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Distribution of Charged Particle Production from Proton-Proton Collisions

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Abstract: We present the two different tunes (A2 and Monash) for Monte Carlo simulation of proton-proton (p-p) collisions at center-of-mass energies of 8 and 13 TeV and its implementation in the PYTHIA8 event generator. We examine the distribution of charged-particle multiplicity as a function of transverse momentum p_T, as well as the average transverse momentum $\langle p_T \rangle$ as a function of the number of charged particles in each event. The measurements use charged particles with transverse momentum more than 500 MeV and absolute pseudorapidity less than 2.5 in cases when at least one of them satisfies these criteria. Lastly, a comparison is provided between the experimental data from the LHC experiment for p-p collisions at $\sqrt{s}$= 8 TeV and 13 TeV, corresponding to integrated luminosities of 160 and 170 μb^{-1}, respectively and the simulated results obtained from the tunes. The results indicate that PYTHIA8 Monash provides the most accurate overall description of the data. It best reproduces the charged particle multiplicity distributions, p_T distributions, and $\langle p_T \rangle$ vs n_{ch}. However, PYTHIA8 A2 shows a better agreement with the multiplicity data more than PYTHIA8 monash, particularly in the low and mid-n_{ch} regions at 13 TeV.

Keywords: PYTHIA8, P-P Collisions, multiplicity distribution, LHC, Quantum Chromodynamics, Monte Carlo event generator.

1. Introduction

Studying high-energy p-p collisions up to 13 TeV allows for the investigation of quark characteristics and the nature of the gluon field within nuclei. At high energies, protons are predominantly filled with gluons, making quarks and antiquarks within them relatively smaller. In such conditions, protons and antiprotons appear almost identical, leading to no significant distinction between colliding protons with protons (as on Large Hadron Collider (LHC)) or protons with antiprotons (as on the Tevatron Collider) [1-3].

When two protons collide, typically, one quark from one proton interacts with a quark from the other, while the remaining partons pass by. Occasionally, a hard process occurs where the colliding partons emit high transverse momentum particles, forming narrow streams of high-energy hadrons known as hadron jets [1, 4-6].

Primary parton-parton interactions have a high energy scale role in hard p-p collisions at LHC energies, in addition to several softer interactions such as fragmentation processes and multiple parton interactions (MPI). These additional interactions, termed the "underlying event" (UE), contribute to charged particle multiplicity, inclusive transverse momentum per unit area, and mean transverse momentum of charged particles [4].

One essential feature of high-energy hadron collisions that has been well studied both theoretically and experimentally is the multiplicity of charged particles emitted. Multiplicity and other global event features measured at LHC energies help explore the interplay between soft and hard processes and improve our knowledge of the properties of nuclear matter in systems that have varying volumes but similar energy densities [7].

While hard scattering contributes a large role in particle production at LHC energies, soft processes still dominate the field. Thus, the study of both components is made possible by measurements of multiplicity and other general event characteristics. Such investigations also contribute to improved modeling of Pb–Pb collisions, as these properties are input in models inspired by Glauber. High multiplicity p-p collisions, which already offer energy densities comparable to those in Au-Au central collisions at Relativistic Heavy Ion Collisions (RHIC) in Brookhaven National Laboratory at 8 TeV, allow comparison of nuclear matter properties in strongly interacting systems with similar energy densities but volumes orders of magnitude smaller[5, 7, 8].

The present work aims to study the dependence of the production of charged particles from PYTHIA8 with two different tunes, relying on various hadronization mechanisms, on the event charged particle multiplicity and the center of mass energy at two different values $\sqrt{S} = 8\,TeV$ and $13\,TeV$ Comparing its results with previous results published by the ATLAS collaboration at the Large Hadron Collider (LHC) is the aim of this study. This comparison will be made easier by comparing simulation results with obtained empirical data, as the LHC has operated at these designated energies [9, 10].

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This is the arrangement of the paper. A brief description of the Monte Carlo event generator utilized in the work is provided in Section 2. We discuss our results in Section 3, and we provide a summary of our investigation with important findings in Section 4.

