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# Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at 13 TeV

The CMS Collaboration[*]

## Abstract

The first observation of electroweak production of same-sign W boson pairs in proton-proton collisions is reported. The data sample corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV with the CMS detector at the LHC. Events are selected by requiring exactly two leptons (electrons or muons) of the same charge, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. The observed significance of the signal is 5.5 standard deviations, where a significance of 5.7 standard deviations is expected based on the standard model. The ratio of measured event yields to that expected from the standard model at leading-order is $0.90 \pm 0.22$. A cross section measurement in a fiducial region is reported. Bounds are given on the structure of quartic vector boson interactions in the framework of dimension-eight effective field theory operators and on the production of doubly charged Higgs bosons.

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The standard model (SM) of particle physics provides an accurate description of observations from many accelerator- and nonaccelerator-based experiments. The discovery of a Higgs boson [1–3] confirmed that W and Z gauge bosons acquire mass using the Higgs mechanism. This discovery motivates further study of the mechanism of electroweak (EW) symmetry breaking through measurements of vector boson scattering (VBS) processes. Physics models beyond the SM predict enhancements in VBS through modifications of the Higgs sector or the presence of additional resonances [4, 5].

The main goal of this analysis is to identify same-sign W boson pairs produced in association with two jets purely via the electroweak interaction. Candidate events contain exactly two identified leptons (electrons or muons) of the same charge, moderate missing transverse momentum ($p_{\mathrm{T}}^{\text{miss}}$), and two jets with a large rapidity separation and a large dijet mass. The selection of same-sign lepton events reduces the contribution from the strong production of W boson pairs, making the experimental signature an ideal topology for VBS studies.

Figure 1 shows representative Feynman diagrams for EW and quantum chromodynamics (QCD) induced same-sign W boson pair production.

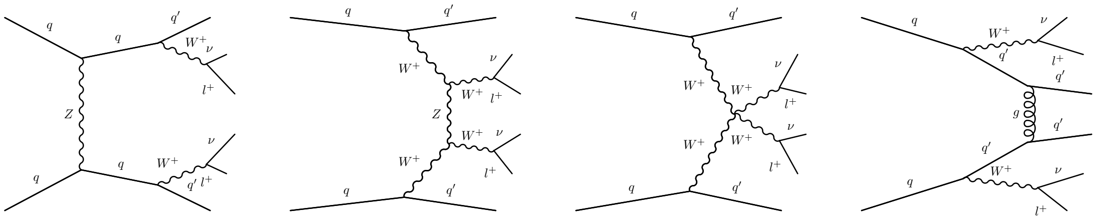

Figure 1: Representative Feynman diagrams for single, triple, and quartic gauge couplings of the EW-induced same-sign W boson pair production (left, middle-left, middle-right) and QCD-induced background (right).

An excess of events with respect to SM expectation could signal the presence of anomalous quartic gauge couplings (aQGC) [6] or the existence of a new resonance, such as a doubly charged Higgs boson. Doubly charged Higgs bosons are predicted in Higgs sectors beyond the SM where weak isotriplet scalars are included [7, 8]. They can be produced via vector-boson fusion (VBF) and decay to pairs of same-sign W bosons [9].

First experimental results for EW same-sign W bosons searches were reported by the ATLAS and CMS Collaborations based on data collected at $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of approximately $20\,\text{fb}^{-1}$ [10, 11]. The observed significance is 3.6 (2.0) standard deviations for the ATLAS (CMS) study, where a significance of 2.8 (3.1) standard deviations is expected based on the SM prediction. This Letter presents a study of VBS in the same-sign W boson pair final state at $\sqrt{s} = 13\,\text{TeV}$. The data sample corresponds to an integrated luminosity of $35.9 \pm 0.9\,\text{fb}^{-1}$ collected with the CMS detector [12] at the CERN LHC in 2016.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity $\eta$ coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [12].

