

Thermodynamical string fragmentation and string density effects in jets

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It has been proposed to search for thermal and collective properties arising from parton-fragmentation processes by examining high jet charged-constituent multiplicities ($N_{j, \text{ch}}$) in proton-proton (pp) collisions. This proposal was initially tested using the PYTHIA 8 event generator with the Monash tune, which incorporates multiparton interactions (MPI) and the MPI-based color reconnection (CR) model. These studies did not reveal any conclusive evidence for the presence of radial flow. In this paper, we expand upon the proposed Monte Carlo study by eliminating selection biases associated with triggering on charged particle multiplicities. Furthermore, MPI are disabled to focus exclusively on jet fragments. We analyze pp collisions at $\sqrt{s} = 13$ TeV simulated with PYTHIA 8, exploring different implementations of the generator: thermodynamical string fragmentation and the standard Lund fragmentation model. The impact of color-string junctions was also explored. Surprisingly, the thermodynamical string fragmentation together with the close-packing of strings mechanism predicts a hint of baryon enhancement in jets. Additionally, the light-flavor baryon-to-meson ratios as a function of j_T exhibit similarities across all PYTHIA 8 implementations, and hint at radial flow-like effects. In contrast, the ratio of heavy-flavor hadrons (Λ_c^+ / D^0) at low j_T as a function of $N_{j, \text{ch}}$ shows a trend similar to that observed as a function of charged-particle multiplicity in minimum-bias data, suggesting that color-string junctions may play a crucial role in heavy baryon production in jets. The same mechanism also predicts a j_T -integrated Λ_c^+ / D^0 ratio that increases with increasing $N_{j, \text{ch}}$. Interestingly, for the lowest $N_{j, \text{ch}}$ value, such a ratio is consistent with the e^+e^- limit, suggesting that jet multiplicity is a potential way to explore more dilute systems covering the multiplicity gap between e^+e^- and pp collisions.

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I. INTRODUCTION

The heavy-ion collider experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL and the Large Hadron Collider (LHC) at CERN aim to study dense quantum chromodynamics (QCD) systems, where a new form of matter, the strongly interacting quark-gluon plasma (QGP) is created. One major discovery of the LHC era is the observation of QGP-like effects in small-collision systems (pp and p-Pb collisions). The origin of the new phenomena has remained an open question for the past decade. In heavy-ion collisions, signatures such as collectivity and strangeness

enhancement have been attributed to the formation of QGP [1–3]. On the one hand, impact-parameter dependent glasma calculations indicate that the energy density, averaged over the transverse area, can reach around 70 GeV/fm³ in pp collisions for charged particle multiplicity densities above 100 [4]. Lattice QCD calculations suggest that this condition is sufficient for QGP formation in pp collisions. However, no signatures of jet quenching have been observed so far [5,6]. Moreover, long-range angular correlations have been observed even in very dilute systems like low-multiplicity pp collisions [7], photonuclear ultra-peripheral Pb-Pb collisions [8], and probably in jets [9]. Although hydrodynamics has been applied to explain the pp and p-Pb data, some theoretical works suggest that it should not be applicable in small-collisions systems [10]. This opens the door to alternative approaches, such as color strings, which have successfully described some aspects of pp and p-Pb data [11–14].

The exploration of diluted QCD systems has continued over the last years. Recently, in Ref. [15] authors postulate

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that a strongly interacting QGP-like system can originate from a fast parton (quark or gluon) as it fragments and propagates through the QCD vacuum. Due to the intrinsic QCD coupling strength, the color fields of the fast parton in the vacuum can produce a large number of secondary partons. These secondary partons can then interact and develop a collective expansion, which is transverse to the trajectory of the parent parton, and extends over a finite space-time volume. The idea is somewhat similar to a Monte Carlo (MC) study that showed that PYTHIA produces radial flowlike effects in dense partonic systems originating from multiparton interactions (MPI) due to string interactions via color reconnection (CR) [16]. Since, in the standard color reconnection schemes implemented in PYTHIA, CR effects are suppressed in jets, no radial flowlike effects and strangeness enhancement were reported in Ref. [15].

Inspired by Ref. [15], the CMS Collaboration reported a new measurement from pp collision data with high jet charged-constituents multiplicities ($N_{j, \text{ch}}$) [9]. They studied two-particle correlations among the charged particle jet constituents as functions of the azimuthal angle and pseudorapidity separations ($\Delta\varphi^*$, $\Delta\eta^*$) in the jet coordinate frame, where η^* and φ^* are defined relative to the direction of the jet axis. The azimuthal correlation was analyzed as a function of $N_{j, \text{ch}}$. For low $N_{j, \text{ch}}$ values, the long-range elliptic anisotropic harmonic, v_2^* , decreases with $N_{j, \text{ch}}$, a characteristic reproduced by models like PYTHIA 8. However, an intriguing rising trend for v_2^* is observed at $N_{j, \text{ch}} > 80$, hinting at a possible onset of collective behavior, which is not reproduced by the MC generators that were tested. The observation is interesting and deserves further study, particularly for high- $N_{j, \text{ch}}$ values.

