Suplemento de la Revista Mexicana de Física **4** 021118 (2023) 1–5

Multiplicity of charged and identified particles within jets

E. Cuautle Flores

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México,
Apartado Postal 70-543, Ciudad de México 04510, México.

S. Arias Santiz

Centro de Investigación en Computación, Instituto Politécnico Nacional (CIC-IPN),
Othon de Mendizabal s/n and Av. Juan de Dios Batiz, Ciudad de México, 07738, México

Received 31 May 2023; accepted 25 July 2023

Jets are commonly used to study Quantum Chromodynamics and search for physics beyond the Standard model. Recent experimental results are analyzed to study hard and soft hadron production mechanisms within jets. The result of this work is the study of hadron production within jets produced in proton-proton collisions generated using PYTHIA 8.3 event generator. We report color reconnection effects on jet multiplicity, multiplicity for identified particles within jets and transverse momenta distributions at 7 and 13 Tev.

Keywords: Quantum chromodynamics; PYTHIA 8.3.

DOI: https://doi.org/10.31349/SuplRevMexFis.4.021118

1. Introduction

Multiplicity is a global observable that allows to characterize events in any colliding systems and has been widely studied by the KNO scaling, for the first time [1, 2] and up to the latest LHC energies [3]. Collimated groups of particles produced by the hadronization of quarks and gluons are called jets. In hadron-hadron collisions, these partons are produced in high-momentum transfer scatterings. Jets are commonly used in physics searches beyond the Standard Model [4-7]. They also contribute to backgrounds in other analyses, including the search for heavy particles. Additionally, the jet shapes help to extract parameters from the model in event generators.

Multiplicity within jets is used to study both the perturbative and non-perturbative QCD processes, and since quarks and gluons have different color factors, the hadronization is sensitive to the initial parton. Thus, the particle content and its momentum distribution within jets can be used to discriminate the type of parton that initiated the jet [8]. It is well known that gluon-initiated jets contain larger particle multiplicities than quark-initiated jets at the same energy, and the transverse momentum of the constituent particles is harder for gluon-initiated jets.

In both *p-p* and *p-Pb* collisions, baryon-to-meson and baryon-to-baryon yield ratios measured in jets differ from the inclusive particle production for low and intermediate hadron P_T (0.6-6 GeV/c) [9]. Ratios measured in the underlying event are in turn, similar to those measured for inclusive particle production.

It is generally assumed that the fragmentation functions are universal between collision systems and energies, and the measurement of the relative production of different heavy-flavor hadron species is sensitive to fragmentation functions used in perturbative QCD (pQCD)-based calculations. However, the experimental results [10] compared to the model indicate no universality.

This work presents a study of jets produced at PP collisions. We analyzed the multiplicity of jets, the multiplicity of identified particles in jets, as well as flow-like effects induced by color reconnection in baryon-to-meson ratios. The analysis is done using PYTHIA 8.3 [11] event generator.

2. Events for the analysis

The data for this analysis were generated using PYTHIA 8 pp collisions at 7 and 13 Tev. 4 million events for each set of data. Soft QCD processes with color reconnection were considered for this analysis to study multiplicity and its comparison with the experiment, as well as jets and their properties [12]. Within these events, jets were reconstructed using the $anti-\mathrm{K_T}$ algorithm with cone radius size R given by the $R=\sqrt{(y_i-y_j)^2+(\phi_i-\phi_j)^2}$, where y_i and ϕ_i are respectively the distance in $\eta-\phi$ space, rapidity and azimuth angle of particle.

2.1. Results and its discussion

The multiplicity of jets at 7 Tev and for three different cone sizes, $R = 0.3, 0.5, 0.7$ is computed with results without significant difference, except at higher multiplicity where a small increase is observed for higher R. For this reason, the figure is not shown.

