Search for heavy resonances at CMS

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Abstract. The search for new physics at the TeV scale is one of the major aspects of the CMS experimental program. This includes a myriad of theoretical models involving resonances that can decay to massive bosons, leptons or jets. An overview of such analyses is presented in this paper as well as the novel dedicated techniques related to the specificity of the event topologies. All analyses presented here use the full 2012 dataset, corresponding to an integrated luminosity of \(\sim 20 \text{ fb}^{-1}\) recorded in proton-proton collisions at \(\sqrt{s} = 8\ \text{TeV}\) with the CMS detector at the CERN LHC.

1. Introduction

The recent discovery by the ATLAS and CMS Collaborations [1, 2, 3] of a particle compatible with the Standard Model (SM) predictions for the Higgs boson enhanced our understanding of the electroweak symmetry (EW) breaking mechanism. But the large difference between the EW scale and the Planck scale, i.e. the hierarchy mass problem, stills remains unsolved. Many theoretical extensions of the SM (BSM theories) predict the existence of new gauge bosons or KK excitations of the graviton that could manifest at the TeV scale. Such resonances would appear as a peak over a continuous background coming from the SM processes. The search for BSM resonances is one of the major aspects of the CMS [4] experimental program and includes dedicated techniques to demonstrate the background predictions are well under control. Almost all analyses presented here use the particle-flow (PF) algorithm [5] to reconstruct and identify all stable particles in the event (electrons, muons, photons, neutral and charged hadrons) by using a thorough recombination of all sub-detectors.

2. Dilepton resonances [6]

Dilepton resonances include the Sequential Standard Model \(Z'_{\text{SSM}}\), the \(Z'_\psi\) predicted by \(E_6\) gauge group grand unified theories, or the Randall-Sundrum graviton \(G_{RS}\), all of which can decay either to a dielectron or a dimuon pair. The main background is the irreducible Drell-Yan background and the selection is mainly based on shower shape variables as well as isolation variables. In order for the analysis to be robust, different data-driven background estimation techniques and cross-check methods have been derived. For the Drell-Yan contribution, the mass spectrum shape is derived from Monte-Carlo simulations and normalized to the number of events in data in the region \(60 < M_{ll} < 120\ \text{GeV} \). The \(tt, tW, WW, WZ\) and \(\tau\tau\) contributions are derived from Monte-Carlo simulations and cross-checked using the data-driven \(e\mu\) method

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which exploits the flavour-symmetric nature of such processes. Finally, the QCD multi-jet component is estimated using the data-driven fake rate method which calculates the probability for a jet, having been reconstructed as an electron, to pass the electron selection\(^2\). Figures 1 (left) and (middle) present the invariant mass spectra of the selected dielectron and dimuon pairs respectively. In each case, the spectrum from data is compared with the sum of the different background components. Excellent agreement is observed along the whole mass range and no significant deviation from the Standard Model processes is observed.

![Figure 1](image_url) The invariant mass spectrum of \(\mu^+\mu^-\) (left) and ee (middle) events. The points with error bars represent the data. The histograms represent the expectations from standard model processes (see text). Upper limits (right) as a function of resonance mass \(M\) on the production ratio \(R_\sigma\) of cross section times branching fraction into lepton pairs for \(Z_{SSM}^{'}\) and \(Z_\psi^{'}\) boson production to the same quantity for \(Z\) bosons.

To extract upper limits on the various model cross sections, a statistical interpretation tool is built based on an unbinned likelihood bayesian technique. The statistical method has the specificity of (a) combining both channels and (b) setting limits on the cross section ratio \(R_\sigma = \sigma_{Z'}/\sigma_Z\) allowing therefore to cancel some systematic uncertainties. Figure 1 (right) gives the 95% CL limits as a function of the dilepton invariant mass for the \(Z_\psi^{'}\) and \(Z_{SSM}^{'}\) models. The median, 68% and 95% quantiles for the expected limits are also shown together with the theoretical predictions. A \(Z'\) with standard model-like couplings can be excluded below 2900 GeV and the superstring-inspired \(Z_\psi^{'}\) below 2570 GeV. RS Kaluza-Klein gravitons are excluded below 2730 (2350) GeV for couplings of 0.10 (0.05), all at 95% CL.

