Evidence for WW/WZ vector boson scattering in the decay channel $\ell vqq$ produced in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

Evidence is reported for electroweak (EW) vector boson scattering in the decay channel $\ell\nu qq$ of two weak vector bosons $WV$ ($V = W$ or $Z$), produced in association with two parton jets. The search uses a data set of proton-proton collisions at 13 TeV collected with the CMS detector during 2016–2018 with an integrated luminosity of 138 fb$^{-1}$. Events are selected requiring one lepton (electron or muon), moderate missing transverse momentum, two jets with a large pseudorapidity separation and a large dijet invariant mass, and a signature consistent with the hadronic decay of a $W/Z$ boson. The cross section is computed in a fiducial phase space defined at parton level requiring all parton transverse momenta $p_T > 10$ GeV and at least one pair of outgoing partons with invariant mass $m_{qq} > 100$ GeV. The measured and expected EW $WV$ production cross sections are $1.90^{+0.53}_{-0.46}$ pb and $2.23^{+0.08}_{-0.11}$ (scale) $\pm$ 0.05 (PDF) pb, respectively, where PDF is the parton distribution function. The observed EW signal strength is $\mu_{EW} = 0.85 \pm 0.12$ (stat)$^{+0.19}_{-0.17}$ (syst), corresponding to a signal significance of 4.4 standard deviations with 5.1 expected. This is the first evidence of vector boson scattering in the $\ell\nu qq$ decay channel at LHC. The simultaneous measurement of the EW and quantum chromodynamics associated diboson production agrees with the standard model prediction.
Introduction

Vector boson scattering (VBS) plays a special role, since the violation of its unitarity coming from direct interaction between vector bosons is prevented by counterbalancing diagrams involving the Higgs boson [4]. This precise cancellation of divergent effects is an important aspect of the SM, and one of the main motivations to study the VBS processes.

In fact, the VBS measurements could provide an additional confirmation of the electroweak (EW) symmetry breaking, as well as a powerful tool to test effects beyond the SM that can perturb the delicate equilibrium present in the total cross section calculation. The VBS production of vector boson pairs is rare at the LHC, since it is a purely EW process of order 6 of the neutral weak current coupling $g_{\text{EW}}^6$, and it has a large background contamination. Only in recent years the data set collected by the LHC experiments has become large enough to permit a measurement in fully leptonic final states [5-10].
Signal and background simulation

The signal is characterized by the presence of a single isolated electron or muon, a moderate amount of missing transverse momentum $p_T^\text{miss}$, and either three or four jets. One pair of jets is required to have a large invariant mass and large pseudorapidity ($\eta$) separation, the typical signature of VBS-like events, whereas the remaining jets are the result of a vector boson decay. If the boson has a high enough momentum in the laboratory reference frame, its decay products can be collected in a single jet, whereas at lower momentum the decay is resolved into two separate jets.

The main sources of background contamination originate from the production of a single W boson accompanied by jets (called W+jets in the following), and $t\bar{t}$ pairs, where one of the W bosons produced by the top quark decays hadronically. Although simulated samples for these backgrounds are available, an approach based on control samples from data is applied to improve the description of these backgrounds in the signal region. The $W+$jets contribution from Monte Carlo (MC) is corrected differentially by exploiting the events in a dedicated control region, which is described in more detail in Section 5. The top quark background shape is taken from MC, but its normalization is measured from data in the dedicated control region.

The following background processes are modeled using MC event generators: nonresonant QCD-associated diboson production (QCD-WW), $t\bar{t}$ and single top quark production (in $s$, $t$ channel and $tW$); Drell–Yan (DY) lepton pair production; $V$ boson production in association with a photon ($W\gamma$ and $Z\gamma$); single vector boson EW production in the vector boson fusion channel (VBF-V); and triboson production (VVV).
Event reconstruction, selection and categorization

Triggers for isolated single leptons with $p_T$ thresholds: 27, 32, 35 GeV for electrons
24, 24, 27 GeV for muons

The final leptons: $p_T$ of at least 35 GeV (30 GeV) for electron (muon) candidates,
pseudorapidity of $|\eta|<2.5$ (2.4) for electrons (muons)

For each event, hadronic jets are clustered from reconstructed particles using the infrared- and
collinear-safe anti-$k_T$ algorithm [46, 47] with a distance parameter of 0.4 (0.8), labeled in the
following as AK4 (AK8) jets.

AK4 and AK8 jets :
$p_T > 30$ GeV and $|\eta|<4.7$ or
$p_T > 200$ GeV and $|\eta|<2.4$, respectively

The pileup-per-particle identification algorithm (PUPPI) [48, 49] and grooming algorithm, “soft drop” (SD)[50–52] that
removes soft, wide-angle radiation from the large radius jet, improving the modeling of the jet mass observable.