2.2. Jets and color reconnection

The color reconnection (CR) was introduced as part of the hadronization model to describe multiplicity and transverse momentum from the experiments. Evidence shows that it also introduces flow-like effects in PP collisions [13]. The

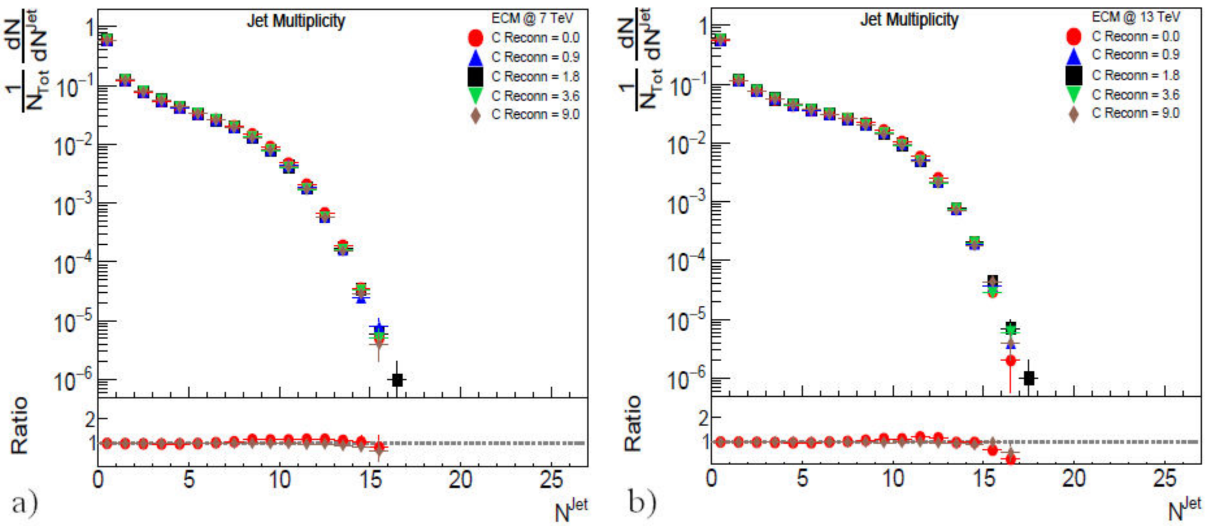

FIGURE 1. Jet multiplicity ($p_T^{Jet} \geq 5$ GeV) for different strengths of color reconnection at a) 7 Tev and b) 13 Tev.

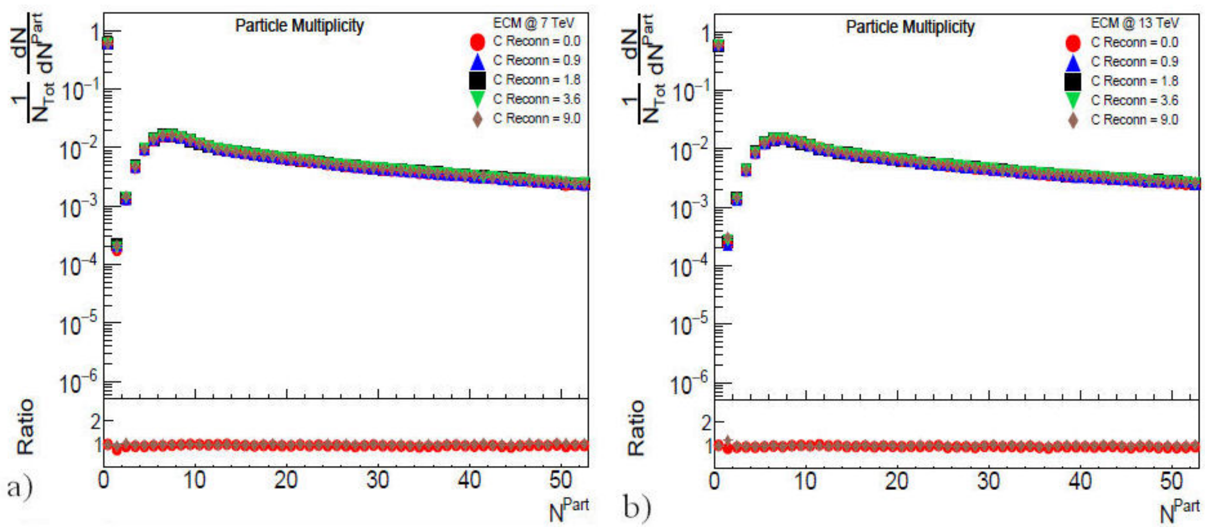

FIGURE 2. Charged particle multiplicity inside jets ($p_T^{Jet} \geq 5$ GeV) for different strengths of color reconnection at a) 7 Tev and b) 13 Tev.

