

Charged particle production as a function of multiplicity and sphericity in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV

CERN Summer Student Programme 2021

CERN Summer Student Report

Supervisors: Antonio Ortiz Velasquez and Guy Paic

Student: Tatiana Nikolaeva,

Lomonosov Moscow State University

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Abstract

This work presents the results that was obtained during the CERN Summer Student Programme 2021. In order to investigate the event structure of collisions, we conducted an analysis of pp, p-Pb and Pb-Pb collisions with collision energy $\sqrt{s_{\text{NN}}} = 5.02$ TeV covering the kinematic range $|\eta| < 0.8$ and $p_{\text{T}} \geq 0.15$ GeV/ c , $0.15 < p_{\text{T}} \leq 4$ GeV/ c and $4 < p_{\text{T}} \leq 20$ GeV/ c . Sphericity distributions and ratios were obtained for all three types of collisions, considering low, middle and high multiplicity classes. Transverse momentum spectra were investigated for the collisions. The measurement of average transverse momentum of particles as a function of event multiplicity was analyzed taking into account sphericity to characterize the event structure.

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1 Introduction

The currently accepted model of Universe formation is a formation as a result of the Big Bang, where matter existed in a special state of non-confined quarks and gluons, the Quark Gluon Plasma (QGP). Experiments constructed to study this phenomenon are carried out at the largest accelerator complexes at different science centres all over the world, such as CERN.

Collisions of heavy ions at high energies make it possible to study nuclear matter at incredibly high energy densities and temperatures. ALICE experiment at the CERN Large Hadron Collider (LHC) aims at studying the physics of strongly-interacting matter and the properties of QGP. The production of particles in collisions of heavy ions and the properties of QGP are studied experimentally as functions of a large number of variables. These variables include both kinematic quantities (such as transverse momentum p_T) and specific variables of nuclear-nuclear collisions (centrality or event multiplicity) necessary to control the size and shape of the collision area.

The design of ALICE experiment is optimized for reconstruction and particle identification in a wide range of transverse momentum in pp, p-Pb and Pb-Pb collisions at the LHC. The relevant detectors for particle identification in ALICE experiment are Inner Tracking System (ITS), Time Projection Chamber (TPC) and Time Of Flight detector (TOF), they are located in the central barrel of ALICE inside a large solenoidal magnet providing a uniform 0.5 T field.

The features of QGP can be characterized by the measurement of high transverse momentum of the particles produced by hadronisation of hard scattered partons in the early stage of the collision. It is expected that these partons lose energy when interacting with the hot and dense quark matter.

Proton-proton collisions at the LHC energies have shown phenomena, similar to the ones observed in heavy-ion collisions. Exploring these similarities is an important physical goal in programs of heavy-ion collision experiments. Therefore, it is important to study not only p-p collisions, but also p-A and A-A collisions in order to estimate the resemblance of their physical properties. A significant way to investigate this phenomenon is to study the mechanisms of production of events depending on the multiplicity of particles - number of particles in an event. Average transverse momentum $\langle p_T \rangle$ of the charged-particle transverse momentum spectrum and its correlation with the charged-particle multiplicity N_{ch} carries information about the underlying particle production mechanism.

To investigate the structure of events in collisions it is useful to introduce another variable - sphericity S_0 [1], [2], [3]. It is defined for a unit vector $\hat{n}_s$ which minimizes the ratio:

$$S_0 = \frac{\pi^2}{4} \min \left(\frac{\sum_i |\vec{p}_{T,i} \times \hat{n}_s|}{\sum_i p_{T,i}} \right)^2 \quad (1)$$

where the sum runs over all reconstructed ITS-TPC tracks. At least three tracks are required within kinematic cuts in order to achieve a good sphericity resolution. There are some important features of sphericity:

- The lower limit of sphericity ($S_0 \rightarrow 0$) - jetty-like events - corresponds to events where all transverse momentum vectors are (anti)parallel or the sum of the p_T is dominated

by a single track.

- The upper limit of sphericity ($S_0 \rightarrow 1$) - isotropic events - corresponds to events where transverse momentum vectors are isotropically distributed. $S_0 = 1$ can only be reached in the limit of an infinite amount of particles.

Therefore, sphericity is a valuable tool to discriminate between jet-like and isotropic events and therefore, to study the event structure. In this work the of average transverse momentum $\langle p_T \rangle$ of inclusive charged particles as a function of event multiplicity N_{ch} is explored taking into account the event shape characterized by sphericity. The aim of this study is to investigate collective properties of pp, p-Pb and Pb-Pb collisions with energies $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

2 Analysis

The data in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV were collected with the ALICE apparatus in 2013 and 2015, respectively [4].

2.1 Event and Track Selection, Calculation Details

In the current analysis we consider particles in in the kinematic range of pseudorapidity $|\eta| < 0.8$ and of the following transverse momentum:

- $p_T \geq 0.15$ GeV/ c
- $0.15 < p_T \leq 4$ GeV/ c
- $4 < p_T \leq 20$ GeV/ c

Moreover, as it was mentioned in the introduction, at least 3 tracks are required each within kinematic cuts for a good sphericity resolution. For track selection procedure, we consider primary charged particles in the analysis. They are defined as all prompt particles produced in the collision, including decay products (except from weak decays of strange hadrons). For a selection of primary particles, the following cuts have been applied on the track level (in addition to mentioned p_T cuts):

- the detector coverage $|\eta_{\text{lab}}| < 0.8$
- $\text{DCAz} < 2$ cm
- $\text{DCAr} < 0.0182 + 0.035/p_t^{1.01}$ cm
- number of crossed rows in the TPC > 120
- ratio of crossed rows over findable cluster in the TPC > 0.8
- fraction of shared TPC clusters < 0.4
- χ^2 per TPC cluster < 4

- no kinks
- TPC refit required
- ITS refit required
- one hit in the SPD
- χ^2 per ITS cluster < 36
- 5-dim. χ^2 TPC constrained track vs. global track < 36

These cuts are common to pp and Pb–Pb analysis.

For this analysis the data runs which contain the TPC and the ITS information were selected. For each type of collisions we used the following datasets and run lists.

For pp collisions we have analysed ESD data from the period LHC15n pass4, the runs are listed below: 244340, 244542, 244343, 244626, 244351, 244627, 244355, 244628, 244359, 244364, 244416, 244421, 244453, 244456, 244480, 244481, 244482, 244483, 244484, 244531, 244540.

For Pb–Pb we are using the dataset LHC15o pass4 lowIR pidfix cookdedx with the following runlist: 245064, 246391, 246392, 245066, 245068, 246390, 244917, 245068, 244918, 246390, 244975, 246391, 244980, 246392, 244982, 244983, 245061, 245064, 245066.

For p–Pb collisions we are using the dataset LHC13c pass2, the runs are listed below: 195529, 195596, 195531, 195633, 195566, 195635, 195567, 195644, 195568, 195673, 195592, 195675, 195593, 195677.

To investigate the production of events depending on the multiplicity of particles, we divide multiplicity for each type of collisions into multiplicity classes with intervals of approximately 5 particles. For pp collisions we consider 10 multiplicity classes with interval of 5 tracks from 3 to 51 tracks. For Pb–Pb collisions there were 600 multiplicity classes with the same intervals from 3 to 3000 tracks. Finally, for p–Pb collisions we took into account 20 multiplicity classes from 3 to 101 tracks.

2.2 Sphericity distributions

As we already mentioned, sphericity is a valuable tool to discriminate between jet-like and isotropic events and, therefore, to investigate the event structure of collisions. We want to consider sphericity distributions for all three types of collisions: pp, Pb–Pb and p–Pb. Proton-proton collisions were studied earlier [5],[6]. It is also important to consider sphericity distributions for different multiplicity classes to see the dependence on low and high number of tracks in an event.

The comparison of sphericity distributions for all three types of collisions and for kinematic cut of $|\eta| < 0.8$ and $p_T \geq 0.15$ GeV/ c is shown in Fig. 1. It can be seen that for low sphericity values errors for ratios at the bottom panels are too big because of insufficient statistics for low sphericities. Moreover, it is clear from the ratios that with the increase of multiplicity class the similarity of sphericity distributions decrease and ratio varies significantly from 1.

