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Search for Resonances Decaying to Three W Bosons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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A search for resonances decaying into a W boson and a radion, where the radion decays into two W bosons, is presented. The data analyzed correspond to an integrated luminosity of 138 fb^{-1} recorded in proton-proton collisions with the CMS detector at $\sqrt{s} = 13$ TeV. One isolated charged lepton is required, together with missing transverse momentum and one or two massive large-radius jets, containing the decay products of either two or one W bosons, respectively. No excess over the background estimation is observed. The results are combined with those from a complementary channel with an all-hadronic final state, described in an accompanying paper. Limits are set on parameters of an extended warped extra-dimensional model. These searches are the first of their kind at the LHC.

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The existence of heavy resonances accessible at the CERN LHC is suggested by various theoretical models that try to address limitations of the standard model (SM). Searching for these resonances in decays to boson pairs (dibosons) has received much attention in recent years [1–6]. In the context of such searches, merged jet reconstruction and classification techniques that aim to identify the origin of a large-radius jet from a Lorentz-boosted hadronically decaying particle have been developed and exploited extensively [7]. Nonetheless, a direct search for a resonance decaying to three vector bosons, a triboson resonance, has never been performed at the TeV scale. In the sub-TeV range, a search for a heavy neutral Higgs boson in the ZWW channel has recently been published [8]. The TeV-scale diboson resonance searches [3–6] are potentially sensitive to a triboson signal. However, as only two of the three bosons are reconstructed, they have not been interpreted in this way. A search at the TeV scale is motivated by various theoretical scenarios including extended warped extra-dimensional models presented in Refs. [9–17] indicating a discovery potential within LHC reach. These models provide extensions of the SM that simultaneously address the problems of the Planck-electroweak hierarchy and the origins of flavor structure.

In this Letter and in an accompanying paper [18], we present the first searches for massive resonances decaying to three W bosons in cascade through $W_{\mathrm{KK}} \to WR$ and $R \to WW$. The W_{KK} is a Kaluza-Klein (KK) [19–22] excited massive gauge boson and R is a scalar radion [23]. The W_{KK} and R bosons are postulated in the Randall-Sundrum extra-dimension scenario [19,20]. The size of the extra dimension is stabilized by introducing a potential with a modulus field [20], resulting in a bulk scalar boson, the radion.

We concentrate on the final-state topology comprising one isolated, charged lepton (ℓ), either electron (e), or muon (μ), missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$), and one or two massive large-radius jets. A similar topology without an isolated ℓ in the final state is considered in Ref. [18]. These two searches use common techniques for jet identification and calibration, which are detailed in Ref. [18], while the combination of the two results is presented in this Letter. The topology studied in this Letter originates from a W boson decaying to an isolated ℓ and its neutrino ν, and two other W bosons decaying into quarks forming hadrons, which are either reconstructed as two individual merged W boson jets, as shown in Fig. 1 (left), or—depending on the relative masses of the W_{KK} and R resonances—as a single jet containing the decay products of both W bosons, as shown in Fig. 1 (right). We also consider the case where one of the two merged W bosons originating from the radion decays leptonically, yielding a nonisolated ℓ inside the jet in addition to the isolated one from the separated W boson decay. The main backgrounds in this analysis are from $W+$jets and top quark-antiquark pair ($t\bar{t}$) production. They are estimated using control regions (CRs) with kinematic properties similar to the corresponding signal regions (SRs). While the analysis is interpreted in terms of one specific model, the search is generic as it is sensitive to many resonant diboson and triboson signals. For example, resonances decaying into WW and WZ can also be detected

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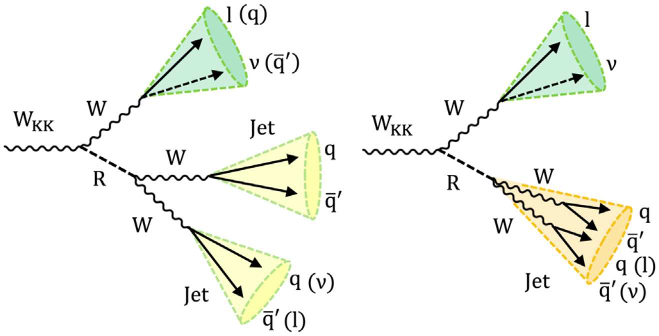