The SD algorithm :
angular exponent $\beta = 0$,
soft cutoff threshold $z_{cut} < 0.1$,
characteristic radius $R_0 = 0.8$ [52],
Event reconstruction, selection and categorization

Two main categories:

- **boosted category** – contains only one AK8 jet, with $p_T > 200$ GeV and $|\eta| < 2.4$, that passes the selection criteria as a hadronically decaying vector boson $V_{\text{had}}$, together with at least two AK4 jets.

- **resolved category** – no AK8 jet $V$ boson candidate is found and instead at least four AK4 jets are reconstructed with $p_T > 30$ GeV the two jets with invariant mass - 85 GeV (the average between the W and Z boson masses) are chosen as the decay product of $V_{\text{had}}$.

The fraction of VBS events in the sample is enhanced requiring a large invariant mass $m_{jj}^{\text{VBS}} > 500$ GeV and large pseudorapidity interval $\Delta \eta_{jj}^{\text{VBS}} = |\eta_{j1}^{\text{VBS}} - \eta_{j2}^{\text{VBS}}| > 2.5$ for the tag jets. The leading VBS tag jet is required to have $p_T > 50$ GeV and the transverse mass of the leptonically decaying $W$ is required to be $m_W^T < 185$ GeV, defined as

$$m_W^T = \sqrt{2 p_T(\ell) \not{p}_T^{\text{miss}} [1 - \cos(\Delta \varphi(p_T(\ell), \not{p}_T^{\text{miss}}))]}$$

(1)

where $p_T(\ell)$ is the $p_T$ of the lepton and $\Delta \varphi(p_T(\ell), \not{p}_T^{\text{miss}})$ is the azimuthal distance between the lepton and the $\not{p}_T^{\text{miss}}$. 
Background estimation

The largest background contribution is the $W$+jets process, followed by the top quark and the QCD multijet backgrounds.

The closure test for this correction is performed by dividing the $W$+jets control region into two subregions, defined by two intervals of $m_T$ closer to (i.e., $[50, 65] \cup [105, 150]$ GeV) or farther (i.e., $[40, 50] \cup [150, +\infty]$ GeV) from the $V$ resonance where the signal region is located. Correction

The top quark background contribution is determined from MC simulation except for its normalization, which is measured in the top quark enriched control region in the final fit to the data.

The QCD multijet background, which may enter the signal region with nonprompt leptons, is estimated from data by measuring the probability for a loosely defined reconstructed lepton originating from a jet to be misidentified as a tightly reconstructed lepton in a phase space region outside the analysis region. The QCD-enriched region is defined by the presence of at least one lepton with the same $p_T$ requirement as for the rest of the analysis, $p_T^{\text{miss}} < 20$ GeV, $m_T^W < 20$ GeV, at least one AK4 jet in the event with $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 1$ from the lepton. The contribution from EW processes with a real lepton is subtracted from this QCD enriched phase space region by means of $W$+jets and DY MC events.
Because of the large background and complex signal topology, the most significant features to separate signal and backgrounds are condensed in a single discriminator built with a deep neural network (DNN). Two different discriminators are optimized for the resolved and boosted categories since the event topology and the kinematics change significantly between the two. The DNN implementation consists of a fully connected neural network with four layers with 64 (32) nodes for the resolved (boosted) topology, trained with stochastic gradient descent implemented via the "Adam" optimizer [61]. The models are trained minimizing the binary cross-the use of regularization techniques, such as Dropout and L2 weights decay [63]. A technique called SHAP (SHapley Additive exPlanations) [64, 65], developed in the field of explainable machine learning, is applied to cross-check the dependence of the DNN model on the input variables and to rank their importance. Among the most important ones, as identified by SHAP and matching the physics expectation, are the $m_{jj}^{VBS}$ variable, the Zeppenfeld variable [66] of the lepton, and the quark/gluon discriminator variable of the leading $V_{had}$ jet. The postfit distribution of the $m_{jj}^{VBS}$ variable is shown in Fig. 2. Table 1 shows the complete list of input variables used for the resolved and boosted topologies, along with their ranking from the SHAP algorithm. The Zeppenfeld variable of a particle $X$ is defined as:

$$Z_X = \frac{\eta^X - \bar{\eta}^{VBS}_{jj}}{\Delta \eta_{jj}^{VBS}},$$

(2)

The centrality [8, 67] variable is defined as $C_{VW} \equiv \min(\Delta \eta_{-}, \Delta \eta_{+})$, with $\Delta \eta_{\pm} \equiv \max(\eta^{VBS}, \eta^{W})$ and $\Delta \eta_{-} = \min(\eta^{VBS}) - \min(\eta^{W})$. The $\eta^{W}$ value is determined assuming the $W$ boson mass from the lepton and $p_T^{miss}$ kinematics.
Signal extraction

Figure 2: Postfit distributions of the $m_{jj}^{VBS}$ observable in the resolved (left) and boosted (right) signal regions. Vertical bars on data points show the statistical error, whereas the gray band is the post-fit uncertainty on MC with all systematic uncertainties included.