This paper reports on the search for baryon enhancement and radial flowlike effects in jets. A crucial difference from Ref. [15] is that the bias due to the multiplicity selection based on charged particles is removed by reporting the hyperon-to- K_S^0 ratios instead of the hyperon-to-charged-pion ratios. In addition, the baryon-to-meson ratio in the charm sector is also investigated. For both studies, various models are tested, including the standard Lund string fragmentation model with different color-reconnection implementations, as well as the thermodynamical string fragmentation model [17]. The current work is relevant for understanding QGP-like effects observed in small systems, and may also help resolve a long-standing puzzle, that in elementary e^+e^- collisions the yields of various hadron species can be well described by a thermal statistical model [18].

The paper is organized as follows. The PYTHIA MC event generator and the different models used in this work are introduced in Sec. II. Section III presents the methodology, as well as comparisons between models and data. Section IV presents the results and discussion. Finally, results are summarized in Sec. V.

II. PYTHIA MODELS

The results presented in this paper are obtained from PYTHIA simulations [19] (version 8.309), which incorporate the Lund string fragmentation model [20]. The Monash tune has been obtained from fits to early LHC data; therefore, it successfully describes several observables at LHC energies. The model incorporates MPI and CR, which are crucial for reproducing the multiplicity distributions as well as the correlation between the average transverse momentum (p_T) and the charged-particle multiplicity [21]. Since the discovery of radial flowlike effects due to the CR mechanism, more advanced CR models have been built [22]. The most common CR models use the leading color (LC) approximation to calculate the color flow on an event-by-event basis; the partonic final states result from color-connecting a quark to another single and unique parton in the event. In the model, gluons carry both a color and an anticolor charge, and therefore they are connected to two other partons. The LC approximation is used in the MPI-based color reconnection model implemented in the Monash tune. In this scheme, each MPI-scattering system is viewed as separate and distinct from all other systems in color space. The color flow of two such systems can be fused, and if so, the partons of the lower- p_T system are added to the strings defined by the higher- p_T system to minimise the total string length. In this paper we also consider color reconnection modes beyond leading color approximation (CR-BLC). The QCD-scheme CR, which considers the minimization of the string length and the color rules from QCD, constructs all pairs of dipoles that are allowed to reconnect by QCD-color rules and switches if the new pair has a lower string length. Junctions can also be directly produced from three, and in some special cases, four dipoles. Here, the multiplet structure of SU(3) is combined with a minimization of the string potential energy, to decide between which partons strings should form, allowing also for “baryonic” configurations. One would expect that MPI increases the number of possible subleading connections. [23]. It is worth mentioning that in the traditional approach, also implemented in the MPI-based CR scheme, CR effects are negligible in jets and are enhanced in active MPI environments. Although the QCD-based CR model implemented in PYTHIA reproduces basic observables well, further tunes have been developed considering different time-dilation constraints [22]. The CR-BLC mode 2, which requires strict causality between dipoles, is proven to reproduce the features seen in the heavy-flavor baryonic sector [24–26].

The models described above are based on the standard Lund string fragmentation, where a tunneling mechanism for string breakups results in a Gaussian suppression of the production of heavier quarks and diquarks, with a further suppression based on the hadronic spin state. In the thermodynamical string fragmentation [17], the Gaussian suppression in mass and p_T is replaced by an exponential

TABLE I. List of the relevant parameters of the different PYTHIA 8 settings used in the current work. Also see Refs. [17,21,22].

PYTHIA 8 Parameter	Monash	Monash	CR-BLC	Thermodyn.	Thermodyn.
		CR-QCD	(mode 2)		CR-QCD
StringPT:sigma	0.335	0.335	0.335	0.335	0.335
StringPT:closePacking	off	off	off	on	on
StringPT:thermalModel	off	off	off	on	on
StringPT:temperature				0.21	0.21
StringPT:expNSP				0.13	0.13
StringZ:aLund	0.68	0.68	0.36	0.68	0.68
StringZ:bLund	0.98	0.98	0.56	0.98	0.68
StringFlav:BtoMratio				0.357	0.357
StringFlav:StrangeSuppression				0.357	0.357
StringFlav:probQQtoQ	0.081	0.081	0.078		
StringFlav:ProbStoUD	0.217	0.217	0.2		
StringFlav:probQQ1toQQ0join {	0.5	0.5	0.0275	0.5	0.5
	0.7	0.7	0.0275	0.7	0.7
	0.9	0.9	0.0275	0.9	0.9
	1.0	1.0	0.0275	1.0	1.0
BeamRemnants:remnantMode	0	1	1	0	1
BeamRemnants:saturation		5	5		5
ColourReconnection:mode	0	1	1	0	1
ColourReconnection:allowDoubleJunRem	on	on	off	on	on
ColourReconnection:m0	0.3	0.3	0.3	0.3	0.3
ColourReconnection:allowJunctions		on	on		on
ColourReconnection:junctionCorrection		1.20	1.20		1.20
ColourReconnection:timeDilationMode		2	2		2
ColourReconnection:timeDilationPar		0.18	0.18		0.18

