Event Shape Engineering and Multiplicity dependent Study of Identified Particle Production in proton+proton Collisions at √s = 13 TeV using PYTHIA

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(Dated: November 13, 2018)

Small system collectivity observed at the LHC energies along with enhancement of strangeness makes high-multiplicity proton+proton collisions very interesting in order to look for QGP-like features, usually found in heavy-ion collisions. It may be interesting to perform a double differential study of different observables in pp collisions in terms of charged particle multiplicity and event shape in order to understand the new dimensions in high-multiplicity pp physics. We study the correlation between the number of multi-partonic interactions (nMPI), event shape (transverse spherocity) and charged particle multiplicity classes. For the first time, we report the simulation results on the spherocity and multiplicity dependent study of (π^+ + π^-), (K^+ + K^-), (p+̄p), K^0, φ and (Λ + ̅Λ) production in pp collisions at √s = 13 TeV using PYTHIA 8. We explore the event shape dependence of the transverse momentum (p_T) spectra, integrated yield, mean transverse momentum (⟨p_T⟩) and particle ratios of the identified particles. A clear spherocity dependence of p_T-spectra is observed for all the particles. The p_T-crossing point of the ratios of jetty and isotropic events to the spherocity-integrated ones, depend on the multiplicity classes. The p_T-differential particle ratio to (π^+ + π^-) for K^0, φ and (Λ + ̅Λ) depends on the spherocity. For (π^+ + π^-), (K^+ + K^-) and (p+̄p), p_T depends on spherocity while for other particles, ⟨p_T⟩ does not depend on spherocity. The p/φ ratio at low-p_T shows a weak p_T dependence for high-multiplicity isotropic events, which is a hydrodynamic-like behavior. Larger dependence of integrated yield on spherocity is observed for high multiplicity compared to the low multiplicity pp collisions. However, the p_T-integrated particle ratio shows less dependence on spherocity which suggests that, the relative increase in integrated yield for different particles as a function of spherocity are similar.

PACS numbers: 13.85.Ni,12.38.Mh, 25.75.Nq, 25.75.Dw

I. INTRODUCTION

Recent multiplicity dependent measurements of identified particle production from the experiments at the Large Hadron Collider (LHC) [1] have revealed QGP-like behavior in high multiplicity proton+proton (pp) collisions, which raise concerns whether pp collisions can be used as a proper benchmark for comparison with heavy-ion results to understand the formation of a medium with high temperature/energy density. Such behaviours have important consequences in understanding the data from heavy-ion collisions at the LHC energies as one should consider the contribution of QGP-like effects in small systems. The origin of these effects needs proper investigation as it has been shown from hydro calculations [2, 3], where a hot and dense QCD medium is implicitly assumed, can describe many features of experimental data. However, this also can be achieved from initial state effects [4, 5]. Similarly, PYTHIA 8 [6] seems to reproduce collectivity-like features in pp collisions, which are attributed to the multi-parton interactions (MPI) [7] and color reconnection (CR) [8] mechanisms. Because of the composite nature of protons, it is possible to have events with multiple parton-parton interactions (MPI) in a single pp collision. This process is one of the key ingredients in PYTHIA [9] and it is well supported by experimental data in pp collisions [10, 11]. The linear increase of J/ψ production [12] at the forward rapidities in pp collisions at the LHC is very well explained through the MPI and CR mechanisms in PYTHIA 8 [13]. The parameters for MPI are usually tuned by looking at the observables like charged particle multiplicity, transverse momentum (p_T) and their correlations. But, this approach excludes many details of pp interactions, which leads to failure of describing different observables like the strange particle production [14, 15] and jet production rate [16] as a function of the event multiplicity. Thus, one should look into new observables which will help to understand the component of hadronic interactions, hard (pQCD) or the soft, which fails to be described by theory, eventually causing overall disagreements. From Pythia 8.180 onwards, the color-reconnection (CR) mechanism is implemented which explains flow-like patterns in pp collisions [8]. This pattern increases with the number of MPI and the average MPI increases with event-multiplicity but it saturates for high-multiplicity [8, 17, 18]. Event shape observables allow the possibility to separate the high and low number of MPI events to isolate the behavior of particles inside jets (hard processes) and that pertaining to the bulk (soft processes).

