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Effect of rope hadronization on strangeness enhancement in *p*-*p* collisions at LHC energies

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The p-p collisions at high multiplicity at LHC show small scale collective effects similar to that observed in heavy ion collisions such as enhanced production of strange and multistrange hadrons, long range azimuthal correlations, etc. The observation of strangeness enhancement in p-p collisions at $\sqrt{s} =$ 7 TeV and 13 TeV as measured by the ALICE experiment is explored using the PYTHIA8 event generator within the framework of microscopic rope hadronization model which assumes the formation of ropes due to overlapping of strings in high multiplicity environment. The transverse momentum (p_T) spectra shape and its hardening with multiplicity is well described by the model. The mechanism of formation of ropes with QCD-based color reconnections also described the observed experimental strangeness enhancement for higher multiplicity classes in p-p collisions at $\sqrt{s} = 7$ TeV and 13 TeV. The enhancement with multiplicity is further investigated by studying the mean p_T ($\langle p_T \rangle$) and the integrated yields ($\langle dN/dy \rangle$) of strange and multistrange hadrons and comparing the predictions to the measured data at LHC for 7 TeV and 13 TeV.

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I. INTRODUCTION

The recent observation of enhanced production of strange and multistrange hadrons in p-p collisions at $\sqrt{s} =$ 7 TeV with high final state multiplicity as measured by the ALICE experiment [1] and long range azimuthal correlations measured by CMS and ATLAS experiment [2–4] have generated a lot of interest in small systems. These observations mimic features present in deconfined matter formed in heavy ion collisions and are manifestations of quark gluon plasma (QGP) dynamics. The QGP observables are studied as a function of charged particle density ($dN_{ch}/d\eta$) in smaller systems and the size of the effects seem to agree with heavy ion collisions for similar charged particle density. Therefore, the possibility of formation of a mini-QGP in small systems for high multiplicity is also being predicted [5].

An enhanced production of strange and multistrange hadrons in heavy ion collisions has long been predicted to be a signature of the formation of the QGP medium [6]. The strange valence quark is not present in the initial state of colliding nuclei and hence are produced by hard partonic scattering processes such as flavor excitation and flavor creation in initial stages of collision and therefore the strange hadrons are predominantly produced in high p_T region. However, in the low p_T region, where the perturbative description fails, the production of strange hadrons is suppressed compared to the light quark (u and d) hadrons owing to the relatively heavier mass of strange quarks. In heavy ion collisions, the enhanced production of strange particles in central and midcentral collisions have been attributed to the abundance of strange and antistrange quarks in the deconfined QGP medium [6,7]. The heavy ion data was also successfully described using statistical thermal models assuming a grand canonical ensemble approach. In peripheral collisions, the strangeness production is similar to that what observed in p-p collisions and was attributed to strangeness canonical suppression. The measurement by ALICE experiment might indicate toward the formation of mini-QGP like system in p-p collisions [1]. Many alternative explanations based on increased and complex interactions among partons in the fragmentation phase of the quantum chromodynamics (QCD) based string hadronization models were put forward to explain some of the experimental observations [8]. The description of these dynamic interactions among partons do not assume a formation of deconfined and thermalized plasma state. One of the mechanism in QCD based on string fragmentation, is rope hadronization, which within the framework

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of color reconnection mechanism, is quite successful in describing the strangeness enhancement [9–11]. The agreement between the predictions of the DIPSY model was good for K_S^0 and Λ while the model underestimated the enhancement for Ξ and Ω. The HERWIG7 [12] model based on cluster hadronizarion has recently implemented a new mechanism of color reconnection where heavier hadrons specifically, baryons are produced in a geometric manner. The model also includes nonperturbative gluon-splitting to create more $s\bar{s}$ pairs in order to explain the recent strangeness enhancement [13]. A new model of cluster reconnections which allowed the reconnections between the baryonic and mesonic clusters was also introduced which led to a better agreement with the data for the production of strange baryons [14]. In this work, we study the strangeness enhancement observed in p-p collisions at $\sqrt{s} = 7$ TeV and 13 TeV using rope hadronization mechanism of PYTHIA8 [9,15] and compare with the ALICE measurement [1]. The predictions of some observables like mean p_T ($\langle p_T \rangle$) and mean integrated yield ($\langle dN/dy \rangle$) of strange hadrons have been studied to understand the dependence of strange particle production on beam energy.

