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Search for resonances in the dijet mass spectrum from 7 TeV pp collisions at CMS ☆

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ABSTRACT

A search for narrow resonances with a mass of at least 1 TeV in the dijet mass spectrum is performed using pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 1 fb^{-1}, collected by the CMS experiment at the LHC. No resonances are observed. Upper limits at the 95% confidence level are presented on the product of the resonance cross section, branching fraction into dijets, and acceptance, separately for decays into quark–quark, quark–gluon, and gluon–gluon pairs. The data exclude new particles predicted in the following models at the 95% confidence level: string resonances with mass less than 4.00 TeV, E_6 diquarks with mass less than 3.52 TeV, excited quarks with mass less than 2.49 TeV, axigluons and colorons with mass less than 2.47 TeV, and W′ bosons with mass less than 1.51 TeV. These results extend previous exclusions from the dijet mass search technique.

The Large Hadron Collider (LHC) has recently delivered an integrated luminosity in excess of 1 fb^{-1} at a centre-of-mass energy $\sqrt{s} = 7$ TeV. This extends considerably the search territory for new physics. In this Letter we report a search for narrow resonances in the dijet mass spectrum, performed with the Compact Muon Solenoid (CMS) detector [1], with sensitivity exceeding that of our previous search [2]. Proton–proton collisions produce two or more energetic jets when the constituent partons are scattered with large transverse momenta, p_T. The invariant mass spectrum of the two jets with largest p_T (dijets) is predicted to fall steeply and smoothly by quantum chromodynamics (QCD). Many extensions of the standard model predict the existence of new massive objects that couple to quarks (q) and gluons (g), and result in resonances in the dijet mass spectrum.

We apply the results of this generic search to the following specific models of narrow s-channel dijet resonances:

- String resonances (S), which are Regge excitations of quarks and gluons in string theory and decay predominantly to qg [3, 4].
- Scalar diquarks (D), which decay to qq and $\bar{q}\bar{q}$, predicted by a grand unified theory based on the E_6 gauge symmetry group [5].
- Mass-degenerate excited quarks (q^*), which decay to qg, predicted if quarks are composite objects [6,7]; the compositeness scale is set to be equal to the mass of the excited quark.
- Axial-vector particles called axigluons (A), which decay to $q\bar{q}$, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$ [8].
- Color-octet colorons (C), also decaying to $q\bar{q}$, predicted by the flavour-universal coloron model, embedding the SU(3) symmetry of QCD in a larger gauge group [9].
- New gauge bosons (W′ and Z′), which decay to $q\bar{q}$, predicted by models that include new gauge symmetries [10]; the W′ and Z′ bosons are assumed to have standard model couplings.
- Randall–Sundrum (RS) gravitons (G), which decay to $q\bar{q}$ and gg, predicted in the RS model of extra dimensions [11]; the value of the dimensionless coupling $\kappa/\overline{M}_{\text{Pl}}$ is chosen to be 0.1.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing an axial field of 3.8 tesla. Within the field volume at central values of pseudorapidity η are the silicon pixel and strip tracker ($|\eta| < 2.4$) and the barrel and endcap calorimeters ($|\eta| < 3$); a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadronic calorimeter (HCAL). An iron/quartz-fiber calorimeter is located in the forward region ($3 < |\eta| < 5$), outside the field volume. For triggering purposes and to facilitate jet reconstruction, the ECAL and HCAL cells are grouped into towers projecting radially outward from the centre of the detector. The energy deposits

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measured in the ECAL and the HCAL within each projective tower are summed to find the calorimeter tower energy. A more detailed description of the CMS experiment can be found elsewhere [1].

The CMS coordinate system has the origin at the center of the detector. The z-axis points along the direction of the anticlockwise beam, with the transverse plane perpendicular to the beam; ϕ is the azimuthal angle, θ is the polar angle, and the pseudorapidity is defined as $\eta \equiv -\ln(\tan[\theta/2])$.