Event shape studies at the LHC [16] allows to extract more informations from the data by separating the jetty (high p_T-jets) and isotropic events (low-Q^2 partonic scatterings). Event generators reported in Ref. [16] overestimate the contribution of events with back-to-back jet structure while underestimates the contribution of...
isotropic events at high multiplicity. This suggests that the average measurements do not contain enough information and proper care is needed while extracting physics from models/event generators. To understand the influence of multi-partonic interactions on the final state in pp collisions, the study of event shape has to be performed in data and models as well. It has been reported that in the transverse sphericity event classes, the number of multi-partonic interactions (nMPI) distributions are narrower compared to that of without any selection of the event shape [18]. This result can help to understand more on the jet production, identified particle ratios (baryon to meson and strange to non-strange) and the steep rise of mean transverse-momenta of charged particles in small systems. A comprehensive differential study using event shapes would reveal interesting features, which could be exploited to get physical information as well as to improve models in the MC event generators. In Ref. [19], the preliminary results from ALICE in pp collisions at \( \sqrt{s} = 13 \) TeV as a function of event shape and multiplicity are compared with event generators such as PYTHIA 8 and EPOS-LHC. The event generators seem to describe the data qualitatively.

In this paper, we perform a comprehensive double differential (event shape and multiplicity) study of identified particle production in terms of \( p_T \)-spectra, integrated yield, mean \( p_T \) and the \( p_T \)-differential and \( p_T \)-integrated particle ratios. We also explore the dependence of event shape and charged particle multiplicity to the multi-partonic interactions in pp collisions.

This article is organized as follows. We start with the complete description of the event generation in PYTHIA 8 and the analysis methodology in Section II. The correlation of MPI, event-multiplicity and transverse sphericity are described in Section III. In the Section IV, we report and discuss the results such as the \( p_T \)-spectra, integrated yield, mean \( p_T \) and the particle ratios for identified particles. Finally, we conclude with summary in the Section V.

II. EVENT GENERATION AND ANALYSIS METHODOLOGY

PYTHIA is an event generator used to simulate ultrarelativistic collision events at high energies among the elementary particles like \( e^\pm, p, \) and \( \bar{p} \). It is incorporated with many models and theory relevant in physics like hard and soft interactions, parton distributions, initial- and final-state parton showers, multipartonic interactions, fragmentation, color reconnection and decay [9].

In our present study, we have used PYTHIA 8.235, an advanced version of PYTHIA 6 which includes the multi-partonic interaction (MPI) scenario as one of the key improvements. In PYTHIA, MPI scenario is crucial to explain the underlying events, multiplicity distributions and flow-like patterns in terms of color reconnection. The detailed explanation of the physics processes in PYTHIA 8.235 can be found in Ref. [20]. We have implemented the inelastic, non-diffractive component of the total cross section for all hard QCD processes (HardQCD = all = on). This analysis is carried out with 250 million events at \( \sqrt{s} = 13 \) TeV with Monash 2013 Tune (Tune:14) [21] and MPI based scheme of color reconnection (ColorReconnection:mode(0)). For the generated events, the hadron level decay is switched off (Hadron-Level:Decay = off). The event selection criteria throughout the analysis is such that only those events were chosen which have at-least 5 tracks (charged particles). Charged particle multiplicities (\( N_{ch} \)) have been chosen in the acceptance of V0 detector in ALICE at the LHC with pseudo-rapidity coverage of V0A (\( 2.8 < \eta < 5.1 \)) and V0C (\( -3.7 < \eta < -1.7 \)) [22]. These events are categorized in ten V0 multiplicity (V0M) bins and we define V0M-I as the top 10 percent of events and V0M-X as the lowest 10 percent of events. The number of charged particle multiplicities in each event in different V0M classes are listed in Table I. The minimum bias events are those events where no selection on charged particle multiplicity is applied. To disentangle the jetty and isotropic events from the average-shaped events, we have applied sphericity (defined in next section) cuts on generated events. In this analysis the sphericity distributions are selected in the pseudo-rapidity range of \( |\eta| < 0.8 \) with a minimum constraint of 5 charged particles with \( p_T > 0.15 \) GeV/c. The jetty events are those having \( 0 \leq S_0 < 0.28 \) with lowest 20 percent and the isotropic events are those having \( 0.63 < S_0 \leq 1 \) with highest 20 percent of the total events [19].