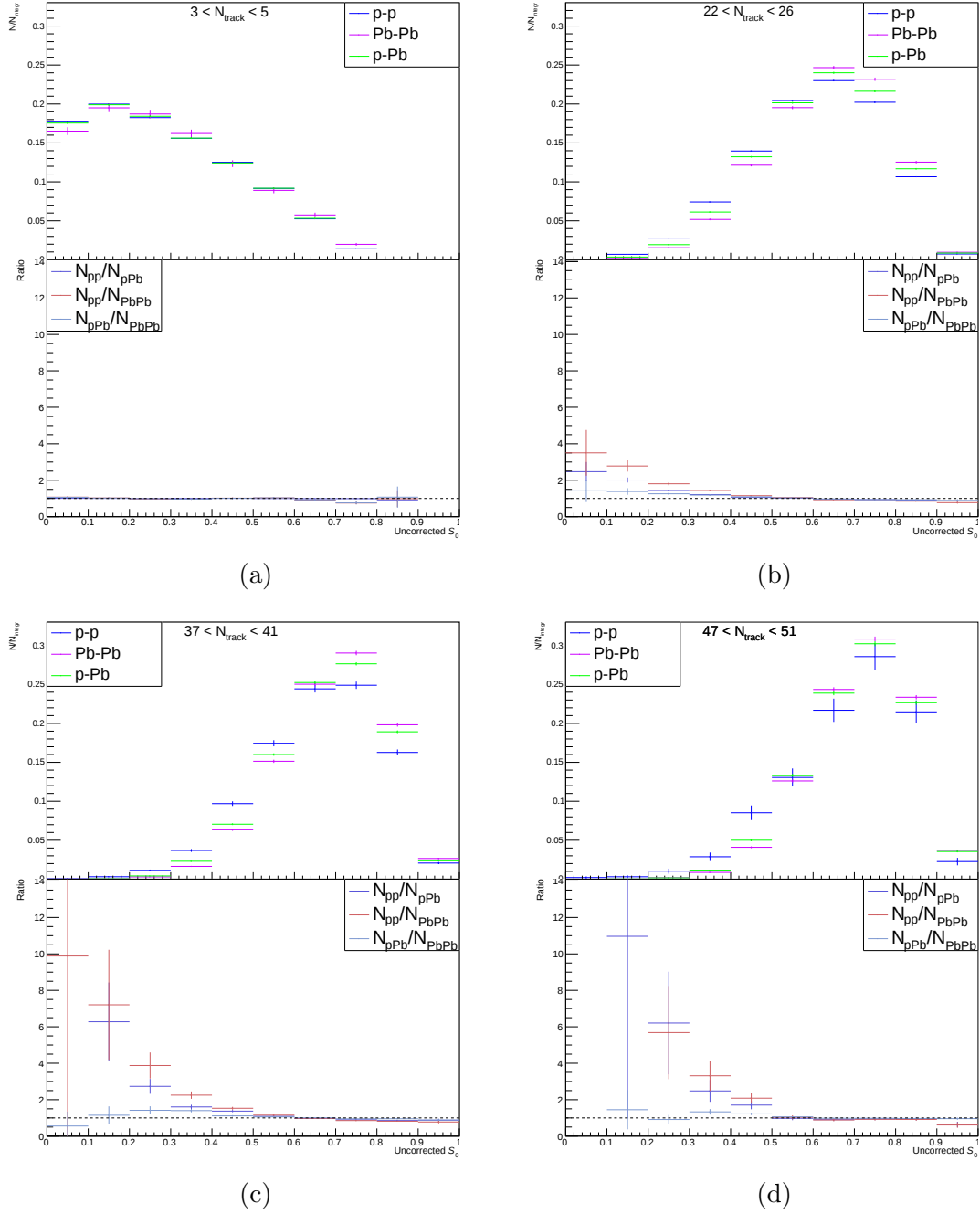


Figure 1: Sphericity distributions and ratios for pp, p-Pb and Pb-Pb collisions for $\sqrt{s_{\text{NN}}} = 5.02$ TeV for low, middle and high multiplicity classes. All sphericities were normalized on the number of events in a given multiplicity class for each collision type. For these distributions the kinematic cut $p_{\text{T}} \geq 0.15$ GeV/c was used.

Next we consider different sets of p_{T} cuts for the sphericity distributions to study soft and hard events of collisions. For $0.15 < p_{\text{T}} \leq 4$ GeV/c the distributions are shown on Fig. 2. It can be seen that there is a significant similarity with the distributions for classical cut

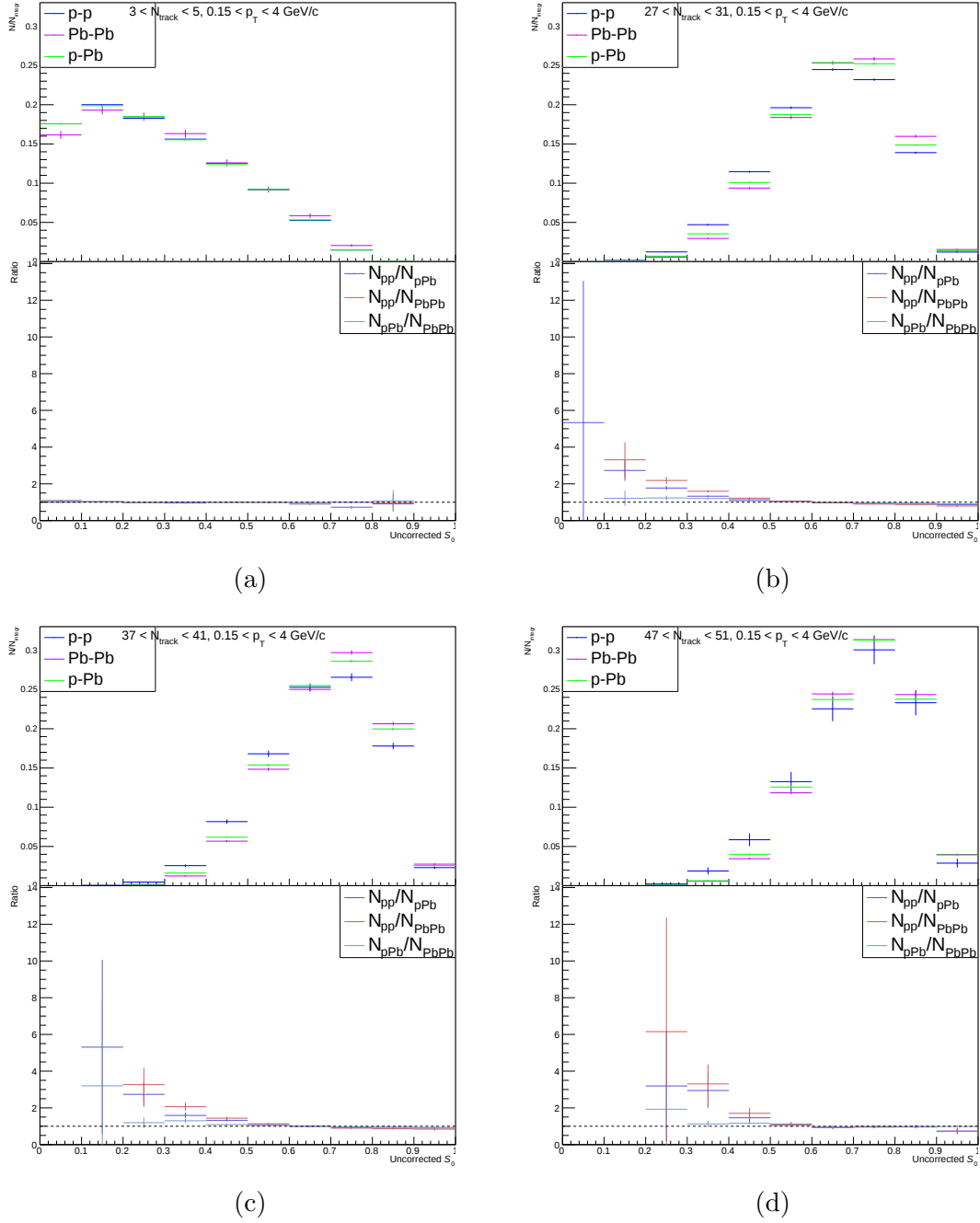


Figure 2: Sphericity distributions and ratios for pp, p-Pb and Pb-Pb collisions for $\sqrt{s_{NN}} = 5.02$ TeV for low, middle and high multiplicity classes. All sphericities were normalized on the number of events in a given multiplicity class for each collision type. For these distributions the kinematic cut $0.15 < p_T \leq 4 \text{ GeV}/c$ was used.