The integrated luminosity of the data sample selected for this analysis is $1.01 \pm 0.06\ \text{fb}^{-1}$. Events are recorded using a two-tier trigger system. Objects satisfying the requirements at the first level (L1) are passed to the High Level Trigger (HLT). The sample was collected with a multijet trigger at the HLT, which is based on H_T, the sum of the transverse energies of all jets in the event with p_T above 40 GeV. The trigger selects events with H_T in the HLT exceeding 550 GeV. Another multijet trigger with a lower H_T threshold and a prescaling of events is used for the purpose of measuring trigger efficiencies. The trigger efficiency is measured from the data to be larger than 99.9% for dijet masses above 838 GeV.

To remove possible instrumental and non-collision backgrounds in the selected sample, jets are required to pass identification criteria that are fully efficient for signal [12]. Events are required to have a reconstructed primary vertex within the range $|z| < 24$ cm.

We consider two types of standard jets with different inputs: particle-flow jets, which we use for the search, and calorimeter jets, which we use as a check. The particle-flow algorithm [13] reconstructs all stable particles in an event by combining information from all subdetectors. The algorithm categorizes all particles into the following five types: muons, electrons, photons, charged hadrons, and neutral hadrons. Particle-flow jets use reconstructed particles as input to the jet reconstruction algorithm, while calorimeter jets use calorimeter energy deposits as the input.

The reconstructed jet energy E is defined as the scalar sum of the energies of the constituents of the jet, and the jet momentum $\vec{p}$ is the corresponding vector sum of the momenta of the inputs. The jet transverse momentum p_T is the component of $\vec{p}$ perpendicular to the beam. The values of E and $\vec{p}$ of a reconstructed jet are corrected for the response of the detector to a generated jet, using Monte Carlo simulations, test beam results, and collision data [14]. Separate corrections are derived for calorimeter jets and for particle-flow jets. The corrections account for pileup of multiple pp collisions [15].

This analysis combines particle-flow jets reconstructed with the anti-k_T algorithm [16] into "wide jets", which we use to measure the mass spectrum and search for new physics. Wide jets are the result of a radiation recovery algorithm for dijets, inspired by recent jet-grooming algorithms [17–19]. The partons from the decay of heavy objects can radiate additional partons, which are often produced at a large angle with respect to the original parton direction and thus are clustered into a separate jet by the anti-k_T jet-clustering algorithm. Wide jets collect more of this final-state radiation and therefore improve the mass resolution for dijet resonances. First, we reconstruct jets using the anti-k_T algorithm with distance parameters $R = 0.5$ (AK5 jets) and $R = 0.7$ (AK7 jets), which are the two standard choices we support for analysis at CMS. In our previous search [2] we used AK7 jets, since they have a larger distance parameter than AK5 jets and capture more radiation. Here we introduce wide jets reconstructed from AK5 jets to produce a wider jet than AK7. We correct the AK5 jet energy and select the two AK5 jets with the highest p_T in the event (leading AK5 jets). Then we add the Lorentz vectors of all other AK5 jets with $p_T > 10$ GeV and $|\eta| < 2.5$ to the closest AK5 leading jet, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, to obtain the two leading wide jets. The parameter ΔR sets the maximum size of the wide jet.