II. ROPE HADRONIZATION

In high energy p-p collisions, the particle production can be simplified into two broad steps namely initial hard scattering leading the production of partons and the subsequent hadronization of the initial parton configuration [16,17]. The generation of partons and the partonic level activity involving multiple parton-parton interactions, the initial and final state radiations, and the activity of beam remnants can be approximately described by perturbative QCD while the fragmentation of the final parton configuration to observable hadrons is completely nonperturbative in nature. The understanding of the later part depends on statistical parametrization of experimental data, realistic modeling, parameter tuning etc. One of the fragmentation models namely The Lund string model [8] has been extremely successful in describing the hadronization process which envisages stretched color flux tubes between two partons leading to linear confinement via massless relativistic string. As the potential energy in the string increases, the quark-antiquark pair move apart and the string breaks producing a new quark-antiquark pair. The hadrons are formed by combining these quarks. In high energy collisions, one can have many such overlapping strings in a small transverse area due to multipartonic interactions leading to description of underlying event activity within the framework of rope hadronization [18,19]. Within this framework, the overlapping colored strings act coherently to form a color rope which subsequently hadronize with a higher effective string tension. The overlap region has higher energy density than nearby regions and as a result, a pressure gradient is created which pushes the strings in the overlap region outwards. The pushing of strings in the transverse direction (string shoving) can mimic flowlike patterns as observed in nucleus-nucleus collisions [20]. The breakup of strings with higher string tension produce more strange quarks and diquarks resulting in enhanced production of baryons and strange hadrons. The mechanism of rope hadronization was first implemented as a correction to the string hadronization model in the DIPSY event generator [11].

III. PYTHIA8 EVENT GENERATOR AND ANALYSIS

PYTHIA8 is a standalone Monte-Carlo event generator for high energy e-e, p-p and μ-μ collisions and has been extensively used to study LHC physics and compare its data. The routines are completely written in C++ (compared to its predecessor PYTHIA6 which was in FORTRAN) with some introduction of new physics and improvisations in the existing processes at both partonic and hadronic level. The details of the physics processes and its implementation can be found in reference [21]. In this present work, the Monash 2013 tune of PYTHIA8 [22] based on larger and recent set of LHC data has been used to generate events for p-p collisions. The multi-parton interactions are enabled with QCD-based color reconnections where one obtains different quark junctions due to reconnections of hadronizing strings [19,23]. The tunings of the rope hadronization are similar to one provided in PYTHIA8 (version 8.235) with shoving. The details of the tunings for rope hadronization is given in Table I. The analysis was also checked with MPI based CR scheme where one obtains smaller string length due to fusion of color flow between partons belonging to different MPI system. The subsequent hadronization is studied within the framework of formation of color ropes. The results (only shown for QCD-based CR scheme) are also compared to the scenario where the mechanism of rope hadronization is not included. The results with rope hadronization without any color reconnections is also shown to indicate the importance of color reconnections.

The analysis is done by generating 50 Million inelastic nondiffractive events with soft QCD processes for p-p

TABLE I. The parameter values of the rope hadronization model used with color reconnection mechanism.

Rope Hadronization	Values
Ropewalk:RopeHadronization	On
Ropewalk:doShoving	On
Ropewalk:r0	0.5
Ropewalk:m0	0.2
Ropewalk:beta	1.0
Ropewalk:tInit	1.0
Ropewalk:deltat	0.05
Ropewalk:tShove	10.0

TABLE II. The values of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ for different multiplicity classes as used by ALICE experiment for p-p collisions at $\sqrt{s} = 7$ TeV [1].

Multiplicity class	$\langle dN_{ch}/d\eta \rangle$
I	21.5 ± 0.6
II	16.5 ± 0.5
III	13.5 ± 0.4
IV	11.5 ± 0.3
V	10.1 ± 0.3
VI	8.45 ± 0.25
VII	6.72 ± 0.21
VIII	5.40 ± 0.17
IX	3.90 ± 0.14
X	2.26 ± 0.12

collisions at $\sqrt{s} = 7$ TeV and 13 TeV with rope hadronization and without it. As the aim of this work is to see whether the strangeness enhancement as observed by ALICE experiment can be explained with the mechanism of rope hadronization, the multiplicity classes were determined by dividing the event sample into ten different event classes based on the total charged multiplicity within the acceptance of ALICE V0 detectors. The yield of strange (K^0_S and $\Lambda + \bar{\Lambda}$) and multistrange hadrons ($\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$) was obtained for $|y| < 0.5$ for different multiplicity classes. The mean pseudorapidity density of charged particles, $\langle dN_{ch}/d\eta \rangle$ was also estimated for $|\eta| < 0.5$. The multiplicity class and the corresponding $\langle dN_{ch}/d\eta \rangle$ range as used by ALICE experiment for the strangeness enhancement study is shown in Table II.

