Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

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A study of vector boson scattering in pp collisions at a center-of-mass energy of 8 TeV is presented. The data sample corresponds to an integrated luminosity of 19.4 fb^{-1} collected with the CMS detector. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign W-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^{\pm}W^{\pm}$ and WZ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

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Vector boson scattering (VBS) and quartic boson couplings are features of the standard model (SM) that remain largely unexplored by the LHC experiments. The observation of a Higgs boson [1–3], in accordance with a key prediction of the SM, motivates further study of the mechanism of electroweak symmetry breaking through measurements of VBS processes. In the absence of the SM Higgs boson, the amplitudes for these processes would increase as a function of center-of-mass energy and ultimately violate unitarity [4,5]. The Higgs boson actually observed by the LHC experiments may restore the unitarity, although some scenarios of physics beyond the SM predict enhancements for VBS through modifications to the Higgs sector or the presence of additional resonances [6,7].

This Letter presents a study of VBS in pp collisions at $\sqrt{s} = 8$ TeV. The data sample corresponds to an integrated luminosity of $19.4 \pm 0.5\ \mathrm{fb}^{-1}$ collected with the CMS detector [8] at the LHC in 2012. The aim of the analysis is to find evidence for the electroweak production of same-sign W-boson pair events. The strong production cross section is reduced by the same-sign requirement, making the experimental signature of same-sign dilepton events with two jets an ideal topology for VBS studies. Candidate events have exactly two identified leptons of the same charge, two jets with large rapidity separation and dijet mass, and moderate missing transverse energy. The final states considered are $\mu^+\mu^+\nu_\mu\nu_\mu jj$, $e^+e^+\nu_e\nu_e jj$, $e^+\mu^+\nu_e\nu_\mu jj$, and their charge conjugates and τ-lepton decays to electrons and muons. Figure 1 shows representative Feynman diagrams for the electroweak and QCD induced production.

The study of VBS presented here leads to measurements of the production cross sections for $W^{\pm}W^{\pm}$ and WZ in a fiducial region. Evidence for electroweak production has been reported by the ATLAS Collaboration [9]. Various extensions of the SM alter the couplings of vector bosons. An excess of events could signal the presence of anomalous quartic gauge couplings (AQGCs) [10]. Doubly charged Higgs bosons are predicted in Higgs sectors beyond the SM where weak isotriplet scalars are included [11,12]; they can be produced via weak vector-boson fusion (VBF) and decay to pairs of same-sign W bosons [13].

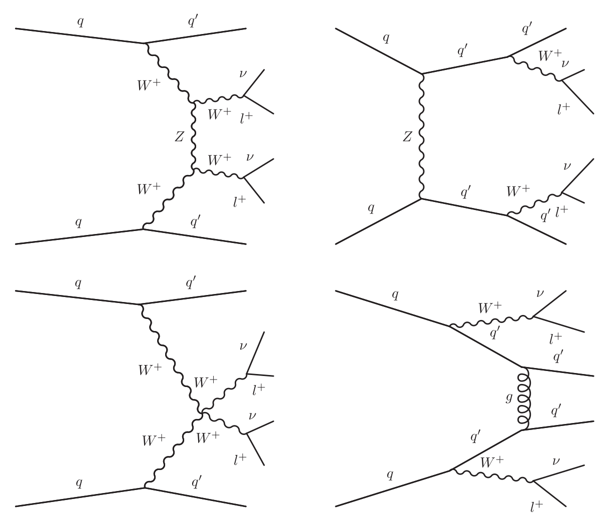

FIG. 1. Representative Feynman diagrams for the electroweak and QCD induced same-sign W-boson pair production.

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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 field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events within 3 μs, using information from the calorimeters and muon detectors. The high level trigger processor farm further reduces the event rate to a few hundred hertz before data storage. Details of the CMS detector and its performance can be found elsewhere [8].

