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Search for resonances decaying to three W bosons in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

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 $138\,\text{fb}^{-1}$ recorded in proton-proton collisions with the CMS detector at $\sqrt{s} = 13\,\text{TeV}$. One isolated charged lepton is required, together with 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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*See Appendix A for the list of collaboration members

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 has received much attention in recent years [1–4]. 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 [5]. Nonetheless, a direct search for a resonance decaying to a three-boson final state, a triboson resonance, has never been performed. Such a search is motivated by various theoretical scenarios including extended warped extra-dimensional models presented in Refs. [6–14] 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 [15], we present the first searches for massive resonances decaying to three W bosons in cascade through $W_{KK} \to WR$ and $R \to WW$. The W_{KK} is a Kaluza–Klein (KK) [16–19] excited massive gauge boson and R is a scalar radion [20]. The W_{KK} and R bosons are postulated in the Randall–Sundrum extra-dimension scenario [16, 17]. The size of the extra dimension is stabilized by introducing a potential with a modulus field [17], resulting in a bulk scalar boson, the radion.

We concentrate on the final-state topology comprising one isolated, charged lepton (ℓ), missing transverse momentum (p_T^{miss}), and one or two massive large-radius jets. A similar topology without an isolated ℓ in the final state is considered in Ref. [15]. These two searches share common techniques, which are detailed in Ref. [15], while the combination of the two results is presented in this Letter. The topology studied in this Letter can originate from a W boson decaying to ℓ and its neutrino ν, and two other W bosons decaying into quarks forming hadrons, which are either reconstructed as two individual merged large-radius 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, large-radius 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 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. Tabulated results are provided in the HEPData record for this analysis [21].

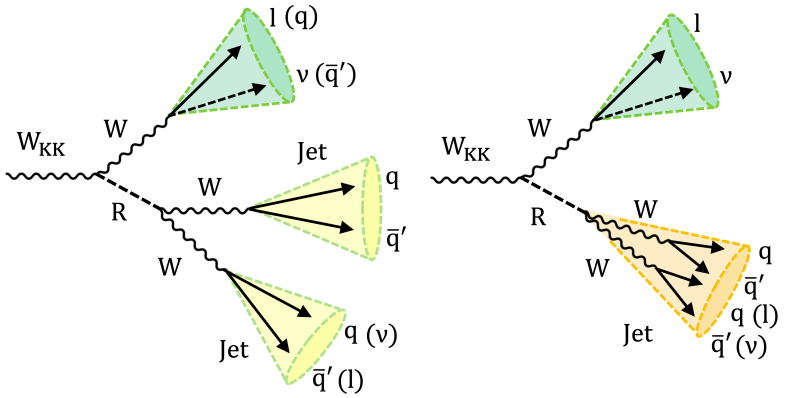

Figure 1: Schematic representation of the decay of a KK excitation W_{KK} to the final states considered in this analysis. Left: three individually reconstructed W bosons; right: one individually reconstructed W boson and two W bosons reconstructed as a single large-radius jet.

The analysis is based on proton-proton (pp) collision data at $\sqrt{s} = 13\,\text{TeV}$ collected by the CMS experiment at the LHC during 2016–2018, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$ [22–24].

The CMS apparatus [25] is a multipurpose, nearly hermetic detector, designed to trigger on [26, 27] and identify electrons, muons, photons, and (charged and neutral) hadrons [28–31]. A global reconstruction "particle-flow" (PF) algorithm [32] 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, $p_{\text{T}}^{\text{miss}}$, and other physics objects [33–35].

Signal events are simulated at leading order (LO) using MADGRAPH5_aMC@NLO v2.4.2 [36], covering a large area of the two-dimensional parameter space of the W_{KK} and R masses ($m_{\text{W}_{\text{KK}}}$ from 1.5 to 5.0 TeV, and m_{R} from 6 to 90% of $m_{\text{W}_{\text{KK}}}$), together with the recommended parameters according to Refs. [8–10, 12], i.e., the KK gravity coupling $g_{\text{grav}} = 6$, the KK gauge couplings $g_{\text{W}_{\text{KK}}} = 3$ and $g_{\text{Z}_{textKK}} = 6.708$, and the confinement parameter $\epsilon = 0.5$. The typical decay branching fraction of $\text{W}_{\text{KK}} \to \text{WR} \to \text{WWW}$ for these parameters can exceed 50% [10]. For the background simulation, $\text{t}\bar{\text{t}}$ production is modeled at next to LO (NLO) with POWHEG v2 [37]. Quantum chromodynamics multijet and W + jets production is 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 [38] 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. [15], where further details can be found, have been used. The interactions of all final-state particles with the CMS detector are simulated using GEANT4 [39]. 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 [26, 27] and then undergo global event reconstruction based on the PF algorithm [32]. The PF candidates are corrected for the effect of pileup [40], and are clustered into jets with the anti-k_{T} algorithm [41] as implemented in the FASTJET package [42]. Two distance parameters are used: 0.4 (0.8) for the AK4 (AK8) jets. The AK4 jets are thereby required to be well separated from any selected AK8 jet with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.8$, where ϕ is the azimuthal angle. The quantity $p_{\text{T}}^{\text{miss}}$ 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 [43]. 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%.

