

Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s} = 8$ TeVS. Chatrchyan *et al.**

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Results are presented of a search for the production of new particles decaying to pairs of partons (quarks, antiquarks, or gluons), in the dijet mass spectrum in proton-proton collisions at $\sqrt{s} = 8$ TeV. The data sample corresponds to an integrated luminosity of 4.0 fb^{-1} , collected with the CMS detector at the LHC in 2012. No significant evidence for narrow resonance production is observed. Upper limits are set at the 95% confidence level on the production cross section of hypothetical new particles decaying to quark-quark, quark-gluon, or gluon-gluon final states. These limits are then translated into lower limits on the masses of new resonances in specific scenarios of physics beyond the standard model. The limits reach up to 4.8 TeV, depending on the model, and extend previous exclusions from similar searches performed at lower collision energies. For the first time mass limits are set for the Randall–Sundrum graviton model in the dijet channel.

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We report on a search for narrow dijet resonances in pp collisions at $\sqrt{s} = 8$ TeV. This search is applicable to all new particles for which the natural resonance width is small compared to the CMS dijet mass resolution [1]. The data sample corresponds to an integrated luminosity of 4.0 fb^{-1} collected with the Compact Muon Solenoid (CMS) [2] at the CERN Large Hadron Collider (LHC) in the spring of 2012.

Many extensions of the standard model (SM) predict the existence of new massive objects that couple to quarks or antiquarks (q or \bar{q}) and gluons (g), resulting in resonances in the dijet mass spectrum. The most stringent bounds on these resonances come from previous CMS [3–5] and ATLAS [6–9] searches. The results presented in this Letter extend the search sensitivity to higher values of the resonance masses.

We consider the following specific models of narrow dijet resonances produced via the s channel: string resonances [10,11]; E_6 diquarks [12]; excited quarks assuming the dimensionless constants accounting for possible deviations from the standard model couplings to be $f = f' = f_s = 1$ [13,14]; axigluons [15,16]; color-octet colorons [17]; the S8 resonance predicted in technicolor models [18]; new gauge bosons (W' and Z') [19]; Randall–Sundrum (RS) gravitons assuming $k/\bar{M}_{\text{Pl}} = 0.1$, where k is related to the curvature of the fifth dimension and \bar{M}_{Pl} is the effective 4D Planck scale [20]. More details on these models and the parameters we assume can be found in Refs. [1,4].

A detailed description of the CMS experiment can be found elsewhere [2]. The CMS coordinate system has the origin at the center of the detector. The z axis points along the direction of the counterclockwise beam; y is the vertical direction and x is chosen to make a right-handed coordinate system; ϕ is the azimuthal angle, θ is the polar angle, and the pseudorapidity is defined as $\eta \equiv -\ln[\tan(\theta/2)]$. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial field of 3.8 T. Within the field volume are located the silicon pixel and strip tracker ($|\eta| < 2.5$), as well as the barrel and endcap calorimeters ($|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter. An iron/quartz fiber calorimeter is located in the forward region ($3 < |\eta| < 5$), outside the field volume. For triggering purposes and to facilitate the reconstruction of hadronizing particles as jets, the calorimeter cells are grouped into towers projecting radially outward from the center of the detector.

Offline particle candidates are reconstructed by using the particle flow (PF) algorithm [21], which categorizes the candidates as muons, electrons (with associated bremsstrahlung photons), photons (unconverted and converted), and charged/neutral hadrons. These PF candidates are then clustered into jets using the anti- k_T algorithm [22] with a distance parameter $R = 0.5$, implemented in the FASTJET package [23]. The jet four-momentum, computed as the vectorial sum of the four-momenta of the constituent PF candidates, is adjusted with corrections derived from Monte Carlo (MC) simulations, test beam results, and pp collision data [24]. The corrections also account for the presence of multiple pp collisions in the same or adjacent bunch crossings (pileup interactions) [25].

Events are selected by requiring at least one reconstructed primary vertex in each event within the range $|z| < 24$ cm. We select jets with $p_T > 30$ GeV and $|\eta| < 2.5$ that meet identification criteria based on the number of

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constituent particles and their energy fractions [26]. The other jets in the event are ignored. Events with fewer than two selected jets are discarded.

