Chapter 16
Double Parton Scattering Measurements at CMS

Rajat Gupta

Abstract Recent results on double parton scattering (DPS) studies using data collected during Run 1 and Run 2 of the LHC with the CMS experiment are presented. Double parton scattering is investigated in several final states including vector bosons and multi-jets. Measurements of observables designed to highlight the DPS contribution are shown and compared to MC predictions from models based on multiple partonic interactions (MPIs) phenomenology.

16.1 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) [1]. 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.

16.2 DPS Measurements at CMS

The study of DPS processes provides valuable information on the transverse distribution of partons in the proton [2] and on the parton correlations in the hadronic wave function [3, 4]. Under the assumption of transverse and longitudinal factorization

R. Gupta—On behalf of the CMS collaboration.

R. Gupta (✉)
Panjab University, Chandigarh, India
e-mail: rajat.gupta@cern.ch; rajatgupta116@gmail.com

P. K. Behera et al. (eds.), *XXIII DAE High Energy Physics Symposium*,
Springer Proceedings in Physics 261,
https://doi.org/10.1007/978-981-33-4408-2_16

of the two single parton interactions, the cross section of a double parton scattering (DPS) process can be written as

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \times \sigma_B}{\sigma_{\text{eff}}} \tag{16.1}$$

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.

The production of same-sign ww production via DPS, from pp collisions of $\sqrt{s} = 8$ [5] and 13 TeV [6] at integrated luminosity of 19.7fb^{-1} and 35.9fb^{-1} respectively, is studied. 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. 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 dilepton events in which the charge of the electron is mismeasured, 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 [7] in order to optimize the discrimination between the signal process and the WZ process.

16.2.1 Constraints on the Double Parton Scattering Cross Section from Same-Sign W Boson Pair Production in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

A first search for same-sign W boson pair production via DPS in pp collisions at a center-of-mass energy of 8 TeV is performed. The results presented are based on the analysis of events containing two same-sign W bosons decaying into either same-sign muon-muon or electron-muon pairs. The analyzed data were collected by the CMS detector at the LHC during 2012 and correspond to an integrated luminosity of 19.7 fb^{-1}. Table 16.1 shows the list of same-sign WW selection criteria chosen to reduce various background processes. The majority of background events originate from processes in which one or both of the leptons, coming from leptonic decays of heavy quarks or in-flight decays of light mesons, pass the event selection criteria.

Thirteen input variables were selected, which exhibit differences in the signal and the WZ background. Overall, the data and simulation are found to be consistent within the uncertainties for all input variables. The BDT discriminant after the full

Table 16.1 Event selection criteria for same-sign W boson pair production in dimuon and electron-muon channels [5]

Dimuon channel	Electron-muon channel
Pair of same-sign leptons	
Leading lepton $p_T > 20$ GeV	
Subleading lepton $p_T > 10$ GeV	
No third isolated and identified lepton with $p_T > 10$ GeV	
$p_t^{\text{miss}} > 20$ GeV	
$m_{ll} > 20$ GeV	
$m_{ll} \notin [75, 105]$ GeV	–
$\lvert p_{T_{\mu_1}} \rvert + \lvert p_{T_{\mu_2}} \rvert > 45$ GeV	–
	No b-tagged jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.1$

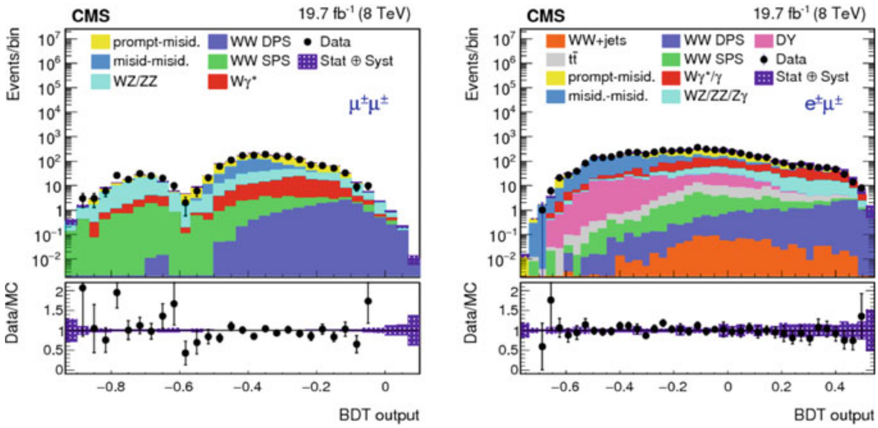

Fig. 16.1 Distribution of the BDT discriminant, for the dimuon channel (left) and for the electron-muon channel (right). The data are represented by the black dots and the shaded histograms represent the pre-fit signal and post-fit background processes. The bottom panels show the ratio of data to the sum of all signal and background contributions [5]

event selection has been applied, is used to extract the limits on the DPS cross section and σ_{eff} using statistical analysis techniques.