3. Dijet resonances \(^7\)

Dijet heavy resonances are predicted by the same models covering the dilepton resonances but, in addition, many other models such as string resonances, scalar diquarks, excited quarks, axigluons, colorons or color-octet scalar (s8) resonances can enter the scope of this analysis. The main background is the QCD multi-jet background. All jets in the event are required to have a transverse momentum greater than 30 GeV and an absolute value of the pseudo rapidity less than 2.5. In order to reduce sensitivity to gluon radiation, this analysis uses the "wide jets" technique \(^8\). The method consists in considering the two leading jets in the event and merge all other jets to the closest leading jet if they are within a distance \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\) and \(R_{\text{wide}} = 1.1\). The invariant mass of the two wide jets is required to be higher than 890 GeV and their pseudo rapidity separation \(|\Delta \eta_{j1j2}|\) be less than 1.3. In addition the scalar sum of the transverse momenta of all jets in the event has to be higher than

\(^2\) This source of background is negligible in the dimuon channel.
650 GeV. Figure 2 (left) shows the invariant mass spectrum of the dijet pair. The background is modeled by the so-called dijet function $f(x) = (p_0(1-x)p_1)/(xp_2+p_3\ln x)$ where $x = M_{jj}/\sqrt{s}$. The function describes very well the background spectrum as one sees from the residuals distribution. The main systematic uncertainties arise from the jet energy scale and resolution (1.25 % and 10 % on the invariant mass, respectively), and from the background parametrization. No significant deviation is observed from the known Standard Model processes. The statistical interpretation method is based on the bayesian formalism and is performed independently at each value of the resonance mass. Figure 2 (right) shows the upper limit on the cross section $\times$ branching ratio $\times$ acceptance as a function of the dijet pair invariant mass for the three decay modes (qq, gg, qg). The theoretical cross sections are also shown for the various models investigated. The upper limits on the cross sections are translated to lower limits on the resonances masses, summarized in Table 1.

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Figure 2. Left: Dijet mass spectrum from wide jets (points) compared to a smooth fit (solid) and to predictions including detector simulation of QCD and signal resonances. The QCD prediction has been normalized to the data. The error bars are statistical only. The bin-by-bin fit residuals, $(\text{data-fit}/\sigma_{\text{data}})$, are shown at the bottom. Right: The observed 95% CL upper limits on $\sigma \times B \times A$ for dijet resonances of the type gluon-gluon, quark-gluon, and quark-quark, compared to theoretical predictions for the various models investigated (see text).
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Table 1. Observed and expected 95% CL exclusions on the mass of various resonances. Systematic uncertainties are included.

| Model                   | Final State | Obs. Mass Excl. [TeV] | Exp. Mass Excl. [TeV] |
|-------------------------|-------------|-----------------------|-----------------------|
| String Resonance (S)    | qg          | 1.20,5.08             | 1.20,5.00             |
| Excited quark ($q^*$)   | qg          | 1.20,3.50             | 1.20,3.75             |
| $E_6$ Diquark (D)        | qq          | 1.20,4.75             | 1.20,4.50             |
| Axigluon (A)/Coloron (C)| qg          | 1.20,3.60 + 3.90,4.08 | 1.20,3.87             |
| Color Octet Scalar (s8) | gg          | 1.20,2.79             | 1.20,2.74             |
| W’ Boson (W’)           | qq          | 1.20,2.29             | 1.20,2.28             |
| Z’ Boson (Z’)           | qg          | 1.20,1.68             | 1.20,1.87             |
| RS Graviton (G)          | qg+gg       | 1.20,1.58             | 1.20,1.43             |

4. VV resonances
Heavy resonances can also decay to a pair of boosted vector bosons which can then decay either leptonically or hadronically. In the leptonic decay, the isolation cones may overlap, requiring
4.1. VV/qV resonances \cite{12}