The signal and background processes are simulated using the Monte Carlo (MC) generator MADGRAPH5_aMC@NLO 2.3.3 [13]. The same-sign W boson pair samples are produced at leading-order (LO) via diagrams with two or fewer QCD and up to six EW vertices. This includes two categories of diagrams: those with exactly two QCD vertices, which we refer to as QCD production, and those with no QCD vertices, which we refer to as EW production. We consider only the EW production as the signal in the analysis, whereas the QCD production is considered as background. This background is small and can be kinematically separated from the signal. The interference between the EW and QCD processes is at the level of a few percent in the signal region and is treated as a systematic uncertainty. The EW category includes diagrams with WWWW quartic interactions and diagrams where two same-sign W bosons scatter through the exchange of a Higgs boson, a Z boson, or a photon. The WZ and ZZ production processes via $\mathrm{q\overline{q}}$ annihilation and the $\mathrm{W}\gamma$ process are generated at LO. The Drell–Yan, $\mathrm{Z}\gamma$, $\mathrm{t\overline{t}}$, $\mathrm{t\overline{t}W}$, $\mathrm{t\overline{t}Z}$, WZZ, WWZ, WWW, and ZZZ samples are generated at next-to-leading order (NLO). The simulated samples of background processes are normalized to the best theoretical prediction. The PYTHIA 8.205 [14] package is used for parton showering, hadronization, and the underlying event simulation, with tune CUETP8M1 [15, 16]. The NNPDF 3.0 [17] set is used as the default set of parton distribution functions. The detector response is simulated by the GEANT4 package [18], based on a detailed description of the CMS detector. Proton-proton interactions occurring in the same beam crossing bin as the event of interest (pileup) are included in the simulation samples. The simulated pileup has a mean of approximately 27 and corresponds to the conditions observed in the 13 TeV data collected in 2016.

The final states considered are $\mathrm{e}^+\mathrm{e}^+\nu_\mathrm{e}\nu_\mathrm{e}jj$, $\mathrm{e}^+\mu^+\nu_\mathrm{e}\nu_\mu jj$, $\mu^+\mu^+\nu_\mu\nu_\mu jj$, and their charge conjugates. The electrons and muons can be directly produced from a W boson decay or from a W boson with an intermediate $\tau$ lepton decay. A suite of single- and double-lepton triggers are used for this analysis [19]. The trigger efficiency for the signal process is larger than 99.8% after all other selection requirements are applied.

A particle-flow algorithm [20] is used to reconstruct observable particles in the event. It combines all subdetector information to reconstruct individual particles and identify them as charged and neutral hadrons, photons, and leptons. Electrons and muons are reconstructed by associating a track reconstructed in the silicon detectors either with a cluster of energy in the electromagnetic calorimeter [21] or a track in the muon system [22]. The $p_\mathrm{T}^\text{miss}$ is defined as the magnitude of the negative vector sum of the transverse momenta of all reconstructed particles (charged and neutral) in the event modified by corrections to the energy scale of reconstructed jets.

The event selection aims to identify same-sign lepton events with the VBS topology, while reducing the contribution from the top quark, Drell–Yan, and WZ background contributions. Two same-sign leptons, electrons or muons, with transverse momentum $p_\mathrm{T} > 25$ (20) GeV for the leading (trailing) lepton and $|\eta| < 2.5$ (2.4) for electrons (muons) are required. Electrons and muons are required to be isolated from other charged and neutral particles in the event. Jets are reconstructed using the anti-$k_\mathrm{T}$ clustering algorithm [23] with a distance parameter $R = 0.4$, as implemented in the FASTJET package [24, 25]. Events are required to contain at least two jets with $p_\mathrm{T} > 30\,\mathrm{GeV}$ and $|\eta| < 5.0$. The VBS topology is targeted by requiring that the two highest $p_\mathrm{T}$ jets have a large dijet mass, $m_{jj} > 500\,\mathrm{GeV}$, a large $\eta$ separation, $|\Delta\eta_{jj}| > 2.5$, and $\max(z_\ell^*) < 0.75$, where $z_\ell^* = |\eta_\ell - (\eta_{j1} + \eta_{j2})/2| / |\Delta\eta_{jj}|$ is the Zeppenfeld variable [26], $\eta_\ell$ is the pseudorapidity of a lepton, and $\eta_{j1}$ and $\eta_{j2}$ are the pseudorapidities of the leading and subleading jet, respectively.