$p_T \geq 0.15 \text{ GeV}/c$.

For harder events with $4 < p_T \leq 20 \text{ GeV}/c$ distributions are shown on Fig. 3. There are only 3 non-zero distributions. It can be seen from the figures that there are huge differences

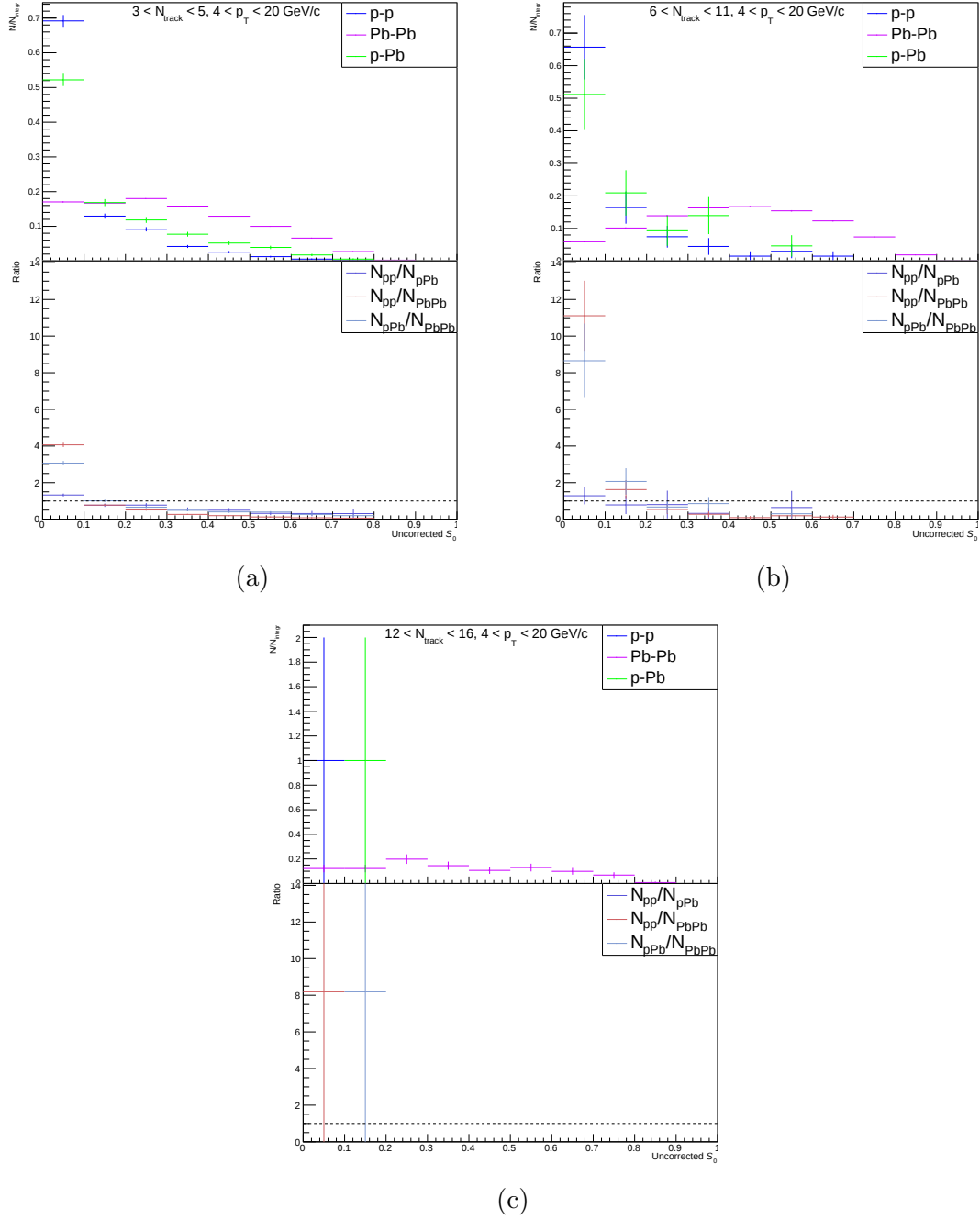


Figure 3: Sphericity distributions and ratios for pp, p-Pb and Pb-Pb collisions for $\sqrt{s_{NN}} = 5.02$ TeV for first 3 multiplicity classes. All sphericities were normalized on the number of events in a given multiplicity class for each collision type. For these distributions the kinematic cut $4 < p_T \leq 20$ GeV/c was used.

of distribution shape for pp and p-Pb collisions. Moreover, for the third multiplicity class there is insufficient number of events for pp and p-Pb collisions for a given data.

2.3 Transverse momentum distributions

Furthermore, it is interesting to compare the properties of jetty-like ($S_0 \rightarrow 0$) and isotropic ($S_0 \rightarrow 1$) events to study the structure of collisions. For this reason below we consider different sphericity classes to compare pp, p-Pb and Pb-Pb data.

We define 10 sphericity classes of events as 10% of full sphericity distribution for an exact multiplicity class. Therefore we count jetty events as 0-10% (low sphericities) of integrated sphericity and isotropic events as 90-100% (high sphericities) for a multiplicity class. An example of such sphericity class division for 3 collision types is shown in Fig. 4.

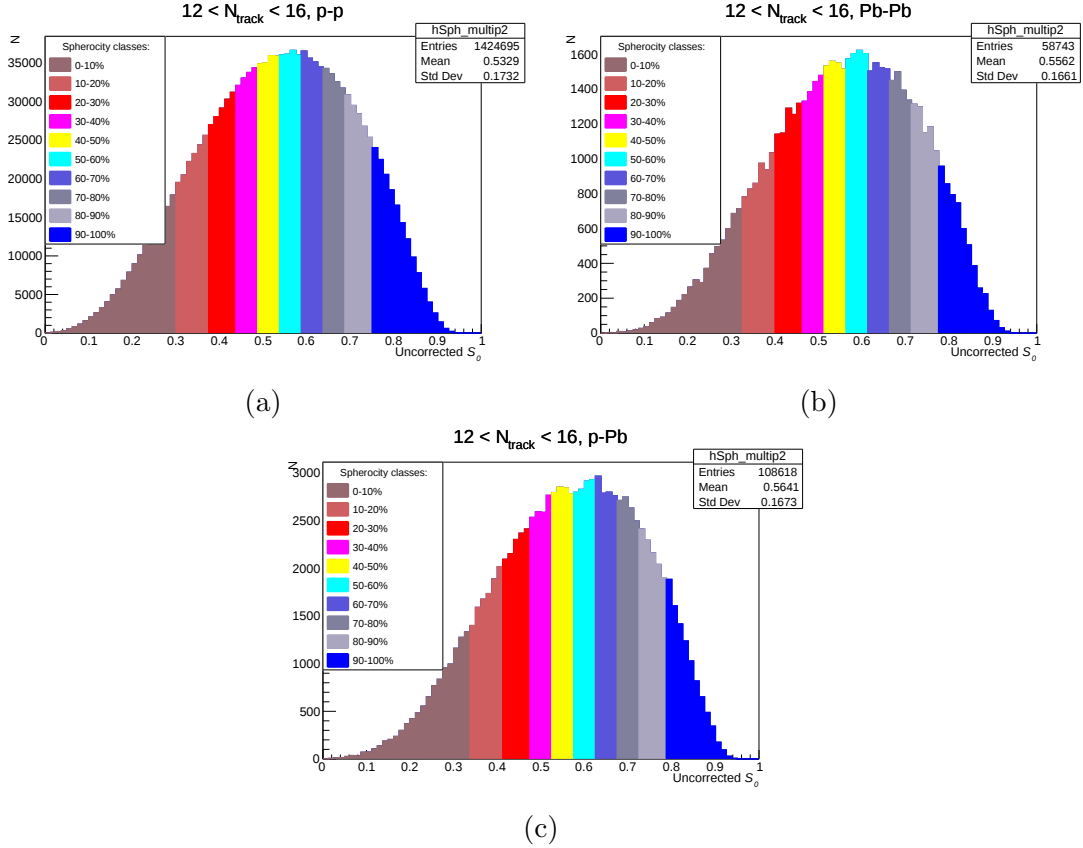


Figure 4: An example of division by sphericity classes in sphericity distributions for pp, p-Pb and Pb-Pb collisions for $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For these distributions the kinematic cut $p_T \geq 0.15$ GeV/c was used.

