Effect of color reconnection and hadronic re-scattering on underlying events in p–p collisions at LHC energies

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Abstract Underlying events dominate most of the hadronic activity in p–p collisions and are spanned from perturbative to non-perturbative quantum chromodynamics (QCD), with sensitivity ranging from multi-scale to very low-x-scale physics. A detailed understanding of such events plays a crucial role in the accurate understanding of Standard Model (SM) and beyond Standard Model physics. The underlying event activity has been studied within the framework of the Pythia 8 Monte Carlo model, considering the underlying event observables mean charged particle multiplicity density \( \langle d^2N/d\eta d\phi \rangle \) and mean scalar \( p_T \) sum \( \langle d^2 \sum p_T / d\eta d\phi \rangle \) as a function of the leading charged particle in the towards, away, and transverse regions of p–p collisions at \( \sqrt{s} = 2.76, 7, \) and 13 TeV. The towards, away, and transverse regions have been defined on an azimuthal plane relative to the leading particle in p–p collisions. The energy dependence of underlying events and their activity in the central and forward regions have also been studied. The effect of hadronic re-scattering, color reconnection, and rope hadronization mechanism implemented in Pythia 8 has been studied in detail to gain insight into the different processes contributing to underlying events in the soft sector.

1 Introduction

A quintessential proton–proton (p–p) collision can be subdivided into two components: the primary hard partonic scattering and other associated activity collectively termed as underlying events (UEs). The cross section of interactions involved in primary hard scattering processes can be determined using perturbative quantum chromodynamics (pQCD) calculations as they involve sufficiently large momentum transfer, and therefore the strong interaction coupling constant is small. On the contrary, the production mechanism of underlying events occur at a lower momentum scale. In order to understand the recent Standard Model measurements at LHC and search for physical phenomena beyond the Standard Model (BSM), it is crucial to have a detailed understanding of the underlying events in p–p collisions [1,2].

Experimentally, the underlying events cannot be distinguished from the primary hard scattering process on an event-by-event basis, and one cannot uniquely determine the origin of the final-state hadrons. Therefore, the observables generally chosen to study the underlying events receive contributions from both hard scattering and underlying events. However, one can utilize the topology of hadron–hadron collisions to understand the accompanying interactions in p–p collisions apart from the initial hard scattering one [3,4].

The traditional approach has been used to study the observables sensitive to UEs on an event-by-event basis. In this approach, the leading particle (particle with highest \( p_T \)) is used to segment the \( \eta – \phi \) space into three distinct regions based on the azimuthal angular difference \( \langle \Delta \Phi \rangle \) relative to the leading particle as shown in Fig. 1. The leading particle acts as a proxy for the main flow of the hard scattering process [1]. The azimuthal angular difference is defined as \( \Delta \Phi = |\Phi – \Phi_L| \), where \( \Phi \) is the azimuthal angle of an outgoing charged particle in an event, and \( \Phi_L \) is the azimuthal angle of the charged particle having the highest transverse momentum \( p_T^{(\text{lead})} \) in the event. The towards region of \( \eta – \Phi \) space is defined as \( |\Delta \Phi| < 60^\circ \), and the away region is defined as \( |\Delta \Phi| > 120^\circ \). The two transverse regions defined as 60° < \( \Delta \Phi < 120^\circ \) and 60° < \( -\Delta \Phi < 120^\circ \) are referred to as the transverse 1 and transverse 2 regions. The transverse region is a combination of the transverse 1 and transverse 2 regions [1]. The towards and away regions are dominated by particles produced in hard processes, while the transverse
Monte Carlo model in the central region with underlying events has been explored using the Pythia 8.3 [6] generator for high-energy particle collisions to study collider physics. The hadronization framework is based on the Lund string model, which is significant when many overlapping strings are present. These strings act coherently to form stronger ropes, which would then be hadronized with larger, effective string tension. Due to rope formation, a smaller number of $q\bar{q}$ pairs is needed to break the rope but having an effective string tension. There is reduction in the rope tension when a new $q\bar{q}$ pair is produced in the process [11,12]. The Pythia 8 rope hadronization model describes the interaction between these strings by two mechanisms implemented as follows:

- **String shoving:** The model allows nearby strings to shove each other with an interaction potential derived from the color superconductor analogy.
- **Flavor ropes:** The model assumes formation of ropes between strings overlapping in a dense environment which is hadronized with larger, effective string tension.

