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2013 J. Phys.: Conf. Ser. 455 012029

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Search for exotic resonances in diboson final states with the CMS detector at the LHC

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Abstract. The results of searches for new resonances decaying to a pair of massive vector bosons (WW, WZ, ZZ) are presented. All searches are performed using 5.0 fb^{-1} of proton-proton collisions, at $\sqrt{s} = 7 \text{ TeV}$ of center of mass energy, collected by the Compact Muon Solenoid detector at the Large Hadron Collider. No significant excess compared to the standard model background expectation is observed, and upper limits at 95% confidence level are set on the production cross section times the branching fraction of hypothetical particles decaying to a pair of vector bosons. The results are interpreted in the context of several benchmark models, such as the Randall-Sundrum gravitons, the Sequential Standard Model W' , and Technicolor. Graviton resonances in the Randall-Sundrum model with masses smaller than $940 \text{ GeV}/c^2$, for coupling parameter $k/\overline{M}_{Pl} = 0.05$ are excluded. Bulk (ADPS) Randall-Sundrum gravitons with masses smaller than $610 \text{ GeV}/c^2$ are excluded, for $k/\overline{M}_{Pl} = 0.05$. Sequential Standard Model W' with masses smaller than $1143 \text{ GeV}/c^2$ are excluded, as well as ρ_{TC} in the $167 - 687 \text{ GeV}/c^2$ mass range, in Low Scale Technicolor models with $M(\pi_{TC}) = 3/4 M(\rho_{TC}) - 25 \text{ GeV}/c^2$.

1. Introduction

Searches for exotic resonances decaying to a pair of massive vector bosons are historically connected to electroweak symmetry breaking models, other than the Higgs mechanism. However, a standard model (SM) Higgs boson with mass around $M_H = 126 \text{ GeV}/c^2$ would not exclude all models being considered, as the Higgs could be accommodated within the theoretical framework. One of the fundamental questions the LHC was designed to elucidate is the electroweak symmetry breaking mechanism, and in many extensions of the SM the generation of mass can be associated with new strong dynamics appearing at the TeV scale. This new dynamics can be due to new interactions arising from extended gauge groups, a composite Higgs boson, or from compact extra dimensions.

Searches for new heavy resonances decaying to a pair of vector bosons VV ($V = W, Z$) are performed, using 5 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ center-of-mass energy pp collisions data collected by the CMS experiment [1] in 2011. Several channels were considered: WZ decaying into three leptons and missing transverse energy [2]; ZZ decaying into a pair of leptons and two jets [3]; WZ or ZZ decaying into a pair of leptons or neutrinos and a single merged jet [4]; and WW, WZ or ZZ decaying into two merged jets [5]. The results were interpreted in several benchmark models: the Sequential Standard Model (SSM) [6], Randall-Sundrum (RS) with SM particles confined in the electroweak brane [7] or allowed to propagate in the bulk (ADPS model) [8], and Low Scale Technicolor (LSTC) [9].



2. $WZ \rightarrow 3\ell + \text{MET}$

A search for new particles decaying via a WZ pair is performed, with $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ in the final state, where $\ell = e, \mu$. The decay under study is characterized by a pair of same-flavor, opposite-charge, isolated leptons with high transverse momentum (p_T) and invariant mass consistent with that of the Z boson, along with a third, high- p_T isolated lepton, and missing transverse energy (MET) associated with the escaping neutrino. The SM backgrounds for this search include the irreducible SM WZ background, top pair events, Z+jets, $Z\gamma$, and $ZZ \rightarrow 4\ell$.

The background is estimated using simulated samples produced with MADGRAPH 5.1 [11] and PYTHIA 6.4.22 [12] generators, which were subject to a full simulation of the CMS detector using GEANT4 [19]. The cross sections are corrected for higher-order effects using next-to-leading-order (NLO) K-factor corrections, obtained using MCFM 6.1 [17]. The signal is simulated using PYTHIA with mass-dependent next-to-NLO (NNLO) cross sections obtained using FEWZ 2.0 [18].