IV. RESULTS AND COMPARISON TO DATA

The analysis was carried out with the generated events using the PYTHIA8 generator and the estimates of various observables were studied and compared to the existing data to understand the mechanism of strange particle production in high multiplicity p-p collisions. The p_T spectra of K^0_S, Λ, Ξ^- and Ω^- for three different multiplicity classes are shown for p-p collisions at $\sqrt{s} = 7$ TeV (left panel) and 13 TeV (right panel) with rope hadronization mechanism in Fig. 1. One can observe that the p_T spectra becomes harder with an increase in multiplicity as observed in data measured by the ALICE experiment. It is also important to note that the hardening is conspicuous for higher mass particles. This feature is consistent with the onset of collectivity in heavy ion collisions. However, it is important to note that the hardening of the spectra as well the hardening becoming more for massive particles is well reproduced by rope hadronization mechanism where the formation of plasma or collectivity is not assumed. The rate of hardening for various multiplicity classes can be compared by estimating the mean p_T ($\langle p_T \rangle$) as a function of multiplicity. Figure 2 compares the $\langle p_T \rangle$ of K^0_S and Ω^- as measured by ALICE experiment with the predictions of PYTHIA8 with (and without) rope hadronization. The estimations for Λ and Ξ is also shown. It is worth noting that the evolution of mean $\langle p_T \rangle$ of strange hadrons with

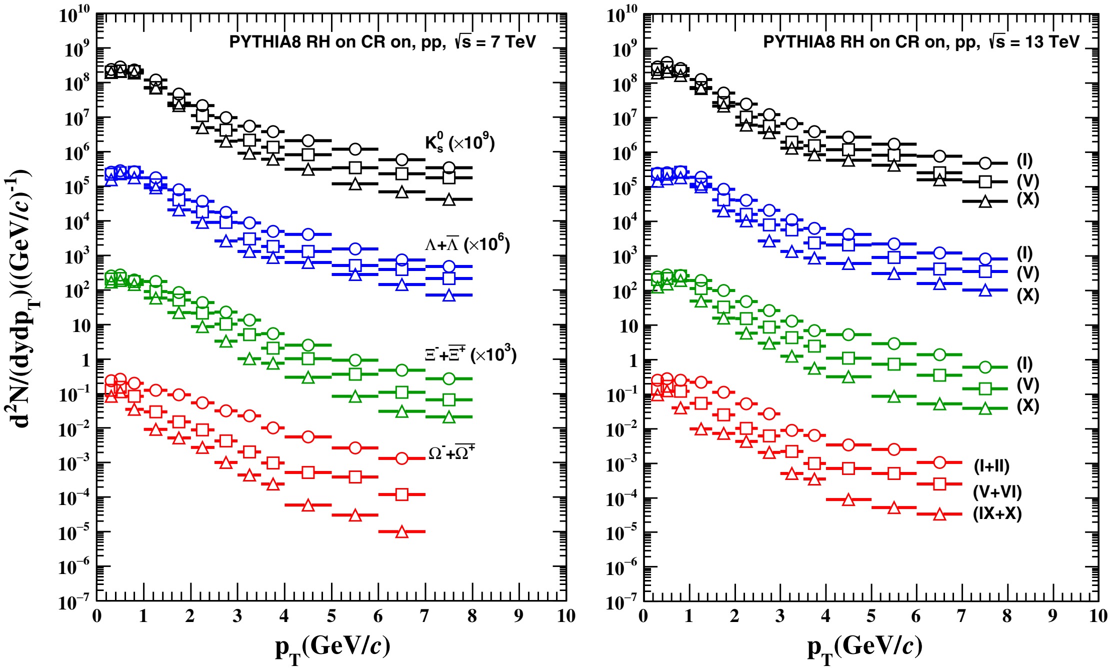

FIG. 1. p_T distribution of strange and multistrange hadrons in p-p collisions at 7 TeV (left panel) and 13 TeV (right panel) for $|y| < 0.5$ generated with PYTHIA8 generator. The distribution are shown with QCD-based color reconnection scheme within the framework of rope hadronization. The open circles, squares and triangles correspond to different multiplicity classes as given in Table I.

