Search for heavy resonances in the W/Z-tagged dijet mass spectrum in pp collisions at 7 TeV

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Search for heavy resonances in the W/Z-tagged dijet mass spectrum in pp collisions at 7 TeV

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ABSTRACT

A search has been made for massive resonances decaying into a quark and a vector boson, qW or qZ, or a pair of vector bosons, WW, WZ, or ZZ, where each vector boson decays to hadronic final states. This search is based on a data sample corresponding to an integrated luminosity of 5.0 fb^{-1} of proton–proton collisions collected in the CMS experiment at the LHC in 2011 at a center-of-mass energy of 7 TeV. For sufficiently heavy resonances the decay products of each vector boson are merged into a single jet, and the event effectively has a dijet topology. The background from QCD dijet events is reduced using recently developed techniques that resolve jet substructure. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV) and upper limits are set on the cross section for resonances decaying to qW, qZ, WW, WZ, or ZZ final states.

1. Introduction

New resonances that decay preferentially into hadronic final states are of particular interest in a variety of scenarios for physics beyond the standard model (SM) [1–9]. Searches for events having a pair of hadronic jets with large invariant mass have been performed by the Compact Muon Solenoid (CMS) and ATLAS experiments at the Large Hadron Collider (LHC) [10,11]. In principle, these searches are also sensitive to final states that include one or two massive vector bosons W/Z because the vector bosons have large hadronic branching fractions and because their masses are much smaller than those of the hypothetical parent states, i.e. they are highly “boosted”. This implies that the pairs of quark jets produced by the vector boson decays merge into single W/Z-jets in a real detector. Due to the large hadronic branching fractions of the vector bosons, at the highest accessible resonance masses, a search in the fully hadronic final state can be more sensitive than searches in leptonic channels. The sensitivity of the present large mass dijet searches is limited by the presence of background from ordinary strong interaction processes that produce pairs of quark and gluon jets.

The analysis presented here exploits the enhancement of the sensitivity of a standard dijet analysis for processes that produce W/Z-jets in the final state by the application of techniques that can identify W/Z-jets and suppress quark and gluon jets (“W/Z-tagging”). This CMS study is performed on pp collision data at a center-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 5.0 fb^{-1}. We consider events with two high-transverse-momentum jets in the final state. We identify “subjets” inside jets using recent developments in the area of jet substructure [12]. Pairs of subjets are used to explicitly reconstruct W or Z bosons, therefore substantially suppressing backgrounds from quantum chromodynamics (QCD) interactions. This search follows closely the procedures of the corresponding dijet search [10], performed in the same dataset, but with strongly reduced QCD background because of the W/Z-tagging.

We consider three benchmark scenarios that would produce singly or doubly tagged events: an excited quark q^* [4] decaying into a quark and a W or Z boson; a Randall–Sundrum (RS) graviton G_{RS} [13] decaying to WW or ZZ; and a heavy partner of the SM W boson W′ which decays to WZ [8]. The most stringent limits on the q^* model have been set in dijet resonance searches at the LHC by considering the qg final state [10] or inclusively all-hadronic final states [11]. The most stringent lower limit (at 95% CL) on the q^* mass to date is 3.3 TeV [10]. Specific searches for the qW and qZ final states have previously been reported at the Tevatron [14,15], which exclude resonances decaying to qW or qZ with masses up to 540 GeV, and at the LHC [16], which extends the mass exclusion of qZ resonances up to 1.94 TeV. For the G_{RS}, there are phenomenological models favoring the decay of the G_{RS} into vector bosons rather than photons or fermions [17–19]. In particular, the ZZ final state has been explored experimentally [20–22],

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setting lower limits on the G_{RS} mass as a function of the coupling parameter $k/\overline{M}_{Pl}$, where k is the curvature of the warped space and $\overline{M}_{Pl}$ the reduced Planck mass ($\overline{M}_{Pl} \equiv M_{Pl}/\sqrt{8\pi}$). For the W′, the most stringent limits are reported in searches with leptonic final states [23,24], and the current lower limit on the W′ mass is 2.5 TeV. The limit varies by 0.1 TeV, depending on the chirality of the W′ couplings. Specific searches in the WZ final state have also been reported [25,26] setting a lower limit of 1.1 TeV.

This Letter is organized as follows. First, the CMS detector, and the simulated and collision data samples on which the analysis is based are briefly described. Then the event reconstruction, and selection are detailed, and the W/Z-tagging technique is described. The following section describes the modeling of detector acceptances and signal efficiencies as well as the validation of the W/Z-tagging techniques with data. After this follows the description of the modeling of the background, the systematic uncertainties and the limit setting procedure. Finally the results and conclusions are presented.