| V0M class | I | II | III | IV | V | VI | VII | VIII | IX | X |
|-----------|---|----|-----|----|---|----|-----|------|----|---|
| \( N_{ch} \) | 39-115 | 30-38 | 25-29 | 21-24 | 18-20 | 15-17 | 12-14 | 9-11 | 4-8 | 0-3 |
III. TRANSVERSE SPHEROCITY, MULTI-PARTONIC INTERACTIONS AND CHARGED PARTICLE MULTIPLICITY

Transverse spherocity for an event is defined for a unit vector \( \hat{n}(n_T, 0) \) which minimizes the following ratio [17, 18, 23]:

\[
S_0 = \frac{\pi^2}{4} \left( \frac{\sum_i \vec{p}_{T_i} \times \hat{n}}{\sum_i p_{T_i}} \right)^2.
\] (1)

By restricting it to transverse plane, spherocity becomes infrared and collinear safe [24]. By construction, the extreme limits of spherocity are related to specific configurations of events in transverse plane. The limit of spherocity is in between 0 to 1. Spherocity becoming 0 would mean that the events are pencil-like (back to back structure) while 1 would mean the events are isotropic. The pencil-like events are hard events while the isotropic events are the result of soft processes. Figure 1 depicts the jetty and isotropic events in the transverse plane.

Upper (Lower) panel of fig. 2 shows the correlation between the spherocity (nMPI) with charged particle multiplicity. A clear charged particle multiplicity dependence of spherocity and nMPI distributions is observed. As we move from low to high multiplicity events, the peak of the spherocity distribution shifts towards right. This indicates that the high multiplicity pp collisions are dominated by isotropic events while the low multiplicity events are dominated by the jetty ones. The nMPI distributions suggest that large number of multi-partonic interactions occur for high multiplicity pp collisions. From fig. 2 one observes that the width of the nMPI distribution increases from lower to higher multiplicity classes making it squat, whereas the height goes down. For all multiplicity classes the distribution seems to be positively skewed. For a given class of multiplicity, as nMPI follows a distribution and towards high-multiplicity it shows a saturation behaviour [18], event multiplicity and nMPI can’t be used uniquely to classify events in pp collisions. We observe larger number of average nMPIs for isotropic events than the jetty events. It is evident from event shape analysis that spherocity along with the charged particle multiplicity (which is correlated with nMPI) should be preferred for a better selectivity of events. We use the spherocity distribution shown in fig. 2 to make a clear distinction between isotropic and jetty events. Further combining spherocity with event multiplicity, we study various observables as discussed in the following section to understand the dynamics of particle production in pp collisions at \( \sqrt{s} = 13 \) TeV.

IV. RESULTS AND DISCUSSION

As discussed in the previous section, we use spherocity as a tool to distinguish the isotropic and jetty events for each multiplicity class. We study the \( p_T \)-spectra, integrated yield, mean transverse momentum for \((\pi^+ + \pi^-), (K^+ + K^-), K^{*0}, (p + \bar{p}), \phi, (\Lambda + \bar{\Lambda})\) as a function of spherocity and charged particle multiplicity. We also study the \( p_T \)-differential and \( p_T \)-integrated particle ratios to \((\pi^+ + \pi^-)\) and \((K^+ + K^-)\) and \((p + \bar{p})\) to \(\phi\) ratio as a function of spherocity for high multiplicity pp collisions. From here onwards, \((\pi^+ + \pi^-), (K^+ + K^-), (p + \bar{p})\) and \((\Lambda + \bar{\Lambda})\) are denoted as pion (\(\pi\)), kaon (K), proton (p) and \(\Lambda\), respectively.

A. \( p_T \)-spectra

Figure. 3 shows the \( p_T \)-spectra for pion, kaon, \( K^{*0} \), proton, \(\phi\) and \(\Lambda\) at mid-rapidity \((|\eta| < 0.5)\) for different multiplicity classes in pp collisions at \( \sqrt{s} = 13 \) TeV. We observe a clear multiplicity dependence of the spectral...
shapes. As we move from low to high charged particle multiplicity, we observe hardening of $p_T$-spectra while the bulk production is similar for all the multiplicity classes. This trend is similar to that in experimental data from ALICE [25] for multiplicity dependence study in pp collisions at $\sqrt{s} = 7$ TeV.

