Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s} = 13\ TeV$

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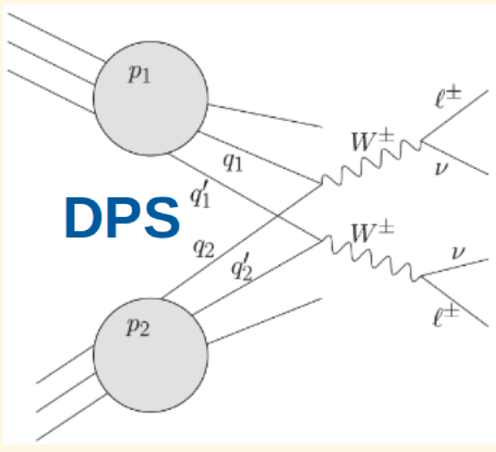
Double-parton interaction

In double-parton scattering (DPS) events two hard parton-parton interactions occur within a single proton-proton (pp) collision. The process has been discussed theoretically in detail. Due to the rarity of the process, further experimental research is needed.



One of the most promising processes to study DPS is same-sign W boson pair production ($W^{\pm}W^{\pm}$) where the two hard scatterings lead to the production of two W bosons with the same charge. For other final states, the cross sections of background processes are significantly larger.

Motivation

- The LHC CMS experiment is ideal for such measurements due to its high luminosity and excellent lepton identification performance.
- DPS provides information about the hadron structure in the transverse plane.
- If precisely measured, DPS could be differentiated against as background in the study of other rare processes.

Event preselection criteria

- Same charge leptons ($e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$) with $p_T^{l_1}$>25 GeV, $p_T^{l_2}$>20 GeV and $|\eta_e|<2.5$, $|\eta_\mu|<2.4$
- Veto additional e (p_T>7 GeV), μ (p_T>5 GeV) and τ_{had} (p_T>20 GeV) candidates
- Missing transverse momentum p_T^{miss}>15 GeV
- Maximum 1 hadron jet with p_T^{jet}>30 GeV, $|\eta_{jet}|<2.5$, $\Delta R_{lj} > 0.4$
- Veto identified b candidates with p_T^{b-jet}>25 GeV, $|\eta_{b-jet}|<2.4$

Input variables for BDT training

- Transverse momenta of the two leptons: $p_T^{l_1}$ and $p_T^{l_2}$
- Missing transverse momenta: p_T^{miss}
- Product of pseudorapidities of the two leptons: $\eta_{l_1} \cdot \eta_{l_2}$
- Absolute sum of pseudorapidities of the two leptons: $|\eta_{l_1} + \eta_{l_2}|$
- Transverse mass of the leading lepton and the missing transverse momenta: $m_T(l_1, p_T^{miss})$
- Transverse mass of the two leptons: $m_T(l_1, l_2)$, where

$$m_T(1,2) = \sqrt{2p_T^{(1)}p_T^{(2)}[1 - \cos\Delta\Phi(1,2)]}$$

- Azimuthal angular separation between the leptons: $|\Delta\Phi(l_1, l_2)|$
- Azimuthal angular separation between the subleading lepton and the missing tranverse momenta: $|\Delta\Phi(l_2, p_T^{miss})|$
- Azimuthal angular separation between the dilepton system and the subleading lepton: $|\Delta\Phi(l_1 l_2, l_2)|$
- Stransverse mass of the dilepton and missing transverse momentum system:

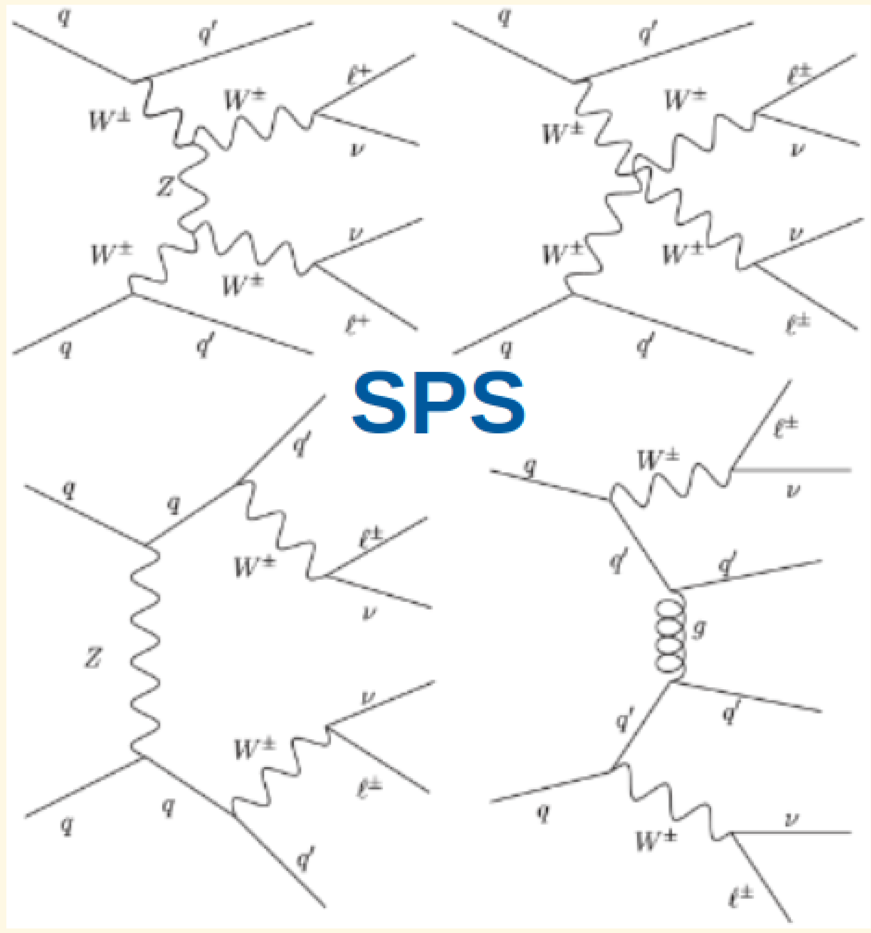
$$m_{T2}(l_1, l_2) = \min_{\vec{p}_T^{miss(1)} + \vec{p}_T^{miss(2)} = \vec{p}_T^{miss}} \left(\max(m_T^{(1)}, m_T^{(2)}) \right)$$

References

[1] CMS Collaboration. Evidence for ww production from double-parton interactions in proton-proton collision at $\sqrt{s} = 13$ tev. *Eur. Phys. J. C*, 80(41), 2020.

[2] T. Sjöstrand et al. An introduction to pythia 8.2. *Compu. Phys. Commun.*, 191, 2015.

Background processes



Similar same-sign dilepton final states can be produced from SPS (Single-Parton Scattering) processes or appear due to the misidentification of final state particles.

Diboson production First and foremost, the WZ process when both bosons decay leptonically and one of the leptons from the Z boson decay is either out of the detector acceptance or does not pass the identification criteria. Other such processes include $W\gamma^*$,$W\gamma$, $Z\gamma$, and ZZ production, as well as the SPS $W^{\pm}W^{\pm}$ and WWW processes.

Lepton misidentification Two types of experimental backgrounds belong here.

(1) Non-prompt lepton background in which one or two of the selected leptons do not originate from the decay of a massive boson from the hard scattering.