The expected and observed upper limits at 95% confidence level (CL) on the cross section for inclusive same-sign WW production via DPS have been extracted. Figure 16.1 shows the distributions of the BDT discriminant having post-fit contributions for the backgrounds and pre-fit ones for the signal, for the dimuon and electron-muon final states with the corresponding uncertainty bands (shown as hatched bands). The expected and observed 95% CL limits on the cross section for same-sign WW production via DPS ($\sigma^{\text{DPS}}_{W^\pm W^\pm}$) are summarized in Table 16.2.

Table 16.2 Expected and observed 95% CL limits on the cross section for inclusive same-sign WW production via DPS for the dimuon and electron-muon channels along with their combination [5]

95% CL	Dimuon	Electron-muon	Combined
Expected	0.67 pb	0.78 pb	0.48 pb
Expected $\pm 1\sigma$	[0.46, 1.00] pb	[0.52, 1.16] pb	[0.33, 0.72] pb
Expected $\pm 2\sigma$	[0.34, 1.45] pb	[0.37, 1.71] pb	[0.24, 1.04] pb
Observed	0.72 pb	0.64 pb	0.32 pb

Assuming the two scatterings to be independent, a limit can be placed on σ_{eff}. A lower 95% CL limit on σ_{eff} can be calculated as

$$\sigma_{\text{eff}} > \frac{\sigma_{W^+}^2 + \sigma_{W^-}^2}{2\,\sigma_{W^\pm W^\pm}^{\text{DPS}}} = 12.2\text{mb}.$$

The obtained lower limit on σ_{eff} is compatible with the values of $\sigma_{\text{eff}} \approx 10$–$20$ mb obtained from measurements at different center-of-mass energies using a variety of processes [8].

16.2.2 Measurement of Double Parton Scattering in Same-Sign WW Production in p-p Collisions at $\sqrt{s} = 13$ TeV with the CMS Experiment

Same-sign $W^\pm W^\pm$ production in which the bosons originate from two distinct parton-parton interactions within the same proton-proton collision is studied in the $\mu^\pm\mu\pm$ and $e^\pm\mu\pm$ final states. A data set of 35.9 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC in 2016, is used. The summary of all kinematic selection imposed at 13 TeV is given in Table 16.3.

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 two lepton-η's, as well as the M_{T2}^{ll} of the two-lepton system and the E_T^{miss}.

Table 16.3 Event selection criteria for same-sign W boson pair production in dimuon and electron-muon channels [6]

Two leptons $e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$
$p_{T\,1\ 2} > 25\ 20$ GeV
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
MET > 15 GeV
nj < 2
nb == 0
Veto on additional leptons
Veto on hadronic τ leptons

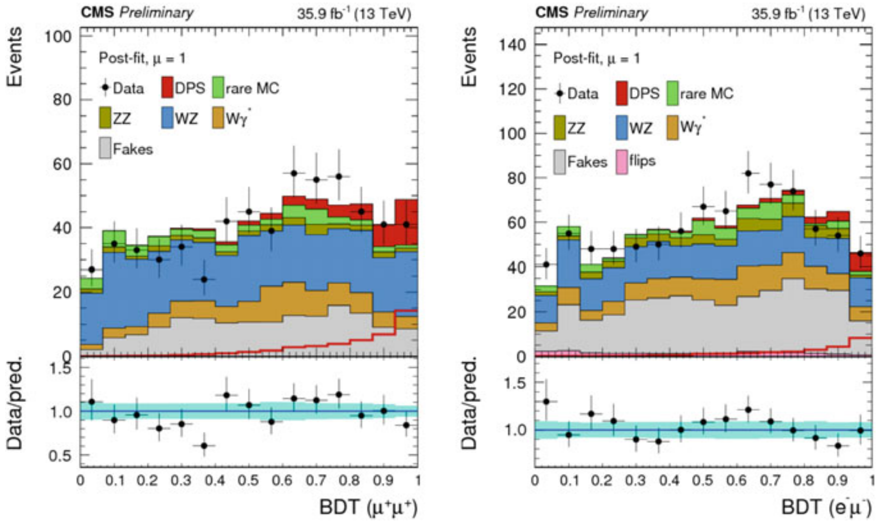

Fig. 16.2 Final BDT classifier output with all background estimations in place for $\mu^+\mu^-$ and $e^-\mu-$ channel. Observed data are shown in black markers with the signal pre-fit expectation as a red histogram and separately imposed as a red line to show the behavior of the signal in the BDT classifier [6]

