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Measurement of the sum of WW and WZ production with W+dijet events in pp collisions at $\sqrt{s} = 7$ TeV

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Abstract A measurement of the inclusive WW+WZ diboson production cross section in proton–proton collisions is reported, based on events containing a leptonically decaying $W$ boson and exactly two jets. The data sample, collected at $\sqrt{s} = 7$ TeV with the CMS detector at the LHC, corresponds to an integrated luminosity of 5.0 fb$^{-1}$. The measured value of the sum of the inclusive WW and WZ cross sections is $\sigma(pp \rightarrow WW + WZ) = 68.9 \pm 8.7$ (stat.) $\pm 9.7$ (syst.) $\pm 1.5$ (lum.) pb, consistent with the standard model prediction of $65.6 \pm 2.2$ pb. This is the first measurement of WW+WZ production in pp collisions using this signature. No evidence for anomalous triple gauge couplings is found and upper limits are set on their magnitudes.

The gauge symmetry of the standard model (SM) fixes the triple gauge boson couplings that determine the self-interactions of $W$ and $Z$ bosons. The pair production of vector gauge bosons allows a direct test of the electroweak sector of the SM [1]. Observation of anomalous triple gauge boson couplings would be an indication of physics beyond the SM.

We report the first measurement of WW+WZ diboson production in pp collisions in the semileptonic final state at the Large Hadron Collider (LHC), where one $W$ boson decays leptonically ($\ell\nu$, with $\ell = e, \mu$) while the other boson ($W$ or $Z$) decays hadronically ($jj$), giving rise to two energetic jets in the final state. Previous measurements in this channel at the Tevatron pp collider include the recent CDF [2] and D0 [3, 4] results. The advantage of reconstructing WW+WZ in the $\ell\nu jj$ decay mode over the purely leptonic final states [5–8] is the larger branching fraction of $W$ and $Z$ bosons to quarks. This advantage is partially offset by the larger backgrounds in the $\ell\nu jj$ channel, coming mainly from W+jets production. In contrast to the fully leptonic decay of WW pairs, the semileptonic process permits a direct measurement of the boson transverse momentum ($p_T$). The sensitivity of WW production to the WW$\gamma$ coupling and of WW and WZ production at high boson transverse momentum to the WWZ coupling makes these processes particularly useful as a probe of anomalous triple gauge boson couplings.

The data correspond to an integrated luminosity of $5.0 \pm 0.1$ fb$^{-1}$ collected in 2010 and 2011 with the Compact Muon Solenoid (CMS) detector in pp collisions at $\sqrt{s} = 7$ TeV at the CERN LHC. The CMS experiment [9] uses a right-handed coordinate system, with the origin at the nominal interaction point, the $x$ axis pointing to the center of the LHC ring, the $y$ axis pointing up, perpendicular to the plane of the LHC ring, and the $z$ axis along the counterclockwise beam direction. The polar angle $\theta$ is measured from the positive $z$ axis and the azimuthal angle $\phi$ is measured in the $x$–$y$ plane. The pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$. 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 silicon pixel and strip trackers and several calorimeters. The tracking system covers the range $|\eta| < 2.5$ and provides a track momentum resolution of 1 % at 100 GeV. The lead tungstate crystal electromagnetic calorimeter (ECAL) covers $|\eta| < 3$ with an energy resolution of about 3 %/$\sqrt{E}$, where $E$ is in GeV [10]. The brass/scintillator hadron calorimeter (HCAL) covers $|\eta| < 3.0$ with an energy resolution of 100 %/$\sqrt{E}$. The muon system consists of gas-ionization detectors inside and around the steel return yoke, and is capable of reconstructing and identifying muons within $|\eta| < 2.4$. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The CMS detector is nearly hermetic, allowing for measurements of the missing transverse energy ($E_T^{\text{miss}}$) in the event. A two-tier trigger system selects the events of interest.

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The data were collected with a suite of single-lepton triggers mostly using $p_T$ thresholds of 24 GeV for muons and 25–32 GeV for electrons. To preferentially select events with on-shell W bosons, the single-electron triggers also require minimum thresholds on $E_T^{\text{miss}}$ in the range 0–25 GeV and on the transverse mass $m_T$ of the electron plus $E_T^{\text{miss}}$ system in the range 0–50 GeV. The overall trigger efficiency is about 94 % (90 %) for muon (electron) data, with a small dependence (a few percent) on $p_T$ and $\eta$. Simulated events are corrected for the trigger efficiency as a function of lepton $p_T$ and $\eta$, and in the case of electrons also as a function of $E_T^{\text{miss}}$. Simulated events are used to develop and validate the methods used in the analysis.