As it was mentioned in the introduction, the transverse momentum spectrum of charged particles carries information of the dynamics of soft and hard interactions, so we consider p_T distributions for all collisions. The normalized p_T distributions and ratios for pp, p-Pb and Pb-Pb collisions for jetty-like, isotropic and integrated sphericity events are shown on Fig. 5, 6 and 7 respectively.

It can be seen from the graphs that for low p_T region (soft events) the distributions are really close to each other, while for high p_T region (hard events) the differences between pp, p-Pb and Pb-Pb collisions become significant.

Regarding the high p_T cut ($4 < p_T \leq 20$ GeV/c), there are significant differences in transverse momentum distributions, see Fig. 8, 9 and 10. It can be seen that there are not so many events in high p_T region, so the statistics is hard to interpret, especially for isotropic events. The ratios indicate that there are significant differences in p_T distributions for each type of collisions within this kinematic cut.

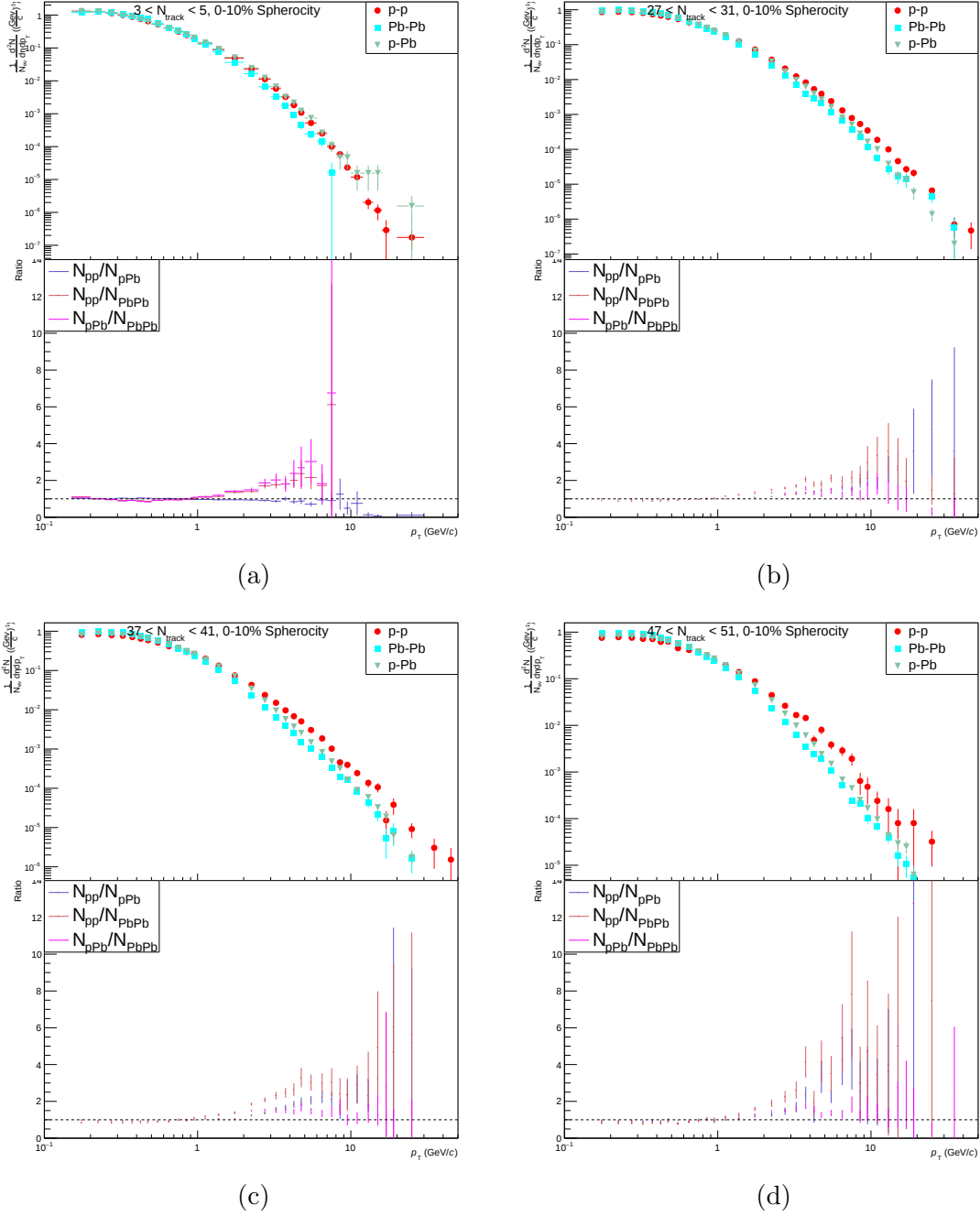


Figure 5: Normalized transverse momentum distributions of particles for low, middle and high multiplicity classes for jetty events at $\sqrt{s_{NN}} = 5.02$ TeV. For these distributions the kinematic cut $p_T \geq 0.15$ GeV/c was used.

