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Underlying Event and Double Parton Scattering Measurements at CMS

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Abstract

Recent results on the double parton scattering studies and measurement of the underlying event activity, performed using proton-proton collisions data collected using the CMS detector are presented. Comparisons to previous results at different center of mass energies are also reported.

Keywords:

1. Introduction

Production of particles in a hadron-hadron collision involves parton-parton scatterings, initial-state radiation (ISR), final-state radiation (FSR), and beam-beam remnants (BBR) interactions. The large parton densities available in the proton-proton (pp) collisions at the CERN LHC result in a significant probability of more than one parton-parton scattering in the same pp collision, a phenomenon known as multiple parton interactions (MPIs). In general, MPI produces mostly low p_T particles and there is small probability of the production of high p_T particles from MPI. Double Parton Scattering (DPS) corresponds to events where two hard parton-parton interactions occur in a single proton-proton collisions. The combination of particle production from MPIs (excluding parton-parton scattering with highest momentum-transfer) and BBR interactions is called underlying event (UE) activity. There are number of CMS measurements on the UE/MPI/DPS at different energies. In this paper, we present recent results on measurement of UE activity using events with leading track and leading jet at centre-of-mass energy of 13 TeV [2],

Measurements of the UE activity using events with a Z-boson (with muonic decay) at a centre-of-mass energy of 13 TeV [1], and DPS measurement in same sign WW production in p-p collision at centre-of-mass energies of 8 [3] and 13 TeV [4].

2. UE Measurements at CMS

The experimental measurement of the UE requires a process that defines the scale of the hard parton-parton scattering, along with a phase space region with enhanced sensitivity to particle production from the UE activity. The UE measurements with different hard processes (high- p_T charged particles or jets, Z+jets events, and tbar+jets events) are useful in understanding the dependence on the nature of the hard process and on the scale of the interaction.

2.1. UE Measurement using leading charged particle tracks and charged jet

A measurement of the UE activity is performed in proton-proton collisions at the centre-of-mass energy of 13 TeV. The UE measurement is performed using leading charged-particles as well as leading charged-particle jets as reference objects. A leading charged-particle or charged-particle jet is required to be produced in the central pseudorapidity region ($|\eta| < 2$) and with transverse momentum $p_T > 0.5$ ($p_T^{jet} > 1$) GeV for leading charged-particle (charged-particle jet).

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The data used in this analysis are selected from an unbiased sample of events whenever there is a beam crossing in the CMS detector. This corresponds to an integrated luminosity of 281 nb^{-1} . Events with exactly 1 primary vertex within 10 cm of the beamspot in the z-direction, 2 cm in the xy-plane, and at least 5 degrees of freedom ($\text{dof} > 4$) are chosen.

Jets are constructed by clustering reconstructed tracks/particles within the interval of $|\eta| < 2.5$ and with $p_T > 0.5 \text{ GeV}$ using the Seedless Infrared-Safe Cone (SIS Cone) jet algorithm [5] with a distance parameter of 0.5. The UE activity is quantified in terms of the total number of charged particles (particle density) and the scalar sum of their p_T (Σp_T density), with $|\eta| < 2$ and $p_T > 0.5 \text{ GeV}$ in the region orthogonal to the azimuthal direction of the leading charged-particle or jet, referred to as the transverse region. The densities of particles within an azimuthal opening angle of ($60^\circ < |\Delta\phi| < 120^\circ$) with respect to the leading jet are defined as the transAVE densities. The transverse region can be split into 2 halves depending on the sign of $|\Delta\phi|$. The transMAX (transMIN) densities are then defined as the densities in the transverse half with a higher (lower) activity. The transDIF density is then defined as the difference of transMAX and transMIN densities. The average Σp_T and particle densities are measured as function of the p_T of the leading particles and jets.

The measurement of the UE activity in terms of the transMAX, transMIN, and transDIF densities improves the differential power in the quantification of the activity coming from MPI. The transMIN activity is expected to largely contain radiation coming from MPI and the transDIF activity is more sensitive to initial and final-state radiation. This differential power allows for improvements in the tuning of the model parameters describing the MPI. UE distributions are corrected to the stable charged particle level using the iterative D’Agostini method [6], which properly considers the bin-to-bin migrations. The systematic uncertainty due to the model dependency (up to 8% in the lowest few bins in p_T^{jet}) of the correction method contributes the most of the total systematic uncertainty. The rest of the uncertainties come from PU (4%), fake mis-modelling (2%), impact parameter significance (0.8%), and vertex degree of freedom (1.5%). In general, the systematic uncertainties vary between the densities in the different regions (transAVE/transDIF/transMAX/transMIN), and as a function of p_T and p_T^{jet} . The corrected distributions of the average particle and Σp_T densities as a function of the p_T of the leading jet/particle are compared with predictions by several Monte Carlo generator tunes.