2. CMS detector

The CMS detector [27] is well suited to the reconstruction of hadronic jets because it incorporates finely segmented electromagnetic and hadronic calorimeters, and a charged-particle tracking system. Charged particles are reconstructed in the inner tracker, which is immersed in a 3.8 T axial magnetic field. The inner tracker consists of three cylindrical layers and two endcap disks at each end of silicon pixel detectors, and ten barrel layers and twelve endcap disks at each end of silicon strip detectors. This arrangement results in full azimuthal coverage ($0 \leqslant \phi \leqslant 2\pi$) within $|\eta| < 2.5$, where η is the pseudorapidity defined as $\eta = -\ln[\tan(\theta/2)]$. CMS uses a polar coordinate system, with the z axis coinciding with the beam axis; θ is the polar angle defined with respect to the positive z axis. Muons are measured in gas-ionizing detectors embedded in the steel return yoke. A lead-tungstate crystal electromagnetic calorimeter (ECAL) up to $|\eta| = 3$ and a brass/scintillator hadronic calorimeter (HCAL) up to $|\eta| = 5$ surround the tracking volume and allow photon, electron, and jet reconstruction. The ECAL and HCAL cells are grouped into towers projecting radially outward from the interaction region. In the central region ($|\eta| < 1.74$) the towers have dimensions $\Delta\eta = \Delta\phi = 0.087$; at higher $|\eta|$, the $\Delta\eta$ and $\Delta\phi$ widths increase. For optimum jet reconstruction, the tracking and calorimeter information is combined in an algorithm called particle flow [28], which is described below.

3. Simulated and collision data samples

The sample of proton–proton collision data at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1}, was collected in 2011. The events were collected using the logical "or" of a set of triggers based on requirements on $H_T = \sum_{\text{jets}} p_T$ (p_T is the transverse momentum of a jet) and the invariant mass of the two highest p_T jets in an event, whose thresholds were raised progressively to cope with an increase in the peak luminosity during 2011.

Data are compared to Monte Carlo (MC) simulations of the QCD background generated using both PYTHIA 6.424 [29] and HERWIG++ 2.4.2 [30]. PYTHIA 6 is used with CTEQ61L [31] and HERWIG++ with MRST2001 [32] parton distribution functions. Tune Z2 (identical to tune Z1 [33] except that Z2 uses the CTEQ6L PDF while Z1 uses CTEQ5L) is used with PYTHIA 6, while the tune version 23 [30] is used with HERWIG++. In this analysis, the background shape is modeled from the data themselves. Therefore, the analysis depends on QCD simulation only to provide guidance and cross checks.

The sensitivity of the event selection to the benchmark processes is evaluated using simulated samples of events from excited quarks, RS gravitons, and W′ production and decay models. The process $qg \to q^* \to W/Z + \text{jet}$ is generated using PYTHIA 6 assuming the couplings to the SU(2), U(1) and SU(3) groups are $f = f' = f_s = 1$ for the production and decay of the q*. The process $G_{RS} \to WW/ZZ$ is generated using HERWIG++ and its cross section is taken from PYTHIA 6. While HERWIG++ contains a more detailed description of the angular distributions than PYTHIA 6 for this process [34], the cross section is taken from PYTHIA 6 which has been used as a reference model in related analyses [20]. RS graviton production is studied with $k/\overline{M}_{Pl} = 0.1$, which determines a resonance width of about 1% of the resonance mass which is about a factor 5 smaller than the experimental resolution for dijets. This width is much smaller than suggested by the model in Ref. [17], which predicts resonance widths of the order of the experimental resolution, allowing for interpretation in this model only approximately. The process $W' \to WZ$ is generated using PYTHIA 6 with Standard Model $V-A$ couplings and without applying k-factors. All Monte Carlo events are passed through the CMS detector simulation based on GEANT4 [35].

4. Event reconstruction and selection

Events are reconstructed using the particle flow algorithm, which attempts to identify and measure all the stable particles in a collision by combining information from all the subdetectors. This algorithm categorizes all particles into five types: muons, electrons, photons, charged and neutral hadrons. The resulting particle flow candidates are passed to the anti-k_T [36] and Cambridge–Aachen (CA) [37,38] jet clustering algorithms, as implemented in FASTJET [39,40] to create jets. A distance parameter of size $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.8$ is used for the CA algorithm, while $R = 0.5$ is used for the anti-k_T algorithm. While the anti-k_T jets are used to select events and reconstruct the dijet invariant mass m_{jj}, the CA jets are used to identify events containing hadronically decaying W or Z bosons. This choice has been made because the CA algorithm was found to be more efficient (for the same mistag rate) at finding hard subjets within the jets in simulation-based studies [12], while the anti-k_T jets have the best energy calibration.

