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Combination of searches for heavy resonances decaying to WW, WZ, ZZ, WH, and ZH boson pairs in proton–proton collisions at $\sqrt{s} = 8$ and 13 TeV

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A statistical combination of searches is presented for massive resonances decaying to WW, WZ, ZZ, WH, and ZH boson pairs in proton–proton collision data collected by the CMS experiment at the LHC. The data are taken at centre-of-mass energies of 8 and 13 TeV, corresponding to respective integrated luminosities of 19.7 and up to 2.7 fb^{-1}. The results are interpreted in the context of heavy vector triplet and singlet models that mimic properties of composite-Higgs models predicting W′ and Z′ bosons decaying to WZ, WW, WH, and ZH bosons. A model with a bulk graviton that decays into WW and ZZ is also considered. This is the first combined search for WW, WZ, WH, and ZH resonances and yields lower limits on masses at 95% confidence level for W′ and Z′ singlets at 2.3 TeV, and for a triplet at 2.4 TeV. The limits on the production cross section of a narrow bulk graviton resonance with the curvature scale of the warped extra dimension $\tilde{k} = 0.5$, in the mass range of 0.6 to 4.0 TeV, are the most stringent published to date.
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1. Introduction

Hypotheses for physics beyond the standard model (SM) predict the existence of heavy resonances that decay to any combination of two among the massive vector bosons (W or Z, collectively referred to as V) or to a V and the scalar SM Higgs boson (H). Among the considered models are those dealing with warped extra dimensions (WED) [1,2] and composite-Higgs bosons [3–6]. Searches for such VV and VH resonances in different final states have previously been performed by the ATLAS [7–12] and CMS [13–20] experiments at the CERN LHC. As all of these searches have similar sensitivities, a statistical combination of the CMS results is provided to improve the overall result. The current status of heavy diboson searches at CMS is also of interest in this respect, with recent work in the all-jet VV [21] and lepton+jet WH [16] decay channels showing possible enhancements.

The benchmark models considered in combining the results are a heavy vector triplet (HVT) model [22] and the bulk scenario [23–25] (G_{bulk} graviton) in the Randall–Sundrum (RS) WED model [1,2]. The HVT model generalizes a large number of models that predict spin-1 resonances, such as those in composite-Higgs theories, which can arise as a singlet, either W′ or Z′ [26–28], or as a V′ triplet (where V′ represents W′ and Z′ bosons) [22]. The HVT and G_{bulk} models are considered as benchmarks for diboson resonances with spin 1 ($W' \to WZ$ or WH, $Z' \to WW$ or ZH), and spin 2 ($G_{\text{bulk}} \to WW$ or ZZ), respectively, produced via quark–antiquark annihilation ($q\overline{q}' \to W'$, $q\overline{q} \to Z'$) and gluon–gluon fusion ($gg \to G_{\text{bulk}}$).

The analyses included in this statistical combination are based on proton–proton (pp) collision data collected by the CMS experiment [29] at $\sqrt{s} = 8$ and 13 TeV, corresponding to respective integrated luminosities of 19.7 and 2.3–2.7 fb^{-1}. Of the 2.7 fb^{-1} recorded at 13 TeV, the detector was fully operational for 2.3 fb^{-1}, while 0.4 fb^{-1} were collected with only the central part of the detector ($|\eta| < 3$) in optimal condition. The signal corresponds to a narrow charge 0 or 1 resonance with a mass >0.6 TeV that decays to any of the two high energy W, Z, or Higgs bosons, where narrow refers to the assumption that the natural relative width is smaller than the typical experimental resolution of 5%, which is true for a large fraction of the parameter space of the reference models. For the mass range under study, the particles emerging from the boson decays are highly collimated, requiring special reconstruction and identification techniques that are in common in these kinds of analyses.

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Table 1
Summary of the properties of the heavy-resonance models considered in the combination. The polarization of the produced W and Z bosons in these models is primarily longitudinal, as decays to transverse polarizations are suppressed.

Model	Particles	Spin	Charge	Main production mode	Main decay mode
HVT model A, $g_V = 1$	W′ singlet	1	±1	$q\bar{q}'$	$q\bar{q}'$
	Z′ singlet	1	0	$q\bar{q}$	$q\bar{q}$
	W′ and Z′ triplet	1	±1, 0	$q\bar{q}'$, $q\bar{q}$	$q\bar{q}'$, $q\bar{q}$
HVT model B, $g_V = 3$	W′ singlet	1	±1	$q\bar{q}'$	WZ, WH
	Z′ singlet	1	0	$q\bar{q}$	WW, ZH
	W′ and Z′ triplet	1	±1, 0	$q\bar{q}'$, $q\bar{q}$	WZ, WH, WW, ZH
RS bulk, $\tilde{k} = 0.5$	G_{bulk}	2	0	gg	WW, ZZ