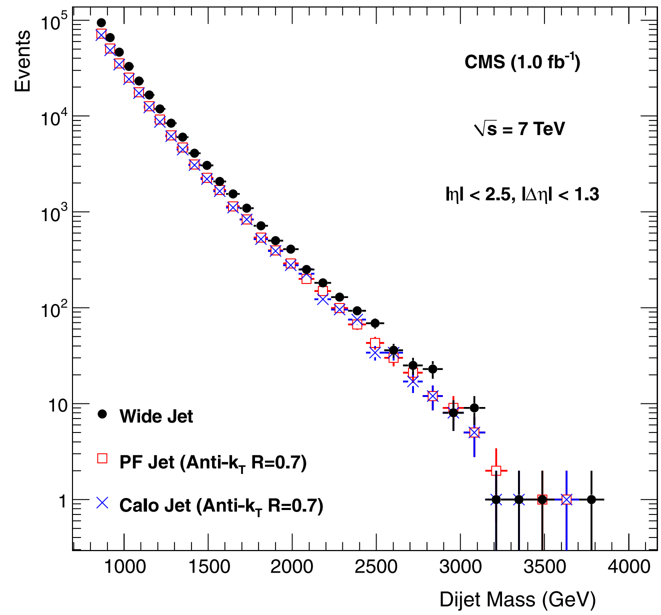

Fig. 1. The number of events observed versus dijet mass for wide jets (solid circles), particle flow AK7 jets (open boxes), and calorimeter AK7 jets (X symbols).

The dijet system is composed of the two leading jets. We require that the pseudorapidity separation $\Delta\eta$ of the two leading jets satisfy $|\Delta\eta| < 1.3$, and that both jets be in the region $|\eta| < 2.5$. These $\Delta\eta$ and η requirements maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD background. The dijet mass is given by $m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$. We select events with $m > 838$ GeV without any requirements on the p_T of the leading jet.

The number of events as a function of dijet mass is shown in Fig. 1 for both calorimeter and particle-flow AK7 jets; the observed rates agree. Fig. 1 also shows that the observed wide jet dijet mass distribution is shifted to higher mass because wide jets collect more energy.

Fig. 2 presents the inclusive dijet mass distribution for pp $\to$ 2 leading wide jets + X, where X can be anything, including additional jets. Wide jets are used and we plot the measured differential cross section as a function of dijet mass in bins approximately equal to the dijet mass resolution [2]. The data are compared to a QCD prediction from PYTHIA v6.424 [20], which includes a simulation of the CMS detector and the jet energy corrections. The prediction uses a renormalization scale $\mu = p_T$ of the hard-scattered partons and CTEQ6L1 parton distribution functions [21], and has been normalized to the data by multiplying the prediction by a factor of 1.33. The shape of the PYTHIA prediction agrees with the data within the jet energy scale uncertainty, which is the dominant systematic uncertainty. To test the smoothness of our measured cross section as a function of dijet mass, we fit the following parameterization to the data:

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

with four free parameters P_0, P_1, P_2, and P_3. This functional form is used in previous searches [22,23,2,24] to describe both data and QCD predictions. In Fig. 2 we show the fit, which has a chi-squared (χ^2) of 27.5 for 28 degrees of freedom, as well as the bin-by-bin significance, defined as the difference between the data and the fit value, divided by the statistical uncertainty of the data. Fig. 3 displays the ratio of the data to the fit. The data are well described by the smooth parameterization.

