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Study of the average transverse sphericity in pp collisions at Large Hadron Collider (LHC) energies

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Abstract: In the current analysis, we have reported the spectra of average transverse-sphericity as a function of multiplicity (N_ch) in pp collisions for primary charged particles ($\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$) in mid pseudo-rapidity of $|\eta| < 0.8$ and in the kinematic transverse momentum range of $p_T > 0.5\ \ GeV/c$ at $\sqrt{s_{NN}}$ = 0.9 and 7 TeV. Two Monte Carlo event generators have been used for current analysis, and the predictions of the model are compared to the results coming from the ALICE experiment based at the Large Hadron Collider (LHC). A detailed analysis has been carried out for three types of events (soft events, hard events and bulk events) categorized by the transverse momentum (p_T) of the charged particles. It is observed that the predictions of model, underestimate ALICE data at larger values of N_{ch} while at the low values of N_{ch}, the calculated values of model are close to ALICE data. The predictions at 0.9 TeV explain ALICE data well. At large values of N_{ch}, the models predominantly produce hard events as compared with those perceived from ALICE data. This variance can be observed in the bulk event class, as event generators produce more hard events, whereas experiment gives more soft events. At high multiplicity, the generators underestimate the production of isotropic events. The event generators favor the production of back to back jets (high-p_T jets, low $< S_T >$) and also generate large multiplicity events.

Keywords: Average transverse sphericity, pseudorapidity, PYTHIA8, EPOS-LHC, multiplicity

1. Introduction

One of the key predictions of the standard model in particle physics is the existence of certain phase transitions in the matter at extreme conditions. Lattice QCD predicts the phase transition at critical temperature and Baryon density. This is the transition from the matter in hadronic form to de-confined form known as quark-gluon plasma (QGP), which was the prevailing state of matter in the universe few microseconds after the Big Bang. The same state can be created in ultra-relativistic collisions of nuclei in particle accelerators and probed at the detector sites. However, since this phase of matter is very short-lived and quickly transforming into another phase of matter, indirect observation methods have to be employed, which rely upon the theory developed from a combination of sub-fields of physics and advanced simulation methods. Because of the high energy density and temperature that are required for the transition in phase to form QGP, in most studies, collisions of heavy-ions accelerated at ultra-relativistic energies are used to study the QGP. In Pb-Pb collisions at the Large Hadron Collider (LHC), the momentum of the two nuclei allows for a collision, which is more than sufficient for such plasma to be produced. Recently, however, there has been a sudden change of focus towards smaller systems, namely collisions between two protons: pp collisions [1]. At LHC energies, pp collisions have shown some characteristics, which are very much similar to be found in heavy ion-collisions [2]. Previously, heavy ion community was on the consensus that to create a partonic system, nuclear collisions must require a bigger volume to study the flow and thermal effects. However, strangeness enhancement [3], radial [4, 5, 6] as well as anisotropic flow [7] has also been perceived in pp and $p - A$ interactions as a function of event multiplicity.

The above mentioned experimental results resemble the signatures of QGP in heavy-ion collisions. The same signatures are interpreted precisely as the outcome of a QGP behaving like a liquid in heavy-ion collisions. This is something which was unexpected, and, thus, very interesting. Because of the small size of the system in pp collision, one was not expecting QGP to form. Therefore, it needs to be found out whether this actually is the case or that the experimental signatures can be explained by conventional mechanisms already incorporated within QCD. In order to get more insight into the answer to this question, it is useful to look at the shape of pp collisions. There are two sorts of events: jetty and spherical. The jetty events are easily understood by QCD as a result of hard processes, and the spherical events can be illustrated by phenomenological technique. In the current work, we have studied the average transverse-sphericity ($< S_T >$) for proton-proton collisions on a wide range of event multiplicity at LHC energies. An event shape observable known as the average transverse sphericity is a momentum space variable [8]. The analysis to study the event shapes is well known for leptonic collisions [9, 10, 11] and also present fascinating

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features in hadronic collisions, in particular underlying event characterization, effects of hadronization and comparison of perturbative QCD (pQCD) computations with high E_T jets [12, 13, 14, 15]. Event shape observables are confined to the plane perpendicular to the beam axis at hadron collider to avoid bias from the boost. The objects (particles or jets), which are participating in the calculation are limited to some kinematic regions enforced by the detectors. For example, in case of the average transverse sphericity ($< S_T >$) defined by the ALICE collaboration, only charged particles having transverse momenta greater than 0.5 GeV/c and pseudorapidity of ($|\eta| < 0.8$) are measured.