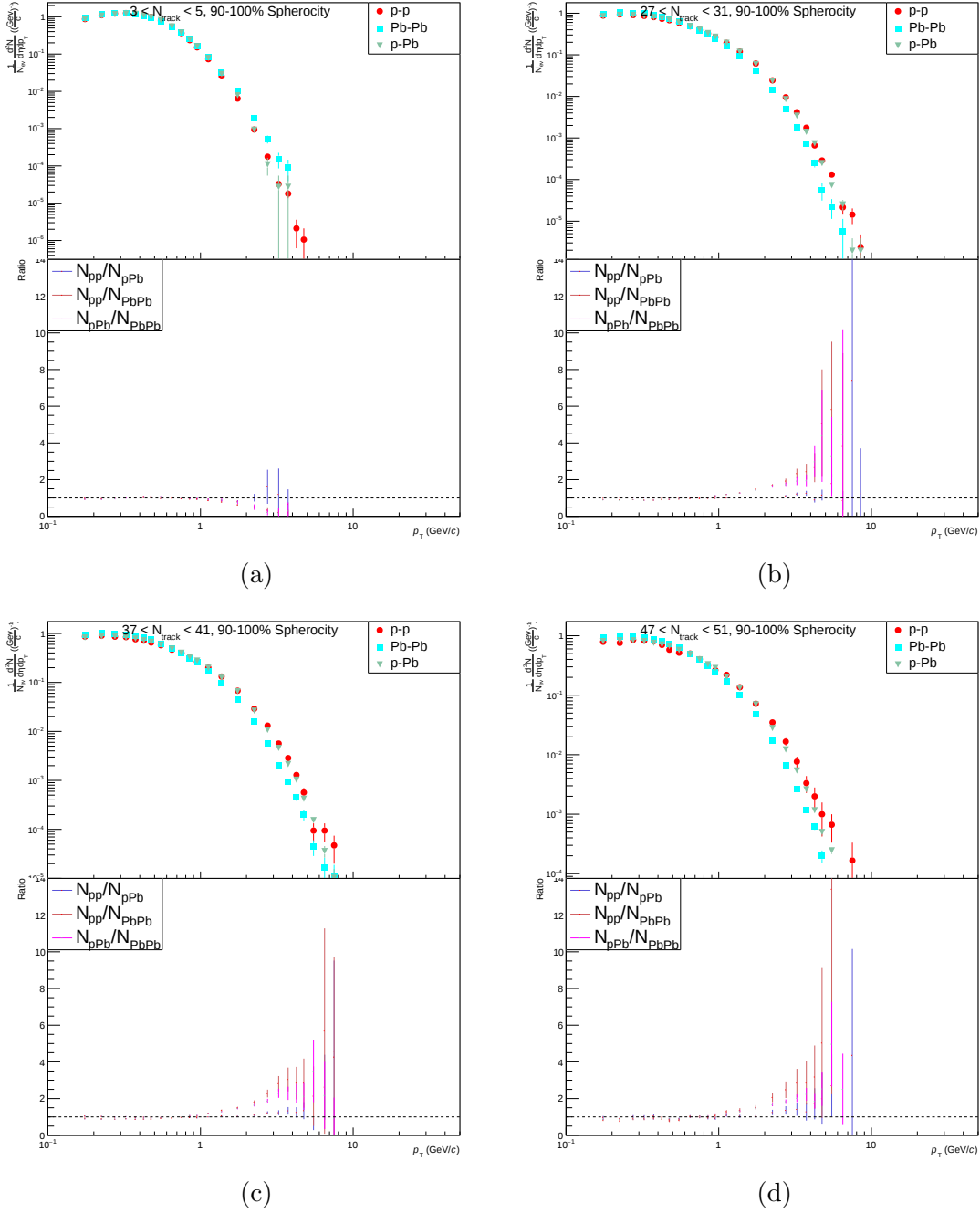


Figure 6: Normalized transverse momentum distributions of particles for low, middle and high multiplicity classes for isotropic events at $\sqrt{s_{NN}} = 5.02$ TeV. For these distributions the kinematic cut $p_T \geq 0.15$ GeV/c was used.

2.4 Average transverse momentum

In this work the measurement of average transverse momentum p_T of particles as a function of event multiplicity is investigated taking into account sphericity to characterize

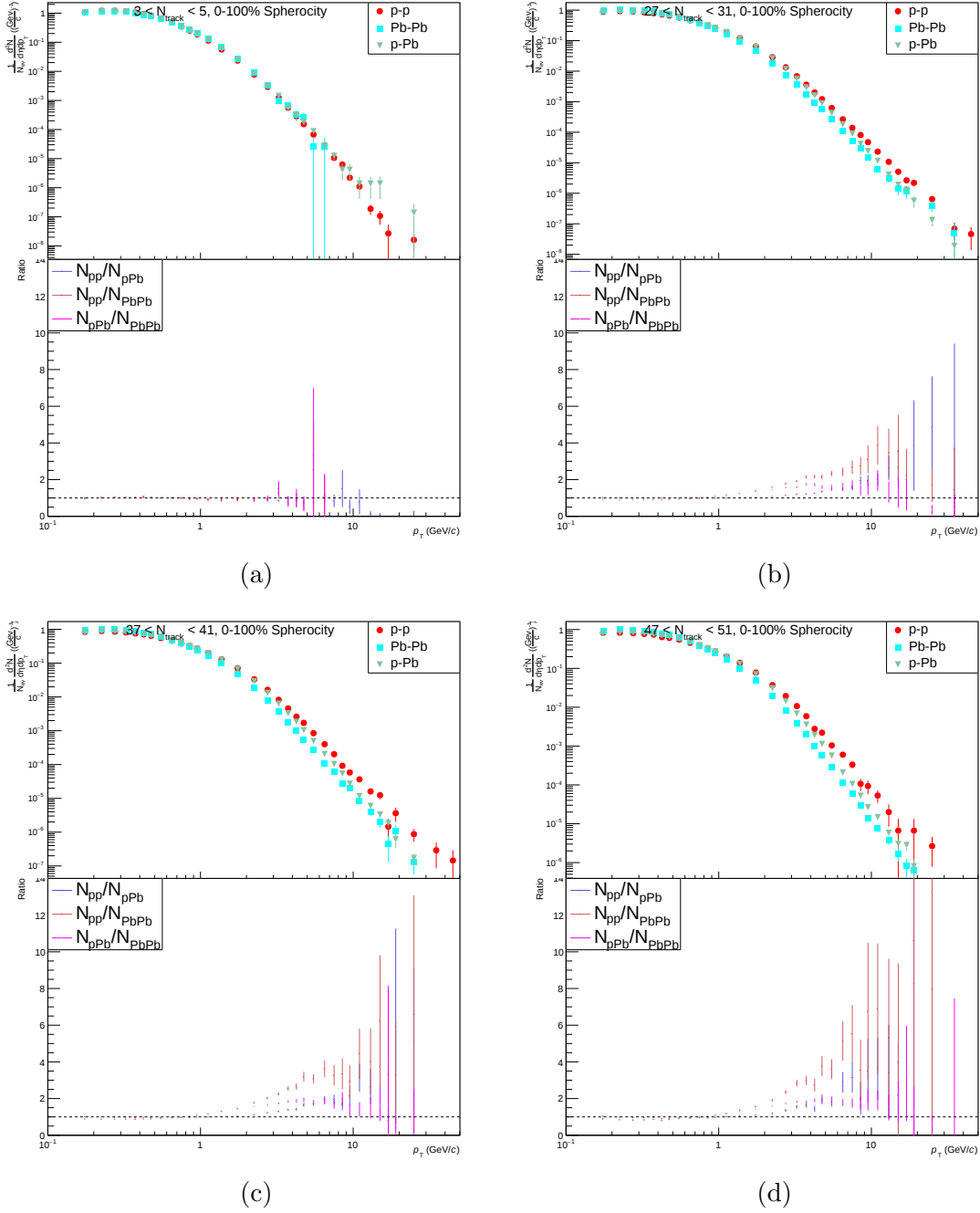


Figure 7: Normalized transverse momentum distributions of particles for low, middle and high multiplicity classes for integrated sphericity events at $\sqrt{s_{NN}} = 5.02$ TeV. For these distributions the kinematic cut $p_T \geq 0.15$ GeV/c was used.

the event shape. The reason to study the difference in average p_T dependence for various types of collisions is to understand the importance of jets in high-multiplicity collisions and their contribution to charged-particle production at low p_T .

Average transverse momentum as a function of event multiplicity in pp collisions at

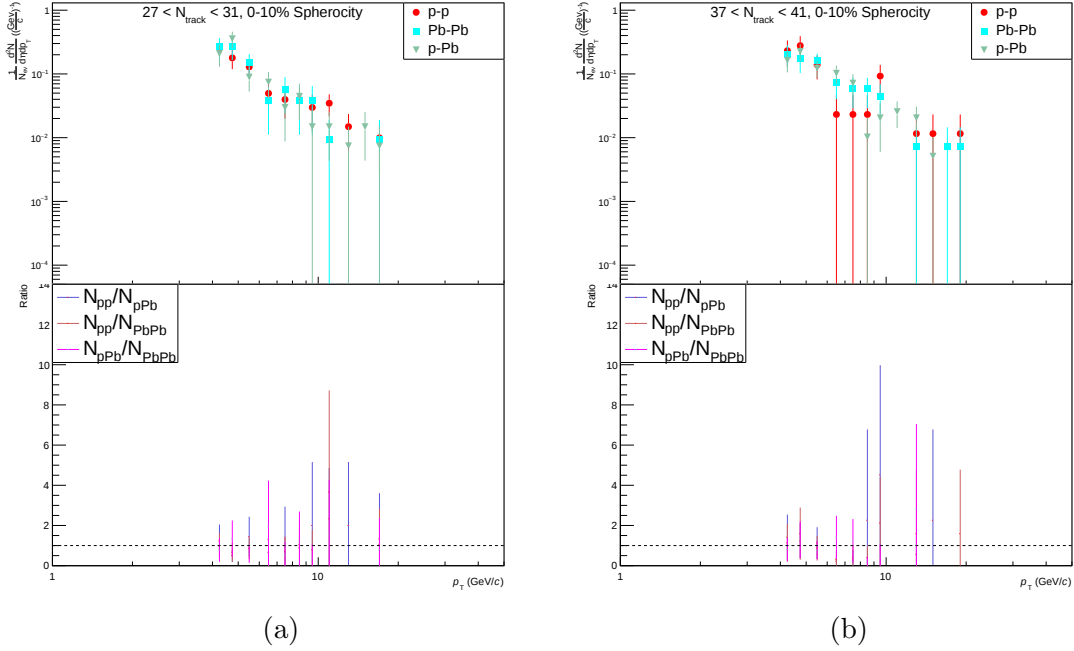


Figure 8: Normalized transverse momentum distributions of particles for middle and high multiplicity classes for jetty events at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For these distributions the kinematic cut $4 < p_T \leq 20$ GeV/c was used.