The transMAX particle densities is shown in figure 1,

as a function of p_T^{jet} . The transAVE and transDIF distributions are not shown as they can be obtained from the transMAX and transMIN (not shown) densities. The measurements are better described by the Monash tune of PYTHIA8. The PYTHIA8 CUETP8M1 describe the measurements within 10–20%. The predictions by the CUETHS1 tune of HERWIG fails in the low p_T region. EPOS describes the low p_T rising region well but fails to describe the plateau region by 20%. Distributions for the average Σp_T densities (not shown) also reveal similar behaviour. In all plots, the densities increase sharply up to 5 (12–15) GeV and then rise slowly with increasing p_T (p_T^{jet}). The level of agreement between simulations and the measurements falls within 10–20% in the plateau region but differs in the low p_T region. The sharp rise with is interpreted in the MC models as due to an increase in the MPI contribution which reaches a plateau at high p_T . A slow increase in large p_T region is mainly due to the increase in the initial and final state radiation contribution. As MPI activity is expected to be uniform in the whole phase-space, the transMIN densities capture mainly the activity coming from MPI whereas transDIF densities give the evolution of the radiation with p_T of the reference object. Comparisons between various MC simulated samples and data across centre-of-mass energies of 0.9, 2.76, 7, and 13 TeV are made for transAVE as a function of p_T^{jet} as shown in figure 2. There is a strong rise in the UE activity as a function of the centre-of-mass energy as predicted by the MC tunes. The transMIN (not shown) densities exhibit a stronger $\sqrt{s}$ dependence than the transDIF (not shown) density, indicating that the activity coming from MPI grows more with $\sqrt{s}$ than that from ISR and FSR.

2.2. UE Measurement using Z-boson process

The Z-boson production is experimentally clean and theoretically well understood, allowing a clear identification of the UE activity. The UE measurement with Z-boson events is complementary to measurements with leading jet and leading track, which will corroborate the universality of the UE. Another advantage of using Z-boson events is the possibility of partial separation of MPI from the radiation contribution [7, 8], which can further improve the optimization of model parameters.

The analysis is performed with a data sample of pp collisions corresponding to an integrated luminosity of 2.1 fb^{-1} at a centre-of-mass energy of 13 TeV, collected using the CMS detector at the LHC [9]. Events are triggered with the requirement of at least two isolated muon candidates with $p_T > 17 \text{ GeV/c}$ and 8 GeV/c for leading and subleading muons respectively.

Figure 1: Comparisons of corrected transMAX average particle densities with the various simulations as a function of (top row) p_T and (bottom row) p_T^{jet} . The error bar represents the statistical and systematic uncertainties added in quadrature. Bottom panels show the ratio of the simulation with the measurements. The brown band in the bottom plot represents the statistical uncertainty in the corrected data whereas the total uncertainty is shown in the yellow band [2].

Figure 2: Comparisons of corrected transAVE particle densities with various simulations at $\sqrt{s} = 0.9, 2.76, 7,$ and 13 TeV as a function of p_{Tjet} [2].

The offline selection criteria require each event to have at least one well reconstructed primary vertex. A recommended tight muon selection is used for selecting the muons, which are required to have a p_T larger than 20 GeV/c and 10 GeV/c respectively, to match the trigger selection. Both muons are required to lie within range of $|\eta| < 2.4$. They are further required to be associated with the primary vertex that has the largest value of p_T squared sum of the associated tracks, designated as the signal vertex. The events with two oppositely charged muons are further required to have an invariant mass ($M_{\mu\mu}$) in the window of 81 – 101 GeV/c². After all the selections, there are about 1.3 million Z candidate events in the data, which is in agreement with simulated samples within 1 – 2% . Selected events have background contributions, mainly from top-quark and diboson processes, of about 0.3% .

In the selected Z-boson events, all the tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2$ are considered for the UE measurements. The track selection efficiencies for data and simulated samples agree within 4 – 5% .

The UE activity is again quantified in terms of the particle density and their Σp_T density. These observables are calculated in different phase-space regions defined with respect to the resultant azimuthal direction of the two selected muons, classified as *towards* region ($|\Delta\phi| < 60^\circ$), *transverse* region ($60^\circ < |\Delta\phi| < 120^\circ$), and *away* region ($|\Delta\phi| > 120^\circ$). The UE observables measured in different regions are studied as a function of p_T of the dimuon system ($p_T^{\mu\mu}$).