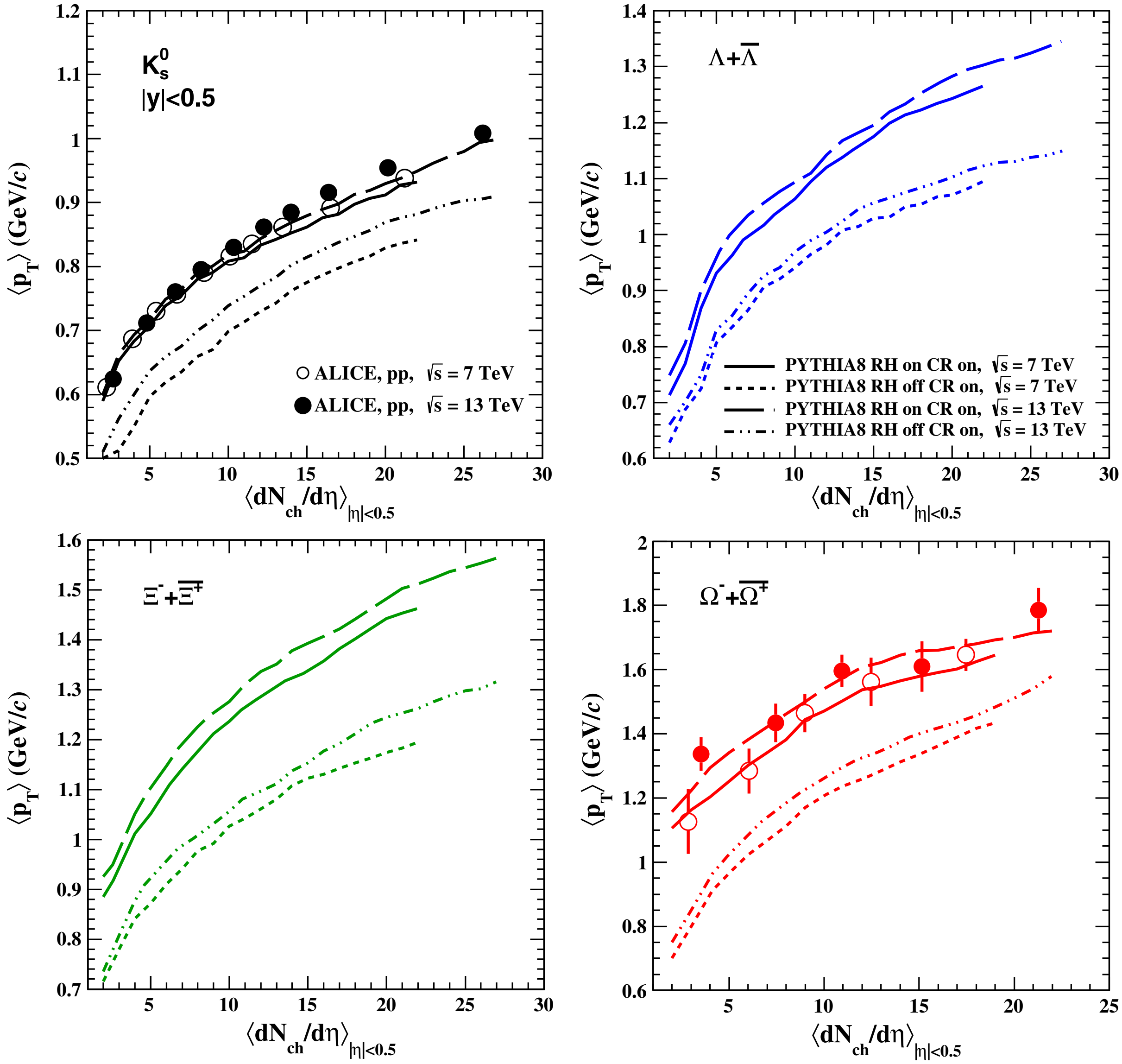

FIG. 2. $\langle p_T \rangle$ as a function of multiplicity ($\langle dN_{ch}/d\eta \rangle$) for strange hadrons predicted by PYTHIA8 with and without rope hadronisation in p-p collisions at $\sqrt{s} = 7$ TeV and 13 TeV. The PYTHIA8 estimations at $\sqrt{s} = 7$ TeV and 13 TeV are also compared to the available data as measured by the ALICE experiment [24].