Several Monte Carlo (MC) event generators are used to simulate the signal and background processes. The leading-order event generator MadGraph 5.2 [14] is used to produce event samples of diboson production via diagrams with two or fewer powers of α_s and up to six electroweak vertices. This includes two categories of diagrams: those with exactly two powers of α_s which we refer to as quantum chromodynamic (QCD) production and those with no powers of α_s, which we refer to as electroweak (EW) production. 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. Double-parton scattering, triboson production, and doubly charged Higgs boson production samples are also generated using MadGraph 5.2. Top-quark background processes are generated with the next-to-leading-order event generator powheg 1.0 [15–18]. The set of parton distribution functions (PDFs) used is CTEQ6L [19] for MadGraph and CT10 [20] for powheg. All event generators are interfaced to pythia 6.4 [21] for the showering of the partons and subsequent hadronization. The pythia parameters for the underlying event were set according to the $Z2^*$ tune [22]. The detector response is simulated by the Geant4 package [23] using a detailed description of the CMS detector. The average number of simultaneous proton-proton interactions per bunch crossing in the 8 TeV data is approximately 21; additional pp interactions overlapping with the event of interest are included in the simulated samples. Collision events are selected by the trigger system requiring the presence of one or two high transverse momentum (p_T) muons or electrons. The trigger efficiency is greater than 99% for events that pass all other selection criteria explained below. A particle-flow algorithm [24,25] is used to reconstruct all observable particles in the event. It combines all the subdetector information to reconstruct individual particles and identify them as charged hadrons, neutral hadrons, photons, and leptons. The missing transverse energy E_T^{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.

The selection of events aims to single out same-sign dilepton events with the VBS topology while reducing the top quark, Drell-Yan, and WZ background processes. All objects are selected following the methods described in Ref. [26]. To avoid bias, the number of events passing the selection was not evaluated until the analysis was complete. Two same-sign lepton candidates, muons or electrons, with $p_T > 20$ GeV and $|\eta| < 2.4(2.5)$ for muons (electrons) are required to be isolated from other reconstructed particles in a cone of $\Delta R = 0.3$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Jets are reconstructed using the anti-k_T clustering algorithm [27] with a distance parameter $R = 0.5$, as implemented in the fastjet package [28,29]. Events are required to have at least two selected jets with $E_T > 30$ GeV and $|\eta| < 4.7$. The VBS topology is targeted by requiring that the two jets with leading p_T have large dijet mass, $m_{jj} > 500$ GeV, and large pseudorapidity separation, $|\Delta\eta_{jj}| > 2.5$.

To suppress top-quark backgrounds ($t\bar{t}$ and tW), a top-quark veto technique is used; it is based on the presence of a soft muon in the event from the semileptonic decay of the bottom quark and on bottom-quark jet tagging criteria based on the impact parameters of the constituent tracks [30]. A minimum dilepton mass, $m_{\ell\ell} > 50$ GeV, is required to reduce the $W +$ jets and top-quark background processes. To reduce the background from WZ production, events with a third, loosely identified lepton with $p_T >$ 10 GeV are rejected. Drell-Yan events can be selected if the charge of one lepton is measured incorrectly. To reduce this background, $|m_{\ell\ell} - m_Z| > 15$ GeV is required for $e^\pm e^\pm$ events. The charge confusion in dimuon events is negligible. The Drell-Yan background is further reduced by requiring $E_T^{\text{miss}} > 40$ GeV.

The nonprompt lepton background originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions, is suppressed by the identification and isolation requirements imposed on muons and electrons. The remaining contribution from the nonprompt lepton background is estimated directly from data. The efficiency for a predefined loose leptonlike object to pass the full lepton selection, typically called the "tight-to-loose ratio" (R_{TL}), is estimated in a control sample with one additional lepton candidate that passes the standard lepton selection criteria. To account for the dependence on kinematic observables, this ratio is parameterized as a function of p_T and η. Systematic uncertainties are obtained by the application of R_{TL} to other control samples, accounting for the sample dependence in the estimation of R_{TL}. The $WZ \to 3\ell\nu$ process is normalized in a data control region by requiring a third fully identified lepton with $p_T > 10$ GeV. The contribution of opposite-sign dilepton events to the signal region is estimated by applying data-to-simulation charge misidentification scale factors to simulated events with two opposite-sign leptons. The charge-misidentification fraction is estimated using Z boson events and is found to be between

TABLE I. Signal and background yields after the full selection. Only statistical uncertainties are reported. The signal, $W^{\pm}W^{\pm}jj$, includes EW and QCD processes and their interference.

	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
$W^{+}W^{+}$	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
$W^{-}W^{-}$	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	...	...	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

0.1% and 0.3% for electrons, while it is negligible for muons.

After the full selection, about 15% of the background is due to the $WZ \to 3\ell\nu$ process and about 75% to nonprompt leptons. Backgrounds from opposite-sign lepton pairs misreconstructed as same-sign ("wrong-sign background"), WW production via double parton scattering (DPS), and triboson production (VVV), which includes top-pair plus boson processes, contribute less than 10%.