suppression. The experimental motivation comes from fixed-target and ISR data, which show that the inclusive p_T distributions are well described by an exponential function, $\exp(-Bp_T)$ with $B \approx 6 \text{ GeV}^{-1}$. The model exhibits its reasonable agreement with LHC data for observables such as the p_T distributions of unidentified charged hadrons, the average transverse momentum as a function of the hadron mass, and hyperon-to-pion ratios as a function of multiplicity. The set of parameters for thermodynamical-string fragmentation includes the modification of string tension due to the local string density [17]. This mechanism is named close packing. In minimum-bias pp collisions an effective string density is introduced for low p_T , while jet fragmentation occurs outside the close-packing string region and is left unaffected. This mechanism changes the flavor composition at high multiplicities. In this paper, we explore the potential impact of these new implementations in high-string density environments such as high jet-charged-constituent multiplicities.

The relevant parameters are summarized in Table I. In the following, the model named as Monash CR-QCD is the Monash tune with the QCD-based CR parameters,

which is essentially Monash tune including color-string junctions. Variations of Monash tune including thermodynamical-string fragmentation with MPI-based and QCD-based CR models are termed Thermodyn. and Thermodyn. CR-QCD models, respectively. Finally, the model CR-BLC mode2 is a tuned version of PYTHIA 8 including color-string junctions.

III. ANALYSIS METHOD

Before discussing the observables in the jet frame, Fig. 1 shows the p_T spectra of various particle species, comparing the model predictions described above with the minimum-bias pp ALICE data [27,28]. Note that there are certain differences between simulations and data in handling charm hadrons: in the current study, the feed-down components into charm hadrons have not been excluded, and a pseudorapidity cut $|\eta| < 1$ was used instead of a rapidity cut $|y| < 0.5$ on the charm hadrons, $|\eta| < 0.5$ on their decay products as considered in Ref. [28]. Overall, all models yield similar results for unidentified charged particles, charged pions, kaons and (anti)protons. The spectral shapes

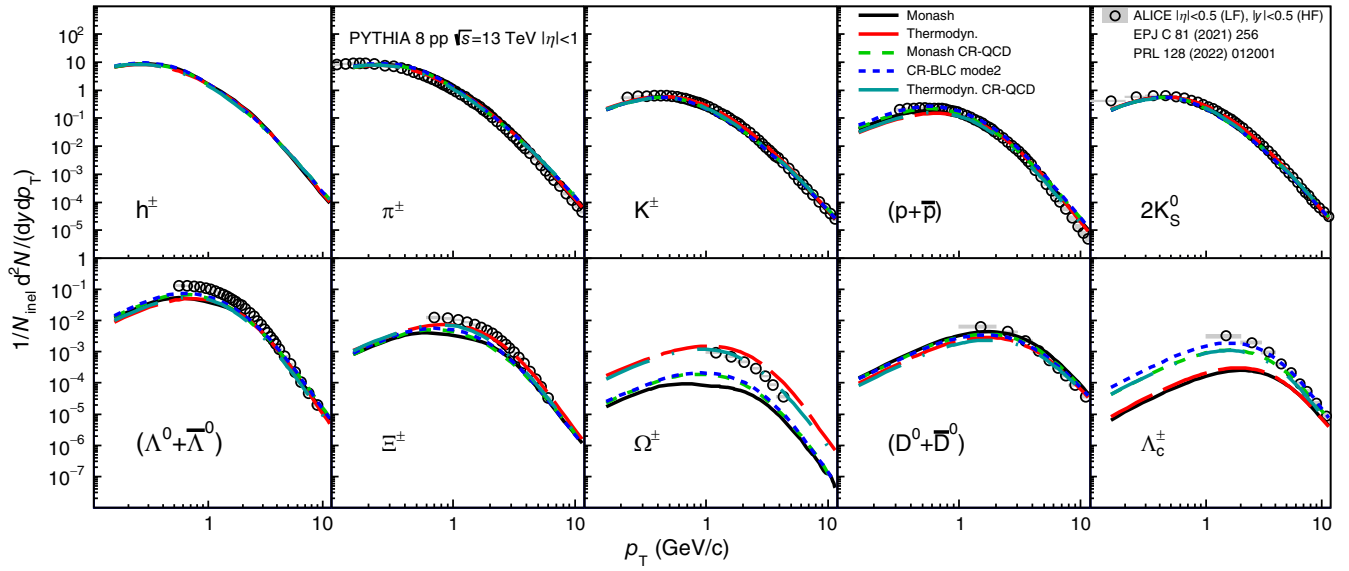


FIG. 1. Midrapidity transverse momentum spectra of identified hadrons in pp collisions at $\sqrt{s} = 13$ TeV. Data are compared with different model predictions.

are well reproduced by models both at low and high p_T . For heavier hadrons, the models deviate from each other. The Λ - p_T spectrum is better described by the Monash CR-QCD and CR-BLC mode2 models suggesting the important role of color-string junctions. The thermodynamical-string fragmentation models predict a slightly lower yield, probably because the model has not been tuned to data. However, the $\Xi^\pm$ and $\Omega^\pm$ baryon- p_T spectra are best described by the simulations, which consider thermodynamical-string fragmentation. Although the best agreement is observed for $\Omega^\pm$, the other models significantly underpredict particle yield within the measured p_T range (1–4 GeV/c). It is worth noting that the Thermodyn. model matches the data better than the Thermodyn. CR-QCD model, which overpredicts the yield. For the heavy-flavor sector (D^0 meson and $\Lambda_c^\pm$), the best description is provided by models incorporating color-string junctions (Monash CR-QCD, CR-BLC mode2, and Thermodyn. CR-QCD), which promote the baryon formation particularly in the charm sector.