2. The Monte Carlo event generator

Utilizing MC generators is essential for the development of the physics program at hadron colliders such as the LHC [11]. The projected signal-like signatures originated in other SM processes that might perturb the observation or background. Monte-Carlo predictions are used to model the signature of a process of interest or signal, which can be a known SM process or a New Physics signature. In addition to conduct physics analyses, MC predictions are essential for determining the sensitivity of certain studies for the design of new accelerators. To establish in advance the technological requirements required to carry out a certain physics measurement, an accurate simulation of the predicted final-state particles is crucial in detector construction.

MC generators are not just important for collider physics. For example, they are commonly employed in the modeling of high energy cosmic ray interactions with the atmosphere, which produce extensive air showers, in the field of cosmic ray physics[12]. The only way that can be used for measuring cosmic rays with energies greater than 1015 eV is to use these showers, which are found by experiments like the Pierre Auger Observatory [13]. At the moment, simulation reliability—particularly with regard to hadronic interactions— links to the dominant source of systematic uncertainty in the interpretation of these observations [14, 15]. Furthermore, there are discrepancies in the quantity of muons generated in these cascades between simulations and observations, which may be the result of a poorly performed simulation of hadronic observables at LHC energies, particularly in forward rapidities [16].

The PYTHIA8 event generator, a widely utilized tool in particle physics and adjacent fields, generates simulations of high-energy particle collisions, particularly focusing on p-p interactions similar to those occurring at the Large Hadron Collider (LHC). Phenomenange of physical phenomena are included in PYTHIA8, including multi-parton interactions, initial- and final-state parton showers, parton distributions, hard and soft interactions, fragmentation, and decay processes. The program employs Monte Carlo techniques to model the stochastic behavior inherent in quantum mechanics, resulting in varied multiparticle outcomes even given identical starting conditions. By combining perturbative calculations and semi-hard and soft physics models, PYTHIA8 traces the progression toward intricate final states [17, 18].

PYTHIA8 is a widely used software for producing high-energy collisions. It is a set of physics models that explain how a complex multi-hadronic final state develops from a few-body hard process. PYTHIA8 has a library of hard processes, models for initial and final parton showers, interactions between multiple partons, beam remnants, string fragmentation, and particle decays. A collection of tools and interfaces to other applications are also included. PYTHIA8 is a completely rewritten version in C++, whereas PYTHIA 6 and earlier versions were developed in Fortran. PYTHIA8 is now in its first major release, and it does not yet completely replace the previous code. Still, it has several novel physics features that make it a desirable choice for LHC physics research [17]. PYTHIA 8 simulate parton showers ordered in p T and use the Lund string model [18] for hadronization. The PYTHIA 8.308 [18] software version is used to produce the p-p collisions. $\sqrt{S} = 8\,TeV\ and\ 13TeV$ are the energies at which the collisions are produced, corresponding to the energy used in LHC between 2012 and 2018. At each C.M. energy, PYTHIA8 produced around 10^7 events when the minimum bias generating settings of the generators were applied. The PYTHIA8 Monash 2013 [19] tune (default tune) was utilized to simulate inelastic p-p collisions, both diffractive and non-diffractive. The Monash parameters are set in a way that provides a faithful description of the experimental data, including the minimum bias charged multiplicity and other event characteristics, that was achieved at the LHC energies. In addition A2 tune, (called A2) [20], is used to obtain the minimum bias and underlying event using the MSTW 2008 LO PDF. The comparison between PYTHIA8 A2 and Monash tuning parameters are listed in Table 1.

To produce the results from PYTHIA8, we used the Rivet [22] interface to PYTHIA8 to run the appropriate Rivet analysis code on the generated events from PYTHIA8. This allowed us to simulate physics experiments with Rivet and PYTHIA8.

2.1. Description of the Lund String Model PYTHIA8

Hadronisation the mechanism for transforming the final outgoing coloured partons into colourless particles is based solely on the Lund string fragmentation framework. The Lund string model serves as the basis for PYTHIA. [23, 24] Let's simplify the concept by using a one-dimensional space with only one type of quark and a single mesonic state with a mass of m. The Lund hadronization model defines the probability,$\mathcal{P}$, for the creation of a certain state consisting of n mesons with momenta $p_i (i = 1, \dots, n)$ using the equation [25, 26]:

$$\mathcal{P} \propto \left\{ \left[\prod_1^n N d^2 p_i \delta(p_i^2 - m^2) \right] \delta^{(2)}\left(\sum p_i - P_{tot}\right) \right\} e^{-bA} \quad (1)$$

A phase space factor is a term represented by curly parentheses, in which the relative weighting of states with different meson counts is governed by the dimensionless constant N. The term bA in the exponent represents the imaginary component of the action of a massless string. This imaginary component leads to the decay of the string and its limited lifetime. A quantifies the spatial-temporal area of the string prior to its separation, while b represents a fixed value.