average transverse momentum distributions have been well described [14] when color reconnection is introduced. Here we present the results of the effects of CR within jets. Since this is a final state interaction, it takes part in the hadronization. Consequently, it modifies the multiplicity distribution. Figure 1 shows jet multiplicity for different strength of color reconnection, at 7 Tev (top) and 13 Tev (bottom). The results are computed for a range of color reconnection values from 0-9, which correspond to the minimum and almost the maximum (10 is the maximum) allowed by the model, finding no significant changes between them. The charged particle multiplicity within jets seems not to change for any value of color reconnection, as one can see in Fig. 2 for 7 Tev (top) and 13 Tev (bottom).

The same distributions can be computed for identified particles within jets, with effects of color reconnection. Figures 3 and 4 show on top the case for pions. Meanwhile, the bottom panel shows the multiplicity of protons. In both cases, the plot below each is the ratio of the multiplicity distribution with the highest and the lowest values divided by the multiplicity with a nominal value of CR, 1.8.

Flow effects within jets can be studied through the ratio of the transverse momentum distribution of the baryon-to-meson and baryon-to-baryon. The Fig. 5 shows the baryon-to-meson ratio for $(p + \bar{p})/(\pi^+ + \pi^-)$, $(\Lambda^0 + \bar{\Lambda}^0)/(2K_s^0)$ and $(\Xi^+ + \Xi^-)$, each panel corresponds to a distribution produced with jets for different transverse momentum minimum required to reconstruct the jet, the values of this transverse momentum are: $3, 5, 20, 100, 200$ GeV, indicating the hardness of jets. The lower panel for each figure shows the ratio of distributions with higher to the minimum transverse momentum distribution. The results show a clear bump for the proton to pion shifted to higher P_T values when the transverse momentum of the jet increases. Similar behavior, but less

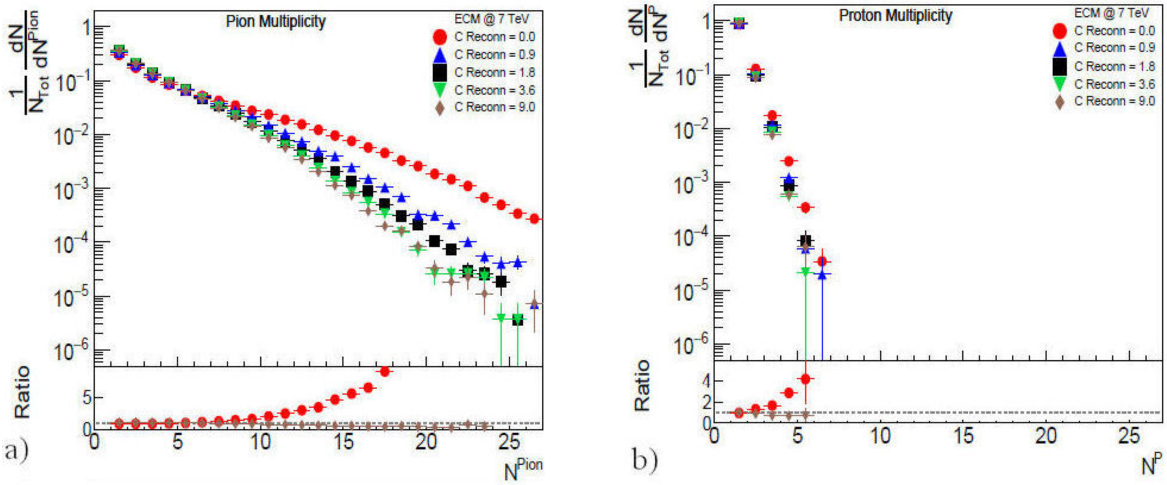

FIGURE 3. Multiplicity distributions of a) pions and b) protons, within jets for different strengths of color reconnection mechanism at 7 Tev.

