Search for a heavy right-handed $W$ boson and a heavy neutrino in events with two same-flavor leptons and two jets at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for a heavy right-handed $W$ gauge boson and a heavy right-handed neutrino at the CERN LHC has been conducted by the CMS collaboration in events with two same-flavor leptons (e or $\mu$) and two jets, using 2016 proton-proton collision data corresponding to an integrated luminosity of 35.9 fb$^{-1}$. No excess above the standard model expectation is seen in the invariant mass distribution of the dilepton plus dijet system. Assuming identical couplings and decay branching fractions as the standard model $W$ gauge boson, and that only one heavy neutrino flavor $N_R$ contributes significantly to the $W_R$ decay width, the region in the two-dimensional $(m_{W_R}, m_{N_R})$ mass plane excluded at a 95% confidence level extends to approximately $m_{W_R} = 4.4$ TeV and covers a large range of neutrino masses below the $W_R$ boson mass. This analysis provides the most stringent limits to date.
1 Introduction

Heavy partners of the standard model (SM) gauge bosons coupling to right-handed fermions are predicted in left-right (LR) symmetric models [1–4]. These models can explain the observed parity violation in the SM as the consequence of spontaneous symmetry breaking at a multi-TeV mass scale. This paper describes a search for such a heavy partner, a heavy right-handed W gauge boson $W_R$, in events with two same-flavor leptons (e or $\mu$) and two jets. The measurement has been conducted by the CMS collaboration at the LHC, using proton-proton collision data corresponding to an integrated luminosity of 35.9 fb$^{-1}$ recorded during the 2016 data-taking period.

The right-handed bosons are assumed to interact with standard model particles with a coupling strength $g_R$. This is a free parameter in most LR models, but we assume a strict LR symmetry in our search so that the coupling constant $g_R$ is the same as $g_L$, the SM coupling constant. We also assume that the right-handed quark mixing matrix is the same as the CKM matrix. In addition to the gauge bosons, LR models usually include heavy right-handed neutrinos ($N_R$) [5, 6]. These heavy neutrinos can explain the very small masses of the SM neutrinos via the see-saw mechanism [7, 8].

In this search, we consider the case in which the $W_R$ boson decays to a first or second generation charged lepton and a heavy neutrino of the same lepton flavor. The heavy neutrino further decays to another charged lepton of the same flavor and a virtual $W_R^*$. The virtual $W_R^*$ decays to two light quarks, producing the decay chain

$$W_R \rightarrow ℓN_R \rightarrow ℓℓW_R^* \rightarrow ℓℓq\bar{q}', ℓ = e \text{ or } μ.$$ 

The quarks hadronize into jets that can be observed by the CMS detector. There is no charge requirement on the leptons, that can be opposite-sign (OS) or same-sign (SS), and the lepton flavour is conserved. The SM processes that have the same final state of two same-flavor leptons and two jets include Drell-Yan production with additional jets (DY + jets), $t\bar{t}$ and single top production, and diboson production ($WZ$, $ZZ$, $WW$) with jets. Contributions due to events with jets misidentified as leptons are considered, but are found to be negligible. The discriminating variable in this search is the invariant mass ($m_{ℓℓjj}$) of the four-object system of the two most energetic leptons and two most energetic jets. We search for an excess of events above the SM prediction for different $W_R$ hypotheses in windows of $m_{ℓℓjj}$.

A search for $W_R$ bosons that was performed by the CMS collaboration at a center-of-mass energy $\sqrt{s} = 8$ TeV excluded $W_R$ masses up to approximately 3 TeV at a 95% confidence level [9]. An excess with a local significance of 2.8 $σ$ was observed in that search in the electron channel at $m_{eejj} \approx 2.1$ TeV. The excess did not appear to be consistent with signal events from the LR symmetric theory. A preliminary result using $\sqrt{s} = 13$ TeV data was recently presented [10]. The search presented in this paper expands upon those searches and revisits the 8 TeV excess, using data collected at $\sqrt{s} = 13$ TeV during 2016, and is independent of the other heavy neutrino searches previously carried out at CMS [11–13] and ATLAS [14–16].

2 The CMS detector

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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors.
Muons are measured 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. [17].

3 Trigger, particle reconstruction and event selection

Events of interest are selected online using a two-tiered trigger system [18]. The first level is composed of custom hardware processors and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 µs. The second level consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to less than 1 kHz before data storage.