The expected signal and background yields are shown in Table I for positive and negative pairs separately and for their sum. The signal corresponds to $W^{\pm}W^{\pm}$ production, including EW and QCD contributions, and their interference, which amounts to approximately 10%. The EW processes constitute 85%–90% of the total signal contribution. The m_{jj} and leading-lepton p_T distributions for the signal and background processes are shown in Fig. 2. In order to quantify the significance of the observation of the production via VBS, a statistical analysis of the event yields is performed in eight bins: four bins in m_{jj} with two bins in the lepton charge.

The signal efficiencies are estimated using simulated samples. In the statistical analysis, shape and normalization uncertainties are considered. The shape uncertainties are estimated by remaking the distribution of a given observable after considering the systematic variations for each source of uncertainty. The lepton trigger, reconstruction, and selection efficiencies are measured using $Z/\gamma^* \to \ell^+\ell^-$ events that provide an unbiased sample with high purity. The estimated uncertainty is 2% per lepton. The uncertainties due to the momentum scale for electrons and muons are also taken into account and contribute 2%. The jet energy scale and resolution uncertainties give rise to an uncertainty in the yields of about 5%. The uncertainty in the event selection efficiency for events with neutrinos yielding genuine E_T^{miss} in the final state is assessed and leads to an uncertainty of 2%. The uncertainty in the estimated event yields, which is related to the top-quark veto, is evaluated by using a $Z/\gamma^* \to \ell^+\ell^-$ sample with at least two reconstructed jets and is found to be about 2%. The statistical uncertainty in the yield of each bin and for each process is also taken into account. The uncertainty of 2.6% in the integrated luminosity [31] is considered for all simulated processes. The normalization of the processes with misidentified leptons has a 36% systematic uncertainty [26], which has two sources: the dependence on the sample composition and the method used to estimate it. The WZ normalization uncertainty is 35%, dominated by the small number of events in the trilepton control region. Theoretical uncertainties are estimated by varying the

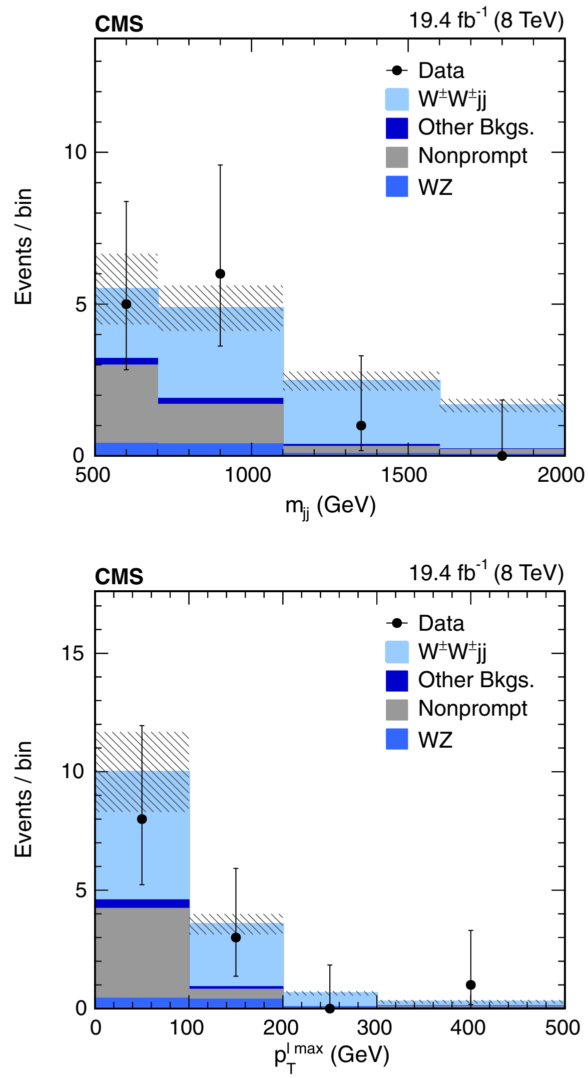

FIG. 2 (color online). The distributions of m_{jj} (top) and leading lepton p_T, $p_T^{\ell,\max}$, in the signal region (bottom). The hatched bars include statistical and systematic uncertainties. The W^+W^+ and W^-W^- candidates are combined in these distributions. The signal, $W^{\pm}W^{\pm}jj$, includes EW and QCD processes and their interference. The histograms for other backgrounds include the contributions from wrong-sign events, DPS, and VVV processes.

renormalization and factorization scales up and down by a factor of two from their nominal value in the event, and found to be 5% for the signal normalization and 50% for the triboson background normalization. A PDF uncertainty of 6%–8% in the normalization of the signal and WZ processes is included. The systematic uncertainties of the background normalizations are taken into account using log-normal distributions.

