Observation of heavy triboson production in leptonic final states in proton-proton collisions at \( \sqrt{s} = 13 \) TeV

The CMS Collaboration

Abstract

An observation of the combined production of three massive vector bosons (VVV with \( V = W, Z \)) in proton-proton collisions at a center-of-mass energy of 13 TeV is reported. The analysis is based on a data sample recorded by the CMS experiment at the CERN LHC corresponding to a total integrated luminosity of 137 fb\(^{-1}\). The searches for individual WWW, WWZ, WZZ, and ZZZ production processes are performed in final states with three, four, five, and six leptons (electrons or muons), or with two same-charge leptons plus one or two jets. The observed (expected) significance of the combined VVV production signal is 5.7 (5.9) standard deviations (sd) and the corresponding measured signal strength is 1.02\(^{+0.26}_{-0.23}\). The significances of the individual WWW and WWZ channels are 3.3 and 3.4 sd, respectively. The measured production cross sections for the individual triboson final states are also reported.
The production of three massive gauge bosons \( VVV \) (\( V = W, Z \)) in high energy pp collisions is interesting because the standard model (SM) predictions for these processes involve the non-Abelian character of the theory [1]. In particular, the presence of quadruple-boson interactions can be probed through VVV final states [2, 3]. Triple-boson interactions and intermediate Higgs bosons also play a role. If new physics beyond the SM is present at high mass scales not far above 1 TeV, then cross section measurements for triple and double gauge boson final states might deviate from SM predictions [4–7]. Up to now, such measurements have remained elusive because production cross sections are low and backgrounds are insurmountable except for rather rare leptonic final states. Next-to-leading order (NLO) SM calculations of VVV production in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) predict cross sections of 509, 354, 91.6, and 37.1 fb for WWW, WWZ, WZZ, and ZZZ final states with uncertainties of approximately 10% [8–12]. These cross section calculations include contributions from the associated production of the Higgs boson (H) with a vector boson (V = W, Z), where H decays to \( W^+W^- \) or ZZ [13–16].

The first evidence of VVV production was recently reported by the ATLAS Collaboration [17] following earlier studies of WWW production in 8 TeV ATLAS [18] and 13 TeV CMS data [19]. This note reports the first observation of VVV production in pp collisions based on a dataset collected with the CMS detector in 2016 through 2018 corresponding to an integrated luminosity of 137 fb\(^{-1}\). Measurements of the production cross sections for individual VVV processes are also reported. Five final states are considered (where \( \ell = e \) or \( \mu \)): \( W^\pm W^\pm W^\mp \rightarrow \ell^\pm \ell^\pm 2\nu \ell^\mp \), \( W^\pm W^\pm Z \rightarrow \ell^\pm \ell^\pm 2\nu \ell^\mp \), \( W^\pm ZZ \rightarrow \ell^\pm \nu 2(\ell^\pm \ell^\mp) \), and \( ZZZ \rightarrow 3(\ell^\pm \ell^\mp) \), which correspond to five exclusive channels: two same-sign (SS) leptons with jets, three (3\( \ell \)), four (4\( \ell \)), five (5\( \ell \)), and six (6\( \ell \)) leptons. Searches in the dilepton and trilepton final states target WWW production; four-lepton events are used to search for WWZ production; and five- and six-lepton events are used to search for WZZ and ZZZ production, respectively. In all of these channels, leptons from VVV production characteristically have relatively large transverse momentum \( p_T \) and tend to be isolated from other particles in the event.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter which provides 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 chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, as well as definitions of the coordinate system used, can be found in Ref. [20].

The data are collected using triggers that require two electrons, two muons, or one electron and one muon which satisfy loose isolation requirements and pass certain \( p_T \) thresholds. For the dielectron trigger, those thresholds are 23 (12) GeV for the leading (subleading) electron while for the dimuon trigger, they are 17 (8) GeV. For the electron+muon trigger, the threshold is 23 GeV for the leading lepton and 12 (8) GeV for the subleading electron (muon).