1.1. Average transverse sphericity

Average transverse sphericity ($< S_T >$) is an event shape observable; it is the momentum space variable. It is explained by using the eigenvalues (λ_1 and λ_2) of the p_T matrix as given by

$$S_{xy}^{L} = \frac{1}{\Sigma_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{bmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{bmatrix} \quad (1)$$

where p_{Ti} is the transverse momenta of the i^{th} particle, p_{xi} and p_{yi} are the x and y components of the momentum, respectively. In an event, the index i run over all the particles. Using the (λ_1, λ_2) as eigenvalues of this momentum matrix, the average transverse sphericity ($< S_T >$) is calculated as follows:

$$< S_T > = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad (2)$$

where $\lambda_1 > \lambda_2$. The value of $< S_T >$ ranges from 0 to 1, and these extremes correspond to two clear physical situations. When $< S_T >$ is close to 0, the event is 'pencil' like or jetty. On the other hand, when $< S_T >$ is close to 1, the event is an isotropic event and known as spherical [17]. This is multiplicity dependent definition. For example $< S_T > \rightarrow 0$ for very low multiplicity events.

2. Methodology

For current analysis, a series of observables is calculated using Monte Carlo event generators. One of the simulation code used to generate these events is PYTHIA8, a dedicated program based on C++ for generating high-energy pp collisions between particles, and another Monte-Carlo event generator, EPOS-LHC is also used for the simulations.

PYTHIA8 is a model used to generate events at high-energy. It describes the various combinations of e^-, e^+, p and $\bar{p}$ collisions at high energy. It has model and theory for different aspects of physics. One can study the soft and hard quantum chromodynamics (QCD) interactions, interactions of multipartons and their distributions. PYTHIA8 is designed to study the particle decays, fragmentation and final state parton showers[18].

EPOS-LHC is a minimum bias Monte Carlo event generator to explain the hadronic collisions, used for the simulations of both the cosmic ray air showers and heavy ion collisions [19]. EPOS-LHC is capable of reproducing minimum bias events with transverse momenta varying from p_T = 0 to a few GeV/c [20, 21]. This model is built on different physics aspects e.g., it takes into account the splitting of parton ladders and off shell remnants [19]. It is tuned to LHC 2012 data and discuss the mechanism of color exchange for excitation of strings. To study the flow parameterization, the Gribov–Regge approach has been used in this model. Due to this fact, it is now able to study the flow in pp collisions, which is comparable to the heavy ion collisions. The EPOS LHC predictions explain the LHC data very well.

3. Results and discussions

In the current analysis, we have shown the spectra of average transverse-sphericity using primary charged particles; $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ in pp collision at $\sqrt{s_{NN}} = 0.9$ and 7 TeV, in the mid-pseudorapidity interval of $|\eta| < 0.8$. For the production of primary charged particles and for our simulations, we have used the Monte Carlo event generators PYTHIA8 and EPOS-LHC. 150K events have been simulated using the two event generators. The analysis is presented for the three event classes classified by the p_T of the charged particles. The PYTHIA and EPOS-LHC have been tuned for the events with $p_T^{max} < 2$ GeV/c (in the absence of hard scattering) are soft events and with $p_T^{max} > 2$ GeV/c (in the presence of one hard scattering) are hard events. All other events having $p_T^{max} > 0$ GeV/c are known as bulk events. The selected p_T range is $0 < p_T < 10$ GeV/c; the low p_T range is used because the bulk of the particles production is concentrated in this range. Because of the large number of particles it is possible to study in detail this range with a Monte Carlo event generators (models). In the high p_T range, the particles can be described using perturbative QCD techniques, which is done by incorporating the color reconnection in models. Mean transverse sphericity has been studied at LHC energies for charged particles in [15] and PYTHIA8 predictions have been tested for them. We have used the EPOS-LHC event generator to check the validity of model's predictions with the ALICE data.