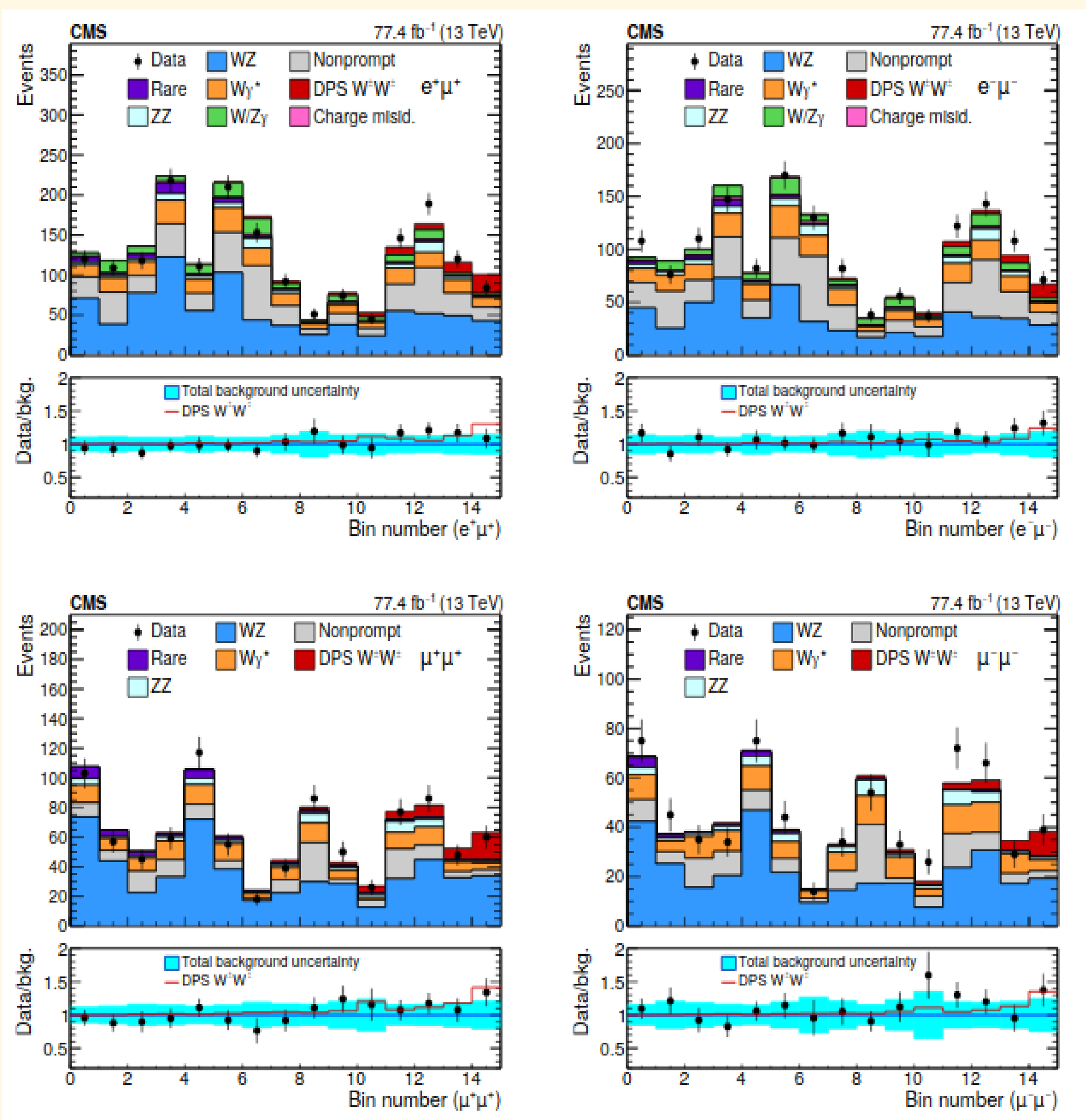
(2) Wrong assignment of the charge of an electron in the reconstruction brings opposite sign lepton pairs as backgrounds.

Analysis strategy

- A preselection is applied to retain events consistent with DPS WW production. From the background processes, WZ production and the non-prompt (misidentified) lepton background are dominant.
- A multivariate classifier method, boosted decision trees (BDT) implemented in the ROOT TMVA framework, is applied. DPS is sensitive to angular variables, so those are important in the separation of the signal events.
- Two separate BDTs were trained to suppress the two dominant backgrounds. The outputs were mapped into a single two-dimensional (2D) classifier. The 2D plane was split into 15 bins, on which the final maximum likelihood fit was performed.

The data recorded by the CMS experiment at a center-of-mass energy of 13 TeV in 2016 and 2017 (corresponding to 77.4 fb^{-1} integrated luminosity) was analysed.

