Chapter 11
Underlying Event Measurements Using CMS Detector at LHC

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Abstract Results of recent underlying event (UE) measurements using data collected by CMS detector are presented. UE measurements are done using events containing a leading charged particle jet, a leading charged particle, a Drell-Yan (DY) lepton pair, and a $t\bar{t}$ pair. Measurements are corrected to remove detector effect and are compared to various Monte Carlo (MC) predictions.

11.1 Introduction

The Underlying Event (UE) is composed of everything which is not originated from hard scatter outgoing partons (quarks and gluons). All QCD interactions except hard interactions constitute UE. The main components of UE are initial state radiations (ISR), final state radiations (FSR), multiple parton interactions (MPI) from semi-hard interactions and beam–beam remnants (BBR) concentrated along the beam direction. The UE measurements help in probing the hadron production in high energy p-p collisions. It is also an important background for precision measurements of new physics searches at LHC and MC modeling. In the present article, the results of UE measurements using leading charged particle & jet, Drell-Yan (DY) events, and $t\bar{t}$ pair are reported. Presented UE measurements are performed using 13 TeV p-p collisions data collected by CMS detector [1] at LHC [2].

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11.2 UE Measurements Using Leading Charged Particles and Jets

UE measurements are done using leading charged particles (jets) [3], having $p_T > 0.5$ GeV ($p_T > 1$ GeV) and $|\eta| < 2$ to ensure good reconstruction efficiency. The leading charged particles having $p_T > 0.5$ GeV and $|\eta| < 2.5$ are used to construct jets. The leading charged particle jets are constructed using the Seedless Infrared-Safe Cone (SIS Cone) jet algorithm. ZeroBias datasets are used for the present measurements, corresponding to an integrated luminosity of 281 nb^{-1}. Events with exactly one primary vertex are selected for the analysis. UE activity is measured in terms of the average charged particle density and average energy density of the leading charged particles (jets). The average charged particle density is defined as the number of tracks (N_{ch}) in any region divided by the area of the same region in η–ϕ space, and average energy density is the scalar sum of tracks transverse momenta (Σp_T) in any region divided by its area in η–ϕ space.

The regions of measurements are defined using the ϕ direction of leading charged particle (jet) as the reference direction:

- $\Delta\phi < 60°$: Towards
- $\Delta\phi > 120°$: Away
- $60° < \Delta\phi < 120°$: Transverse 1
- $-60° < \Delta\phi < -120°$: Transverse 2

$\Delta\phi$ is the difference between the ϕ direction of leading charged particle and any other charged particle. Among the Transverse 1 and Transverse 2 regions, the region having higher value of UE observables, i.e., the average charged particle density and average energy density is defined as TransMax region and another one as TransMin region.

In order to compare the data with various theory predictions, data measurements are corrected using RooUnfold package. Corrected distributions are compared with predictions of PYTHIA8, EPOS & Herwig++ MC samples. The predictions of Herwig++ fail in the low p_T region and EPOS fail in the plateau region. Overall Monash tune of PYTHIA8 provides the best description of data as shown in Fig. 11.1 (left). UE observables at $\sqrt{s} = 2.76$ TeV are compared with the measurements at $\sqrt{s}$ = 13 TeV, an increase of 60–70% is observed in UE activity with increase in $\sqrt{s}$ from 2.76 TeV to 13 TeV (shown in Fig. 11.1 (middle & right)). Increase is observed in the UE activity with increase in $\sqrt{s}$ since contribution from MPI increases with increasing $\sqrt{s}$.

11.3 UE Measurements Using DY Lepton Pair

UE measurements are performed using DY events with dimuon final state ($qq \rightarrow \mu^+\mu^-$) [4]. These events have a clean experimental signature and also theoretically well understood, which implies precise and accurate measurements of the UE activ-

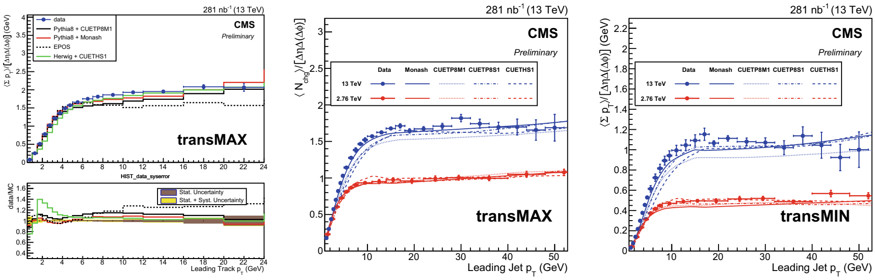

Fig. 11.1 Unfolded distribution of energy density as a function of leading track p_T is compared with MCs, i.e., PYTHIA8, EPOS, Herwig++, etc. predictions. Bottom panel shows the ratio of the corrected measurements to the MCs predictions (left). UE densities at 2.76 TeV are compared with the same at 13 TeV (middle & right). UE activity grows strongly (by 60–70%) with increase in centre-of-mass energy [3]