A Monte Carlo simulation can generate the outcome of the given equation by repeatedly generating mesons, starting from one end of the string. Each meson consumes a percentage of the remaining energy, denoted as z. The probability distribution or splitting function gives a relevant z-value to each step [25]:

$$f(z) = N\frac{(1-z)^a}{z}e^{\left(\frac{-bm^2}{z}\right)} \quad (2)$$

The constant "a" is determined by the normalization constraint $\int f(z)\ dz = 1$, which is related to "N" and "b". The production points for the pairs will be located in a hyperbola in the four-dimensional space-time, with a characteristic proper time determined by [25]:

$$\langle\tau^2\rangle = \frac{1+a}{b\kappa^2} \quad (3)$$

where κ is the magnitude of the string tension. The relationship between the timescale and the particle multiplicity is expressed by equation [25, 27]:

$$\frac{dN}{dy} \sim \sqrt{\langle\tau^2\rangle}\frac{\kappa}{m} = \sqrt{\frac{1+a}{bm^2}} \quad (4)$$

Table 1*:* displays the PYTHIA8 A2 and Monash tunes' parameters. **[19-21].**

Parameter	A2 tune	Monash tune
MultipartonInteractions:pT0Ref	1.90	2.28
MultipartonInteractions:ecmPow	0.30	0.215
MultipartonInteractions:a1	0.03	-
MultipartonInteractions:expPow	-	1.85
BeamRemnants:reconnectRange	2.28	1.8

3. Results and discussion

In the kinematic range $p_T > 500\ MeV$ and $|\eta| < 2.5$, the plots show the corrected primary charged particle distributions for events with $n_{ch} \geq 1$. The distributions are compared with forecasts derived from models adjusted to various data. facilitating the comparison with models easier, the data[9, 10] are given as inclusive-inelastic distributions with few model-dependent corrections.

The following distributions are measured:

- $1/(2\pi p_T N_{ev}) \cdot d^2N_{ch}/(d\eta\ dp_T)$
- $1/N_{ev} \cdot dN_{ev}/dn_{ch}$
- $\langle p_T\rangle vs\ n_{ch}$

Here, The first quantity is charged particle multiplicity distributions as function of transvers momentum (p_T), the second quantity is quantity is charged particle multiplicity distributions as function of n_{ch}, and the last quantity is the average transverse momentum as a function of the number of charged particles, $1/N_{ev}$ is a normalization factor, n_{ch} is the number of primary charged particles involved in a given event, N_{ev} is the event yield for the selected events, N_{ch} is the total number of primary charged particles in all of the data sample's selected events, and η is the particle's pseudorapidity. p_T is the component of the momentum of the charged particle that is transverse to the direction of the beam. When a charged particle with a mean lifetime of $\tau > 300\ ps$ is produced directly in p- p interactions or by the decay of directly produced particles with $\tau < 30\ ps$, it is referred to as a primary charged particle; particles produced as a particle decays with $\tau > 30\ ps$ are referred to as secondary particles. In addition, the primary charged particles must satisfy the kinematic selection requirements of $|\eta| < 2.5$ and $p_T > 100$ MeV or 500 MeV.[9, 10]

We studied the multiplicity dependence of charged particles on p_T spectra distributions in P-P collisions using our simulations. To obtain the simulated data, we employed the PYTHIA8 Monash tune and the PYTHIA8 A2 tune. The tunes mentioned above are used to simulate 9 million events. We compared the simulated data with the real data of the LHC experiment [9, 10] at $\sqrt{S}$= 8 and 13 TeVin order to verify the validity of the simulation results that we obtained from these tunes. Figures 1 and 2 display the fit to the transverse momentum spectra of charged particles in proton-proton collisions at $\sqrt{S}$= 8 and 13 TeV, respectively. The panel at the bottom shows the ratio of simulated data to experimental data. It seems that for the p_T distribution, predictions of the PYTHIA8 Monash and the PYTHIA8 A2 tunes are matching with the experimental data at low-p_T but, at high-p_T The PYTHIA8 A2 tune doesn't give a good fit with the experimental data. Additionally, the PYTHIA8 Monash data consistently shows less charged particles than the PYTHIA8 A2 data. We can see that, when the center-of-mass energies increased the difference between the simulated data and experimental data increased at high-p_T.

