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Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at $\sqrt{s} = 8\,$TeV

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ABSTRACT: A search is reported for massive resonances decaying into a quark and a vector boson (W or Z), or two vector bosons (WW, WZ, or ZZ). The analysis is performed on an inclusive sample of multijet events corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$, collected in proton-proton collisions at a centre-of-mass energy of $8\,$TeV with the CMS detector at the LHC. The search uses novel jet-substructure identification techniques that provide sensitivity to the presence of highly boosted vector bosons decaying into a pair of quarks. Exclusion limits are set at a confidence level of 95% on the production of: (i) excited quark resonances q^* decaying to qW and qZ for masses less than $3.2\,$TeV and $2.9\,$TeV, respectively, (ii) a Randall-Sundrum graviton G_{RS} decaying into WW for masses below $1.2\,$TeV, and (iii) a heavy partner of the W boson W' decaying into WZ for masses less than $1.7\,$TeV. For the first time mass limits are set on $W' \to WZ$ and $G_{RS} \to WW$ in the all-jets final state. The mass limits on $q^* \to qW$, $q^* \to qZ$, $W' \to WZ$, $G_{RS} \to WW$ are the most stringent to date. A model with a "bulk" graviton G_{bulk} that decays into WW or ZZ bosons is also studied.

Contents

1 Introduction

Several models of physics beyond the standard model (SM) predict the existence of resonances with masses above 1 TeV that decay into a quark and a W or Z vector boson, or into two vector bosons. In proton-proton (pp) collisions at the energies reached at the Large Hadron Collider (LHC), vector bosons emerging from such decays usually would have sufficiently large momenta so that the hadronization products of their $\overline{q}q(')$ decays would merge into a single massive jet [1]. We present a search for events containing one or two jets of this kind in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The data sample, corresponding to an integrated luminosity of $19.7 \, \text{fb}^{-1}$, was collected with the CMS detector at the LHC.

The signal is characterized by a peak in the dijet invariant mass distribution m_{jj} over a continuous background from SM processes, comprised mainly of multijet events from quantum chromodynamic (QCD) processes. The sensitivity to jets from W or Z bosons is enhanced through the use of jet-substructure techniques that help differentiate such jets from remnants of quarks and gluons [2, 3], providing the possibility of "W/Z-tagging". This search is an update of a previous CMS study [4] performed using data from pp collisions at $\sqrt{s} = 7$ TeV. Besides increased data-sample size and larger signal cross sections from the increase in centre-of-mass energy, this analysis also benefits from an improved W/Z-tagger based on "N-subjettiness" variables, introduced in ref. [5] and defined in section 3.

We consider four reference processes that yield one W/Z-tagged or two W/Z-tagged all-jet events: (i) an excited quark q* [6, 7] that decays into a quark and either a W or a Z boson, (ii) a Randall-Sundrum (RS) graviton G_{RS} that decays into WW or ZZ bosons [8, 9],

(iii) a "bulk" graviton G_{bulk} that decays into WW or ZZ [10–12], and (iv) a heavy partner of the SM W boson (W′) that decays into WZ [13].

Results from previous searches for these signal models include limits placed on the production of q* at the LHC as dijet [14–16] or γ+jet [17] resonances, with a q* lighter than $\approx$3.5 TeV at a confidence level (CL) of 95% [14]. Specific searches for resonant qW and qZ final states at the Tevatron [18, 19] exclude q* decays into qW or qZ with $m_{q^*} < 0.54$ TeV, and results from the LHC [4, 20] exclude q* decays into qW or qZ for $m_{q^*} < 2.4$ TeV and $m_{q^*} < 2.2$ TeV, respectively.

Resonances in final states containing candidates for WW or ZZ systems have also been sought [21–24], with lower limits set on the masses of G_{RS} and G_{bulk} as a function of the coupling parameter $k/\overline{M}_{Pl}$, where k reflects the curvature of the warped space, and $\overline{M}_{Pl}$ is the reduced Planck mass ($\overline{M}_{Pl} \equiv M_{Pl}/\sqrt{8\pi}$) [8, 9]. The bulk graviton model is an extension of the original RS model that addresses the flavour structure of the SM through localization of fermions in the warped extra dimension. The experimental signatures of the G_{RS} and G_{bulk} models differ in that G_{bulk} favours the production of gravitons through gluon fusion, with a subsequent decay into vector bosons, rather than production and decay through fermions or photons, as the coupling to these is highly suppressed. As a consequence, G_{bulk} preferentially produces W and Z bosons that are longitudinally polarized, while G_{RS} favours the production of transversely polarized W or Z bosons. In this study, we use an improved calculation of the G_{bulk} production cross section [10, 25] that predicts a factor of four smaller yield than assumed in previous studies [21, 22].

The most stringent limits on W′ boson production are those reported for searches in leptonic final states [26, 27], with the current limit specified by $m_{W'} > 2.9$ TeV. Depending on the chirality of the W′ couplings, this limit could change by $\approx$0.1 TeV. Searches for W′ in the WZ channel have also been reported [22, 28, 29] and set a lower limit of $m_{W'} > 1.1$ TeV.

The CMS detector, the data, and the event simulations are described briefly in section 2. Event reconstruction, including details of W/Z-tagging, and selection criteria are discussed in section 3. Section 4 presents studies of dijet mass spectra, including SM background estimates. The systematic uncertainties are discussed in section 5, the interpretation of the results in terms of the benchmark signal models is presented in section 6, and the results are summarized in section 7.

2 The CMS detector, data, and simulated event samples

The CMS detector [30] is well-suited to reconstructing particle jets, as it contains highly segmented electromagnetic and hadronic calorimeters and a fine-grained precision tracking system. Charged-particle trajectories are reconstructed in the inner silicon tracker, which consists of a pixel detector surrounded by silicon strip detectors and is immersed in a 3.8 T magnetic field. A lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume, and provide complementary information for reconstructing photons, electrons, and jets. Muon trajectories are measured in gas ionization detectors embedded in the outer steel return yoke of the CMS magnet.

CMS uses a coordinate system with the origin located at the nominal collision point, the x axis pointing towards the centre of the LHC ring, the y axis pointing up (perpendicular to the plane containing the LHC ring), and the z axis along the counterclockwise beam direction. The azimuthal angle, ϕ, is measured with respect to the x axis in the (x, y) plane, and the polar angle, θ, is defined with respect to the z axis. The tracker covers the full azimuthal range of $0 \le \phi < 2\pi$ within $|\eta| < 2.5$, where η is the pseudorapidity defined as $\eta = -\ln[\tan(\theta/2)]$. The coverages of the ECAL and HCAL extend to $|\eta| < 3$ and $|\eta| < 5$, respectively. The calorimeter cells are grouped into towers projecting radially outward from the centre of the detector. In the central region ($|\eta| < 1.74$) the towers have dimensions $\Delta\eta = \Delta\phi = 0.087$ radians, and these increase with $|\eta|$ in the forward regions.

