Production of heavy flavored particles in *pp* collisions: A unified model description for results of experimental measurements by ALICE and LHCb

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The study of heavy-flavored baryon and meson production in proton-proton (pp) collisions provides crucial insight into the hadronization mechanisms of quantum chromodynamics (QCD). In this work an attempt has been made to describe the existing ALICE and LHCb results on the p_{T}-differential production cross section of Λ_c^+, D^0, Λ_b^0, and $\bar{B}^0$, and p_{T}-dependent Λ_c^+/D^0 and $\Lambda_b^0/\bar{B}^0(B^0)$ ratios, in light of the color-string junction inspired PYTHIA-8.314 model. A comparison of the results obtained with various event samples generated with different tuning parameters and the existing experimental results of ALICE and LHCb at $\sqrt{s} = 7$ and 13 TeV underlines the relevance of string-junction dynamics in heavy-flavored particle production. The results of the present investigation reveal that while stopping the junction-antijunction reconfiguration in the nonperturbative PYTHIA-8.314 model successfully describes the considered ALICE experimental observables of the charm sector, on the other hand, allowing junction-antijunction reconfiguration, keeping other fragmentation parameters the same, better describes the LHCb experimental observables of both charm and bottom sectors.

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I. INTRODUCTION

String junctions are believed to be fundamental topological structures that can be produced and liberated in the nuclear collisions, and under appropriate orientation of the color field, the string junctions can migrate over a considerable rapidity space [1]. With this argument, it was shown in Ref. [1] that the Monte Carlo (MC) model-generated event sample of PYTHIA-8.310 [2,3] string junction can successfully explain the experimental results of the $\bar{\Lambda}/\Lambda$ ratio of both ALICE ($-0.8 < y < 0.8$) and LHCb ($2.0 < y < 4.5$) experiments for p + p collisions at $\sqrt{s} = 0.9$ and 7.0 TeV. Further, it is well known that, unlike light-flavored quarks, the heavy-flavored quarks such as charm and bottom quarks are mainly produced in the initial hard scatterings of the collisions as well as in parton showers [4,5]. Such quarks, because of their large mass, cannot be produced during the hadronization process. As a result, the total number of produced heavy-flavor hadrons solely depends on the production rate of parent heavy quarks and remains unaffected by the hadronization process [5,6] or late-stage rescatterings. However, the hadronization process determines the relative abundances of the various heavy-flavored hadron species and their kinematics [5]. Given these properties of heavy-flavored hadrons, understanding their production mechanism becomes particularly intriguing. The ratio of a heavy-flavor baryon to a heavy-flavored meson serves as one of the key probes to gain insight into this process [7,8]. In contrast to light-flavored quarks, the heavy-flavor quarks, produced in the early stages of the collisions, traverse the dense quantum chromodynamics (QCD) medium created in the nuclear collisions, thereby carrying the signatures of that medium [9]. One notable signature is the observed enhancement of the heavy-flavor baryon-to-heavy-meson ratio in nuclear collisions compared to the vacuumlike electron-position ($e^+ + e^-$) collisions [10–13]. Additionally, in small-collision systems such as p + p or p + Pb collisions at Large Hadron Collider (LHC) energies, an increased fraction of heavy-flavored baryons is observed, accompanied by a corresponding decrease in the fraction of heavy-flavored mesons, relative to the measurements in $e^+ + e^-$ or e^- + p collisions [14]. This observation highlights the nonuniversality of the fragmentation fractions among different collision systems. Furthermore, experiments at LHC have revealed that the ratio of heavy-flavored baryon to heavy-flavored meson exhibits significant dependence on both the transverse momentum p_{T} and the charged-particle multiplicity. At low p_{T}, the heavy-flavored baryon-to-meson ratio in p + p collisions is enhanced in comparison to that in $e^+ + e^-$ collisions [10,13]. This enhancement is also evident in high-multiplicity p + p collisions, whereas at low multiplicity, the ratio aligns with the value measured in $e^+ + e^-$ collisions. These findings suggest that the evolution of heavy-flavored quarks into the final-state hadron is also influenced by the density of the hadronic interactions created in the collision [13]. In Ref. [6], it was shown that, in comparison to other studied models, the PYTHIA-8.311 string junction with the additional nondefault

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tuning parameters successfully described the ALICE results on the p_{T} dependence of the Λ_c^+/D^0 ratio for p + p collisions at $\sqrt{s} = 13$ TeV. However, no such result was found to be reported on the comparison of the Λ_c^+/D^0 ratio in the LHCb acceptance. Further, the authors of Ref. [6] also studied the LHCb results on the p_{T} variation of the Λ_b^0/B^0 ratio for p + p collisions at $\sqrt{s} = 13$ TeV, but none of the studied tunes could give a proper description of the Λ_b^0/B^0 ratio. In this work, an attempt has been made with the various tunes of PYTHIA-8.314 p + p collision event samples at $\sqrt{s} = 7$ and 13 TeV, to discuss the experimentally measured ratios of heavy-flavored baryons to heavy mesons, particularly Λ_c^+/D^0 at both ALICE and LHCb acceptances, and Λ_b^0/B^0 at LHCb acceptance. It is worth mentioning here that no ALICE experimental results are available on the Λ_b^0/B^0 ratio. Guided by some genuine physics requirements, attempts have also been made to change the various parameters of the studied model to better describe the experimentally observed results of ALICE and LHCb.

II. METHODOLOGY

A. Description of the event sample

For completeness of the article, in this section, brief descriptions of the various tunes of PYTHIA-8.314 event generator and the parameters changed therein for the present investigation are narrated. The PYTHIA-8.314 event generator is used to generate events of inelastic p + p collisions at $\sqrt{s} = 7$ and 13 TeV, via `SoftQCD:inelastic=on`, which includes both diffractive and nondiffractive processes. This aligns with the experimental minimum-bias trigger referenced in Refs. [10,13,15–17], which consider all types of inelastic events. However, for the ALICE measurement of the Λ_c^+/D^0 ratio in p + p collisions at $\sqrt{s} = 13$ TeV [18], single-diffractive events were experimentally excluded by requiring coincident signals in both ALICE V0 scintillator arrays. Accordingly, a similar event selection is implemented in the simulated samples at $\sqrt{s} = 13$ TeV by requiring at least one generated particle within each of the pseudorapidity intervals corresponding to the two V0 scintillator arrays [$(2.8 < \eta < 5.1)$ and $(-3.7 < \eta < -1.7)$]. Furthermore, geometrical acceptance cuts of the ALICE ($|\eta| < 0.8$) and LHCb ($2.0 < \eta < 5.0$) detectors were also implemented while analyzing the generated event samples.