ity. UE activity is studied as a function of resultant transverse momentum ($p_T^{\mu\mu}$), using p-p collisions data corresponding to an integrated luminosity of 2.1 fb^{-1} and pileup (PU) $\sim$20. Events having at least two isolated muons with $p_T > 17$ GeV/c (8 GeV/c) for leading (subleading) muon are selected. Also selected events lie within a narrow mass window, $81 < M_{\mu\mu} < 101$ GeV/c^2 are having at least one well reconstructed vertex. Charged particles having $p_T > 0.5$ GeV and $|\eta| < 2$ are used for the analysis. Mis-reconstructed tracks are removed using high-purity reconstruction algorithm. Muons are reconstructed using particle-flow algorithm. Both muons are required to lie in the region, $|\eta| < 2.4$. Corrected data measurements are compared with different MC predictions, i.e., MADGRAPH + PYTHIA8, POWHEG + Herwig++, and POWHEG + PYTHIA8 MC combinations. Corrected distribution of particle density as a function of $p_T^{\mu\mu}$ in Away region is compared with different MC predictions as shown in Fig. 11.2. POWHEG in combination with Herwig++ overestimates the data by 10–15% whereas PYTHIA8 in combination with POWHEG and MADGRAPH show good agreement with data measurements having difference up to 5%. Charged particle density is also compared in Towards, Away, and Transverse regions (shown in Fig. 11.3 (left)). In Away region, fast rise is observed due to recoiling hadronic activity but in Towards and Transverse regions, growth is comparatively slow due to large spatial separation. UE measurements at $\sqrt{s} = 13$ TeV are compared with the previous measurements at $\sqrt{s} = 7$, 1.96 TeV presented in Fig. 11.3 (right). UE activity shows 25–30% rise on moving from 7 to 13 TeV and 60–80% on moving from 1.96 TeV to 7 TeV. For lower values of $p_T^{\mu\mu}$, POWHEG + PYTHIA8, POWHEG + HERWIG++ predictions show bit slow increase as compared to data measurements, but data-MC agreement improves for the higher values of $p_T^{\mu\mu}$.

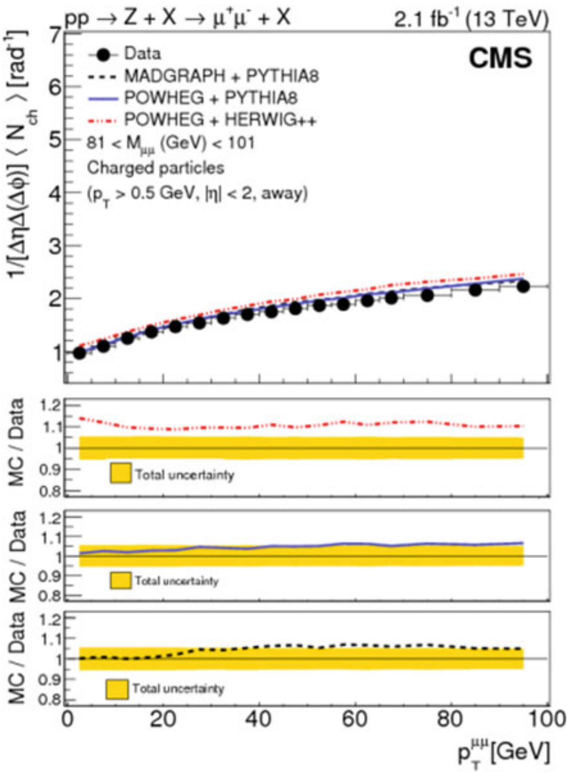

Fig. 11.2 Unfolded distribution of particle density as a function of $p_T^{\mu\mu}$ (Away region) is compared with MC predictions. POWHEG and MADGRAPH in combination with PYTHIA8 gives the best description of data (within 5%). Bottom panel shows the ratio of the corrected measurements to the MCs predictions [4]

