PROCEEDINGS OF SCIENCE

Double parton scattering studies in CMS

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The double parton scattering (DPS) process in proton-proton collisions at a center-of-mass energy of 7 and 13 TeV has been investigated using various final states. This includes multi-Jets, including b-jets, as well as same-sign W bosons with each W boson decaying into a lepton and associated neutrino. The observables most sensitive to double parton scattering are defined and studied. A multivariate analysis is developed in order to enhance the DPS sensitivity. A limit on the DPS yield has been evaluated.

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1. Introduction

In high energy proton-proton (pp) collisions at the LHC, due to the composite nature of protons, it is possible to have two or more distinct hard parton-parton interactions occurring simultaneously in a single pp collision. At fixed final state invariant masses, such cross sections tend to increase with collision energy because partons with successively lower momentum fractions are being probed. Multiple soft parton-parton collisions are called multiple parton interactions (MPI), in contrast with those where only a single pair of partons produces a hard scattering, referred as single parton scattering (SPS). Large hadronic activity is observed in the soft regime, characterized by small transverse momenta (p_T) of the produced particles. For relatively large p_T values, the observation of MPI will mostly focus on two simultaneous hard scatterings, i.e. on double parton scattering (DPS)[1].

The effective cross section, σ_{eff}, is a measure of the transverse distribution of partons inside the colliding hadrons and their overlap in a collision. If A and B are two independent processes, whose production cross sections are σ_A and σ_B, respectively, σ_{eff} can be expressed in terms of the DPS cross section (σ^{DPS}_{A+B}) and the single process cross sections by:

$$\sigma_{eff} = \frac{m \cdot \sigma_A \cdot \sigma_B}{\sigma^{DPS}_{A+B}} \tag{1.1}$$

where the symmetry factor m = 1/2, if processes A and B are identical otherwise m = 1.

2. DPS using same-sign W boson pairs

A useful feature of same-sign W boson pair production is the cross section, of the order of 10^{-1} pb, which has comparable contribution for DPS and SPS, whereas the opposite-sign W pair production cross section for SPS events dominates over the DPS one by a factor of $\approx$ 100[2].

This analysis studied DPS events with two same sign leptons and two respectively associated neutrinos in the final state at 13 TeV[3]. The data sample corresponds to an integrated luminosity of 35.9 fb^{-1}, recorded by the CMS experiment in 2016. A detailed description of the CMS detector can be found elsewhere[4]. In case of DPS the two W bosons are produced in first approximation independent of each other, and they are expected to be randomly distributed in the azimuthal plane and with less p_T as compared to SPS production. Hence, the muons produced from DPS are less boosted as compared to the leptons produced from SPS, and there would not be any correlation between the two muons in the azimuthal plane.

Events are selected by requiring exactly two leptons, electron or muon, of the same electric charge with p_T greater than 25 (20) GeV for the leading (subleading) lepton, and $|\eta|$ < 2.5 (2.4) for electrons (muons). The distance between the leptons must satisfy $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.1$. Leptons are identified using a multivariate technique that is trained on $t\bar{t}$ events to optimize efficiency on prompt leptons from W boson decays versus leptons stemming from other sources, such as so-called "fake" leptons from heavy flavor decays and other mis-reconstruction effects.

After several control and validation studies, a Multi-Variate Analysis (MVA) using a Boosted Decision Tree (BDT) has been performed in order to improve sensitivity to DPS events with respect to a single observable study. The idea is to use the BDT estimator to get a response shape with the highest possible DPS sensitivity; therefore many sensitive kinematic observables have been put into the BDT training process. The BDT response is studied on top of the same-sign offline base selection and results are shown in Figure 1.