The event sample is generated initially with PYTHIA Monash [19] (default), designated as PYTHIA_MON, as a baseline. In this tune, the Lund string model for quark-diquark fragmentation [20,21] is implemented along with the multiparton-interaction (MPI)-based color reconnection scheme [22,23]. A second event sample with the string-junction model [24,25] of PYTHIA is generated with color-reconnection (CR) mode 1 (default) (via `ColourReconnection:mode=1`) combined with the new beam-remnant model (via `BeamRemnants:remnantMode=1`) and is labeled as PYTHIA_SJ. In this model, a new QCD-based color-reconnection (QCDCR) scheme [25] is implemented, introducing a new mechanism of baryon-antibaryon pair production [2]. This mechanism involves the rearrangement of color flow in a multiparton system, enabling three color-triplet quarks (or antiquarks) to be connected into a Y-shaped topological structure known as a string junction (antistring junction) that favors "shortest string length" [6]. This is in addition to the default mechanism of baryon-antibaryon pair production via the string fragmentation to diquark-antidiquark pairs, as implemented in PYTHIA_MON [2]. Physically, the string junctions represent the confinement field spanned between the three colored quarks (or antiquarks) in an overall color-neutral state [6]. When freed from the attached quarks, this topological structure is believed to behave as a free-floating entity in the color field [1] and act as the carrier of the baryon number [1,2,6,25]. The string junctions can be liberated from the incoming beam protons in the fragmentation regions from the remaining valence quarks of the beam remnants, making it possible that the charge and baryon numbers move independently [1]. By default, this feature is disabled in the string-junction model (color-reconnection mode 1) of PYTHIA, which leads to the production of diquarks from the beam remnants at extreme rapidities. However, PYTHIA allows us to switch on this feature by setting the flag `BeamRemnants:beamJunction=on`, thereby liberating string junctions and free quarks instead of diquarks from the beam remnants [26]. The contribution of string junctions from the beam remnants was previously found to be successful in describing the excess baryon over antibaryon production in the LHCb acceptance, in particular [1]. Hence, a third event sample with the same PYTHIA_SJ, with the contribution of the *liberated* string junctions from the fragmentation regions, is generated by enabling this flag. This event sample is designated as "PYTHIA string junction with remnants' contribution" (PYTHIA_SJ_RC). The tuning parameters of all these event samples are summarized in Table III.

In this investigation, 105 000 000 events were generated for each of the above settings for inelastic p + p collisions at $\sqrt{s} = 7$ and 13 TeV.

B. Calculation of differential production cross section and integrated luminosity

With our generated PYTHIA event samples, the differential production cross section of a particle as a function of transverse momentum p_{T} and rapidity y was estimated by dividing the particle yield (as a function of p_{T} and y) by integrated luminosity L_{int}, that is

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{L_{\mathrm{int}}}\frac{d^2N}{dp_T dy}, \tag{1}$$

where L_{int} is defined as

$$L_{\mathrm{int}} = \frac{\text{Total number of events}}{\text{Cross section}_{(\text{inelastic})}} = \frac{N_{ev}}{\sigma_{\mathrm{INEL}}}. \tag{2}$$

Here, σ_{INEL} corresponds to the cross section of inelastic p + p collisions, whose value is obtained from the PYTHIA-8.314 event generator for the studied two different center-of-mass energies $\sqrt{s} = 7$ and 13 TeV, and is shown in Table I. The calculated values of integrated luminosities are also shown in Table I.

TABLE I. Values of inelastic cross section and integrated luminosity for the generated PYTHIA-8.314 event samples.

Collision system	No. of events	$\sigma_{\rm INEL}$ (mb)	$L_{\rm int}$ $(\mu b)^{-1}$
$pp_{\rm INEL}$ $\sqrt{s} = 7$ TeV	105 000 000	71.07	1477.416
$pp_{\rm INEL}$ $\sqrt{s} = 13$ TeV	105 000 000	78.07	1344.946

C. Classification of prompt and nonprompt charmed hadrons

Charm hadrons can be classified according to their production mechanism as prompt or nonprompt. Prompt charmed hadrons are those that are produced directly in collision through the hadronization process or through the decays of excited open-charmed and charmonium states that occur within the strong-interaction time scale(10^{-23} s). On the other hand, nonprompt charm hadrons are those that are produced through the weak decays of the bottom hadrons [14,27] and other heavier-charm hadrons. In this study, the prompt and nonprompt Λ_c^+ and D^0 are classified in the PYTHIA-generated event samples by identifying their mother particles. The nonprompt Λ_c^+ and D^0, whose mother particles have PDG particle-identification code (PID) associated with the bottom and other heavier-charmed hadrons, such as PID 5122, 5112, 5212, 5222, 5132, 5232, 5332, 5142, 5242, 5342, 5442, 5512, 5522, 5532, 5542, 5554, 4222, 4212, 4112, 4232, 4132, 4332, 4412, 4422, 4432, 4444, 511, 521, 531, 541, 411, and 431, are filtered from the event samples and are not considered for further analysis [28].

III. RESULTS AND DISCUSSIONS

To gain insight into the production mechanism of heavy-flavored hadrons, PYTHIA-generated event samples of different tunes were compared with the various published experimental results of the ALICE [10,15,18] and the LHCb [13,16,17] experiments. In Secs. III A and III B, we report the results of our studies on the charmed sector and the bottom sector, respectively. Section III C focuses on the effect and validation of the models, in the light of results of our earlier works on Λ baryons, reported in Ref. [1].

A. Comparison of Λ_c^+ and D^0 experimental results with model estimations

This section focuses on the differential production cross section of prompt Λ_c^+ and D^0, as measured by ALICE [10,15] ($|y| < 0.5$) and LHCb [16] ($2.0 < y < 4.5$) collaborations in p + p collisions at $\sqrt{s} = 7$ TeV. It is noteworthy that while the results of the ALICE collaboration on the production of Λ_c^+ and D^0 are the average of the particles and their charge conjugates [10,15], for the LHCb experimental data points, it is the sum of the two [16]. The LHCb collaboration has reported measurements on the $p_{\rm T}$-differential production cross section of D^0 over five consecutive rapidity intervals ($2.0 < y < 2.5$, $2.5 < y < 3.0$, $3.0 < y < 3.5$, $3.5 < y < 4.0$, $4.0 < y < 4.5$). Therefore, to obtain the $p_{\rm T}$-differential production cross section of D^0 across the rapidity interval of $2.0 < y < 4.5$, the differential production cross section values presented in Table VII of Ref. [16] were summed across the five rapidity intervals for each specified $p_{\rm T}$ bin. The associated statistical and systematic uncertainties were summed using the quadrature method. Furthermore, we have multiplied the LHCb measurement on Λ_c^+ production by a correction factor [10], which takes into account the most recent value of the branching ratio (BR) for the $\Lambda_c^+ \longrightarrow pK^-\pi^+$ decay [28]. Given that the BR term appears in the denominator of the differential production cross-section expression, the correction factor is obtained as follows:

$$\frac{(d\,\sigma/d\,p_T)_{\rm new}}{(d\,\sigma/d\,p_T)_{\rm old}} = \frac{{\rm BR}(\Lambda_c^+ \longrightarrow pK^-\pi^+)_{\rm old}}{{\rm BR}(\Lambda_c^+ \longrightarrow pK^-\pi^+)_{\rm new}} = \frac{5.0}{6.24} = 0.80. \tag{3}$$

This correction is specifically limited to LHCb results on Λ_c^+ production. For all other experimental results [10,13,15–18] used in the present study, the deviation of the previously reported BR from the most recent measurement documented in Ref. [28] remains within 2 percent. This variation falls within the established bounds of the uncertainties associated with the experimental data points, making further correction irrelevant in these cases. It is to be noted here that the uncertainty linked to the recent BR value has not been considered in the correction of LHCb results on Λ_c^+ production.