The CMS event reconstruction is based on the particle-flow (PF) algorithm [21] which combines information from the tracker, calorimeters, and muon systems to identify charged and neutral hadrons, photons, electrons, and muons, known collectively as PF candidates. Muons and electrons from W and Z boson decays, known as prompt leptons, are selected for offline analysis using standard criteria [22, 23]. Events containing \( \tau \) leptons decaying into charged hadrons are rejected by requiring no isolated tracks aside from selected electrons and muons. PF candidates are clustered into jets using the anti-\( k_T \) algorithm with a distance parameter of 0.4 [24–26]. Jets with \( p_T > 20 \text{ GeV} \) and \(|\eta| < 5\) are selected for analysis unless they are within
$\Delta R < 0.4$ of a prompt lepton. Jets containing the decay of a $b$ quark are identified using the loose working point of the deep combined secondary vertex $b$ tagging algorithm [27]. To increase the efficiency for identifying low-$p_T$ $b$ jets, a soft-$b$-tag object [28] is defined using a track-based secondary vertex reconstruction.

The primary pp interaction vertex is taken to be the reconstructed vertex with the largest summed $p_T^2$ where the sum is calculated using track-based jets and the associated track-based missing transverse momentum ($p_T^{\text{miss}}$) [29]. Track-based jets are constructed using only charged tracks associated to the given vertex, and the track-based $p_T^{\text{miss}}$ is the negative vector sum of the transverse momenta of those jets. In addition to the primary interaction, other pp interactions (pileup) produce extra charged particles and neutral energy in the detector. Charged tracks originating from pileup are removed from consideration and the average neutral energy density from pileup is estimated and subtracted from the reconstructed jets and from the calculation of lepton isolation [30].

The previous search for WWW production [19] was based on sequences of requirements called sequential cuts. In this note, that approach is extended to cover all five channels. In addition, motivated by the relatively high yields in the SS, $3\ell$, and $4\ell$ channels, multivariate techniques based on boosted decision trees (BDT) [31–35] are applied, which outperform the sequential-cut analyses. In view of the difficulty of isolating a significant WWW or WWZ signal, both analyses are presented here. The primary results are those obtained with the BDT-based approach.

The acceptances, efficiencies, and kinematic properties of the signal and background processes are determined using a combination of data and simulated events. The POWHEG 2.0 generator [36–39] and the MadGraph5_aMC@NLO 2 (2.2.2 or 2.4.2) generator [40] are used to generate VVV signal events including VH as well as diboson (WW, WZ, and ZZ) and single-$t$ background events. The MadGraph5_aMC@NLO 2 is used in the leading-order (LO) mode with the MLM jet matching [41] to generate SM $t\bar{t}$, $t\bar{t}+X$ ($X=W,Z,H$), $W$+jets, $Z$+jets, $W\gamma$, and $W^\pm W^\mp$ events. The most precise cross section calculations available are used to normalize the simulated samples, and usually correspond to either NLO or next-to-NLO accuracy [16, 40, 42–49]. Parton showering, hadronization, and the underlying event are modeled by PYTHIA 8.2 (8.205 or 8.230) [50] with parameters set by the CUETP8M1 or CP5 tune [51, 52]. The NNPDF3.0 or 3.1 [53–55] parton distribution functions (PDF) are used in the generation of all simulated samples. Pileup is simulated and the GEANT4 [56] package is used to mimic the response of the CMS detector.