Techniques for identification of b quark jets are used to veto top quark events. These techniques are based on b quark jet tagging criteria that combine the information from displaced tracks with the information from secondary vertices associated with the jet using a multivariate technique, and on the possible presence of a soft muon in the event from the semileptonic decay of the bottom quark [27, 28]. A minimum dilepton mass, $m_{\ell\ell} > 20\,\text{GeV}$, is required to reduce nonprompt lepton processes. To reduce the background from WZ production, events with a third loosely identified lepton with $p_{\mathrm{T}} > 10\,\text{GeV}$ or an identified hadronically-decaying $\tau$ lepton with $p_{\mathrm{T}} > 18\,\text{GeV}$ are rejected. Drell–Yan events can be selected if the charge of one lepton is measured incorrectly. The charge mismeasurement in dimuon events is negligible, while this background is not negligible for dielectron events. An invariant mass veto, $|m_{\ell\ell} - m\mathrm{Z}| > 15\,\text{GeV}$, is imposed for $\mathrm{e}^{\pm}\mathrm{e}^{\pm}$ events. The Drell–Yan background is further reduced by requiring $p_{\mathrm{T}}^{\text{miss}} > 40\,\text{GeV}$.

A WZ $\to 3\ell\nu$ control region is defined by requiring an additional identified lepton with $p_{\mathrm{T}} > 10\,\text{GeV}$ and an opposite-sign same-flavor lepton pair with an invariant mass consistent with that of the Z boson. The background contribution from charge misidentification is estimated by applying a data-to-simulation efficiency correction to charge misidentified electrons in bins of $\eta$. estimated using Drell–Yan events. The charge misidentification rate, estimated using Drell–Yan events, is between about 0.01% in the barrel region and about 0.3% in the endcap region for electrons.

The nonprompt lepton backgrounds originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions are suppressed by the identification and isolation requirements imposed on electrons and muons. The remaining contribution from the nonprompt lepton background is estimated directly from data following the technique described in Ref. [11]. All other background processes are estimated from simulation applying corrections to account for small differences between data and simulation, as described below.

The lepton trigger, reconstruction, and selection efficiencies are measured using Drell–Yan events that provide an unbiased sample with high purity. The estimated uncertainty is less than 2% per lepton. The uncertainties in the momentum scale for electrons and muons are also taken into account and contribute about 1%. The jet energy scale and resolution uncertainties give rise to an uncertainty in the yields of up to 7%. The uncertainty in the estimated event yields related to the top quark veto is evaluated by using a $\mathrm{Z}/\gamma^{*} \to \ell^{+}\ell^{-}$ sample with at least two reconstructed jets and is 3% or smaller. The statistical uncertainty due to the finite size of each simulated sample is also taken into account. The uncertainty of 2.5% in the integrated luminosity determination [29] is considered for all processes estimated from simulation and for the fiducial cross section. The normalization of the processes with misidentified leptons is estimated with a systematic uncertainty of 30%. The WZ background normalization uncertainty is 20–40%, dominated by the statistical uncertainty arising from the small number of events in the trilepton control region. Theoretical uncertainties are estimated by varying simultaneously the renormalization and factorization scales up and down by a factor of two from their nominal value in each event, and, depending on kinematic region, are up to 12% for the signal normalization and 20% for the triboson background normalization. The interference between the EW signal and the QCD-induced same-sign W boson production background is estimated using the PHANTOM 1.2.8 generator [30] and is treated as a systematic uncertainty of 4.5% in the signal yield. An uncertainty in the parton distribution function contributes 5% to the signal times acceptance [31].

