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Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration[*]

Abstract

A search for narrow resonances in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ is presented. The invariant mass distribution of the two leading jets is measured with the CMS detector using a data set corresponding to an integrated luminosity of $2.4\,\mathrm{fb}^{-1}$. The highest observed dijet mass is 6.1 TeV. The distribution is smooth and no evidence for resonant particles is observed. Upper limits at 95% confidence level are set on the production cross section for narrow resonances with masses above 1.5 TeV. When interpreted in the context of specific models, the limits exclude string resonances with masses below 7.0 TeV, scalar diquarks below 6.0 TeV, axigluons and colorons below 5.1 TeV, excited quarks below 5.0 TeV, color-octet scalars below 3.1 TeV, and W' bosons below 2.6 TeV. These results significantly extend previously published limits.

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Deep inelastic proton-proton (pp) collisions often produce two or more energetic jets when the constituent partons are scattered with large transverse momenta (p_{T}). The invariant mass m_{jj} of the pair of jets having the largest values of p_{T} in the event (the dijet) has a spectrum that is predicted by quantum chromodynamics (QCD) to fall steeply and smoothly with increasing dijet mass [1]. Many extensions of the standard model predict the existence of new massive particles that couple to quarks (q) and gluons (g) and can be detected as resonances in the dijet mass spectrum. In this Letter, we report a search for narrow resonances, those with natural widths that are small compared to the experimental resolution. The search uses the dijet mass spectrum measured with the CMS detector at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$. The data correspond to an integrated luminosity of $2.4\,\mathrm{fb}^{-1}$ from the 2015 running of the CERN LHC (Run 2).

The most stringent current bounds on dijet resonance production have been presented by the CMS [2–6] and ATLAS [7–11] Collaborations, using proton-proton collisions at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ from LHC Run 1. A summary of previous searches and a comparison of the different strategies are presented in Ref. [12]. The present search is expected to be more sensitive than previous studies for dijet masses above 2 TeV. We present a model-independent search and, in addition, consider the following models of s-channel dijet resonances: string resonances [13, 14], scalar diquarks [15], axigluons [16, 17], colorons [17, 18], excited quarks (q^*) [19, 20], color-octet scalars [21], new gauge bosons (W' and Z') [22], and Randall–Sundrum (RS) gravitons (G) [23]. More details on the specific choices of couplings for these models can be found in Ref. [4].

The CMS detector and its coordinate system, including the azimuthal angle ϕ (in radians) and the pseudorapidity η, are described in detail in Ref. [24]. Events are selected using a two-tier trigger system. Events satisfying loose jet requirements at the first level (L1) are examined by the high-level trigger (HLT), where jets are clustered from particle-flow (PF) [25, 26] candidates, discussed in the next paragraph. The jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 3$ are used to compute H_{T}, the scalar sum of the jet p_{T}. Events are accepted if they have $H_{\mathrm{T}} > 800\,\mathrm{GeV}$ or include a jet with $p_{\mathrm{T}} > 500\,\mathrm{GeV}$. At least one reconstructed vertex is required with $|z| < 24\,\mathrm{cm}$. The primary vertex is defined as the vertex with the highest sum of p_{T}^2 of the associated tracks.

The PF algorithm is used to reconstruct the particles in an event and to identify them as muons, electrons (with associated Bremsstrahlung photons), photons (unconverted and converted into $\mathrm{e}^+\mathrm{e}^-$ pairs), and either charged or neutral hadrons. These PF candidates are clustered into jets using the anti-k_t algorithm [27] with a distance parameter of 0.4, implemented in the FASTJET package [28]. Charged PF candidates not originating from the primary vertex are removed prior to the jet finding. An event-by-event jet-area-based correction [29–31] is applied to the jets to remove the estimated energy from additional collisions in the same or adjacent bunch crossings (pileup). The jet momenta and energies are further corrected using calibration constants obtained from simulation, test beam results, and pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$, using methods described in Ref. [31] with all in situ calibrations obtained from the current data. All jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$. The two jets with largest p_{T} are defined as the leading jets. Jet identification criteria [32] are applied to remove spurious jets associated with calorimeter noise. An event is rejected if either of the two leading jets does not satisfy the jet identification criteria.

Geometrically close jets are combined into “wide jets” and used to determine the dijet mass, as in our previous searches [3–6]. The wide-jet algorithm reduces the analysis sensitivity to gluon radiation from the final state partons. The two leading jets are used as seeds and the four-vectors of all other jets, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, are added to the nearest leading jet to obtain two wide jets, which then form the dijet system. The background from t-channel dijet events is suppressed by requiring the pseudorapidity separation of the two wide jets to satisfy $|\Delta\eta_{jj}| < 1.3$. The above requirements, originally developed for the analysis of Run 1 data, maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD dijet background. It has been verified that these requirements remain optimal for collisions at $\sqrt{s} = 13\,\text{TeV}$. We select events with $m_{jj} > 1.2\,\text{TeV}$ for which the combined L1 trigger and HLT are found to be fully efficient.