The signals of interest are simulated using JHUGEN [31, 32], PYTHIA 6.426 [33], and HERWIG++ 2.5.0 [34] Monte Carlo (MC) event generators, and processed through a simulation of the CMS detector, based on GEANT4 [35]. Tune Z2* [36] is used in PYTHIA, while the version 23 tune [34] is used in HERWIG++. The CTEQ61L [37] parton distribution functions (PDF) are used for PYTHIA and the MRST2001 [38] leading-order (LO) PDF for HERWIG++. The q* → W+jet and Z+jet processes are generated using PYTHIA.

The RS graviton production is studied for $k/\overline{M}_{\rm Pl} = 0.1$, which sets the resonance widths at $\approx$1% of the resonance mass, a factor of five smaller than the experimental resolution in $m_{\rm jj}$ for resonance masses considered in the analysis. RS graviton cross sections from PYTHIA are used in the analysis to maintain consistency in comparisons with related studies [21]. On the other hand, HERWIG++ contains a more precise description of the angular distributions for $G_{\rm RS}$ production than PYTHIA [39], and is therefore used to model the $G_{\rm RS}$ signal.

Bulk graviton events are generated with $k/\overline{M}_{\rm Pl}$ ranging from 0.1 to 0.5. Due to the detector resolution on the $m_{\rm jj}$ peak, the increase of the resonance width with $k/\overline{M}_{\rm Pl}$ has no impact on the signal distribution for $k/\overline{M}_{\rm Pl}$ values in the considered range. The reference samples are generated assuming $k/\overline{M}_{\rm Pl} = 0.2$, with JHUGEN interfaced to PYTHIA for the showering and hadronization of quarks. Bulk graviton production is studied up to $k/\overline{M}_{\rm Pl} = 0.5$, where the resonance width is $\approx$1% of the resonance mass. The W' → WZ process is generated using PYTHIA, assuming SM $V - A$ couplings [33]. The cross section values are scaled to next-to-next-to-leading order (NNLO) values with the K-factors obtained using the simulation code FEWZ 2.0 [40].

All simulated samples are passed through the standard CMS event reconstruction software. Data are compared to simulated samples of multijet events, generated using both HERWIG++ and MADGRAPH 5v1.3.30 [41], and interfaced to PYTHIA for parton showering and hadronization. The simulated sample of multijet events serves only to provide guidance and cross-checks, as the distribution of the background is modelled from data.

3   Event reconstruction and selections

In this study the event selection, in the online trigger as well as offline, utilizes a global view of the event involving information combined from the individual subdetectors. Online, events are selected by at least one of two specific triggers, one based on the scalar sum of

the transverse momenta p_T of the jets, and the other on the invariant mass m_{jj} of the two jets with highest p_T. The offline reconstruction, described below, is also based on a global event description.

Events must have at least one reconstructed vertex with $|z| < 24$ cm. The primary vertex is defined as the one with the largest summed p_T^2 of its associated tracks. Individual particles are reconstructed and identified using the particle-flow (PF) algorithm [42, 43], and divided into five categories: muons, electrons, photons (including their conversions into e^+e^- pairs), charged hadrons, and neutral hadrons. Charged PF candidates not originating from the primary vertex are discarded, which reduces the contamination from additional pp interactions in the same or neighbouring bunch crossings (pileup). Ignoring isolated muons, jets are clustered from the remaining PF candidates using the Cambridge-Aachen (CA) [44, 45] jet clustering algorithm, as implemented in FASTJET [46, 47]. A distance parameter $R = 0.8$ is used for the CA algorithm. An event-by-event correction based on the jet area method [48–50] is applied to remove the remaining energy deposited by neutral particles originating from other interaction vertices. The pileup-subtracted jet four-momenta are then corrected to account for the difference between the measured and true energies of hadrons [50]. Finally, events with jets originating from calorimeter noise are rejected, requiring that a fraction of the jet energy is also detected in the tracking system. Following this selection, the jet reconstruction efficiencies (estimated from simulation) are larger than 99.9%, and contribute negligibly to the systematic uncertainties for signal events.

Events are selected by requiring at least two jets with $p_T > 30$ GeV and $|\eta| < 2.5$. The two jets of highest p_T are required to have a pseudorapidity separation $|\Delta\eta| < 1.3$ to reduce background from multijet events [51]. The invariant mass of the two selected jets is required to have $m_{jj} > 890$ GeV, which leads to a 99% trigger efficiency, with a negligible systematic uncertainty.

The event selection efficiency for signal is estimated using fully simulated signal event samples, as described below. These studies also show that less than 1% of the events decaying to WW or ZZ that pass the event selection criteria are from WW $\rightarrow \ell\nu_\ell\overline{q}q'$ or ZZ $\rightarrow \ell^+\ell^-\overline{q}q$ decays, where ℓ refers to a muon or an electron. Further, less than 1% of the selected WW events are from WW $\rightarrow \tau\nu_\tau\overline{q}q'$ decays, and only 3% of the selected ZZ events correspond to ZZ $\rightarrow \tau^+\tau^-\overline{q}q$ decays. Hence, these contaminants are negligible and the event selection efficiency is dominated by the final states where the W and Z bosons decay to quarks.

Although we use a full simulation to derive the exclusion limits, to enable reinterpretation of the results in models with other acceptances, in the following we consider the global efficiency approximated by the product of "nominal acceptances" and the W/Z tagging efficiency, restricted to final states where the W or Z boson decay to quarks. A matching is required within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$ of the generated W and Z bosons decaying to quarks and their reconstructed single jets, as part of the nominal acceptances. The product of nominal acceptances and the W/Z tagging efficiency, ignoring leptonic decays and the correlations between detector acceptance and W/Z tagging, agree to better than 10% with the full simulations.
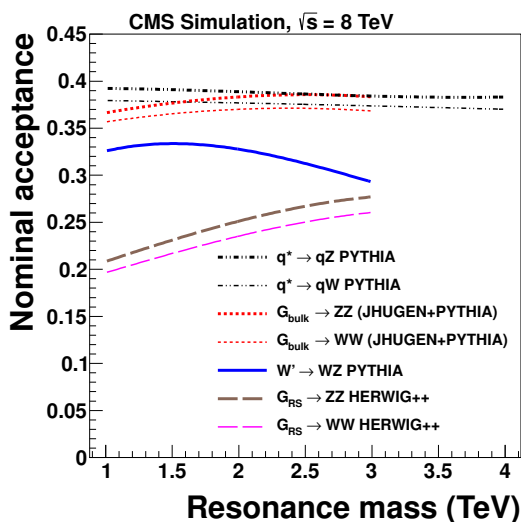
Figure 1. The fraction of simulated signal events expected for vector bosons decaying into two quarks, reconstructed as two jets, that pass the geometrical acceptance criteria ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$), shown as a function of the dijet invariant mass.