event multiplicity is well reproduced by rope hadronization for both 7 TeV and 13 TeV. The PYTHIA8 tune where there is no formation of color ropes do not describe the evolution satisfactorily and the discrepancy becomes more for strange hadrons with higher mass.

The enhanced production of strange hadrons is quantified by measuring the ratio of strange hadron yield with respect to the yield of pion (nonstrange particle) in the same acceptance. Figure 3 compares the enhancement of strange and multistrange hadrons as a function of multiplicity as measured by ALICE experiment to the values obtained with PYTHIA8 generator. As can be seen in the figure, the mechanism of rope hadronization (with color reconnections) in PYTHIA8 describes the observed experimental strangeness enhancement in p-p collisions at $\sqrt{s} = 7$ TeV while the estimations without rope hadronization do not agree. The estimations with rope hadronization and without color reconnections underestimates the measured data. This indicates that the mechanism of color reconnection is absolutely necessary to describe the enhancement. The QCD based color reconnection mechanism in PYTHIA8 introduced the formation of junction topology which leads to an enhanced production of baryons. This qualitatively explains the enhancement of strange baryons but is not in agreement with that observed in data. The additional mechanism of string overlap (forming ropes) in high multiplicity scenario leading to higher string tension resulted in an enhanced production of strange quarks and diquarks. The formation of ropes leads to an enhanced production of baryons as well as strange particles.

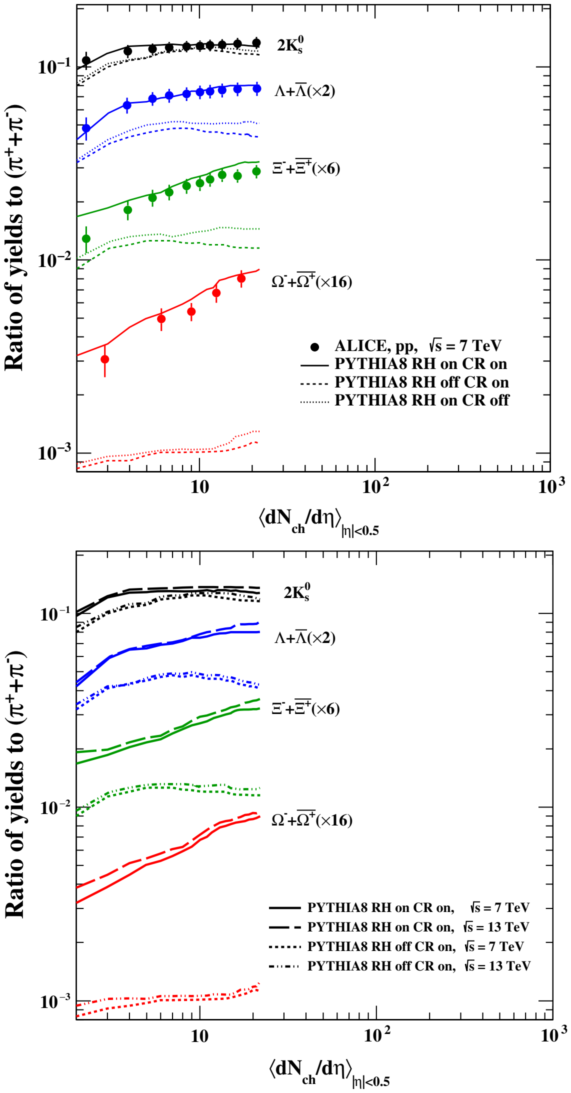

FIG. 3. (Upper panel) Ratio of yield of strange hadrons to pions as a function of $dN_{ch}/d\eta$ for $|\eta| < 0.5$. The solid markers are data as measured by ALICE experiment at LHC [1]. The solid and dotted lines are estimates of PYTHIA8 (with color reconnection) rope hadronization ON and OFF, respectively. The data points and the PYTHIA8 predictions are suitably scaled for visibility. (Lower panel) The PYTHIA8 estimates of the ratio for p-p collisions at $\sqrt{s} = 13$ TeV compared to 7 TeV.