For jet observables, the simulations were performed with the HardQCD setting and a phase-space cut of $\hat{p}_T > 550$ GeV/c. Jets were clustered using the anti- k_T algorithm [29] with the energy recombination scheme and a resolution parameter $R = 0.8$. Jets with charged-jet transverse momenta $550 < p_T^{\text{jet}} < 1000$ GeV/c were used. The mean $\hat{p}_T$ is about 744 GeV/c. To correct for the bias introduced by the phase-space cut, we applied a p_T^{jet} -dependent correction, which is in the order of 15% at $p_T^{\text{jet}} = 550$ GeV and vanishes toward higher momenta. We made sure through a cross-check with $\hat{p}_T > 250$ GeV/c that the phase-space cut has negligible effect on our observables. Also note that we applied a selection on p_T^{jet} corresponding to charged jets. Applying full jet

transverse-momentum selection similarly to Ref. [9] results in a momentum shift, which affects the reach in $N_{j,\text{ch}}$ but the baryon-to-meson ratios are largely unaffected. Since we focus on jet observables, we disabled multiparton interactions to avoid background from the underlying event unrelated to the jets. In the analysis, we use the jet frame [15] to define the kinematics of jet constituents as $\mathbf{p}^* = (j_T, \eta^*, \varphi^*)$, where j_T is the momentum component perpendicular to the jet axis, and η^* - φ^* were already defined.

IV. RESULTS AND DISCUSSION

Figure 2 (left) shows the $N_{j,\text{ch}}$ distributions for various model settings. The jet multiplicities show slight variations depending on the color-reconnection scheme and also differ slightly in the case of thermodynamical string fragmentation. In particular, the high- $N_{j,\text{ch}}$ tail is slightly reduced in the Monash CR-QCD, CR-BLC mode2, and Thermodyn. CR-QCD models compared to Monash. The η^* distributions, shown in the right panel, appear to be independent of the model settings used. In the jet coordinate system, low- η^* values correspond to charged particles that are separated from the jet axis by large angles, whereas the high- η^* values are associated with particles at small angles relative to the jet direction. All curves exhibit a steep rise up to $\eta^* \approx 0.86$, which is related to the choice of the jet resolution parameter ($R = 0.8$).

To reveal the dynamics of various constituents within a jet, their production can be analyzed using kinematic variables in the comoving frame. Figure 3 shows different baryon-to-meson ratios as a function of j_T , for different models, in several $N_{j,\text{ch}}$ classes.

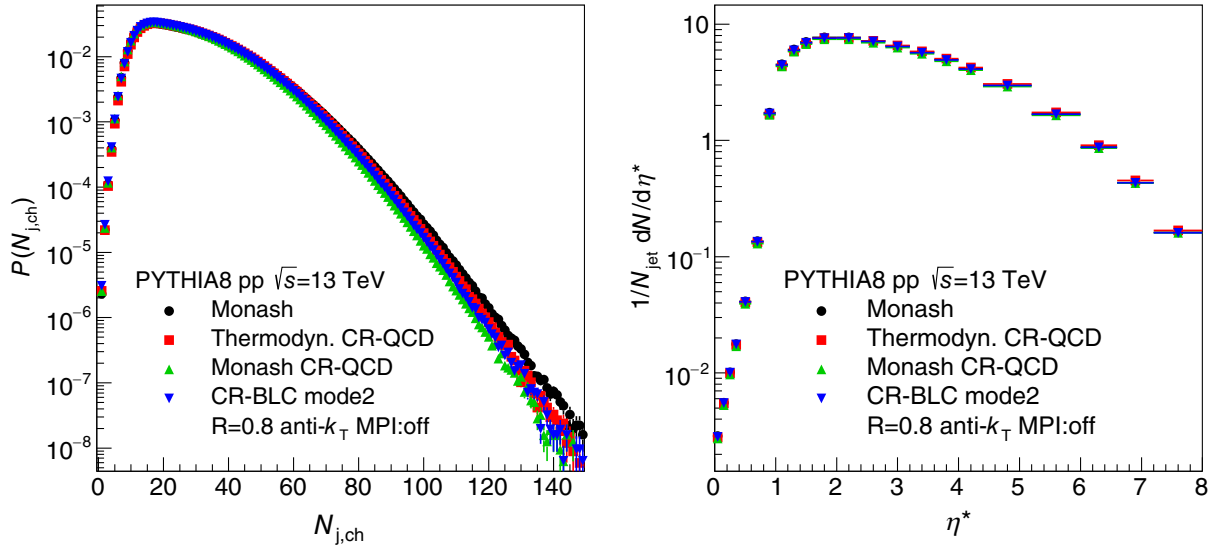


FIG. 2. Jet charged-constituent multiplicity (left) and η^* (right) distributions for different model settings. Results for pp collisions at $\sqrt{s} = 13$ TeV are displayed. MPI is off in all cases.

