Effect of color reconnection on multiplicity dependent charged particle production in PYTHIA-generated pp collisions at the LHC energies

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Abstract The transverse momentum ($p_T$) spectra of inclusive charged particles and its dependence on charged-particle multiplicity are studied in pp collisions at $\sqrt{s} = 7$ and 13 TeV using the Monte Carlo event generator PYTHIA 8.212 (Monash tune). The results of the minimum bias pp collisions are compared with the ALICE published results at the same energies. The variations of the effective temperature ($T_{\text{Eff}}$) and average transverse momentum ($\langle p_T \rangle$) with charged-particle multiplicity are also studied. The $p_T$ spectra of the charged particles are observed to get harder with increasing charged-particle multiplicity. Moreover, a sharp increase in the $T_{\text{Eff}}$ and $\langle p_T \rangle$ with increasing multiplicity followed by a gradual decrease with the further increase in multiplicity could also be observed. Further, it could be observed that the color reconnection (CR) mechanism has a considerable effect on flattening the $T_{\text{Eff}}$ and $\langle p_T \rangle$ with increasing multiplicity, which indicates that phase-transition may not necessarily be the only mechanism that could give rise to such an effect.

1 Introduction

Relativistic heavy-ion collisions provide a unique opportunity to investigate the properties of matter created under extreme conditions of temperature and density, in which, the degrees of freedom of the matter under exploration might change from hadronic to partonic resulting Quark-Gluon Plasma (QGP) [1,2]. Different experiments, namely NA49, NA50 etc. of SPS at the CERN [3] and STAR and PHENIX of RHIC at the BNL [4–10], have been designed to create and characterize QGP in the laboratory. Several results from these experiments have already provided significant indications of the formation of the QGP state, and further, its existence has also been confirmed by the latest results from ALICE and CMS experiments of LHC at the CERN [11–15]. Contrary to this, the proton–proton (pp) system, with a few valence partons for the collisions, has traditionally been used as reference measurements for the heavy-ion collisions. However, at the LHC energies, the high-multiplicity (average charged-particle multiplicity density greater than 16) pp events of $\sqrt{s} = 7$ TeV [16] can be compared with those of the p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [17] and peripheral Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV [11,18]. And there are several evidences that the matter formed in such events exhibits collective-like effects providing hints that such collective behaviors are not the characteristic of heavy-ion collisions only [19–22]. At the LHC energies, the colliding protons are expected to have a rich structure with additional sea partons, beyond the minimal three quarks state [23,24]. Therefore, the pp collisions at the LHC energies can be considered as the collisions of two composite structures and several workers opined that the collisions of such composite structures can produce significant numbers of partons. These partons now can evolve through various phases of space-time and might form a system where quarks and gluons are in thermal equilibrium reminiscent of those formed in heavy-ion collisions [20,25].

The transverse momentum ($p_T$) spectra of the charged particles produced in collisions carry information about the collisions dynamics and full space-time evolution of the system from initial to the final stage of the collisions [26]. The flattening of the $p_T$ spectra with multiplicity (the total number of charged particles produced in the mid-<(pseudo)rapidity region in an event) is traditionally considered as an indication of the onset of formation of a mixed phase of de-confined par-
tons and hadrons. In the hydrodynamical model, the inverse slope of the \( p_T \) spectra is considered as a measure of the combined effect of the kinetic freeze-out temperature and transverse expansion flow of the system [27–30]. Thus, studies on the \( p_T \) spectra provide information about the effective temperature (\( T_{\text{Eff}} \)) of the system. The effective temperature of the system can be extracted from a fit of the \( p_T \) spectra using an exponential function as defined in Eq. (2) [28–31]. Observation of a plateau-like region in the variation of \( T_{\text{Eff}} \) against multiplicity is considered as a possible signal of formation of a mixed-phase, similar to that observed in the change of temperature with entropy for the first-order phase-transition [27,29]. Moreover, studies on the average transverse momentum (\( \langle p_T \rangle \)) with multiplicity are often carried out to realise a possible phase-transition from QGP to hadron. Here again, the flattening of \( \langle p_T \rangle \) with multiplicity is considered to be an indication of QCD type phase-transition [27,29]. In this work, an attempt has therefore been made to study the dependence of the \( p_T \) spectra, \( T_{\text{Eff}} \) and \( \langle p_T \rangle \) of the charged particles for different charged-particle multiplicity (the total number of primary charged particles produced in \( \eta \) < 0.8 in an event) interval in pp collisions at \( \sqrt{s} = 7 \) and 13 TeV using the MC event generator PYTHIA 8.212 (Monash tune) [32].