Candidate events are required to have three reconstructed leptons within the acceptance of $|\eta| < 2.5$ (2.4) for electrons (muons), where $\eta \equiv -\ln(\tan(\theta/2))$ and θ is the polar angle. Z boson candidates are reconstructed from pairs of opposite-sign, same-flavor leptons with the highest and second-highest p_T greater than 20 and 10 GeV/c, respectively, and with invariant mass between 60 and 120 GeV/c². The lepton from the W candidate is required to have tighter identification and isolation requirements, and the events with MET > 30 GeV are selected. The observed invariant mass distribution of WZ candidates (M_{WZ}) is shown in Fig. 1. An additional selection requirement is applied on the scalar sum of the transverse momenta of the charged leptons (L_T), dependent on the mass of the signal hypothesis. Fig. 2 shows the M_{WZ} distribution corresponding to the $W' = 600$ GeV hypothesis, where $L_T > 290$ GeV.

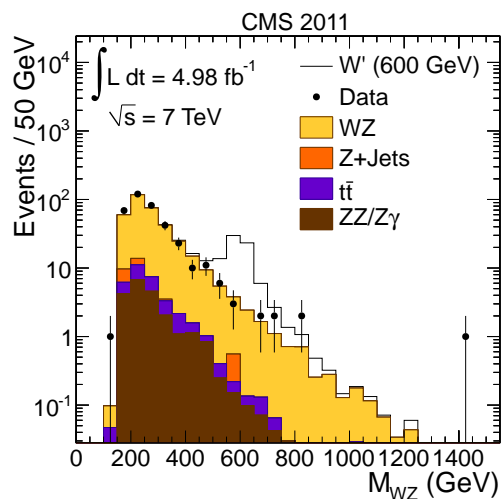


Figure 1. Distribution of the WZ invariant mass for the SM background, W' mass point at 600 GeV/c² and observed data, before application of the L_T requirement.

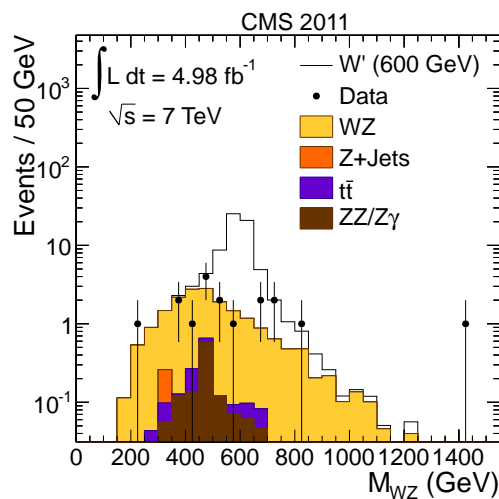


Figure 2. Distribution of the WZ invariant mass for the SM background, W' mass point at 600 GeV/c² and observed data. The selection of $L_T > 290$ GeV/c² is applied.

No significant excess above the SM expectation is observed. Exclusion limits on the production cross section $\sigma(\text{pp} \rightarrow W'/\rho_{TC} \rightarrow WZ) \times \mathcal{B}(WZ \rightarrow 3\ell\nu)$ are determined using CL_S [10] statistics (Fig. 3). SSM W' with masses below 1143 GeV/c² are excluded. For LSTC, with the chosen parameters $M(\pi_{TC}) = 3/4 M(\rho_{TC}) - 25$ GeV/c², ρ_{TC} hadrons with masses between 167 and 687 GeV/c² are also excluded. Fig. 4 shows the LSTC limits as a function of the ρ_{TC} and π_{TC} masses.