Before discussing the particle ratios, it is important to note that the models predict larger emission angles and j_T values for high jet charged-constituent multiplicities compared to the inclusive and low- $N_{j, \text{ch}}$ event classes. Conversely, lower emission angles (and lower j_T values) are expected for low $N_{j, \text{ch}}$ pp collisions. This effect is due to a correlation between jet-charged-constituent multiplicity and the flavor of its initiating parton, with high- $N_{j, \text{ch}}$ values predominantly associated to gluon-initiated jets and low- $N_{j, \text{ch}}$ values to quark-initiated jets [15].

In the light-flavor sector, all models (Monash, Monash CR-QCD, CR-BLC mode2, and Thermodyn. CR-QCD) exhibit some common features in baryon-to-meson ratios. For $j_T > 5$ GeV/c, the proton-to-pion and the Λ^0 -to- K_S^0 ratios are grouped into low- $N_{j, \text{ch}}$ and high- $N_{j, \text{ch}}$ ranges, with the ratios for $0 < N_{j, \text{ch}} < 20$ and $20 < N_{j, \text{ch}} < 40$ being lower than those for the higher $N_{j, \text{ch}}$ intervals: 40–60, 60–80, 80–100, 100–120. This grouping may reflect the flavor of the initiating parton. Looking at the details, the ratios are slightly multiplicity dependent, as they increase with increasing $N_{j, \text{ch}}$. On the other hand, for lower j_T values ($j_T < 5$ GeV/c) the multiplicity dependence is stronger: the ratios are depleted from the low- to high- $N_{j, \text{ch}}$ classes. For all $N_{j, \text{ch}}$ classes, the ratios show a bump structure which shifts toward higher j_T values with increasing $N_{j, \text{ch}}$. The effect is similar to that observed in p_T in the standard multiplicity analysis, where it is attributed to radial flowlike effects [30]. All these features, except for the multiplicity grouping, are also present in the $\Xi^\pm$ -to- K_S^0 particle ratio. The presence of the bump is not obvious in the case of the multistrange $\Omega^\pm$ -to- K_S^0 ratio, except in the Thermodyn. CR-QCD model, where a strong enhancement of $\Omega^\pm$ is

observed compared to other models. However, this enhancement is less pronounced in high- $N_{j, \text{ch}}$ pp collisions at low- j_T , and only gets stronger with $N_{j, \text{ch}}$ toward mid- and high- j_T values.

For the heavy-flavor particle ratio, Λ_c/D^0 , no enhancement is seen with the Monash model at low j_T . However, Monash CR-QCD shows a clear Λ_c^+/D^0 enhancement at lower j_T values, which is more pronounced with increasing $N_{j, \text{ch}}$. This phenomenon is even stronger for the CR-BLC mode2 and Thermodyn. CR-QCD models. Keeping in mind that string junctions have an impact on the baryon-to-meson ratio at low p_T [26,31–33], the observed patterns in jets could be due to color-string junctions. One should remember that the Λ_c^+/D^0 ratios as a function of p_T are well described by PYTHIA 8 including color-string junctions. A similar feature to the $N_{j, \text{ch}}$ -dependent excess at low j_T values has also been seen in CR-BLC simulations toward higher p_T values, where the Λ_c^+/D^0 ratios were found to depend on the jet activity [34]. Regarding the CR-BLC mode2 and Thermodyn. CR-QCD models, it is also interesting to note that for the highest $N_{j, \text{ch}}$ class, the maximum value for Λ_c^+/D^0 is approximately 0.35, similar to the value reported for the lowest inclusive multiplicity class in Ref. [24] suggesting that intra-jet multiplicities is a promising venue to explore the multiplicity gap between e^+e^- to pp collisions. This conclusion is further supported by the fact that for the lowest $N_{j, \text{ch}}$ class the ratios are nearly flat and consistent with the corresponding ratios measured in e^+e^- collisions at LEP, which was found to be $0.113 \pm 0.013(\text{stat}) \pm 0.006(\text{syst})$ [35]. Note that in the low- $N_{j, \text{ch}}$ limit, one would expect the jet sample to be dominated by quark-initiated jets. It is also important to note that while there are more recent models for color reconnection with

