRemnants:beamJunction = on”-->. 1. beam diquark is broke and fragmented, 2. The valence quarks carry the proton’s electric charge and continue forward into the fragmentation region to form fast mesons, while the junction is free to move