In the analysis reported in this paper, the global efficiency is estimated from the full simulation of signal events, without applying the matching requirement. In this way, the correlations between the acceptance and W/Z-tagging efficiency are properly taken into account. However, interpreting this search in terms of these nominal acceptances and W/Z-tagging efficiencies for any arbitrary model requires the implementation of an additional uncertainty of 10%.

The nominal acceptance, shown in figure 1 as a function of the dijet resonance mass for several signals, takes into account the angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$), the matching, and the branching fraction into quark final states. The acceptance for the G_{RS} model is lower than for the G_{bulk} model, primarily because the G_{RS} model predicts a wider distribution in $|\Delta\eta|$. The rise in acceptance for the G_{RS} model is primarily due to the narrowing of the $|\eta|$ distribution with increasing resonance mass.

The two jets of highest p_T are chosen as candidates of highly boosted W or Z bosons decaying to quarks, and passed through a tagging algorithm based on jet pruning [2, 52–54]. Each jet is reclustered using all the particles that form the original CA jet, associating with each step of the recombination procedure a measure of the jet's "softness". The CA clustering algorithm starts from a set of "protojets" given by the PF particles. Iteratively these protojets are combined with each other until a set of jets is found. Given two protojets i, j of transverse momenta p_T^i and p_T^j, the recombination, that is the sum of their transverse momenta p_T^p, is considered soft if: (i) its hardness z is found to be $z < 0.1$, where z is the smaller of the two values of p_T^i/p_T^p and p_T^j/p_T^p, or (ii) when the two protojets have a distance ΔR larger than some D_{cut}, where the value of D_{cut} is given by m^{orig}/p_T^{orig}, with m^{orig} and p_T^{orig} representing the mass and p_T of the original CA jet. If a recombination
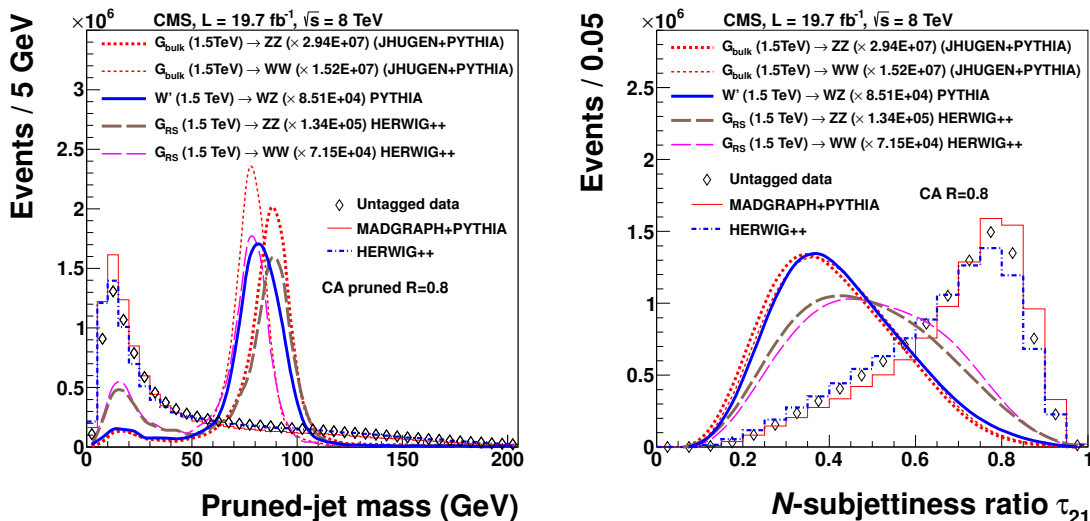
Figure 2. Distribution for (left) pruned-jet mass m_{j} and (right) jet N-subjettiness ratio τ_{21} in data, and in simulations of signal and background events. All simulated distributions are scaled to match the number of events in data. MadGraph/pythia and herwig++ refer to QCD multijet event simulations.

is identified as soft, the protojet with smaller p_{T} is discarded. If the pruned jet has a mass within $70 < m_{\mathrm{j}} < 100\,\mathrm{GeV}$, it is tagged as a W/Z candidate. This mass requirement was optimized specifically for this analysis. The distributions of m_{j} for data, and for simulated signal and background samples, are shown in figure 2 (left). Fully merged jets from W and Z decays are expected to generate a peak at $m_{\mathrm{j}} \approx 80$–$90\,\mathrm{GeV}$, while jets from multijet events and not-fully-merged W and Z bosons give rise to a peak around $20\,\mathrm{GeV}$. The disagreement observed at small values of m_{j} [55] can be ignored, as the W and Z candidates with $m_{\mathrm{j}} < 70\,\mathrm{GeV}$ are not considered in the analysis and the overall background normalization is determined with a fit to the data.

We achieve additional discrimination against multijet events by considering the distribution of jet constituents relative to the jet axis. In particular, we quantify how well the constituents of a given jet can be arranged into N subjets. This is done by reconstructing the full set of jet constituents (before pruning) with the k_{T} algorithm [56] and halting the reclustering when N distinguishable protojets are formed. The directions of the N jets are used as the reference axes to compute the N-subjettiness [5, 57, 58] τ_N of the original jet, defined as

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \, \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}), \qquad (3.1)$$

where $p_{\mathrm{T},k}$ is the p_{T} of the particle constituent k of the original jet, and $\Delta R_{n,k}$ is its angular distance from the axis of the nth subjet (with $n = 1, 2, \ldots, N$). The normalization factor d_0 for τ_N is $d_0 = \sum_k p_{\mathrm{T},k} R_0$, with R_0 set to the distance parameter R of the original CA jet. To improve the discriminating power, we perform a one-pass optimization of the directions of the subjet axes by minimizing τ_N [3, 57]. By using the smallest $\Delta R_{n,k}$ to weight the value of $p_{\mathrm{T},k}$ in eq. (3.1), τ_N yields small values when the jet originates from the hadronization of N

quarks. We therefore use the ratio $\tau_{21} = \tau_2/\tau_1$ as a discriminant between the two-pronged $W \to \bar{q}q'$ or $Z \to \bar{q}q$ decays and single jets in multijet events. The discriminating power of τ_{21} for different resonance models can be seen in figure 2 (right). The MC simulations of multijet background and the data peak near ≈ 0.8, whereas the signal distributions have a larger fraction of events at smaller values of τ_{21}. We found a slightly better significance using N-subjettiness without pruning, taking pileup uncertainties into account.