The combined effect of formation of ropes and color reconnection is able to describe the observed trend in data. A similar result where the charged particle multiplicity was measured in the forward region with rope hadronization mechanism can be found here [9]. The predicted enhancement for p-p collisions at $\sqrt{s} = 13$ TeV and its comparison with 7 TeV is shown in the lower panel of Fig. 3. There is no significant difference in enhancement obtained for 13 TeV for similar multiplicity classes. In a previous study, it was shown that the yield ratio, Λ/K_S^0, did not vary much as a function of multiplicity for p-p collisions at $\sqrt{s} = 7$ TeV [1] and the observation was not explained by PYTHIA8 predictions. However, one observes that the variation of ratio, Λ/K_S^0, with multiplicity is described well when one incorporates the mechanism of rope formation as shown in Fig. 4. The observation also indicated that the observed strangeness enhancement is not due to the hadronic mass or specie of the particle but can be attributed to enhanced production of strange particles due to possible formation of color ropes. The enhancement was further investigated by comparing the multiplicity dependence of the integrated yields of strange hadrons (K_S^0, Λ, Ξ^- and Ω^-) in p-p collisions at $\sqrt{s} = 7$ TeV and 13 TeV. The PYTHIA8 predictions are compared to the available data in Fig. 5. One observes that the mechanism of rope hadronization (with color reconnection) essentially captures the evolution of enhancement with multiplicity and the estimates are in good agreement with the data. One can also conclude that the enhancement is driven by the event activity rather than the variation in center of mass energies. It can be seen that the evolution of integrated yield with $\langle dN_{ch}/d\eta\rangle$ for K_S^0 can be described without the formation of ropes while the same is not predicted for strange baryons. However, there is a good agreement with the data (within the experimental errors) when one includes the rope hadronization scenario. This study shows that the mechanism of rope hadronization within the framework of QCD-based color reconnection model describes the essential features of strangeness enhancement in p-p collisions without assuming the formation of a thermalized plasma as predicted in Refs. [19,20]. However, one needs to extend this study to heavy flavors, higher mass resonance particles etc to see observable effects of the mechanism of color reconnection and rope hadronization.

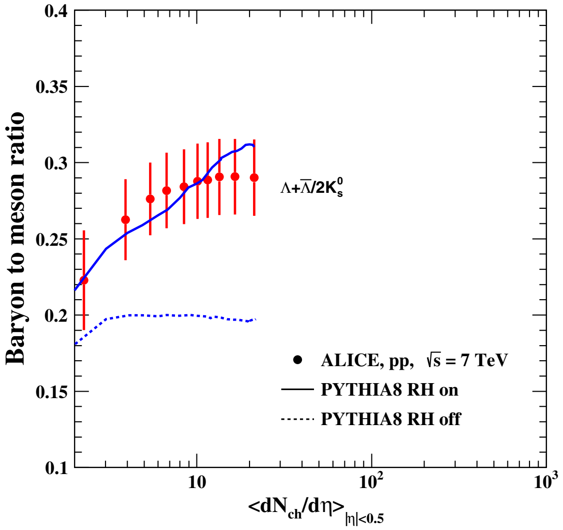

FIG. 4. Λ/K_s^0 ratio as a function of $\langle dN_{ch}/d\eta\rangle$.