To improve the dijet invariant mass resolution, we account for final state radiation (FSR) by forming a wide jet [4,27] around each leading jet. The wide jets are formed by clustering additional jets to the closest leading jet within a distance $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1.1$. The four-momentum of each wide jet is computed as the sum of the four-momenta of the constituent jets. To suppress background events coming from quantum chromodynamics (QCD) processes, we require that the pseudorapidity separation of the two wide jets satisfies $|\Delta\eta_{jj}| < 1.3$, and that both wide jets are reconstructed in the region $|\eta| < 2.5$. These angular requirements maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD background. The dijet mass is given by $m_{jj} = \sqrt{(E_{j1} + E_{j2})^2 - |\vec{p}_{j1} + \vec{p}_{j2}|^2}$, where E_{ji} and \vec{p}_{ji} ($i = 1, 2$) are the energy and the momentum of a wide jet. We select events with $m_{jj} > 890$ GeV to maintain a fully efficient trigger as discussed below.

Events are filtered using a two-tier trigger system. Events satisfying loose jet requirements at the first level (L1) are passed to the high level trigger (HLT), where jets are clustered from PF candidates built online. Online jets with transverse momenta $p_T > 40$ GeV and $|\eta| < 3.0$ are used to compute H_T , the scalar sum of the jet p_T , and m_{jj} , the invariant mass of the two wide jets. Events with $H_T > 650$ GeV or $m_{jj} > 750$ GeV are accepted. For the offline analysis selection presented above, the combined L1 and HLT triggers are found to be more than 99.9% efficient.

We show in Fig. 1 the dijet mass distribution in bins approximately equal in width to the dijet mass resolution [3]. The data are compared with the expected leading-order (LO) QCD background generated by using PYTHIA v6.424 [28], including a GEANT4-based [29] simulation of the CMS detector. This approach follows closely that described in [30], but uses the CTEQ6L PDF (Z2 tune) instead of the CTEQ5L PDF (Z1 tune). The QCD prediction uses a renormalization and factorization scale $\mu = p_T$ of the hard-scattered partons and CTEQ6L1 parton distribution functions [31], and has been normalized to the data. The normalization factor of 1.34 was found to be consistent with the next-to-leading-order K factor [32,33]. The shape of the PYTHIA prediction agrees with the data within the statistical precision.

For comparison we also display in Fig. 1 the shape expected for a W' boson with a mass of 1.5 TeV and an E_6 diquark with a mass of 3.5 TeV. The signal samples are generated by using PYTHIA with the D6T tuning [28] and the same GEANT4-based CMS simulation used for the QCD background sample. The predicted mass distributions have a Gaussian core from the jet energy resolution and a tail towards lower mass values, primarily due to FSR. The

contribution of this low-mass tail to the line shape depends on the parton content of the resonance (qq , $q\bar{q}$, qg , and gg). Resonances decaying to gluons, which are more susceptible than quarks to the FSR, have a larger tail. For high-mass resonances, there is also another significant contribution depending on both parton distributions and the natural width of the Breit-Wigner resonance shape: when the resonance is produced by interaction of non-valence partons in the proton, the low-mass component of the Breit-Wigner resonance shape is amplified by a larger parton probability at low fractional momentum, producing a large tail at low-mass values. The shapes shown for a hypothetical W' boson and an E_6 diquark in Fig. 1 result from Crystal Ball [34] fits to the generated event distributions.

The background from QCD multijet production is described by the analytical function

$$\frac{d\sigma}{dx} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3 \ln(x)}},$$