Differences are observed in signal distributions predicted with HERWIG++ (for G_{RS}), with PYTHIA (q^*, W'), and with JHUGEN/PYTHIA (G_{bulk}), for the mass m_j of pruned jets and for τ_{21}. These differences arise from unlike polarization of the vector bosons in the various signals models and from differences between HERWIG++ and PYTHIA in the modelling of the showering and hadronization of partons. In particular, values for the polarization of the vector bosons are related to different predictions for τ_{21} in the G_{RS} and G_{bulk} models as noted in ref. [3]. Differences in the modelling of the small m_j regions for pruned jets have been observed previously [55]. The showering and hadronization differences are taken into account in the estimation of systematic uncertainties, as discussed below.

We select "high-purity" (HP) W/Z jets by requiring $\tau_{21} \leq 0.5$, and "low-purity" (LP) W/Z jets by requiring $0.5 < \tau_{21} < 0.75$. Events with just one W/Z tag are classified according to these two categories. The events with two W/Z-tagged jets are always required to have one HP W/Z tag, and are similarly divided into HP and LP events, depending on whether the other W/Z-tagged jet is of high or low purity. The selection criterion for the HP category is chosen to give optimal average performance for the models used in this search. The LP category adds sensitivity, especially at large values of m_{jj}, where the rate in the HP category drops along with the background rate.

The identification rates expected for the W and Z selection criteria for signal and background events in different event categories are shown in figure 3 as a function of m_{jj}. As expected from figure 2 (right), the background simulation shows disagreements in modelling the identification rate for background events in data; however, the dependence as a function of p_T is well modelled. While the background simulation is not used to model the background in the analysis, it shows how well the simulation models the p_T dependence of substructure variables. The W/Z-tagging efficiency for signal events in the HP categories drops at high p_T, while it is more stable in the LP categories, primarily because the τ_{21} distribution is p_T-dependent.

The modelling of the signal efficiency is cross-checked through a W-tagging efficiency estimated using merged $W \to \bar{q}q'$ decays in $t\bar{t}$ events [3]. The efficiency is obtained using ℓ+jets events with two b-tagged jets, one of which has $p_T > 200\,\text{GeV}$. Such events are dominated by $t\bar{t}$ production. The data are compared to simulated $t\bar{t}$ events, generated with MADGRAPH, interfaced to PYTHIA for parton showering, and provide scale factors of 0.86 ± 0.07 and 1.39 ± 0.75, respectively, for HP and LP events. These values are derived following the method described in ref. [3] for the selections applied in this analysis, and are used to match the simulated samples to data. The uncertainties in the scale factors contribute to the systematic uncertainty in the selection efficiency for signal.
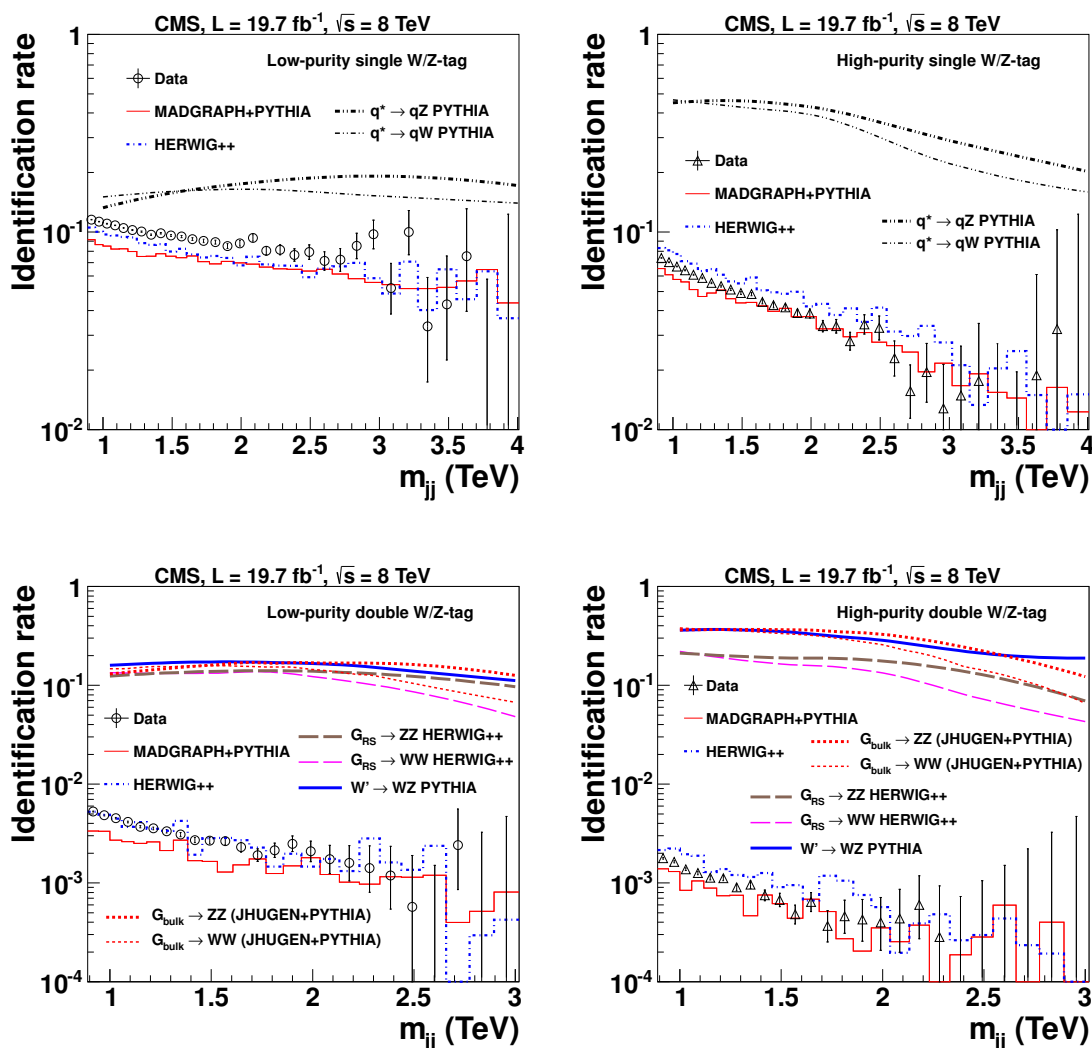
Figure 3. Identification rate for W and Z boson selections as a function of m_{jj} for quark and gluon jets in data and in simulation of background events, and for jets from W and Z bosons in simulation of signal events, with (upper left) one LP or (upper right) HP W/Z-tag, and the fraction of (lower left) doubly-tagged events in the LP and (lower right) HP category. The identification rate is computed for $W/Z \to \overline{q}q' \to$ jets events, where the jets have $|\eta| < 2.5$ and $|\Delta\eta| < 1.3$. MADGRAPH/PYTHIA and HERWIG++ refer to QCD multijet event simulations.