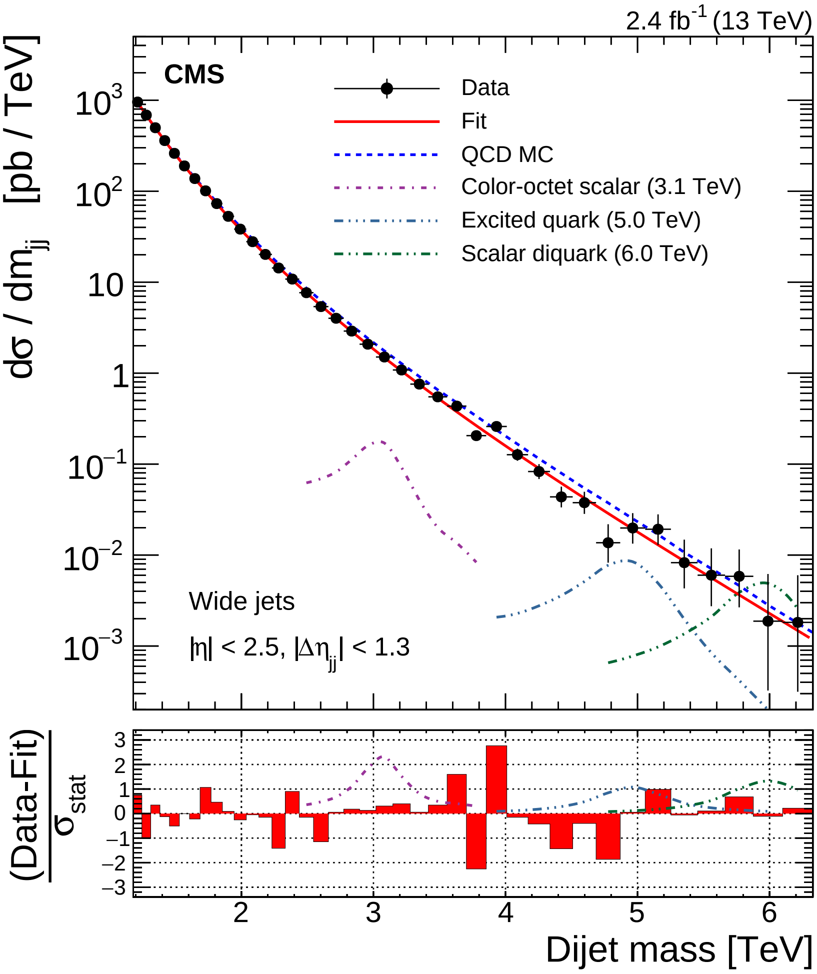

Figure 1: Dijet mass spectrum (points) compared to a fitted parameterization (solid curve) and to the prediction of the PYTHIA 8 [33] QCD MC event generator including simulation of the detector (dashed curve). The lower panel shows the difference between the data and the fitted parametrization, divided by the statistical uncertainties. The predicted distributions of narrow resonance signals for three models, with resonance mass values corresponding to the respective 95% confidence level exclusion limit, are shown in both panels (dash-dotted curves).

Figure 1 shows the dijet mass spectrum, defined as the observed number of events in each bin divided by the integrated luminosity and bin width, with predefined bins of width corresponding to the dijet mass resolution [2]. The highest dijet mass observed is 6.1 TeV. The data are compared with a leading-order QCD Monte Carlo (MC) prediction from the PYTHIA 8 (v205) [33] generator with the CUETP8M1 tune [34, 35], including a GEANT4-based [36] simulation of the CMS detector. The PYTHIA simulation uses the NNPDF2.3LO [37] parton distribution functions (PDF). The renormalization and factorization scales are both set at the p_{T} value of the hard-scattered partons. The MC prediction is normalized to the integrated contents of the data in Fig. 1, requiring multiplication of the predicted cross section by a factor of 0.88.

To test the smoothness of the measured dijet mass spectrum, we fit the data with the parameterization

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

where $x = m_{\mathrm{jj}}/\sqrt{s}$ and P_0, P_1, P_2, and P_3 are fitted parameters. This functional form was also used in previous searches [2–11, 38] to describe the data and the QCD predictions. In Fig. 1 we show the result of the binned maximum likelihood fit, which yields $\chi^2 = 31$ for 35 degrees of freedom, where the χ^2 is determined using the Poisson uncertainties shown in Fig. 1. The data are seen to be well described by the fit.

