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Double Parton Scattering Measurements at the CMS Experiment

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Recent results relevant for the characterization of double parton scattering are presented by the CMS experiment. These results include studies of complex final states like multiple jets (including b-tagged jets); vector bosons accompanied by jets; and same-sign vector boson pairs, at various LHC energies in proton-proton collisions. Evidence for DPS processes is provided by comparisons with phenomenological models. Cross sections of various DPS processes are measured, or an upper limit is set; and a translation to the effective DPS cross section parameter within the factorization assumption is given, including a comparison of numerous results from other experiments and accelerators.

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1. Introduction

The idea of multi-parton interactions (MPI) dates back to the invention of the parton model. When more than one hard parton-parton scattering happens in a single p+p interaction, the final state may contain objects that are less likely to be produced by a single-parton scattering (SPS) process, or objects that exhibit different (less) correlations in angle or momentum. The charged particle multiplicity and the underlying event accompanying a hard-scattered parton are all sensitive to MPI. The study of double parton scattering (DPS) processes provides valuable information on the transverse distribution of partons in the proton and on the multi-parton correlations in the hadronic wave function. The probability of a DPS is quantified by the effective cross section, σ_{eff}. The inclusive cross section of the simultaneous occurrence of processes A and B in hadron-hadron collisions, $\sigma_{\mathrm{DPS}}^{\mathrm{A+B}}$, can be written as

$$\sigma_{\mathrm{DPS}}^{\mathrm{A+B}} = \frac{m}{2}\frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}},$$

where σ_{A} and σ_{B} are the inclusive cross sections of the individual processes A and B, $m = 1$ when A and B are identical, while $m = 2$ when they are distinguishable. The effective cross section represents the transverse interaction area where double parton interactions take place. The contributions from DPS processes increase with center-of-mass energies as the gluon density becomes large at low x. Therefore, the LHC is an ideal tool to study DPS processes in various final state channels.

Double parton scattering can be studied by looking for signatures like four jets; two jets and a vector boson; three jets and a photon; or multiple same-sign vector bosons. The LHC opens the door for investigations of high mass (or momentum) final states. Experimentally, those studies are challenged by the background of the same final state produced by a single parton scattering. Background estimations that involve multi-particle final states usually rely partially on data as well as on phenomenological calculations to increase the much desired precision. In these proceedings, selected CMS results are presented on DPS using various final states.

2. Final states with jets

Proton-proton collisions with four high-p_{T} jets in the final state can be investigated for contributions of DPS. It is useful to identify (tag) two of these jets originating from a b (or anti-b) quark, as they may come from a separate hard scattering with respect to the light jets. Thus, various kinematical distributions between the two b-jets and the two light jets can be compared to models including (or ignoring) MPI. One of these kinematical variables is ΔS, the azimuthal angle difference between the two dijet pairs; its distribution is presented on Fig. 1. For the MPI, the correlation between the b-jets and the light jets is expected to be weak, leading to a significant MPI contribution at low ΔS. This is visible on Fig. 1, where the data is well described by perturbative QCD calculated at NLO with parton shower and MPI, while these dijet angular correlations do not agree with models where the MPI process is not activated [1]. The measured cross section of the inclusive four-jet final state with two b-jets was found to be $\sigma(\mathrm{pp} \to \mathrm{bb} + \mathrm{jj} + \mathrm{X}) = 69 \pm 3$ (stat.) ± 24 (syst.) nb for the kinematic region of $p_{\mathrm{T}} > 20$ GeV and $|\eta_{\mathrm{b(j)}}| < 2.4(4.7)$.