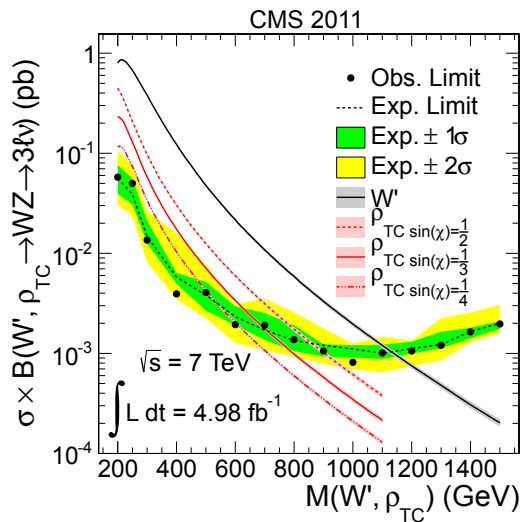


Figure 3. Expected and observed upper limits as a function of the WZ mass for W' and ρ_{TC} along with the 1 and 2 σ uncertainties.

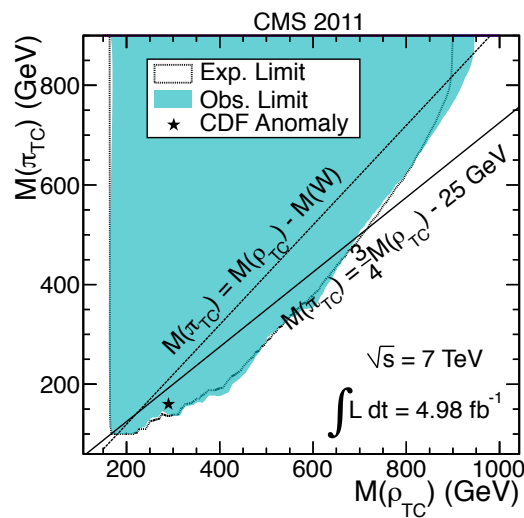


Figure 4. Exclusion region at 95% confidence level (CL) for Low Scale Technicolor as a function of the ρ_{TC} and π_{TC} masses.

3. $ZZ \rightarrow 2\ell + jj$

A search for new heavy narrow spin-2 resonances decaying via a ZZ pair is performed, with $Z \rightarrow \ell^+\ell^-$ and $Z \rightarrow q\bar{q}$ in the final state, where $\ell = e, \mu$. The full decay chain is reconstructed and the invariant mass of the candidate Z boson pair, M_{ZZ} , is investigated in a mass range between 400 and 1200 GeV/c^2 . The dominant SM background is Z boson production with associated jets (Z +jets).

Candidate events are required to have two reconstructed leptons within the acceptance of $|\eta| < 2.5$ (2.4) for electrons (muons), and highest and second-highest p_T greater than 40 and 20 GeV/c , respectively. Events are also required to have jet pairs, reconstructed with the anti- k_T [15] algorithm with a distance parameter $R = 0.5$, within $|\eta| < 2.4$ and with $p_T > 30$ GeV/c . Z boson candidates are reconstructed from pairs of opposite-sign, same-flavor leptons with invariant mass between 70 and 110 GeV/c^2 and from pair of jets with invariant mass between 75 and 105 GeV/c^2 . The events are separated in categories of jet flavor, introducing tags for b flavor jets (b -tag), in order to better discriminate signal and background. An angular analysis is also performed, using an angular likelihood discriminant based on the probability ratio of the signal and background hypotheses.

The background is estimated from data, using a sideband in the M_{ZZ} distribution. A cross-check of the estimated background is performed, using simulated samples produced with MADGRAPH 5, SHERPA 1.13 [13] and PYTHIA 6.4.24. The signal is modeled using simulated samples produced with a dedicated generator for spin-2 resonances [20], for both RS and ADPS models. The M_{ZZ} distribution for 1 b -tag category is shown in Figs. 5 and 6, for the electron and muon channels, respectively.