Table 16.4 Results obtained from a constrained fit to the BDT classifier [6]

	Expected	Observed
$\sigma_{\mathrm{DPSWW}}^{\mathrm{pythia}}$	1.64 pb	$1.09^{+0.50}_{-0.49}$ pb
$\sigma_{\mathrm{DPSWW}}^{\mathrm{factorized}}$	0.87 pb	
Significance for $\sigma_{\mathrm{DPSWW}}^{\mathrm{pythia}}$	3.27 σ	2.23 σ
Significance for $\sigma_{\mathrm{DPSWW}}^{\mathrm{factorized}}$	1.81 σ	
UL in the absence of signal	<0.97 pb	<1.94 pb

Figure 16.2 shows the distribution of the BDT classifier in one of the $\mu^+\mu+$ and $e^-\mu-$ channel. Overall good agreement between the background predictions is observed in the low-BDT classifier region. Indicative from Fig. 16.2, and evident from Table 16.4, the observed yield of the DPS WW signal process is lower than the expectation. Therefore, 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 2.23 σ. Conversely, applying the factorization approach with an expected cross section of 0.87 pb, and an expected significance of 1.81 σ 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.

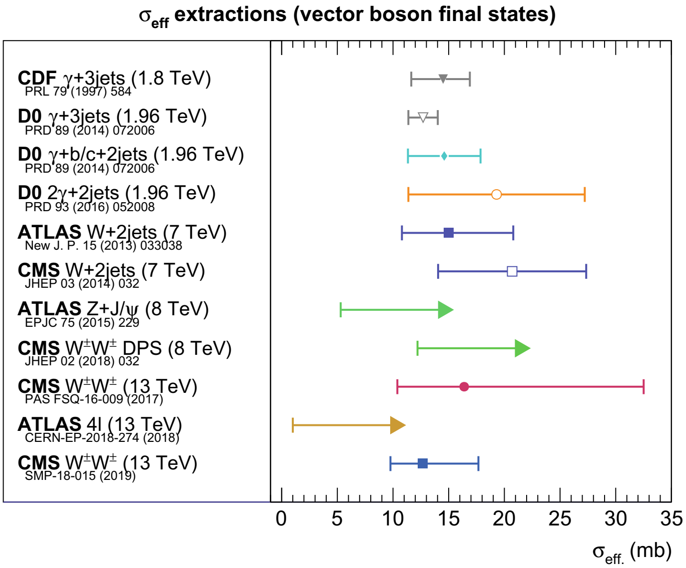

Fig. 16.3 The effective cross section of DPS measured at various energies and final states by different experiments

16.3 Summary

DPS measurements using same-sign WW process at 8 and 13 TeV are presented. DPS studies are important for better understanding of new physics searches and partonic structure of hadrons. In Fig. 16.3, 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 other.

References

1. T. Sjostrand, M. van Zijl, A multiple interaction model for the event structure in Hadron collisions. Phys. Rev. D **36**, 2019 (1987). https://doi.org/10.1103/PhysRevD.36.2019
2. M. Diehl, D. Ostermeier, A. Schafer, Elements of a theory for multiparton interactions in QCD. JHEP **1203**, 089 (2012). Erratum: [JHEP **1603**, 001 (2016)]. https://doi.org/10.1007/JHEP03(2012)089, https://doi.org/10.1007/JHEP03(2016)001
3. D. Treleani, G. Calucci, Inclusive and exclusive cross-sections, sum rules. Adv. Ser. Direct. High Energy Phys. **29**, 29 (2018). https://doi.org/10.1142/9789813227767_0003, arXiv:1707.00271 [hep-ph]
4. M. Rinaldi, S. Scopetta, V. Vento, Double parton correlations in constituent quark models. Phys. Rev. D **87**, 114021 (2013). https://doi.org/10.1103/PhysRevD.87.114021, arXiv:1302.6462 [hep-ph]

5. A.M. Sirunyan et al., [CMS Collaboration], Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV. JHEP **1802**, 032 (2018). https://doi.org/10.1007/JHEP02(2018)032, arXiv:1712.02280 [hep-ex]
6. CMS Collaboration, Measurement of double parton scattering in same-sign WW production in p-p collisions at $\sqrt{s} = 13$ TeV with the CMS experiment, CMS-PAS-FSQ-16-009 (2017)
7. A. Hocker et al., TMVA—Toolkit for multivariate data analysis. physics/0703039 [physics.data-an]
8. S. Chatrchyan et al., [CMS Collaboration], Study of double parton scattering using W + 2-jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV. JHEP **1403**, 032 (2014). https://doi.org/10.1007/JHEP03(2014)032, arXiv:1312.5729 [hep-ex]