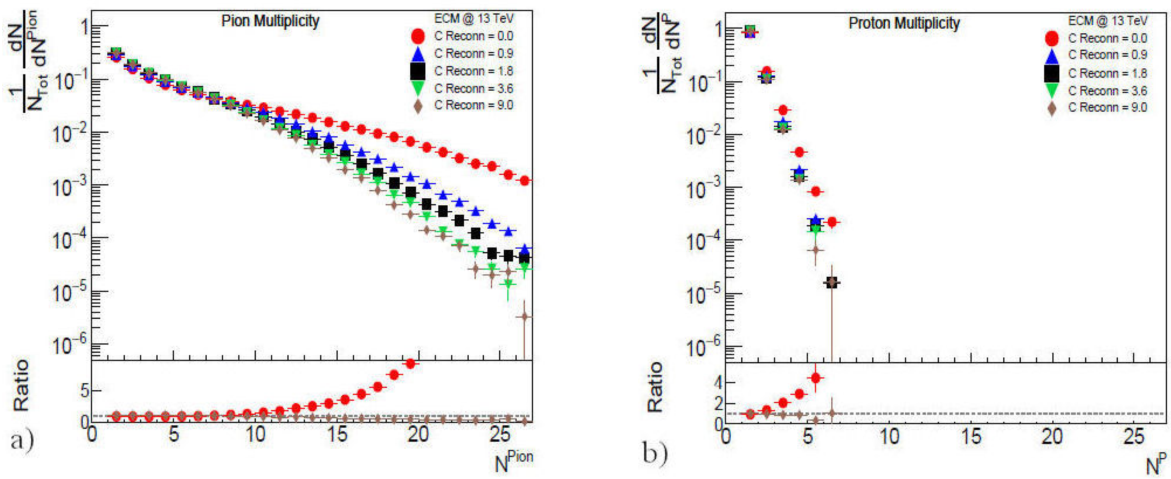

FIGURE 4. Multiplicity distributions for a) pions and b) protons, within Jets for different strengths of color reconnection, at 13 Tev.

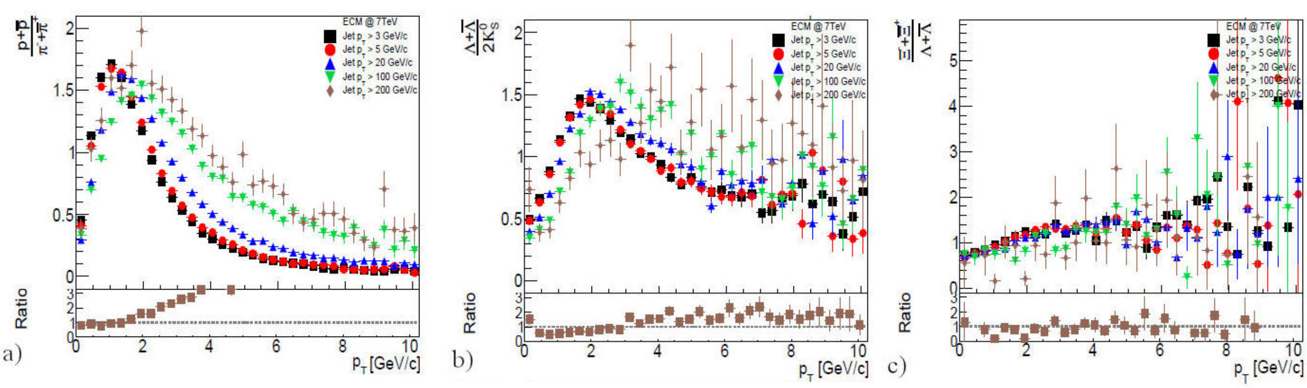

FIGURE 5. Transverse momentum of particles within a jet at 7 Tev for a) $(P+\bar{P})/(\pi^{+}+\pi^{-})$, b) $(\Lambda^0+\bar{\Lambda}^0/2K_s^0)$, and c) $(\Xi^{+}+\Xi^{-})/(\Lambda^0+\bar{\Lambda}^0)$) for different transverse momentum minimum of the jet. The bottom of each distribution shows the ratio for transverse momentum P_T larger to 200 GeV/c to those of P_T larger than 3 GeV/c.