Figure 1 (upper left) shows the spectra of average transverse sphericity for soft events. The model's predictions agrees well with ALICE data except the few data points at large multiplicity, where the few data points (5 data points) of models are lower than the ALICE data. For the hard events (upper right), the PYTHIA8 and EPOS-LHC predictions matches to each other for up-to N_{ch} = 10. While both models' predictions satisfy ALICE data up-to N_{ch} = 6, after that, EPOS-LHC predictions get lower about

10% than ALICE data and PYTHIA8 predictions agree well with the ALICE data at that it does not take fully into account the hydrodynamics simulation and the multiple parton scatterings. EPOS-LHC better describes the soft p_T region, that is why all the distributions of EPOS-LHC at the low p_T values describe the experiment very well. The statistical errors are lying within the data points and are not visible in the spectra of average transverse-sphericityhigh multiplicities. For the bulk events, in Figure 1 (lower bottom), models described ALICE data very well for N_{ch} = 10, later, small deviations are observed in EPOS-LHC predictions. The observed deviations of EPOS-LHC are due to the fact.

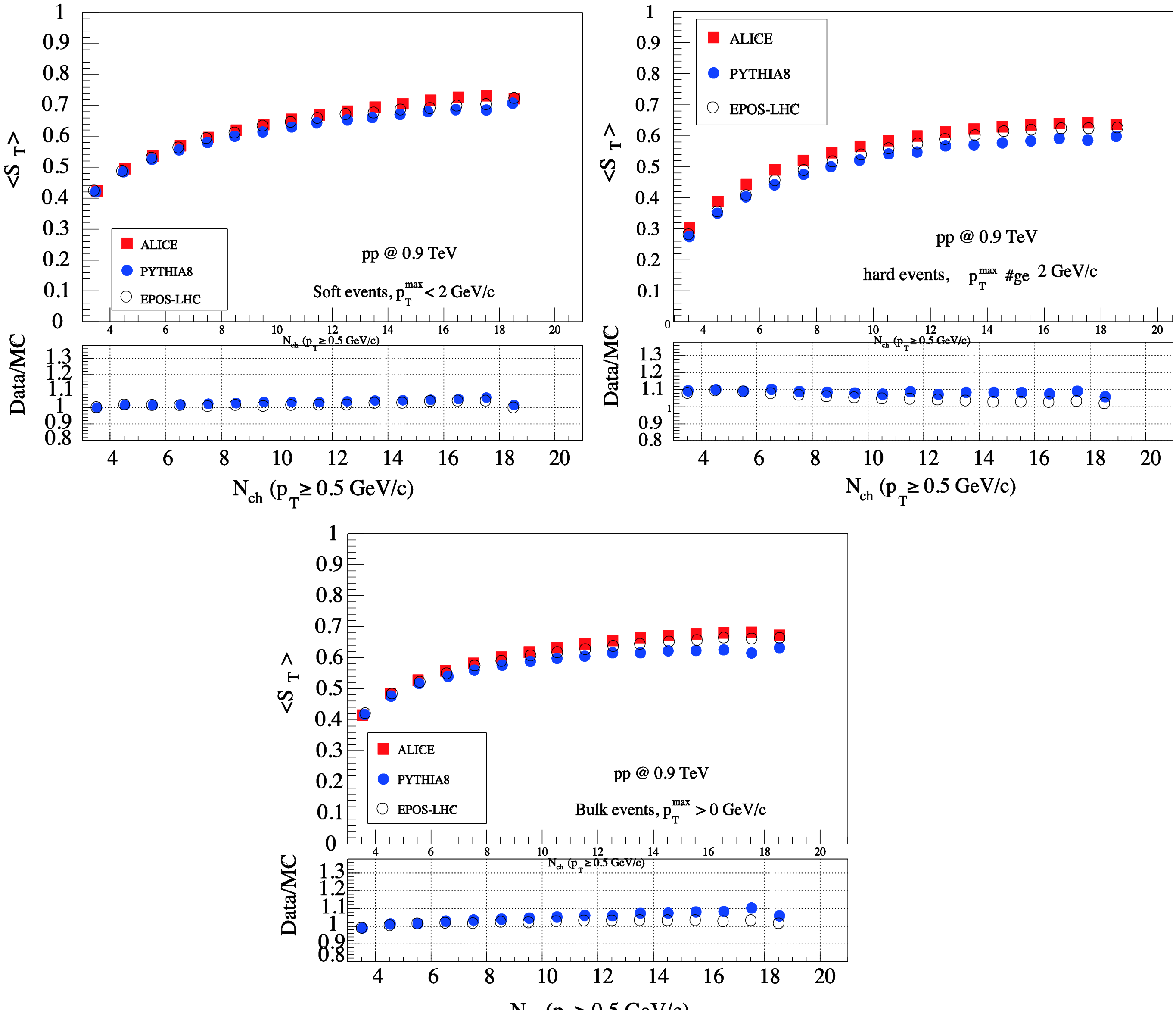