Figure 3: The DNN discriminator distribution, taken from simulation, for VBS signal and backgrounds in the resolved (left) and boosted (right) signal regions normalized to unity.
Systematic uncertainties

Table 2: Breakdown of the uncertainties in the EW WV VBS signal strength measurement.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu_{\text{EW}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
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</tr>
<tr>
<td>Limited sample size</td>
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</tr>
<tr>
<td>Normalization of backgrounds</td>
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</tr>
<tr>
<td>Experimental</td>
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</tr>
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<td>b-tagging</td>
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<td>Jet energy scale and resolution</td>
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</tr>
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<td>Integrated luminosity</td>
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<tr>
<td>Lepton identification</td>
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<tr>
<td>Boosted V boson identification</td>
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<tr>
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<td>Signal modeling</td>
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</tr>
<tr>
<td>Background modeling</td>
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<tr>
<td>Total</td>
<td>0.22</td>
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</table>
Three separate maximum likelihood fits:

- the measurement of the purely EW signal strength $\mu_{EW}$ keeping the QCD WV production contribution fixed to the SM prediction $\mu_{QCD} = 1$;
- the measurement of the signal strength considering as signal the EW and QCD WV processes together;
- a two-dimensional simultaneous measurement of the signal strengths $\mu_{EW}$ and $\mu_{QCD}$.

Figure 5: Results for the EW-signal-only fit, keeping the QCD WV contribution fixed to the SM prediction. Upper plots: post-fit DNN discriminator distributions for the resolved (left) and the boosted (right) signal regions. The signal contribution is plotted both stacked on top of the background processes and also overlaid to show the signal postfit distribution. The expected yield is the sum of signal and background. Lower plots: background-subtracted DNN discriminator distribution for the resolved (left) and the boosted (right) categories. Vertical bars on data points show the statistical error, whereas the gray band is the post-fit uncertainty on MC with all systematic uncertainties included.
A fiducial phase space region is defined at parton level requiring all partons to have $p_T > 10\text{GeV}$ and at least one pair of outgoing partons with invariant mass $m_{qq} > 100\text{GeV}$. The SM prediction for the EW WV production cross section in this fiducial region is $2.23^{+0.08}_{-0.11}$ (scale) $\pm 0.05$ (PDF) pb. The measured EW WV production cross section is $1.90^{+0.53}_{-0.46}$ pb, corresponding to an observed EW-only signal strength of:

$$\mu_{\text{EW}} = \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} = 0.85 \pm 0.12 \text{ (stat)}^{+0.19}_{-0.17} \text{ (syst)} = 0.85^{+0.23}_{-0.21},$$

(3)

where $\sigma_{\text{obs}}$ and $\sigma_{\text{SM}}$ are the observed and predicted cross sections, respectively, with an expectation of $1.00^{+0.24}_{-0.22}$. The observed significance for the SM EW WV signal is 4.4 standard deviations with 5.1 expected.
Results

Considering instead the signal as the overall EW and QCD-associated diboson production, the measured and expected cross sections are $16.4^{+3.5}_{-2.8}$ pb and $16.9^{+2.9}_{-2.1}$ (scale) $\pm$ 0.5 (PDF), respectively, extracted in the same fiducial phase space region as the EW-only one. The overall signal strength $\mu = \sigma_{\text{obs}} / \sigma_{\text{SM}}$, with an expectation of $1.00^{+0.21}_{-0.20}$, is measured as:

$$\mu_{\text{EW+QCD}} = 0.97 \pm 0.06 \text{ (stat)}^{+0.19}_{0.21} \text{ (syst)} = 0.97^{+0.20}_{-0.22}. \quad (4)$$

The fit is also performed leaving as free independent parameters the signal strengths of the EW and QCD-associated WV production components ($\mu_{\text{EW}}$ and $\mu_{\text{QCD}}$). The result of the 2D fit is shown in Fig. 6, where the expected and observed minima are presented, together with the 68 and 95% confidence level (CL) contours built from the likelihood function. The measured signal strengths are in agreement with the SM predictions within the 68% CL.
Summary

The first evidence for the electroweak (EW) production of a WV (V = W or Z) pair plus two jets in the $\ell vqq$ decay channel is reported.

Events are separated into two categories:
- The hadronically decaying W or Z boson is reconstructed as one large-radius jet,
- Identified as a pair of jets with dijet mass close to the boson mass.