Left panel of Fig. 4 shows the spherocity dependence of $p_T$-spectra of identified particles for minimum bias pp collisions. The right panel shows the ratio of $p_T$-spectra for isotropic and jetty events to the spherocity integrated events. We observe the crossing of the ratios for pions, kaons and protons at around 3 GeV/c while for other particles we do not observe the crossing of ratios till 9 GeV/c. This suggests that for minimum bias pp collisions, the production of pions, kaons and protons at low $p_T$ are dominated by isotropic events while after 3 GeV/c, the production is dominated by jetty events. For resonances ($K^{*0}$ and $\phi$) and $\Lambda$, the production is dominated by isotropic events till 9 GeV/c, which indicate different production mechanisms for resonances compared to stable particles.

Figure 5 shows the ratio of $p_T$-spectra for isotropic and jetty events to the spherocity integrated events for V0M-I (left) and V0M-X (right) multiplicity classes. To see the effect of multiplicity on the crossing point of jetty and isotropic events, we have taken the lowest (V0M-X) and the highest (V0M-I) multiplicity classes for a comparison. For stable particles like, $\pi$, $K$ and $p$, the crossing point moves towards high-$p_T$, while going from low ($\sim 1$ GeV/c) to high multiplicity classes ($\sim 3$ GeV/c). This indicates that particle production in high-multiplicity collisions are dominated by isotropic events whereas in low multiplicity it is dominated by jetty events. The preliminary results from ALICE [19] shows a mass dependence of the crossing points for high multiplicity pp collisions which could be attributed to flow-like behavior. Although the color reconnection in PYTHIA mimics a flow-like behavior [8], we do not observe mass dependence of crossing points with the default color reconnection setting. Contrary to the results from minimum bias pp collisions, we observe crossing points for resonances and $\Lambda$ for both V0M-I and V0M-X classes. For high multiplicity pp collisions, the crossing point is around 6 GeV/c while for low multiplicity pp collisions, we could not observe the crossing point due to limited statistics.

### B. Integrated yields ($dN/dy$)

Figure 6 shows the dN/dy of pions, kaons, $K^{*0}$, protons, $\phi$, and $\Lambda$ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic, jetty and spherocity integrated events for pp collisions at $\sqrt{s} = 13$ TeV. Pion being the lightest particle, the integrated yield is the maximum compared to other particles. The mass and charged particle multiplicity dependence of integrated yield for spherocity integrated events is similar to the experimental data from ALICE [25] for multiplicity dependence study in pp collisions at $\sqrt{s} = 7$ TeV. As it appears, in low-multiplicity classes, the effect of spherocity is minimal, whereas towards higher-multiplicity classes, it starts playing a role in making a separation of jetty to isotropic events for all identified particles. The contribution to integrated yield is always dominated by the isotropic events but we observe significant contributions from jetty events as well. As we have observed in the top panel of fig. 2, the contribution to dN/dy from jetty events decreases with charged particle multiplicity. The bottom panel of fig 6 shows the spherocity integrated-scaled yield as a function of minimum-bias-scaled charged particle multiplicity. Slowly towards higher multiplicity classes, a clear separation of jetty to isotropic events is observed. The separation however is the highest for the lightest meson, $\pi$. The values of integrated yield of identified particles for different multiplicity classes in isotropic, jetty and spherocity integrated events are tabulated in Table II.
FIG. 4: (Color online) Left Panel: $p_t$-spectra for pion, kaon, $K^{+0}$, proton, $\phi$, and $\Lambda$ for minimum bias pp collisions as a function of spherocity. The blue squares are for isotropic events and red triangles are for jetty events and open circles are for $S_0$ integrated events. Right Panel: Ratio of $p_t$-spectra for isotropic and jetty events to the spherocity integrated events for V0M-I (left) and V0M-X (right) multiplicity class. The blue squares are for isotropic events and red triangles are for jetty events.

FIG. 5: (Color online) Ratio of $p_t$-spectra for isotropic and jetty events to the spherocity integrated events for V0M-I (left) and V0M-X (right) multiplicity class. The blue squares are for isotropic events and red triangles are for jetty events.
For low multiplicity classes, we do not observe spherocity dependence on charged particle multiplicity for isotropic (blue squares), jetty (red triangles) and spherocity integrated (open circles) events. The trend of particle ratios involving $K^\ast_0$ and spherocity integrated events. The trend of particle ratios involving $K^\ast_0$ and spherocity integrated events.