$\sqrt{s_{\text{NN}}} = 13$ TeV was already studied [6]. Our task was to perform the same analysis to obtain this dependence for pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and make a comparison for jetty-like, isotropic and integrated sphericity events.

The average transverse momentum is calculated in the kinematic range $|\eta| < 0.8$ and for three p_T ranges that we mentioned in the introduction.

For classical p_T cut the dependencies $\langle p_T \rangle(N_{\text{trk}})$ are shown on Fig. 11. It can be seen that for all types of collisions for jetty events the average p_T is the highest, for isotropic events it is the lowest and average p_T of full sphericity events is between them.

To compare the average p_T for all collision systems we plotted $\langle p_T \rangle(N_{\text{trk}})$ for them on the same picture, see Fig. 13. It can be seen that Pb-Pb values of $\langle p_T \rangle$ are, in general, lower than for p-Pb and pp. Moreover, for isotropic and full integrated events values of small systems - p-Pb and pp - are really close to each other, while for jetty events the values for all types are significantly different.

The similar hierarchy of p_T in jetty, isotropic and full sphericity events was observed for other p_T cuts. For $0.15 < p_T \leq 4$ GeV/c, in general, average transverse momentum is lower than for classical cut $p_T \geq 0.15$ GeV/c. The dependence for this case is shown on Fig. 12.

Regarding the cut $4 < p_T \leq 20$ GeV/c, as it was discussed in section 2.2, there are only few multiplicity classes with non-zero sphericity values and therefore, with non-zero average p_T values. Therefore, it is hard to obtain similar dependencies for this set of cuts. However, one can take into account total multiplicity for the analysis this case and not above the cut. With this method, it is possible to obtain average p_T dependence for this p_T region, see Fig. 14. Statistics is still low in this situation, however now there are a lot of non-zero data in

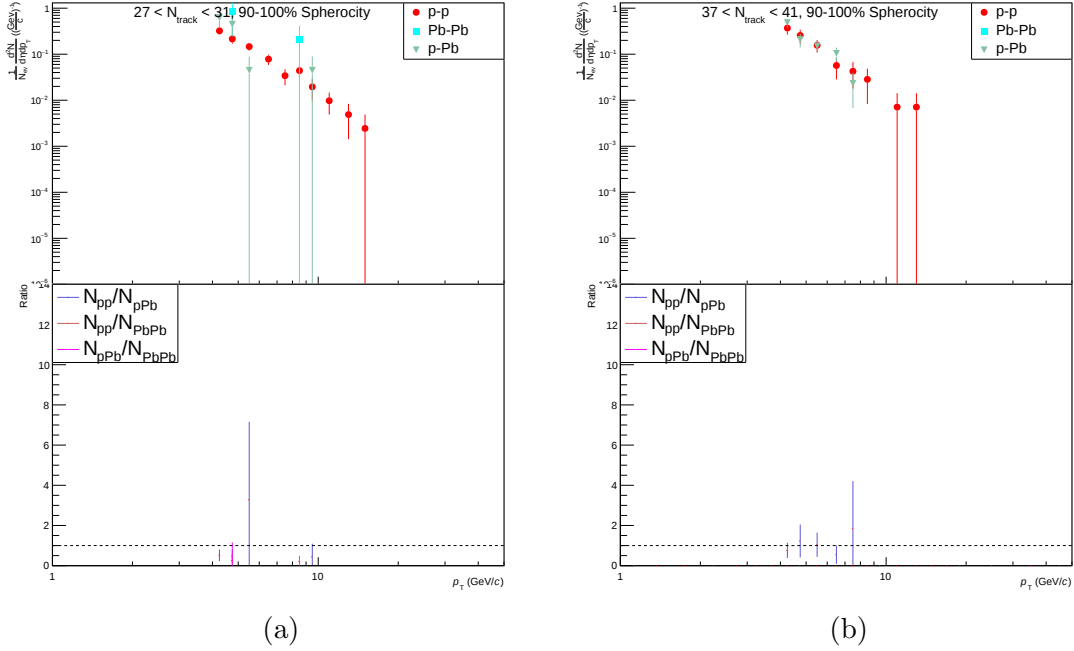


Figure 9: Normalized transverse momentum distributions of particles for middle and high multiplicity classes for isotropic events at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For these distributions the kinematic cut $4 < p_{\text{T}} \leq 20$ GeV/ c was used.

histograms. However, it is important to notice that the same hierarchy of mean p_{T} values for jetty, isotropic and full sphericity events is also valid.

3 Results

Collisions of pp, p-Pb and Pb-Pb were analyzed at the center-of-mass energy $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The measurements were performed in the kinematic range of $|\eta| < 0.8$ and $p_{\text{T}} \geq 0.15$ GeV/ c , $0.15 < p_{\text{T}} \leq 4$ GeV/ c and $4 < p_{\text{T}} \leq 20$ GeV/ c .

Sphericity distributions and ratios were obtained for all three types of collisions, considering low, middle and high multiplicity classes. A comparison of sphericity showed that with an increase in the multiplicity class, the distributions become less close to each other, since the ratio varies significantly from 1. The analogous distributions for cut for low p_{T} (soft events) demonstrated significant similarity with general cut, while for high p_{T} (hard events) it showed considerable differences.

Normalized transverse momentum spectra were obtained for pp, p-Pb and Pb-Pb collisions. The comparison indicates that at low p_{T} region the distributions for three types of collisions are close to each other, while for high p_{T} region the difference between collisions is significant.

The measurement of average transverse momentum of particles as a function of event multiplicity was analyzed taking into account sphericity to characterize the event structure. As pp collisions were studied earlier, the new dependencies are in accordance with already