In the context of the aforementioned collision system, the ALICE measurement on prompt Λ_c^+ production was compared in Ref. [10] with POWHEG + PYTHIA6 model and GM-VFNS [29] scheme. These models showed a significant underestimation of the experimental data. On the other hand, the theoretical predictions from the GM-VFNS and FONLL [30] schemes have been more or less successful in describing both the ALICE and LHCb measurements for prompt D^0 production [15,16]. Additionally, regarding the LHCb measurements of prompt Λ_c^+ production, the predictions from the GM-VFNS scheme were found to be broadly consistent with the experimental data, considering the associated experimental and theoretical uncertainties [16]. However, due to the considerable uncertainties tied to these models and schemes, a conclusive remark on the agreement with the experimental data could not be made. The present investigation aims to gain a deeper understanding of the underlying production mechanisms of Λ_c^+ and D^0 hadrons by utilizing the more recent version of PYTHIA 8.3, i.e., PYTHIA-8.314 MC event generator, with reduced associated uncertainties.

Figure 1 shows the ALICE and LHCb measurements on the $p_{\rm T}$-dependent differential production cross section of prompt Λ_c^+ and D^0, compared with the predictions from the considered tunes of the PYTHIA-generated event samples of the present investigation. In these figures, the black markers represent the experimental data points of ALICE and LHCb, with the corresponding error bars indicating statistical uncertainties. The boxes surrounding these markers represent systematic uncertainties associated with the

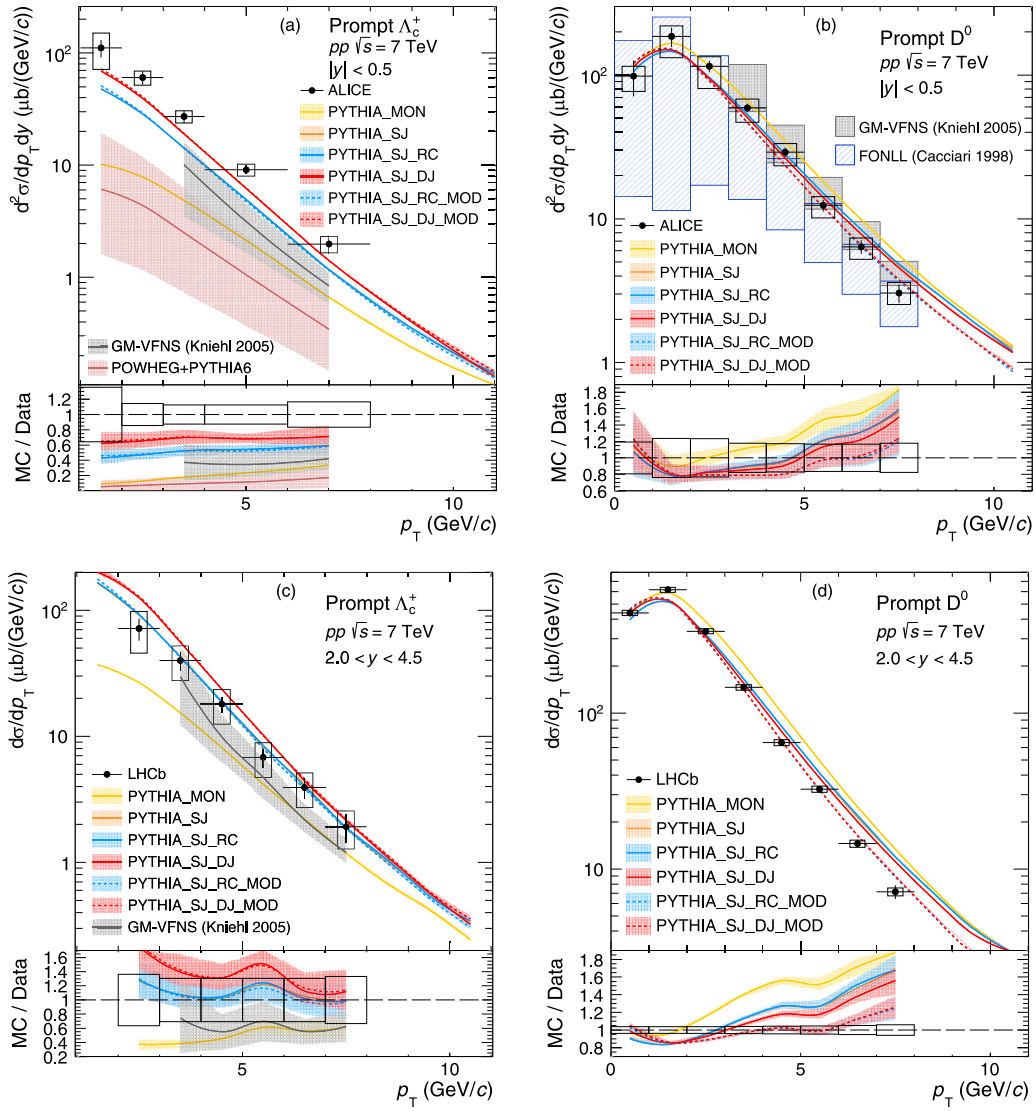


FIG. 1. p_T-dependent differential production cross section of Λ_c^+ [(a), (c)] and D^0 [(b), (d)] measured by ALICE [10,15] and LHCb [16] experiments in p + p collisions at $\sqrt{s} = 7$ TeV, respectively, compared with various model predictions. Specific theoretical calculations cited are GM-VFNS (Ref. [29]), FONLL (Ref. [30]), and POWHEG + PYTHIA6 (taken from Ref. [10]).The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples. The lower panel of each plot illustrates the ratio between the event sample and the experimental data points.

measurements. The solid and dashed lines represent the predictions from the model-generated event samples, and the associated shaded bands indicate the statistical uncertainties due to the finite sample size. The lower panels of each plot show the ratios between the various model-generated predictions and the corresponding experimental data points. From Figs. 1(a)–1(d), it is evident that the default PYTHIA Monash tune (PYTHIA_MON) greatly underestimates the production of Λ_c^+ at both ALICE and LHCb acceptances. Conversely, it overestimates the production of D^0, particularly at high p_T, for both these experiments. Within the acceptance of ALICE, though PYTHIA_SJ and PYTHIA_SJ_RC, with the default color-reconnection mode 1, could result in a better estimation of Λ_c^+ and D^0 production than the estimated values of the earlier models, including PYTHIA_MON, there is a noticeable difference in the predictions of the model yield of Λ_c^+ in particular, implying that the string junction alone with the default color-reconnection mode 1 is not enough to describe the ALICE results of Λ_c^+ production. However, within the acceptance of LHCb, the same two event samples PYTHIA_SJ and PYTHIA_SJ_RC show a better agreement with the experimental yield of Λ_c^+ and D^0 [Figs. 1(c) and 1(d)]. Within ALICE and LHCb acceptances, the event samples PYTHIA_SJ and PYTHIA_SJ_RC almost coincide with each other, indicating that "liberated" string junctions from beam remnants do not play any significant role in the production of Λ_c^+ and D^0.