Such resonances can happen in the context of excited quarks (q∗ → qV) or new heavy gauge bosons from GUT models (W′ → WZ) as well as KK excitations of the graviton in the context of the Randall-Sundrum or bulk scenarios. A focus is made here on the all-hadronic channel where the dominant source of background is the QCD multi-jet process. The selection makes use of the jet substructure technique, jet pruning algorithm and V-tagging method mentioned in Section 4. Events are selected that contain at least two jets with invariant mass higher than 890 GeV and pseudo rapidity separation |Δηjj| less than 1.3. In addition, each jet is classified as a high-purity jet (HP-jet) or a low purity jet (LP-jet) depending if τ21 < 0.5 or 0.5 < τ21 < 0.75, respectively. The remaining background is estimated, in each channel, using the fit function $f(x) = p_0 x^{p_1}/x^{p_2}$ with $x = M_{jj}/\sqrt{s}$. The main sources of systematic uncertainty arise from the V-tagging procedure, which amount to 7.5% (54%) in the HP (LP) category. Figure 8 shows the invariant mass spectra of the dijet pairs in the cases of single (top left) and double (top right) W/Z tag. In each case, the spectra are shown for the low and high purity categories and compared to the Monte-Carlo predictions from MADGRAPH/PYTHIA and HERWIG++. The agreement is very good in each case/category and no significant deviation is observed from the known Standard Model processes. The statistical interpretation is based on an asymptotic frequentist method (CLs method). Figure 8 (bottom row) shows the upper limits on the cross section $\times$ branching ratio for the models of excited quarks and Randall-Sundrum gravitons. Lower limits are set at the 95% confidence level on masses of excited quark resonances decaying into qW and qZ at 3.2 and 2.9 TeV, respectively. Randall-Sundrum gravitons $G_{RS}$ decaying into WW are excluded up to 1.2 TeV, and W′ bosons decaying into WZ, for masses less than 1.7 TeV. The corresponding expected limits amount to 3.0 and 2.6 TeV for excited quark resonances decaying into qW and qZ, respectively and to 1.3 and 1.6 TeV for Randall-Sundrum gravitons $G_{RS}$ decaying into WW and W′ bosons decaying into WZ, respectively. These mass limits are the most stringent up to date.

4.2. VV semileptonic resonances \cite{13}

Such resonances are characterized by the presence, in the event, of at least 2 jets and either one lepton with missing transverse energy or two leptons ($X → VV → l\nu qq/l\bar{q}q$). Two main...
components arise in these searches: the $l\nu + V$-jet and the $ll + V$-jet components depending whether the $W$ or the $Z$ decays leptonically. The lepton selection is based on shower shape and isolation in a way similar to the selection in the dilepton analysis (Section [2]). The jet selection is subject to the jet pruning and jet substructure techniques in a similar way as in the $VV/qV$ resonances analysis (Section [1.1]). Each jet is classified as a high-purity jet (HP-jet) or a low purity jet (LP-jet) depending if $\tau_{21} < 0.5$ or $0.5 < \tau_{21} < 0.75$. In addition the transverse momentum of each jet is required to be greater than 30 GeV and its absolute pseudo rapidity be less than 2.4. The $V$-tagging requirement is also applied and each $V$-jet is tagged as a $W$-jet or a $Z$-jet depending on the pruned jet mass. Events are furthermore selected based on the $V$-boson transverse momentum and the presence of missing transverse energy. Additional criteria to ensure the back-to-back topology are required. After the full selection, the dominant source of background comes from the $V$+jet process. The overall normalization of this background contribution is estimated through a fit in sidebands of the pruned jet mass ($M_j$) while the shape is taken from the low $M_j$ sideband and extrapolated to the signal region using an extrapolation function derived from Monte-Carlo predictions. Figure 4 (left) shows the pruned jet mass spectrum from data together with the different background predictions, in the case of the $e\nu$ channel for the HP category. Sources of background other than the $V$+jet are extracted from Monte-Carlo predictions. The residual distribution in the bottom pad shows a good level of agreement between the fit and the data. The statistical interpretation is based on an asymptotic frequentist method (CLs method) with an unbinned shape analysis. The categories
are all combined and the results are further combined with the results from the corresponding analysis in the all hadronic channel (Section 4.1). Figure 4 (right) shows the 95% CL limit on the bulk graviton production cross section as a function of the graviton mass. In region I, only the $ll+V$-jet channel contributes. In region II, both $ll+V$-jet and $l\nu+V$-jet channels contribute. In region III, both the semi-leptonic and all-hadronic channels contribute. Upper limits at 95% CL are set on the bulk graviton production cross section in the range from 700 to 10 fb for resonance masses between 600 and 2500 GeV, respectively.