The above mechanisms are expected to influence the event activity and hence can play an important role in the contributions to the underlying events. Therefore, it will be interesting to study the effects of these mechanism on the event observables in the transverse, towards, and away regions.

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**Fig. 1** The topology of $p$–$p$ collision where the azimuthal plane is segmented into towards, away, and transverse regions in an event defined by the $\Delta \phi$ angle relative to leading particle direction [13]
3 Results and discussion

The observables used to study the underlying events are defined as follows:

- Mean charged particle multiplicity density, $\langle d^2 N / d\eta d\phi \rangle$: defined as the number of charged particles per unit pseudo-rapidity ($\Delta\eta$) per unit azimuthal angular difference ($\Delta\phi$).
- Mean charged particle scalar $p_T$ sum, $\langle d^2 \sum p_T / d\eta d\phi \rangle$: defined as the $p_T$ sum of charged particles per unit pseudo-rapidity ($\Delta\eta$) per unit azimuthal angular difference ($\Delta\phi$) [1, 13].

The transverse region is further subdivided into a TransMAX and TransMIN region based on either transverse 1 or transverse 2 regions having the largest or smallest number of charged particles or mean scalar $p_T$ sum. The area factor is $\delta\phi = 2\pi/3$ for the towards, away, and transverse regions, while for the TransMAX and TransMIN regions it is $\delta\phi = \pi/3$. The particles are selected to have $p_T > 0.5$ GeV/c, with $|\eta| \leq 2.5$. The underlying event activity in the forward region has been explored for $-6.6 < \eta < -5.2$. Figures 2 and 3 show the variation of $\langle d^2 N / d\eta d\phi \rangle$ and $\langle d^2 \sum p_T / d\eta d\phi \rangle$ as a function of $p_T^{\text{lead}}$ for $p+p$ collisions at $\sqrt{s} = 13$ TeV. The Pythia 8 predictions are compared with the ATLAS measurements [13]. Recently, the hadronic re-scattering was introduced in Pythia 8 to study the effect of re-scattering of final-state hadrons on final observables [8]. The figures also depict the predictions with (and without) hadronic re-scattering. The general shape of the evolution is similar for the three regions; that is, it exhibits a characteristic rapid rise for low values of $p_T^{\text{lead}}$ with an abrupt change of around 4.5 GeV/c for $p_T^{\text{lead}}$. In the transverse region, the curve almost saturates, showing a plateau-like behavior, while for the other two regions it shows an increasing trend. This point of transition is mostly attributed to reduction in the impact parameter of $p+p$ interactions and hence a change from the soft to hard scattering regime. Therefore, one can see a continued activity from hard processes in the towards and away regions as the $p_T^{\text{lead}}$ increases, while the transverse region is least affected. This is consistent with the pedestal effect where the overlap between colliding protons is complete, and any further growth seen is related to hard processes or contamination from the same, rather than more MPI scattering. As the towards region includes the leading charged particle, the multiplicity is slightly lower compared to the away region, as there is less energy available for additional particle production. The increase of the $\sum p_T$ densities in the forwards and away regions indicates the partitioning of the energy in each region in terms of charged particle production. The towards and away regions are the active regions compared to the transverse for higher values of $p_T^{\text{lead}}$.

The effect of hadronic re-scattering for the $\langle d^2 N / d\eta d\phi \rangle$ is negligible at low $p_T^{\text{lead}}$, while for higher values it describes the data better in the forwards and away regions. In the transverse region, the hadronic re-scattering overpredicts the measured data. There is no effect of the hadronic re-scattering for $\langle d^2 \sum p_T / d\eta d\phi \rangle$.

Figures 4 and 5 show $\langle d^2 N / d\eta d\phi \rangle$ and $\langle d^2 \sum p_T / d\eta d\phi \rangle$ as a function of $p_T^{\text{lead}}$ in the TransMAX and TransMIN regions. The TransMIN region is dominated by the pedestal effect, while the TransMAX region receives contributions from MPIs and contamination from hard scattering processes. One can observe an increase in charged particle densities in the TransMAX region, with $p_T^{\text{lead}}$, as it receives contributions from hard processes, and the hadronic re-scattering slightly overpredicts the measured data. Similarly, for mean $\sum p_T$ densities, one can observe a slightly increasing trend in activity, with $p_T^{\text{lead}}$, for the TransMAX region, while it shows no activity in the TransMIN region with no effect of hadronic re-scattering in either of the regions.