The m_{jj} distributions for singly and doubly tagged LP and HP event samples are shown in figure 4. These distributions provide the basis for the search. The analogous distributions from MADGRAPH/PYTHIA and HERWIG++ multijet simulations, normalized to the number of events in data, are shown. Only the dominant background from multijet production without systematic uncertainties is shown in this comparison. The prediction from HERWIG++ decreases more steeply with an increase in m_{jj} than that for MADGRAPH/PYTHIA. We estimate from simulation that backgrounds from $t\overline{t}$, W+jets and Z+jets events with the vector bosons decaying into quark final states contribute less than 2% of total background.
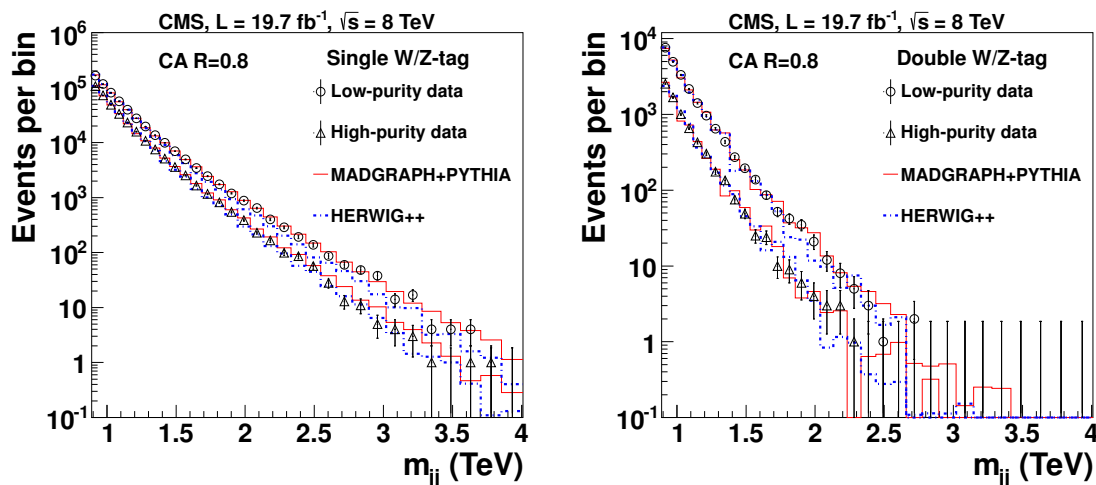
Figure 4. The m_{jj} distributions for (left) singly and (right) doubly tagged events in data, and for QCD multijet (MadGraph/pythia and herwig++) simulations, normalized to data.
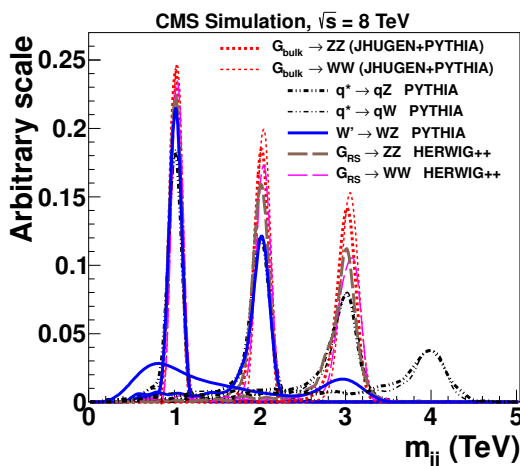

Figure 5. Distribution in m_{jj} expected in the HP categories corresponding to resonance masses of 1, 2, 3 TeV, for all models, and 4 TeV, for q^* models. All distributions are normalized to the same area.

4 The search for a peak in the mass spectrum

Figure 5 shows the m_{jj} distributions expected for the HP category of $G_{RS} \rightarrow ZZ/WW$, $G_{bulk} \rightarrow ZZ/WW$, $W' \rightarrow WZ$, and $q^* \rightarrow qW/qZ$, for four resonance masses. A linear interpolation between a set of reference distributions (corresponding to masses of 1.0, 1.5, 1.8, 2.0, 2.2, 2.5, 3.0, and 4.0 TeV) is used to obtain the expected distribution for other values of resonance mass. Because of the interplay between the PDF and the resonance width, the W' distribution for large resonance masses is also characterized by a contribution

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at small masses that peaks near $\approx 0.8\,\mathrm{TeV}$. This search is not sensitive to this component because of the overwhelming background from multijet production. This feature is not observed for the other signal models, which assume a narrow width.

Background from multijet events is modelled by a smoothly falling distribution for each event category, given by the empirical probability density function

$$P_D(m_{\mathrm{jj}}) = \frac{P_0(1 - m_{\mathrm{jj}}/\sqrt{s})^{P_1}}{(m_{\mathrm{jj}}/\sqrt{s})^{P_2}} \ . \tag{4.1}$$

For each category, the normalization factor P_0 and the two parameters P_1 and P_2 are treated as uncorrelated. This parameterization was deployed successfully in searches in dijet mass spectra [51]. A Fisher F-test [59] is used to check that no additional parameters are needed to model the individual background distribution, for each of the four cases considered.

We search for a peak on top of the falling background spectrum by means of a maximum likelihood fit to the data. The likelihood $\mathcal{L}$, computed using events binned as a function of m_{jj}, is written as

$$\mathcal{L} = \prod_i \frac{\lambda_i^{n_i} \mathrm{e}^{-\lambda_i}}{n_i!}, \tag{4.2}$$

where $\lambda_i = \mu N_i(S) + N_i(B)$, μ is a scale factor for the signal, $N_i(S)$ is the number expected from the signal, and $N_i(B)$ is the number expected from multijet background. The parameter n_i quantifies the number of events in the ith m_{jj} mass bin. The background $N_i(B)$ is described by the functional form of eq. (4.1). While maximizing the likelihood as a function of the resonance mass, μ as well as the parameters of the background function are left floating.

Figure 6 shows the m_{jj} spectra in data with a single W/Z-tag, and with a double W/Z-tag. The solid curves represent the results of the maximum likelihood fit to the data, fixing the number of expected signal events to 0, while the bottom panels show the corresponding pull distributions, quantifying the agreement between the background-only hypothesis and the data. The expected contributions from q* and G$_{\mathrm{RS}}$ resonances for respective masses of 3.0 and 1.5 TeV, scaled to their corresponding cross sections, are given by the dash-dotted curves.