The leptons in the final state carry a large fraction of the rest energy of the $W_R$. Thus, a trigger with a high momentum requirement on the lepton will be highly efficient for our signal. We use single muon triggers for the muon channel and for an auxiliary measurement that is used to estimate the $t\bar{t}$ background. In particular, the logical OR of two triggers (one considering muons constructed from both the tracker and the muon chambers and the other considering only tracker-muons) is required to select a dimuon event. A $p_T$ requirement of 50 GeV, based on an online measurement of the momentum, is applied for each muon. This trigger combination had the lowest $p_T$ threshold, was unprescaled during the entire 2016 data-taking period, was not restricted in pseudorapidity ($\eta$) beyond detector acceptance, and did not require any isolation. For events with electrons, we use two separate double electron triggers with slightly lower momentum thresholds than the single muon trigger, depending on the data-taking period. In each of the two triggers, two electrons with $p_T > 33$ GeV are required. Each electron trigger consists of an electromagnetic calorimeter deposit and a pixel hit associated with a track and they differ for a pixel match requirement on one electron.

Global event reconstruction is performed via the particle-flow algorithm [19, 20], which consists of reconstructing and identifying each individual particle with an optimized combination of all subdetector information. Electron candidates are reconstructed from tracks linked to ECAL energy deposits. Electrons are then identified as a primary charged particle track and potentially many ECAL energy clusters corresponding to this track extrapolation to the ECAL and to possible bremsstrahlung photons emitted along the way through the tracker material. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The experimental mass resolution for barrel-barrel (barrel-endcap) dielectron pairs with a mass of 1 TeV is 1% (1.5%). To correct discrepancies in energy scale and resolution between data and simulations the electron energy scale was corrected in data by a multiplicative factor dependent on $\eta$ and $R_9$ (defined as the ratio of the energy in a $3 \times 3$ matrix of crystals centered around the most energetic one and the full energy collected by the super-cluster) and the electron energy in simulated events was smeared with a Gaussian smearing dependent on $\eta$ and $R_9$. Differences in electron ID efficiency between data and simulation were taken into account by applying a scale factor of $0.972 \pm 0.006$ in the barrel and $0.983 \pm 0.007$ in the endcaps.

Muons are identified as a track in the central tracker consistent with either a track or several hits in the muon system, associated with an energy deficit in the calorimeters. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The $p_T$ resolution in the barrel is better than 10% for muons with $p_T$ up to 1 TeV [21]. The muon momentum resolution in data is well described by simulation and its uncertainty is given by a smearing of 1% in
the barrel and 2% in the endcaps in simulated events. The muon curvature distributions in data and simulations are compared for different $\eta$ and $\phi$ ranges, resulting in a momentum scale uncertainty of 3% in the barrel and up to 9% in the endcaps. To account for differences in reconstruction and identification efficiencies between data and simulations scaling factors are applied to simulated events as a function of $\eta$. Systematics related to $p$-dependent scaling factors are neglected since they have an impact of less than 1.4%.

Charged hadrons are identified as charged particle tracks neither identified as electrons, nor as muons. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Neutral hadrons are identified as HCAL energy clusters not linked to any charged hadron trajectory, or as ECAL and HCAL energy excesses with respect to the expected charged hadron energy deposit. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

For each event, hadronic jets are clustered from reconstructed particles with the infrared and collinear safe anti-$k_T$ algorithm, operated with a size parameter $R$, where $R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ with rapidity $y$ and azimuthal angle $\phi$, of 0.4 [22, 23]. If identified as coming from additional collisions in the same or adjacent bunch crossings (pileup), the charged hadrons are removed from the list of reconstructed particles using the pileup charged-hadron subtraction (CHS) algorithm [24]. The jet momentum is determined as the vectorial sum of all particle momenta in this jet, and is found in the simulation to be within 5 to 10% of the true momentum over the whole $p_T$ spectrum and detector acceptance. Jet energy corrections are derived from the simulation and are confirmed with in situ measurements with the energy balance of dijet and photon + jet events [25]. Jet identification algorithms [26] also remove contributions to jets from calorimeter noise and beam halo.