Furthermore, it has been observed that both models overestimate the p_T-differential production cross section for the D^0 meson compared to the experimental measurements

from ALICE and LHCb. Since mesons are primarily produced through string fragmentation, as described by the Lund string model [2,20,21], this discrepancy is believed to have arisen from the parametrization of the Lund symmetric-fragmentation function [19], which results in increased yields at high p_{T}. The expression of this symmetric-fragmentation function is given as follows [2]:

$$f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_T^2}{z}\right), \tag{4}$$

where z is the fraction of longitudinal momentum that a newly formed hadron takes from the remaining string system during a single string fragmentation, and m_T denotes the transverse mass.

The parameters a and b are known as Lund parameters, which characterize the shape of the fragmentation function and must be constrained by a fit to experimental data [19]. By adjusting these parameters independently, one can alter both the average hardness and the width of the fragmentation spectra, thus impacting the resultant p_{T} spectra. In PYTHIA 8.314, the default values for these parameters are set to $a = 0.68$ and $b = 0.98$, which are based on the fits to e^+e^- data [19]. However, the expression in Eq. (4) is only valid for string ends attached to light-flavored quarks (antiquarks), which can be treated as essentially massless [2]. In cases where one of the string ends is attached to a heavier quark, such as a charm or bottom quark, the Bowler's modification [31] incorporated in the Artru-Mennesier model [32] is generally preferred over the Lund symmetric-fragmentation function. This modified symmetric-fragmentation function is given as

$$f(z) \propto \frac{(1-z)^a}{z^{1+r_Q bm_Q^2}} \exp\left(-\frac{bm_T^2}{z}\right), \tag{5}$$

where m_Q represents the mass of the heavy quark, while r_Q is a multiplicative factor, typically approximated to unity but can be constrained by a fit to experimental data.

Altmann *et al.*, in their recent publication [6], reported their findings on the estimation of the Λ_c^+/D^0 ratio using MC-generated event sample for p + p collisions at $\sqrt{s} = 13$ TeV. Their study demonstrated that the string-junction model in the QCDCR scheme (color-reconnection mode 1) of PYTHIA, exhibited an improved agreement with the experimental measurement from ALICE [18] on the Λ_c^+/D^0 ratio. Notably, the authors used nondefault values for several tuning parameters in their generated set of data, including Lund parameters and Bowler's multiplicative factor set to $a = 0.36$, $b = 0.56$, and $r_c = 1.5$. Additionally, they disabled in their generated event sample, a flag `ColourReconnection:AllowDoubleJunRem`, which is associated with the QCD-based color-reconnection scheme. The complete set of tuning parameters used in their investigation is detailed in the Appendix of Ref. [6]. Since the work of Altmann *et al.* on the Λ_c^+/D^0 ratio was limited to the ALICE results on p + p collisions at $\sqrt{s} = 13$ TeV, we generated a new PYTHIA event sample for p + p collisions at $\sqrt{s} = 7$ TeV, incorporating the parameters specified in Ref. [6]. The objective of this exercise is to investigate the extent of agreement between the results of experimental measurements of ALICE and LHCb on the production cross section of Λ_c^+ and D^0 for p + p collisions at $\sqrt{s} = 7$ TeV with the above-mentioned nondefault implementations of the QCDCR model. This newly generated event sample is labeled as PYTHIA_SJ_DJ.

It can be easily seen from the same Fig. 1(a) that the plot with this newly generated event sample (PYTHIA_SJ_DJ) is in much better agreement with the ALICE results on Λ_c^+ production, surpassing previous model comparisons. Moreover, it also reduces the previously observed discrepancies in the D^0 production compared to the ALICE and LHCb measurements. This improved agreement with the D^0 production, compared to the default QCDCR model, is correlated with the adjusted parameters associated with the symmetric-fragmentation function implemented in this event sample. The better agreement is similarly reflected in Fig. 2(a), where the result of the generated event sample (PYTHIA_SJ_DJ) shows a better agreement with the ALICE experimental results on the Λ_c^+/D^0 ratio measurement. The observed enhancement in the production of the Λ_c^+ baryon, and thus the Λ_c^+/D^0 ratio, may be associated with the deactivation of the flag `ColourReconnection:AllowDoubleJunRem`. This flag, integral to the QCDCR scheme in PYTHIA, governs whether a directly connected junction-antijunction pair can be reconfigured into two distinct string configurations. The final outcome is based on comparing the λ measure (or the string length) [25] of the junction-antijunction pair with that of the two possible string configurations. When the flag is disabled, the junction system is preserved, and a q-$\bar{q}$ pair may be inserted between the junction-antijunction pair, with energy and momentum redistributed from the adjacent legs of the junction system [2,25]. This mechanism effectively increases the likelihood of baryon and antibaryon production, such as Λ_c^+ and its antiparticle, during the hadronization process. However, despite these modifications, the production of Λ_c^+ and, thus, the Λ_c^+/D^0 ratio remains still underestimated relative to ALICE measurements at $\sqrt{s} = 7$ TeV. On the other hand, the increased production of Λ_c^+ baryons adversely affects the model's agreement with the LHCb measurements at $\sqrt{s} = 7$ TeV, as demonstrated in Fig. 1(c). As a result, the model tends to significantly overestimate the Λ_c^+/D^0 ratio reported by LHCb [Fig. 2(b)], although achieving improved agreement with the LHCb measured D^0 production.