Since no significant excess is observed, exclusion limits at the 95% confidence level (CL) were set on the product of the graviton cross section and branching fraction of $G_{KK} \rightarrow ZZ$. The upper limits are calculated using the CL_s method and compared to the theoretical values. Fig. 7 shows the upper limits for the RS model and compares them to the LO theoretical expectations for two values of the coupling parameter k/\bar{M}_{Pl} , 0.05 and 0.1. Gravitons with masses smaller than 945 GeV/c^2 are excluded, for $k/\bar{M}_{Pl} = 0.1$, and gravitons with masses smaller than 720 GeV/c^2

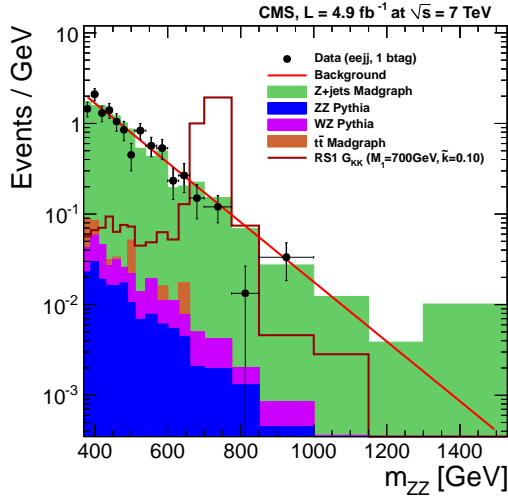


Figure 5. The m_{ZZ} invariant mass distribution for data, simulated background and data-estimated background, after final selection in the 1-btag category, for the electron channel.

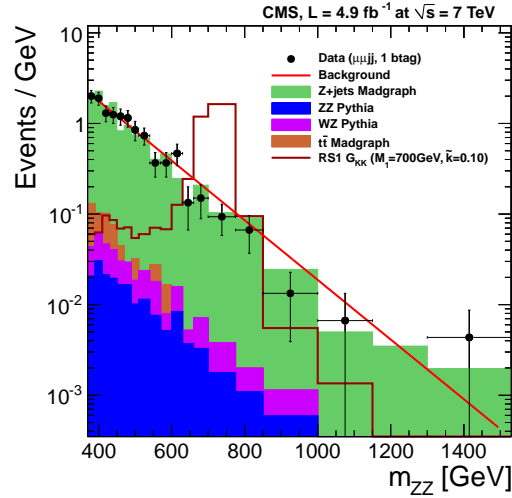


Figure 6. The m_{ZZ} invariant mass distribution for data, simulated background and data-estimated background, after final selection in the 1-btag category, for the muon channel

and in the range 760 – 850 GeV/ c^2 are excluded for $k/\overline{M}_{Pl} = 0.05$. Fig. 8 shows the results for ADPS model, excluding graviton masses smaller than 720 GeV/ c^2 , for $k/\overline{M}_{Pl} = 0.1$, and smaller than 610 GeV/ c^2 , for $k/\overline{M}_{Pl} = 0.05$.

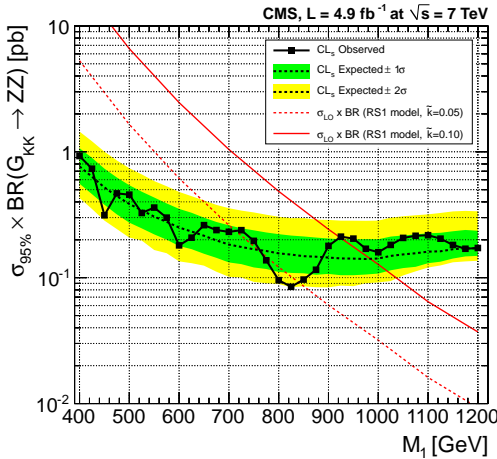


Figure 7. Observed and expected 95% CL upper limits on $\sigma \times \text{BR}(G_{KK} \rightarrow ZZ)$. The graviton signal was generated according to the RS1 model.