Signs of the MPI process can be also found in events with jets and a W boson in the final state, in the $W \to \mu\nu$ channel. The analysis method involved a template fit to kinematical distributions,

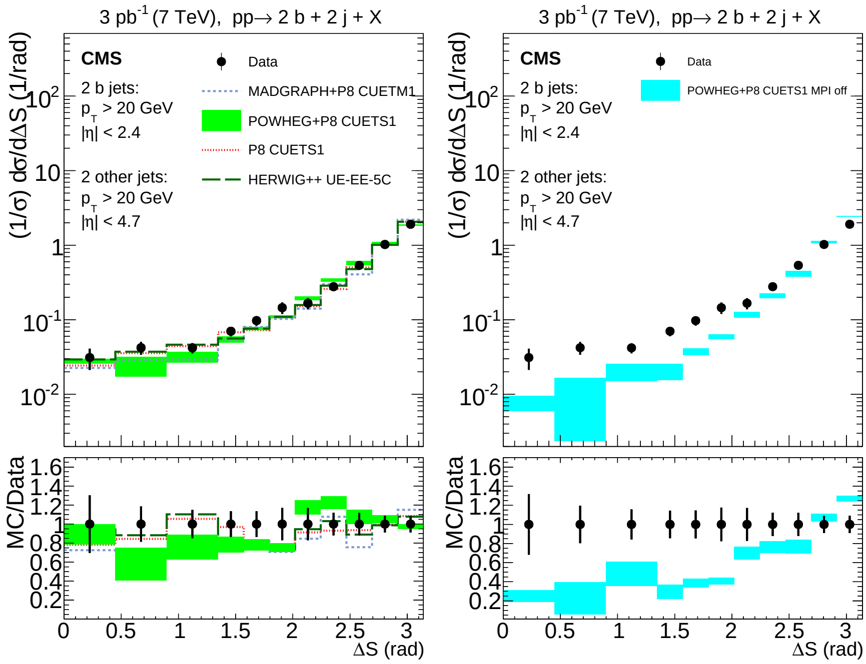

Figure 1: Normalized cross sections as a function of ΔS, compared to the POWHEG, MadGraph, PYTHIA 8 (P8) and HERWIG++ models (left), and to the POWHEG+PYTHIA 8 tune CUETS1 without MPI (right) [1]. The lower panels show the ratios of the MC predictions over the data. The error bars on the represent the total uncertainties, while the band shows the theoretical uncertainty.

like the the relative p_{T}-balance between the two jets, defined as the ratio of the vectorial sum and the scalar sum of the jet momenta, $\Delta^{\mathrm{rel}} p_{\mathrm{T}}$, or the azimuthal angle between the W boson and the dijet system, ΔS. Those distributions can be seen on Fig. 2. The fraction of W+jets events originating from the DPS process was found to be 0.055 ± 0.002 (stat.) ± 0.014 (syst.). The conclusion from the comparison of the data with the MadGraph 5 + PYTHIA 8 and with the POWHEG 2 + PYTHIA 6 models is that MPI is necessary for an agreement between experiment and theory. Quantitatively, the result for the effective cross section is $\sigma_{\mathrm{eff}} = 20.7 \pm 0.8$ (stat.) ± 6.6 (syst.) mb [2].

3. Final states with vector boson pairs

DPS was also studied in same-sign vector boson pair production, using the $W^{\pm}W^{\pm} \to \mu^{\pm}\mu^{\pm}$ + MET and the $W^{\pm}W^{\pm} \to \mathrm{e}^{\pm}\mu^{\pm}$ + MET decay channels in the data set collected in 2016 at 13 TeV. While this process may originate from DPS naturally, the lowest-order Feynman diagrams leading to same-sign W pair production in SPS always indicate a presence of two high-energy jets in the final state. Therefore, a veto on more than one jets was employed to suppress the SPS background. The leading and sub-leading charged lepton was required to be in the $p_{\mathrm{T}} > 25$ GeV and $p_T > 20$ GeV range, respectively. Furthermore, events with at least 15 GeV missing energy were selected in order to enhance collisions producing neutrinos. No b-jets above a p_{T} of 25 GeV, nor additional leptons were allowed in the same collision, followed by a veto on hadronic τ decays.