pronounced, is observed for $(\Lambda^0 + \bar{\Lambda}^0)/(2K_s^0)$. Baryon-to-baryon ratio, as shown in the bottom panel of Fig. 5 presents a continuous growth, and it is very similar to any restriction of the transverse momentum of jets.

3. Conclusions and perspectives

We present the effects of color reconnection on jets and their properties through the jet multiplicity and multiplicity of charged and identified hadrons within jets. Jets analyzed were generated with P_P collisions at 7 and 13 Tev in the center of mass energy, using PYTHIA 8 event generator. The main results are: jet multiplicity has slight cone size dependence; the multiplicity of charged particles has a slight dependence on jet P_T ; however, multiplicity within the jet is significantly different for identified particles, especially for pions.

Color reconnection included in jet production has almost no effect on jet multiplicity, but within jets, is observed a strong dependence on identified light particles, like pions or kaons. On the other hand, this effect is less perceptible for heavy particles like proton, Λ, Ξ, and others. Finally, the baryon-to-meson ratio results show a bump with a significant shift to higher P_T when the transverse momentum of the jet increases. This dependence decreases for multi-strange hadrons. This kind of analysis could be helpful to investigate the no universality of hadronization, observed experimentally [9, 10]. It could also be valuable to understand the KNO scaling within jets [15] in terms of different models of color reconnection and multiple parton interactions and effects of initial and final state radiation.

Acknowledgments

This work has been supported in part by PAPIIT-UNAM and CONAHCyT under projects IG100322 and A1-S-16215, respectively.