Results



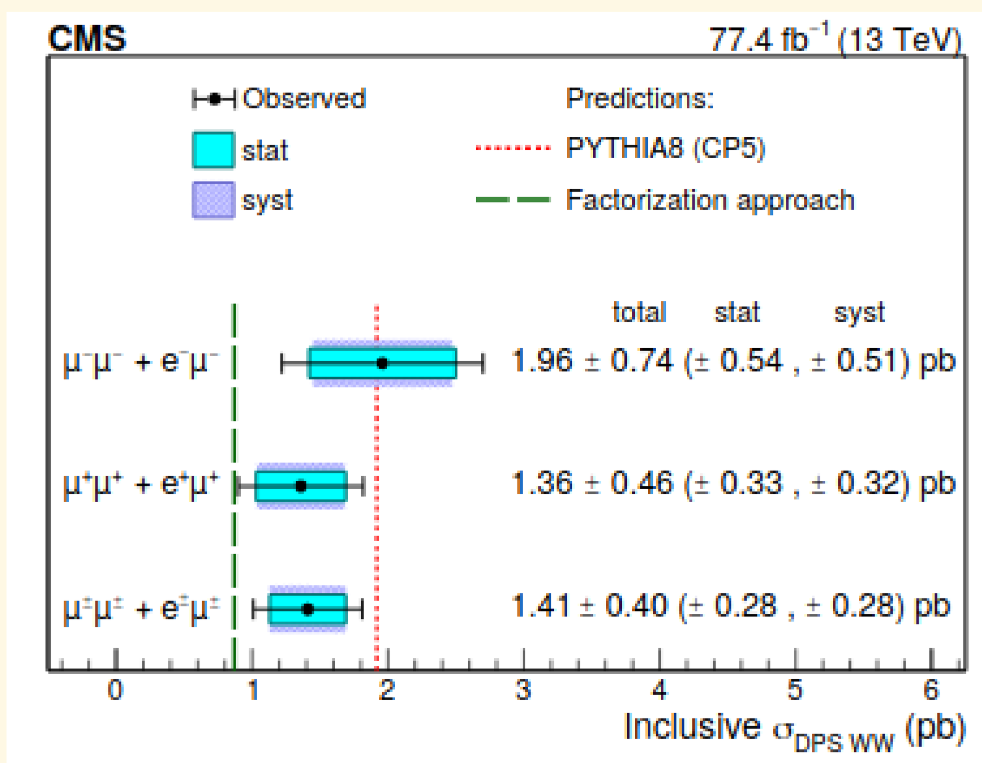
Final BDT classifier output for $e\mu$ (upper) and $\mu\mu$ (lower) final states, in the positive (left) and negative (right) charge configuration. Observed data are compared with the sum of the backgrounds normalised to their postfit yields. [1]

PYTHIA[2] generator is used to measure the kinematic acceptance, defined as the ratio of events having a same-charge electron-muon or dimuon pair from the W boson decays and passing the analysis-level kinematic selection to the total number of generated events.

Inclusive production cross sections are derived.

	Value	Significance (standard deviations)
$\sigma_{DPS\,WW,exp}^{PYTHIA}$	1.92 pb	5.4
$\sigma_{DPS\,WW,exp}^{factorized}$	0.87 pb	2.5
$\sigma_{DPS\,WW,obs}$	1.41 ± 0.28 (stat) ± 0.28 (syst) pb	3.9
σ_{eff}	$12.7^{+5.0}_{-2.9}$ mb	—

Cross section and significance predictions by PYTHIA and by a factorisation approach, as well as these values measured in the data. [1]



Observed cross section with statistical and systematic uncertainties for the studied lepton configurations. The ee configuration is not considered due to the expected higher level of background. [1]

The observed 3.9 σ significance falls short of a discovery but provides the first evidence for the existence of the DPS WW process.

Ongoing and planned research

Goal: Provide a more precise DPS WW cross section determination, and reach the 5 σ significance for discovery.

- Analyse the full Run 2 data sample collected in 2016-2018 with CMS in pp collisions with a reoptimised BDT method.
- Improve the boosted decision tree classifier and test the multiclassification method in TMVA which, instead of the usual two classes of signal and background, uses three classes, signal, WZ and non-prompt background. A multi-dimensional analysis of the multiclassification BDT outputs is needed.
- Investigate further the possible BDT input variables and define the optimal list.