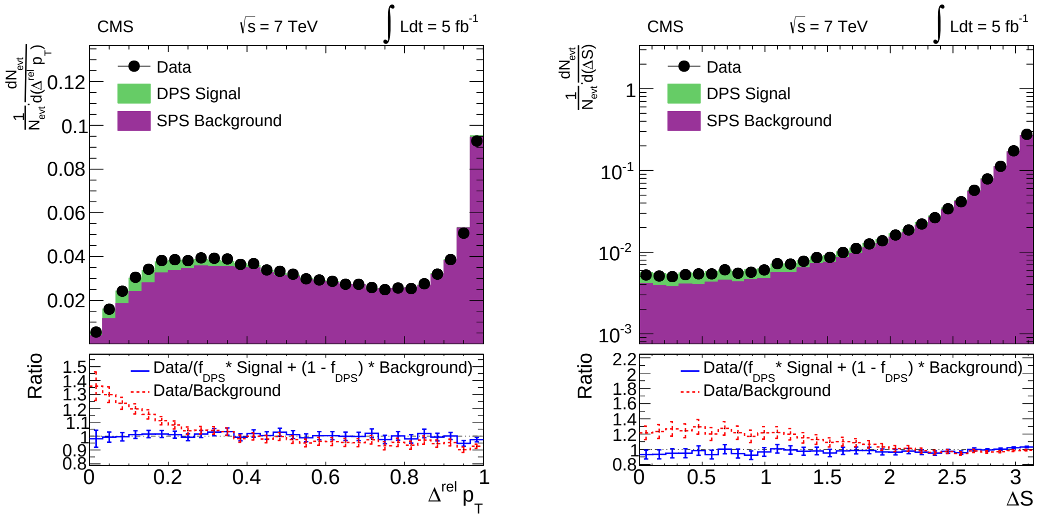

Figure 2: Fit results for the DPS-sensitive observables $\Delta^{\text{rel}} p_{\text{T}}$ (left) and ΔS (right) [2]. Corrected data distributions are fitted with signal and background templates.

A boosted decision tree classifier was used to distinguish the signal from background, assembled from 11 sensitive kinematical variables. The distribution of the output of the BDT classifier is plotted on Fig. 3 for the $\mu^{\pm}\mu^{\pm}$ final state, where the various background contributions are represented by the stacked colored histograms. The expected background yield in the $\mu^{+}\mu^{+}$ final state is 578.6 ± 50.3, while the expected signal yield is 41.1 ± 1.0, and 604 events have been observed in 35.9 fb^{-1} of data. For negative muon pairs, these numbers are 409.2 ± 38.2, 20.6 ± 0.5 and 411, respectively. A fit to the constrained BDT classifier provides a cross section for the DPS process of $1.09^{+0.50}_{-0.49}$ pb (2.23 σ), while the prediction of the PYTHIA 8 event generator is 1.64 pb. The observed upper limit in the absence of the signal is 1.94 pb [3].

A similar analysis was recently completed and published at 8 TeV by the CMS experiment, measuring same-sign W boson pairs using 19.7 fb^{-1} of data [4]. Besides the pair of same-sign leptons, which had to exceed a p_{T} of 20 (10) GeV for the leading (sub-leading) one, no further isolated and identified lepton was allowed in the same collision in the $p_{\text{T}} > 10$ GeV range. The minimal missing energy as well as the minimal dilepton mass requirement was placed at 20 GeV. The dilepton mass was not allowed to be close to the Z boson mass, i.e. in the $75 < m_{\text{ll}} < 105$ GeV range. The scalar sum of the lepton momenta had to exceed 45 GeV, and b-jets were not allowed in the final state in the $p_{\text{T}} > 30$ GeV and $|\eta| < 2.1$ range.

A boosted decision tree was used to characterize events based on various kinematical variables. The distribution of the BDT discriminant in the $\mu^{\pm}\mu^{\pm}$ and in the $e^{\pm}\mu^{\pm}$ channels is presented in Fig. 4. With the available data statistics, no significant excess could be observed above the SPS process, and the upper limit observed for the DPS process was 0.32 pb with a 95% confidence level. Therefore, a lower limit of 12.2 mb was set for the effective cross section parameter σ_{eff} with the same CL. The left panel of Fig. 5 summarizes these limits for the dimuon and for the electron-muon channels as well as for the combined one. All these limits are consistent with both the predictions by the PYTHIA 8 event generator and with the factorization approach for the DPS cross section. The summary of some of the effective DPS cross section measurements, including those discussed