FIG. 1. Schematic representation of the decay of a KK excitation W_{KK} to the final states considered in this analysis. Left: three individually reconstructed W bosons with resolved R; right: one individually reconstructed W boson and two merged W bosons reconstructed as a single large-radius jet.

through this search, although with a lower efficiency than in the dedicated analyses [3,4]. Tabulated results are provided in the HEPData record for this analysis [24].

The analysis is based on proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the LHC during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} [25–27].

The CMS apparatus [28] is a multipurpose, nearly hermetic detector, designed to trigger on [29,30] and identify electrons, muons, photons, and (charged and neutral) hadrons [31–34]. A global reconstruction "particle-flow" (PF) algorithm [35] combines the information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from gas-ionization muon detectors interleaved with the solenoid return yoke, to build τ leptons, jets, $p_{\mathrm{T}}^{\mathrm{miss}}$, and other physics objects [36–38].

Signal events are simulated at leading order (LO) using MADGRAPH5_aMC@NLO v2.4.2 [39] with the recommended parameters according to Refs. [11–13,15], i.e., the KK gravity coupling $g_{\mathrm{grav}} = 6$, the KK gauge couplings $g_{W_{\mathrm{KK}}} = 3$ and $g_{Z_{\mathrm{KK}}} = 6.708$, and the confinement parameter $\epsilon = 0.5$. In the two-dimensional parameter space, W_{KK} masses $m_{W_{\mathrm{KK}}}$ from 1.5 to 5.0 TeV and R masses m_R from 6 to 90% of $m_{W_{\mathrm{KK}}}$ are covered. The decay branching fraction of $W_{\mathrm{KK}} \to WR \to WWW$ for these parameters typically exceeds 50% [13]. For the background simulation, $t\bar{t}$ production is modeled at next-to-LO (NLO) with POWHEG v2 [40]. Quantum chromodynamics multijet production and $W+$jets production are simulated at LO with MADGRAPH5_aMC@NLO. The other backgrounds are generated at NLO with MADGRAPH5_aMC@NLO (WW, s-channel single t) and POWHEG (WZ, ZZ, t-channel single t, Wt).

The generated events are interfaced with PYTHIA 8.230 [41] to simulate the fragmentation, parton shower, and hadronization of partons in the initial and final states, along with the underlying event. The same simulation settings as for Ref. [18], where further details can be found, have been used. The interactions of all final-state particles with the CMS detector are simulated using GEANT4 [42]. Simulated events include the contribution of particles from additional pp interactions within the same or nearby bunch crossings (pileup) and are corrected to reproduce the distribution of the number of pileup interactions observed in data.

The events are collected with single-electron or single-muon triggers [29,30] and then undergo global event reconstruction based on the PF algorithm [35]. The PF candidates are corrected for the effect of pileup [43], and are clustered into jets with the anti-k_{T} algorithm [44] as implemented in the FASTJET package [45]. Two distance parameters are used: 0.4 for AK4 jets and 0.8 for large-radius AK8 jets. The AK4 jets are required to be well separated from any selected AK8 jet with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.8$, where η is the pseudorapidity and ϕ the azimuthal angle. The quantity $p_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the magnitude of the vector transverse momentum (p_T) sum of all reconstructed PF candidates in an event.

The AK4 jets arising from b quark hadronization and decay (b jets) are identified using the deep neural network (DNN) algorithm DEEPCSV, which takes as input tracks that are displaced from the primary vertex, secondary vertices, and jet kinematic variables [46]. A working point on the output of the DEEPCSV algorithm is chosen such that the efficiency of identifying a b jet is about 65%–75%, while the probability of misidentifying a light-flavor (q) or gluon (g) jet as a b jet is about 1%. To identify massive AK8 jets, a "modified mass-drop" correction algorithm [47,48], known as the "soft-drop" algorithm [49] (with parameters $\beta = 0$ and $z_{\mathrm{cut}} = 0.1$), is applied to remove soft and wide-angle radiation from the jet, and the resulting "groomed jet mass" (m_j) is used.