The distribution of charged particle density as a function of the charged particles generated in the P-P collision at $\sqrt{S}$= 8 and 13 TeV respectively, is shown in Figs. 3 and 4. At low numbers of charged particles, all tunes predict more events than are seen in the data; this is compensated by an underestimating of the tails of the distributions. It should be remembered that a deviation in one place must be compensated by a deviation in the opposite direction somewhere else because of normalization $(1/N_{ev})$. Furthermore, these data clearly show that the PYTHIA8 tunes show an excess of $N_{ch} = 1$ events, whereas the default tune regularly shows a lower fraction of occurrences with $N_{ch} > 40$ and the other tune continually shows a larger fraction. When $N_{ch} = 1$, the PYTHIA8 generator accurately predicts the number of occurrences; but, for higher N_{ch} values, it diverges from the data distributions.

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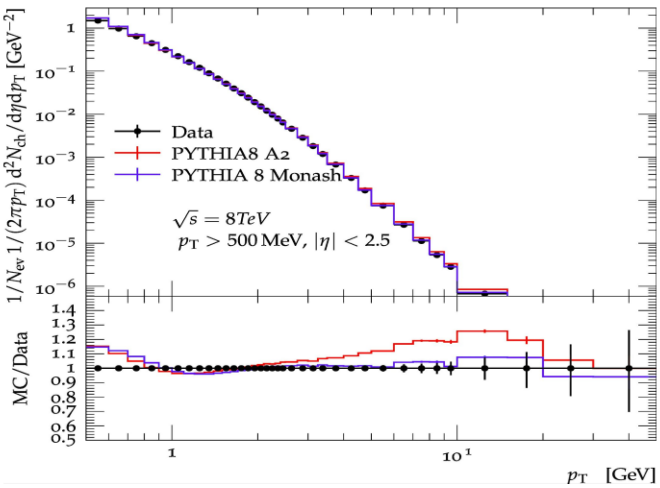

Figure 1: (color online) upper panel show the Charged particle transvers momentum (p_T) spectra fitted to the two different tunes of PYTHIA8 simulations with measurements from the LHC experiment for P-P collision at $\sqrt{s} = 8TeV$ [9].lower panel shows the ratios of all different tune configurations to data.

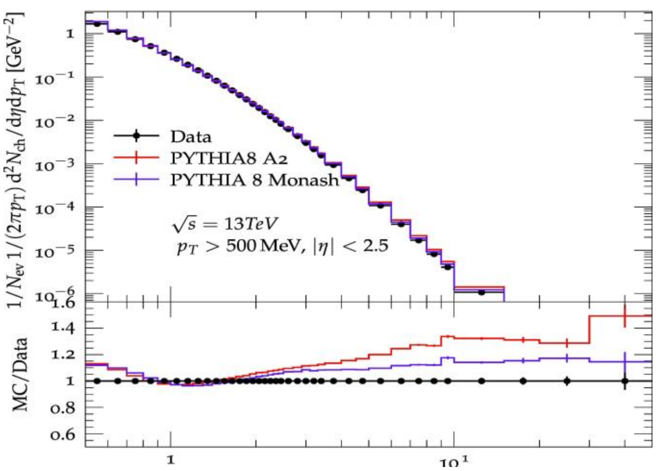

Figure 2: (color online) upper panel show the Charged particle transvers momentum (p_T) spectra fitted to the two different tunes of PYTHIA8 simulations with measurements from the LHC experiment for P-P collision at $\sqrt{s} = 13TeV$ [10]. lower panel shows the ratios of all different tune configurations to data.