The hadronic activity has been also studied in the forward regions (higher $\eta$ regions) where the contamination from hard scattering processes is expected to be minimal, and all three regions are therefore sensitive to the underlying events. Figures 6 and 7 show $\langle d^2 N / d\eta d\phi \rangle$ and $\langle d^2 \sum p_T / d\eta d\phi \rangle$ as a function of $p_T^{\text{lead}}$ in the forward region with $-6.6 < \eta < -5.2$. It can be observed that at low $p_T^{\text{lead}}$, there is a sharp rise in both $\langle d^2 N / d\eta d\phi \rangle$ and $\langle d^2 \sum p_T / d\eta d\phi \rangle$ with $p_T^{\text{lead}}$ in the towards, away, and transverse regions due to increased multi-partonic interactions, but from $\sim 4.0$ GeV/c onwards, both the observables saturates in all three regions. This interesting observation of the plateau in the towards and away regions is in contrast with the observation at the central region. This indicates the near absence of contributions from hard scattering processes in forward regions [5]. The effect of hadronic re-scattering is similar, as discussed earlier, in the towards, away, and transverse regions in the forward pseudo-rapidity region, as observed in central regions. Figures 8 and 9 show the same in the TransMAX and TransMIN regions at $\sqrt{s} = 13$ TeV, and the trend is similar to that observed in central regions.

The energy dependence of the underlying events in $p+p$ collisions have been studied at center-of-mass energy values of $\sqrt{s} = 2.76$, 7, and 13 TeV and have been shown in Figs. 10 and 11. One can observe that there is a strong rise in mean charged particle multiplicity and mean $\sum p_T$ densities with increasing $\sqrt{s}$ due to increased partonic event activity. It is also observed that on going from 2.76 TeV to 13 TeV, the mean charge multiplicity and mean scalar $p_T$ sum is almost doubled, which implies that the multi-partonic interaction (MPI) activity grows more with center-of-mass energy [14, 15]. It was also shown in reference [15] that the dependence on beam energy becomes vanishingly small as the charged particle densities are scaled by the relative rise in multiplicity.
Fig. 2 $\langle d^2N/d\eta d\phi \rangle$ as a function of $p_T^{lead}$ for the towards, away, and transverse regions in p–p collisions at $\sqrt{s} = 13$-TeV regions with (and without) the effect of hadronic re-scattering.

Fig. 3 $\langle d^2 \sum p_T / d\eta d\phi \rangle$ as a function of $p_T^{lead}$ for the towards, away, and transverse regions in p–p collisions at $\sqrt{s} = 13$-TeV regions with (and without) the effect of hadronic re-scattering.
Fig. 4 \( \langle d^2N/d\eta d\phi \rangle \) as a function of \( p_{\text{lead}}^T \) for the TransMAX and TransMIN regions in p–p collisions at \( \sqrt{s} = 13 \text{ TeV} \) regions with (and without) the effect of hadronic re-scattering.

The additional studies carried on the effect of color recon-nections can be observed in Figs. 12 and 13. The color reconnection mechanism plays a crucial role in the underlying event observables, as it governs the interactions between the partons of different \( p_T \) scales before the hadronization process. It modifies the particle production in the events with a large number of multi-partonic interactions. It can be seen that the estimations with color reconconnections are in good agreement with the measured data compared to the events without color reconconnections which overpredict the data, emphasizing the importance of the color reconnection mechanism [16]. Furthermore, it shows the comparison of three different modes of color reconnection (CR): MPI-based, QCD-based and gluon move-based models implemented in Pythia 8.

Fig. 5 \( \langle \sum p_T/d\eta d\phi \rangle \) as a function of \( p_{\text{lead}}^T \) for the TransMAX and TransMIN regions in p–p collisions at \( \sqrt{s} = 13 \text{ TeV} \) regions with (and without) the effect of hadronic re-scattering.