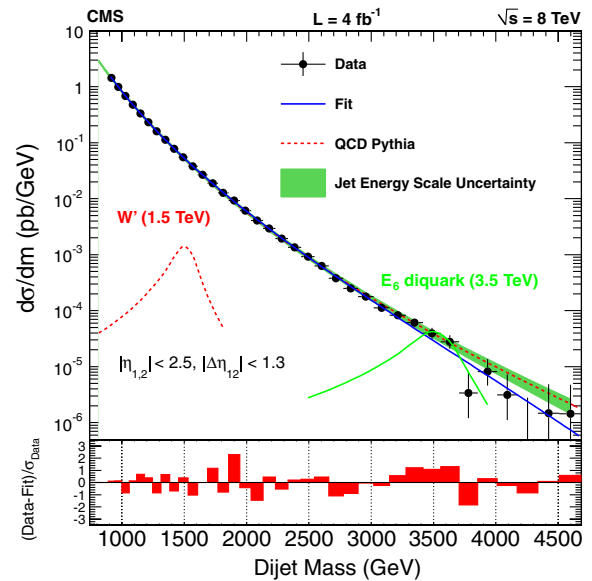


FIG. 1 (color online). The dijet mass spectrum from wide jets (points) compared with a smooth fitted curve (solid line) and with the predicted QCD background [28] (dashed line). The QCD background curve has been normalized to the data (see text) and a linear smoothing between the bins has been applied. The vertical bars on the data points represent the statistical uncertainty, the horizontal bars indicate the bin widths. The shaded band shows the contribution from the systematic uncertainty in the jet energy scale. Also shown are the predictions for a W' boson with a mass of 1.5 TeV, and an E_6 diquark with a mass of 3.5 TeV, obtained fitting the expected distribution to a Crystal Ball [34] function and normalizing the area to the predicted cross section. The bottom part of the plot displays the bin-by-bin residuals (data minus the integral over a bin of the smooth function fitted to the data) divided by the statistical uncertainty in the data.

with the variable $x = m_{jj}/\sqrt{s}$ and four free parameters P_0 , P_1 , P_2 , and P_3 . This functional form has been used in previous searches [3,6,7,35] to describe both data and QCD predictions. The fit is performed maximizing a binned likelihood, the bins being defined as in Fig. 1. The fit result, also shown in Fig. 1, has a chi-squared (χ^2) of 25.7 for 32 degrees of freedom. The bottom part of the figure shows the difference between the data and the fit value, normalized to the statistical uncertainty in the data. Assuming a pure $q\bar{q}$ final state, the largest upward deviation of the data corresponds to a local significance of 2.3σ and a global significance of 0.6σ once including the look elsewhere effect. Different assumptions on the final state composition gives smaller values.

A data-driven determination of the background is obtained through a smooth fit to the data. We use the dijet mass spectrum from wide jets, the background parametrization, and the dijet resonance shapes to set specific limits on new particles produced from and decaying to the same parton pair qq (or $q\bar{q}$), qg , and gg . A separate limit is determined for each process (denoted simply qq , qg , gg) because of the dependence of the signal line shape on the final state, induced by the different amount of FSR for gluons and quarks.

The systematic uncertainty in the determination of the dijet mass is dominated by the uncertainty in the jet energy scale [24] and the uncertainty in the jet energy resolution. The jet energy scale uncertainty translates into a 1.3%