PYTHIA includes color reconnection (CR) mechanism, a string fragmentation mechanism that considers final partons to connect through their color charge in such a way that the total string length becomes minimum. Therefore, two partons produced from independent hard scattering are color connected and make a large transverse boost [33]. Several recent experimental results of pp collisions, particularly of high-multiplicity events, have shown a number of collective behaviors such as enhanced production of baryon over meson at intermediate \( p_T \), mass-dependent growth in \( \langle p_T \rangle \) with multiplicity, enhancement of (multi-)strange hadrons, ridge-like structure, non-zero \( v_2 \) coefficients similar to those observed in heavy-ion collisions [11,16,20,21,34]. However, when compared with the PYTHIA generated MC data, the CR mechanism is found to mimic a number of such collective-like effects, although the results of the PYTHIA model with CR are not in quantitative agreement with the experimental observations [16,20,35]. Further, more recently, it has been observed that the CR mechanism in PYTHIA has significant effects on the intermittent behavior of charged particles produced in high-multiplicity pp collisions [22]. It, therefore, becomes very much pertinent to investigate the role of the color reconnection on other global signatures of collective behaviors of heavy-ion collisions, particularly when Run3 data analysis in pp collisions at \( \sqrt{s} = 13.6 \) TeV is in progress. Inspired by this argument, in this work, a detailed multiplicity-dependent study on global observables of hadron-hadron collisions, in particular, \( T_{\text{Eff}} \) & \( \langle p_T \rangle \), for different strengths of the CR mechanism has been undertaken to assess the contribution of color reconnection on the signature of collective behavior of pp collision.

2 Event generator: PYTHIA 8.2

For the present study, pp collisions data at various colliding energies of LHC were simulated using PYTHIA 8.2 event generator. The event statistics for the analysis are presented in Table 1. The PYTHIA is a general-purpose pQCD-based Monte Carlo (MC) event generator for the simulation of high-energy lepton–lepton and hadron–hadron collisions. It consists of a coherent set of physics models to describe the evolution of a few-body hard-scattering process to a complex multiparticle final state. The physics processes include hard and soft interactions, models for parton distributions, initial and final state parton showers, multiple parton–parton interactions (according to the QCD improved parton model, in high-energy hadronic collisions, each hadron can be considered as a collection of several numbers of partons. Due to the composite nature of hadrons, it becomes possible to have multiple partons hard scatterings i.e. events in which two or more distinct hard parton can interact simultaneously in a single hadron-hadron collision. This is known as multiparton interactions (MPI)), hadronization (hadronization or fragmentation is the process of turning the colored outgoing partons into colourless hadrons. This transition is non-perturbative and must be handled by models. In PYTHIA 8.2, the hadronization model is based on the Lund string model [36,37], which is the core of the previous PYTHIA programs. Even though the main mechanism of string hadronization is similar to the previous PYTHIA version, a significant activity could be observed in the area of hadronization, due to the observation of collective-like effects in hadronic collisions), color reconnection, particle decay, and beam remnant [38]. The PYTHIA Monte Carlo (MC) event generator is capable of describing charged-particle multiplicity distributions in proton–proton collisions of \( \sqrt{s} = 7 \) and 13 TeV within 20%, but not above \( N_{ch} = 60 \) and the pseudorapidity distributions of charged particles in pp collisions at \( \sqrt{s} = 7 \) (0.9) TeV with an overestimation of 12% (5%) [39–42]. In the present

| Center-of-mass energy (\( \sqrt{s} \)) (GeV) | CR | RR | No. of events (Millions) |
|-------------------------------------------|----|----|------------------------|
| 7                                        | On | RR = 1.8 (default) | 125                     |
| 13                                       | On | RR = 1.8 (default) | 73                      |
| 13                                       | Off| RR = 0.0           | 16.6                    |
| 13                                       | On | RR = 3.0           | 56                      |
| 13                                       | On | RR = 3.6           | 71                      |
study, the PYTHIA 8.212 version has been used. The availability of large sets of data and high-precision results from different experiments have made it possible for a detailed comparison of results and hence, provided opportunities for model development and refinement of various model parameters for a better description and prediction. Therefore, different parameters of the PYTHIA model have been improved or tuned from time to time by comparing the available experimental results for a better description of data as well as for a more in-depth understanding of the underlying collision dynamics. Therefore, the pp events are generated using the Monash 2013 tune of PYTHIA 8.212, which has several updated values of different parameters for multiparton interactions, color reconnection, etc. that are tuned to describe the results of the LHC Run 1 data [32]. For the generation of events in pp collisions at \( \sqrt{s} = 7 \) and 13 TeV, both the soft and hard QCD processes have been considered. In the case of soft QCD processes, the inelastic part of the total cross-sections is considered. For the hard process, all the standard 2 \( \rightarrow \) 2 processes have been used. Moreover, during the event generation process, only primary charged particles are considered as defined in [43]. For this study, only minimum bias events i.e. the events without any selection criteria on impact parameter are generated.