We quantify the consistency of the data with the null hypothesis as a function of resonance mass for the benchmark models through the local p-value. The largest local significance in the singly W/Z-tagged sample is observed for the hypothesis of a q$^* \to$ qW resonance of mass 1.5 TeV, and is equivalent to an excess of 1.8 standard deviations. The largest local significance in the doubly tagged event sample corresponds to an excess of 1.3 standard deviations for a G$_{\mathrm{RS}} \to$ WW resonance of mass 1.9 TeV. Using the G$_{\mathrm{bulk}} \to$ WW/ZZ model, where the LP and HP categories contribute in different proportions compared to the case for the G$_{\mathrm{RS}} \to$ WW model, yields no excess larger than one standard deviation.

Using pseudo-experiments, we estimated the probability of observing a local statistical fluctuation of at least two standard deviations in any mass bin. This probability corresponds to an equivalent global significance of one standard deviation. The m_{jj} distri-
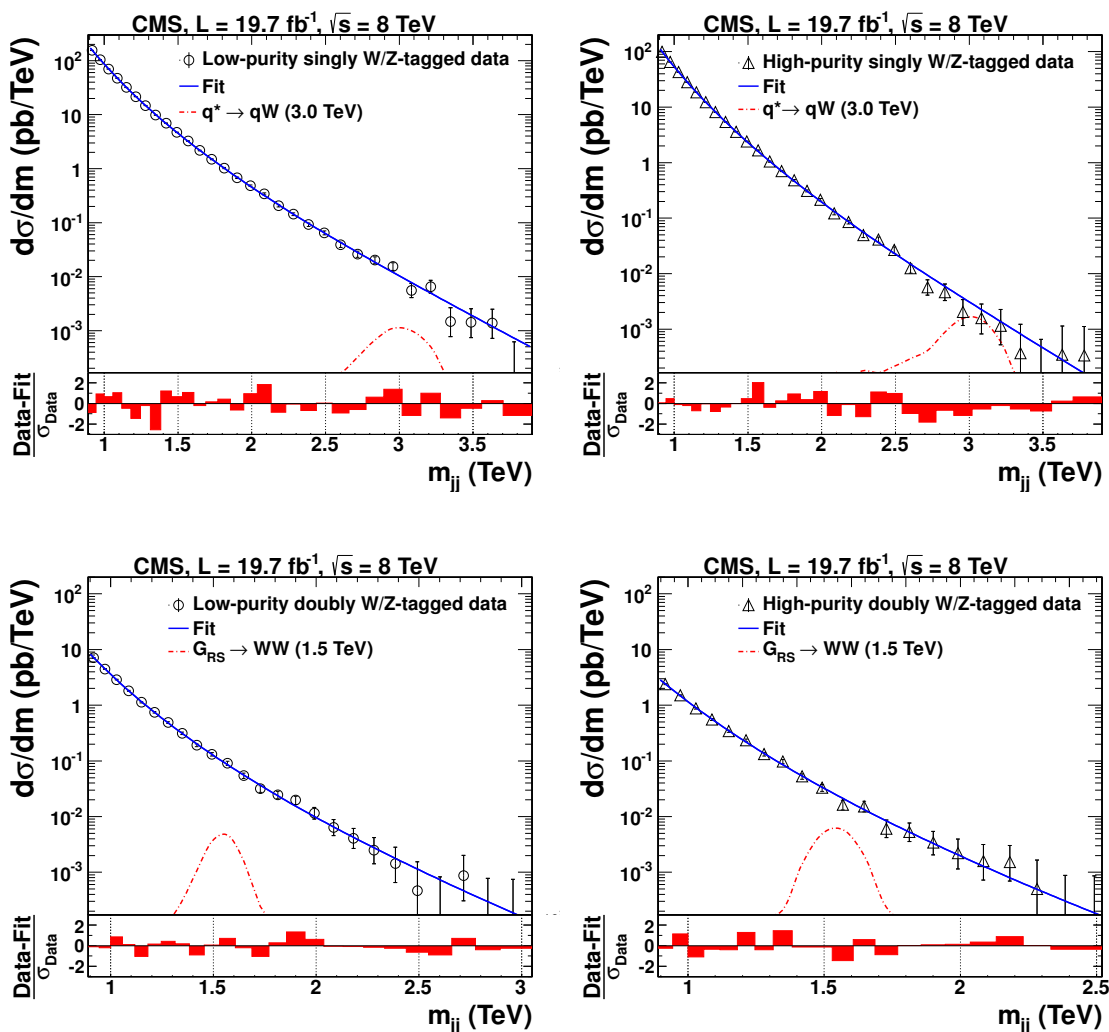
Figure 6. Distribution in m_{jj}, respectively, for (upper left) singly-tagged LP events and (upper right) HP events, and for (lower left) doubly-tagged LP events and (lower right) HP events. The solid curves represent the results of fitting eq. (4.1) to the data. The distribution for $q^* \to qW$ and $G_{RS} \to WW$ contributions, scaled to their corresponding cross sections, are given by the dash-dotted curves. The corresponding pull distributions ($\frac{\text{Data}-\text{Fit}}{\sigma_{\text{Data}}}$, where σ_{Data} represents the statistical uncertainty in the data in a bin in m_{jj}) are shown below each m_{jj} plot.

butions are used to set upper limits on the product of the production cross sections and decay branching fractions for the benchmark models.

5 Systematic uncertainties

The largest contributions to systematic uncertainties are associated with the modelling of the signal, namely the determination of the W/Z-tagging efficiency, jet energy scale (JES), jet energy resolution (JER), and integrated luminosity.

Source	Relevant quantity	LP uncertainty (%)	HP uncertainty (%)
Jet energy scale	Resonance shape	1	1
Jet energy resolution	Resonance shape	10	10
W-tagging	Efficiency (per jet)	7.5	54
Tagging p_T-dependence	Efficiency (per jet)	<4	<12
Pileup	Efficiency (per jet)	<1.5	<1.5
Integrated luminosity	Yield (per event)	2.6	2.6
PDF	Yield (per event)	5–15	5–15

Table 1. Summary of systematic uncertainties. The labels HP and LP refer to high-purity and low-purity event categories, respectively.

The uncertainty in the efficiency for singly W/Z-tagged events is estimated using the ℓ+jets control sample from $t\bar{t}$ events described above. Uncertainties of 7.5% and 54% in the respective scale factors for HP and LP tagging include contributions from control-sample statistical uncertainties, and the uncertainties in the JES and JER for pruned jets. Since the scale factors are estimated only in the kinematic regime of the $t\bar{t}$ sample, where the W decay products merge and the b quarks are reconstructed as separate jets, we use the simulation just to extrapolate to larger W/Z-jet p_T. The efficiency is therefore estimated as a function of p_T for two showering and hadronization models, using G_{bulk} samples generated with the JHUGEN event generator interfaced to PYTHIA and HERWIG++. The differences are respectively within 4% and 12% for HP and LP tagged jets, significantly smaller than the statistical uncertainties in the scale factors. Other systematic uncertainties in tagging efficiency are even smaller. Because of the rejection of charged particles not originating from the primary vertex, and the application of pruning, the dependence of the W/Z-tagging efficiency on pileup is weak, and the uncertainty in the modelling of the pileup distribution is <1.5%. These systematic contributions refer to a singly W/Z-tagged jet, and are applied to each of the two leading jets in doubly W/Z-tagged events.