Events with exactly one isolated e (μ) with $p_T > 55$ GeV and $|\eta_{e(\mu)}| < 2.5(2.4)$ and no second isolated e (μ) with $p_T > 35(20)$ GeV are selected. Furthermore, we require $p_{\mathrm{T}}^{\mathrm{miss}} > 80(40)$ GeV for the e (μ) channel. The p_T of the reconstructed leptonically decaying W boson candidate must exceed 200 GeV. The neutrino is reconstructed as in Ref. [50] using $p_{\mathrm{T}}^{\mathrm{miss}}$ and requiring the effective mass of the $\ell\nu$ system to be consistent with the W boson mass. Jets overlapping with the selected isolated lepton within $\Delta R_{j\ell} < 1.0$ are removed. Selected events need to have one or two AK8 jets with $p_{\mathrm{T}}^{j} > 200$ GeV and $|\eta^{\mathrm{j}}| < 2.4$. For events with only one jet, m_j is required to be greater than 60 GeV, while for events with two jets the jet with maximum m_j is required to have $60 < m_j^{\mathrm{max}} < 100$ GeV and the other jet mass is referred to as m_j^{min}. Events with identified b jets or more than two AK4 jets are vetoed. The scalar p_T sum of the reconstructed leptonically decaying W boson and the selected AK8 jets is required to be greater than 1 TeV. The invariant mass of the reconstructed $\ell\nu+$jet(s) system, $m_{j\ell\nu}$ or $m_{jj\ell\nu}$

for one or two selected AK8 jets, respectively, must exceed 1.1 TeV.

Several different radion decay topologies are considered. A collimated radion decay into two merged hadronic W boson jets ($R \to WW \to 4q$) yields a single jet containing the decay products of either all four quarks (designated as R^{4q}) or only three of them (R^{3q}). A merged radion decay with one of the W bosons decaying leptonically ($R \to WW \to \ell\nu qq$) yields a jet containing the decay products of two quarks from the $W \to q\bar{q}'$ decay as well as an overlapping nonisolated charged lepton. This topology is designated as $R^{\ell qq}$. In rare cases where the decay $R \to WW \to \ell\nu qq$ results in a lepton that still fulfills the isolation criteria even though it is overlapping with a jet, we remove the overlapping jet and consider the only remaining jet to correspond to the W boson from the W_{KK} resonance decay. Possibilities other than these contribute less than 5% of the signal yield and therefore are not considered.

To increase discrimination of signal from background, the substructure of the selected AK8 jets is analyzed using the DNN-based DEEPAK8 jet classification algorithm [51]. This algorithm has been trained using simulated events to identify hadronic decays of W and Higgs bosons (H, in the $4q$ mode), as well as top quarks, based on the reconstructed particles and secondary vertices associated with the corresponding jet. In the default training of the algorithm, the masses of the signal jets are used, and therefore signals with masses different to the ones mentioned above cannot be identified. Thus, we make use of the algorithm's mass-decorrelated version to identify jets exhibiting substructure compatible with a merged radion decay (R^{4q}, R^{3q}, and $R^{\ell qq}$), but with arbitrary mass. For the identification of merged radion jet candidates, we combine the algorithm's outputs to simultaneously discriminate $W \to q\bar{q}'$ jets and signal jets similar to $H \to WW \to 4q$ from jets originating from the hadronization of a q or g. We call the resulting discriminants for merged radion decays "deep-WH" and for W bosons "deep-W." Similarly, a discriminant named "deep-t" is formed to distinguish top quarks from q/g jets. The DEEPAK8 discriminant values peak towards unity for the selected type of jets and towards zero for the rejected q/g background jets. A detailed description of these variables together with their performance for different jet types can be found in Ref. [18].