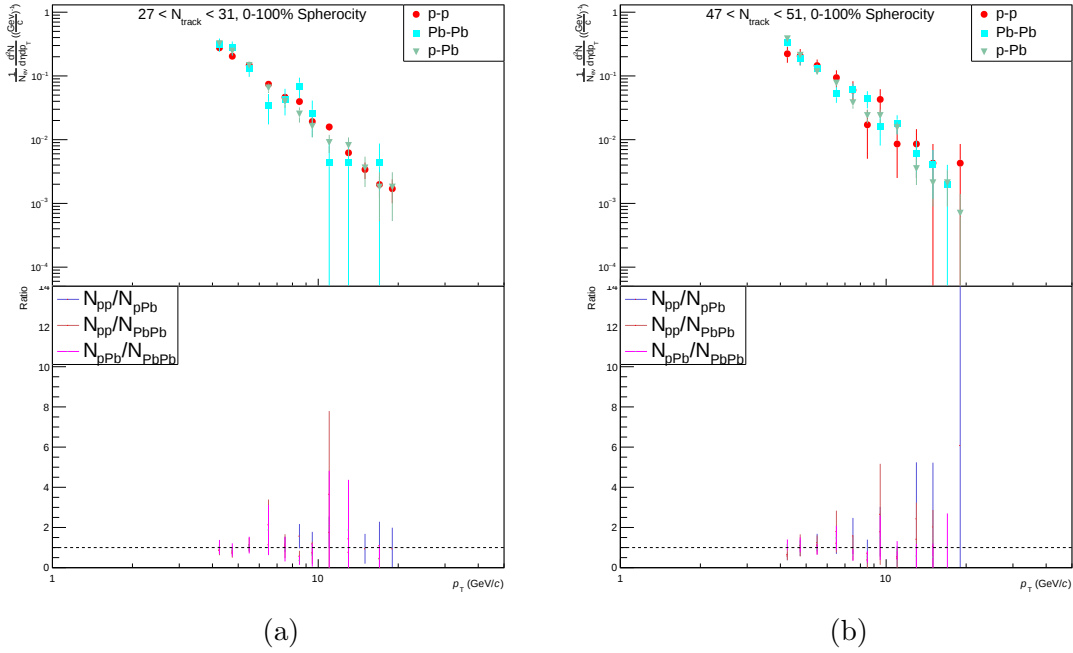


Figure 10: Normalized transverse momentum distributions of particles for middle and high multiplicity classes for integrated sphericity events at $\sqrt{s_{NN}} = 5.02$ TeV. For these distributions the kinematic cut $4 < p_T \leq 20$ GeV/c was used.

obtained. For all cuts for jetty events the average p_T values are the highest, for isotropic events they are the lowest and of full sphericity events they are in between. It is hard to obtain similar dependencies of average p_T for hard events cut $4 < p_T \leq 20$ GeV/c, as there are only 3 multiplicity classes with non-zero sphericities in this case.

4 Discussion

Collisions of protons at the LHC energies revealed some phenomena which are very similar to those observed in collisions of heavy ions. Therefore, properties of small (pp and p-A) and large (A-A) collisions recently has been studied actively by researchers. Obtained results could be used to unveil some similarities and differences in the structure or features of pp, p-Pb and Pb-Pb collisions.

In this work we considered sphericity and transverse momentum distributions for different multiplicity classes. To compare the distributions for each collision type, we plotted ratios for pp, p-Pb and Pb-Pb data to see how close they are. This analysis could allow us to follow the behaviour of variables at low and high p_T regions or multiplicity classes.

By analysing the change of ratios with evolution of multiplicity, one can see that with an increase of multiplicity class, the differences of distributions between small and large collision systems become more significant. This phenomenon was expected, as in pp and p-Pb we deal with collisions one to one, while in Pb-Pb the structure of collisions is more complicated, as there are bulks of particles there. However, there are also some interesting results regarding

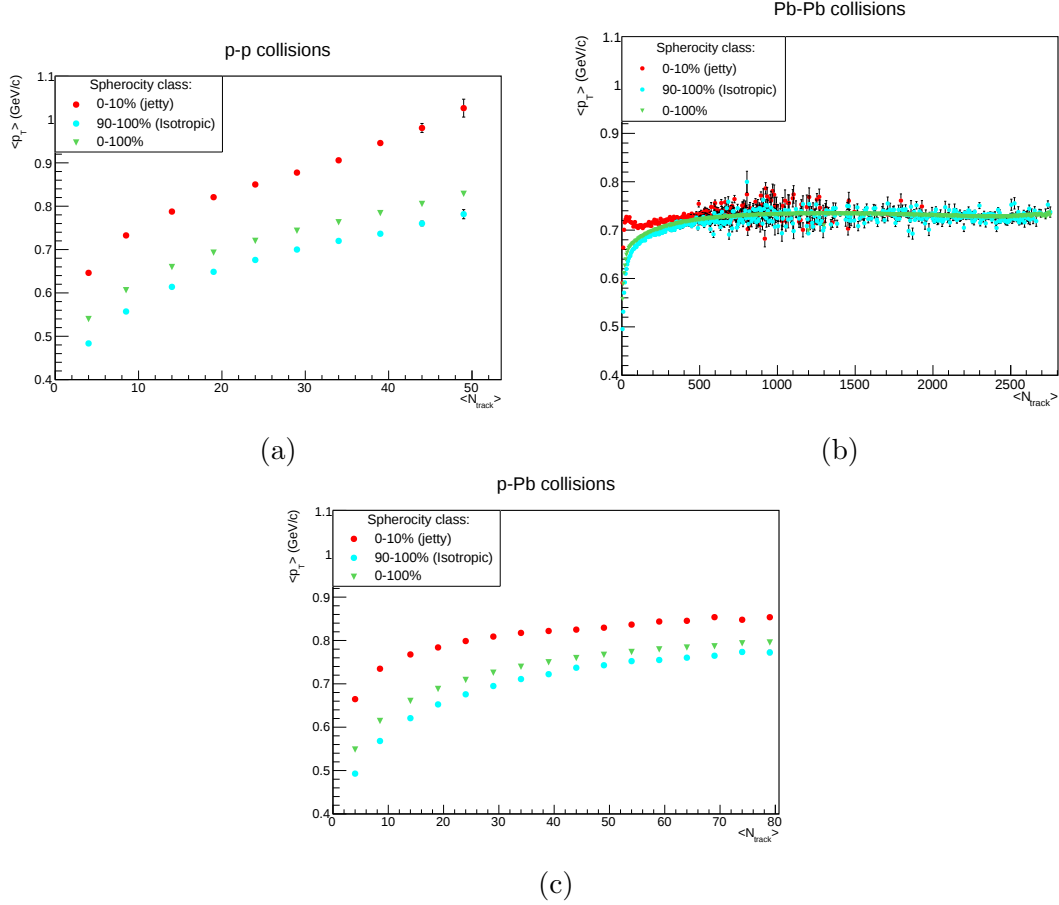


Figure 11: Average transverse momentum as a function of event multiplicity in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $p_T \geq 0.15$ GeV/ c . Results for the spherocity-integrated case (0 – 100%) are contrasted with the measurements for the most jet-like (0 – 10%) and isotropic (90 – 100%) events.

low multiplicities. One can see from ratios for both spherocity and transverse momentum distributions, that even for low multiplicities there are remarkable difference for small and large collision systems. This might be due to the fact that, as we mentioned above, the structure of collisions for small and large systems plays an important role. It might be also due to parton energy loss in collisions, but this should be carefully checked. The interpretation of the results for pp, p-Pb and Pb-Pb might require the estimation of jet effects in collisions.

All in all, the difference of distributions even at small multiplicity classes is an interesting observation that should be investigated further.

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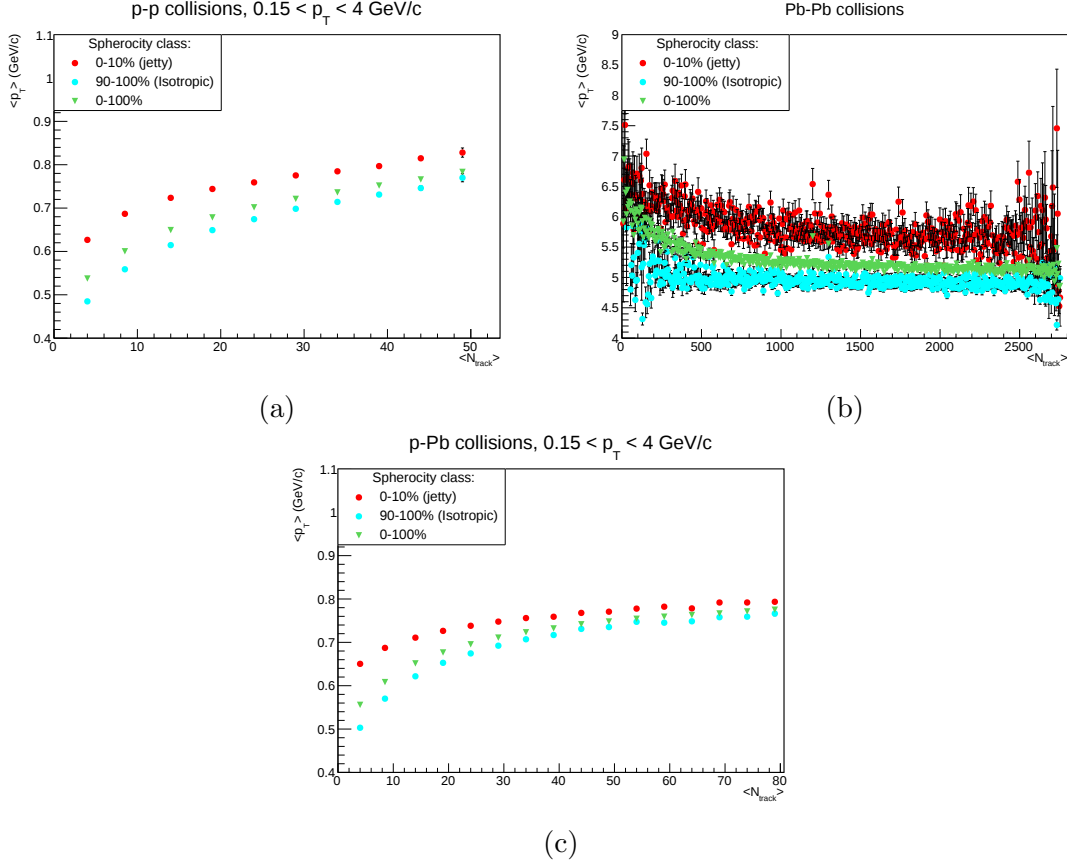