The cross section is extracted for a fiducial signal region. The fiducial region is defined by requiring two same-sign leptons with $p_T{}^{\ell} > 10$ GeV and $|\eta_\ell| < 2.5$, two jets with $p_T{}^{j} > 20$ GeV and $|\eta^j| < 5.0$, $m_{jj} > 300$ GeV, and $|\Delta\eta_{jj}| > 2.5$ and is less stringent than the event selection for our signal region. The measured cross section is corrected for the acceptance in this region using the MadGraph MC generator, which is also used to estimate the theoretical cross section. The acceptance ratio between the selected signal region and the fiducial region is 36% considering generator-level jet and lepton properties only. The overall acceptance times efficiency is 7.9%.

The MadGraph prediction of the same-sign W-boson pair cross section is corrected by a next-to-leading order to leading-order cross section ratio estimated using vbfnlo [32–34]. The fiducial cross section is found to be $\sigma_{\text{fid}}(W^\pm W^\pm jj) = 4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})$ fb with an expectation of 5.8 ± 1.2 fb.

In addition to the dilepton same-sign signal region, a $WZ \to 3\ell\nu$ control region is studied by requiring an additional lepton with p_T larger than 10 GeV. This control region allows the measurement of a fiducial cross section of the $WZjj$ process and is $\sigma_{\text{fid}}(WZjj) = 10.8 \pm 4.0(\text{stat}) \pm 1.3(\text{syst})$ fb with an expectation of 14.4 ± 4.0 fb. The fiducial region is defined in the same way as for the WW analysis, but requiring one more lepton with $p_T{}^{\ell} > 10$ GeV and $|\eta_\ell| < 2.5$. The acceptance ratio between the selected signal region and the fiducial region is 20% considering generator-level jet and lepton properties only. The overall acceptance times efficiency is 3.6%.

To compute the limits and significances, the CL_s [35–37] construction is used. The observed (expected) significance for the $W^\pm W^\pm jj$ process is 2.0σ (3.1σ). Considering the QCD component of the $W^\pm W^\pm jj$ events as background and the EW component together with the EW-QCD interference as signal, the observed (expected) signal significance reduces to 1.9σ (2.9σ).

Various extensions to the SM alter the couplings between vector bosons. Reference [10] proposes nine independent C- and P-conserving dimension-eight effective operators to modify the quartic couplings between the weak gauge bosons. The variable $m_{\ell\ell}$ is more sensitive to AQGCs than $p_T^{\ell,\max}$, $m_{\ell\ell jj}$, and m_{jj}. Figure 3 (top) shows the expected $m_{\ell\ell}$ distribution for three values of $F_{T,0}/\Lambda^4$; Λ is the scale of new physics and $F_{T,0}$ is the coefficient of one of the nine effective operators. The observed and expected upper and lower limits at 95% confidence level (C.L.). on the nine