The average transverse momentum as a function of particle multiplicity is the last set of distributions considered in this paper's main section. Figs. 5 and 6, shows the average p_T as a function of N_{ch} at two energies represents P-P collision at 8 TeV and 13 TeV, respectively. At 8 TeV the slope versus N_{ch} for high values of N_{ch} seems to be well described by two tunes but the absolute value is best modeled by PYTHIA8 Monash. While PYTHIA8 Monash is the most accurate tune for the absolute value, two tunes appear to sufficiently describe the slope versus N_{ch} at large values of N_{ch} at 8 TeV. Slope and absolute value of the tunes differ at the highest center-of-mass energy above 70 particles. Also, none of the tunes well describes the data at low levels of n_{ch}.

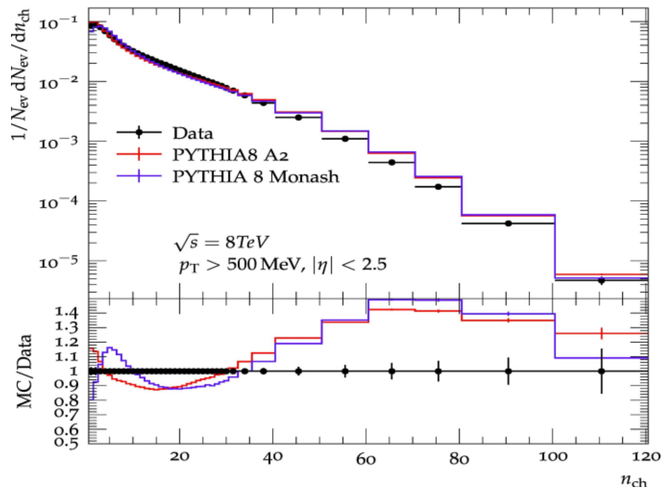

Figure 3: (color online) Density of charged particles as a function of charged particles generated in P-P collision at $\sqrt{s} = 8TeV$ from the two different tunes of PYTHIA8 simulations is compared with the measurements from the LHC experiment [9]. lower panel shows the ratios of all different tune configurations to data.

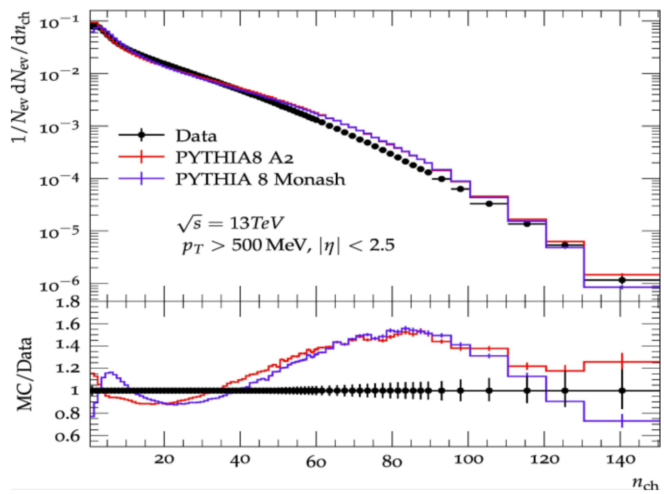

Figure 4: (color online) Density of charged particles as a function of charged particles generated in P-P collision at $\sqrt{s} = 13TeV$ from the two different tunes of PYTHIA8 simulations is compared with the measurements from the LHC experiment [10]. lower panel shows the ratios of all different tune configurations to data.

4. Summary and Conclusions

In the present study, we studied the transverse momentum distribution and multiplicity of charged particles produced by 8 TeV and 13 TeV p-p collisions. These collisions are simulated by using Monash and A2 tunes. The simulations were compared to experimental data.

We observed that both tunes struggle with describing the p_T distribution at high-p_T, particularly for the PYTHIA8 A2 tune at 13 TeV. Additionally, the number of charged particles predicted by PYTHIA8 Monash is consistently lower than the data, especially at higher multiplicities. This discrepancy between simulated and experimental data increases with collision energy, particularly for high-p_T particles.

We found that when center-of-mass energy increases at high-p_T, the difference between simulated and experimental data rises. Furthermore, all tunes predict an excess of events with low charged particle multiplicity ($n_{ch} = 1$) compared to the data, while underestimating events with high multiplicity ($n_{ch} > 40$).

The average p_T as a function of n_{ch} also revealed limitations in the tunes. While both tunes capture the slope at high n_{ch} for 8 TeV, PYTHIA8 Monash provides a better absolute value fit. At 13 TeV and above 70 particles, both tunes diverge from the data in terms of slope and absolute value. Notably, none of the tunes accurately describe the data at low n_{ch} values.