The MadGraph5 event generator produces parton-level events with a W boson and up to four partons on the basis of matrix-element (ME) calculations. The ME–parton shower (ME–PS) matching scale $\mu$ is taken to be 20 GeV [12], and the factorization and renormalization scales are both set to be 20 GeV [12], and the factorization and renormalization scales are both set to be 20 GeV [12]. The MadGraph5 1.3.30 [11] event generator produces parton-level events with a W boson and up to four partons on the basis of matrix-element (ME) calculations. The ME–parton shower (ME–PS) matching scale $\mu$ is taken to be 20 GeV [12], and the factorization and renormalization scales are both set to be 20 GeV [12]. Samples of $t\bar{t}$ and Drell–Yan events are also generated with MadGraph. Single-top production is modeled with Powheg 1.0 [13]. Multijet and diboson samples (WW, WZ, ZZ) are generated with Pythia 6.422 [14]. Pythia provides the parton shower simulation in all cases, with parameters of the underlying event set to the Z2 tune [15]. The set of parton distribution functions used is CT10L [16]. A Geant4-based simulation [17] of the CMS detector is used in the production of all Monte Carlo (MC) samples. Multiple proton–proton interactions within a bunch crossing (pileup) are simulated, and the triggers are emulated. All simulated events are reconstructed and analyzed as measured collision events.

Events are selected with one well-identified and isolated lepton (muon or electron), large missing transverse energy, and exactly two high-pT hadrons in the tracker, ECAL, and HCAL, within a surrounding cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$, excluding the lepton itself, is required to be less than 10 % of the measured $p_T$ of the muon, or less than 5 % of the measured $p_T$ of the electron. Here $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and in azimuthal angle, respectively. To reduce the backgrounds from fully leptonic decays, such as Drell–Yan and electroweak diboson processes, we exclude events in which there is any other loosely identified lepton (with $p_T > 10$ GeV for muons and $p_T > 20$ GeV for electrons) in the event.

Jets are reconstructed from calorimeter and tracker information using a particle-flow technique that combines information from several subdetectors [20]. The anti-$k_T$ clustering algorithm [21, 22] with a distance parameter of 0.5 is used. Jets that overlap with isolated leptons within $\Delta R = 0.3$ are not considered. Jet-energy corrections are applied to account for the nonlinear energy response of the calorimeters and for other instrumental effects [23]. These corrections are based on in situ measurements using dijet, $\gamma$+jet, and Z+jet data samples [24]. Pileup collisions and the underlying event add to the energy of the reconstructed jets. The median energy density from pileup is evaluated in each event and the corresponding energy is subtracted from each jet [25]. In addition, charged tracks that do not originate from the primary vertex are not considered for jet clustering [26]. We verified that these procedures successfully remove the dependence of jet response on the number of interactions in a single event. A jet-quality requirement, primarily based on the energy balance between charged and neutral hadrons in a jet, is applied to remove poorly reconstructed jets. Only events containing exactly two jets with $p_T > 35$ GeV and within $|\eta| < 2.4$ are selected for the analysis. To reduce contamination from $t\bar{t}$ background, events are discarded if one or more jets pass high-efficiency b-quark jet identification criteria based on the presence of a secondary vertex within the jet [27]. An accurate $E_T^{\text{miss}}$ measurement is essential to distinguish the W signal from multijet backgrounds and to reconstruct the full event kinematics of the WW system. We use $E_T^{\text{miss}}$ measured in the event using the full particle-flow reconstruction [28] and require $E_T^{\text{miss}} > 25$ (30) GeV for the muon (electron) channel. To reduce the background from processes that do not contain W decay, we require that the transverse mass of the W candidate exceed 30 GeV (50 GeV) in muon (electron) data [29].

We measure the dijet mass $(m_{jj})$ distribution, as shown in Fig. 1(a). The relative contributions of the known SM processes are determined using an unbinned maximum-likelihood fit over the mass range 40–150 GeV. The fit is performed separately for the muon and electron channels since their background compositions differ. Table 1 lists the SM processes included in the fit. The normalization of the diboson WW+WZ contribution is a free parameter. The normalizations of the background components are allowed to vary within Gaussian constraints around their central values. For multijet events, this central value is obtained from an independent two-component fit to the $E_T^{\text{miss}}$ distribution which
determines the corresponding fraction in the data [29]. The fit uncertainty is used as a constraint on the multijet contribution. The central values for all other processes are obtained from next-to-leading-order (NLO) or higher-order calculations, and the constraints are taken from the theoretical uncertainties listed in Table 1. With the exception of multijet production, the shape of the mjj distribution for all processes is obtained from simulation. Multijet events contribute to the total background when jets are misidentified as isolated leptons. Their mjj shape can be derived from data events with lepton candidates that fail the isolation requirements. The fluctuations in the shapes and yields of subleading backgrounds have a minor impact on the overall fit.