For the comparison with predictions from different simulations and tuning of model parameters, the UE distributions are corrected to the stable charged particle level using the iterative D’Agostini method [6], which properly considers the bin-to-bin migrations. At particle level, muons and charged particles are required to have the same kinematic selections as at detector level. The 4-dimensional response matrix is constructed using MADGRAPH + PYTHIA8 events, and is used to unfold the detector level distributions. The unfolded measured distributions can get biased due to the selection criteria and simulated samples used for the unfolding. Table 1 summarizes the dominant systematic uncertainties in the particle and Σp_T density.

The unfolded distributions of the UE activity as a function of $p_T^{\mu\mu}$ are compared with predictions from various simulations. In order to understand the MPI evolution with centre-of-mass energies, measurements are also compared with previous results from Tevatron and LHC.

Figure 3 shows the UE activity as a function of $p_T^{\mu\mu}$ at the centre-of-mass energy of $1.96, 7,$ and 13 TeV. The

Observable	Uncertainty
Model dependency	2–5%
Tracking efficiency	4–6%
Pileup	0.5%
Trigger	0.1%
Physics background	0.5–1%
Rochester momentum correction	0.4%–0.7%

Table 1: Summary of the systematic uncertainties in the particle and Σp_T density [1].

predictions of the POWHEG event generator with PYTHIA8, as well as with HERWIG++, are also shown. The ratios of simulations to the measurements are shown in the bottom panel of each plot. The POWHEG + PYTHIA8 predictions describe the measurements within 10% at centre-of-mass energies of 1.96 TeV and 7 TeV, and within 5% at 13 TeV. The combination of POWHEG and HERWIG++ describes the measurements within 10–15%, 10–20%, and 20–40% at a centre-of-mass energy of 13 TeV, 7 TeV, and 1.96 TeV respectively.

To quantify the energy dependence of the UE activity, events with a $p_T^{\mu\mu}$ smaller than 5 GeV/c are considered. An upper cut on $p_T^{\mu\mu}$ reduces the radiation contribution and the resulting UE activity is mainly from MPI. With a requirement of $p_T^{\mu\mu} < 5$ GeV/c, the UE activity is similar in the *towards* and *transverse* regions. Therefore, the UE activity is combined in these two regions. Figure 4 shows the UE activity, after an upper cut of 5 GeV/c on $p_T^{\mu\mu}$, as a function of the centre-of-mass energy for data and the simulated samples. The predictions from POWHEG + PYTHIA8, without MPI, are also shown. It is clear from the comparison of the distributions, with and without MPI, that there is very small contribution from radiation, which increases very slowly with centre-of-mass energy. The energy evolution is better described by POWHEG events hadronized with PYTHIA8, whereas hadronization with HERWIG++ overestimates the UE activity at all energies.

Figure 3: Comparison of UE activity measured at $\sqrt{s} = 13$ TeV with the measurements at 7 TeV and 1.96 TeV, by the CMS and CDF experiments, for particle density in the *transverse* region as a function of $p_T^{\mu\mu}$ [1]. The measured data distributions are also compared with predictions of POWHEG + PYTHIA8 and POWHEG + HERWIG++. The bottom panel of each plot reports the ratios of model predictions to the measurements. The error band in the bottom panel represents the statistical and systematic uncertainties added in quadrature.

Figure 4: Σp_T density, with $p_T^{\mu\mu} < 5$ GeV/c as a function of centre-of-mass energy for data, and predictions from simulations by POWHEG + PYTHIA8, and POWHEG + HERWIG++ [1]. The predictions of POWHEG + PYTHIA8 without MPI are also shown. Error bars represent the statistical and systematic uncertainties added in quadrature.

3. DPS Measurements at CMS

The study of DPS processes provides valuable information on the transverse distribution of partons in the proton [10] and on the parton correlations in the hadronic wave function [11, 12]. Under the assumption of transverse and longitudinal factorization of the two single parton interactions, the cross section of a double parton scattering (DPS) process can be written as

$$\sigma_{AB}^{\text{DPS}} = \frac{n}{2} \frac{\sigma_A \times \sigma_B}{\sigma_{\text{eff}}}, \quad (1)$$

where A and B denote the single parton scattering (SPS) processes, and σ_A and σ_B their respective SPS cross sections. The factor n is unity if processes A and B are the same, and $n = 2$ if $A \neq B$. The parameter σ_{eff} is related to the extent of the parton distribution in the plane orthogonal to the direction of motion of the protons. Study of the same-sign WW production via DPS, from p-p collisions at $\sqrt{s} = 8$ and 13 TeV at integrated luminosity of 19.7fb^{-1} and 35.9fb^{-1} respectively. The study is performed using same-sign W boson pair final state, with each boson decaying into a muon and an associated neutrino for 8 TeV measurements. For 13 TeV DPS measurements, the $\mu^+\mu^+$ final state is combined with the $e^+\mu^+$ channel, in order to enhance sensitivity. A multivariate analysis has been performed in order to enhance the signal sensitivity; a limit on the DPS yield, along with corresponding σ_{eff} , has been estimated.