The effect of rope hadronization with the QCD-based color reconnection model on charged particle multiplicity density and mean scalar sum \( p_T \) has been shown as a function of \( p_{\text{lead}}^T \) at \( \sqrt{s} = 13 \text{ TeV} \) for the towards, away, and transverse regions in Figs. 14 and 15 for the string shoving and with flavor ropes. The rope hadronization mechanism describes the interaction of the overlapping strings produced in a small transverse area. The effect is more pronounced in high-multiplicity events and forms. The string shoving mechanism refers to the pushing action of nearby strings before hadronization and can increase the multiplicity due to gluon excitations. One observes an increase in mean charged particle multiplicity density for all three regions as an effect of the string shoving, and it describes the data better in the transverse region. The switching of the flavor rope mechanism...
Fig. 6 $\langle d^2N/d\eta d\phi \rangle$ as a function of $p_T^{\text{lead}}$ for the towards, away, and transverse regions in p–p collisions at $\sqrt{s} = 13$ TeV for $-6.6 < \eta < -5.2$ with (and without) the effect of hadronic re-scattering.

Fig. 7 $\langle d^2 \sum p_T/d\eta d\phi \rangle$ as a function of $p_T^{\text{lead}}$ for the towards, away, and transverse regions in p–p collisions at $\sqrt{s} = 13$ TeV for $-6.6 < \eta < -5.2$ with (and without) the effect of hadronic re-scattering.
enables the nearby strings to interact with each other to form color ropes. These ropes, due to increased string tension, preferably hadronize to massive particles. Therefore, there is a slight decrease in multiplicity density. There is a negligible effect of string shoving and flavor ropes on the mean scalar $p_T$ sum.

These studies, together with the predictions of other models like Herwig\textsuperscript{7} [17,18] and Sherpa [19], can act as a baseline for understanding the processes at the partonic and hadronic levels to understand the contribution of underlying events in future experimental studies.

### 4 Summary

The underlying event activity in p–p collisions has been studied at $\sqrt{s} = 2.76$, 7, and 13 TeV in the central and forward regions with $|\eta| < 2.5$ and $-6.6 < \eta < -5.2$, respectively, using the Pythia 8 event generator. The hadronic activity due to underlying events has been studied by segmenting the azimuthal plane the in towards, away, and transverse regions. The transverse region is sensitive to underlying event activity, while the towards and away regions receive dominant contributions from the primary hard scattering. The observables, mean charged particle multiplicity density ($\langle d^2N/d\eta d\phi \rangle$) and mean scalar $p_T$ sum ($\langle d^2\sum p_T/d\eta d\phi \rangle$) were investigated as a function of leading $p_T$ with (and without) the effect of hadronic re-scattering.
Fig. 10 \( \langle d^2 N / d\eta d\phi \rangle \) as a function of \( p_T^{\text{lead}} \) for the towards, away, and transverse regions for \( p-p \) collisions at \( \sqrt{s} = 2.76, 7 \) and 13 TeV.

Fig. 11 \( \langle \sum p_T / d\eta d\phi \rangle \) as a function of \( p_T^{\text{lead}} \) for the towards, away, and transverse regions for \( p-p \) collisions at \( \sqrt{s} = 2.76, 7 \) and 13 TeV.
Fig. 12 \( \langle d^2 N/d\eta d\phi \rangle \) as a function of \( p_T^{\text{lead}} \) for the towards, away, and transverse regions at \( \sqrt{s} = 13 \) TeV for different modes of color reconnections.

Fig. 13 \( \langle d^2 \sum p_T d\eta d\phi \rangle \) as a function of \( p_T^{\text{lead}} \) for the towards, away, and transverse regions at \( \sqrt{s} = 13 \) TeV for different modes of color reconnections.
Fig. 14 $\langle d^2N/d\eta d\phi \rangle$ as a function of $p_T^{\text{leading}}$ for rope hadronization with flavor ropes and string shoving.

Fig. 15 $\langle d^2 \sum p_T/d\eta d\phi \rangle$ as a function of $p_T^{\text{leading}}$ for rope hadronization with flavor ropes and string shoving.
hadronization has also been studied. This study can act as a baseline for fine-tuning of event generators, focusing on underlying events.

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