11.4 UE Measurements Using $t\bar{t}$ Pair

UE measurements in $t\bar{t}$ pair production channel are performed using data collected at $\sqrt{s}$ = 13 TeV [5], corresponding to an integrated luminosity of 35.9 fb^{-1}. Events having one electron, one muon (having $p_T > 20$ GeV and $|\eta| < 2.4$) with opposite charge sign and two jets (originated from hadronization and fragmentation of b quarks) in final state are used for the measurements as this final state has high purity. Also the decay products of hard processes can be easily distinguished. Jets are reconstructed using the infrared and collinear safe anti-k_T algorithm. The jets having $p_T > 15$ GeV are selected for the measurements. Dilepton mass (m(ll)) distribution is compared to the sum of expectations of signal and background as shown in Fig. 11.4 (left). The m(ll) variable is estimated with a resolution >2%. Good resolution of m(ll) variable estimation implies precise measurements of UE dependence on the energy scale of hard process which is correlated with m(ll) variable. The

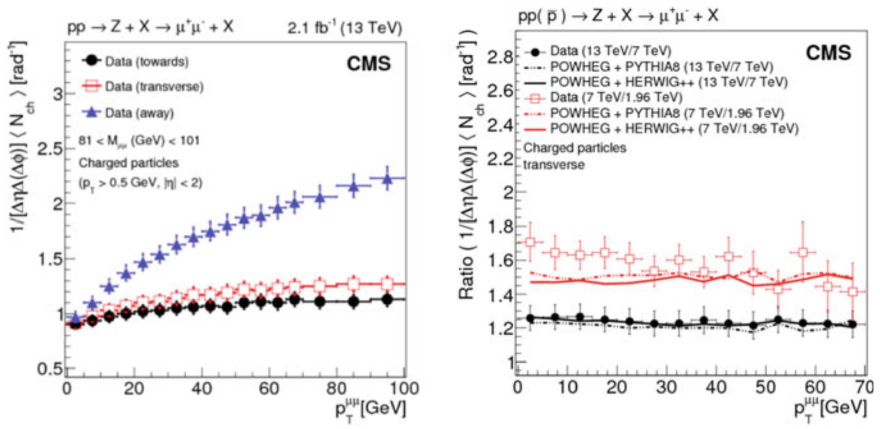

Fig. 11.3 The average charged particle density as a function of $p_T^{\mu\mu}$ is compared in the Away, Towards, and Transverse regions (left). The average charged particle at 13 TeV is compared with the previous measurements at 7 and 1.96 TeV (right) [4]

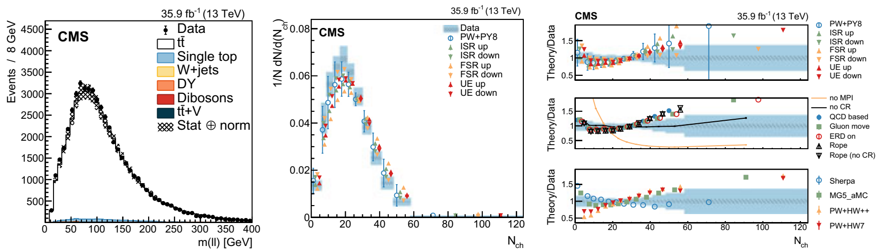

Fig. 11.4 Dilepton mass, m(ll) variable distribution is compared to the sum of expectations of signal and backgrounds (left). Shaded region represents the total uncertainty, i.e., systematic plus statistical. The differential cross section as a function of N_{ch} is compared to POWHEG + PYTHIA8 predictions as well as to different setups (middle). Corrected data is compared to different models (right). POWHEG + PYTHIA8 setup shows overall nice agreement with the data [5]

differential cross-sectional distribution as a funcion of N_{ch} (shown in Fig. 11.4 (middle)) is compared to the predictions of POWHEG + PYTHIA8 and different setups (in Fig. 11.4 (right)), obtained by varying the parameters of CUETP8M2T4 tune of PYTHIA8. POWHEG + Herwig++ and POWHEG + Herwig7-based setups show different behavior from PYTHIA8-based setups. POWHEG + PYTHIA8 combination provides the best description of data measurements.

11.5 Summary

The evolution of UE activity is studied as a function of centre-of-mass energy, and strong dependency is observed. UE measurements in top quark pair production show no deviation from universality hypothesis even at higher energies. The overall good description of the UE activity by MC predictions confirms the universality of the physical processes producing the underlying event in p-p collisions at high energies. Results obtained from UE measurements via different channels are valuable feedback to further constrain phenomenological models, useful for the understanding of particle production at low p_T.

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