To reconstruct $W_R$ candidates, we select the two most energetic leptons and the two most energetic jets. The leading (subleading) leptons are required to have $p_T > 60$ (53) GeV and be within detector acceptance in pseudorapidity ($|\eta| < 2.4$). Due to the acceptance of the electromagnetic calorimeter, electrons are further restricted to be in the region of $|\eta| < 1.442$ or $|\eta| > 1.566$. To reduce muons originating from hadron decays or pion punch-through in jets, we remove muons where the sum of the momenta from additional tracks inside a cone of $R < 0.3$ around the muon is more than 10% of the muon transverse momentum. To consider only isolated electrons, in a cone of $R < 0.3$ centered on the electron candidate, the sum $p_T$ of all tracks inside the cone not associated with the electron must be below 5 GeV. We use dedicated, highly optimized identification algorithms to select high momentum leptons [21, 27]. The two jet candidates must have $p_T > 40$ GeV and be within the pseudorapidity range $|\eta| < 2.4$. We require all selected objects to be separated from each other by imposing a $\Delta R > 0.4$ requirement between all jets and leptons.

## 4 Data samples and simulation

We use several auxiliary data samples to estimate signal and background contributions to our search and to validate our event selection. We use Monte Carlo (MC) simulation in the calculation of signal efficiency and in the estimation of some of the SM backgrounds. In these simulations, the response of the CMS detector is modeled using the GEANT4 package [28]. Pileup contributions are modeled by superimposing simulated minimum bias interactions onto the primary hard scatter. The simulated distribution of the number of pileup events is matched to what is observed in the data.
For estimating the acceptance and efficiency of detecting $W_R$ bosons, simulated signal samples in both $eejj$ and $\mu\mu jj$ final states are generated assuming $m_{N_R} = \frac{1}{2}m_{W_R}$ using the PYTHIA 8.2 program [29]. The simulated data samples used to estimate the background processes are generated with several generators. The DY + jets and $t\bar{t}$ samples are generated with aMC@NLO [30, 31] using next-to-leading order (NLO) calculations for the simulation. Diboson (WW, WZ, and ZZ) samples are generated using PYTHIA 8.2, while for $W^+ j$ events we use MADGRAPH 5 [32] and for single top quark events we use POWHEG 1.0 [33, 34]. Diboson, $W^+ j$ and single top samples use NLO calculations for the cross sections to which the samples are normalized. For all samples, PYTHIA is used for parton showering, fragmentation and hadronization with the 13 TeV underlying event tune CUETP8M1 [35].

We define different regions to estimate the contributions from the different SM backgrounds (control regions) and to look for the signal we are interested in (signal region). To study the background contribution from Drell-Yan events we use a data sample defined by the presence of two same-flavor, opposite-charge e or $\mu$ leptons and two jets. The invariant mass of the dilepton system must satisfy $m_{\ell\ell} < 200$ GeV. We call this the “low-dilepton mass control region”. The “flavor control region” is defined by an event sample composed of one muon, one electron, and two jets. The invariant mass of the two-lepton system must satisfy $m_{\ell\ell} > 200$ GeV, while the four-object invariant mass is required to be above 600 GeV. This selection is used to study the $t\bar{t}$ background contribution. Finally, the signal region consists of events with two leptons with the same flavor and two jets. The invariant mass of the two-lepton combination must be above 200 GeV, to avoid contamination from resonant Z boson production. The four-object invariant mass must be greater than 600 GeV to avoid turn-on effects due to the kinematic requirements on the objects. There is no charge requirement on the leptons, to preserve acceptance to a wider class of models.

Using the selection requirements described above, the acceptance $\times$ efficiency for $W_R$ signals rises from 30% at $m_{W_R} = 1000$ GeV to 57% for $m_{W_R} > 3000$ GeV in the electron channel, and from 40% to 75% in the muon channel. For both channels the signal efficiency plateaus at $m_{W_R} = 3000$ GeV. The efficiency for electron events is lower than the muon event efficiency due to the gap between the ECAL barrel and endcap in which electrons cannot be reconstructed, and due to tighter ID selection requirements for electrons than for muons.

5 Background estimation

Standard model processes that produce events with the same final state particles as our signal model include Drell-Yan production of lepton pairs with additional jets in the final state, and $t\bar{t}$ and diboson production. DY + jets and $t\bar{t}$ are irreducible backgrounds and make up the bulk of the background events in the signal region. Contributions from diboson backgrounds are minimized by the dilepton mass requirement ($m_{\ell\ell} > 200$ GeV). We also consider backgrounds where object misidentification leads to events with two leptons and two jets in the final state. These backgrounds include $W$ production plus additional jets, single top events with additional jets, and QCD multijet events. These reducible backgrounds do not significantly contaminate our signal or control regions.