Figure 8 shows the $p_T$-differential particle ratio to pions for high multiplicity pp collisions in isotropic, jetty and spherocity integrated events. The trend of particle ratios involving $K^\ast_0$ and $\phi$ for $S_0$-integrated events are similar to that of experimental data in pp collisions at $\sqrt{s} = 13$ TeV [26]. The kaon to pion and proton to pion ratios seem to be independent of spherocity classes but we observe a clear spherocity dependence of $K^\ast_0$.

C. Mean Transverse Momentum ($\langle p_T \rangle$)

The $\langle p_T \rangle$ of pions, kaons, $K^\ast_0$, protons, $\phi$, and $\Lambda$ at mid-rapidity ($|\eta| < 0.5$) as a function of charged particle multiplicity for isotropic, jetty and spherocity integrated events are shown in fig. 7. The obtained $\langle p_T \rangle$ for all multiplicity classes in different spherocity events are tabulated in Table III for all the measured particle species. For low multiplicity classes, we do not observe spherocity dependence which indicate that the $\langle p_T \rangle$ from isotropic and jetty events are similar to average event-shape. However, for high multiplicity pp collisions spherocity dependence on $\langle p_T \rangle$ is observed for pions, kaons, protons and $\Lambda$. This is one of the reasons that one should use spherocity as a selective parameter along with the charged particle multiplicity. We do not observe the spherocity dependence for resonances for all charged particle multiplicity classes.

After studying these observables in details, let us now focus on the highest multiplicity class, which is of special importance to us, for understanding the spherocity dependent $p_T$-differential particle ratios.

D. Particle Ratios
\[ \frac{K^0}{\phi} \text{ and } \Lambda \text{ to pion ratio as a function of } p_T. \] At low-\( p_T \), the dependence on spherocity is negligible for all identified particles. However, at high-\( p_T \) the ratios of \( K^0 \) to pions are higher for isotropic events as compared to jetty events. Considering kaon to pion ratio as a measure of strangeness enhancement, although we see a \( p_T \)-dependent strangeness production, this seems to be independent of event spherocity. Further the proton to pion ratio, which is a measure of baryon to meson ratio, is independent of event spherocity. This ratio increases up to \( p_T \sim 3-4 \) GeV/c and then decreases towards higher-\( p_T \) making the high-\( p_T \) domain meson rich. This is similar to the experimental observations [27, 28]. For the ratios of \( K^0 \), \( \phi \) and \( \Lambda \) to pions, the spherocity integrated events show a \( p_T \)-independent behavior after around 2 GeV/c, whereas for isotropic events these ratios show a sharp rise. These observations open up new domain of studies, which may shed light on particle production mechanisms taking event multiplicity, spherocity and \( p_T \)-differential particle ratios.

The \( p_T \)-differential particle ratios to kaons for high multiplicity pp collisions in isotropic, jetty and spherocity integrated events are shown in fig. 9. The proton to kaon ratio seems to be independent of spherocity classes up to \( p_T \sim 9 \) GeV/c. But we observe a clear spherocity dependence of \( K^0 \), \( \phi \) and \( \Lambda \) to kaon ratios as a function of \( p_T \). At low-\( p_T \), the \( K^0 \), \( \phi \) and \( \Lambda \) to kaon ratios are higher for jetty events and also lower for isotropic events compared to the spherocity-integrated events. However, at high \( p_T \) a complete opposite behavior is observed. And this behavior is similar to particle ratio with respect to pions.

Figure 10 shows the \( p_T \)-differential particle ratio of proton to \( \phi \) for minimum bias (left panel) and high multiplicity (right panel) pp collisions in isotropic, jetty and spherocity integrated events. Assuming QGP-like behavior is driven by hydrodynamics, one would expect similar shape of \( p_T \) spectra at low-\( p_T \) for proton and \( \phi \) due to their similar masses [29]. A comparison of \( p/\phi \) ratio in minimum bias and high multiplicity pp collisions shows a flatness at low-\( p_T \) in isotropic events for high-multiplicity pp collisions. This hints to the QGP-like behavior in high multiplicity pp collisions. It is worth noticing that at low-\( p_T \) the \( p/\phi \) ratio for isotropic events are more flatter compared the \( S_0 \)-integrated ones. This leads to an interesting finding that while comparing the experimental \( p/\phi \) ratio from high multiplicity pp collisions to the heavy-ion data [30], one should separate jetty events from all the events.