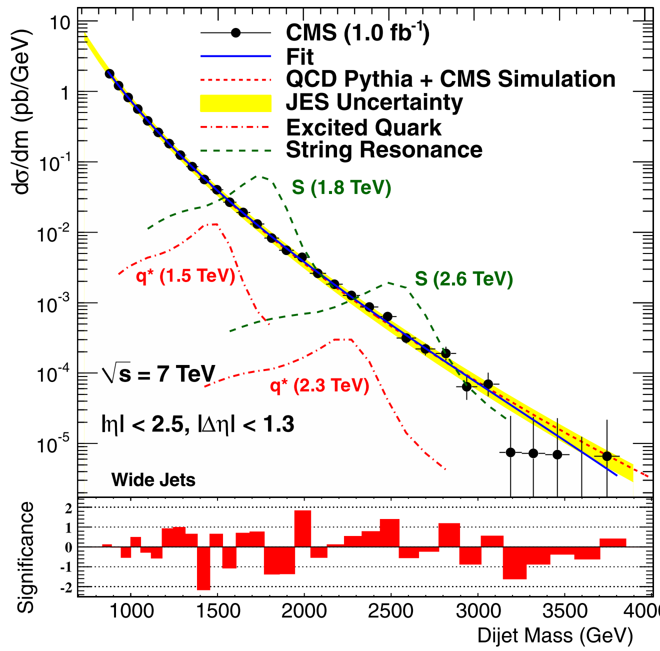

Fig. 2. Dijet mass spectrum from wide jets (points) compared to a smooth fit (solid) and to predictions [20] including detector simulation of QCD (short-dashed), excited quark signals (dot-dashed), and string resonance signals (long-dashed). The QCD prediction has been normalized to the data (see text). The error bars are statistical only. The shaded band shows the systematic uncertainty in the jet energy scale (JES). The bin-by-bin significance of the data-fit difference (see text) is shown at bottom.

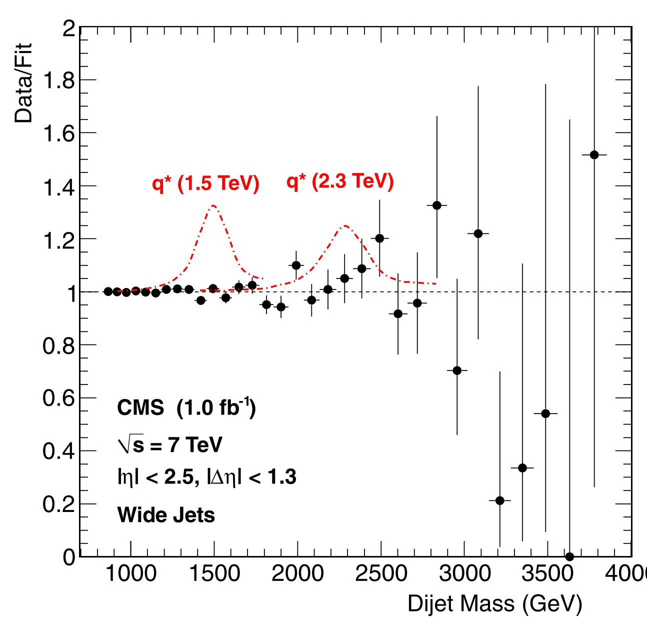

Fig. 3. Ratio (points) between the dijet mass data from wide jets and the smooth fit, compared to the simulated ratios for excited quark signals (dot-dashed) in the CMS detector. The error bars represent statistical uncertainties only.

We search for narrow resonances, for which the natural resonance width is small compared to the CMS dijet mass resolution. Figs. 2 and 3 present the predicted dijet mass distribution for excited quarks using PYTHIA v6.424 and the CMS detector simulation. The predicted mass distributions have a Gaussian core coming from the jet energy resolution and a tail towards lower mass from QCD radiation. This can be seen in Fig. 4, which shows examples of the predicted dijet mass distribution of resonances from three different parton pairings: $q\bar{q}$ (or qq) resonances from the process $G \to q\bar{q}$ [11], qg resonances from $q^* \to qg$ [6], and gg resonances from $G \to gg$ [11]. The increase of the width of the measured mass shape and the shift of the mass distribution towards lower masses are enhanced when the number of gluons in the final state is larger, because QCD radiation is larger for gluons than for quarks. The distributions in Fig. 4 are generically valid for other resonances with the same parton content and with a natural width small compared to the dijet mass resolution, and are examples of the shapes we use to set limits on dijet resonances. Wide-jet reconstruction gives a little better resolution than AK7-jet reconstruction, as shown in Fig. 4 for gg resonances. There is no indication of narrow resonances in our data, as shown in Figs. 2 and 3.