The mjj spectrum of the dominant W+jets component is described using the shape from MADGRAPH simulation after taking into account the uncertainties due to the factorization and renormalization scale (both equal to q) and ME–PS matching scale μ [36]:

\[
F_{W+jets} = \alpha \mathcal{F}_{W+jets}(\mu_0^2, q^2) + \beta \mathcal{F}_{W+jets}(\mu_0^2, q_0^2) + (1 - \alpha - \beta) \mathcal{F}_{W+jets}(\mu_0^2, q_0^2),
\]

where \( \mathcal{F}_{W+jets} \) denotes the mjj shape from simulation. The parameters \( \mu_0, \mu_0' \) and \( q_0, q_0' \) correspond to the default (alternative) values of \( \mu \) and q, respectively. The parameters \( \alpha \) and \( \beta \) are free to vary during the fit and remain within the physical ranges (0 ≤ \( \alpha, \beta \) ≤ 1 and 1 − \( \alpha - \beta \) ≥ 0). We take \( \mu_0' = 2\mu_0 \) or 0.5\( \mu_0 \) (\( q_0' = 2q_0 \) or 0.5\( q_0 \)), depending on which alternative sample provides a better fit to the data. Thus, the fit probes variations of a factor of two in both \( \mu \) and q (with the corresponding shape fluctuations accounted for when setting exclusion limits).

Figure 1(a) shows the observed mjj distribution for both channels combined, together with the fitted projections of the contribution of various SM processes. Figure 1(b) shows the same distribution after subtracting all SM contributions from data except for WW+WZ events. Figure 1(c) shows the pull distribution, i.e. the normalized residual defined as \( (\text{data} - \text{fit}) / \text{(fit uncertainty)} \), where the fit uncertainty is computed at each data point by propagating the uncertainty in the normalization coefficients. The yields of various SM components, as determined by the fit, are reported in Table 2.

In order to ensure robustness against fit parameters and to account for corresponding biases we validate the fit procedure by performing pseudo-experiments. In each experiment, we generate the mjj pseudo-data for the SM processes, taking into account the correlations between the yields, and then perform a fit to each pseudo-data mjj distribution. The results for both the muon and electron channels indicate that there is a small bias (~8.6 % and ~6.6 %) in the WW+WZ yield, corresponding to less than 0.4 standard deviations, and that the fit slightly overestimates the uncertainty on the yield. These effects are corrected for in the final result. The validation procedure shows that biases in all background yields and errors are small. The fit results for the background components are statistically consistent with

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**Table 1** Treatment of background mjj shapes and normalizations in a fit to the data. The cross section values are calculated with the programs cited on the corresponding rows. The background normalizations are constrained to Gaussian distributions with the listed central values and widths. The treatment of multijet events is described in the text.

<table>
<thead>
<tr>
<th>Process</th>
<th>Shape</th>
<th>Constraint on normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson (WW+WZ)</td>
<td>MC</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>W+jets</td>
<td>MC</td>
<td>31.3 pb ± 5 % (NLO) [30]</td>
</tr>
<tr>
<td>t\bar{t}</td>
<td>MC</td>
<td>163 pb ± 7 % (NLO) [31]</td>
</tr>
<tr>
<td>Single top</td>
<td>MC</td>
<td>85 pb ± 5 % (NNLL) [32–34]</td>
</tr>
<tr>
<td>Drell–Yan+jets</td>
<td>MC</td>
<td>3.05 pb ± 4.3 % (NNLO) [35]</td>
</tr>
<tr>
<td>Multijet (QCD)</td>
<td>data</td>
<td>( E_{\text{min}}^{\text{fit}} ) in data</td>
</tr>
</tbody>
</table>
the expectations, with the exception of W+jets, where 11 % fewer events for muons and 15 % fewer events for electrons, compared to the expectation, are observed. Overall, the approach produces a high quality model of the data (Fig. 1(a)), where the pull distribution is consistent with 0 (Fig. 1(c)), and allows us to extract the diboson peak (Fig. 1(b)).