**Figure 4.** Left: Distribution of the pruned jet mass, $m_{\text{jet}}$, in the $l\nu+V$-jet analysis in the electron channel for the HP category. Data are shown as black markers. At the bottom of each plot, the bin-by-bin fit residuals, $(\text{data-fit})/\sigma_{\text{data}}$, are shown together with the uncertainty band of the fit normalized by $\sigma_{\text{data}}$. Right: observed (solid) and expected (dashed) 95% CL upper limit on the graviton production cross section obtained with this analysis and the analysis of the all-hadronic channel. The cross section for the production of a bulk graviton with $k/M_{Pl} = 0.5$ is shown as a red solid curve.

5. WZ resonances in leptonic channel

Such processes are characterized by a resonance, such as the $W'$ from the SSM or the $\rho$ from Technicolor, that decays to a $W$ and a $Z$, both decaying leptonically ($X \rightarrow WZ \rightarrow l\nu ll$). The dominant background is the irreducible SM $WZ$ process. The lepton selection is based on shower shape and isolation criteria similar to the dilepton analysis (Section 2), where, in this case however, a modified isolation cone is used (Section 4). Events are then selected containing at least three leptons with two opposite charge leptons with mass $M_{lll}$ between 71 and 111 GeV. The mass of the three leptons $M_{3l}$ has to be higher than 120 GeV in order to remove events where $M_{3l}$ is close to the $Z$ boson mass and a minimum missing transverse energy of 30 GeV is required to account for the neutrino from the $W$ decay. Also, the distance between the lepton from the $Z$ and the lepton from the $W$ $\Delta R(lZ,lW)$ is to be higher than 0.3. Additional criteria such as the sum of the lepton transverse momenta $L_t$ and the mass of the $WZ$ pair $M_{WZ}$ are also exploited and optimized for the best expected limit. Figure 5 shows the distributions of these two variables (left and middle) for the various sources of background, $W'$ bosons of 1 and 1.5 TeV, as well as for the data. One sees that good discrimination is possible between the signal and the different background contributions. The statistical interpretation is based on a counting experiment (bayesian formalism). Figure 5 (right) shows the 95% CL upper limit on the cross section $\times$ branching ratio as a function of the resonance ($W'$ or $\rho_{TC}$) mass. These upper limits get translated to lower limits on the resonance mass of 1470 GeV for the $W'$ and 1140 GeV for the $\rho_{TC}$. 

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Figure 5. The WZ invariant mass (left) and $L_T$ (middle) distributions for the background, signal, and observed events after the WZ candidate selection. The last bin includes overflow events. The $(\text{obs-bkg})/\sigma$ in the lower panel is defined as the difference between the number of observed events and the number of expected background events divided by the total statistical uncertainty. Limits (right) at 95% CL on $\sigma \times B(W' \rightarrow 3l\nu)$ as a function of the mass of the W' (blue) and $\rho_{TC}$ (red), along with the 1 $\sigma$ and 2 $\sigma$ combined statistical and systematic uncertainties indicated by the green (dark) and yellow (light) band, respectively. The theoretical cross sections include a mass-dependent NNLO K-factor. The thickness of the theory lines represents the PDF uncertainty associated with the signal cross sections.