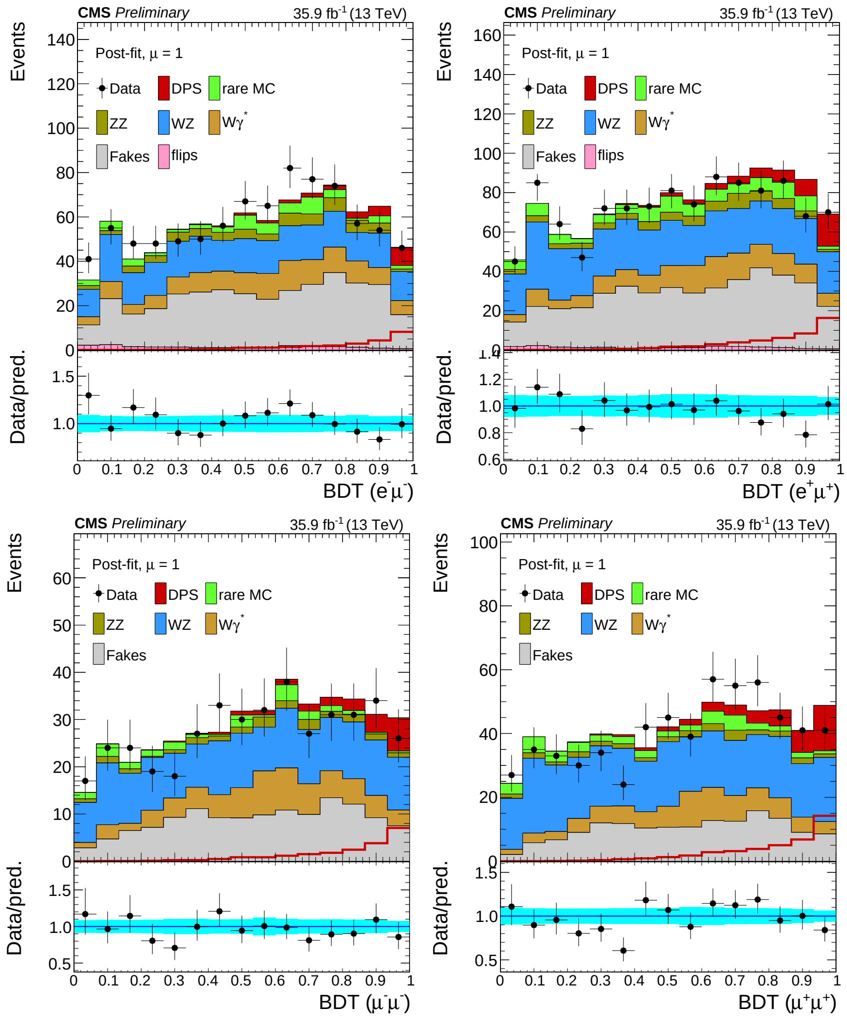

Figure 1: Final BDT classifier output with all background estimations in place for $e\mu$ in the two charges in the top row and $\mu\mu$ in the bottom row. Observed data are shown in black markers with the signal pre-fit expectation as a red histogram and separately imposed as a red line to show the 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].

Upper limits on the signal strength for the inclusive WW DPS process, as well as observed cross sections and significances in the presence of the signal process can be extracted out of the constrained fit to the BDT classifier distributions without any cross section needed for the input signal MC events. However, quoting an expected significance is always related to the prior expectation of the cross section of the signal process. This expectation of the cross section can be obtained in different ways. On one hand, generating signal events with the PYTHIA8 generator with the CUETP8M1 tune as done for the signal MC sample leads to an expected cross section of 1.64 pb for the inclusive WW DPS process. On the other hand, an expected cross section can also be calculated by using the simplified approach of factorization of the SPS processes as presented in Eq. 1. By using the highest order cross section for inclusive W boson production and decay at next-to-next-to leading order accuracy in QCD and next-to-leading order in electroweak corrections, 189 ± 7 nb, along with the measured value of $\sigma_{eff} = 20.7 \pm 6.6$ mb[5], results in an expected cross section for the inclusive WW DPS process of 0.87 ± 0.28 pb. Table 1 summarizes these numbers extracted from the constrained fit to the BDT classifier distributions.

Table 1: Results obtained from a constrained fit to the BDT classifier[3].

	Expected	Observed
$\sigma_{DPS_{WW}}^{pythia}$	1.64 pb	$1.09^{+0.50}_{-0.49}$
$\sigma_{DPS_{WW}}^{factorized}$	0.87 pb	
significance for $\sigma_{DPS_{WW}}^{pythia}$	3.27	2.23
significance for $\sigma_{DPS_{WW}}^{factorized}$	1.81	
UL in the absence of signal	0.97	1.94

3. DPS using 2b-jets + 2jets

Measurements of differential cross sections for the production of at least four jets, two of them initiated by a b-quark, in pp collisions have been studied as a function of the transverse momentum p_T and pseudorapidity η, together with the correlations in azimuthal angle and the p_T-balance among the jets[6]. The data sample was collected in 2010 at $\sqrt{s}$ = 7 TeV with an integrated luminosity of 3 pb^{-1}. Events with at least four jets with p_T > 20 GeV are selected. To study the production of pairs of different flavored jets via DPS, the two highest p_T jets are associated in the "b-quark jet pair", while the remaining two compose the "light quark jet pair". Fig. 2 shows the differential normalized cross sections as a function of ΔS between the two dijet pairs (most DPS-sensitive observable), defined as:

$$\Delta S = arccos\left(\frac{\vec{p_T}\,(bottom1, bottom2) \cdot \vec{p_T}\,(light1, light2)}{|\vec{p_T}\,(bottom1, bottom2)| \cdot |\vec{p_T}\,(light1, light2)|}\right) \tag{3.1}$$

The measured distribution is compared to predictions of POWHEG + PYTHIA 8, MADGRAPH + PYTHIA 8, PYTHIA 6, PYTHIA 8 and HERWIG ++. ΔS is not well described by any prediction: in particular, all of them, except HERWIG ++ and PYTHIA 8 in a lesser extent, underestimate the region at values of $\Delta S < 2$. This study shows the need for multiple parton interaction (MPI) contributions in the simulation in order to describe correlation observables between jets.

References

[1] M. Diehl et al., "Elements of a theory for multiparton interactions in QCD", JHEP 03 89 (2012).

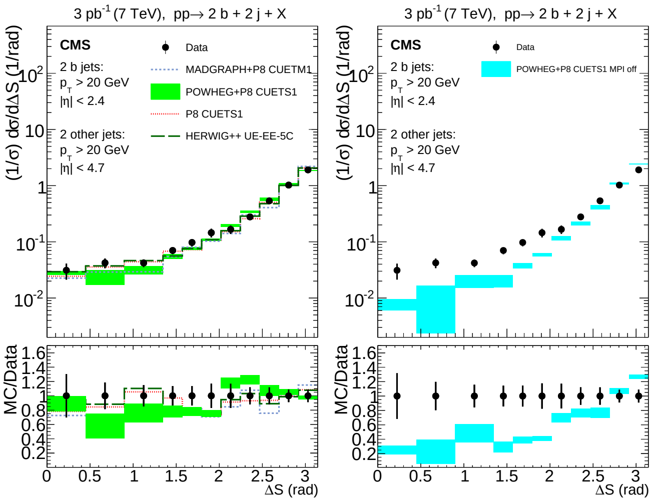

Figure 2: Normalized cross sections unfolded to the stable particle level as a function of ΔS, compared to different MC predictions[6].

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