Events must have at least one reconstructed vertex within $|z| < 15$ cm, to suppress backgrounds solely triggered by calorimeter noise. The primary vertex is defined as the vertex with highest sum of squared track transverse momenta (p_T^2). Charged particles not originating from it are removed from the inputs to the jet clustering algorithms. This requirement removes particles which arise from additional pp interactions in the same pp bunch crossing (pileup interactions). An event-by-event jet-area-based correction [41–43] is applied to remove the remaining pileup energy which is due to neutral particles originating from the other vertices. The pileup-subtracted jet four momenta are finally corrected to account for the difference between the measured and true responses to hadrons [43]. When jets are decomposed into subjets, as described later, the energy estimate relies on the calibrated reconstructed input particles without further corrections.

Events are initially selected by requiring that they have at least two anti-k_T jets with $p_T > 30$ GeV and $|\eta| < 2.5$. The two highest-p_T jets are required to have a pseudorapidity separation $|\Delta\eta| < 1.3$ to reduce the QCD dijet background [44]. Finally, the dijet invariant mass is required to be larger than 890 GeV. This threshold is defined by the triggers, which were found to be 99% efficient for dijet events with masses above this threshold.

In events passing this selection, "boosted" (high p_T) hadronically decaying W or Z bosons are identified with a W/Z-tagging algorithm using jet pruning [45], a technique which removes the softest components of the jets. In the jet pruning technique [46,47], a jet is reclustered using all the particles used to build

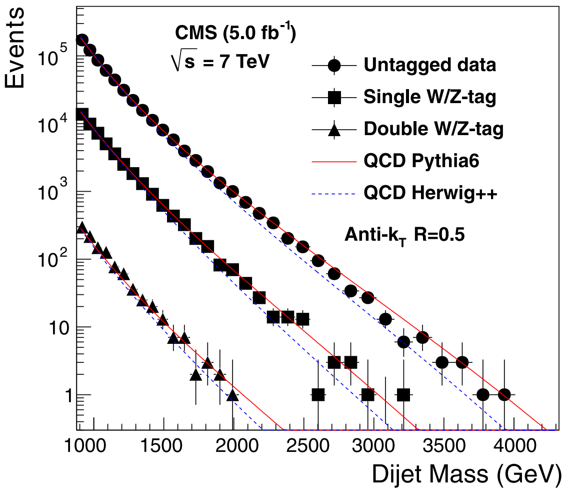

Fig. 1. Comparisons of the dijet invariant mass distributions between data and Monte Carlo (PYTHIA 6 and HERWIG++) simulations. The three sets of lines correspond to the inclusive dijet category (no W/Z-tag required), single W/Z-tagged, and double W/Z-tagged events. The simulations are normalized to the number of data events in each category.

a CA jet, ignoring in each recombination step the softer "protojet" if the recombination is softer than a given threshold $z_{\mathrm{cut}} = 0.1$ or forms an angle ΔR wider than $D_{\mathrm{cut}} = 0.5 m^{\mathrm{orig}}/p_{\mathrm{T}}^{\mathrm{orig}}$ with respect to the previous recombination step, where m^{orig} and $p_{\mathrm{T}}^{\mathrm{orig}}$ are the mass and transverse momentum of the original CA jet. The hardness of a recombination z is defined as $z = \min(p_{\mathrm{T}}^{i}, p_{\mathrm{T}}^{j})/p_{\mathrm{T}}^{p}$, where p_{T}^{i} and p_{T}^{j} are the p_{T} of the two protojets to be combined and p_{T}^{p} is the p_{T} of the combined jet. The following selection is then applied to the pruned jets to identify jets from hadronic W/Z decays by exploiting the variables used in Ref. [48]. The total pruned jet mass m_{jet} must satisfy 70 GeV $< m_{\mathrm{jet}} <$ 100 GeV. Two subjets are obtained by undoing the last clustering iteration of the pruned jet clustering. The ratio of masses of the highest mass subjet (m_1) and the total pruned jet mass is defined as the *mass drop* $\frac{m_1}{m_{\mathrm{jet}}}$. To discriminate against QCD jets, the mass drop is required to satisfy $\frac{m_1}{m_{\mathrm{jet}}} < 0.25$. These criteria are designed to select W and Z candidates in which the subjets are similar in energy and mass.

Comparisons of the dijet invariant mass distributions for untagged, single-tagged, and double-tagged event samples are shown in Fig. 1. The data are shown as solid points and the PYTHIA 6 and HERWIG++ simulations are shown as solid red and dashed blue curves, respectively. The simulations are normalized to the number of data events in each category and the shapes are compared; the agreement of the normalization driven by the W/Z-tagging efficiency is discussed in the next section. The PYTHIA 6 prediction is found to agree with the data while the HERWIG++ prediction decreases more steeply with mass. However, no systematic uncertainties are taken into account and only the dominant background from QCD interactions is considered.

5. Signal characterization

A search for dijet resonances corresponding to several benchmark physics models is performed. Using the W/Z-tagging algorithm, both single W/Z-tag and double W/Z-tag events are examined. The signals that would be produced by the benchmark physics models have different characteristics that are described below.