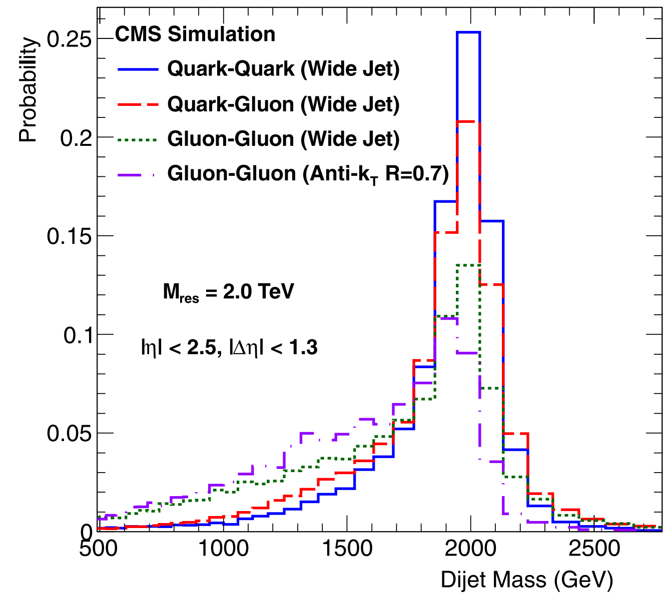

Fig. 4. Simulation of the expected dijet mass distributions in the CMS detector from a narrow 2.0 TeV resonance of type quark–quark (solid), quark–gluon (dashed), and gluon–gluon (dotted) using wide jet reconstruction, and of type gluon–gluon using anti-k_T jet reconstruction with distance parameter $R = 0.7$ (dot-dashed).

We use the dijet mass data from wide jets, the background (QCD) parameterization, and the dijet resonance shapes to set specific limits on new particles decaying to the parton pairs qq (or $q\bar{q}$), qg, and gg. The dominant sources of systematic uncertainty are the jet energy scale (2.2%), the jet energy resolution (10%), the integrated luminosity (6%), and the statistical uncertainty on the background parameterization, which are all considered nuisance parameters. The jet energy scale uncertainty is shown in Fig. 2 and is equivalent to a 15% uncertainty in the background cross section. For setting upper limits we use a Bayesian formalism with a uniform prior for the signal cross section [25]. To incorporate systematic uncertainties we use a fully Bayesian treatment, integrating the likelihood over these nuisance parameters. We calculate the posterior probability density as a function of resonance cross section independently at each value of the resonance mass. Table 1 lists the generic upper limits at the 95% confidence level (CL) on $\sigma \times B \times A$, i.e. the product of the cross section (σ), the branching fraction (B), and the acceptance (A), for the kinematic requirements $|\Delta\eta| < 1.3$ and $|\eta| < 2.5$, for qq, qg, and gg resonances. The acceptance for isotropic decays is $A \approx 0.6$ independent of resonance mass. The observed upper limits in Table 1 can be compared to predictions of $\sigma \times B \times A$ at the parton level, without any detector simulation, in order to determine mass limits on new particles.

Table 1
The observed upper limits at the 95% CL on $\sigma \times B \times A$, as a function of the new-particle mass, for narrow resonances decaying to dijets with partons of type quark–quark (qq), quark–gluon (qg), and gluon–gluon (gg). The limits apply to the kinematic range where the two jets have pseudorapidity $|\eta| < 2.5$ and $|\Delta\eta| < 1.3$.