Using the jet mass and the deep-WH and deep-W discriminants, selected events are split into six SRs based on the signal topology. Jets with $m_j > 100$ GeV ($60 < m_j < 100$ GeV) are considered as radion (W boson) candidates and thus required to pass a deep-WH (deep-W) selection, while for lower-mass jets with $m_j < 60$ GeV no such condition is applied. For events with one selected jet, targeting the merged radion jet topology, three regions (SR1–3) are defined using different m_j windows of 60–100, 100–200, and >200 GeV, respectively. For SR1 (SR2–3), we additionally demand deep-$W > 0.7$ (deep-$WH > 0.7$). Events with two jets, considered as candidates for the resolved radion topology, are categorized into SR4–6 as follows. The SR4 (SR5) categories have both jets with $60 < m_j < 100$ GeV and require exactly two (one) jets with deep-$W > 0.5$. Events with $60 < m_j^{\max} < 100$ GeV and deep-$W > 0.7$ for the higher-mass jet and $m_j^{\min} < 60$ GeV for the lower-mass jet are placed in SR6. Requiring deep-W(deep-WH) > 0.7 results in a background rejection of approximately 74 (67)%, while maintaining a signal selection efficiency of about 65 (70)%.

The deep-W and deep-WH variables are both calibrated in the same data regions enriched in SM $W+$jets and top quark events. To serve as proxies, the SM events are split into various W, q/g, and top quark categories mimicking the signal decay structure. Both signal and proxy jets are categorized by geometrically matching parton-level information to the reconstructed jets. Jets from single W boson decays in SM events are used as proxy jets for resolved signal and merged $R^{\ell qq}$ events. As there is no direct correspondence to any SM event topology for R^{4q} and R^{3q} events, fully merged top quark jets ($t \to bqq$) serve as proxies in this case. By performing a simultaneous fit of the proxy templates to the data in regions with different relative compositions, we derive corresponding scale factors (SFs) and associated uncertainties. These SFs are applied per matched jet category to correct selection efficiencies in simulation for the deep-W and deep-WH spectra. This calibration procedure is validated in various jet samples. The detailed procedure is presented in Ref. [18].

The main backgrounds, $W+$jets, and $t\bar{t}$ production, are estimated using CRs. The $t\bar{t}$ CRs are defined by inverting the b jet veto, removing the deep-W(deep-WH) discriminant selection criteria defined for the SRs, and allowing for up to four additional AK4 jets to increase the number of selected events. Similarly, for the $W+$jets CRs, the deep-W(deep-WH) selection criteria are inverted, and $t\bar{t}$ events are vetoed by requiring deep-$t < 0.4$. All other backgrounds are estimated using simulation and are subtracted from the data for this procedure. A linear fit is performed to the ratio of the data to the background of interest ($W+$jets or $t\bar{t}$), using the $m_{j\ell\nu}$ or $m_{jj\ell\nu}$ distributions, depending on the region, to extract a correction function for the background shape and normalization in the corresponding SR.

The final signal and background yields are determined simultaneously by performing a maximum likelihood fit to the $m_{j\ell\nu}$ and $m_{jj\ell\nu}$ distributions in data for SR1–3 and SR4–6, respectively. Systematic uncertainties affecting signal and background yields are treated as nuisance parameters and profiled in the statistical interpretation using log-normal and Gaussian constraints for rate and shape uncertainties, respectively.

Uncertainties in the background normalization and shape are derived from the data in the CRs. In particular, the statistical uncertainty in the CR fits to the $m_{j\ell\nu}$ and $m_{jj\ell\nu}$

distributions is propagated to the SRs through constraints on modeling parameters common to the SR and CR. Both rate and shape uncertainties are evaluated separately for the $W+$jets and top quark backgrounds, and are treated as uncorrelated across the SRs.