Moreover, in the more recent PYTHIA 8.240 version [44, 45], the mechanisms of string shoving and rope hadronization have been included. Recently, in the very latest version of PYTHIA i.e., PYTHIA 8.3, the mechanisms of rope hadronization and string shoving have been updated [46].

### 3 Results and discussions

At first, 125 M & 73 M events generated for pp collisions at \( \sqrt{s} = 7 \) and 13 TeV respectively using the Monash (default) tune of the PYTHIA 8.212 event generator are analyzed. Hereafter, the Monash (default) tune of the PYTHIA 8.212 version is referred to as PYTHIA 8.212 Monash.

As a quality assurance test of our generated sets of data, within the acceptance of the ALICE detector, the pseudorapidity distributions of the primary charged particles in minimum bias (MB) pp collisions at \( \sqrt{s} = 7 \) and 13 TeV are plotted in Fig. 1a and compared with the published results of the ALICE Collaboration [39,47]. From the figure, it is readily evident that the pseudorapidity distributions of the PYTHIA 8.212 Monash generated data are in good agreement with the ALICE experimental results.

For the measurement of \( p_T \) distributions, the \( p_T \) of the particle is calculated using the following formula:

\[
p_T = \sqrt{p_x^2 + p_y^2}.
\]

where \( p_x \) and \( p_y \) are the momenta of a particle in the x and y direction which are obtained from the PYTHIA 8.212 Monash generated data. In order to compare results of the PYTHIA-generated data with ALICE, pseudorapidity (|\( \eta \)| < 0.8) and transverse momentum (\( p_T > 0.15 \) GeV/c) cuts have been used. Also, a cut on selection of only primary charged particle produced during the collisions has been applied.

In Fig. 1b, the transverse momentum distributions of the primary charged particles with PYTHIA 8.212 Monash generated data are plotted for minimum bias pp collisions at \( \sqrt{s} = 7 \) and 13 TeV and compared with the published results of ALICE [47,48]. It could be observed from the figure that for pp collisions at \( \sqrt{s} = 7 \) TeV, except for the low \( p_T \) region (<0.8 GeV/c), the PYTHIA 8.212 Monash and ALICE results are in good agreement in the studied \( p_T \) range. Further, the disagreement between the PYTHIA 8.212 Monash generated though experimental data of ALICE for \( \sqrt{s} = 13 \) TeV is found to be a little high and remains within the limit of 20%. It is important to note that the ALICE published \( p_T \) spectra for pp collisions at \( \sqrt{s} = 7 \) TeV is measured for inelastic events (INEL) [48], whereas, for \( \sqrt{s} = 13 \) TeV, the spectra is measured for all INEL events having at least one charged particle produced with \( p_T > 0 \) in |\( \eta \)| < 1 (INEL > 0) [47]. As the tuning of different parameters of the PYTHIA 8.212 Monash has performed for inelastic events, better agreement of the \( p_T \) spectra in pp collisions at \( \sqrt{s} = 7 \) TeV is justifiable [32].

The total number of charged particles produced in an event i.e., charged-particle multiplicity (N\(_{ch}\)) provides central information about the particle production mechanism and is considered as an important global observable of nuclear collisions [49,50]. As the PYTHIA 8.212 Monash generated sets of data are quite successful in describing the results of pseudorapidity and \( p_T \) spectra of ALICE at the studied energies; it is therefore expected that a study on the \( p_T \) spectra, T\(_{Eff}\) and \( \langle p_T \rangle \) of the primary charged particles for different charged-particle multiplicity would provide better insight about pp collision dynamics.