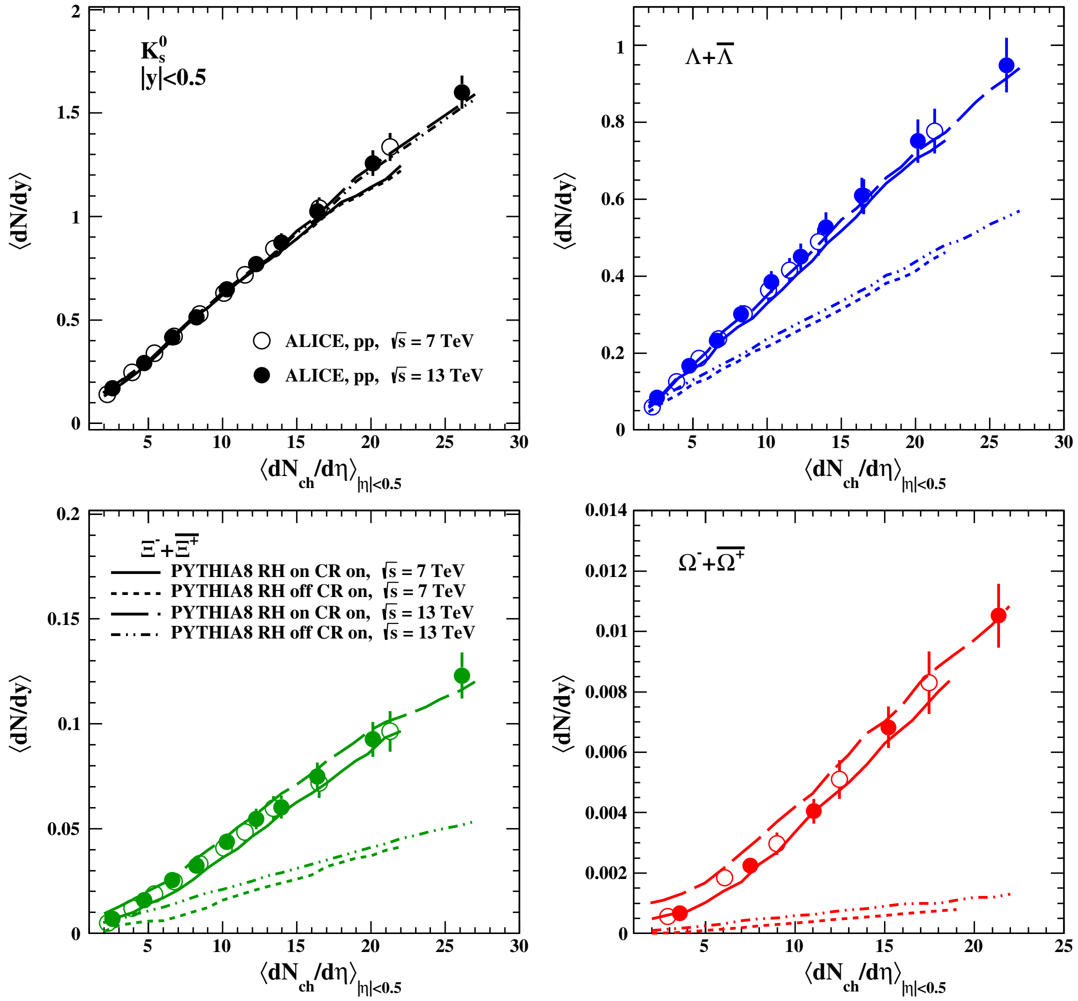

FIG. 5. The PYTHIA8 predictions of p_T integrated yields for K_S^0, $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$ as a function of $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$ using rope hadronization. The estimations are also compared to the data measured by the ALICE experiment at LHC [24].

V. SUMMARY

The recent observation of enhanced production of strange and multistrange hadrons in *p*-*p* collisions at $\sqrt{s} = 7$ TeV and 13 TeV as measured by ALICE experiment is well described by the microscopic model of rope hadronization implemented in PYTHIA8. The p_T spectra of the strange hadrons (K_S^0, $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \Omega^+$) for different multiplicity classes were observed to harden with an increase in multiplicity and the hardening was conspicuous for particles with higher mass. This was further investigated by studying the multiplicity dependence of $\langle p_T\rangle$ and $\langle dN/dy\rangle$ of the strange hadrons. The evolution of these observables was nicely described by the combined effect of mechanism of rope hadronization and QCD-based color reconnection. The predictions without either of these mechanisms did not describe the data. The rope hadronization which do not assume the formation of any thermalized plasma state also described the strangeness enhancement (which is quantified by the ratio of strange hadrons to pions) observed in data for *p*-*p* collisions at $\sqrt{s} = 7$ TeV and 13 TeV. The observed strangeness enhancement seems to saturate at higher multiplicities for both the collision energies. It will be interesting to observe the application of rope hadronization mechanism to other particle production scenarios involving higher mass particles such as heavy flavor hadrons and resonance particles to obtain a clear understanding of this effect.

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