Monte Carlo simulation is used to estimate the background from high-mass Drell-Yan lepton pairs produced in association with additional jets since no high purity control region has been identified having the same kinematics as the signal region. The normalization of DY + jets in the simulation is corrected to match the event counts in data by means of a scale factor (SF) measured in the low $m_{\ell\ell}$ control region described in Section 4, considering the events under the Z peak resonance in the range $80 < m_{\ell\ell} < 100$ GeV in the dilepton invariant mass.
Table 1: Transfer factor applied to the number of events in flavor control region to estimate the number of \( t\bar{t} \) events in the \( e\mu jj \) and \( \mu\mu jj \) signal regions.

| Channel          | Transfer factor | Stat. uncertainty | Syst. uncertainty |
|------------------|-----------------|-------------------|-------------------|
| \( e\mu jj \rightarrow eeejj \) | 0.423           | 0.010             | 0.071             |
| \( e\mu jj \rightarrow \mu\mu jj \) | 0.720           | 0.015             | 0.144             |

distribution. This scale factor takes into account residual mis-modeling between data and simulation, including the signal region requirements on the jets. The measured scale factor is \( 1.07 \pm 0.01 \) (stat.) in both the electron and muon channels.

To verify that the SF measured for DY + jets around the Z peak is valid also at higher masses we use a dedicated control region, called “low \( m_{\ell\ell jj} \) control region” and defined as the signal region but with \( m_{\ell\ell jj} < 600 \text{ GeV} \). In this control region we check that the agreement between data and simulation in events with high dilepton mass is good.

We compare the kinematic distributions in the two different channels of the low-dilepton mass control region defined above. The agreement in this control region is especially important since we derive the estimate for the DY + jets background directly from simulation. The distributions of kinematic quantities in the low-dilepton mass control region with the scale factor already applied are shown in Fig. 1 for both muon and electron channels. In these plots, all expected SM backgrounds, except Drell-Yan and \( t\bar{t} \), are referred to as Other backgrounds. Good agreement is observed in the shapes of the kinematic distributions in both cases.

The \( t\bar{t} \) background contribution is estimated directly from data in the flavor control region defined in Section 4, which has the same kinematics as the \( t\bar{t} \) events in the signal region. To produce a clean \( t\bar{t} \) sample, the contribution from other standard model processes is estimated from simulation and subtracted. For this estimate, we assume that there is no contamination from signal events in the flavor control region. This assumption corresponds to an imposition of the conservation of individual lepton flavor on our signal models. For example, the decay of a \( W_R \) boson cannot, at leading order, yield events with an \( e\mu jj \) final state. The control region is thus signal free, and we use these events to estimate the \( t\bar{t} \) background without having to correct for any signal contamination.

To calculate the number of events from \( t\bar{t} \) production in the \( e\mu jj \) and the \( \mu\mu jj \) signal regions, we use the \( t\bar{t} \) simulated events to find the transfer factors \( R_{e\mu/\ell\ell} \) (\( \ell\ell = ee \) or \( \mu\mu \)) between the \( e\mu jj \) final state and the signal regions. These factors are evaluated from the ratio of the number of events in the distributions of the \( m_{eejj} \) and \( m_{\mu\mu jj} \) signal regions over the \( m_{e\mu jj} \) flavor control region. The number of events in the signal region is then given by

\[
N_{t\bar{t}}(\text{signal region}) = N_{t\bar{t}}(\text{flavor control region}) \times R_{e\mu/\ell\ell}.
\] (1)