The final states of interest consist of one isolated lepton (electron e or muon μ), $p_{\text{T}}^{\text{miss}}$, and one or two massive large-radius (AK8) jets arising from hadronic W boson decays. As shown in Fig. 1 (right), the final state with one large-radius jet is expected to contain all the decay products of the radion decay, whereas the final state with two jets shown in Fig. 1 (left) probes the resolved decay of the radion into two separately reconstructed W bosons. To identify massive jets, a

"modified mass-drop" correction algorithm [44, 45], known as the "soft-drop" algorithm [46] (with parameters $\beta = 0$ and $z_{\text{cut}} = 0.1$), 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 $p_{\text{T}} > 55\,\text{GeV}$ and $|\eta_{\text{e}(\mu)}| < 2.5\,(2.4)$ and no second isolated e (μ) with $p_{\text{T}} > 35\,(20)\,\text{GeV}$ are selected. Furthermore, we require $p_{\text{T}}^{\text{miss}} > 80\,(40)\,\text{GeV}$ 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. [47] using $p_{\text{T}}^{\text{miss}}$ 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 $\Delta R_{\text{j}\ell} < 1.0$ are removed. Selected events need to have one or two AK8 jets with $p_{\text{T}}^{\text{j}} > 200\,\text{GeV}$ and $|\eta^{\text{j}}| < 2.4$. For events with only one jet, m_{j} is required to be greater than 60 GeV, while for events with two jets the maximum and minimum m_{j} are required to be $60 < m_{\text{j}}^{\text{max}} < 100\,\text{GeV}$ and $m_{\text{j}}^{\text{min}} < 100\,\text{GeV}$, respectively. 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, $m_{\text{j}\ell\nu}$ or $m_{\text{jj}\ell\nu}$ for one or two selected AK8 jets, respectively, must exceed 1.1 TeV.

Several different radion decay topologies are considered. A merged radion with two merged hadronic W boson decays ($\text{R} \to \text{WW} \to 4\text{q}$) yields either a single jet containing the decay products of all four quarks (designated as $\text{R}^{4\text{q}}$) or only three of them ($\text{R}^{3\text{q}}$). A radion decay with one of the W bosons decaying leptonically ($\text{R} \to \text{WW} \to \ell\nu\text{qq}$) yields a jet containing the decay products of two quarks from the $\text{W} \to \text{q}\overline{\text{q}}'$ decay as well as an overlapping nonisolated charged lepton. This topology is designated as $\text{R}^{\ell\text{qq}}$. In rare cases where the latter decay ($\text{R} \to \text{WW} \to \ell\nu\text{qq}$) results in the isolated lepton overlapping with one of the two jets in the event, we remove the overlapping jet and consider the remaining jet to correspond to the prompt W boson. 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 [48]. 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 ($\text{R}^{4\text{q}}$, $\text{R}^{3\text{q}}$, $\text{R}^{\ell\text{qq}}$), but with arbitrary mass. For the identification of merged radion jet candidates, we combine the algorithm's outputs to simultaneously discriminate $\text{W} \to \text{q}\overline{\text{q}}'$ jets and signal jets similar to $\text{H} \to \text{WW} \to 4\text{q}$ from jets originating from the hadronization of a q or g.

The DEEPAK8 discriminant values peak towards unity for radion and W boson jets and towards zero for the q/g background jets. We call the resulting discriminant for merged radions "deep-WH", and for W bosons "deep-W". Similarly, a discriminant named "deep-t" is formed to distinguish top quarks from q/g jets. A detailed description of these variables together with their performance for different jet types can be found in Ref. [15].

Using the jet mass and the deep-W (WH) discriminants, selected events are split into six SRs based on the signal topology. Jets with $m_{\text{j}} > 100\,\text{GeV}$ ($60 < m_{\text{j}} < 100\,\text{GeV}$) are considered as radion (W boson) candidates and thus required to pass a deep-WH (deep-W) selection, while for lower-mass jets with $m_{\text{j}} < 60\,\text{GeV}$ no such condition is applied. For events with one

selected jet, targeting the merged radion jet topology, three regions (SR1–SR3) are defined using different m_{j} windows of 60–100, 100–200, and >200 GeV, respectively. For SR1 (SR2–SR3), 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 $60 < m_{\mathrm{j}} < 100$ GeV and require exactly two (one) jets with deep-W $>$ 0.5, respectively. Events with $60 < m_{\mathrm{j}}^{\mathrm{max}} < 100$ GeV and deep-W $>$ 0.7 for the higher-mass jet and $m_{\mathrm{j}}^{\mathrm{min}} < 60$ GeV for the lower-mass jet are placed in SR6.

