Study of multiplicity dependence of heavy flavor production in p−p collisions using rope hadronization mechanism

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The multiplicity dependence of the production of the charm mesons in p−p collisions at $\sqrt{s} = 7$ TeV and 13 TeV as measured by ALICE experiment has been investigated using Pythia 8 event generator by studying the effect of various processes at partonic level such as the effect of different modes of color reconnections and rope hadronization. The relative yields (Yield/⟨Yield⟩) of D-mesons and $J/\psi$ as a function of relative charged particle multiplicity for various transverse momentum ($p_T$) ranges as measured by the ALICE experiment are in reasonable agreement with the estimations of Pythia 8 model within the framework of microscopic processes. The relative yields of B mesons for various $p_T$ intervals ($1 < p_T < 20$ GeV/c) have also been predicted in p−p collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV.

I. INTRODUCTION

Heavy quarks like charm and beauty are produced in ultra-relativistic hadronic collisions by hard scatterings between partons of the incoming hadrons. Due to their large mass ($m_Q \gg \Lambda_{QCD}$), heavy quarks are produced at the very initial stages of the collisions and the production cross-section is well described by the perturbative Quantum Chromodynamics (pQCD) calculations. The theoretical calculations based on general-mass variable-flavour-number scheme, GM-VFNS [1] or fixed order with next-to-leading-log resummation, FONLL [2] - [5] predict the inclusive production cross-sections of charm mesons in p−p collisions at Large Hadron Collider (LHC). The collinear factorisation theorem at next to leading order (NLO) has been implemented in both the calculations. Alternatively, the leading order (LO) calculations based on the framework of $k_T$- factorisation [6] describes the D-meson production cross-section in p−p collisions at the LHC.

The production of heavy-flavour particles as a function of charged particle multiplicity in p−p collisions at LHC energies is relevant as it allows one to study the production as a function of event activity at the partonic level as the charged particle multiplicity is closely associated with the number of multi-partonic interactions (MPIs). The MPIs refer to many hard and semi-hard partonic interactions occurring in a single collision. As heavy flavors are predominantly produced via hard scattering processes while charged particle production is dominated by soft processes, this study can illuminate about the interplay between hard and soft mechanisms, specifically, the influence of underlying event activities in particle production.

At LHC energies, the particle production depends on the beam energy as well as on the impact parameter of the two colliding protons. This can affect the contributions emanating from gluon radiation and multi-partonic interactions (MPI) which can influence the production of heavy flavor quarks. The fluctuations in the gluon density also affects the particle production in high multiplicity regime. Therefore, the final state particles produced in the collision can be described by a two-component approach where the hard component is well described by pQCD inspired models while the soft one depends on phenomenological modelling of underlying events.

The relative yield of charm hadron production has been measured as a function of charged particle multiplicity with the ALICE experiment at the LHC in p−p collisions at $\sqrt{s} = 7$ TeV [7]. These heavy flavour particles are measured from the reconstruction of prompt D-mesons and non-prompt $J/\Psi$. The relative yield of D-meson species ($D^0$, $D^\pm$, and $D^*$) is observed to increase with an increase in charged particle multiplicity and the trend is similar across all the measured $p_T$ in-
tervals. The relative yields of average D-meson species as a function of charged particle multiplicity have faster increase at higher multiplicities and exhibits a deviation from linear behaviour. At central rapidity, the yield of open charm and hidden charm hadrons show similar increase with multiplicity, which indicates that enhancement of the relative yields of heavy flavour is due to $c\bar{c}$ and $b\bar{b}$ production process rather than hadronization. Several model studies such as Pythia 8 [9], EPOS3 [10][11], and percolation calculation [12][13] have been performed to describe the open heavy flavour relative yield as a function of charged particle multiplicity. EPOS3 and percolation calculation qualitatively describe the enhancement of the relative yield of open heavy flavour hadrons with charged particle multiplicity. However, Pythia 8 underestimated the data at high multiplicities. In heavy-ion collisions, the produced system undergoes a collective expansion (described well by hydrodynamics) and influences the transverse momentum distributions of light hadrons. The recent measurements in high-multiplicity $p$–$p$ collisions at the LHC mimics such a collective behaviour. If heavy flavor quarks participated in such a collective motion in high-multiplicity events, their relative yields might vary as a function of $p_T$. The EPOS3 with hydro component was able to describe the qualitative non-linear evolution of the yield with multiplicity. In percolation model, the target and projectile in the high energy hadronic collisions interact by exchange of colour sources between them. These colour sources have finite size and their number is reduced effectively in high density collisions due to coherence. As a result, the multiplicity due to soft sources decrease while the hard sources are not affected by this.