Multiplicity distributions of the PYTHIA 8.212 Monash generated charged particles produced in pp collisions at \( \sqrt{s} = 7 \) and 13 TeV within the mid-pseudorapidity range (|\( \eta \)| < 0.8) are shown in Fig. 2 and are compared with the results of ALICE. From the figure, it could be observed that the results of ALICE and PYTHIA 8.212 Monash are in very good agreement. Moreover, it is seen that the charged-particles multiplicity increases with increasing center-of-
uncertainties, which are statistical and systematic. pp collisions contain both pseudorapidity distributions in ALICE results for the published results of the ALICE Collaboration [39,47,48]. ALICE results compared with the published results of the ALICE Collaboration [40].

To be collisions of two balls of partons [23,24]. The high-mass energy. At LHC energies, pp collisions are considered to be collisions of two balls of partons [23,24]. The high-multiplicity events occur at a small impact parameter, and therefore, the number of particles thus produced is expected to be higher due to the large energy-momentum transfer as well as for the increased number of multiparticle collisions [51,52]. It is quite natural that the $p_T$ spectra of the particles in such events also get affected, and a change in the behavior of the spectra is obvious, if studied as a function of charged-particle multiplicity.

In Fig. 1 a, b the $p_T$ spectra of the charged particles for different charged-particle multiplicity intervals are plotted for pp collisions at $\sqrt{s} = 7$ and 13 TeV, respectively with our generated sets of data. The charged particle $p_T$ spectra are observed to become harder with increasing charged-particle multiplicity for both the studied energies. This characteristic behavior is similar to that proposed by Van Hove, in which, it is argued that the flattening of the $p_T$ spectra with increasing multiplicity might indicate the de-confinement transition from hadron gas to quark-gluon plasma [27].

At low $p_T (\lesssim 2$ GeV/c) [53], the charged particles transverse momentum spectra can be parametrized by Eq. 2 [28].

$$\frac{dN}{p_T dp_T} \sim C \times exp \left( -\frac{p_T}{T_{\text{Eff}}} \right),$$

(2)

where $T_{\text{Eff}}$ is the effective temperature of the system containing the contribution from both the kinetic freeze-out temperature and transverse expansion flow. The $T_{\text{Eff}}$ is estimated from the fit of data points in Fig. 3a, b by Eq. 2. The white solid line in the figures represents the fit of the data points.

In Fig. 4a, b, the variations of the $T_{\text{Eff}}$ and $\langle p_T \rangle$ for different charged-particle multiplicity have been plotted respectively with the PYTHIA 8.212 Monash generated data of pp collisions at $\sqrt{s} = 7$ and 13 TeV. It is interesting to observe from these figures that both the $T_{\text{Eff}}$ and $\langle p_T \rangle$ increase sharply with the increase of charged-particle multiplicity up to $N_{ch} < 30$. However, with the further increase of multiplicity, the increasing behavior of the $T_{\text{Eff}}$ and $\langle p_T \rangle$ gradually slows down and tends to reach a plateau-like region, particularly in $T_{\text{Eff}}$ vs. multiplicity plot. As PYTHIA 8.212 Monash does not include hadron to QGP phase-transition, the appearance of this plateau-like region for the PYTHIA-generated data suggests that apart from such transition, some other mechanisms, which may not necessarily be related to phase-transition could also give rise to such an effect. However, the observed sharp increase of $\langle p_T \rangle$ with $N_{ch}$ could be attributed, within a model of hadronizing strings, to multiparton interactions and to a final state color reconnection mechanism [42].
Further, $T_{\text{Eff}}$ and $\langle p_T \rangle$ do not show any significant dependence on the center-of-mass energy, which suggest that as long as the multiplicity remains the same, $T_{\text{Eff}}$ and $\langle p_T \rangle$ of the system do not change.

Color reconnection (CR) is found to give several collective-like behaviors as observed in the heavy-ion collisions in pp data [11, 21]. Thus, studies on the effect of CR on transverse momentum and other related observables might shed light on collisions dynamics of the system under investigation. The parameter that determines the strength of the color reconnection in PYTHIA is known as the reconnection range (RR). To see the effect of the color reconnection mechanism on our studied observables, three new sets of data of 16.6M, 56M and 71M events with RR = 0.0, 3.0 and 3.6, respectively, are generated at the highest collisions energy available at the LHC Run2 for pp collisions, i.e., $\sqrt{s} = 13$ TeV and further analysis is carried out with these datasets only.