1. A. Polyakov, A Similarity hypothesis in the strong interactions. 1. Multiple hadron production in e^+e^- annihilation, Zh. *Sov. Phys. JETP* **32** (1971) 296.
2. Z. Koba, H. B. Nielsen, and P. Olesen, Scaling of multiplicity distributions in high-energy hadron collisions, *Nucl. Phys. B* **40** (1972) 317, https://doi.org/10.1016/0550-3213(72)90551-2.
3. Y. Kulchitsky and P. Tsiareshka, Study of the KNO scaling in pp collisions at $\sqrt{s}$ from 0.9 to 13 TeV using results of the ATLAS at the LHC, *Eur. Phys. J. C* **82** (2022) 462, https://doi.org/10.1140/epjc/s10052-022-10420-y.
4. A. Tumasyan *et al.*, Search for new particles in events with energetic jets and large missing transverse momentum in protonproton collisions at $\sqrt{s}$ = 13 TeV, *JHEP* **2021** (2021) 153, https://doi.org/10.1007/JHEP11(2021)153.
5. A. M. Sirunyan *et al.*, Search for long-lived particles using displaced jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV, *Phys. Rev. D* **104** (2021) 012015, https://doi.org/10.1103/PhysRevD.104.012015.
6. G. Aad *et al.*, A search for the decays of stopped long-lived particles at $\sqrt{s}$ = 13 TeV with the ATLAS detector, *JHEP* **2021** (2021) 173, https://doi.org/10.1007/JHEP07(2021)173.
7. G. Aad *et al.*, Search for bottom-squark pair production in pp collision events at $\sqrt{s}$ = 13 TeV with hadronically decaying τ-leptons, b-jets and missing transverse momentum using the ATLAS detector, *Phys. Rev. D* **104** (2021) 032014, https://doi.org/10.1103/PhysRevD.104.032014.
8. P. T. Komiske, E. M. Metodiev, and J. Thaler, An operational definition of quark and gluon jets, *JHEP* **2018** (2018) 059, https://doi.org/10.1007/JHEP11(2018)059.
9. S. Acharya *et al.*, Production of K_S^0, Λ $(\bar{\Lambda})$, $\Xi^{\pm}$, and $\Omega^{\pm}$ in jets and in the underlying event in pp and p-Pb collisions, *JHEP* **2023** (2023) 136, https://doi.org/10.1007/JHEP07(2023)136.
10. S. Acharya *et al.*, Λ_c^+ Production and Baryon-to-Meson Ratios in pp and p-Pb Collisions at $\sqrt{sNN}$ =5.02 TeV at the LHC, *Phys. Rev. Lett.* **127** (2021) 202301, https://doi.org/10.1103/PhysRevLett.127.202301.
11. C. Bierlich *et al.*, A comprehensive guide to the physics and usage of PYTHIA **8.3** (2022), https://doi.org/10.21468/SciPostPhysCodeb.8.
12. S. Arias, E. Cuautle, and H. León Vargas, Jet fragmentation properties with CMS open-data, *Phys. Scripta* **98** (2023) 035305, https://doi.org/10.1088/1402-4896/acba51.
13. A. Ortiz Velasquez *et al.*, Color Reconnection and Flow-like Patterns in pp Collisions, *Phys. Rev. Lett.* **111** (2013) 042001, https://doi.org/10.1103/PhysRevLett.111.042001.
14. B. B. Abelev *et al.*, Multiplicity dependence of the average transverse momentum in pp, p-Pb, and Pb-Pb collisions at the LHC, *Phys. Lett. B* **727** (2013) 371, https://doi.org/10.1016/j.physletb.2013.10.054.
15. R. Vértesi, A. Gémes, and G. G. Barnaföldi, Koba-Nielsen-Olesen-like scaling within a jet in proton-proton collisions at LHC energies, *Phys. Rev. D* **103** (2021) L051503, https://doi.org/10.1103/PhysRevD.103.L051503.
16. P. Skands, S. Carrazza, and J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 Tune, *Eur. Phys. J. C* **74** (2014) 3024, https://doi.org/10.1140/epjc/s10052-014-3024-y.
17. J. R. Christiansen and P. Z. Skands, String Formation Beyond Leading Colour, *JHEP* **2015** (2015) 3, https://doi.org/10.1007/JHEP08(2015)003.
18. C. Bierlich and J. R. Christiansen, Effects of color reconnection on hadron flavor observables, *Phys. Rev. D* **92** (2015) 094010, https://doi.org/10.1103/PhysRevD.92.094010.

19. J. Bellm *et al*., Herwig 7.0/Herwig++ 3.0 release note, *Eur. Phys. J. C* **76** (2016) 196, https://doi.org/10.1140/epjc/s10052-016-4018-8.

20. R. J. Fries, V. Greco, and P. Sorensen, Coalescence Models For Hadron Formation From Quark Gluon Plasma, *Ann. Rev. Nucl. Part. Sci*. **58** (2008) 177, https://doi.org/10.1146/annurev.nucl.58.110707.171134.

21. J. Adam *et al*., Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in p-Pb collisions at $\sqrt{sNN}$ = 5.02 TeV, *Phys. Lett. B* **760** (2016) 720, https://doi.org/10.1016/j.physletb.2016.07.050.

22. V. Khachatryan *et al*., Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC, *Phys. Lett. B* **768** (2017) 103, https://doi.org/10.1016/j.physletb.2017.01.075.

23. J. L. Nagle and W. A. Zajc, Small System Collectivity in Relativistic Hadronic and Nuclear Collisions, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 211, https://doi.org/10.1146/annurev-nucl-101916-123209.

24. H. León Vargas and the ALICE collaboration, Connecting the underlying event with jet properties in pp collisions at $\sqrt{s}$ = 7 TeV with the ALICE experiment, *J. Phys. Conf. Ser*. **389** (2012) 012004, https://doi.org/10.1088/1742-6596/389/1/012004.