To have a direct comparison to experimental measurements, let us now consider the \( p_T \)-integrated particle ratios with respect to pions and kaons as a function of spherocity classes and charged particle multiplicity. Upper (lower) panel of fig. 11 shows \( p_T \)-integrated particle ratio to pions (kaons) for high multiplicity pp collisions in isotropic, jetty and spherocity integrated events. Although, we observe significant spherocity dependence of integrated yield of different particles (fig. 6), we do not observe any large dependence of \( p_T \)-integrated particle ratios to pions and kaons. This suggests that the relative increase in integrated yield for different particles as a function of spherocity are similar, while indicating that the domain of transverse momentum is very crucial for the nature of particle production. As expected, the ratios of particles with respect to lighter mass particle seem to increase with charged particle multiplicity. The slight increasing trend of \( K/\pi \), \( K^{*0}/\pi \) and \( \Lambda/\pi \) suggests strangeness enhancement in high multiplicity pp collisions [1]. The trend of \( p_T \)-integrated particle ratios for \( \phi \) to \( \pi \) and \( \phi \) to K in \( S_0 \)-integrated events is similar to that of experimental data in pp collisions at \( \sqrt{s} = 13 \) TeV [31]. Due to possible re-scattering effects, the experimental data for \( K^{*0}/K \) decreases with charged particle multiplicity [31]. But we do not observe the same trend, which indicates that PYTHIA fails to explain the possible re-scattering effects. While comparing the upper and lower panel of fig. 11, one can observe that although the spherocity dependence on the particle ratio is not high but the dependence seems to be opposite compared to integrated yield in fig. 6. For all the identified particle ratios to pions and kaons, the contribution from jetty

![Image](image_url)

**FIG. 8.** (Color Online) \( p_T \)-differential particle ratio to pions for high multiplicity pp collisions in isotropic (blue squares), jetty (red triangles) and spherocity integrated (open circles) events.
events are higher compared to the isotropic ones. This leads to the conclusion that while studying the QGP-like behavior in pp collisions, one should separate the jetty events from the total events.

As one can observe throughout the studies discussed here, the resonance particles, namely K*0, \( \phi \) behave differently for all the observables. This hints for further investigation related to the production mechanism of resonances both in pp and heavy-ion collisions.

V. SUMMARY AND CONCLUSION

We have made an extensive study of various observables taking spherocity and event multiplicity in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) using the pQCD inspired PYTHIA 8 model. The aim of the present study is to understand the high-multiplicity pp events at the highest LHC energy in view of a possible formation of QGP-droplet in pp collisions. In view of QGP-like behaviors observed in the LHC pp collisions and the fact that pp no longer serves as a baseline to understand a possible nuclear medium formation in heavy-ion collisions at the LHC energies, it is crucial to understand the mechanism of particle production in these high-multiplicity events. Through these simulation studies, we invoke the explicit inclusion of MPI and CR effects responsible for particle production in pp collisions and then through transverse sphericity and multiplicity dependent analysis we try to understand various aspects of identified particle production in LHC pp collisions. Our findings are summarized as below:

1. We study the correlation between the multipartonic interactions, event shape (transverse sphericity) and charged particle multiplicity.

2. We report the simulation results on the event shape and multiplicity dependent study of \((\pi^+ + \pi^-), (K^+ + K^-), (p+\bar{p}), \text{K}^{*0}, \phi \text{ and } (\Lambda + \bar{\Lambda})\) production in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) using PYTHIA 8.235 for the first time. This could be confronted to experimental data, when become available.

3. We explore the event shape dependence of the transverse momentum \((p_T)\) spectra, integrated yield, mean transverse momentum \((\langle p_T \rangle)\) and particle ratios of the identified particles. A clear spherocity dependence of \(p_T\)-spectra is observed for all the particles.

4. The crossing of the ratios of jetty and isotropic events to the sphericity-integrated ones, depend on the multiplicity classes.

5. \(\langle p_T \rangle\) of \((\pi^+ + \pi^-), (K^+ + K^-)\) and \((p+\bar{p})\) depend on spherocity while for other particles, \(\langle p_T \rangle\) does not depend on spherocity.

6. Contrary to \(\langle p_T \rangle\), the \(p_T\)-differential particle ratios to \((\pi^+ + \pi^-)\) for \(\text{K}^{*0}, \phi \text{ and } (\Lambda + \bar{\Lambda})\) depend on event spherocity while the ratios remain independent for kaons and protons.