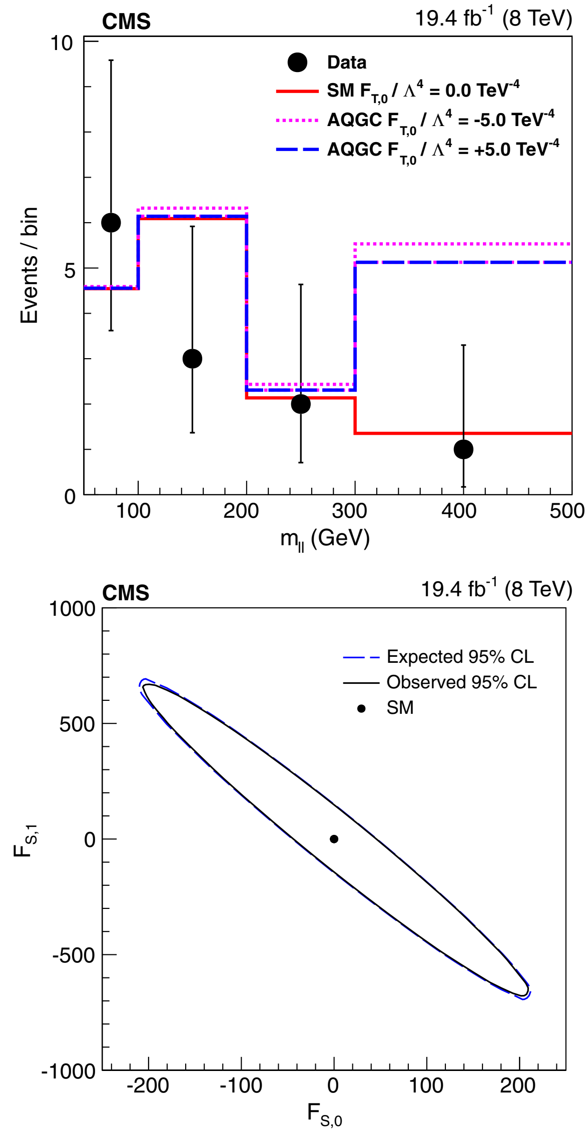

FIG. 3 (color online). The $m_{\ell\ell}$ distributions (top) after full selection with all SM backgrounds and $F_{T,0}/\Lambda^4 = -5.0$, 0 (SM), and 5.0 TeV^{-4}; the last bin includes overflow events. Observed and expected two-dimensional 95% C.L. (bottom) for F_{S0}/Λ^4 and F_{S1}/Λ^4.

coefficients are shown in Table II, where all the results 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. Some operators for anomalous quartic gauge boson couplings may lead to tree-level unitarity violation. We also report the values of the operator coefficient for which unitarity is restored at the scale of 8 TeV, the unitarity limit. In addition to the limits on individual operator coefficients, the expected and observed two-dimensional 95% C.L. on $F_{S,0}/\Lambda^4$ and $F_{S,1}/\Lambda^4$ are presented in Fig. 3 (bottom): a linear combination of those operators leads to a scaling of the SM cross section.

Doubly charged Higgs bosons are predicted in models that contain a Higgs triplet field. Some of these scenarios

TABLE II. Observed and expected upper and lower limits at 95% C.L. on the nine dimension-eight operators that affect quartic couplings between the weak gauge bosons. Limits from unitarity are reported. The units are TeV^{-4}.

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

predict same-sign dilepton events from $W^\pm W^\pm$ decays with a VBF topology. The cross section for VBF production of $H^{\pm\pm}$ and decay to $W^\pm W^\pm$ is directly proportional to the vacuum expectation value of the triplet. The remaining five parameters in the model of the Higgs potential are adjusted to get the given $m_{H^{\pm\pm}}$ hypothesis while requiring one of the scalar singlets to have a mass of 125 GeV. The Georgi-Machacek model of Higgs triplets [38] is considered. For $m_{H^{\pm\pm}} = 200\,(800)$ GeV the following parameters are used: $\lambda_1 = 1$, $\lambda_2 = 1$, $\lambda_3 = 1$, $\lambda_4 = 2.37\,(4)$, and $\lambda_5 = 0.432\,(7.26)$. By using the m_{jj} distribution, 95% C.L. upper limits on $\sigma_{H^{\pm\pm}}\mathcal{B}(H^{\pm\pm} \to W^\pm W^\pm)$ are derived as shown in Fig. 4. The experimental results are overlaid with theoretical cross sections for three values of the vacuum expectation value.

In summary, a study of vector boson scattering in pp collisions at $\sqrt{s} = 8$ TeV has been presented based on a data sample corresponding to an integrated luminosity of $19.4\ \mathrm{fb}^{-1}$. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign W-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^\pm W^\pm$ and WZ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

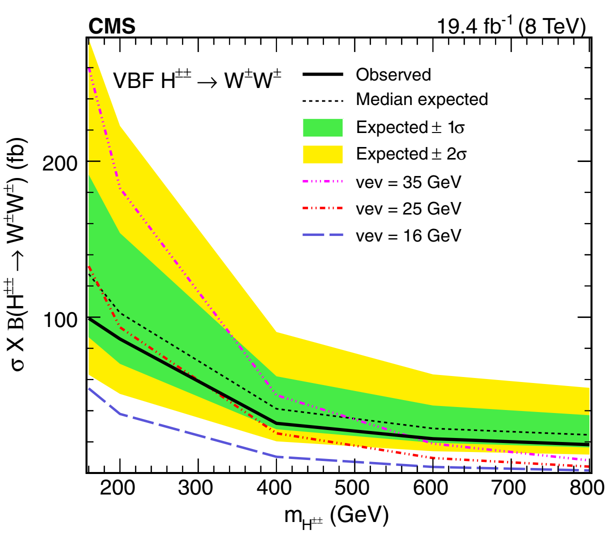

FIG. 4 (color online). Expected and observed 95% C.L. upper limits on the cross section times branching fraction, $\sigma_{H^{\pm\pm}}\mathcal{B}(H^{\pm\pm} \to W^\pm W^\pm)$. Theoretical cross sections for three values of the vacuum expectation value (vev) are overlaid.

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