Three separate maximum likelihood fits are performed:
1. the measurement of the purely EW signal strength $\mu_{EW}$ keeping the quantum chromodynamics (QCD) WV contribution fixed to the SM prediction $\mu_{QCD} = 1$;
2. the measurement of the signal strength considering as signal the EW and QCD WV processes together;
3. a two-dimensional simultaneous measurement of the signal strengths $\mu_{EW}$ and $\mu_{QCD}$.

The observed significance for the SM EW WV signal is 4.4 standard deviations with 5.1 expected.

Overall, both the WV EW-only measurement and the simultaneous EW and QCD WV measurements are in agreement with the SM predictions within the 68% confidence level.
Backup slides
Figure 1: Examples of Feynman diagrams contributing to the analyzed final state: purely EW VBS process contributions (upper left diagram), s-channel Higgs boson contribution (upper right diagram), and nonresonant diboson production (lower diagram).
Systematic uncertainties

- Discrepancies in the lepton reconstruction and identification efficiencies between data and MC simulation. Their impact on the signal region is less than 1% for both electrons and muons.
- The trigger efficiency uncertainty is also smaller than 1%.
- The electron and muon momentum scale uncertainties are computed by varying the lepton momenta within their 1σ uncertainty, and the resulting uncertainty in the signal yield is less than 1%.
- Jet energy scale and resolution uncertainties are evaluated by shifting the $p_T$ value of the jets, and thus directly affecting the reconstructed jet multiplicity and $p_T^{miss}$ measurement [72]; several independent sources are considered and partially correlated among different data sets, resulting in up to 4%.
- The b-tagging data/MC corrections are associated with different uncertainty sources and correlated among all processes - 5%, on the signal and background.
- Uncertainty in the $p_T^{miss}$ estimation due to unclustered energy is also included and calculated by varying the momenta of particles that are not identified with either a jet or a lepton; its effect is negligible.
- The uncertainty in the pileup modeling is applied to all the relevant MC samples by varying the minimum bias cross section used to generate the pileup distribution by 1 sigma [73] and estimated to be less than 1%.
- The theoretical scale uncertainty for the EW-only WV signal is 5%.
- For the QCD-associated diboson production is 25%.
- The overall impact on the EW-only signal strength determination from the choice of renormalization and factorization scales is 11%.
- The uncertainty in the modeling of the parton shower is 4%.
Soft Drop method

Soft Drop Condition: \[
\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta,
\] (1.1)

where \(p_{T1}\) are the transverse momenta of the constituents with respect to the beam, \(\Delta R_{12}\) is their distance in the rapidity-azimuth plane, \(z_{\text{cut}}\) is the soft drop threshold, and \(\beta\) is an angular exponent. By construction, eq. (1.1) fails for wide-angle soft radiation. The degree

![Figure 1](image-url)

**Figure 1:** Phase space for emissions on the \((\log \frac{1}{z}, \log \frac{R_0}{\theta})\) plane. In the strongly-ordered limit, emissions above the dashed line (eq. (2.2)) are vetoed by the soft drop condition. For \(\beta > 0\), soft emissions are vetoed while much of the soft-collinear region is maintained. For \(\beta = 0\) (mMDT), both soft and soft-collinear emissions are vetoed. For \(\beta < 0\), all (two-prong) singularities are regulated by the soft drop procedure.
<table>
<thead>
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Influence of QCD parton shower in deep learning
invisible Higgs through vector boson fusion

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Vector boson fusion established itself as a highly reliable channel to probe the Higgs boson and an avenue to uncover new physics at the Large Hadron Collider. This channel provides the most stringent bound on Higgs’ invisible decay branching ratio, where the current upper limits are significantly higher than the one expected in the Standard Model. It is remarkable that merely low-level calorimeter data from this characteristically simple process can improve this limit substantially by employing sophisticated deep-learning techniques. The construction of such neural networks seems to comprehend the event kinematics and radiation pattern exceptionally well. However, the full potential of this outstanding capability also warrants a precise theoretical projection of QCD parton showering and corresponding radiation pattern. This work demonstrates the relation using different recoil schemes in the parton shower with leading order and higher-order computation.
References


Event reconstruction, selection and categorization

VBS production of pairs of vector bosons, WV, in association with two jets originating from the scattered incoming partons

W boson decays leptonically and the second boson decays hadronically

Events are required to contain exactly one tightly identified and isolated lepton \([57, 58]\) associated with the W boson leptonic decay

Events containing a second loosely identified lepton with \(p_T > 10\text{ GeV}\) are vetoed. Finally, we require a missing transverse momentum \(p_T^{\text{miss}} > 30\text{ GeV}\) in the event. The missing transverse momentum vector \(\vec{p}_T^{\text{miss}}\) is computed as the negative vector sum of the transverse momenta of all the particle candidates in an event \([59]\).