Finally, the average p_T as a function of multiplicity reveals limitations in both tunes at low and high multiplicities, particularly at 13 TeV. While PYTHIA8 Monash offers a better description of the slope at high n_{ch} for 8 TeV collisions, neither tune accurately captures the absolute value at high center-of-mass energies.

The results indicate that PYTHIA8 Monash provides a more accurate than PYTHIA8 A2 overall description of the data. It best reproduces the charged particle multiplicity distributions, p_T distributions, and $\langle p_T \rangle\ vs\ n_{ch}$. However, in the low and mid-n_{ch} regions at 13 TeV, PYTHIA8 A2 shows a better agreement with the multiplicity data.

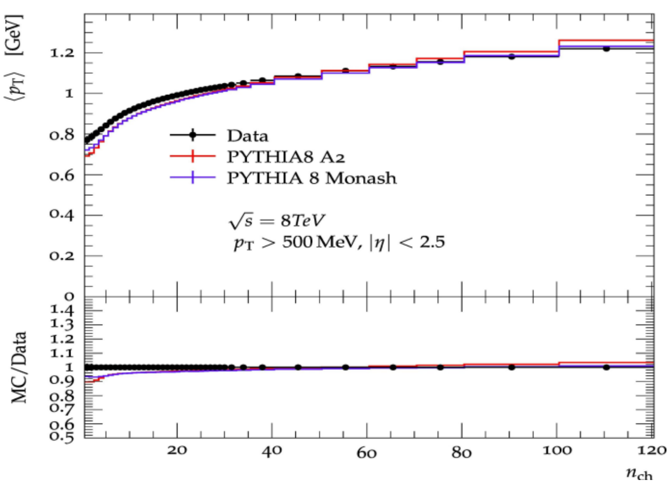

Figure 5: (color online) For events with $n_{ch} \geq 1\ and\ p_T > 500MeV$ at $\sqrt{s} = 8TeV$ The average transverse momentum as a function of the number of charged particles in the event from the two varying tunes of PYTHIA8 simulations is compared with the results from the LHC experiment [9].The lower panel shows the ratios of all different tune configurations to data.

CRediT authorship contribution statement

Methodology, N. N. Abdallah and S. El-Sharkawy; Formal analysis, S. El-Sharkawy. and M. Gamal; data curation, N. N. Abdallah and S. El-Sharkawy; Funding acquisition, N. N. Abdallah; Project administration, N. N. Abdallah and S. El-Sharkawy; Resources, N. N. Abdallah; Software, M. Gamal; Supervision, N. N. Abdallah; Validation, N. N. Abdallah and S. El-Sharkawy; Writing original draft, N. N. Abdallah and M. Gamal; Writing review & editing, N. N. Abdallah and S. El-Sharkawy All authors have read and agreed to the published version of the manuscript.

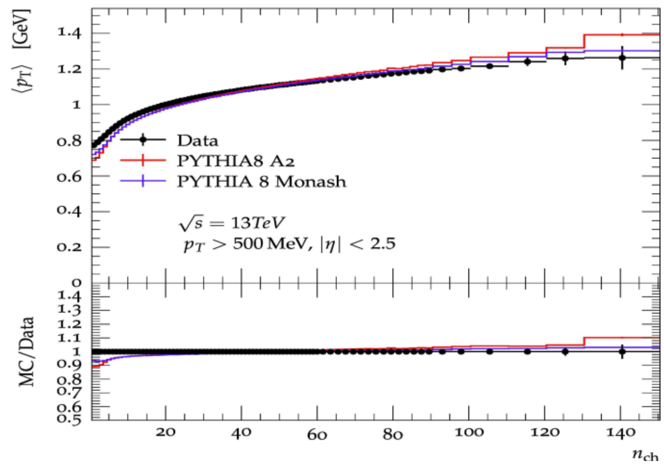

Figure 6: (color online) For events with $n_{ch} \geq 1\ and\ p_T > 500MeV$ at $\sqrt{s} = 13TeV$, The average transverse momentum as a function of the number of charged particles in the event from the two varying tunes of PYTHIA8 simulations is compared with the results from the LHC experiment [10]. The lower panel shows the ratios of all different tune configurations to data.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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