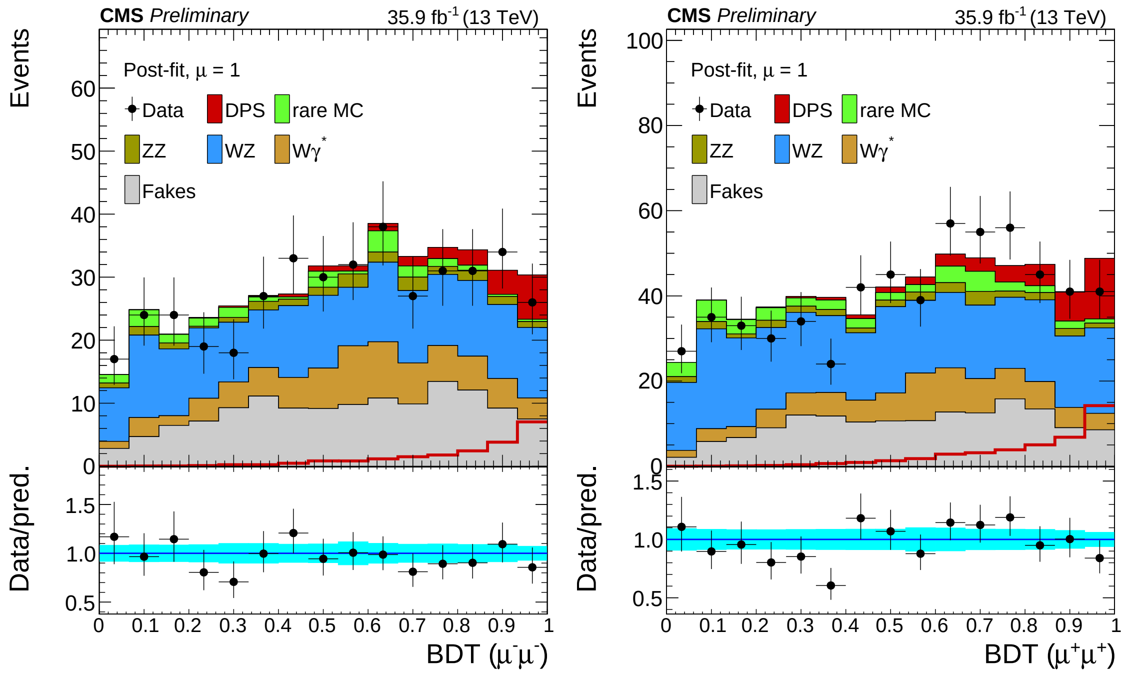

Figure 3: Final Boosted Decision Tree classifier output with all background estimations in place for $\mu^-\mu^-$ (left) and $\mu^+\mu^+$ (right) pairs [3]. Observed data are shown in black markers with the signal pre-fit expectation as a red histogram and separately imposed as a red line to show the behavior of the signal in the BDT classifier. Backgrounds are shown by colored histograms. Each plot features a ratio histogram showing the data compared to the signal+background expectation.

above, is shown on the right panel of Fig. 5.

In summary, multi-parton interactions are studied in the CMS experiment in various channels involving multiple jets, vector bosons with multi-jets and vector boson pairs. Experimental challenges include designing appropriate and sensitive observables to DPS; advanced multivariate analysis methods, and collecting data with a high integrated luminosity with appropriate on-line selections. This active research field provides important new observations of processes with remarkably small cross sections, testing the Standard Model in an interesting and extreme corner of the possible final states. With more data being collected, new opportunities open up in quantitative measurements of double parton scattering.

Acknowledgments

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References

[1] CMS Collaboration, V. Khachatryan et al., *Studies of inclusive four-jet production with two b-tagged jets in proton-proton collisions at 7 TeV*, *Phys. Rev.* **D94** (2016) 112005 [1609.03489].