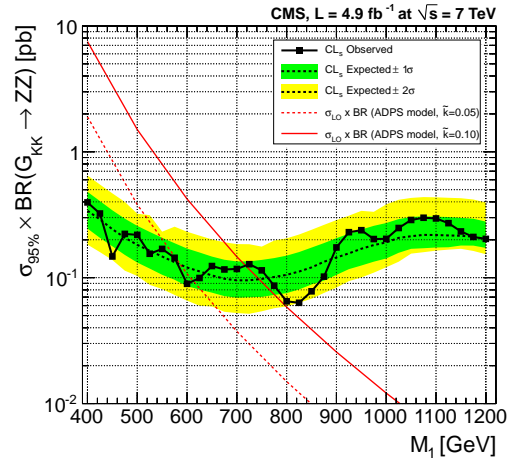


Figure 8. Observed and expected 95% CL upper limits on $\sigma \times \text{BR}(G_{KK} \rightarrow ZZ)$. The graviton signal was generated according to the ADPS model.

4. WZ/ZZ \rightarrow 2 ℓ or 2 ν + j

A search for heavy resonances decaying to WZ and ZZ states is performed, where the Z boson is allowed to decay to leptons ($Z \rightarrow \ell^+ \ell^-$, $\ell = e, \mu$) or neutrinos ($Z \rightarrow \nu \bar{\nu}$) and the second

boson decay to hadrons, $V \rightarrow q\bar{q}$. For heavy resonances, its decay produces a highly boosted system, and each the two quarks from the V are emitted very close to each other, producing overlapping jets reconstructed as a single jet with mass close to the V mass, a topology different from the typical quark or gluon jet. This feature is exploited, for resonances heavier than 700 GeV/c^2 , complementing the analysis for lower masses in the $ZZ \rightarrow 2\ell j j$ channel. The main SM backgrounds are from Z +jets, $t\bar{t}$ +jets, W +jets, and di-boson production.

For the leptonic channel, candidate events are required to have two reconstructed leptons within detector acceptance and $p_T > 45 \text{ GeV}/c$, and one anti- k_T $R = 0.7$ jet with $p_T > 30 \text{ GeV}/c$ and $|\eta| < 2.4$. Z candidates are reconstructed with invariant mass of leptons in the range $70 < M_Z < 110 \text{ GeV}/c^2$ and with $p_T > 150 \text{ GeV}$, and V candidates have mass in the range $65 < M_j < 120 \text{ GeV}/c^2$ and $p_T > 250 \text{ GeV}/c$. The background is determined from data, using the sideband of the V mass, and the signal is generated with PYTHIA 6.4.24. Fig. 9 shows the distribution of the M_{VZ} for the electron channel.

For the MET channel, events are required to have one anti- k_T $R = 0.7$ jet with $p_T > 300 \text{ GeV}/c$ and $|\eta| < 2.4$, and MET larger than 300 GeV . Events are rejected if they have isolated leptons or more than two jets with $p_T > 30 \text{ GeV}$. The background is determined from data, using the ABCD method in the variables of the mass of the jet and the transverse mass of the jet-MET system. A correction factor ρ is introduced to account for the correlation between the jet mass and the jet-MET transverse mass. Signal events are generated with PYTHIA 6.4.24, as well as SM background events for cross-check purposes. Fig. 10 shows the distribution of the jet-MET transverse mass for the simulated backgrounds and data in the search region.

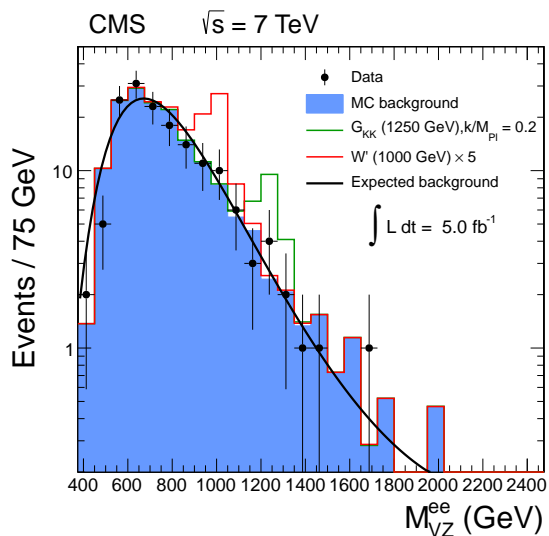


Figure 9. The comparison of the estimated background with the total MC background and the data for M_{VZ} distributions for the electron channel.