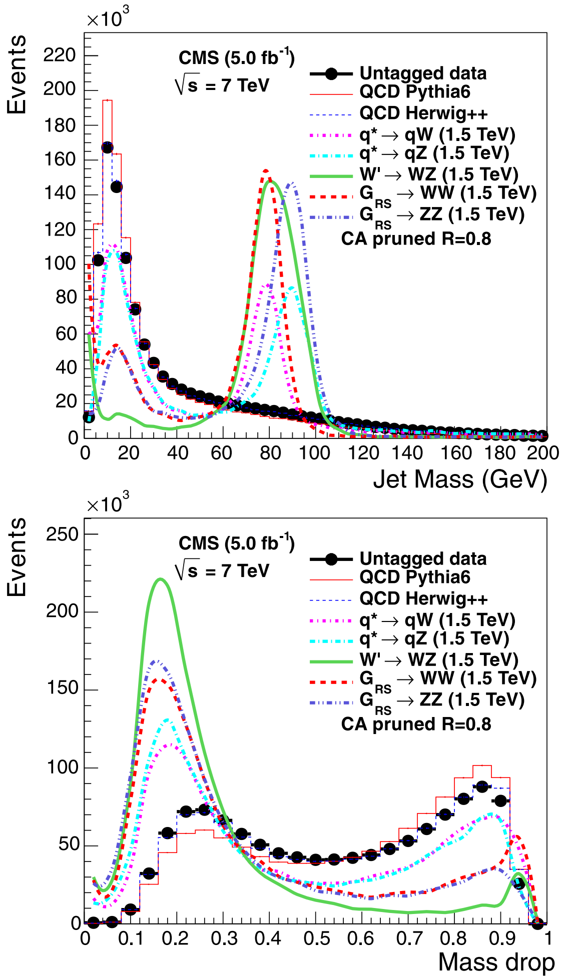

Fig. 2. Pruned jet mass (top) and mass drop (bottom) in data, signal and background simulations. The signal simulation distributions are plotted as smooth curves connecting the histogram entries (using the same binning as the data distribution). All simulation distributions have been scaled to match the number of data events.

The pruned jet mass and mass drop distributions in data, signal, and background simulations are shown in Fig. 2. The discriminating power of the pruned jet mass and mass drop for the different signals is evident. In both the pruned jet mass and the mass drop distributions, small differences may be seen between the results obtained with HERWIG++ (WW, ZZ) and PYTHIA 6 (WZ, qW, qZ), which arise from differences in the showering and hadronization models used by these generators. This effect is taken into account in the estimate of the systematic uncertainties on the tagging efficiency, as described below.

The acceptance, defined as the product of signal branching fraction into dijet final states B(W/Z → jets) times angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$), is shown in Fig. 3. Each model relevant for the singly (doubly) tagged data analysis is shown in the dijet invariant mass range up to 2 TeV (3 TeV). The fraction of events that produce dijet events, which have survived the kinematic selection, is between 26% and 47%. This fraction includes also the branching fraction of W/Z decaying into objects which are reconstructed as jets. The different behavior of the acceptance for W′ and G_{RS} at low dijet masses is due to different angular distributions generated by PYTHIA 6 and HERWIG++.

The W/Z-tagging efficiency, which is not part of the acceptance, is shown for signal and background events in Fig. 4. The signal efficiency, determined from the simulation, is found to be between 20% and 45% (8% and 22%) for single (double) W/Z-tagged signals. The W-tagging efficiency is larger than the Z-tagging efficiency due to the choice of the jet mass window cut, which rejects a larger

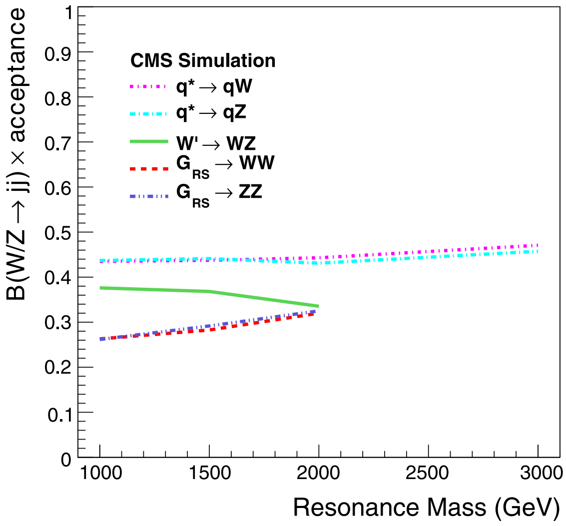

Fig. 3. The branching fraction into dijet final states $B(W/Z \rightarrow \text{jets})$ times angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$). The W/Z-tagging efficiencies are excluded from the acceptance.