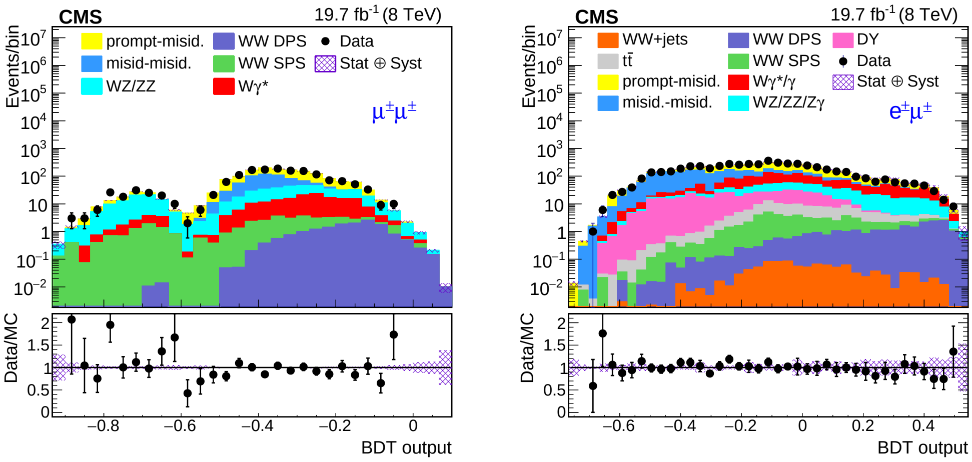

Figure 4: Distribution of the Boosted Decision Tree discriminant, for the dimuon channel (left) and for the electron-muon channel (right) [4]. The data are represented by the black dots and the shaded histograms represent the pre-fit signal and post-fit background processes. The bottom panels show the ratio of data to the sum of all signal and background contributions. The hatched bands include both the statistical and systematic uncertainties.

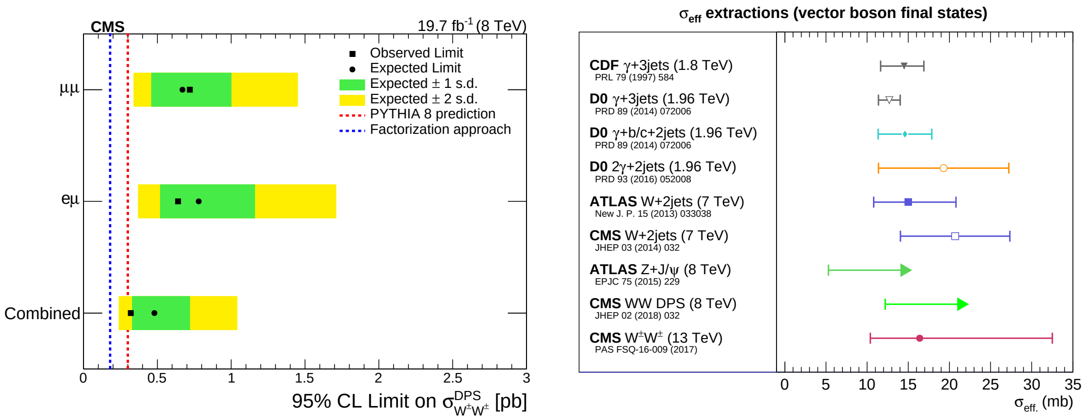

Figure 5: Left: expected and observed upper limits corresponding to 95% confidence level on the same-sign $\sigma^{\mathrm{DPS}}_{\mathrm{W^\pm W^\pm}}$ for the dimuon and electron-muon final states at 8 TeV, along with their combination [4]. The predicted values of $\sigma^{\mathrm{DPS}}_{\mathrm{W^\pm W^\pm}}$ from PYTHIA 8 and from the factorization approach are also shown. Right: summary of some of the σ_{eff} measurements involving final states with jets, photons and vector bosons.

[2] CMS Collaboration, S. Chatrchyan et al., *Study of double parton scattering using W + 2-jet events in proton-proton collisions at $\sqrt{s}$ = 7 TeV*, *JHEP* **03** (2014) 032 [1312.5729].

[3] 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*, Tech. Rep. CMS-PAS-FSQ-16-009, https://cds.cern.ch/record/2257583, CERN, Geneva, 2017.

[4] CMS Collaboration, A. M. Sirunyan et al., *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* **02** (2018) 032 [1712.02280].