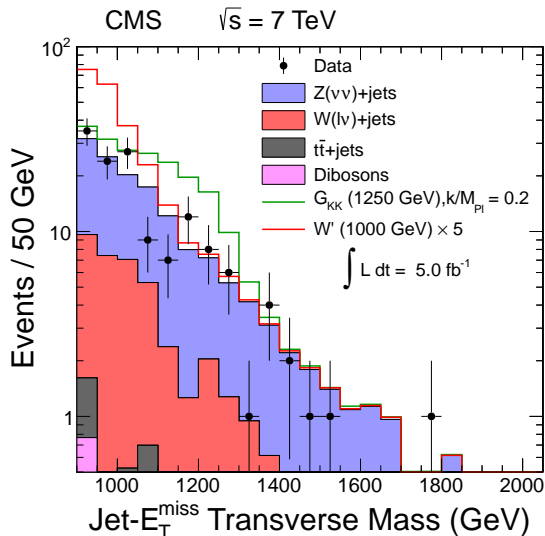


Figure 10. Comparison between ρ -corrected simulated backgrounds and data in the search region for jet-MET transverse mass distribution.

No significant excess is observed over the expected background. The CL_S statistical method is employed to search for exotic VZ resonances. 95% CL exclusion limits on the combined products of the cross section times the branching ratio $\sigma(pp \rightarrow W') \times \mathcal{B}(W' \rightarrow WZ)$ and $\sigma(pp \rightarrow G_{KK}) \times \mathcal{B}(G_{KK} \rightarrow ZZ)$ for the three final states are set, as a function of the mass of the hypothetical resonance. In the Randall-Sundrum model, graviton resonances with masses between 750 – 880 (800) GeV/c^2 at NLO (LO) are excluded for $k/\overline{M}_{Pl} = 0.05$, as seen in Fig. 11. SSM W' masses are excluded between 700 – 940 (890) GeV/c^2 at NNLO (LO), as seen in Fig. 12.

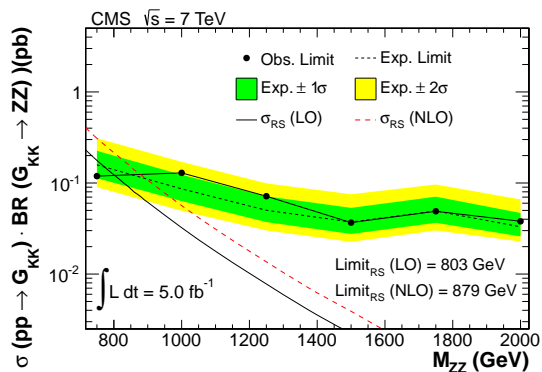


Figure 11. Observed and expected 95% CL upper cross section limits and comparison with the theoretical predictions in RS graviton model with $k/\overline{M}_{Pl} = 0.05$ for the combination of electron, muon, and MET channels.

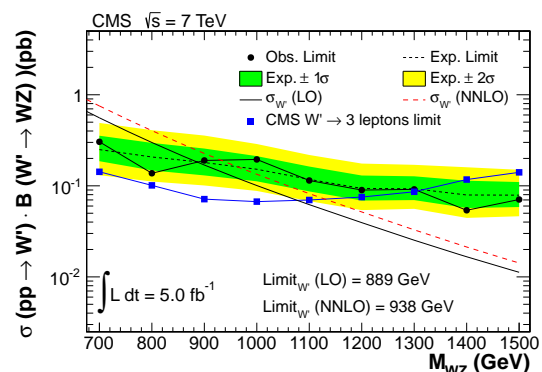


Figure 12. Observed and expected 95% CL upper cross section limits and comparison with the theoretical predictions in W' model for the combination of electron, muon, and MET channels.