Thus, while the tuning parameters associated with the symmetric-fragmentation function within PYTHIA_SJ_DJ (for $\sqrt{s} = 7$ TeV) have reduced the discrepancies previously observed with our earlier PYTHIA_SJ_RC model estimation of D^0 production for both ALICE and LHCb measurements, some disagreement still persists. To address these, we have embarked on further refinement of these tuning parameters, with the aim of improving the agreement between the experimental and MC-estimated D^0 meson production for both ALICE and LHCb. For this tuning procedure, we began with the default implementations of the QCDCR model of PYTHIA, iteratively adjusting the parameters related to the symmetric-fragmentation function using the hit and trial method, until we reached a minimum value of χ^2/NDF between the prediction of the model and the experimental data,

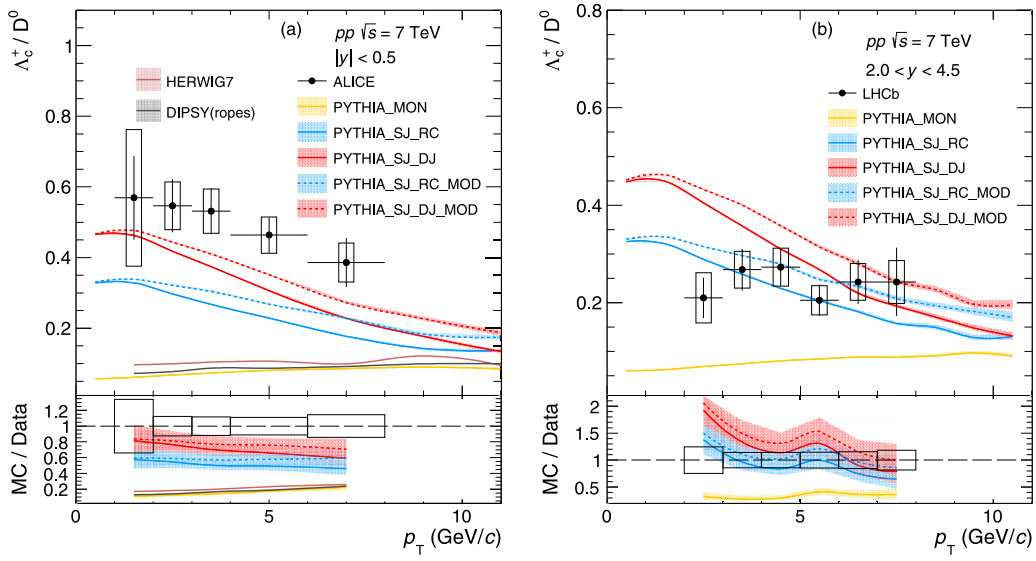


FIG. 2. Comparisons of p_T-dependent Λ_c^+/D^0 ratio measured by (a) ALICE [10] and (b) LHCb [10,16] in p + p collisions at $\sqrt{s} = 7$ TeV with different model predictions. HERWIG7 and DIPSY are taken from Ref. [10]. The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples.

and is listed in Table II. The values for the Lund parameters a and b, alongside Bowler's multiplicative factor for charm quark r_c, for which we settle in the present investigation, are $a = 1.1$, $b = 0.6$, and $r_c = 1.5$.

The rationale for these specific tunings is to reduce the high-p_T yield of the D^0 meson and, thus, minimize the discrepancies in comparison to experimental observations. However, these tunings also exert an influence on the high-p_T yield of Λ_c^+ baryons, as they affect the momentum fractions acquired by all hadrons formed through the string-fragmentation process [19]. Guided by the fact that, in PYTHIA, an enhanced diquark relative to quark production enhances the baryon relative to meson production [33], to compensate for underproduction of Λ_c^+ baryons at high p_T, the diquark production relative to quark production [19] in the string-fragmentation process was incrementally increased from its default value of 0.081 to 0.12. In the PYTHIA event generator, these adjustments are configured as follows:

```
StringZ:aLund=1.1
StringZ:bLund=0.6
StringZ:rFactC=1.5
StringFlav:probQQtoQ=0.12
```

TABLE II. Minimum values of χ^2/NDF as obtained from various model comparisons with the experimental p_T-differential production cross section of D^0 mesons.

Event samples	D^0 ALICE	D^0 LHCb
PYTHIA_MON	10.483	118.336
PYTHIA_SJ_DJ	5.810	42.070
PYTHIA_SJ_RC	8.943	82.132
PYTHIA_SJ_RC with $a = 1.1, b = 0.6, r_C = 1.5$	2.317	13.735

Subsequently, the PYTHIA_SJ_RC and the PYTHIA_SJ_DJ event samples have been regenerated, incorporating these updated parameters for both $\sqrt{s} = 7$ and 13 TeV. For ease of reference, these two newly generated event samples will be labeled as PYTHIA_SJ_RC_MOD and PYTHIA_SJ_DJ_MOD. It is important to note that we have utilized the PYTHIA_SJ_RC instead of the PYTHIA_SJ, considering the demonstrated efficacy of the former, as elaborated in Ref. [1].

The comparisons of the outcomes from these newly generated event samples (PYTHIA_SJ_RC_MOD and PYTHIA_SJ_DJ_MOD) with the experimental measurements are shown in Figs. 1 and 2. The plots in Fig. 1 show that with these modifications, both PYTHIA_SJ_RC_MOD and PYTHIA_SJ_DJ_MOD, exhibit the most substantial agreement with the experimentally measured p_T-dependent D^0 production cross section, as reported by ALICE and LHCb. Additionally, these modifications lead to a marked enhancement in the production of Λ_c^+ baryons in PYTHIA_SJ_DJ_MOD, thereby increasing the Λ_c^+/D^0 ratio, which aligns more closely with the measurements from ALICE for both $\sqrt{s} = 7$ [Fig. 2(a)] and 13 TeV results (Fig. 3). This enhancement, nonetheless, results in an overestimation when compared to LHCb measurements [Fig. 2(b)]. However, a certain degree of underestimation still persists in the alignment of the model-generated predictions with the ALICE experimental data points at $\sqrt{s} = 7$ TeV.

In contrast, PYTHIA_SJ_RC_MOD demonstrates a commendable capability to accurately reproduce the LHCb measurements on the Λ_c^+/D^0 ratio [Fig. 2(b)]. Within the ALICE-detector acceptance, this model-generated event sample shows a marginal improvement in the agreement with the ALICE measurements compared to the default string-junction model implementation [Figs. 2(a) and 3].

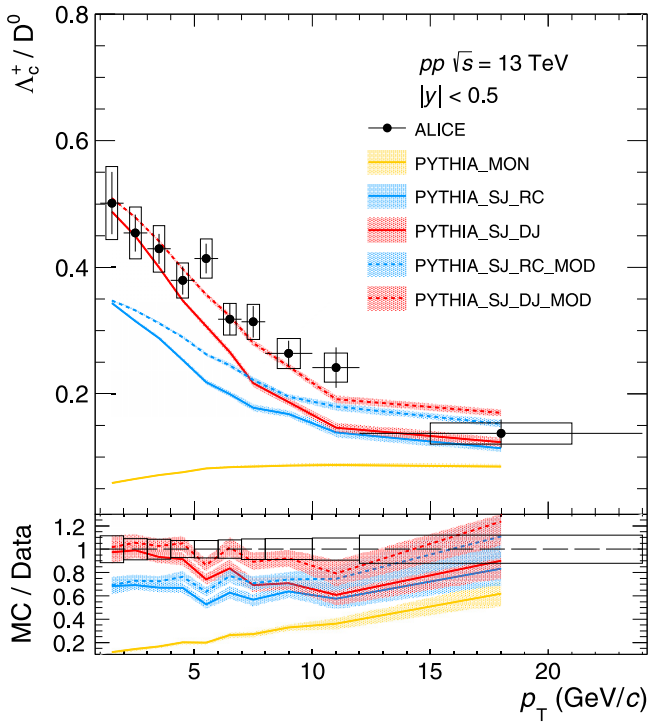


FIG. 3. Comparison of p_T-dependent Λ_c^+/D^0 ratio measured by ALICE [18] in p + p collisions at $\sqrt{s} = 13$ TeV with different model predictions. The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples.