The $p_T$ spectra obtained from the PYTHIA 8.212 Monash generated data in pp collisions at $\sqrt{s} = 13$ TeV for different values of the RR parameter are compared with the ALICE data, and the results are shown in the upper panel of Fig. 5. From the ratio plots (middle panel), it is observed that in the low $p_T$ region, CR off data overestimates (up to 85%) the ALICE data, whereas, it underestimates (up to 29%) in the intermediate $p_T$ region. On the other hand, the RR = 3.0 and 3.6 generated data provides a little better description of the ALICE data than the default RR data at low $p_T$, although it becomes worse at the intermediate $p_T$.

In the lower panel of Fig. 5, a comparison of $p_T$ spectra for different values of the RR parameter to default RR is shown. From these ratio plots, it is readily evident that with CR off, particles tend to produce at low $p_T$ compared to that of intermediate and high $p_T$ regions. However, for higher reconnection range values (RR = 3.0 and 3.6), particle production favors at the intermediate $p_T$ than the low $p_T$ region. This enhancement of charged particles for RR = 3.0 and 3.6, is similar to those observed for the $p/\pi$ ratio in Ref. [21] with the default CR (RR = 1.5) in PYTHIA 4C tune. This usually occurs because of the experience of a higher boost by the particles due to increase in the strength of the CR mechanism, resulting in the shift of particles from a low to a comparatively higher $p_T$ region.

The variation of $T_{\text{Eff}}$ and $\langle p_T \rangle$ with charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV for different $p_T$ and $\langle p_T \rangle$ almost remain constant starting from low to high multiplicity interval class, when, CR mechanism is switched off. This behavior suggests that the properties of the medium formed are independent of the charged-particle multiplicity produced in the collisions, when no CR mechanism is implemented in PYTHIA 8.212 Monash. On the contrary, with the increase of RR values (3.0 and 3.6) in PYTHIA 8.212 Monash, the increasing behavior of $T_{\text{Eff}}$ and $\langle p_T \rangle$ is found to be slightly sharper than that of the default RR results. It is interesting to note that the increase of the $T_{\text{Eff}}$ and $\langle p_T \rangle$ with RR seems to slow down gradually for increasing RR parameters, and no significant difference could be observed between the results of RR = 3.0 and 3.6. These behaviors indicate that the color reconnection mechanism in PYTHIA 8.212 Monash has a substantial role in the flattening of observables like $T_{\text{Eff}}$ and $\langle p_T \rangle$ for $N_{\text{ch}} > 30$. However, a further increase of CR’s strength beyond a certain limit may not necessarily affect the behavior of the system considerably.
Fig. 4 Variation of (a) effective temperature and (b) average $p_T$ as a function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 7$ and 13 TeV for PYTHIA 8.212 Monash generated data.

Moreover, to gather some useful information about the collective-like behavior in small systems, further studies on pions, kaons, and protons $\langle p_T \rangle$ have been carried out in pp collisions at $\sqrt{s} = 13$ TeV with the same sets of PYTHIA 8.212 Monash generated data. It has recently been observed with ALICE data that pions, kaons, and protons $\langle p_T \rangle$ increase with the increasing multiplicity, and the effect is more pronounced for heavier particle, i.e., for protons [35]. This behavior is similar to that observed in the lower energy pp, p–Pb, and Pb–Pb collisions. In heavy-ion collisions, such a mass-dependent effect is considered to be a manifestation of the hydrodynamical evolution of the system [11]. However, for small colliding systems, the reasons for such mass-dependent enhancement of $\langle p_T \rangle$ are beyond one’s comprehension. To better understand the origin of such effect for pp collisions, studies with MC generated data were also performed and the results are reported in Ref. [35]. It has been observed in Ref. [35] that the PYTHIA model with color reconnection mechanism (default) can describe the ALICE results on $\langle p_T \rangle$ for pions quantitatively whereas, only a qualitative evolution of kaons and protons $\langle p_T \rangle$ with increasing multiplicity could be observed. For a more quantitative description of experimental $\langle p_T \rangle$ evolution with multiplicity and particle mass, as well as to have better insight into the observed results of kaons & protons, in this work the analysis on $\langle p_T \rangle$ has been carried out with the PYTHIA 8.212 Monash generated data of different CR strength. To make comparison with experimental results more meaningful, the event classification in the PYTHIA 8.212 Monash generated data is performed on the number of charged particles produced in the pseudorapidity region $2 < \eta < 5$ and $-3.7 < \eta < -1.7$, in the same way as done in Ref. [35]. Then, the mean charged-particle multiplicity is estimated for $|\eta| < 0.5$. The results obtained with different sets of data with RR = 0.0, 1.8 (default), 3.0 and 3.6 are plotted in Fig. 7 and are compared with the published results of ALICE. It could be observed from the figure that for RR = 3.0 and 3.6, pions $\langle p_T \rangle$ are overestimated from the ALICE and...
default PYTHIA 8.212 Monash results. On the other hand, kaons and protons $\langle p_T \rangle$ can be described well by the results of RR = 3.0 and 3.6 for charged-particle multiplicity density greater than 13. However, for multiplicity density less than 13, although it underestimates ALICE results, the agreement is still better than the default RR value. These results suggest that the color reconnection mechanism can surely mimic to a significant extent, the mass-dependent hardening of experimental $\langle p_T \rangle$ of 13 TeV pp collision. The observed flow-like effect, produced by the CR does not require thermalisation or the formation of a medium. Moreover, the results obtained with PYTHIA 8.212 Monash model generated data for different CR strengths could not provide a quantitative and simultaneous description of $\langle p_T \rangle$ of $\pi$, $K$ and $p$ in all multiplicities. This behavior indicates that the boost generated by the CR mechanism may not be the only cause of mass-dependent hardening of $\langle p_T \rangle$ that is observed in experimental data. Also, these results provide a hint that mass-dependent hardening of $\langle p_T \rangle$ for $\pi$, $K$ and $p$ with increasing multiplicity can’t be considered as a clear signal of the hydrodynamic evolution of the system.