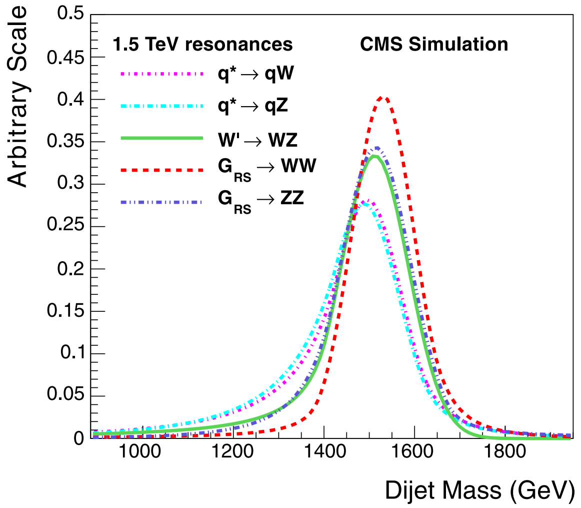

Fig. 5. The signal dijet invariant mass distributions for 1.5 TeV $G_{RS} \rightarrow WW$, $G_{RS} \rightarrow ZZ$, $W' \rightarrow WZ$, $q^* \rightarrow qW$, and $q^* \rightarrow qZ$ resonances, computed using anti-k_T jets with $R = 0.5$. Crystal-Ball functions fit to the simulated distributions are shown. The distributions in the plot are scaled to the same integral.

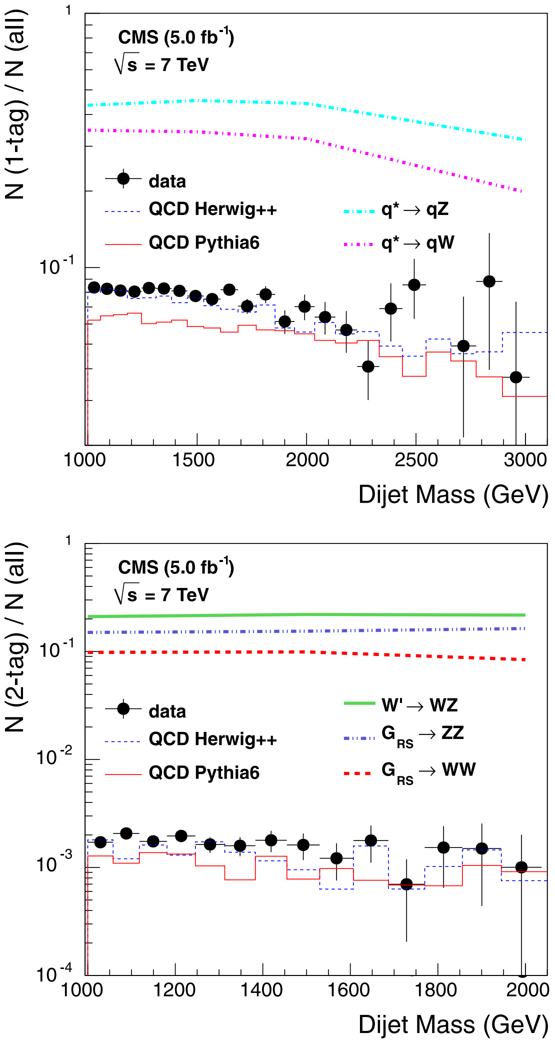

Fig. 4. Efficiency of requiring 1 W/Z-tag (top) and 2 W/Z-tags (bottom) in signal and background simulations, and in data for events passing the angular acceptance requirement ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$).

fraction of W bosons by requiring $m_{\text{jet}} > 70$ GeV. The simulation modeling of the signal efficiency is cross-checked by measuring the W/Z-tagging efficiency in semileptonic $t\bar{t}$ data and by comparing it with the same efficiency obtained using the same procedure for $t\bar{t}$ simulation generated with MADGRAPH 4.4.12 [49] and showered with PYTHIA 6. We follow the same procedure as described in Ref. [50]. The ratio of the two efficiencies results in a scale factor of 0.98 ± 0.03 which is then applied to the efficiencies for signals in the dijet data. The uncertainties on the scale factor are propagated into the systematic uncertainties on the overall signal efficiency.

As described above, the production and decay of the G_{RS} is modeled with HERWIG++. A difference of up to 18% on the double-tag efficiency in the RS graviton WW/ZZ signal simulations between PYTHIA 6 and HERWIG++ is observed. The difference can be attributed in equal parts to the different showering algorithms and the hadronization algorithms. The different underlying event modeling has only a small impact of <1%. This discrepancy is accounted for as a systematic uncertainty on the double-tag efficiency. For the single-tag efficiency a 9% uncertainty is assigned based on the double-tag efficiency uncertainty of 18% assuming an identical difference in tagging efficiency for the two vector bosons in the case of 100% efficiency, representing an upper limit on this uncertainty.