6. Light/heavy flavour three jet resonances [15]

Such resonances are predicted by scenarios like heavy coloured fermions or R-parity violating (RPV) gluinos where the pair-produced resonances can decay, individually to 3 jets ($XX \rightarrow qqqqqq$). The topology of the event is therefore characterized by the presence of at least 6 jets. In order to correctly reconstruct the event, this search uses the novel jet ensemble technique [16] that recombines jets to find correct triplets and is the first of its kind to include heavy flavour jets. It is divided into two categories: the light flavour inclusive mass search covering the mass range 400-1500 GeV and the heavy flavour low and high mass searches covering the mass ranges 200-600 GeV and 600-1500 GeV, respectively. The dominant source of background is the QCD multi-jet process which reduction is based on a selection that uses dedicated discrimination variables. First, a criterion on the transverse momentum of the fourth highest transverse momentum jet (sixth highest transverse momentum jet) is optimized for the low mass heavy search (inclusive and high mass heavy search). Second, a correlation is observed, in Monte-Carlo simulations, between the mass of the jet triplet $M_{jjj}$ and the sum of their transverse momenta ($\sum_{i=1}^{3} p_{t,j}^i$). A criterion is therefore imposed on the triplet mass where: $M_{jjj} < \sum_{i=1}^{3} p_{t,j}^i - \Delta$. The value of $\Delta$ is determined from Monte-Carlo simulations and chosen so as to cover as broad a range as possible for values of the resonance mass. Finally, the sphericity of the signal events is exploited as they tend to be more spherical than background events. The sphericity tensor is defined as $S^{\alpha\beta} = \sum p^\alpha p^\beta / \sum |p|^2$ together with its eigenvalues $\lambda_i$ and the sphericity defined as $S = (3/2) \times (\lambda_2 + \lambda_3)$. The background estimation proceeds twofold. In the light and high mass heavy flavour, the $t\bar{t}$ background is determined from Monte-Carlo predictions while the SM multi-jet spectrum shape is extracted from the data in a b-jet control region. This estimation technique is further validated by considering the $t\bar{t}$ process as the signal, extracting its cross section and finding a good agreement with the theoretical value. No significant evidence of a new resonance is observed and 95 % CL upper limits on the resonance production cross section $\times$ branching ratio are derived using the asymptotic frequentist approach (CLs method) based
on a profile likelihood. Figure 6 shows those limits as a function of the triplet invariant mass in the case of the light (left) and heavy (right) flavour search. The red dashed lines correspond to the $+1\sigma$ and $-1\sigma$ theoretical predictions on the cross section times branching ratio, $\sigma$ being the uncertainty on that prediction. This searches adopts a conservative approach and uses the $-1\sigma$ theoretical curve to translate upper limits on cross section $\times$ branching ratio to lower limits on the resonance mass. For RPV gluinos, masses are excluded below 650 GeV in the light flavour search and in the region between 200 and 835 GeV in the heavy flavour search.

![Graph showing observed and expected 95% CL cross section limits as a function of mass for the triplet invariant mass.](image)

**Figure 6.** Observed and expected 95% CL cross section limits as a function of mass for the inclusive (left) and heavy-flavour searches (right). The limits for the heavy-flavour search cover two mass ranges, one for low-mass gluinos ranging from 200 to 600 GeV, and one for high-mass gluinos covering the remainder of the mass range up to 1500 GeV. The solid red lines show the NLO+NLL predictions, and the dashed red lines give the corresponding one-standard deviation uncertainty bands.

7. Conclusion

Results from searches for new massive resonances in CMS were presented, including a variety of theoretical models as well as many decay channels. No significant deviation from the corresponding SM processes was observed. Upper limits on the resonance production cross section were set at 95% CL and, when possible, translated to lower limits on the resonance mass. In many of the searches presented here, those results are the most stringent up to date. Those will be extended by the results from LHC Run II foreseen in mid 2015. In view of the higher instantaneous luminosity and centre of mass energy expected, most of those results will be superseded after $\sim 1 \, fb^{-1}$ of data has been collected, which is likely to happen in a few weeks.

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