Figure 1. Average transverse sphericity as a function of charged particle multiplicity at $\sqrt{s_{NN}} = 0.9\ TeV$ at the mid-pseudorapidity. The ALICE data [15] have been compared with the PYTHIA8 and EPOS-LHC event generator's simulations. (Upper left) soft events with $p_T^{max} < 2\ GeV/c$, (Upper right) hard events with $p_T^{max} < 2\ GeV/c$ and (bottom) bulk events with $p_T^{max} > 0\ GeV/c$

Figure 2 shows the spectra of average transverse-sphericity as a function of N_{ch} at $\sqrt{s_{NN}} = 0.9\ and\ 7\ TeV$ for the different event classes (soft, hard and bulk events, respectively). The sphericity increases for primary charged particles for lower multiplicities although ALICE data show slight increase in behaviour for larger multiplicity values. For soft events (upper left figure) at $\sqrt{s_{NN}} = 7\ TeV$, the models explain ALICE data very well for up-to N_{ch} = 10. After N_{ch} = 10, the PYTHIA8 prediction is 5 to 8% lower and EPOS-LHC prediction is about 8% $--$12% lower than the ALICE data. For the hard events (upper right figure), the deviations of data to model are higher. The PYTHIA8 predictions are lower about 10% and EPOS-LHC predictions are lower about 15% than ALICE data after N_{ch} = 25. For the bulk events (lower figure), the observed deviations emerging from the models start from the N_{ch} = 5. Large deviations are observed from the models to the data. At large values of N_ch , the event generators predominantly generate hard events as compared to ALICE data.