The effect of pileup on the W/Z-tagging efficiency was also checked. Because of the rejection of charged particles not originating from the primary vertex and the application of pruning, the pileup dependence is weak and the uncertainty of the modeling of the pileup distribution is less than 2%.

The dijet mass dependence of the W/Z-tagging efficiency for background events shown in Fig. 4 is adequately described by the simulation. Therefore, no additional systematic uncertainty is assigned on the dijet mass dependence of the modeling of the W/Z-tagging in simulation.

Fig. 5 shows the signal shapes for $G_{RS} \rightarrow ZZ/WW$, $W' \rightarrow WZ$, and $q^* \rightarrow qW/qZ$, all of which correspond to a resonance mass of 1.5 TeV. The differences for the different models are to a large extent due to the different tagging efficiencies for W and Z and to a smaller extent to differences in the models in PYTHIA 6 and HERWIG++. The lower cut of 70 GeV on the jet mass in the W/Z-tag biases the resonance peak for WW, WZ and qW towards higher masses, especially when two tags are applied on the WW sample.

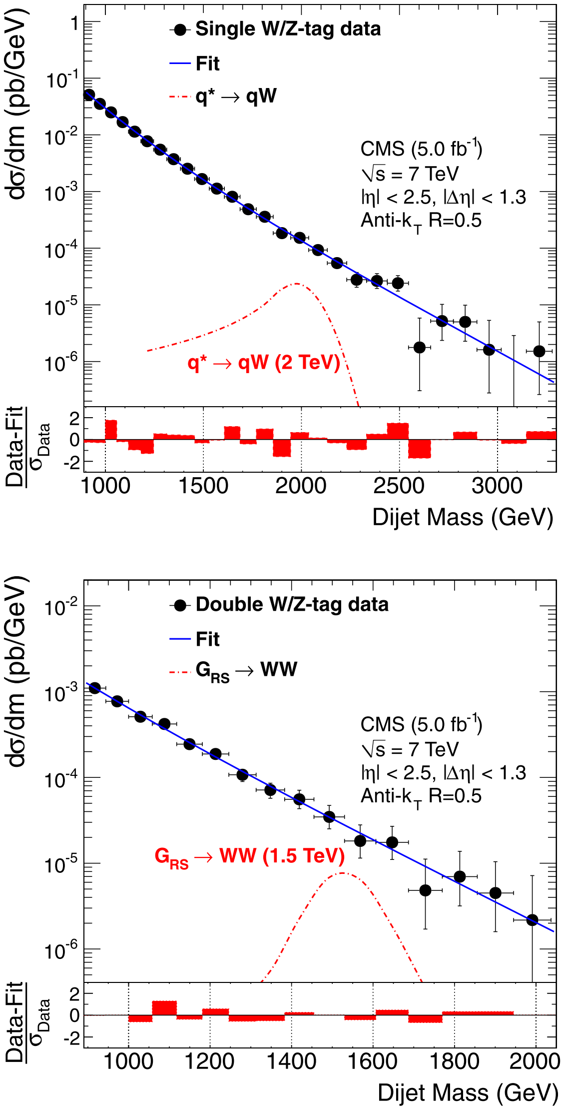

Fig. 6. The single (top) and double (bottom) W/Z-tagged m_{jj} distributions (points) in data fitted with the QCD background parametrization (solid curve). For the double W/Z-tagged distribution $P_3 = 0$ is assumed in Eq. (1). Signal shape distributions for $q^* \to qW$ and $G_{RS} \to WW$ with arbitrary cross sections are also shown. The bottom panes show the corresponding pull distributions ($\frac{\text{Data}-\text{Fit}}{\sigma_{\text{Data}}}$). There are no data events with dijet masses larger than the range of these plots.

We have checked that this behavior is reproduced in both PYTHIA 6 and HERWIG++. The difference in resolution between the singly tagged and doubly tagged resonance shapes is also due to this bias of the extra W/Z-tag requirement. Resonance shapes were simulated at masses of 1, 1.5, 2 and 3 TeV and a linear interpolation was used to obtain the shapes at intermediate masses.

6. Background shape parametrization

The shape of the QCD background in the dijet spectrum is modeled using a simple parametrization which has been successfully deployed in previous searches [51]. The background model is given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}, \tag{1}$$

where m denotes the dijet mass and $\sqrt{s}$ the pp center of mass energy. P_0 acts as a normalization parameter for the probability density function, and P_1, P_2, P_3 describe its shape. For the single W/Z-tagged analysis, all parameters are free to float in the fit. For the double W/Z-tagged analysis, P_3 is not needed as suggested by a Fisher F-test [52] and a simpler parametrization with P_3 fixed to 0 is used.

Fig. 6 shows the dijet mass spectra from single and double W/Z-tagged data fitted to Eq. (1) and the corresponding pull distributions, demonstrating the agreement between the background-only probability density function and the data.