Using the transfer factor, we can account for the difference in efficiency and acceptance between electrons and muons in these final states. The values of the scale factors obtained are given in Table 1. The ratio of events \( R_{e\mu/\ell\ell} \) as a function of the four-object mass distribution is fit to a constant. A systematic uncertainty is assigned by fitting the ratio to a linear polynomial and taking the difference between the values of the polynomial at high and low four-object masses. Figure 2 shows a comparison between simulated events and data for several kinematic variables in the flavor control region. While we do not use simulated events to estimate the \( t\bar{t} \) background contribution, the agreement between simulation and data suggests that other modeling using the simulation, such as the signal acceptance, is well-motivated.
Figure 1: Distribution of kinematic quantities for events in the low-dilepton mass control region. The four-object invariant mass (on the top) and the dilepton transverse momentum (on the bottom) for the DY $\mu\mu$ plus two jets selection are shown on the left. The dilepton mass (on the top) and the scalar sum of all jets $p_T$ (on the bottom) for the DY $ee$ plus two jets selection are shown on the right. The error bands on the MC histograms only include statistical uncertainties. The error bars in the ratio represent the statistical uncertainties of data and MC calculated with the standard error propagation of $\frac{N_d}{N_s}$ given $N_d$ the number of data events in the bin and $N_s$ the number of simulated events in the bin.
Figure 2: Kinematic distributions for events in the flavor control region. The dilepton mass (top left), the four-object mass (top right), the scalar sum of all jets $p_T$ (bottom left) and the number of jets (bottom right) are shown. The error bands on the MC histograms only include statistical uncertainties. The error bars in the ratio represent the statistical uncertainties of data and MC calculated with the standard error propagation of $\frac{N_d}{N_s}$ given $N_d$ the number of data events in the bin and $N_s$ the number of simulated events in the bin.
6 Results

The signals considered in this analysis are characterized by the shape of the invariant mass distribution that extend over several thousands of GeV. No further assumptions are made on the signal shape. While the LR symmetric models provide a motivation for the $\ell\ell jj$ final state, we do not further optimize our search for any particular model to allow sensitivity to other models, beyond the mass search region study described below. The strategy to search for an excess of events is effective in analyzing the data without exploiting other characteristics of the signal model used as benchmark and to reduce the effect of uncertainties on the shapes of the backgrounds, especially in the high $m_{\ell\ell jj}$ region. The expected number of signal and background events is estimated by counting the events falling in a particular $m_{\ell\ell jj}$ window. The upper and lower limits of the mass window are chosen as a function of the $m_{W_R}$ mass to obtain the lowest expected cross section upper limits. Other approaches were studied to assure that this mass window optimisation is not biased towards best limits. The size of the mass range varies from as low as 120 GeV for the electron final state at the low end ($m_{W_R} \simeq 800$ GeV) to as high as 3500 GeV in the high masses. For muons, the mass range varies less, and gets as large as 2000 GeV. The upper and lower bounds are fit to a third degree polynomial to reduce the effect of statistical fluctuations in the optimization procedure.

The probability of the observed number of events being produced by a combination of background and signal with a cross section $\sigma$ is calculated using the Bayesian approach with flat prior. The software used for the computation of the limits was developed by the CMS collaboration for the Higgs discovery effort and is based on ROOSTATS [36]. The exclusion limit on the cross section $\sigma$ is defined as the upper bound of the 95% credibility interval determined from the posterior likelihood distribution for the signal cross section. This procedure is repeated for each mass hypothesis.

In order to take into account the uncertainties, pseudo-experiments are performed, varying the expected number of events from signal and background according to the uncertainties as described below. The median of the distribution of the excluded cross section produced by pseudo-experiments and the intervals containing 68% and 95% of the pseudo-experiments are then quoted in the “expected” limits and their uncertainties.

The sources of systematic error considered in this analysis are the overall luminosity [37], the normalization uncertainty on t$t$, the uncertainties on proton PDFs, factorization, and renormalization scales for Drell-Yan and the systematic effects of object reconstruction. These last systematic uncertainties, affecting the shape of the four-object mass distribution, include uncertainties on the jets and leptons energy scales and resolutions, and on the lepton reconstruction, trigger, isolation and identification scale factors. The range of values on signal and background of these uncertainties are shown in Table 2.

The overall luminosity affects only the normalization of $m_{\ell\ell jj}$, as the uncertainty on the t$t$ extrapolation SF, given by the sum in quadrature of its statistical and systematical uncertainties evaluated as described in Section 5. The uncertainties on DY are implemented as a function of $m_{\ell\ell jj}$ following the PDF4LHC prescription [38], and affect both shape and normalization of $m_{\ell\ell jj}$. Table 3 shows the range of values of these uncertainties, which are included in the evaluation of the limits as nuisance parameters with lognormal priors.