Mass (TeV)	Upper limit (pb)			Mass (TeV)	Upper limit (pb)		
	qq	qg	gg		qq	qg	gg
1.0	1.098	1.245	1.851	2.6	0.0619	0.0749	0.1011
1.1	0.777	0.909	1.374	2.7	0.0470	0.0577	0.0781
1.2	0.662	0.732	1.079	2.8	0.0356	0.0440	0.0601
1.3	0.486	0.535	0.803	2.9	0.0274	0.0336	0.0455
1.4	0.284	0.332	0.518	3.0	0.0210	0.0257	0.0348
1.5	0.231	0.265	0.395	3.1	0.0158	0.0196	0.0268
1.6	0.201	0.226	0.326	3.2	0.0118	0.0151	0.0209
1.7	0.168	0.190	0.280	3.3	0.0091	0.0117	0.0163
1.8	0.115	0.138	0.207	3.4	0.0075	0.0097	0.0136
1.9	0.113	0.131	0.183	3.5	0.0065	0.0085	0.0117
2.0	0.121	0.140	0.193	3.6	0.0061	0.0078	0.0105
2.1	0.108	0.130	0.183	3.7	0.0059	0.0074	0.0096
2.2	0.093	0.115	0.160	3.8	0.0057	0.0071	0.0091
2.3	0.089	0.108	0.148	3.9	0.0055	0.0068	0.0084
2.4	0.085	0.102	0.138	4.0	0.0052	0.0064	0.0080
2.5	0.077	0.092	0.125	4.1	0.0048	0.0060	0.0073

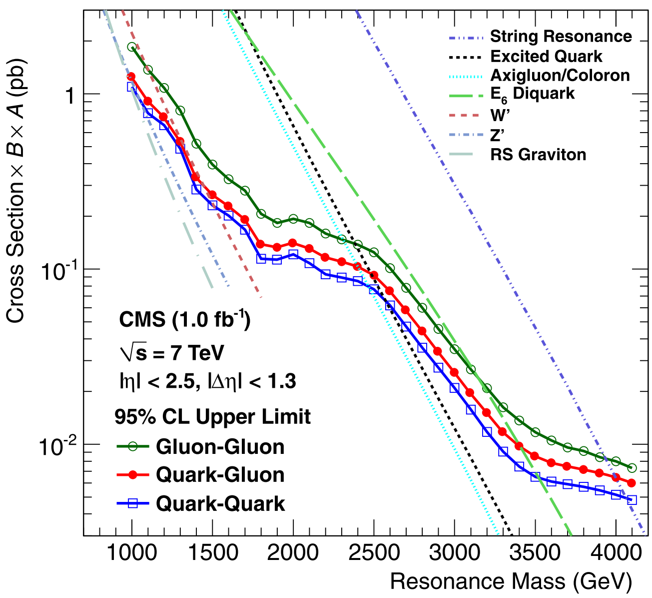

Fig. 5. The 95% CL upper limits on $\sigma \times B \times A$ for dijet resonances of type gluon–gluon (open circles), quark–gluon (solid circles), and quark–quark (open boxes), compared to theoretical predictions for string resonances [3], E_6 diquarks [5], excited quarks [6], axigluons [8], colorons [9], new gauge bosons W′ and Z′ [10], and Randall–Sundrum gravitons [11].

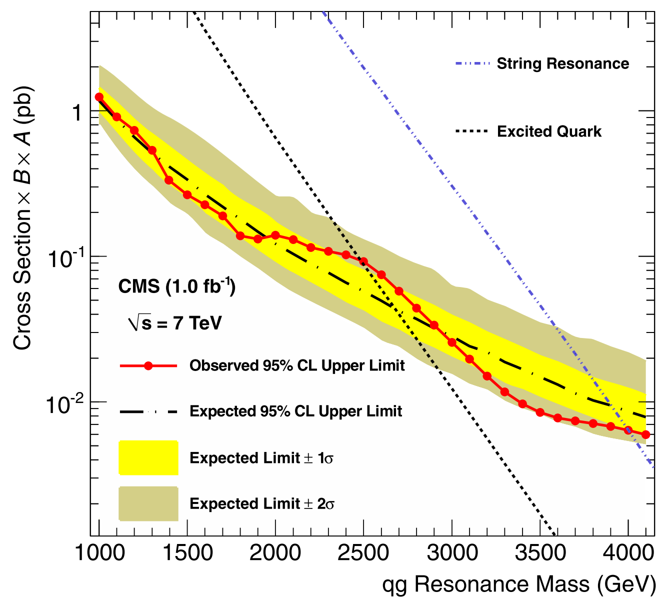

Fig. 6. The observed 95% CL upper limits on $\sigma \times B \times A$ for quark–gluon dijet resonances (points) are compared to the expected limits (dot-dashed) and their expected statistical variation at the 1σ and 2σ levels (shaded bands) and are also compared to the theoretical predictions for string resonances [3] and excited quarks [6].