In conclusion, the comparison of the p_T-differential production cross sections of Λ_c^+ and D^0, along with their respective ratio, as measured by both ALICE and LHCb experiments with our MC results, indicates that the PYTHIA_SJ_DJ_MOD-generated event sample of this investigation gives the best agreement with the experimental results of ALICE on p_T-differential production cross section of Λ_c^+, D^0 as well as p_T-dependent Λ_c^+/D^0 ratio among all the studied models. However, the experimental results of LHCb on all the above-mentioned observables are found to be best represented by our generated event sample of PYTHIA_SJ_RC_MOD model.

B. Comparison of Λ_b^0 and $\bar{B}^0(B^0)$ experimental results with model estimations

Altmann *et al.* [6], using the same model (here labeled as PYTHIA_SJ_DJ) for p + p collisions at $\sqrt{s} = 13$ TeV, which they used to describe the ALICE result on the Λ_c^+/D^0 ratio at the same energy, also estimated Λ_b^0/B^0 ratio and compared their findings with the available LHCb experimental result [13]. Their findings showed that the PYTHIA_SJ_DJ event sample significantly overestimated the LHCb results. Moreover, there are reports from the LHCb experiment on the p_T-differential production cross section times the branching ratio (BR) of Λ_b^0, $\bar{B}^0$ and their ratio $R_{\Lambda_b^0/\bar{B}^0}$, defined as

$$R_{\Lambda_b^0/\bar{B}^0} = \frac{\sigma\left(\Lambda_b^0\right) \mathrm{BR}\left(\Lambda_b^0 \longrightarrow J/\psi\, p K^-\right)}{\sigma(\bar{B}^0)\, \mathrm{BR}(\bar{B}^0 \longrightarrow J/\psi\, \bar{K}^{*0})} \tag{6}$$

for p + p collisions at $\sqrt{s} = 7$ TeV [17]. However, no attempt has been made so far to make a comparison of the above-mentioned LHCb experimental findings with the model prediction. In this section, we make an attempt to discuss these experimental results with PYTHIA_SJ_RC_MOD-generated event sample. Our PYTHIA_SJ_RC_MOD event sample predicted results, along with the other model predictions on estimation of the p_T-differential production cross section times BR of Λ_b^0 and $\bar{B}^0$ for p + p collisions at $\sqrt{s} =$ 7 TeV, as well as the LHCb measured results, are shown in Fig. 4. To keep consistency with the experimental plots, the p_T-dependent production ratio of Λ_b^0 and $\bar{B}^0$ at $\sqrt{s} = 7$ TeV, inclusive of the considered b-hadron decay branching ratios, i.e., $R_{\Lambda_b^0/\bar{B}^0}$ is plotted in Fig. 5(a), whereas, in Fig. 5(b) the p_T-dependent production ratio of Λ_b^0 and B^0 at $\sqrt{s} = 13$ TeV is plotted.

The plots presented in Fig. 4 clearly show that, within LHCb acceptance, the PYTHIA_MON model is capable of describing the production of $\bar{B}^0$ mesons; however, it significantly underestimates the production of Λ_b^0 baryons. On the other hand, PYTHIA_SJ_DJ, along with its modified event sample PYTHIA_SJ_DJ_MOD, which incorporates the adjustments on the parametrization of the symmetric-fragmentation function, demonstrates a more favorable estimation for Λ_b^0 production [Fig. 4(a)], concurrently underestimates the $\bar{B}^0$ production [Fig. 4(b)]. This observed discrepancy may be attributed to the deactivation of the flag `ColourReconnection:allowDoubleJunRem` in the PYTHIA_SJ_DJ (as well as PYTHIA_SJ_DJ_MOD). Such deactivation leads to an increase in the production of Λ_b^0 baryons than the production of $\bar{B}^0$ mesons. The reduced yield of $\bar{B}^0$ mesons results in a considerable overestimation of the $R_{\Lambda_b^0/\bar{B}^0}$ ratio at $\sqrt{s} = 7$ TeV [Fig. 5(a)]. A similar conclusion can be drawn regarding the discrepancy observed by Altmann *et al.* [6] on Λ_b^0/B^0 ratio at $\sqrt{s} =$ 13 TeV [Fig. 5(b)]. On the other hand, PYTHIA_SJ_RC_MOD underestimates the production of both Λ_b^0 and $\bar{B}^0$ by a comparable margin, suggesting that the string-junction model in the default CR mode 1 may not adequately account for the production of bottom quarks. This inadequacy is supported by the results shown in Figs. 4(a) and 4(b).

Given that the mass of the bottom quark (as well as charm quark) is significantly greater than the Λ_{QCD} scale, they cannot be produced through nonperturbative hadronization processes, such as via string fragmentation [4–6]. Instead, these quarks must be produced before the hadronization during the initial hard scatterings through leading-order perturbative processes, such as $q\bar{q} \longrightarrow b\bar{b}$, $gg \longrightarrow b\bar{b}$, as well as through parton showers involving gluon splitting [4,34]. The mass of the bottom quark is a critical parameter in the perturbative description, influencing both the matrix-element calculations and the available phase space [4]. Therefore, the chosen value for the bottom quark mass exhibits considerable sensitivity concerning the production cross section of bottom