The SS and $3\ell$ channels target WWW production [19]. The SS channel requires exactly two SS leptons with $p_T > 25$ GeV and one or more jets. The dilepton mass $m_{ll}$ must exceed 20 GeV. This channel is subdivided into nine signal regions according to the flavors of the leptons ($e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$) and the jets content: “1J” for events with exactly one jet; “$m_{jj}$-in” for events containing two or more jets with the mass of the two jets closest in $\Delta R$ compatible with the W boson mass (65 < $m_{jj}$ < 95 GeV); “$m_{jj}$-out” for the remaining events with two or more jets. The background processes fall broadly in three categories. The first category contains trilepton processes with one lepton either not selected or not reconstructed (“lost”). Such backgrounds include WZ and $t\bar{t}$Z production and are reduced by requiring $m_T^{\text{max}} > 90$ GeV, where $m_T^{\text{max}}$ is the largest transverse mass obtained from $p_T^{\text{miss}}$ and any lepton in the event. The second category consists of processes with SS lepton pairs, mainly via $W^\pm W^\pm$+jets and $t\bar{t}W^\pm$ production. This contribution is suppressed by requiring the two highest-$p_T$ jets to have $m_{jj} < 500$ GeV or $|\Delta y_{jj}| < 2.5$. The third category includes $W$+jets and $t\bar{t}$+jets production where a final state jet or photon is misidentified as a charged lepton and are labeled nonprompt. These back-
ground contributions are suppressed using stricter lepton identification and isolation requirements and by requiring $\not{p}_T > 45 \text{ GeV}$. All backgrounds containing top quarks are further reduced by excluding events with b-tagged jets or soft b-tags. The background due to charge mismeasurement in Drell-Yan production is relevant only for dielectron events and is brought to a negligible level by requiring $|m_{\ell\ell} - m_Z| > 10 \text{ GeV}$.

The 3$\ell$ channel is subdivided according to the number of same-flavor opposite-sign leptons pairs (SFOS): 0SFOS, 1SFOS, and 2SFOS. At least one lepton is required to have $p_T > 25 \text{ GeV}$ while the others must have $p_T > 20 \text{ GeV}$, except in 0SFOS where all three leptons are required to have $p_T > 25 \text{ GeV}$. Events in 1SFOS and 2SFOS must contain no jets while the presence of one jet is allowed in 0SFOS. The background sources are similar to those in the SS category. Events with b-tagged jets are excluded to suppress nonprompt-lepton background from processes involving top quarks. The contribution from triple prompt lepton final states is suppressed by requiring the masses of all SFOS pairs to be incompatible with the Z boson mass and with low-mass resonances. Additional background reduction is achieved with the following requirements: if exactly one SFOS lepton pair is found, $m_T^{3\ell}$ defined as the transverse mass $m_T$ calculated from the third lepton and $p_T^{\text{miss}}$ must be larger than 90 GeV; and, for events with no SFOS pairs, $m_T^{\text{max}} > 90 \text{ GeV}$. Background contributions from nonprompt leptons and converted or misidentified photons are reduced by requiring large $p_T$ of the three-lepton system $p_T^{3\ell} > 50 \text{ GeV}$, and a large azimuthal separation $\Delta \phi \left( \vec{p}_T^{3\ell}, \vec{p}_T^{\text{miss}} \right) > 2.5$ between $\vec{p}_T^{\text{miss}}$ and the $\vec{p}_T$ of the three-lepton system, $p_T^{3\ell}$. Background contributions from photon conversions in which the photon is radiated in a Z boson decay are suppressed by requiring that the three-lepton invariant mass $m_{3\ell}$ is not close to the Z boson mass.

The 4$\ell$ channel targets WWZ production. The Z boson is identified through its decay to an SFOS lepton pair with $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$. These leptons are required to have $p_T > 25 \text{ (10) GeV}$ for the (sub)leading lepton. The (sub)leading lepton of the remaining non-Z leptons must have $p_T > 25 \text{ (10) GeV}$. The dominant background comes from ZZ production, so the cases of different-flavor (e$\mu$) and same-flavor (ee/µµ) non-Z lepton pairs are handled separately. The same-flavor invariant mass is required to differ from $m_Z$ by at least 10 GeV. Other background contributions consist of tZ, tWZ, tH, and WZ events. The rejection of events with b-tagged jets reduces contributions from top quarks and a requirement that $m_{\ell\ell} > 12 \text{ GeV}$ for all opposite-sign lepton pairs suppresses backgrounds from low-mass resonances. The 4$\ell$ channel is subdivided into seven signal regions: for the e$\mu$ category there are four bins in $m_{\ell\ell}$ and $m_{T2}$ [57] and for the ee/µµ category there are three bins based on $p_T^{4\ell}$ and $p_T^{\text{miss}}$.