In addition to these observed upper limits, we also calculate the expected upper limits using pseudo-experiments: searches conducted on random samples of events generated from our smooth background parameterization. The use of wide jets instead of AK7 jets improves the expected upper limits on the resonance cross section by roughly 20% for gg, 10% for qg, and 5% for qq resonances.

In Fig. 5 we compare the observed upper limits to the model predictions as a function of resonance mass. The predictions are from lowest-order calculations [26] of the product $\sigma \times B \times A$ using CTEQ6L1 parton distributions [21]. New particles are excluded at the 95% CL in mass regions for which the theory curve lies above our upper limit for the appropriate pair of partons. We also determine the expected lower limit on the mass of each new particle by comparing the expected cross section limits to the model predictions. An example of the expected limits is shown in Fig. 6 where for qg resonances we compare the expected limits and their uncertainty bands to both observed limits and model predictions. Our search starts at a resonance mass of 1 TeV, and all quoted exclusions start at this mass value. The observed and expected limits are listed in Table 2. For string resonances the expected mass limit is 3.90 TeV and we exclude masses less than 4.00 TeV; this extends our previous exclusion of $0.5 < M(\mathrm{S}) < 2.5$ TeV [2]. For E_6 diquarks the expected limit is 3.28 TeV and we exclude masses less than 3.52 TeV; this extends our previous exclusions of $0.50 < M(\mathrm{D}) < 0.58$ TeV, $0.97 < M(\mathrm{D}) < 1.08$ TeV, and $1.45 < M(\mathrm{D}) < 1.60$ TeV [2]. For excited quarks the expected mass limit is 2.68 TeV and we exclude masses less than 2.49 TeV; this extends our previous exclusion of $0.5 < M(\mathrm{q}^*) < 1.58$ TeV [2] and the ATLAS exclusion of $0.6 < M(\mathrm{q}^*) < 2.15$ TeV from the dijet mass spectrum [24]. For axigluons or colorons the expected mass limit is 2.66 TeV and we exclude masses less than 2.47 TeV; this extends our previous exclusions of $0.50 < M(\mathrm{A,C}) < 1.17$ TeV and $1.47 < M(\mathrm{A,C}) < 1.52$ TeV [2], and the ATLAS exclusion of

Table 2
For each model we list the observed and expected upper values of the excluded mass range at 95% CL. The lower value of the excluded mass range from this search is 1 TeV.

Model	Excluded mass (TeV)	
	Observed	Expected
String resonances	4.00	3.90
E_6 diquarks	3.52	3.28
Excited quarks	2.49	2.68
Axigluons/colorons	2.47	2.66
W′ bosons	1.51	1.40

$0.6 < M(\mathrm{A,C}) < 2.1$ TeV [24]. For W′ bosons the expected mass limit is 1.40 TeV and we exclude masses less than 1.51 TeV; this extends the CDF exclusion of $0.3 < M(\mathrm{W}') < 0.8$ TeV from the dijet mass spectrum [22]. We do not set any mass limits on Z′ bosons and RS gravitons. The systematic uncertainties included in this analysis reduce the excluded upper masses by 0.03 TeV or less for each type of new particle.

In summary, the dijet invariant mass distribution has been measured to be a smoothly falling distribution, as expected within the standard model. There is no evidence for new particle production. We present generic upper limits on the product $\sigma \times B \times A$ that can be applied to any model of dijet resonance production. We set specific mass limits on string resonances, E_6 diquarks, excited quarks, axigluons, flavour-universal colorons, and W′ bosons, all of which extend previous exclusions from the dijet mass search technique.

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