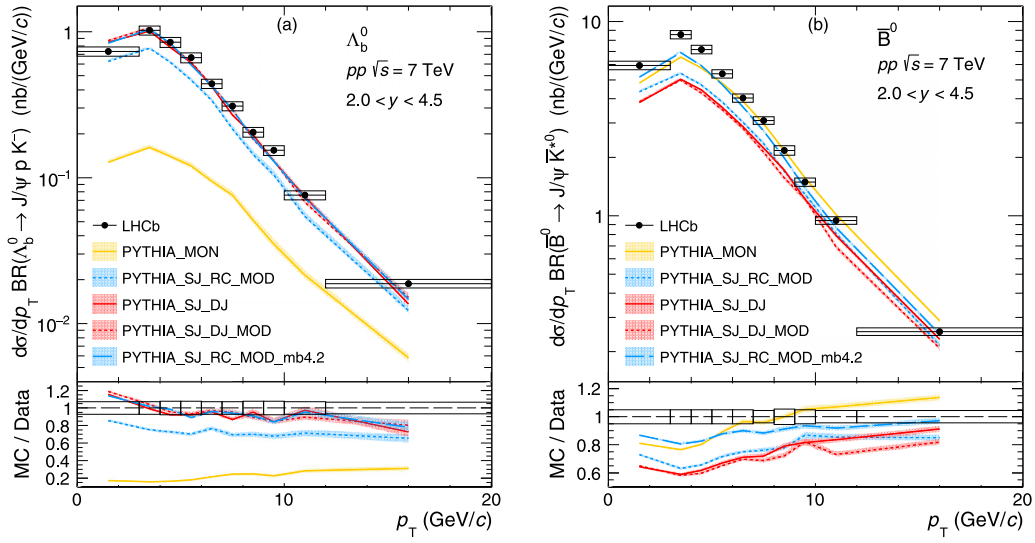


FIG. 4. A comparison of model predictions with the experimental p_T-dependent differential production cross section times branching ratio of (a) Λ_b^0 and (b) $\bar{B}^0$ measured by LHCb [17] in p + p collisions at $\sqrt{s} = 7$ TeV. The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples.

quarks. In PYTHIA version 8.314, the default mass of the bottom quark is set as $m_b = 4.8$ GeV/c^2, which is based on a standardized mass for charm quark ($m_c = 1.5$ GeV/c^2) [35] and the conventional mass formula referenced in Refs. [4,36].

In pursuit of increasing the production cross section of bottom quarks, the mass was reduced to a value of $m_b = 4.2$ GeV/c^2 (via `5:m0=4.2`), as proposed in Ref. [34]. This configuration lowers the threshold required for the creation of bottom-quark and antiquark pairs during both initial hard scatterings and parton showers [4], thereby facilitating an increased production cross section for bottom hadrons. Additionally, similar to the modifications implemented for charm quarks in Sec. III A, the Bowler's multiplicative factor for bottom quark (r_b) is raised from its default of 0.855 to 0.96 again by the hit-and-trial method. With these modified values of m_b and r_b, keeping all other parameters the same, the event sample PYTHIA_SJ_RC_MOD is regenerated, and this newly generated event sample is named for convenience as PYTHIA_SJ_RC_MOD_mb4.2. The tuning parameters associated with this event sample are summarized in Table III. As

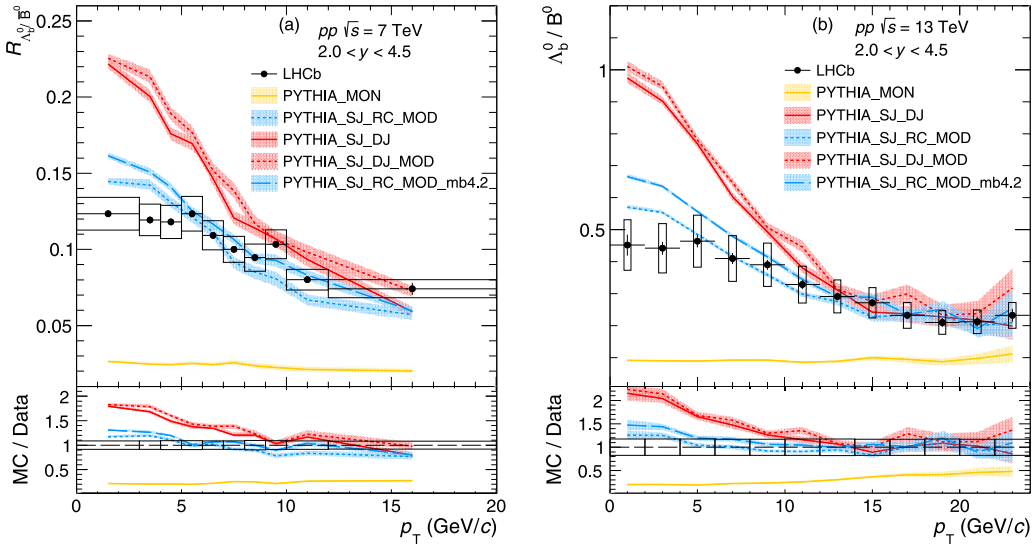


FIG. 5. A comparison of model predictions with experimental p_T-dependent (a) $R_{\Lambda_b^0/\bar{B}^0}$ and (b) Λ_b^0/B^0 ratio measured by LHCb [13,17] in p + p collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV. The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples.

TABLE III. Full list of modified parameters of the PYTHIA-8.314-generated event samples.

Parameters	PYTHIA_MON(default)	PYTHIA_SJ	PYTHIA_SJ_RC	PYTHIA_SJ_RC_MOD	PYTHIA_SJ_RC_MOD_mb4.2	PYTHIA_SJ_DJ	PYTHIA_SJ_DJ_MOD
ColourReconnection:mode	0	1	1	1	1	1	1
ColourReconnection:allowDoubleJunRem	on	on	on	on	on	off	off
BeamRemnants:remnantMode	0	1	1	1	1	1	1
BeamRemnants:beamJunction	–	off	on	on	on	off	off
StringZ:aLund	0.68	0.68	0.68	1.1	1.1	0.36	1.1
StringZ:bLund	0.98	0.98	0.98	0.6	0.6	0.56	0.6
StringZ:rFactC	1.32	1.32	1.32	1.5	1.5	1.5	1.5
StringZ:rFactB	0.855	0.855	0.855	0.855	0.96	0.855	0.855
StringFlav:mesonCvector	0.88	0.88	0.88	0.88	0.88	1.5	1.5
StringFlav:probStoUD	0.217	0.217	0.217	0.217	0.217	0.20	0.20
StringFlav:probQQtoQ	0.081	0.081	0.081	0.12	0.12	0.078	0.12
MultiPartonInteractions:pT0Ref	2.28	2.28	2.28	2.28	2.28	2.25	2.25
5:m0	4.8	4.8	4.8	4.8	4.2	4.8	4.8

evident from Fig. 4, this event sample provides the most favorable agreement with the p_T-dependent differential production cross section of Λ_b^0 and $\bar{B}^0$, indicating that the default bottom quark mass in PYTHIA may be too high to accurately reflect the substantial production of bottom quarks as observed experimentally. From Fig. 5(a), it is interesting to see that despite PYTHIA_SJ_RC_MOD underestimates the production of both Λ_b^0 and $\bar{B}^0$, it still exhibits reasonably good agreement with the experimentally measured $R_{\Lambda_b^0/\bar{B}^0}$ ratio. However, the event sample PYTHIA_SJ_RC_MOD_mb4.2 not only gives good agreement with the experimentally measured values of p_T-differential production cross section of Λ_b^0, $\bar{B}^0$ but also $R_{\Lambda_b^0/\bar{B}^0}$ ratio at $\sqrt{s} = 7$ [Fig. 5(a)], and Λ_b^0/B^0 at $\sqrt{s} = 13$ TeV [Fig. 5(b)], indicating that PYTHIA_SJ_RC_MOD_mb4.2 remains the most successful model out of all the considered models of the present investigation in describing the considered heavy-baryon-to-heavy-meson ratios at LHCb acceptance.