The deep-W (WH) variables are calibrated in dedicated 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. While there is direct correspondence between signal and SM events for jets containing single W boson decays, this is not the case for merged signal jets ($\mathrm{R}^{4\mathrm{q}}$, $\mathrm{R}^{3\mathrm{q}}$, $\mathrm{R}^{\ell\mathrm{qq}}$). The W boson jets are used as the proxy for $\mathrm{R}^{\ell\mathrm{qq}}$ jets, while fully merged top quark jets ($\mathrm{t} \to \mathrm{bqq}$) are used as the proxy for $\mathrm{R}^{3\mathrm{q}}$ as well as for $\mathrm{R}^{4\mathrm{q}}$. The number of signal decays not matching any category is less than 5%. By performing a fit of the proxy components to the data in regions with different relative compositions, we derive the corresponding scale factors (SFs) and their associated uncertainties. These SFs are applied per matched jet category to correct selection efficiencies in simulation for the deep-W (WH) spectra. This calibration procedure is validated in various jet samples. The detailed procedure is presented in Ref. [15].

The main backgrounds, W + jets and $\mathrm{t\bar{t}}$ production, are estimated using CRs. The $\mathrm{t\bar{t}}$ CRs are defined by inverting the b jet veto and removing the deep-W (WH) discriminant selection criteria defined for the SRs, also allowing for up to four additional AK4 jets to increase the number of selected events. Similarly, for the W + jets CRs, the deep-W (WH) selection criteria are inverted, additionally vetoing $\mathrm{t\bar{t}}$ events 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 $\mathrm{t\bar{t}}$), using the $m_{\mathrm{j}\ell\nu}$ or $m_{\mathrm{jj}\ell\nu}$ 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 $m_{\mathrm{j}\ell\nu}$ and $m_{\mathrm{jj}\ell\nu}$ 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 $m_{\mathrm{j}\ell\nu}$ ($m_{\mathrm{jj}\ell\nu}$) distributions is propagated to the SRs. 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 $p_{\mathrm{T}}^{\mathrm{j}}$. 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. Since the objects used in the calibration procedure have the same decay structure as the signal, but can exhibit features such as different color flow and quark flavor that affect the DEEPAK8 performance, additional uncertainties are considered. These uncertainties are evaluated based on the shape differences between signal and SM proxy jets in the deep-W (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 HERWIG 2.7 parton shower program [49]. The resulting differences in the SR yields of 0–25% are assigned as rate uncertainties. A detailed description of the uncertainty evaluation procedure can be found in Ref. [15]. 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 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 [15]. The SF uncertainties are treated as correlated among the two channels (apart from the SFs of q/g jets). 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, 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.

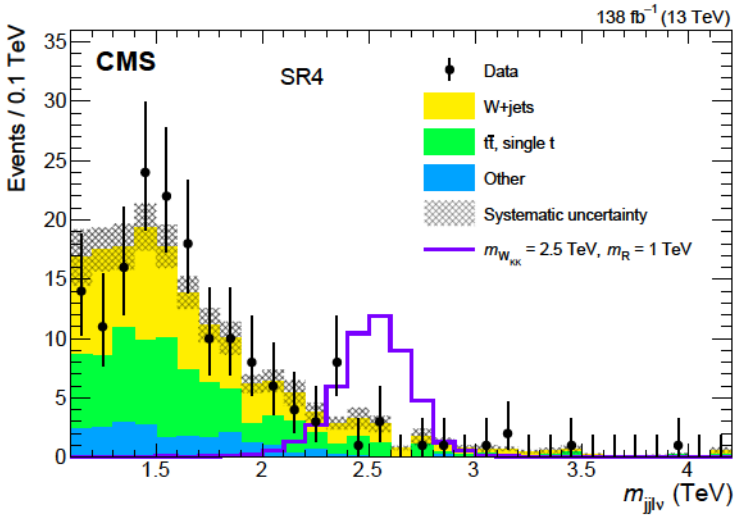

Figure 2: Background-only post-fit distribution of the reconstructed $\ell\nu$+jets system $m_{jj\ell\nu}$ in data and simulation for SR4. The shape of a triboson signal with $m_{W_{KK}} = 2.5$ TeV and $m_R = 1$ TeV is also shown as a violet solid line, normalized to the theoretical production cross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

The asymptotic approximation [50] of the CL_s technique [51, 52] 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. For the combination with the fully hadronic analysis [15], 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 narrow resonance. For radion masses between 0.2 and 1.2 TeV, triboson resonances are excluded up to $m_{W_{KK}} = 3.3$ and 3.7 TeV by the $\ell\nu$+jets analysis and the combination, respectively.