The simulated signal and background yields, as well as the observed data yields, are shown in Table 1 for all six channels separately, along with their sum. The two dominant sources of background events arise from nonprompt leptons and the WZ process. The distributions of $m_{jj}$ and $m_{\ell\ell}$ in the signal region are shown in Fig. 2. An excess of events with respect to the background-only hypothesis is observed. In order to quantify the significance of the observation of the EW production of same-sign W boson pairs, a statistical analysis of the event yields is performed with a fit to the ($m_{jj}$,$m_{\ell\ell}$) two-dimensional distributions. The fit is performed simultaneously in the signal region and in the WZ control region, although only the $m_{jj}$ distribution is used in the latter region. The aim of using the WZ control region is to determine the number of WZ background events in the signal region as a function of $m_{jj}$. The lepton flavor is not used to separate event samples. The EW signal yield and the WZ background normalization are free parameters of the fit. All background contributions can vary within the estimated uncertainties. The data excess is quantified by calculating the p-value using a profile likelihood ratio test statistic [32–34]. The observed (expected) statistical significance of the signal is 5.5 (5.7) standard deviations. The ratio of measured signal event yield to that expected from the SM is $0.90 \pm 0.22$.

Table 1: Estimated signal and background yields after the selection. The statistical uncertainties are reported for all six channels, while the sums are reported with the statistical and systematic uncertainties added in quadrature. The processes contributing to less than 1% of the total background are not listed, but included in the total background yield.

| | $e^+e^+$ | $e^+\mu^+$ | $\mu^+\mu^+$ | $e^-e^-$ | $e^-\mu^-$ | $\mu^-\mu^-$ | Total |
|---|---|---|---|---|---|---|---|
| Data | 14 | 63 | 40 | 10 | 48 | 26 | 201 |
| Signal + total bkg. | $19.0 \pm 1.9$ | $67.6 \pm 3.8$ | $44.1 \pm 3.4$ | $11.8 \pm 1.8$ | $38.9 \pm 3.3$ | $23.9 \pm 2.8$ | $205 \pm 13$ |
| Signal | $6.2 \pm 0.2$ | $24.7 \pm 0.4$ | $18.3 \pm 0.4$ | $2.5 \pm 0.1$ | $8.7 \pm 0.2$ | $6.5 \pm 0.2$ | $66.9 \pm 2.4$ |
| Total bkg. | $12.8 \pm 1.9$ | $42.9 \pm 3.8$ | $25.7 \pm 3.4$ | $9.4 \pm 1.8$ | $30.2 \pm 3.3$ | $17.4 \pm 2.8$ | $138 \pm 13$ |
| Nonprompt | $5.6 \pm 1.7$ | $24.9 \pm 3.6$ | $18.4 \pm 3.3$ | $5.0 \pm 1.6$ | $19.9 \pm 3.2$ | $14.2 \pm 2.8$ | $88 \pm 13$ |
| WZ | $3.0 \pm 0.2$ | $8.5 \pm 0.3$ | $4.4 \pm 0.2$ | $1.9 \pm 0.2$ | $5.2 \pm 0.3$ | $2.2 \pm 0.1$ | $25.1 \pm 1.1$ |
| QCD WW | $0.6 \pm 0.1$ | $1.7 \pm 0.1$ | $1.3 \pm 0.1$ | $0.2 \pm 0.1$ | $0.6 \pm 0.1$ | $0.4 \pm 0.1$ | $4.8 \pm 0.4$ |
| $W\gamma$ | $1.4 \pm 0.5$ | $3.6 \pm 0.9$ | $0.2 \pm 0.2$ | $0.8 \pm 0.4$ | $2.3 \pm 0.7$ | — | $8.3 \pm 1.6$ |
| Triboson | $0.8 \pm 0.2$ | $2.2 \pm 0.4$ | $1.2 \pm 0.3$ | $0.3 \pm 0.1$ | $0.9 \pm 0.3$ | $0.5 \pm 0.2$ | $5.8 \pm 0.8$ |
| Wrong sign | $1.5 \pm 0.6$ | $1.4 \pm 0.4$ | — | $1.1 \pm 0.5$ | $1.2 \pm 0.4$ | — | $5.2 \pm 1.1$ |