4 Summary

Transverse momentum spectra of the produced primary charged particles have been studied in pp collisions at the LHC energies using the Monte Carlo event generator PYTHIA 8.212 Monash and are compared with the pseudorapidity and $p_T$ spectra of the ALICE Collaboration for $\sqrt{s} = 7$ and 13 TeV. The results of default PYTHIA 8.212 Monash generated data are found to be in good agreement with the experimental data. With PYTHIA 8.212 Monash generated data, the $p_T$ spectra are observed to flatten with increasing charged-particle multiplicity. The variations of effective temperature and the average transverse momentum of the system as a function of multiplicity exhibit a plateau-like region in $T_{\text{Eff}}$ and $\langle p_T \rangle$ with increasing multiplicity. Since PYTHIA 8.212 Monash does not include QCD type phase-transition, the appearance of a plateau-like region with PYTHIA 8.212 Monash generated data hints that the aforesaid de-confinement transition may not necessarily be the only mechanism that could give rise to such an effect. A further study with PYTHIA 8.212 Monash generated data shows that the $T_{\text{Eff}}$ and $\langle p_T \rangle$ have no significant variation with charged-particle multiplicity when CR is switched off. On the other hand, with the increase of color reconnection strength, i.e., reconnection range (RR) value, the variations of $T_{\text{Eff}}$, and $\langle p_T \rangle$ against charged-particle multiplicity increase initially more sharply and then gradually saturates. No significant CR strength dependence variation of $T_{\text{Eff}}$ and $\langle p_T \rangle$ could be observed for RR = 3.0 and 3.6. Thus, from this study, it is evident that the color reconnection mechanism in PYTHIA 8.212 Monash has a significant effect on inclusive charged particles $p_T$ spectra, $T_{\text{Eff}}$ and $\langle p_T \rangle$ up to a certain threshold value of RR. The observed collective-like behavior such as flattening of $T_{\text{Eff}}$ and $\langle p_T \rangle$ for $N_{\text{ch}}>30$ could be a manifestation of the color reconnection between the partons produced in hard multi-particle interaction. Further studies on identified particles such as pions, kaons, and protons’ $\langle p_T \rangle$ with different values RR parameter of PYTHIA 8.212 Monash suggest that even though the color reconnection mechanism can mimic the mass-dependent hardening of $\langle p_T \rangle$ as observed in the ALICE experimental pp data, a simultaneous and quantitative description of the same is not possible with different strengths of the CR mechanism. These differences between the results of the MC and experimental data suggest that although the CR mechanism can mimic several collective-like effects as observed in the heavy-ion collisions, it may not be the only cause of collective-like behaviour observed in experimental data of pp collisions.
Fig. 7 Pions, kaons and protons average $p_T$ as a function of charged-particle multiplicity in $pp$ collisions at $\sqrt{s} = 13$ TeV for the PYTHIA 8.212 Monash generated data with different values of reconnection range (RR) parameter are compared with the results of the ALICE data

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Data availability statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: The PYTHIA 8.212 Monte Carlo model is an open access event generator. Further, all necessary information about the data has already been included in the manuscript in the form of tables and figures and thus there is no need to provide raw data as such.]

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