7. Weak \(p_T\)-dependence of proton to \(\phi\) ratio at low-\(p_T\) in isotropic high-multiplicity pp events indicates a hydrodynamic behavior. This, along with a signal of strangeness enhancement, hints for QGP-like behavior in high multiplicity pp collisions.

8. Larger dependence of integrated yield on sphericity is observed for high multiplicity compared to the low multiplicity pp collisions. However, the \(p_T\)-integrated particle ratio shows less dependence on sphericity which suggests that, the relative increase in integrated yield for different particles as a function of sphericity are similar.

9. \(\text{K}^{*0}, \phi\)-like resonances showing completely different behavior than the stable particles needs further investigation both in pp and heavy-ion collisions for a better understanding of particle production mechanism.

The present studies in view of the high-multiplicity era of pp collisions at the LHC energies bear high-level of importance in view of a possible QGP-like medium formation in pp collisions, while giving enough differential information about particle production mechanism taking into account event multiplicity, event sphericity, the transverse momentum and multi-partonic interactions. Availability of experimental data in near future
would help us having a better understanding of underlying physics behind the high-multiplicity pp collisions at the LHC energies. In addition, these studies should help in fine-tuning the pQCD based event generators, while comparing similar findings in experimental data.

Acknowledgements

The authors acknowledge the financial supports from ALICE Project No. SR/MF/PS-01/2014-IITI(G) of Department of Science & Technology, Government of India. ST acknowledges the financial support by DST-INSPIRE program of Government of India. The authors gratefully acknowledge the initial discussions with Dr. Antonio Ortiz Velasquez and Dr. Sudipan De. The authors would like to acknowledge the usage of resources of the LHC grid computing facility at VECC, Kolkata.

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FIG. 11: (Color Online) $p_T$-integrated particle ratio to pions (upper panel) and kaons (lower panel) for high multiplicity pp collisions in isotropic (blue squares), jetty (red triangles) and spherocity integrated (open circles) events.

VI. APPENDIX

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TABLE II: Integrated yield of identified particles in isotropic, jetty and $S_0$ integrated events.

| V0M Event Class | $\pi$ | $K$ | $K^{*0}$ | p | $\phi$ | A |
|-----------------|------|-----|--------|---|------|---|
| Jetty I         | 4.416 | 1.006 | 0.618 | 0.552 | 0.077 | 0.138 |
| Isotropic I     | 6.651 | 1.491 | 0.752 | 0.775 | 0.092 | 0.165 |
| $S_0$ integrated I | 5.988 | 1.348 | 0.712 | 0.710 | 0.087 | 0.157 |
| Jetty II        | 3.417 | 0.773 | 0.458 | 0.428 | 0.055 | 0.104 |
| Isotropic II    | 4.878 | 1.084 | 0.525 | 0.562 | 0.063 | 0.114 |
| $S_0$ integrated II | 4.312 | 0.962 | 0.498 | 0.511 | 0.060 | 0.110 |
| Jetty III       | 3.012 | 0.678 | 0.374 | 0.373 | 0.046 | 0.084 |
| Isotropic III   | 4.118 | 0.900 | 0.415 | 0.469 | 0.050 | 0.090 |
| $S_0$ integrated III | 3.633 | 0.803 | 0.397 | 0.427 | 0.048 | 0.087 |
| Jetty IV        | 2.784 | 0.621 | 0.317 | 0.342 | 0.038 | 0.071 |
| Isotropic IV    | 3.056 | 0.790 | 0.344 | 0.410 | 0.040 | 0.075 |
| $S_0$ integrated IV | 2.496 | 0.710 | 0.331 | 0.377 | 0.039 | 0.073 |
| Jetty V         | 2.538 | 0.555 | 0.242 | 0.298 | 0.029 | 0.053 |
| Isotropic V     | 3.120 | 0.656 | 0.252 | 0.337 | 0.029 | 0.054 |
| $S_0$ integrated V | 2.829 | 0.605 | 0.246 | 0.317 | 0.029 | 0.054 |
| Jetty VI        | 2.450 | 0.531 | 0.208 | 0.280 | 0.024 | 0.046 |
| Isotropic VI    | 2.934 | 0.612 | 0.215 | 0.310 | 0.025 | 0.046 |
| $S_0$ integrated VI | 2.687 | 0.569 | 0.211 | 0.294 | 0.024 | 0.046 |
| Jetty VII       | 2.371 | 0.506 | 0.174 | 0.261 | 0.020 | 0.038 |
| Isotropic VII   | 2.773 | 0.569 | 0.179 | 0.282 | 0.020 | 0.037 |
| $S_0$ integrated VII | 2.560 | 0.534 | 0.176 | 0.270 | 0.020 | 0.038 |
| Jetty VIII      | 2.290 | 0.481 | 0.135 | 0.238 | 0.015 | 0.028 |
| Isotropic VIII  | 2.602 | 0.521 | 0.137 | 0.248 | 0.015 | 0.028 |
| $S_0$ integrated VIII | 2.432 | 0.498 | 0.135 | 0.241 | 0.015 | 0.028 |
| Jetty IX        | 2.242 | 0.466 | 0.110 | 0.223 | 0.012 | 0.022 |
| Isotropic IX    | 2.485 | 0.491 | 0.110 | 0.227 | 0.012 | 0.022 |
| $S_0$ integrated IX | 2.351 | 0.477 | 0.109 | 0.222 | 0.012 | 0.022 |
TABLE III: Average transverse momentum of identified particles in GeV/c for isotropic, jetty and $S_0$ integrated events.