The cross section is extracted in a fiducial signal region, defined using MC generator quantities by requiring two same-sign leptons from W boson decays with $p_T^\ell > 20\,\text{GeV}$ and $|\eta_\ell| < 2.5$, two jets with $p_T^j > 30\,\text{GeV}$ and $|\eta^j| < 5.0$, $m_{jj} > 500\,\text{GeV}$, and $|\Delta\eta_{jj}| > 2.5$. In this definition, the leptons are defined at particle level post final state radiation and $W \to \tau\nu \to \ell\nu\nu\nu$ decays are excluded. The measured cross section is corrected for the acceptance in this region using the MadGraph5_aMC@NLO generator, which is also used to estimate the theoretical cross section at LO. The fiducial cross section is measured to be $\sigma_{\text{fid}}(W^\pm W^\pm jj) = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\,\text{fb}$. The predicted theoretical cross section at LO is $4.25 \pm 0.27$ fb, in agreement with the measurement. The uncertainty in the theoretical cross section stems from scale variations and parton distribution functions. Complete NLO QCD and EW corrections to $W^+W^+$ scattering [35] are computed using similar selection requirements as presented in this paper. The NLO EW corrections to the fiducial cross section are dominant and negative ($-13\%$). The overall efficiency within the fiducial region is $34.8 \pm 0.3\,(\text{stat}) \pm 2.3\,(\text{syst})\%$, while the fraction of events that are outside the fiducial region, but are nonetheless selected at the reconstruction level is $20.6 \pm 0.3\,(\text{stat})\%$. This fraction is rather large because leptonic $\tau$ decays are not included in the definition of the fiducial region. Including the leptonic $\tau$ decays reduces the value to $4.9 \pm 0.1\,(\text{stat})\%$.

Various extensions of the SM alter the couplings between vector bosons. Reference [6] proposes nine independent charge conjugate and parity-conserving dimension-eight effective operators to modify the quartic couplings. In this case, the $m_{\ell\ell}$ distributions in both the signal and WZ regions are used to perform the statistical analysis. The EW production is treated as a background consistent with the SM expectation and can vary within the estimated uncertainties. The observed and expected 95% confidence level (CL) limits for the nine coefficients, shown in Table 2, are obtained by varying the effective operators one by one. The effect of possible aQGCs on the WZ process in the signal region is negligible because the background is normalized using data. The table also shows the most stringent 95% CL limits reported by the CMS Collaboration previously.

Table 2: Observed and expected 95% CL limits on the coefficients for higher-order (dimension-eight) operators in the effective field theory Lagrangian. The last column summarizes the previously observed limits obtained by the CMS Collaboration together with the appropriate reference.

| | Observed limits ( TeV $^{-4}$) | Expected limits ( TeV $^{-4}$) | Previously observed limits ( TeV $^{-4}$) |
|---|---|---|---|
| $f_{S0}/\Lambda^4$ | $[-7.7, 7.7]$ | $[-7.0, 7.2]$ | $[-38, 40]$ , [11] |
| $f_{S1}/\Lambda^4$ | $[-21.6, 21.8]$ | $[-19.9, 20.2]$ | $[-118, 120]$ , [11] |
| $f_{M0}/\Lambda^4$ | $[-6.0, 5.9]$ | $[-5.6, 5.5]$ | $[-4.6, 4.6]$ , [36] |
| $f_{M1}/\Lambda^4$ | $[-8.7, 9.1]$ | $[-7.9, 8.5]$ | $[-17, 17]$ , [36] |
| $f_{M6}/\Lambda^4$ | $[-11.9, 11.8]$ | $[-11.1, 11.0]$ | $[-65, 63]$ , [11] |
| $f_{M7}/\Lambda^4$ | $[-13.3, 12.9]$ | $[-12.4, 11.8]$ | $[-70, 66]$ , [11] |
| $f_{T0}/\Lambda^4$ | $[-0.62, 0.65]$ | $[-0.58, 0.61]$ | $[-0.46, 0.44]$ , [37] |
| $f_{T1}/\Lambda^4$ | $[-0.28, 0.31]$ | $[-0.26, 0.29]$ | $[-0.61, 0.61]$ , [37] |
| $f_{T2}/\Lambda^4$ | $[-0.89, 1.02]$ | $[-0.80, 0.95]$ | $[-1.2, 1.2]$ , [37] |