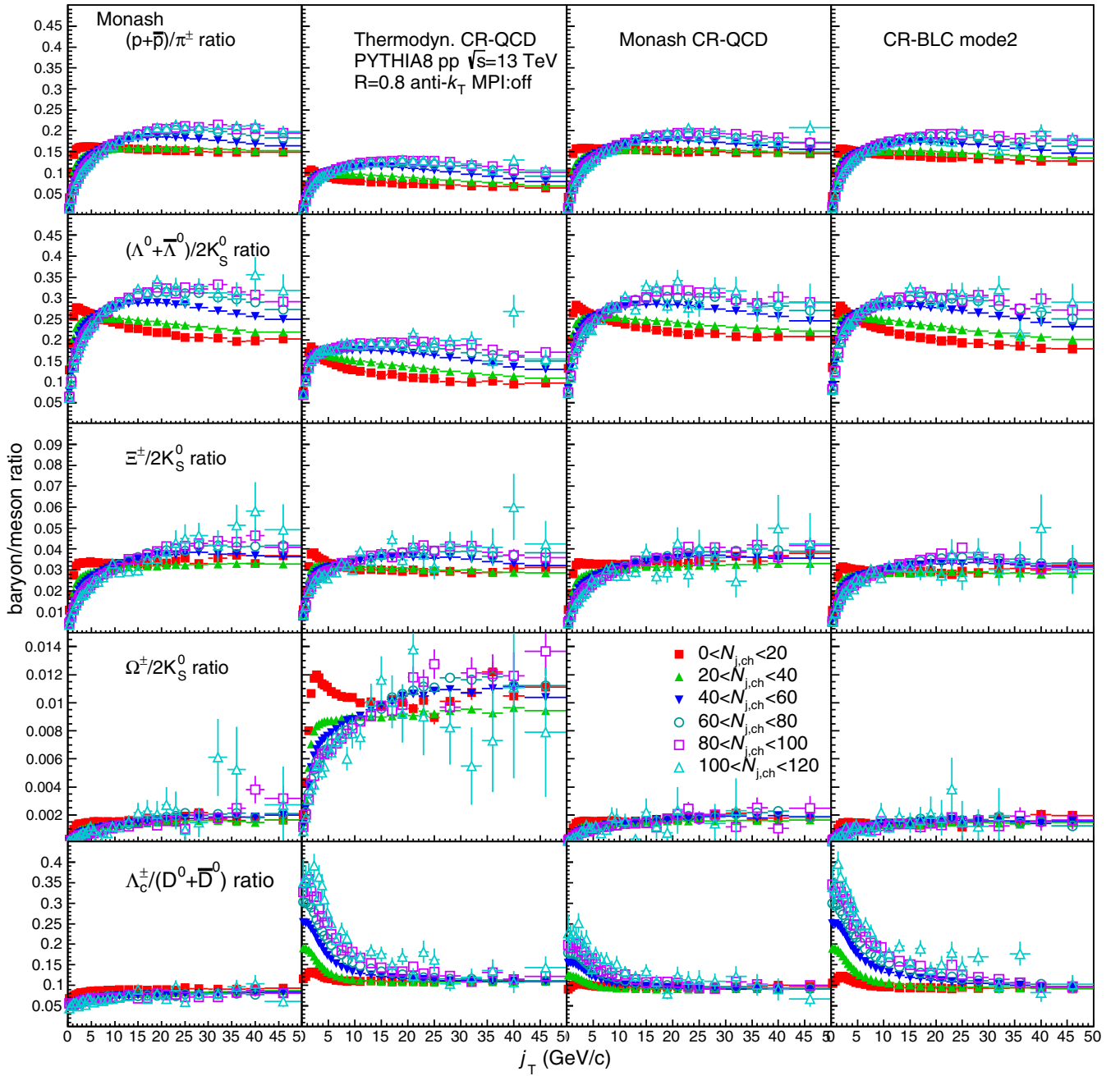


FIG. 3. Baryon-to-meson ratios as a function of j_T for different jet charged-constituent multiplicity intervals. Results are shown for pp collisions at $\sqrt{s} = 13$ TeV, simulated with different PYTHIA settings. MPI is off in all cases.

color junctions [36,37], there is no significant difference of the Λ_c/D^0 predictions provided by CR-BLC and these new models. Therefore, we stick to CR-BLC, which is widely used by the community.

Figure 4 shows the baryon-to-meson ratios integrated over j_T , as a function of $N_{j, \text{ch}}$. A notable feature is that the standard Lund string fragmentation (Monash, Monash CR-QCD, and CR-BLC mode2 models) predicts higher $(p + \bar{p})/(\pi^+ + \pi^-)$ and Λ^0/K_S^0 and lower $\Xi^\pm/K_S^0$ and $\Omega^\pm/K_S^0$ ratios than the Thermodyn. CR-QCD model in the full $N_{j, \text{ch}}$

range. The standard Lund model predicts either decreasing or nearly constant particle ratios with increasing $N_{j, \text{ch}}$. In contrast, the Thermodyn. CR-QCD model shows a continuous increase in $(p + \bar{p})/(\pi^+ + \pi^-)$, Λ^0/K_S^0 , and $\Xi^\pm/K_S^0$ with increasing $N_{j, \text{ch}}$. This indicates a kind of baryon enhancement for jet constituents. However, for $\Omega^\pm/K_S^0$, the Thermodyn. CR-QCD model predicts a ratio that is five times higher than that predicted by other models, and a decreasing trend with increasing jet multiplicity, which aligns with the findings reported by authors of the