5. $WW/WZ/ZZ \rightarrow jj$

A search focused on models predicting new heavy particles with a pair of vector bosons as decay products is performed, with the two bosons each decaying to a single merged jet. The background is substantially suppressed by identifying subjets which correspond to the original daughter jets that have merged, using recent developments in the area of jet substructure. The subjets are used to explicitly reconstruct the W or Z boson. A massive jet which is a candidate to be a W or a Z is called W/Z -tagged.

Jets are reconstructed in the events using two algorithms: anti- k_T with $R = 0.5$ and Cambridge-Aachen (CA) [16] with $R = 0.8$. Candidate events must have at least two anti- k_T jets with $p_T > 30$ GeV/ c and $|\eta| < 2.5$, and the two leading p_T jets are required to have $|\Delta\eta| < 1.3$ and $M_{jj} > 890$ GeV/ c^2 . For the W/Z -tag, the jets reconstructed with CA are pruned, in a process where soft and wide-angle particles (relative to the parent in the cluster) are ignored, and events are selected if the number of subjets $N_{sub} = 2$, the pruned jet mass M_{jet} in the range 70 – 100 GeV/ c^2 and the mass drop $M_1/M_{jet} < 0.25$, where M_1 is the mass of the hardest subjet. The discrimination power of the mass of the pruned jet selection is shown in Fig. 13.

The QCD background shape is modeled in the dijet spectrum using a simple parametrization which has been successfully deployed in previous searches in the dijet mass spectrum. In the limit setting, the background fit parameters used are obtained by best signal plus background fit to the data points for each signal hypothesis. The signal shapes are simulated with PYTHIA 6.4.24 and HERWIG++ [14]. The double W/Z -tagged M_{jj} distribution in data fitted with the background parametrization is shown in Fig. 14, along with the signal shape distribution for RS graviton decaying to WW with arbitrary cross sections.

There is no significant evidence for new particle production in the W/Z -tagged dijet spectrum. 95% CL upper limits on the cross section for double W/Z -tagged dijet events are set, as shown in Fig. 15, for WW resonances, and Fig. 16, for WZ resonances. The sensitivity of the measurement with the present dataset is not sufficient to extract meaningful mass limits on the RS graviton with $k/\overline{M}_{Pl} = 0.1$ and SSM W' , but the cross section limits are the most stringent in this final state to date.

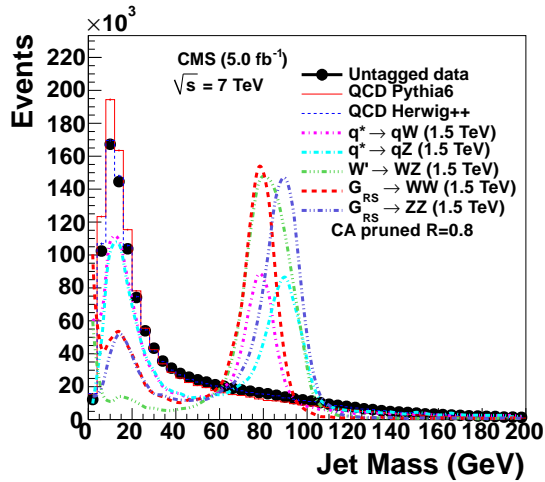


Figure 13. Pruned jet mass in data, signal and background simulations. All simulated distributions have been scaled to match the number of data events.

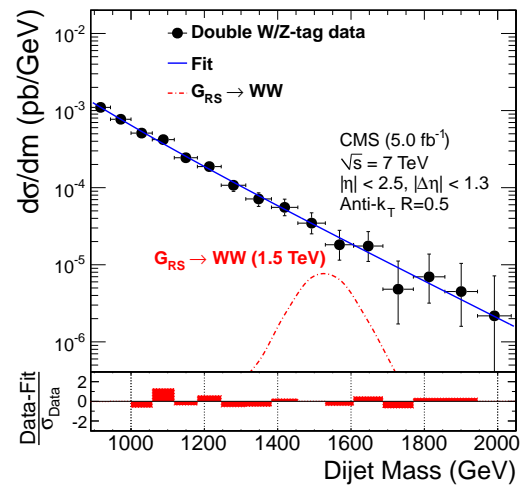


Figure 14. The double W/Z-tagged M_{jj} distributions in data fitted with the QCD background parametrization. Bottom pane: the corresponding pull distributions.