Since no sizable deviation from the background-only hypothesis is seen, exclusion limits are set on the product of cross section, acceptance, and branching fraction for the five considered final states: qW, qZ, WW, WZ, and ZZ.

7. Systematic uncertainties

The sources of systematic uncertainties are summarized as follows. The only background-related systematic uncertainty is the choice of background parametrization which is discussed in Section 8. The leading signal-related systematic uncertainties are the W/Z-tagging efficiency (Section 5), jet energy scale (JES), jet energy resolution (JER), and luminosity measurement. Because the trigger and reconstruction efficiencies are larger than 99% in the relevant dijet mass range, the uncertainties associated with these efficiencies are negligible.

In the jet p_T- and η-regions considered in this analysis, the JES has an uncertainty of 2–3% [43]. The p_T- and η-dependent uncertainty is propagated to an uncertainty on the reconstructed dijet invariant mass of 2.2%, which is approximately mass independent. The effect of the JES uncertainty on the calculation of the limits is estimated by varying the resonance dijet mass in the statistical analysis. The JER is known to a precision of 10% and its tails are in agreement between data and simulation [43]. The effect of the JER uncertainty on the calculation of the limits is estimated by varying the reconstructed resonance width in the statistical analysis. The luminosity has an uncertainty of 2.2% [53], which is also taken into account in the statistical analysis.

8. Limit setting procedure

For setting upper limits on the resonance production cross section a Bayesian formalism with uniform prior for the cross section is used, following the procedure used in Ref. [51]. The binned likelihood, L, can be written as:

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}, \tag{2}$$

where

$$\mu_i = \alpha N_i(S) + N_i(B), \tag{3}$$

n_i is the observed number of events in the ith dijet mass bin, $N_i(S)$ is the expected number of events from the signal in the ith dijet mass bin, α scales the signal amplitude, and $N_i(B)$ is the expected number of events from background in the ith dijet mass bin. The background $N_i(B)$ is estimated as the background component of the best 5(4)-parameter fit of Eq. (3) to the singly (doubly) tagged data points. The signal is not restricted to be positive for the background estimate fit although it is restricted in the Bayesian prior for the signal. A flat prior in α, which is the same as a flat prior in the resonance production cross section, is assumed.

The dominant sources of systematic uncertainty (the jet energy scale, the jet energy resolution, the integrated luminosity, and the W/Z-tagging efficiency) are considered as nuisance parameters associated to log-normal priors. The uncertainty on the background