Analyses were performed using all-lepton, lepton+jet, and all-jet final states that include decays of W and Z bosons into charged leptons ($\ell = e$ or μ) and neutrinos (ν), as well as the reconstructed jets evolved from the $q\bar{q}^{(\prime)}$ products of the boson decays. The latter include $W \to q\bar{q}'$ and $Z \to q\bar{q}$. The analyses use $H \to b\bar{b}$ and $H \to WW \to q\bar{q}'q\bar{q}'$ decays of the Higgs boson, which are labeled as $b\bar{b}$ or $q\bar{q}q\bar{q}$, together with a vector boson decaying to hadrons. Final states with the Higgs boson decaying into a $\tau^+\tau^-$ lepton pair are also considered. In all, we combine results from the following final states: $3\ell\nu$ (8 TeV) [13]; $\ell\ell q\bar{q}$ (8 TeV) [14]; $\ell\nu q\bar{q}$ (8 TeV) [14]; $q\bar{q}q\bar{q}$ (8 TeV) [15]; $\ell\nu b\bar{b}$ (8 TeV) [16]; $q\bar{q}\tau\tau$ (8 TeV) [17]; $q\bar{q}b\bar{b}$ and 6q (8 TeV) [18]; $\ell\nu q\bar{q}$ (13 TeV) [19]; $q\bar{q}q\bar{q}$ (13 TeV) [19]; and $\ell\ell b\bar{b}$, $\ell\nu b\bar{b}$, and $\nu\nu b\bar{b}$ (13 TeV) [20]. Since some more forward parts of the detector, which provide information for the calculation of the missing transverse momentum, were not in optimal condition for a fraction of the 2015 data-taking period, the analyses of 13 TeV data in the $\ell\nu q\bar{q}$, $\ell\nu b\bar{b}$ and $\nu\nu b\bar{b}$ decay channels are based on the dataset corresponding to the integrated luminosity of 2.3 fb^{-1} rather than 2.7 fb^{-1}.

Given the limited experimental jet mass resolution, the $W \to q\bar{q}'$ and $Z \to q\bar{q}$ candidates cannot be fully differentiated, and individual analyses can be sensitive to several different interpretations in the same model. For example, the final state $\ell\nu q\bar{q}$ is sensitive to HVT W′ decays to a WZ boson pair as well as to Z′ decays to WW boson pairs. The sum of contributions from multiple signals with their respective efficiencies is sought in the combination. For this reason, separate interpretations are given below for a vector triplet V′ and for vector singlets (W′ or Z′).

This letter is structured as follows. After a brief introduction to the benchmark models in Section 2, a summary of the analyses entering the combination is given in Section 3. The combining procedure is described in Section 4, and finally the results and summary are provided in Sections 5 and 6.

2. Theoretical models

As indicated above, heavy diboson resonances are expected in a large class of models that attempt to accommodate the difference between the electroweak and Planck scales. We perform the combination in the context of seven benchmark theories formulated to cover different spin, production, and decay options for resonances decaying to VV and VH. The properties of models for spin-1 and spin-2 resonances are briefly discussed in the following two subsections, with benchmark resonances summarized in Table 1. For both spin-1 and spin-2 resonances, the signal cross sections used in this paper are given in Tables A.1 and A.2 of the Appendix.

2.1. Spin-1 resonances

Several extensions of the SM such as composite Higgs [3–6] and little Higgs [30,31] models can be generalized through a phenomenological Lagrangian that describes the production and decay of spin-1 heavy resonances, such as a charged W′ and a neutral Z′, using the HVT model.

The HVT couplings are described in terms of four parameters:

(i) c_H describes interactions of the new resonance with the Higgs boson or longitudinally polarized SM vector bosons;
(ii) c_F describes the interactions of the new resonance with fermions;
(iii) g_V gives the typical strength of the new interaction and
(iv) m'_V is the mass of the new resonance.

The W′ and Z′ bosons couple to the fermions through the combination of parameters $g^2 c_F/g_V$ and to the H and vector bosons through $g_V c_H$, where g is the $SU(2)_L$ gauge coupling. The Higgs boson is assumed to be part of a Higgs doublet field. Therefore, its dynamics are related to the Goldstone bosons in the same doublet by SM symmetry. Those Goldstone bosons are equivalent to the corresponding longitudinally polarized W and Z bosons in the high energy limit according to the "Equivalence Theorem" [32]. The coupling of the Higgs boson to the W′ and Z′ resonances can thus be described by the same coupling as used for the longitudinal W and Z bosons.

The production of W′ and Z′ bosons at hadron colliders is expected to be dominated by the process $q\bar{q}^{(\prime)} \to$ W′ or Z′. Two benchmark models are studied, denoted A and B, that were suggested in Ref. [22]. In model A, weakly coupled vector resonances arise from an extension of the SM gauge group. In model B, the heavy vector triplet is produced by a strong coupling mechanism, as embodied in theories such as in the composite Higgs model. Consequently, in model A the branching fractions to fermions and SM massive bosons are comparable, whereas in model B, fermionic couplings are suppressed. Therefore, in the context of WW, WZ, ZH, and WH resonance searches, model B is of more interest, since model A is strongly constrained by searches in final states with fermions. In both options, the heavy resonances couple as SM custodial triplets, so that W′ and Z′ are expected to be approximately degenerate in mass, and the branching fractions $\mathcal{B}(W' \to WH)$ and $\mathcal{B}(Z' \to ZH)$ to be comparable to $\mathcal{B}(W' \to WZ)$ and $\mathcal{B}(Z' \to WW)$. We consider model A ($c_H = -g^2/g_V^2$, $c_F = -1.3$) with parameter $g_V = 1$, and model B ($c_H = -1$, $c_F = 1$) with parameter $g_V = 3$. A value of $g_V = 3$ is chosen for model B to represent strongly coupled electroweak symmetry breaking, e.g. composite Higgs models, while assuring small natural widths relative to the experimental resolution. We also consider heavy resonances that couple to W′ and Z′ as singlets, i.e. expecting only one charged or neutral resonance at a given mass, as summarized in Table 1.

Previous searches for a W′ boson decaying into a pair of SM massive bosons (WZ, WH) provide a lower mass limit of 1.8 TeV in model A ($g_V = 1$) and 2.3 TeV in model B ($g_V = 3$), where the

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