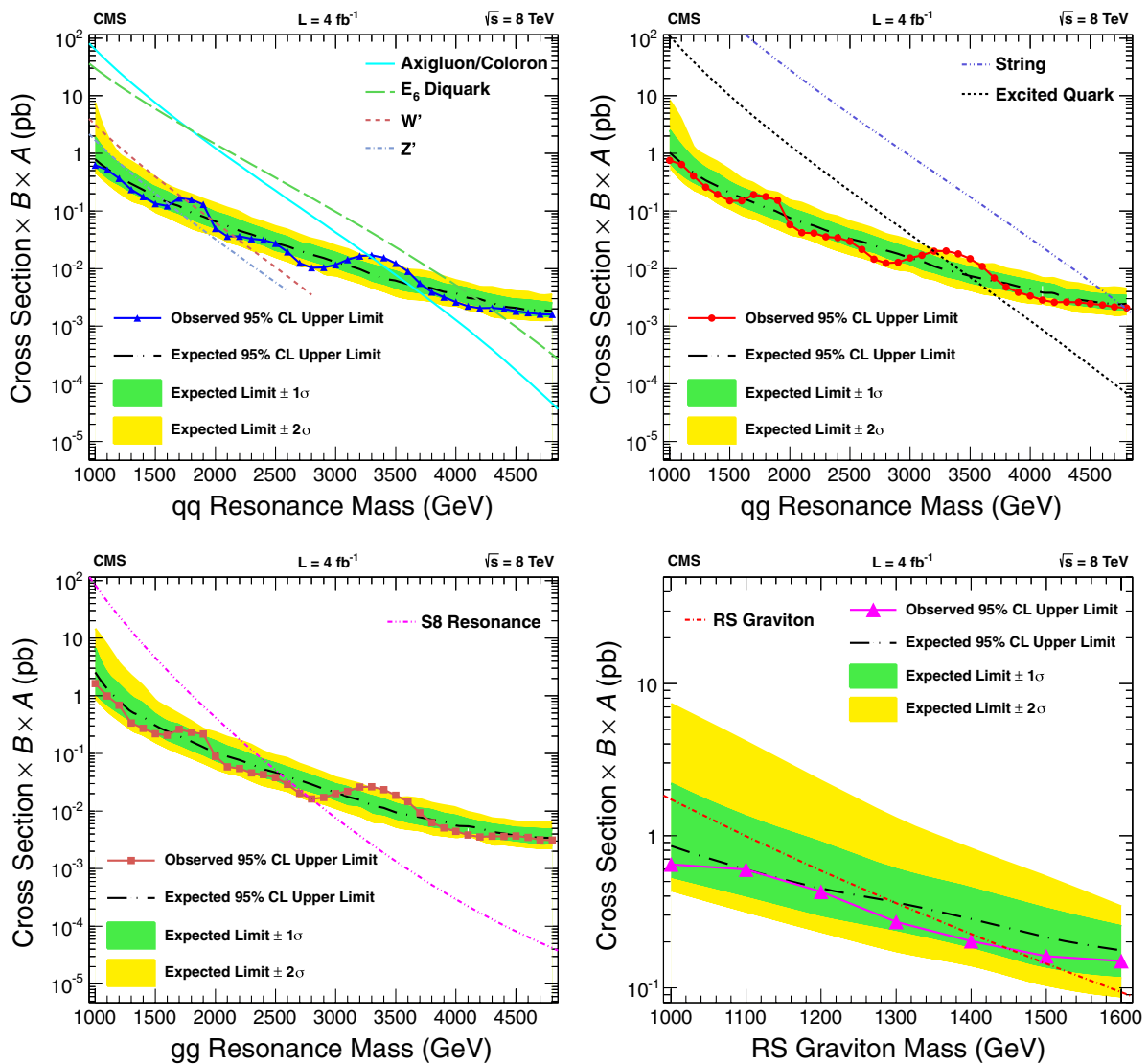


FIG. 2 (color online). Observed upper limits at 95% C.L. on $\sigma \times \mathcal{B} \times A$ for resonances decaying to qq , qg , and gg final state (points and solid lines) compared with the expected limits (dot-dashed dark lines) and their variation at the 1σ and 2σ levels (shaded bands). Predicted cross sections for various resonance assumptions are shown. The signal shape for the RS model is obtained by weighting the shapes for qq and gg final states according to LO calculations of the relative branching fractions.

relative uncertainty in the dijet mass, roughly independent from the mass value; it is propagated to the search by shifting the reconstructed dijet mass of the signal by 1.3% compared to the nominal resolution value. The jet energy resolution uncertainty translates into an uncertainty of 10% in the resolution of the dijet mass [24]; this uncertainty is propagated to the search by smearing and unsmearing the reconstructed dijet mass of the signal according to a Gaussian distribution with σ fixed at 10% of the mass value.

The precision of the overall signal normalization is limited by the knowledge of the integrated luminosity (4.4%) [36]. The statistical uncertainty in the background parametrization introduces a systematic uncertainty in the signal strength. We verified that the use of different parametrizations for the description of the background has a negligible effect compared to the statistical uncertainty in the data, over the whole dijet spectrum. Similarly, MC studies show that the dependence of the signal mass shapes on the number of pileup interactions is negligible. The systematic uncertainties included in this analysis reduce the lower limit on resonance masses by less than ~ 15 GeV, depending on the model.

To set upper limits on the signal cross section we use a Bayesian formalism [37] with a uniform prior for the positive signal cross section; a null probability is assigned to negative values of the cross section; log-normal priors are used to model systematic uncertainties, which are treated as nuisance parameters. We calculate the posterior probability density as a function of resonance cross section independently at each value of the resonance mass. The data are fitted to the background function plus a signal line shape, the signal cross section being a free parameter. The resulting fit function with the signal cross section set to zero is used as the background hypothesis. The uncertainty in the background shape is incorporated by marginalizing over the background fit parameters (not including the signal cross section) after diagonalizing the covariance matrix to account for the correlations in the parameters. 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 was estimated for the qq resonances to be $92.1 \pm 0.4\%$, $95.2 \pm 0.4\%$, and $95.8 \pm 0.3\%$ at respective signal masses of 1500, 2500, and 3000 GeV.

We show in Fig. 2 the observed upper limits at the 95% confidence level (C.L.) on $\sigma \times \mathcal{B} \times A$, i.e. the product of the cross section (σ), the branching fraction (\mathcal{B}) of the resonance into the relevant final state, and the acceptance (A) for reconstructing two jets with $|\Delta\eta_{jj}| < 1.3$ and $|\eta| < 2.5$, for narrow resonances which decay into qq , qg , and gg final states. For example the acceptance for an isotropic decays is $A \approx 0.6$, roughly independent of resonance mass. For the RS graviton, which couples either to a pair of gluons or to a quark-antiquark pair, the model-dependent

limits on cross section are derived using a weighted average of the qq and gg dijet mass shapes, where the weights correspond to the relative branching fractions for these two final states, calculated at LO [20]. The expected limits on cross sections shown in Fig. 2 are estimated with pseudoexperiments generated using background shapes which are determined by signal-plus-background fits to the data.