The first step is involved in selecting an inclusive region of phase space with minimal cuts for trigger and some QCD suppression [3, 4].

After the event selection, the remaining background contributions include WZ production, backgrounds in which one of the two leptons is “fake”, as well as minor contributions of opposite-sign di-lepton events in which the charge of the electron is mis-measured, and rare processes such as tri-boson production, or ZZ production. Since the most important background is WZ production in which both bosons decay leptonically and one of the leptons from the Z boson is subsequently out of acceptance or not reconstructed, therefore a multivariate discriminator is trained with a boosted decision tree (BDT) algorithm in order to optimize the discrimination between the signal process and the WZ process.

Eleven input variables were selected which all exhibit differences in the signal and the WZ background.

As compared to 8 TeV DPS analysis, three new variables were included at 13 TeV measurement, namely the product of the two lepton- η 's, the absolute sum of the two lepton- η s, as well as the M_{T2}^l of the two-lepton system and the E_T^{miss} [3].

Results are obtained after combining all described backgrounds in the two separate flavor configurations, $\mu\mu$ and $e\mu$, and two separate charge configurations, $\ell^+\ell^+$, and $\ell^-\ell^-$, resulting in four independent distributions of the BDT classifier variable. Dividing into the two charge configurations maximizes the sensitivity of the analysis, since the signal process is enhanced in the $\ell^+\ell^+$ configuration, whereas the backgrounds exhibit more symmetry between the two charges.

Figure 5 and Figure 6 shows the distribution of the BDT classifier in $\mu^+\mu^+$ channel at 8 and 13 TeV respectively. Overall good agreement between the background predictions is observed in the low-BDT classifier region. A slight over-prediction of the background plus signal is seen in the high-BDT classifier region.

Figure 5: Final BDT classifier output with all background estimations in place for $\mu^+\mu^+$ channel. Observed data are shown in black markers with the signal pre-fit expectation as a red histogram and separately imposed as a red line to show the behavior of the signal in the BDT classifier. All backgrounds are shown with their post-fit values and uncertainties in the other colored histograms. Each plot features a ratio histogram showing the data compared to the background expectation with post-fit uncertainties [3].

At 8 TeV, although no direct measurements of DPS yield are made with current statistics, exclusion limit on DPS signal strength was set. BDT response shape gives the limit estimation, excluding at 95% CLs a signal strength $r > 1.897$ (28 DPS events), with an expected exclusion of $r > 2.01$ (30 DPS events), which means an upper limit on $\sigma_{WW}^{\text{DPS}} < 1.12$ pb at 95% of confidence level. Considering the two scattering to be independent and no correlation between interacting partons, the lower limit on σ_{eff} can be written as, $\sigma_{\text{eff}} > 5.91$ mb.

At 13 TeV, although from the PYTHIA8 cross section of 1.64 pb a significance of 3.27 is expected, the measured cross section is below that value at $1.09^{+0.50}_{-0.49}$ pb with a significance of 2.23σ . Conversely, applying the factorization approach with an expected cross section of

Figure 6: Final BDT classifier output with all background estimations in place for $\mu^+\mu^+$ channel. Observed data are shown in black markers with the signal pre-fit expectation as a red histogram and separately imposed as a red line to show the behavior of the signal in the BDT classifier. All backgrounds are shown with their post-fit values and uncertainties in the other colored histograms. Each plot features a ratio histogram showing the data compared to the background expectation with post-fit uncertainties [4].

0.87 pb, and an expected significance of 1.81σ results in a larger than expected cross section. The upper limit on the cross section in the absence of signal is expected to be < 0.97 pb and measured to be < 1.94 pb. This result presents the most precise measurement of the DPS WW process to date.

4. Summary

Measurement of UE activity at 13 TeV using events with inclusive Z Bosons and leading jets/tracks at 13 TeV are presented. There is scope of further improvements in the UE modeling, especially in the energy dependence. The present measurement, in combination with previous results, will be important for the further optimization of the model parameters in various simulations. DPS measurements using same-sign WW process at 8 and 13 TeV are also presented. DPS studies are important for better understanding of new physics searches and partonic structure of hadrons. In Figure 7 the CMS results for effective sigma at 8 and 13 TeV are compared to measurements done at different energies and final states by various experiments. Generally all measurements of σ_{eff} are consistent between each others. 13 TeV results are the most precise measurement of the DPS WW process to date.

Figure 7: The effective cross section of DPS, measured at various energies and final states by different experiments.

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