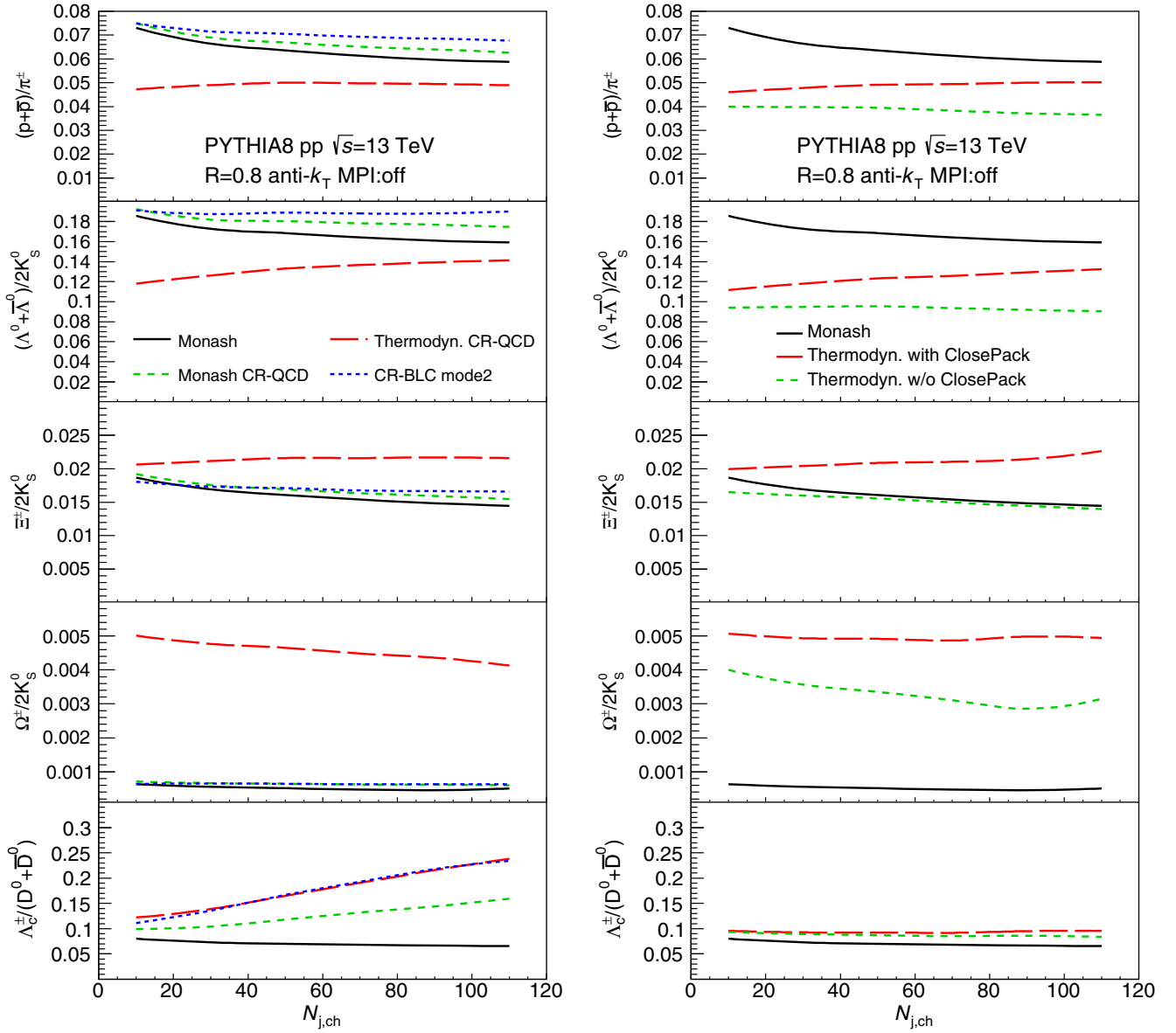


FIG. 4. Baryon-to-meson ratios as a function of the jet charged-constituents multiplicity. Results for pp collisions at $\sqrt{s} = 13$ TeV simulated with different PYTHIA settings. The different color-reconnection schemes (left) and the effect of thermodynamical string fragmentation with and without close packing (right) are compared to the Monash tune. MPI is off in all cases.

thermodynamical string fragmentation model [17]. In this model, heavier hadrons tend to be produced at large p_T values (in the jet), which might explain the difference from the standard Lund fragmentation model. The same paper notes that the Ω yield normalized to the charged-pion yield decreases with growing multiplicity, likely due to phase-space constraints. Looking at Table I, one notices the parameter `StringFlav:BtoMratio` in the Thermodyn. CR-QCD model, which controls the relative rate of baryon-to-meson production. We changed this parameter and verified that the multiplicity dependence of the baryon-to-meson ratios were not affected by such a variation.

Finally, the Λ_c^+/D^0 ratio shows an increasing trend with $N_{j, \text{ch}}$ for the models including color-string junctions (Monash CR-QCD, CR-BLC mode2, and Thermodyn. CR-QCD models), while there is an opposite trend for Monash. It is worth mentioning that ALICE data exhibit a p_T -integrated Λ_c^+/D^0 ratio that is multiplicity independent. Thus, intra-jet studies in the data could be highly valuable for testing different baryon production models and contribute to a deeper understanding of the QGP-like effects observed in small systems.