The 5$\ell$ and 6$\ell$ channels target WZZ and ZZZ production. Event yields in these categories are low due to small cross sections and branching fractions. Since background contributions are low, the selection maximizes the signal efficiency. The two leading leptons are required to have $p_T > 25 \text{ GeV}$ while other leptons must have $p_T > 10 \text{ GeV}$. Events in the 5$\ell$ channel are required to contain two SFOS lepton pairs with $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$. The transverse mass $m_T$ calculated from the remaining lepton and $p_T^{\text{miss}}$ must be larger than 50 GeV when that lepton is an electron. Events with b-tagged jets are rejected. The background in the 5$\ell$ channel consists almost entirely of ZZ events with a nonprompt lepton; subdominant contributions arise from tZ and tH production. Events in the 6$\ell$ channel are required to have three SFOS pairs and a sum of the transverse momenta of the six leptons larger than 250 GeV. The very small 6$\ell$ background comes from tH and ZZ processes.

Background sources with a particular number of prompt leptons and no nonprompt leptons are evaluated using MC simulations. These simulations are extensively checked with several
control regions enriched in the main sources of background events. Both the predicted numbers of events and relevant kinematic distributions are compared to observations and good agreement is found in all cases. The precision of the comparison is used to assess systematic uncertainties on these background contributions. Background contributions from sources with one or more nonprompt leptons cannot be reliably evaluated using MC simulations, so data-driven estimates are used instead. These estimates rely on the fact that nonprompt leptons tend to be less isolated than prompt ones. For the WWW channels, following Ref. [19], the contribution of events with a nonprompt lepton is evaluated using a sample of events in which one lepton satisfies loose identification criteria but fails the tight criteria. The number of events in this region determines the estimate of the nonprompt background in the signal region using a scale factor computed with a separate event sample rich in nonprompt leptons. This scale factor is taken to be the ratio of the number of events that pass the tight selection criteria to those that pass the loose criteria. For the 5ℓ channel, a sample of events with three prompt leptons and one nonprompt lepton, dominated by WZ production, is used to verify the MC prediction of background contributions with a nonprompt lepton. Nonprompt leptons are a minor background for all other channels.

Figure 1: Comparison of the observed numbers of events from the BDT-based selections to the predicted yields after fitting. The VVV signal is shown stacked on top of the total background and is based on theoretical SM cross sections. The expected significance L in the middle panel represents the number of sd with which the null hypothesis (no signal) is rejected. The lower panel shows the pulls for the fit result.

The signal strength μ, defined as the measured production cross section times branching fraction divided by the expected SM value, is determined through simultaneous fits to all twenty-one signal regions. In one version of the fit, four independent signal strengths (μWW, μWZZ, μWZ, and μZZZ) are used. In the other version, a common single signal strength μcomb is used for all four processes. Several sources of systematic uncertainty are taken into account. The most important sources involve the estimation of background contributions; the uncertainties range from 5% to 25% and come mainly from limited statistical precision in the control regions. The uncertainty in the data-driven background estimate of non-prompt backgrounds also contributes significantly at 50%. Uncertainties for trigger efficiencies, lepton identification and energy resolution, jet energy scale, and b-jet tagging efficiency range from 1% to 9%. A 2.5–2.6%
uncertainty on the integrated luminosity is assessed [58–60]. Uncertainties due to limitations of the theory include missing higher-order corrections (2–14%), PDF uncertainties (2–7%), and the strong coupling constant \( \alpha_s \) (1%). Theory and experimental uncertainties are taken to be correlated across different channels. Statistical uncertainties are much larger than systematic uncertainties. The expected significance of the combined sequential-cut selection is 5.4 standard deviations (sd), and the observed significance is 5.0 sd. The observed (expected) significance for the individual triboson production processes are 2.5 (2.9) sd for WWW, 3.5 (3.6) sd for WWZ, 1.6 (0.7) sd for WZZ, and 0.0 (0.9) sd for ZZZ.

Figure 2: Best fit values of the signal strengths for the BDT-based analyses (blue) and the sequential-cut analyses (black). For ZZZ production, a 95% CL upper limit is shown. The stated numerical values correspond to the BDT-based analysis.