The JES has an uncertainty of 1–2% [50, 60], and its p_T and η dependence is propagated to the reconstructed value of m_{jj}, yielding an uncertainty of 1%, regardless of the resonance mass. The impact of this uncertainty on the calculated limits is estimated by changing the dijet mass in the analysis within its uncertainty. The JER is known to a precision of 10%, and its non-Gaussian features observed in data are well described by the CMS simulation [50]. The effect of the JER uncertainty in the limits is also estimated by changing the reconstructed resonance width within its uncertainty. The integrated luminosity has an uncertainty of 2.6% [61], which is also taken into account in the analysis. The uncertainty related to the PDF used to model the signal acceptance is estimated from the eigenvectors of the CTEQ66 [37] and MRST2006 [62] sets of PDF. The envelope of the upward and downward variations of the estimated acceptance for the two sets is assigned as uncertainty and found to be 5%–15% in the resonance mass range of interest. A summary of all systematic uncertainties is given in table 1.

Process	Observed excluded mass limit (TeV)	Expected excluded mass limit (TeV)
$q^* \to qW$	3.2	3.0
$q^* \to qZ$	2.9	2.6
$W' \to WZ$	1.7	1.6
$G_{RS} \to WW$	1.2	1.3

Table 2. Summary of observed limits on resonance masses at 95% CL and their expected values, assuming a null hypothesis. The analysis is sensitive to resonances heavier than 1 TeV.

6 Results

The asymptotic approximation [63] of the LHC CL_s method [64, 65] is used to set upper limits on the cross sections for resonance production. The dominant sources of systematic uncertainties are treated as nuisance parameters associated with log-normal priors in those variables, following the methodology described in ref. [66]. For a given value of the signal cross section, the nuisance parameters are fixed to the values that maximize the likelihood, a method referred to as profiling. The dependence of the likelihood on parameters used to describe the background in eq. (4.1) is removed in the same manner, and no additional systematic uncertainty is therefore assigned to the parameterization of the background.

The HP and LP event categories are combined into a common likelihood, with the two uncertainties in the W/Z-tagging efficiencies considered to be anticorrelated between HP and LP tagging because of the exclusive selection on τ_{21}, while the remaining systematic uncertainties in signal are taken as fully correlated. The variables describing the background uncertainties are treated as uncorrelated between the two categories. The LP category contributes to the sensitivity of the analysis, especially at large values of m_{jj}. The combined expected limits on the $G_{RS} \to WW$ production cross sections are, respectively, a factor of 1.1 and 1.6 smaller at $m_{jj} = 1.0$ TeV and 2.9 TeV than the limit obtained from the HP category alone.

Figures 7 and 8 show the observed and background-only expected upper limits on the production cross sections for singly and doubly W/Z-tagged events, computed at 95% CL, with the predicted cross sections for the benchmark models overlaid for comparison. Table 2 shows the resulting exclusion ranges on resonant masses. Compared to the previous search in this channel at $\sqrt{s} = 7$ TeV [4], the mass limits on $q^* \to qW$ and $q^* \to qZ$ are increased, respectively, by 0.8 and 0.7 TeV and for the first time mass limits are set on $W' \to WZ$ and $G_{RS} \to WW$ models. No mass limits are set on $G_{RS} \to ZZ$, $G_{bulk} \to WW$ and $G_{bulk} \to ZZ$, since the analysis is not sensitive to the small predicted cross sections.

The systematic uncertainties have minor impact on the limits. The largest contributions are 5%, 5%, and 3% from W/Z-tagging efficiency, JES, and JER, respectively. These numbers are obtained by quoting the largest change in the observed exclusion limit on the $G_{RS} \to WW$ production cross section, over the entire examined mass range, when the corresponding uncertainties are removed.
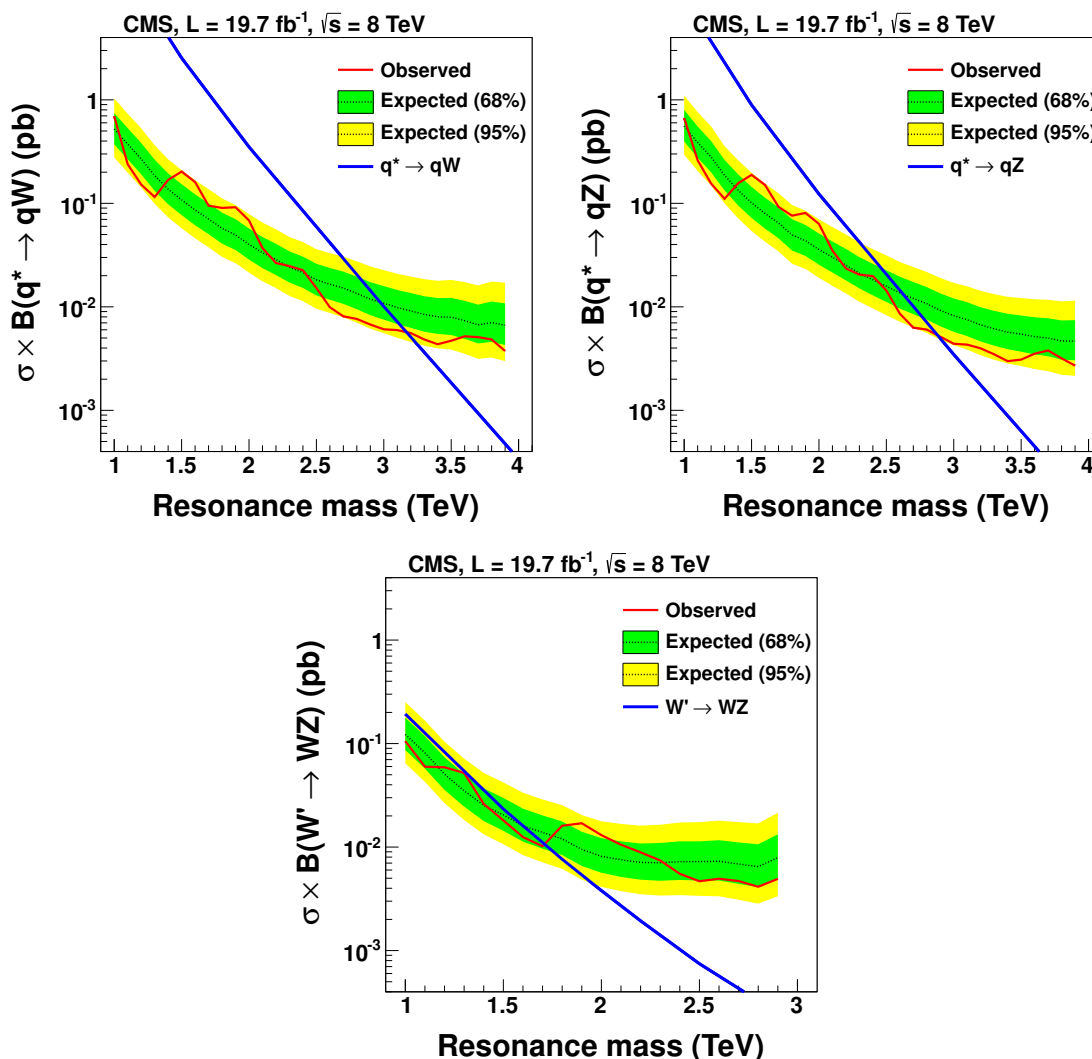
Figure 7. Expected and observed 95% CL limits on the production cross section as a function of the resonance mass for (upper left) qW resonances, (upper right) qZ resonances, and (bottom) WZ resonances, compared to their predicted cross sections for the corresponding benchmark models.