The observed and expected upper limits can be compared to the predictions for $\sigma \times \mathcal{B} \times A$ before including any detector simulation, in order to determine mass limits on new particles. The calculations shown are obtained in the narrow-width approximation using CTEQ6L1 parton distributions [31]. New particles are excluded at the 95% C.L. in mass regions for which the theoretical curve lies above our upper limit for the appropriate final state.

We list in Table I the observed cross section limits for qq , qg , and gg resonances, as a function of the resonance mass. We determine the expected lower limit on the mass of new resonances by comparing the expected cross section limits to the model predictions. The observed and expected mass exclusions are reported in Table II for various models.

In summary, a search for narrow resonances decaying into a pair of jets has been performed using a data sample corresponding to an integrated luminosity of 4.0 fb^{-1} collected in pp collisions at $\sqrt{s} = 8$ TeV. In the analyzed data sample there is no significant evidence for new

TABLE I. Observed upper limits at the 95% C.L. on $\sigma \times \mathcal{B} \times A$ for resonances decaying to qq , qg , and gg final states as a function of the resonance mass. Experimental systematic uncertainties are taken into account in the limit calculation.

| Mass [GeV] | Upper limit on $\sigma \times \mathcal{B} \times A$ (pb) | | |
|------------|--|--------|--------|
| | qq | qg | gg |
| 1000 | 0.62 | 0.75 | 1.6 |
| 1200 | 0.37 | 0.40 | 0.69 |
| 1400 | 0.18 | 0.19 | 0.27 |
| 1600 | 0.12 | 0.15 | 0.21 |
| 1800 | 0.16 | 0.18 | 0.23 |
| 2000 | 0.050 | 0.058 | 0.089 |
| 2200 | 0.036 | 0.041 | 0.055 |
| 2400 | 0.031 | 0.034 | 0.043 |
| 2600 | 0.019 | 0.021 | 0.029 |
| 2800 | 0.010 | 0.012 | 0.016 |
| 3000 | 0.012 | 0.015 | 0.020 |
| 3200 | 0.017 | 0.020 | 0.026 |
| 3400 | 0.016 | 0.018 | 0.024 |
| 3600 | 0.0090 | 0.011 | 0.015 |
| 3800 | 0.0039 | 0.0047 | 0.0063 |
| 4000 | 0.0026 | 0.0034 | 0.0045 |
| 4200 | 0.0021 | 0.0026 | 0.0036 |
| 4400 | 0.0020 | 0.0026 | 0.0036 |
| 4600 | 0.0017 | 0.0023 | 0.0035 |
| 4800 | 0.0016 | 0.0021 | 0.0031 |

TABLE II. Observed and expected exclusions at the 95% C.L. on the mass of various resonances. Experimental systematic uncertainties are included.

| Model | Final state | Observed excluded mass range [TeV] | Expected excluded mass range [TeV] |
|------------------|-----------------|------------------------------------|------------------------------------|
| String resonance | qg | [1.0, 4.78] | [1.0, 4.75] |
| Excited quark | qg | [1.0, 3.19] | [1.0, 3.47] |
| E_6 diquark | qq | [1.0, 4.28] | [1.0, 4.16] |
| Axigluon/coloron | $q\bar{q}$ | [1.0, 3.27] | [1.0, 3.60] |
| S8 resonance | gg | [1.0, 2.79] | [1.0, 2.54] |
| W' boson | $q\bar{q}$ | [1.0, 1.73] | [1.0, 1.97] |
| Z' boson | $q\bar{q}$ | [1.0, 1.62] | [1.0, 1.58] |
| RS graviton | $q\bar{q} + gg$ | [1.0, 1.45] | [1.0, 1.29] |

particle production. Upper limits are set on the product $\sigma \times \mathcal{B} \times A$ that can be applied to any model of narrow dijet resonance production. Specific lower limits are presented on the mass of string resonances, excited quarks, axigluons, colorons, S8 resonances, E_6 diquarks, W' and Z' bosons starting at 1.0 TeV and extending up to 4.8 TeV for some models. In most cases, these limits extend the previous exclusions obtained using the dijet mass spectrum. The first mass limit on Randall–Sundrum gravitons decaying to dijets is shown.

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