Figure 12: Average transverse momentum as a function of event multiplicity in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $0.15 < p_T \leq 4$ GeV/c. Results for the sphericity-integrated case (0 – 100%) are contrasted with the measurements for the most jet-like (0 – 10%) and isotropic (90 – 100%) events.

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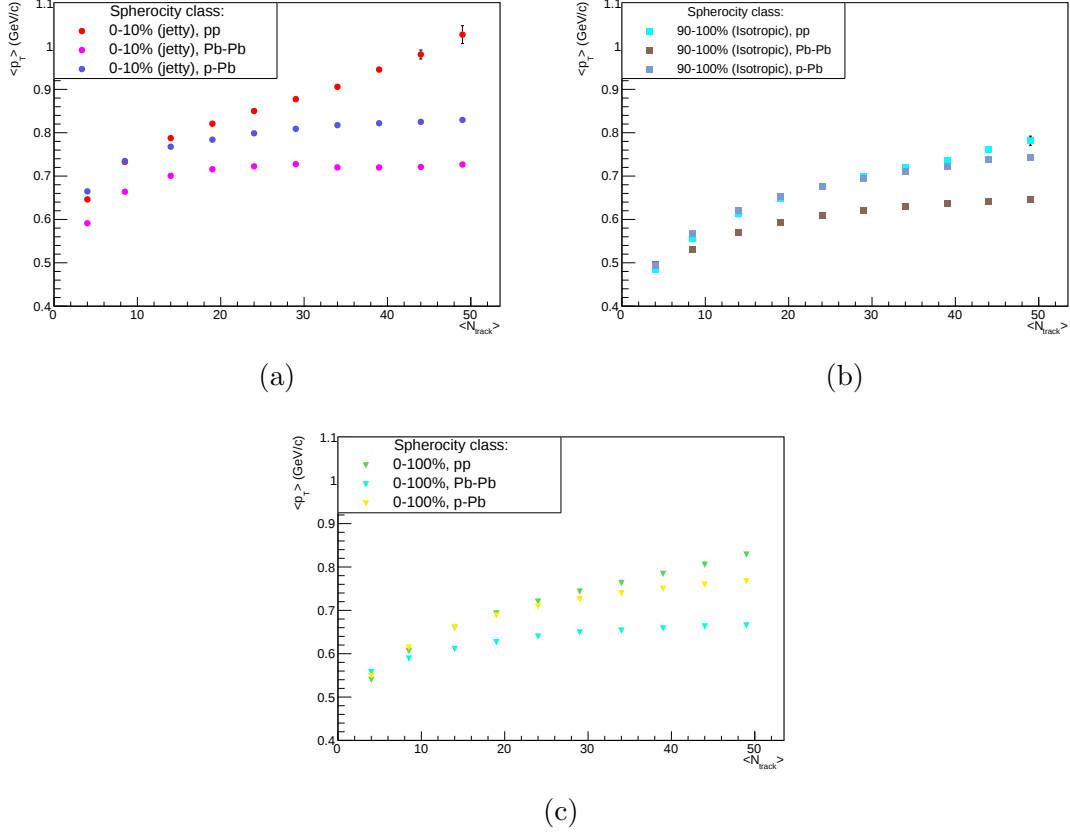


Figure 13: Average transverse momentum as a function of event multiplicity in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $p_T \geq 0.15$ GeV/c. Results for the sphericity-integrated case, jet-like and isotropic events are shown separately on each graph.

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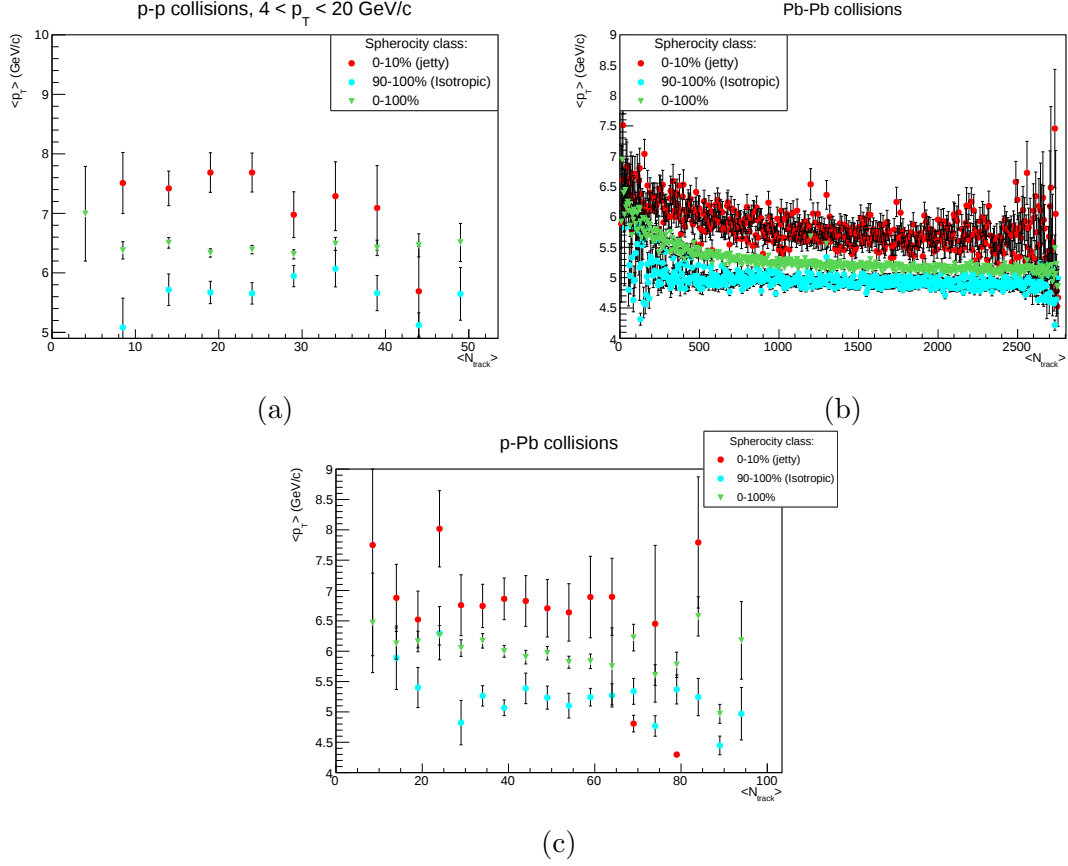


Figure 14: Average transverse momentum as a function of event multiplicity in pp, p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $4 < p_T \leq 20$ GeV/c. Results for the sphericity-integrated case (0 – 100%) are contrasted with the measurements for the most jet-like (0 – 10%) and isotropic (90 – 100%) events.