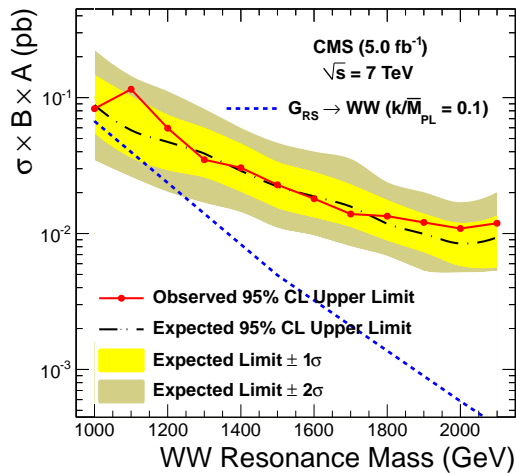


Figure 15. Expected and observed limits for WW resonances. The predicted cross sections as a function of resonance mass for the considered benchmark model is overlaid.

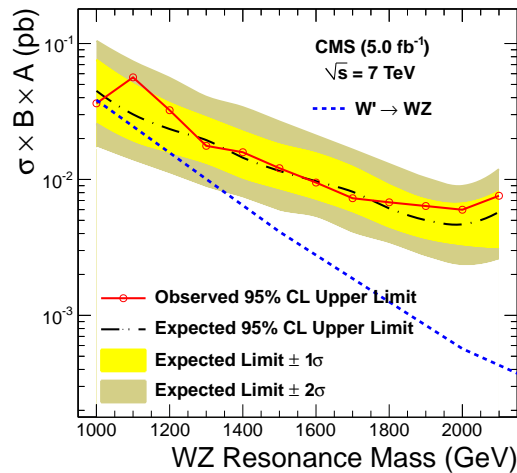


Figure 16. Expected and observed limits for WZ resonances. The predicted cross sections as a function of resonance mass for the considered benchmark model is overlaid.

6. Summary

The results of searches for new resonances decaying to a pair of massive vector bosons (WW, WZ, ZZ) were presented. All analyses used datasets of proton-proton collisions at $\sqrt{s} = 7$ TeV of center of mass energy, corresponding to 5.0 fb^{-1} of integrated luminosity collected by the Compact Muon Solenoid experiment at the Large Hadron Collider in 2011. The analyzed final states were $WZ \rightarrow 3\ell + \text{MET}$, $ZZ \rightarrow 2\ell jj$, $WZ/ZZ \rightarrow 2\ell/2\nu + j$ and $WW/WZ/ZZ \rightarrow jj$. No significant excesses compared to the standard model background expectation were observed, and upper limits at 95% confidence level were set on the production cross section times the branching

fraction of hypothetical particles decaying to a pair of vector bosons. The results were interpreted in the light of several benchmark models, such as the Randall-Sundrum gravitons, the Sequential Standard Model W' , and Technicolor. Graviton resonances in the Randall-Sundrum model were excluded for masses smaller than $938 \text{ GeV}/c^2$, for coupling parameter $k/\overline{M}_{Pl} = 0.05$. For ADPS bulk Randall-Sundrum gravitons, masses smaller than $610 \text{ GeV}/c^2$ were excluded, for $k/\overline{M}_{Pl} = 0.05$, and smaller than $720 \text{ GeV}/c^2$, for $k/\overline{M}_{Pl} = 0.1$. Sequential Standard Model W' with masses smaller than $1143 \text{ GeV}/c^2$ were excluded, as well as ρ_{TC} in the $167 - 687 \text{ GeV}/c^2$ mass range, in Low Scale Technicolor models with $M(\pi_{TC}) = 3/4 M(\rho_{TC}) - 25 \text{ GeV}/c^2$. The most stringent upper limits to date on the cross section of double W/Z-tagged dijet events were set.

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