In summary, a search has been presented for resonances decaying in cascade through $W_{KK} \to WR$ 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 colli-

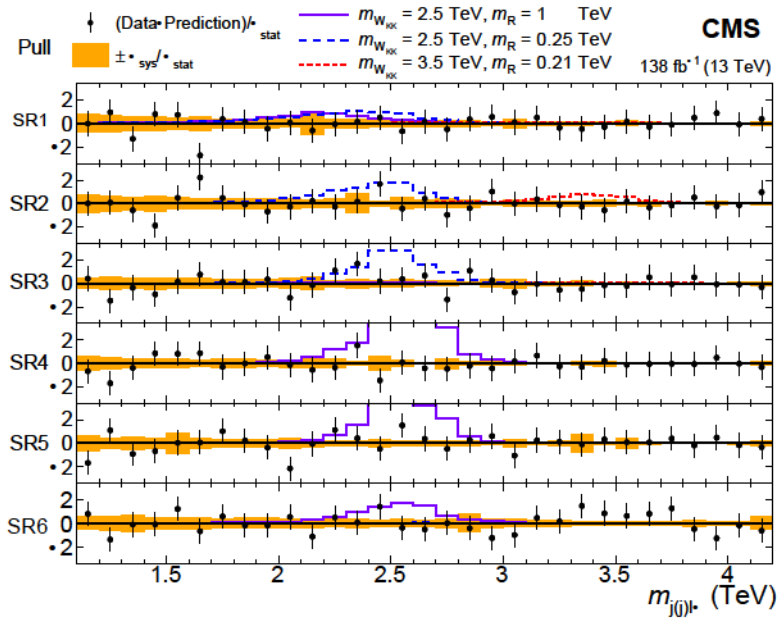

Figure 3: Pull distributions showing (Data−Prediction)/σ_{stat} of the background-only fit to the reconstructed $\ell\nu$+jets system $m_{\text{j}\ell\nu}$ ($m_{\text{jj}\ell\nu}$) for all SRs, where σ_{stat} is the statistical uncertainty. Post-fit systematic uncertainties are indicated by the shaded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

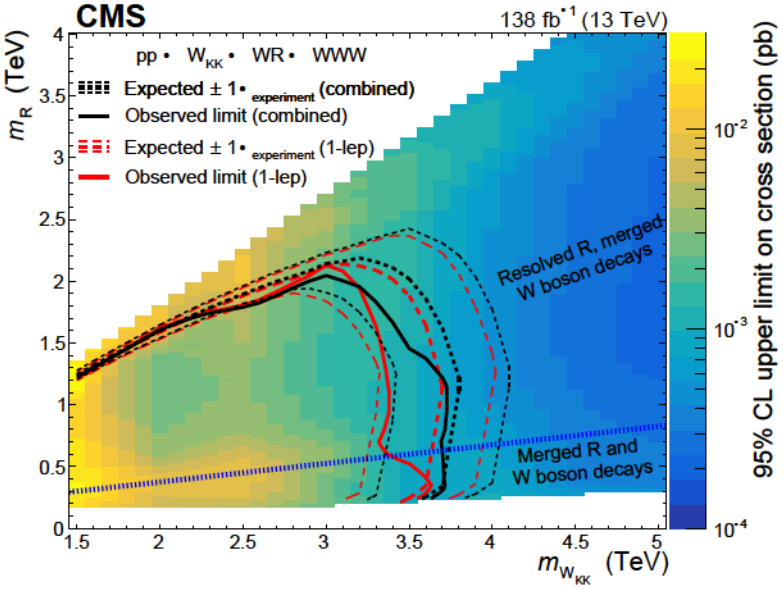

Figure 4: Observed upper limits at 95% CL on the product of the signal cross section and the branching fraction to three W bosons as functions of the W_{KK} and R resonance masses. Expected (dashed lines) and observed (solid lines) lower mass limits are shown as well for the particular parameters of 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. [15] are shown in black.

sion 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 WW jet and those with two separated W boson jets are simultaneously probed by combining jet substructure algorithms. These novel radion identification and calibration technics 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 [15]. Limits are set on an extended warped extra-dimensional model. These are the first searches for the production of triboson resonances at the LHC.

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