In order to propagate the uncertainties on object reconstruction, a large number of pseudo-experiments is performed, varying all the uncertain variables at the same time in an uncorrelated fashion, each according to a Gaussian distribution with mean equal to the nominal value and $\sigma$ equal to the uncertainty of the single source. The variations are performed before the
Table 2: Effect of object reconstruction’s systematic uncertainties on signal and background yields.

| Uncertainty                      | Signal (%) | Background (%) |
|----------------------------------|------------|----------------|
| Jet Energy Resolution            | 3.2 - 25.8 | 0.9 - 25.2     |
| Jet Energy Scale                 | 0.2 - 28.9 | 4.8 - 26.8     |
| Electron Energy Resolution       | 3.7 - 4.8  | 2.7 - 4.5      |
| Electron Energy Scale            | 3.7 - 6.4  | 4.9 - 5.9      |
| Electron Reco/Trigger/ID         | 8.7 - 10.9 | 6.1 - 10.4     |
| Muon Energy Resolution           | 4.7 - 10.1 | 6.2 - 11.9     |
| Muon Energy Scale                | 4.7 - 10.2 | 6.2 - 11.9     |
| Muon Trigger/ID/Iso              | 2.3 - 4.7  | 1.9 - 5.2      |

Table 3: Uncertainties affecting $m_{\ell\ell jj}$ shape and normalization. The $t\bar{t}$ SFs affect the $t\bar{t}$ background, the DY PDF, factorization, and renormalization scales affect the DY + jets background and the luminosity affects both signal and backgrounds.

| Uncertainty                                      | Magnitude (%)               |
|--------------------------------------------------|-----------------------------|
| $t\bar{t}$ extrapolation $ee/\mu\mu$ SF           | 16.9 (stat.+syst.)          |
| $t\bar{t}$ extrapolation $\mu\mu/ee$ SF           | 20.1 (stat.+syst.)          |
| DY ee PDF                                        | 15 – 70 (syst.)             |
| DY ee renormalization/factorization              | 5 – 40 (syst.)              |
| DY $\mu\mu$ PDF                                 | 10 – 70 (syst.)             |
| DY $\mu\mu$ renormalization/factorization        | 10 – 50 (syst.)             |
| Luminosity                                       | 2.5 (stat.+syst.)           |

The expected number of events for signal and background used to extract the limits by the mean of the pseudo-experiment distribution, and its standard deviation is the propagated uncertainty. The uncertainties on object reconstruction are then implemented as nuisance parameters with lognormal priors in the limits evaluation. In this counting experiment all the shape variations on $m_{\ell\ell jj}$ effectively become normalization uncertainties, since the effect on the number of events in a specific mass range due to the variations in the shape of the $m_{\ell\ell jj}$ distribution is considered for the upper limit extraction.

Table 4: Observed number of events and magnitudes of systematic and statistical uncertainties for the expected events in different $W_R$ mass windows. All uncertainties are in number of events. In each table cell, the entry is of the form (mean ± stat. ± syst.).

| $M_{W_R}$ [GeV] | Data | Signal | $Z/\gamma^*$ | $t\bar{t}$ | Others | All backgrounds |
|-----------------|------|--------|--------------|------------|--------|----------------|
| 2200            | 56   | 474.0 ± 3.7 ± 44.7 | 15.72 ± 1.72 ± 3.04 | 23.56 ± 3.15 ± 2.84 | 9.06 ± 1.83 ± 2.29 | 48.34 ± 4.03 ± 4.75 |
| 2800            | 15   | 114.10 ± 0.89 ± 10.64 | 4.12 ± 0.83 ± 0.79 | 5.82 ± 1.37 ± 0.78 | 4.01 ± 1.16 ± 0.83 | 13.95 ± 2.12 ± 1.39 |
| 3600            | 3    | 19.20 ± 0.15 ± 1.79  | 0.98 ± 0.28 ± 0.18  | 0.42 ± 0.42 ± 0.03  | 0.20 ± 0.20 ± 0.02  | 1.60 ± 0.35 ± 0.19  |

| $M_{W_R}$ [GeV] | Data | Signal | $Z/\gamma^*$ | $t\bar{t}$ | Others | All backgrounds |
|-----------------|------|--------|--------------|------------|--------|----------------|
| 2200            | 74   | 744.0 ± 4.7 ± 47.5 | 35.04 ± 2.47 ± 4.82 | 40.10 ± 5.37 ± 6.98 | 11.98 ± 2.01 ± 1.30 | 87.12 ± 6.24 ± 8.58 |
| 2800            | 18   | 170.0 ± 1.1 ± 13.1  | 8.34 ± 1.09 ± 1.28  | 9.91 ± 2.67 ± 1.82  | 2.66 ± 0.94 ± 0.30  | 20.91 ± 3.05 ± 2.24  |
| 3600            | 4    | 29.20 ± 0.19 ± 2.75 | 1.63 ± 0.52 ± 0.46 | 0.72 ± 0.72 ± 0.10 | 0.21 ± 0.21 ± 0.01 | 2.56 ± 0.91 ± 0.47 |