Several uncertainties are taken into account for the DEEPAK8 discriminants and are evaluated as functions of m_j and p_{T}^{j}. Residual differences between data and simulation observed in the validation regions result in a 10% uncertainty for all jet types. Additional uncertainties are derived by considering an alternative parton shower simulation and evaluating the effect on the SFs for signal and background jets. Since the objects used in the calibration procedure have a similar decay structure to the signal, but can exhibit features such as different color flow and quark flavor that affect the DEEPAK8 performance, additional uncertainties are considered for the signal. These uncertainties are evaluated based on the shape differences between signal and SM proxy jets in the deep-W and deep-WH spectra. They amount to 10%–40% for $R^{\ell qq}$, R^{3q}, and R^{4q} events, and to 100% for signal events not matching these categories. To further account for the different p_{T}^{j} regimes of signal and proxy jets used in the derivation of the SFs, signal events are simulated with the HERWIG2.7 parton shower program [52]. The resulting differences in the SR yields of up to 25% are assigned as rate uncertainties. A detailed description of the uncertainty evaluation procedure can be found in Ref. [18]. Uncertainties due to pileup, integrated luminosity, trigger, lepton reconstruction, parton distribution functions (PDFs), renormalization and factorization scales, and jet energy scale and resolution, largely affecting signal only, are in total found to be less than 3% in the rate. They have negligible effect on the shape of the $\ell\nu+$jets mass distributions.

The results of this search are statistically combined with those from the search in the fully hadronic final state [18]. The SF uncertainties are treated as correlated among the two channels. Uncertainties in pileup modeling, PDFs, renormalization and factorization scales, as well as the jet energy scale and resolution are also treated as correlated. All other uncertainties are treated as uncorrelated.

The background-only post-fit distribution of the reconstructed $\ell\nu+$jets system $m_{jj\ell\nu}$ for the most sensitive region for the resolved signal, SR4, is shown in Fig. 2. The results for the six SRs of this search are presented in the form of pull distributions [(Data-Prediction)/σ_{stat}] of the background-only fit in Fig. 3. Selected signals have been added on top of the background. The data are consistent with the background expectation.

The asymptotic approximation [53] of the CL$_s$ technique [54,55] is used to set limits. The lower mass limits at 95% confidence level (CL) of the $\ell\nu+$jets analysis are shown in Fig. 4. An excess of events in data around $m_{jj\ell\nu}=$ 3.5 TeV in SR6 results in a weaker than expected observed limit for the resolved signal. For the combination with the fully hadronic analysis [18], lower mass limits are also shown as well as upper limits on the product of the signal cross section and the branching fraction to three W bosons for a resonance with decay width significantly smaller than the detector resolution. For radion masses between 0.2 and 1.2 TeV, triboson resonances are excluded up to $m_{W_{\mathrm{KK}}}=$ 3.3 and 3.7 TeV by the $\ell\nu+$jets analysis and the combination, respectively.

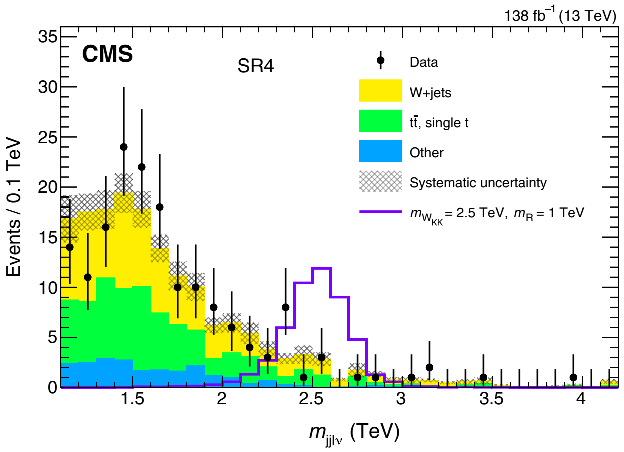

FIG. 2. Background-only post-fit distribution of the reconstructed $\ell\nu+$jets system $m_{jj\ell\nu}$ in data and simulation for SR4. The shape of a triboson signal with $m_{W_{\mathrm{KK}}}=2.5$ and $m_R=1$ TeV is also shown as a violet solid line, normalized to the theoretical production cross section.