In recent studies [14], it has been observed that the microscopic model of rope hadronization along with color reconnection mechanism implemented in Pythia 8 [15][16], successfully described the enhancement of strange and multi-strange hadrons in $p$–$p$ collisions and it does not assume the formation of a de-confined and thermalized plasma state. In high multiplicity regime, the colored strings tend to overlap with each other to form colored ropes with higher effective string tension which eventually hadronizes to particles with higher mass. The primary aim of this work is to investigate the effect of rope hadronization on the heavy flavour production. The relative yield of D-meson, B-meson and $J/\psi$ as a function of charged particle multiplicity has been studied with rope hadronization mechanism in $p$–$p$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV for three different modes of color reconnection mechanism.

II. ANALYSIS

The analysis is based on 100 million inelastic, non-diffractive events generated with soft-QCD processes using Pythia 8 generator for $p$–$p$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV. Pythia 8 is a Monte-Carlo event generator which has been frequently used in high energy physics, specially for $e^-$–$e^+$, $p$–$p$ and $\mu$–$\mu$ collisions. Pythia 8 [9] is the successor of Pythia 6 [8], with some introduction of new physics processes like multi-partonic interactions (MPI), color reconnections (CR) etc. and some improvisations in the existing processes at both partonic and hadronic level. One of the major improvements in Pythia 8 is the involvement of $c$ and $b$ quarks in MPI $2 \rightarrow 2$ hard sub-processes. The details of the physics processes and its implementation can be found in reference [19]. The idea of color reconnections stems from the fact that the multiple interactions can lead to generation of many color strings. It is not unreasonable to consider to connect the strings in appropriate manner to reduce the string length and hence the potential energy. The way these strings are connected leads to three modes of color reconnections in Pythia 8. The multi-parton interactions (MPI) and different modes of color reconnections (CR- 0/1/2) are enabled to study the effect of these mechanism on the heavy flavor yield. Additionally, the effect of rope hadronization (RH) has been studied. More details on RH can be found in [17][18]. The various combinations of processes used for this study are: (i) RH on CR(0) on, (ii) RH on CR(1) on, (iii) RH on CR(2) on, (iv) RH off CR(0) on, (v) RH off CR(1) on, (vi) RH off CR(2) on.

The yields of D-mesons ($D^0$, $D^+$, $D^{++}$), B-mesons ($B^0$, $B^+$) and their charge conjugates are estimated in the mid-rapidity region, $|y| < 0.5$ in five $p_T$ intervals, from 1 GeV/$c$ to 20 GeV/$c$. The charged particle multiplicity class definition is obtained within the acceptance of ALICE V0 detector ($-3.7 < y < -1.7$ and $2.8 < y < 5.1$) to reduce the auto-correlation. Therefore, the charged particle multiplicity for $|y| < 0.5$ was obtained for each multiplicity class. The inclusive yields of $J/\psi$ are obtained in forward rapidity region, $2.5 < y < 4.0$ for $p_T > 0$ and the charged particle multiplicity is estimated within $|y| < 1.0$. The study was carried out to compare the effect of various processes
like color reconnections and rope hadronization on the yield of heavy flavor mesons. The obtained estimations were compared to the experimental results as measured by ALICE experiment in the same energy [6]. In the experimental result, the relative yield of D⁰-mesons are measured in the mid-rapidity region, |y| < 0.5 and the relative charged particles are estimated from the V0 detectors.