To include the statistical uncertainties on each process in the evaluation of the limits, Gamma distributions are used [39]. In the limit estimation, pseudo-experiments are generated based on the expected number of events, sampled according to a Gamma distribution and multiplied by the log-normal distributions of the systematics uncertainties.
Figure 3: Four-object mass distribution in the signal region for the electron channel on the left and for the muon channel on the right. The error bars on the MC histograms only include statistical uncertainties. The error bars in the ratio represent the statistical uncertainties of data and MC calculated with the standard error propagation of $\frac{N_d}{N_s}$ given $N_d$ the number of data events in the bin and $N_s$ the number of simulated events in the bin. The gray error band around 1 represents instead the systematic uncertainty of the simulation.

In Table 4, the expected number of events, including the statistical and systematic uncertainty from the signal ($W_R$), DY, $t\bar{t}$ and additional smaller background sources are reported together with the observed number of events, for several representative $W_R$ mass points. In Fig. 3, we present the observed four-object mass distributions in the signal region including the expected backgrounds and the signal shape for $m_{W_R} = 4$ TeV.

Expected and observed exclusion limits at 95% confidence level on the signal cross section are shown in Fig. 4, taking into account all the systematic and statistical uncertainties described in this section. For this model, which consider $m_{N_R} = \frac{1}{2}m_{W_R}$, the observed exclusion limit on the mass is 4.4 TeV for both channels, while the expected exclusion limit is 4.4 TeV for the electron channel and 4.5 TeV for the muon channel. The most significant excess is observed at $m_{W_R} \approx 3.4$ TeV in the electron channel. Assuming that only one heavy neutrino flavor $N_R$ contributes significantly to the $W_R$ decay width, the region in the two-dimensional $(m_{W_R}, m_{N_R})$ mass plane is analyzed, covering a large range of neutrino masses below the $W_R$ boson mass. The $W_R$ cross section limits obtained for $m_{N_R} = \frac{1}{2}m_{W_R}$ are scaled to this 2D plane by applying a $m_{W_R}$ and $m_{N_R}$ dependent scale factor to the cross section limit. This SF is calculated using $W_R$ signal events at the Feynman diagram level which pass the signal selection, and accounts for the change in $W_R$ acceptance and efficiency as the $m_{N_R}$ changes for a fixed $m_{W_R}$. The expected and observed upper limits on the cross section for different $W_R$ and $N_R$ mass hypothesis is shown in Fig. 5. For $m_{N_R} \lesssim \frac{1}{2}m_{W_R}$ the selection applied to Feynman diagram level $W_R$ events underestimates the $W_R$ acceptance times efficiency compared to the selection applied to fully reconstructed $W_R$ events. The 2D exclusion limits are then very low in the $m_{N_R} \lesssim \frac{1}{2}m_{W_R}$ region, as shown in Fig. 5.

7 Summary

In summary, a search for a right-handed $W$ analogue to the $W$ gauge boson in the decay channel of two leptons and two jets has been presented. No excess over standard model backgrounds
Figure 4: Limit on $\sigma(pp \to W_R) \times BR(W_R \to \ell\ell jj)$ with systematic uncertainties for the electron channel on the left and for the muon channel on the right. The inner (green) band and the outer (yellow) band indicate the regions containing, respectively, the 68% and 95% of the distribution of limits expected under the signal plus background hypothesis. Right-handed bosons with $m_{W_R} < 4.4$ TeV are excluded.

are observed. A new W boson-like particle, with standard model couplings, decaying via a new heavy neutrino, up to a mass of 4.4 TeV, is excluded at 95% confidence level by the data, providing the most stringent limits to date.

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Figure 5: Upper limit on the cross section for different W_R and N_R mass hypothesis, for the electron channel on the left and for the muon channel on the right. The expected and observed exclusions are shown as the dotted (blue) curve and the solid (red) curve, respectively. The thin dotted (blue) curves indicate the region containing the 68% of the distribution of limits expected under the signal plus background hypothesis.

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