| Event Class | $\pi$  | $K$  | $K^*$ | $p$  | $\phi$ | $\Lambda$ |
|-------------|------|------|------|------|-------|----------|
| Jetty       | 1.017| 1.436| 1.265| 1.757| 1.282 | 1.042    |
| Isotropic   | 0.783| 0.933| 0.968| 0.943| 1.765 | 1.368    |
| $S_0$ integrated | 0.786| 0.908| 1.295| 1.039| 1.454 | 1.397    |
| Jetty       | 0.882| 1.022| 1.307| 1.301| 1.408 | 1.179    |
| Isotropic   | 0.744| 0.942| 1.214| 1.090| 1.388 | 1.246    |
| $S_0$ integrated | 0.755| 0.951| 1.226| 1.106| 1.348 | 1.235    |
| Jetty       | 0.824| 1.103| 1.203| 1.294| 1.282 | 1.162    |
| Isotropic   | 0.734| 0.920| 1.194| 1.068| 1.294 | 1.260    |
| $S_0$ integrated | 0.742| 0.939| 1.191| 1.094| 1.293 | 1.257    |
| Jetty       | 0.798| 1.043| 1.181| 1.217| 1.314 | 1.183    |
| Isotropic   | 0.726| 0.899| 1.175| 1.057| 1.298 | 1.218    |
| $S_0$ integrated | 0.731| 0.916| 1.168| 1.077| 1.299 | 1.216    |
| Jetty       | 0.760| 0.974| 1.130| 1.125| 1.198 | 1.163    |
| Isotropic   | 0.707| 0.879| 1.137| 1.026| 1.249 | 1.193    |
| $S_0$ integrated | 0.712| 0.890| 1.130| 1.043| 1.243 | 1.181    |
| Jetty       | 0.713| 0.913| 1.053| 1.047| 1.155 | 1.093    |
| Isotropic   | 0.683| 0.840| 1.082| 0.969| 1.189 | 1.125    |
| $S_0$ integrated | 0.686| 0.852| 1.069| 0.985| 1.176 | 1.112    |
| Jetty       | 0.666| 0.838| 0.965| 0.964| 1.056 | 1.005    |
| Isotropic   | 0.641| 0.777| 0.997| 0.885| 1.089 | 1.033    |
| $S_0$ integrated | 0.645| 0.790| 0.983| 0.905| 1.075 | 1.016    |
| Jetty       | 0.615| 0.760| 0.866| 0.863| 0.948 | 0.892    |
| Isotropic   | 0.584| 0.680| 0.871| 0.769| 0.954 | 0.896    |
| $S_0$ integrated | 0.593| 0.708| 0.865| 0.799| 0.948 | 0.890    |
| Jetty       | 0.578| 0.694| 0.776| 0.787| 0.844 | 0.801    |
| Isotropic   | 0.533| 0.604| 0.746| 0.669| 0.812 | 0.766    |
| $S_0$ integrated | 0.550| 0.638| 0.756| 0.715| 0.820 | 0.777    |
| Jetty       | 0.575| 0.685| 0.754| 0.790| 0.810 | 0.782    |
| Isotropic   | 0.517| 0.575| 0.694| 0.640| 0.750 | 0.714    |
| $S_0$ integrated | 0.542| 0.622| 0.719| 0.705| 0.777 | 0.745    |