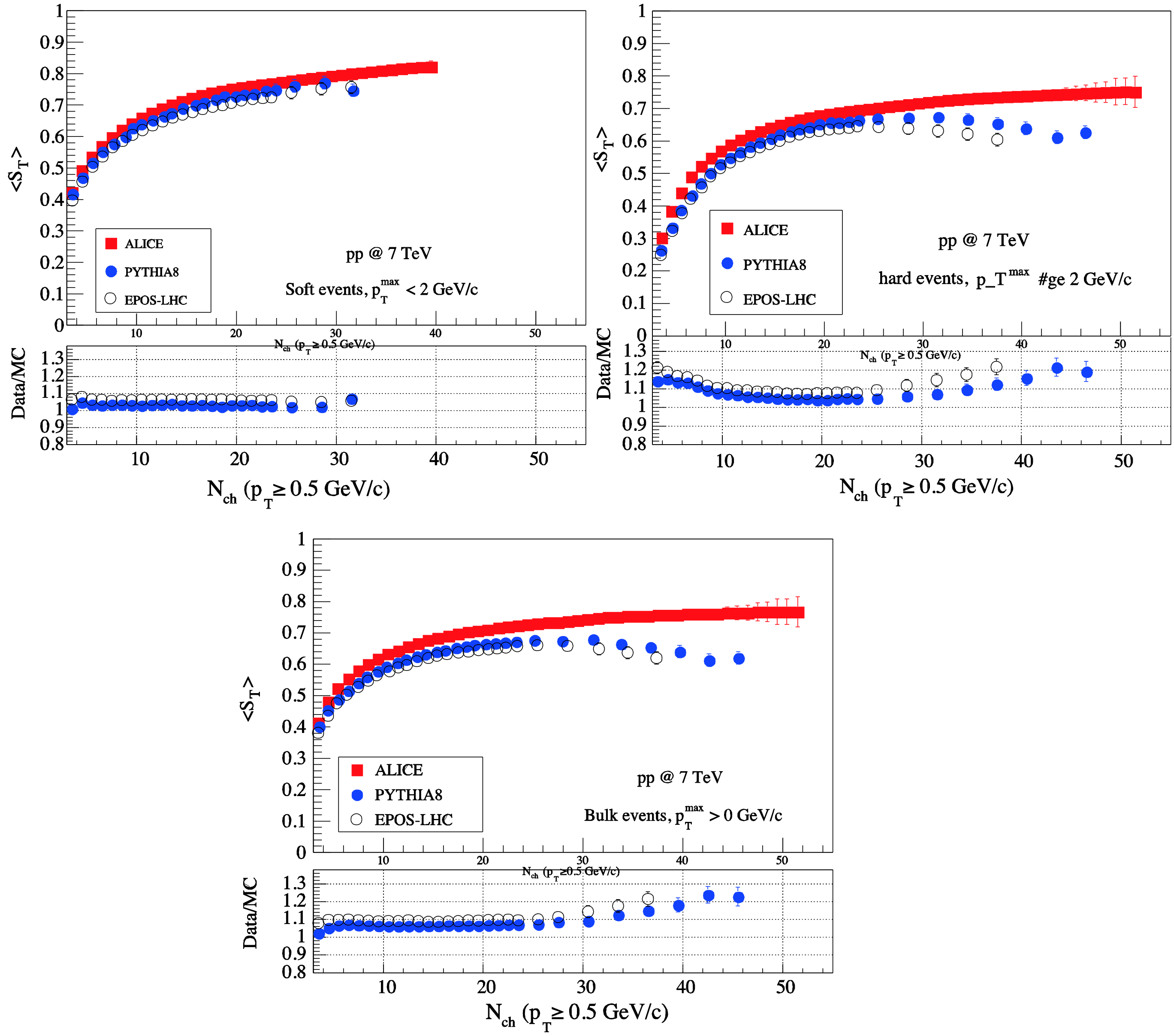

Figure 2. Average transverse sphericity as a function of charged particle multiplicity at $\sqrt{s_{NN}} = 7\ TeV$ at mid pseudorapidity. The ALICE data are compared with the PYTHIA8 and EPOS-LHC event generator simulations. Soft events with $p_T^{max} < 2\ GeV/c$ (upper left), hard events with $p_T^{max} < 2\ GeV/c$ (upper right), and (bottom) bulk events with $p_T^{max} > 0\ GeV/c$

Figure 3, shows the ratio of energies. It is observed that the EPOS-LHC predictions underestimate the ALICE data, while the PYTHIA8 predictions are somewhat near to the experimental data except at larger values of N_{ch}.

4. Conclusion

We have reported the spectra of average transverse sphericity for primary charged particles in mid pseudorapidity interval $|\eta| < 0.8$ using the Monte Carlo event generators at $\sqrt{s_{NN}} = 0.9\ and\ 7\ TeV$. The PYTHIA8 and EPOS-LHC models have been used for the current analysis and models' predictions are compared with that of ALICE data based at LHC. The analysis is shown for three types of events classified by the p_T of the charged particle: events with $p_T^{max} < 2\ GeV/c$ (soft events), with $p_T^{max} > 2\ GeV/c$ (hard events) and $p_T^{max} > 0\ GeV/c$ (bulk events). It is observed that the models' predictions show a decrease in S_T at high multiplicity, while ALICE data show a slight increase in behaviour or can be considered as almost constant. It is clear from the Figures 1 and 2 that the transverse sphericity seem to depend upon the multiplicity. At high multiplicity, the simulation models underestimate the production of isotropic events. It is clear that the event generators favour the production of large multiplicity events by producing the back-to-back jets (high p_T, (low $< S_T >$).