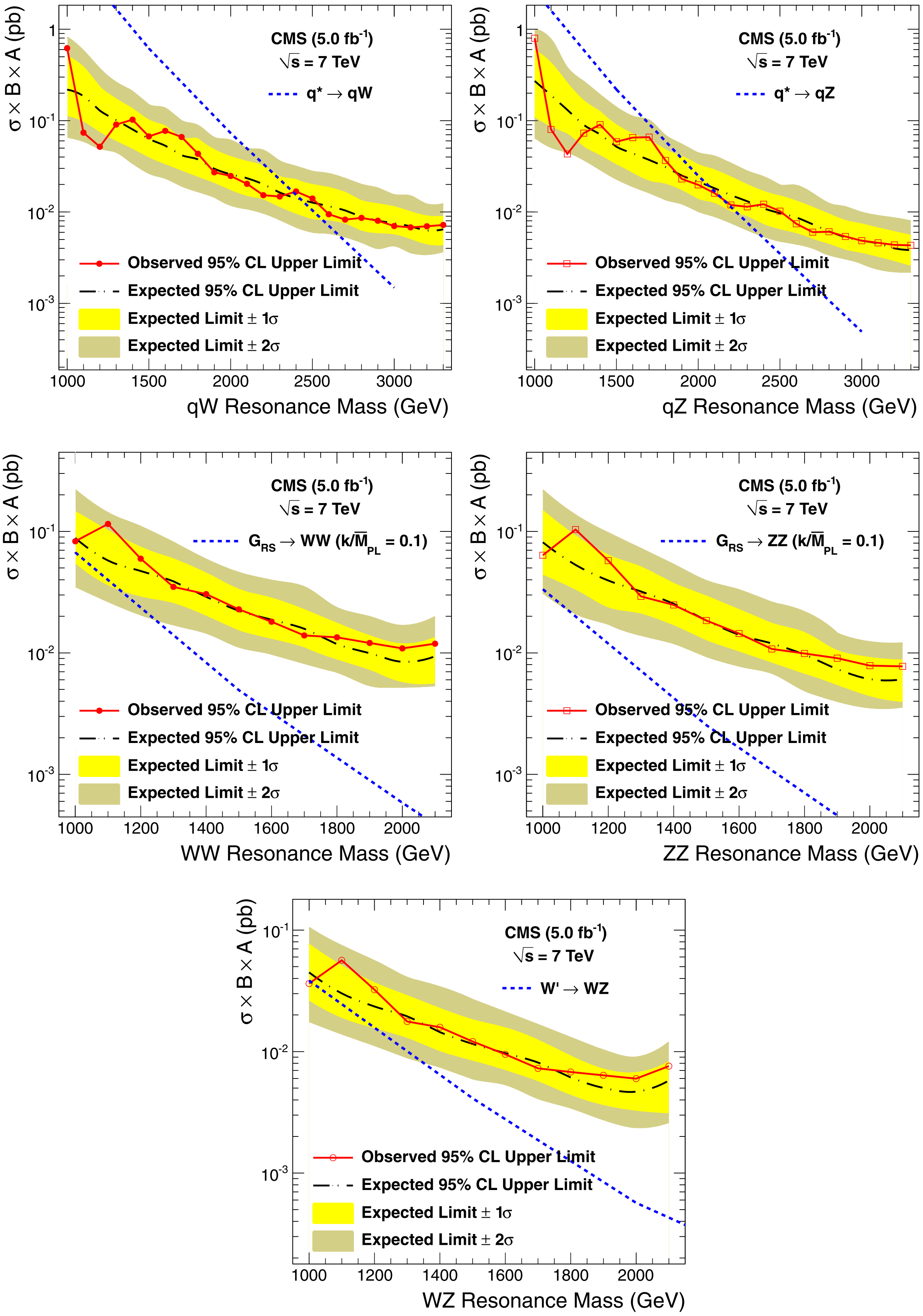

Fig. 7. Expected and observed limits for qW (top-left), qZ (top-right), WW (center-left), ZZ (center-right) and WZ (bottom) resonances. Here, B × A in the vertical axis label contains the branching fraction of $G_{\mathrm{RS}} \to \mathrm{WW/ZZ} \to 2$ jets or $\mathrm{q}^* \to \mathrm{qW/qZ} \to 2$ jets, as well as the acceptance for reconstructing the jets in $|\eta| < 2.5$, $|\Delta\eta| < 1.3$. The predicted cross sections as a function of resonance mass for the considered benchmark models are overlaid.

shape is taken into account with nuisance parameters associated to Gaussian priors representing variations of the fit parameters along the eigenvectors of their correlation matrix. The systematic uncertainties are accounted for using a fully Bayesian treatment and integrating the likelihood over nuisance parameters.

The 95% confidence level (CL) upper limit σ_S is calculated from the normalized posterior probability density P_{post} as follows:

$$\int_0^{\sigma_S} P_{\text{post}}(\sigma)\,\mathrm{d}\sigma = 0.95. \qquad (4)$$

This method of using the data first to constrain the background fit and second to extract the limit induces a bias in the coverage of the limits. The actual coverage is reduced to 93.6% (94.3%) at a WW (qW) signal mass of 1200 GeV (1800 GeV).

9. Results

Fig. 7 shows the 95% CL cross section upper limits derived from the single and double W/Z-tagged event samples. The predicted cross sections as a function of resonance mass for the considered benchmark models are overlaid. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV), whereas a limit of 2.43 TeV (2.07 TeV) is expected. These are the most stringent limits in the qW and qZ final states to date. The sensitivity of our measurement with the present dataset is not sufficient to extract substantive mass limits on the G_{RS} with $k/\overline{M}_{\text{Pl}} = 0.1$ nor the heavy SM-like W′ boson, but the cross section limits are the most stringent in the fully hadronic final state to date. Comparing to the cross section limits on G_{RS} decays to ZZ in the corresponding semileptonic final states [20–22], this analysis sets a stronger cross section limit above a G_{RS} mass of roughly 1.4 TeV. The cross section limits on final states with ZZ are stronger than those with WW because the efficiency for tagging a Z is larger than that for a W. The predicted cross section for WW is twice as large as for ZZ in the G_{RS} model because of charge-conjugation.

The dominant source of systematic uncertainty is the jet energy scale. Removing all systematic uncertainties on the single and double tagged searches would decrease the upper limit on the cross section by less than 20% at all values of resonance mass, which would translate into a change on resonances mass limits of roughly 3%.

10. Summary

A data sample corresponding to an integrated luminosity of 5.0 fb^{-1} collected in pp collisions at $\sqrt{s} = 7$ TeV with the CMS detector was used to measure the W/Z-tagged dijet mass spectrum using the two leading jets within the pseudorapidity range $|\eta| < 2.5$ and with pseudorapidity separation $|\Delta\eta| < 1.3$. By suppressing the QCD background with the selection of candidates for vector bosons decaying to hadrons within jets, no evidence was found for new particle production in the W/Z-tagged dijet spectrum. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV) and upper limits on the cross section for resonances decaying to qW, qZ, WW, WZ, or ZZ final states. These are the most stringent limits in the qW and qZ final states to date.

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