Doubly charged Higgs bosons are predicted in models that contain a Higgs triplet field. Some of these scenarios predict same-sign lepton events from $W^{\pm}W^{\pm}$ decays with a VBF topology. The Georgi–Machacek model of Higgs triplets [38] is considered. The couplings depend on

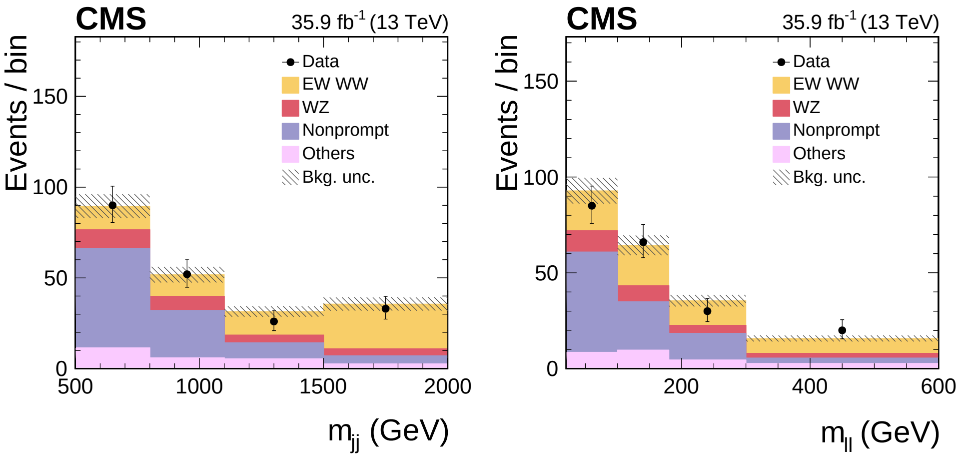

Figure 2: Distributions of $m_{jj}$ (left) and $m_{\ell\ell}$ (right) in the signal region. The normalization of the EW $W^{\pm}W^{\pm}$ and background distributions corresponds to the result of the fit. The hatched bands include statistical and systematic uncertainties from the predicted yields. The histograms for other backgrounds include the contributions from QCD WW, W$\gamma$, wrong-sign events, double parton scattering, and triboson processes. The overflow is included in the last bin.