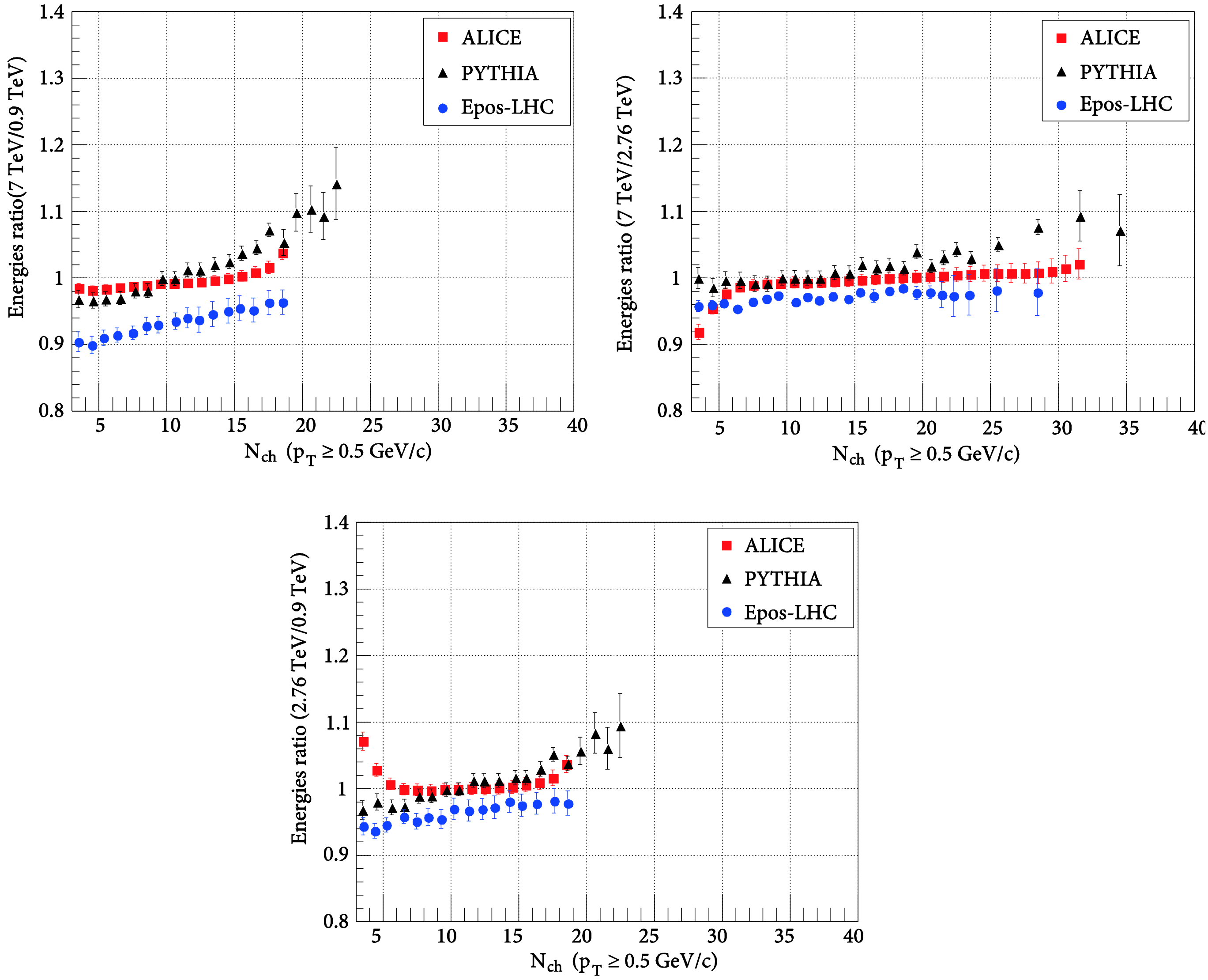

Figure 3. Ratio of energies produced from the simulation and ALICE data.

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