Systematic uncertainties arising from the jet energy are estimated from W bosons decaying hadronically in a sample of semileptonic t ¯{\text{t}} events. The mean and resolution of the reconstructed dijet mass distribution in data agree to within 0.6 % of the expectations from simulation (this discrepancy is accounted for as an explicit systematic uncertainty), with negligible effect on acceptance. A small difference in E_T^{\text{miss}} resolution [28] between data and simulation affects the signal acceptance at the 0.5 % level. Further systematic uncertainties on the signal yield are due to the uncertainty on the trigger efficiency in data (1 %), and on the lepton reconstruction and selection efficiencies (2 %) [29]. The uncertainty due to the b-jet veto is negligible. The uncertainty in the luminosity measurement is 2.2 % [38]. The uncertainty in WZ production ratio. The values of N\_\text{acceptance calculation we assume the SM value for the WW to L\_\text{event selection, and}}

Table 2  Event yields determined from a maximum-likelihood fit to the data. The total uncertainty is computed using the full covariance matrix. Owing to a higher kinematic threshold the product of acceptance × efficiency is smaller for the electron channel. The term A\_\varepsilon includes W and Z branching fractions [37]

<table>
<thead>
<tr>
<th>Process</th>
<th>Muon channel</th>
<th>Electron channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson (WW+WZ)</td>
<td>1900 ± 370</td>
<td>800 ± 310</td>
</tr>
<tr>
<td>W plus jets</td>
<td>67380 ± 590</td>
<td>31640 ± 850</td>
</tr>
<tr>
<td>t ¯{\text{t}}</td>
<td>1660 ± 120</td>
<td>950 ± 70</td>
</tr>
<tr>
<td>Single top</td>
<td>650 ± 30</td>
<td>310 ± 20</td>
</tr>
<tr>
<td>Drell–Yan+jets</td>
<td>3610 ± 160</td>
<td>1410 ± 60</td>
</tr>
<tr>
<td>Multijet (QCD)</td>
<td>300 ± 320</td>
<td>4190 ± 870</td>
</tr>
<tr>
<td>Data</td>
<td>75419</td>
<td>39365</td>
</tr>
<tr>
<td>Fit χ^2/N_{\text{ dof}} (probability)</td>
<td>9.73/12 (0.64)</td>
<td>5.30/12 (0.95)</td>
</tr>
<tr>
<td>Acceptance × efficiency (A_\varepsilon)</td>
<td>(5.15 ± 0.24) × 10^{-3}</td>
<td>(2.63 ± 0.12) × 10^{-3}</td>
</tr>
<tr>
<td>Expected WW+WZ yield from simulation</td>
<td>1700 ± 60</td>
<td>870 ± 30</td>
</tr>
</tbody>
</table>
Fig. 2 Dijet $p_T$ distributions for (a) the muon and (b) the electron channels after full selection and with the requirement $75 \text{ GeV} < m_{jj} < 95 \text{ GeV}$. The stacked histogram shapes are taken from simulation or, where applicable, from data-driven estimates. They are normalized according to the fit to the observed $m_{jj}$ spectrum in data. Below we show the Data/MC ratio with the (dashed) red lines corresponding to the shape uncertainty. The last bin includes the overflow (Color figure online).

plane, computed using the modified frequentist CL$_S$ [39, 42] technique with profile likelihood as the test statistic, are shown in Fig. 3. The limit setting procedure combines fit results from muon and electron channels. We obtain the following one-dimensional observed 95 % CL limits assuming the SM value for the other parameter: $-0.038 < \lambda < 0.030$, $-0.11 < \Delta \kappa_\gamma < 0.14$. These limits are competitive with, and in some cases improve upon, the sensitivity of the combined LEP experiments listed in Refs. [37, 43–46]. The ATLAS Collaboration recently reported limits in the fully leptonic channel for WZ [7] and WW [8] production. Limits obtained from fully leptonic channels are weaker due to the smaller branching fractions.

In summary, a measurement of the sum of the inclusive WW and WZ production cross sections has been performed using events containing a leptonically decaying W and two jets. The measured value for the cross section is $\sigma(p p \to \text{WW} + \text{WZ}) = 68.9 \pm 8.7$ (stat.) $\pm 9.7$ (syst.) $\pm 1.5$ (lum.) pb, which is consistent with the SM prediction. This is the first measurement of WW+WZ production in pp collisions using this signature. No evidence for anomalous triple gauge couplings is found, and limits are set on their magnitudes.

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