The discrimination of signal and background events in the SS, 3\( \ell \), and 4\( \ell \) channels is enhanced by employing BDTs. The training and optimization of the BDTs was carried out for each channel individually using simulated background and signal events. A minimum value of each BDT output variable substitutes for the categorizations of events and all the kinematic requirements applied in the sequential-cut analyses. In the SS and 3\( \ell \) channels, two separate BDTs are trained: the first one to separate signal from nonprompt background and the second one to separate signal from the rest of the background. These two BDTs are applied sequentially. In the 4\( \ell \) channel, a similar strategy is pursued except that the two BDTs are targeted against ZZ and t\( \bar{t} \)Z backgrounds specifically. There are two kinematic subchannels called bins for events with same-flavor Z decays and five for different-flavors. The improvement in sensitivity due to the use of BDTs varies channel by channel and is in the range 5–15%. No BDTs are used for the WZZ and ZZZ channels.

The yields in the individual signal regions obtained using the BDTs are shown in Fig. 1. The significance \( L \) of the expected numbers of events in a single channel is computed taking systematic uncertainties into account. Pulls are the differences in the numbers of observed and predicted events normalized to the uncertainties on the numbers of predicted events. Assuming the SM production of VVV events, the expected significance of the fit with a single signal strength \( \mu_{\text{comb}} \) is 5.9 sd and the observed significance is 5.7 sd. The observed (expected) significances for the individual triboson production processes are 3.3 (3.1) for WWW, 3.4 (4.1) for WWZ, 1.7 (0.7) for WZZ, and 0.0 (0.9) for ZZZ. The measured signal strengths correspond
Table 1: Measured cross sections obtained with the BDT-based analyses. The uncertainties listed are statistical and systematic. The VVV cross section is calculated from the fit for $\mu_{\text{comb}}$. For the ZZZ channel, 95% confidence level upper limits are reported.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross section (fb)</th>
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<tbody>
<tr>
<td>Higgs boson contributions as signal</td>
<td></td>
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<tr>
<td>VVV</td>
<td>$1010^{+210}_{-200} + 150$</td>
</tr>
<tr>
<td>WWW</td>
<td>$590^{+160}_{-150} + 150$</td>
</tr>
<tr>
<td>WWZ</td>
<td>$300^{+150}_{-100} + 40$</td>
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<tr>
<td>WZZ</td>
<td>$200^{+140}_{-110} + 70$</td>
</tr>
<tr>
<td>ZZZ</td>
<td>$&lt;200$</td>
</tr>
<tr>
<td>Higgs boson contributions as background</td>
<td></td>
</tr>
<tr>
<td>VVV</td>
<td>$370^{+140}_{-130} + 80$</td>
</tr>
<tr>
<td>WWW</td>
<td>$190^{+110}_{-100} + 80$</td>
</tr>
<tr>
<td>WWZ</td>
<td>$100^{+80}_{-70} + 30$</td>
</tr>
<tr>
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</tr>
<tr>
<td>ZZZ</td>
<td>$&lt;80$</td>
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to total cross sections as listed in Table 1; leptonic branching fractions for W and Z decays are taken from Ref. [61]. If VH is taken to be background, then the combined observed (expected) significance for $\mu_{\text{comb}}$ is 2.9 (3.5) $\sigma$ and the measured cross sections are listed in Table 1. Signal strengths obtained using both sequential-cut and BDT-based approaches and with VH production counted as signal are summarized in Fig. 2.

In summary, data recorded with the CMS experiment during the LHC Run 2 amounting to 137 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV were used to search for the production of triple heavy gauge bosons observed in leptonic final states. The significance of the observation is 5.7 standard deviations (sd) with 5.9 sd expected. For WWW (WWZ) production, the observed significance is 3.3 sd (3.4 sd) compatible with 3.1 sd (4.1 sd) expected. Measured cross sections for individual production processes for WWW, WWZ, and WZZ and an upper limit for ZZZ were reported and are in agreement with the expectations of the standard model. This note documents the first evidence for WWW and WWZ production and the first observation of the combined heavy triboson production by the CMS Collaboration.

References