III. RESULTS AND DISCUSSION

The relative yield of D⁰ is obtained as a function of relative charged-particle multiplicity in two p_T intervals, 2 < p_T < 4 GeV/c and 4 < p_T < 8 GeV/c for the various modes of color reconnections available in Pythia 8. The effect of rope formation which is more pronounced in high multiplicity collisions has also been considered in this study. The results are compared to the measured data in Fig. 1. The measured yields by ALICE, represented by the solid squares are normalized for inelastic cross-section, while the open squares represent the yields which are not corrected for the trigger selection efficiency factor and are normalised to the visible cross-section. The relative yields of D⁰ show an increasing trend with the charged particle multiplicity and the increase is not linear. The formation of color ropes together with color reconnection mechanism qualitatively describes the measured data for all multiplicity classes. The non-linear rise at higher multiplicity could be due to an increased production of heavy flavor particles from hadronizing ropes.

The D-meson (mean yield of D⁰, D±, D*±) relative yields as a function of the relative charged particle multiplicity in p–p collisions at √s = 7 TeV and 13 TeV for five p_T intervals is shown in Fig. 2 and Fig. 3 respectively. All the shown combinations of different modes of microscopic processes exhibit stronger than linear increasing trend with the increase in relative charged particle multiplicity. A faster increase is observed compared to linear trend for higher multiplicity classes in different p_T intervals when the rope hadronization is implemented. The relative yields of D-mesons increase with an increase in p_T intervals for both the energies. It can be observed form Fig. 2 and Fig. 3 that, there is no considerable collision energy dependence on the relative yields of D-mesons indicating that the charm production is dependent on underlying event activity which is more pronounced with increasing multiplicity.

The relative yield of inclusive J/ψ as a function of relative charged particle multiplicity is obtained in Pythia 8 for p–p collision at √s = 7 TeV. The obtained values are compared with the measured ALICE data and shown in Fig. 4. It is evident from Fig. 4 that the formation of color ropes along with color reconnection mechanism in Pythia 8 qualitatively describes the increase in relative yield of inclusive J/ψ measured in data. However, it underestimates the measured data. This might suggest that the production of J/ψ mesons are not significantly affected by underlying event mechanisms.

An additional study was carried out in the beauty sector to estimate the multiplicity dependence of B-mesons. Figure 5 and Fig. 6 depicts
the relative yields of B-meson (Avg. of B\(^0\), B\(^+\) and their charge conjugates) as a function of the relative charged particle multiplicity in p–p collisions at \(\sqrt{s} = 7\) TeV and 13 TeV, respectively, obtained with different processes for five \(p_T\) intervals. A similar increasing trend is observed for all the combinations of Pythia 8 with the relative charged particle multiplicity as seen for D-mesons. It will be an interesting experimental observation in the upcoming measurements at LHC in beauty sector. The study describes the multiplicity dependence of D-meson production with rope hadronization mechanism without assuming any collectivity in the produced system while the \(J/\psi\) production is underestimated by the model. A detailed comparison from estimations from other models like Herwig7 and Sherpa can help us understand the contributions emanating from hadronization mechanism and other underlying event processes.

### IV. SUMMARY

The multiplicity dependence of the production of the open charm (D mesons), open beauty (B mesons) and hidden charm (\(J/\psi\)) mesons in p–p collisions at \(\sqrt{s} = 7\) TeV and 13 TeV has been explored using the different microscopic mechanism of Pythia 8 model and the estimations have been compared to recent measurements by ALICE experiment at LHC. The formation of ropes due to overlap of many strings in high multiplicity events along with the partonic color reconnection mechanism provides a good qualitative and a reasonable
quantitative description of the multiplicity dependence of the relative yields of D-mesons and J/$\psi$ in p–p collisions at $\sqrt{s} = 7$ TeV measured by the ALICE experiment. The relative yields of B mesons for various $p_T$ intervals (1 < $p_T$ < 20 GeV/$c$) have also been predicted in p–p collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV. The relative yields of D-mesons and B-mesons exhibited a non-linear increasing trend with an increase in relative charged particle multiplicity for all $p_T$ intervals. The observed increasing trend of relative yields is influenced by the $c\bar{c}$ and $b\bar{b}$ production processes. This study can act as an interesting baseline for the upcoming measurements at LHC in heavy flavor sector.

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FIG. 6. Relative B-meson (Avg. of B⁰, B⁺ and their charge conjugate) yield as a function of relative charged-particle multiplicity in p−p collision at √s = 13 TeV for different p_T intervals.