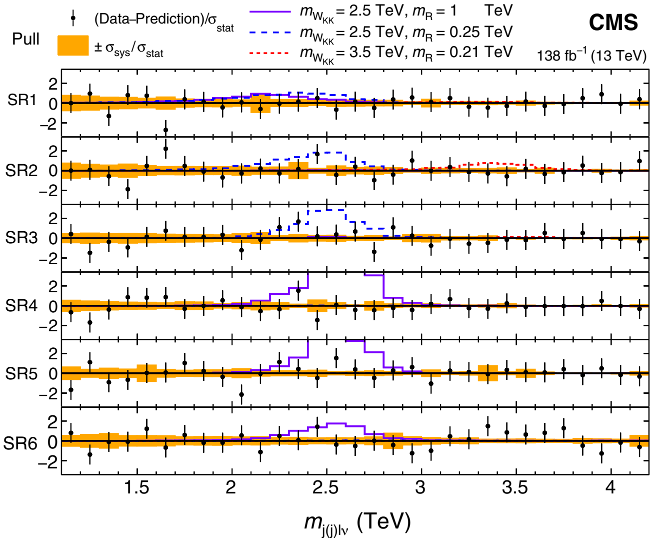

FIG. 3. Pull distributions showing (data-prediction)/σ_{stat} of the background-only fit to the reconstructed $\ell\nu+$jets system $m_{j\ell\nu}$ or $m_{jj\ell\nu}$ for all SRs, where σ_{stat} is the statistical uncertainty. Post-fit systematic uncertainties are indicated by the shaded bands. Examples of signal scenarios normalized to their theoretical production cross section are shown using solid, dashed, and dotted lines.

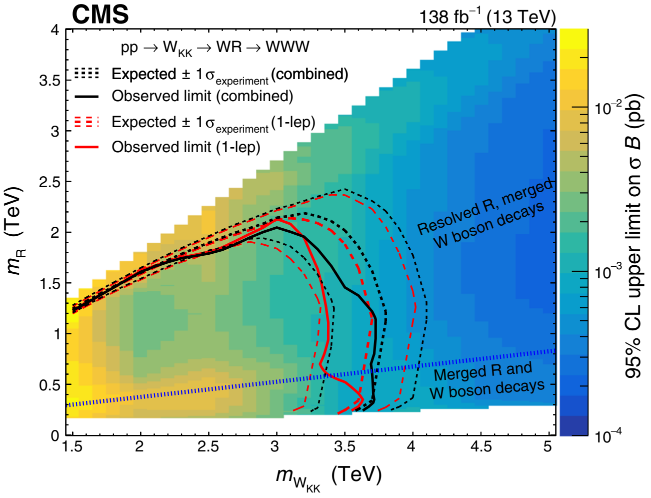

FIG. 4. Observed upper limits at 95% CL on the product of the signal cross section and the branching fraction ($\sigma\mathcal{B}$) to three W bosons as functions of the W_{KK} and R resonance masses. Expected (dashed lines) and observed (solid lines) lower mass limits are shown as well for the particular parameters of the explored model. The blue straight dashed line indicates the border between merged and resolved radion cases. The limits obtained from this analysis are shown in red, and the results of the combination with Ref. [18] are shown in black.

In summary, a search has been presented for resonances decaying in cascade through $W_{\mathrm{KK}} \to WR$ and $R \to WW$ to three W bosons, where W_{KK} is a massive Kaluza-Klein excitation of a gauge boson and R is a scalar radion. The analysis is performed using proton-proton collision data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. The final states considered contain one isolated charged lepton, missing transverse momentum, and one or two massive large-radius jets. Radion decay configurations with two W bosons merged in a single jet and those with two separated W boson jets are simultaneously probed by combining jet substructure algorithms. These novel radion identification and calibration techniques are also applicable to Lorentz-boosted Higgs boson decays. Results agree with the predictions of the standard model and are combined with those of the analysis in the fully hadronic final state [18]. Limits are set on an extended warped extra-dimensional model. These are the first searches for the production of TeV-scale triboson resonances at the LHC.

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