It is worth noting that the Thermodyn. CR-QCD model produces baryon enhancement relative to mesons (except for the Ω baryon), and also predicts a Λ_c^+/D^0 ratio that starts

from ≈ 0.11 (close to the e^+e^- limit) followed by an increase with increasing $N_{j,\text{ch}}$. Then the question is whether these effects have to do with the CR model and/or the close-packing mechanism. The plot on the right-hand side of Fig. 4 shows the baryon-to-meson ratios integrated over j_T , as a function of $N_{j,\text{ch}}$ for the Thermodyn. model, where no color-string junctions are considered. Simulations including the close-packing mechanism exhibit baryon enhancement relative to mesons for $(p + \bar{p})/(\pi^+ + \pi^-)$, Λ^0/K_S^0 , $\Xi^\pm/K_S^0$, and $\Omega^\pm/K_S^0$ particle ratios. On the contrary, the enhancement is not observed when the close-packing mechanism is disabled. Therefore, such an enhancement in the light and strange baryon sector is due to thermodynamical string fragmentation and the close-packing mechanism. In contrast, looking at the heavy flavor sector, the Λ_c^+/D^0 ratio is nearly flat in Thermodyn. model suggesting the importance of color-string junctions in the production of heavy baryons.

V. CONCLUSIONS

This paper reports on intra-jet identified-hadron production as a function of the jet charged-constituent multiplicity ($N_{j,\text{ch}}$) in pp collisions at $\sqrt{s} = 13$ TeV simulated with PYTHIA 8. The jet frame is used to define the kinematics of jet constituents: j_T is the momentum component perpendicular to the jet axis, η^* and φ^* are the pseudorapidity and azimuthal angle coordinates with respect to the jet axis, respectively. The multiparton interaction mechanism is turned off. Given that only charged particles are considered to calculate $N_{j,\text{ch}}$, the light-flavor baryon yields are normalized to the K_S^0 yield. Thus, no bias in the neutral-to-charged particle ratio affects the results.

The pp collisions are simulated using the Monash tune, which implements the MPI-based CR model. The effect of color-string junctions is studied by means of a comparison between the Monash tune and the so-called Monash CR-QCD model. Other studies were performed that included variations of the Monash tune, including thermodynamical string fragmentation with MPI-based and QCD-based CR models named Thermodyn. and Thermodyn. CR-QCD models, respectively. Finally, the model CR-BLC mode2, which is a tuned version of PYTHIA 8 including color-string junctions, was also included in the study.

- (i) The $N_{j,\text{ch}}$ and η^* distributions are only slightly or not affected by the choice of the PYTHIA settings.
- (ii) For all PYTHIA models the proton-to-pion and the Λ^0 -to- K_S^0 ratios show low-high multiplicity grouping trend for $j_T > 5$ GeV/c, possibly reflecting the flavor of the jet-initiating parton. The ratios show a bump structure that shifts toward higher j_T values with increasing $N_{j,\text{ch}}$. This effect is reminiscent of the radial flowlike effects observed in the p_T spectra as a function of the

inclusive charged particle multiplicity. These features, except the multiplicity grouping, are also seen in the $\Xi^\pm$ -to- K_S^0 particle ratios. The presence of the bump is not obvious in the case of the multistrange $\Omega^\pm$ -to- K_S^0 ratio, except in the thermodynamical string fragmentation model, where a strong enhancement of $\Omega^\pm$ is observed compared to other models.

- (iii) Λ_c^+/D^0 as a function of j_T is little or not multiplicity dependent for Monash tune. However, color-string junctions (Monash CR-QCD) produce an increase in the Λ_c^+/D^0 ratio at low j_T with increasing $N_{j,\text{ch}}$. The effect gets enhanced for the tune CR-BLC mode2, which also includes color-string junctions. The size of the effects for the later model is consistent with that produced by Thermodyn. CR-QCD model. This effect is similar to the multiplicity-dependent Λ_c^+/D^0 as a function p_T reported by ALICE. For the lowest $N_{j,\text{ch}}$ class, the ratio is nearly flat and is consistent with the corresponding ratios measured in e^+e^- collisions at LEP.
- (iv) Regarding the j_T -integrated baryon-to-meson particle ratios for the light-flavored sector, the Thermodyn. model with string density effects (close-packing mechanism) produces ratios that increase with $N_{j,\text{ch}}$. On the other hand, the Λ_c^+/D^0 ratio shows an increasing trend with $N_{j,\text{ch}}$ for models including color-string junctions. The ratio departs from ≈ 0.11 (consistent with e^+e^- limit) and increases with $N_{j,\text{ch}}$. These findings encourage intra-jet studies to be relevant in covering the multiplicity gap between e^+e^- and pp collisions.

The results presented in this paper provide new observables that can be used to test thermodynamics-inspired fragmentation models, as well as the role of color-string junctions in the heavy-flavored hadron production from small to large systems.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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