C. Robustness check of PYTHIA_SJ_RC_MOD_mb4.2-generated event sample

To check the robustness of our PYTHIA_SJ_RC_MOD_mb4.2 model-generated event sample, the ALICE and LHCb experimental results on the measurement of $\bar{\Lambda}/\Lambda$ ratio as a function of y for p + p collisions at $\sqrt{s} = 7$ TeV is compared with our model prediction and is plotted in Fig. 6. From this figure, it is readily evident that the MC event sample generated with PYTHIA_SJ_RC_MOD_mb4.2 shows even a better agreement than the results reported in Ref. [1] with the experimental $\bar{\Lambda}/\Lambda$ ratio at ALICE and LHCb acceptances

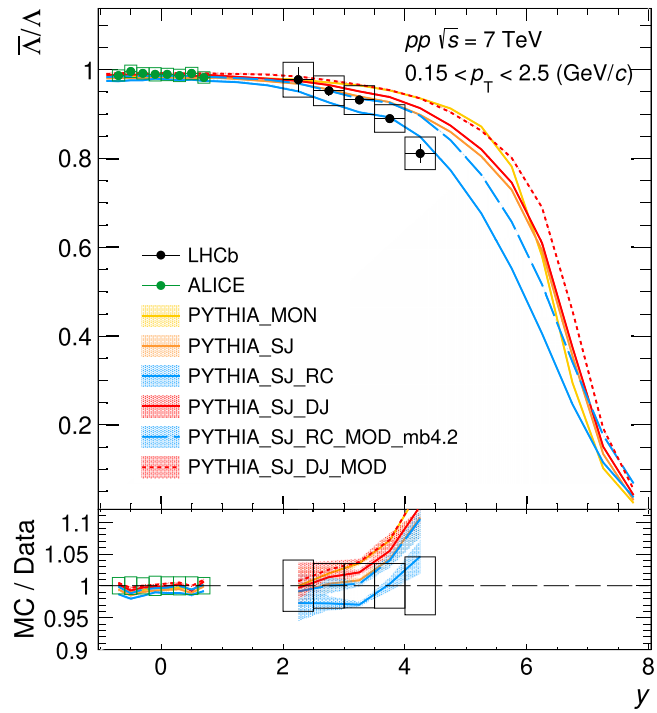


FIG. 6. Comparison of rapidity-dependent $\bar{\Lambda}/\Lambda$ ratio measured by ALICE [37] and LHCb [38] in p + p collisions at $\sqrt{s} = 7$ TeV with various model predictions. The error bars associated with the data points represent the statistical uncertainty, whereas the square boxes around the data points represent the systematic uncertainty. The shaded region around the solid and dashed lines represents the statistical uncertainty associated with the generated event samples.

($y < 3.5$). The disagreement between the generated and experimental data points is well within 10% of the uncertainties.

Thus, PYTHIA_SJ_RC_MOD_mb4.2 model-generated event sample has been found to be successful in describing the experimental rapidity-dependent $\bar{\Lambda}/\Lambda$ ratio, p_{T}-differential production cross section of Λ_c^+, D^0, Λ_b^0, $\bar{B}^0$, p_{T}-dependent ratio of Λ_c^+/D^0 and $R_{\Lambda_b^0/\bar{B}^0}$ within LHCb acceptance in p + p collisions at $\sqrt{s} = 7$ TeV (see Supplemental Material [39]), as well as p_{T}-dependent Λ_b^0/B^0 ratio of LHCb experiment at $\sqrt{s} = 13$ TeV. However, ALICE experiment results on p_{T}-differential production cross section of Λ_c^+, D^0 at $\sqrt{s} =$ 7 TeV and p_{T}-dependent Λ_c^+/D^0 at both $\sqrt{s} = 7$ and 13 TeV were best described by PYTHIA_SJ_DJ_MOD.

IV. SUMMARY

In this paper, various MC-generated event samples with different tunings of the PYTHIA-8.314 event generator, based on the string junction, a Y-shaped fundamental topological entity of QCD, are used to study the available experimental p_{T}-differential production cross sections of heavy-flavored baryons (Λ_c^+ and Λ_b^0) and mesons (D^0 and $\bar{B}^0$) in p + p collisions at $\sqrt{s} = 7$ TeV in both ALICE and LHCb acceptances. Moreover, the p_{T}-dependent ratios of Λ_c^+/D^0 and $\Lambda_b^0/\bar{B}^0(B^0)$ at $\sqrt{s} = 7$ and 13 TeV have also been studied and compared. From the discussions on the charm sector, one can conclude that the event sample PYTHIA_SJ_DJ_MOD, with fragmentation parameters ($a = 1.1$, $b = 0.6$, $r_c = 1.5$, and $probQQtoQ = 0.12$), is the most successful model in describing the ALICE experimental results on p_{T}-differential production cross sections of Λ_c^+ and D^0 in p + p collisions at $\sqrt{s} = 7$ TeV, as well as their p_{T}-dependent ratios at both $\sqrt{s} = 7$ and 13 TeV. However, among all generated event samples, PYTHIA_SJ_RC_MOD provides the most reasonable description of the p_{T}-differential production cross sections of Λ_c^+ and D^0, along with the p_{T}-dependent Λ_c^+/D^0 ratio in p + p collisions at $\sqrt{s} = 7$ TeV in the LHCb acceptance. Moreover, the p_{T}-differential production cross sections of Λ_b^0, $\bar{B}^0$ in p + p collisions at $\sqrt{s} = 7$ TeV, and the p_{T}-dependent $\Lambda_b^0/\bar{B}^0$ (B^0) ratio in p + p collisions at $\sqrt{s} = 7$ and 13 TeV in the LHCb acceptance could also be well described by PYTHIA_SJ_RC_MOD_mb4.2 event sample with a reduced bottom quark mass ($m_b = 4.2$ GeV/c^2) and Bowler's multiplicative factor for bottom quark (r_b) set to 0.96. Here, it is worth mentioning that the reduction in the bottom quark mass and modification to the Bowler's multiplicative factor for bottom quark in this event sample have no significant effect on the observables studied in the charm sector (see Supplemental Material [39]). Thus, the model PYTHIA_SJ_DJ_MOD (by not allowing junction-antijunction reconfiguration) could successfully describe the ALICE experimental observables of the present investigation of the charm sector, whereas the model PYTHIA_SJ_RC_MOD_mb4.2 (by allowing junction-antijunction reconfiguration) can explain the considered LHCb experimental observables of both charm and bottom sectors. However, a single set of tuning parameters that can describe all the observables of the present investigation for both ALICE and LHCb results is yet to be realized.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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