7 Summary

An inclusive sample of multijet events corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$, collected in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the CMS detector, is used to measure the W/Z-tagged dijet mass spectrum for the two leading jets, produced within the pseudorapidity range $|\eta| < 2.5$ with a separation in pseudorapidity of $|\Delta\eta| < 1.3$. The generic multijet background is suppressed using jet-substructure tagging techniques that identify vector bosons decaying into $\bar{q}q'$ pairs merged into a single jet. In particular, the invariant mass of pruned jets and the N-subjettiness ratio τ_{21} of each jet are used to reduce the initially overwhelming multijet background. The remaining background is estimated through a fit to smooth analytic functions. With no evidence for a peak on top of the smoothly falling
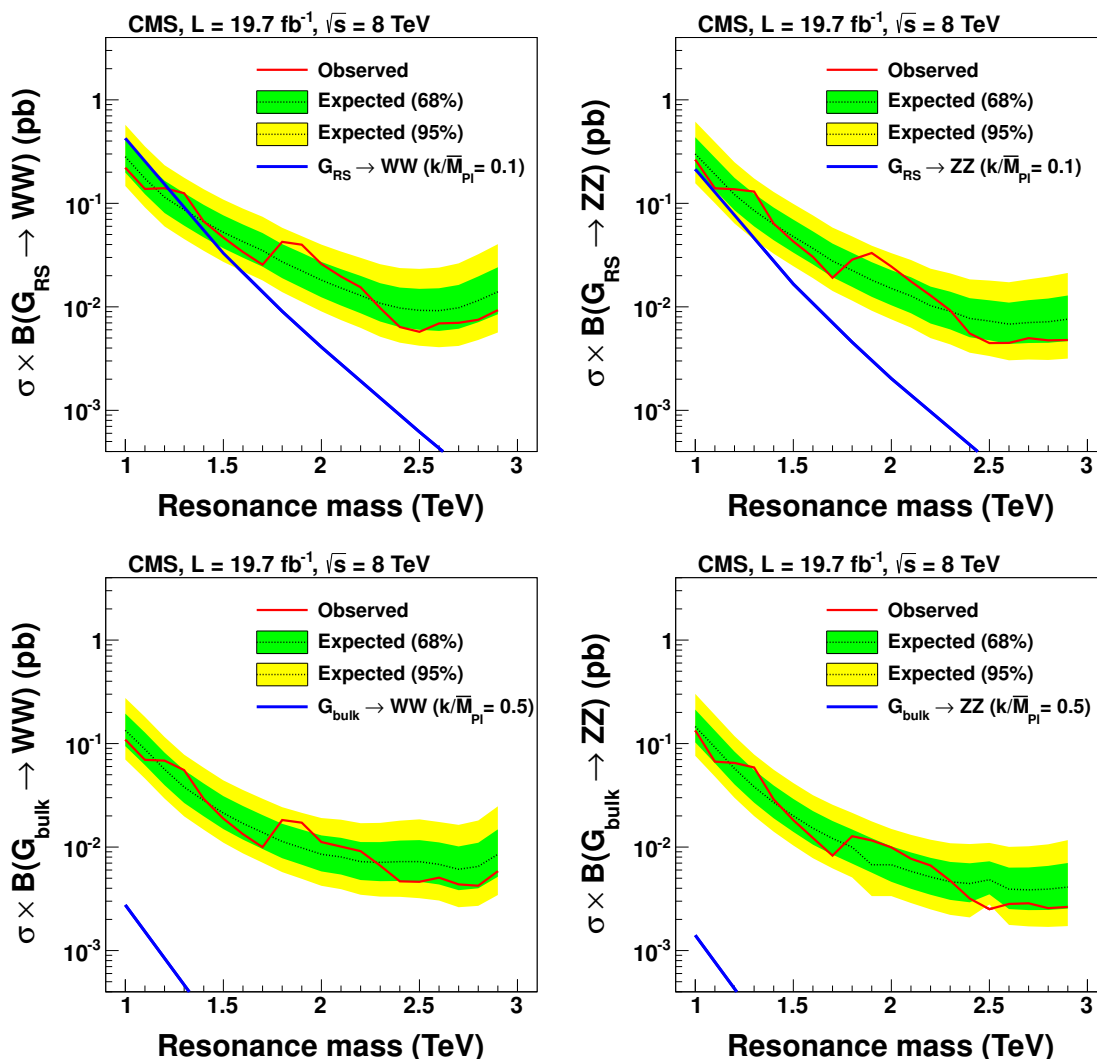
Figure 8. Expected and observed 95% CL limits on the production cross section as a function of the resonance mass for (upper left) $G_{RS} \to WW$ resonances, (upper right) $G_{RS} \to ZZ$ resonances, (bottom left) $G_{bulk} \to WW$ resonances, and (bottom right) $G_{bulk} \to ZZ$ resonances, compared to the predicted cross sections.

background, 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. For the first time mass limits are set on $W' \to WZ$ and $G_{RS} \to WW$ in the all-jets final state. The mass limits on $q^* \to qW$, $q^* \to qZ$, $W' \to WZ$, $G_{RS} \to WW$ are the most stringent to date. A model with a "bulk" graviton G_{bulk} that decays into WW or ZZ bosons is also studied, but no mass limits could be set due to the small predicted cross sections.

Acknowledgments

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