$m_{\mathrm{H}^{\pm\pm}}$ and the parameter $\sin\theta_{\mathrm{H}}$, or $s_{\mathrm{H}}$, where $s_{\mathrm{H}}^2$ denotes the fraction of the W boson mass generated by the vacuum expectation value of the triplets. The expected signal event yields for VBF production of $\mathrm{H}^{\pm\pm}$ decaying to $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ is directly proportional to $s_{\mathrm{H}}^2$. The remaining five parameters in the model are adjusted to achieve the given $m_{\mathrm{H}^{\pm\pm}}$ hypothesis, while requiring one of the scalar singlets to have a mass of 125 GeV. By using the $(m_{jj}, m_{\ell\ell})$ two-dimensional distribution in the signal region and the $m_{jj}$ distribution in the WZ control region simultaneously to discriminate between signal and background processes, 95% CL upper limits on $\sigma_{\mathrm{VBF}}(\mathrm{H}^{\pm\pm})\,\mathcal{B}(\mathrm{H}^{\pm\pm} \to \mathrm{W}^{\pm}\mathrm{W}^{\pm})$ can be derived, as shown in Fig. 3 (left). The excluded $s_H$ values as a function of $m_{\mathrm{H}^{\pm\pm}}$ are shown in Fig. 3 (right). As discussed before, the WZ background contribution in the signal region is constrained using the control region and the EW production is treated as a background. The blue region shows the parameter space for which the $\mathrm{H}^{\pm\pm}$ total width exceeds 10% of $m(\mathrm{H}^{\pm\pm})$, where the model is not applicable [39]. The observed limit excludes $s_{\mathrm{H}}$ values greater than 0.18 and 0.44 at $m(\mathrm{H}^{\pm\pm}) = 200$ and 1000 GeV, respectively. The Georgi–Machacek model also predicts singly charged Higgs bosons. Results based on this model have been reported by the CMS Collaboration in a search for VBF $\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}$ production [40]. The observed limits of this search for doubly charged Higgs bosons are stronger by about a factor of two.

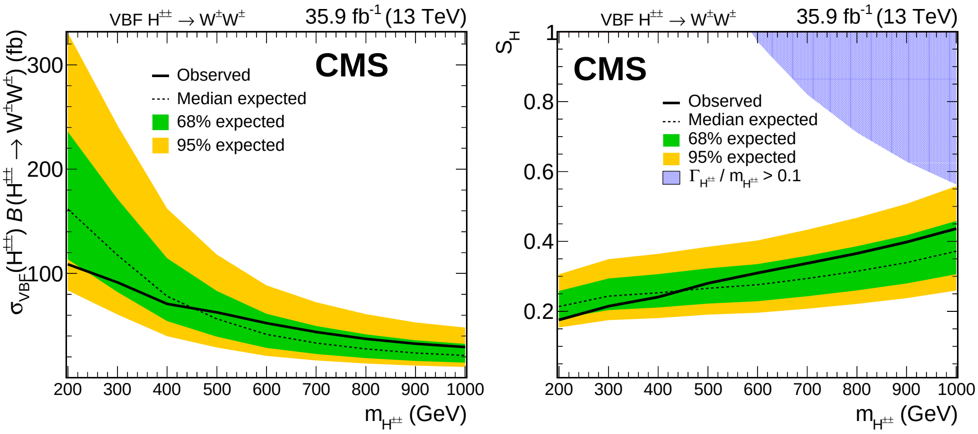

Figure 3: Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_{\mathrm{VBF}}(\mathrm{H}^{\pm\pm})\,\mathcal{B}(\mathrm{H}^{\pm\pm} \to \mathrm{W}^{\pm}\mathrm{W}^{\pm})$ (left) and on $s_{\mathrm{H}}$ in the Georgi–Machacek model (right) as a function of doubly charged Higgs boson mass. The blue area in the upper-right corner covers the region where the model is not applicable [39].

In summary, we present the first observation of electroweak production of same-sign W boson pairs in proton-proton collisions. The data sample corresponds to an integrated luminosity of 35.9 $\mathrm{fb}^{-1}$ collected at $\sqrt{s} = 13$ TeV with the CMS detector. Events are selected by requiring exactly two leptons of the same charge, moderate $p_{\mathrm{T}}^{\mathrm{miss}}$, and two jets with large rapidity separation and large dijet mass. The two dominant sources of background events after the event selection requirements have been applied are nonprompt leptons and the $\mathrm{WZ} \to 3\ell\nu$ process. The observed significance is 5.5 standard deviations, where a significance of 5.7 standard deviations is expected based on the SM. The ratio of measured event yields to that expected from the standard model at leading-order is $0.90 \pm 0.22$. A cross section measurement in a fiducial region is reported consistent with SM predictions. Bounds on the structure of quartic vector boson interactions are improved by a factor of up to six compared to previous results. Upper limits are given on the production cross section times branching fraction of doubly charged Higgs bosons.

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