We search in the dijet mass spectrum for narrow resonances. Figure 2 shows example dijet mass distributions for simulated signal events, generated with the PYTHIA 8 program. The predicted mass distributions have Gaussian cores from the jet energy resolution, and tails towards lower mass values primarily from QCD radiation. The contribution of this low-mass tail to the

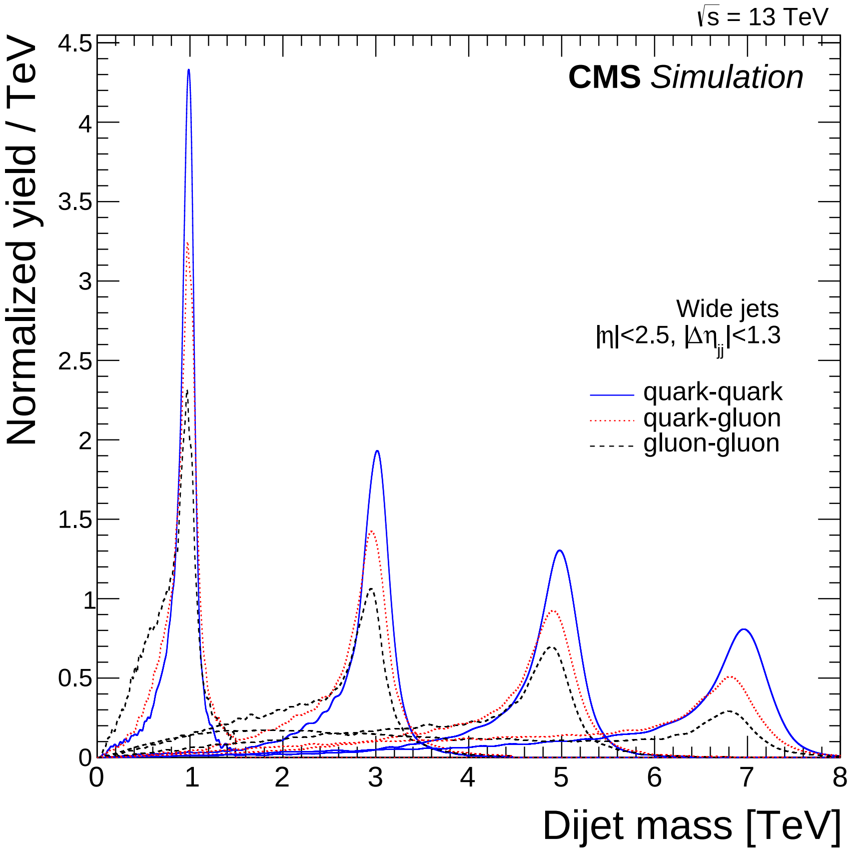

Figure 2: The reconstructed resonance mass spectrum predicted by the PYTHIA 8 [33] MC event generator, including simulation of the detector, for resonances generated with mass values 1, 3, 5, and 7 TeV, for quark-quark processes modeled by $\mathrm{q\bar{q}} \to \mathrm{G} \to \mathrm{q\bar{q}}$ (solid), for quark-gluon processes modeled by $\mathrm{qg} \to \mathrm{q}^* \to \mathrm{qg}$ (dotted), and for gluon-gluon processes modeled by $\mathrm{gg} \to \mathrm{G} \to \mathrm{gg}$ (dashed), where G is a RS graviton and q^* is an excited quark.

lineshape depends on the parton content of the resonance (qq, qg, or gg). Resonances containing gluons, which emit QCD radiation more strongly than quarks, have a more pronounced tail. For the high-mass resonances, there is also a significant contribution that depends both on the PDF and on the natural width of the Breit–Wigner resonance. For resonances produced through interactions of nonvalent partons in the proton, the low-mass component of the Breit–Wigner resonance distribution is amplified by the rise of the parton probability distribution at low fractional momentum. These effects cause a large tail at low mass values. Neglecting the tails, the approximate value of the dijet mass resolution varies with resonance mass from 7% at 1.5 TeV to 4% at 7 TeV.

There is no evidence for a narrow resonance in the data, as seen from Fig. 1. The most significant excess in the data relative to the background fit occurs for a dijet mass of 3.9 TeV. A fit to the hypothesis of a narrow qq resonance, which includes contributions from the bin at 3.9 TeV and neighboring bins, has a local statistical significance of 1.7 standard deviations. Figure 1 includes example signal distributions of the three kinds of narrow resonances (qq, qg, and gg) at the mass values (6.0, 5.0, and 3.1 TeV) corresponding to the limit set on the respective models (scalar diquark, excited quark, and color-octet scalar). These limits are presented below.

We use the dijet mass spectrum from wide jets, the background parameterization, and the dijet resonance shapes to set limits on new particles decaying to the parton pairs qq (or $q\overline{q}$), qg, and gg. A separate limit is determined for each final state (qq, qg, and gg) because of the dependence of the dijet resonance shape on the type of the two final-state partons.

The dominant sources of systematic uncertainty are the jet energy scale, jet energy resolution, integrated luminosity, and the estimation of background. The uncertainty in the jet energy scale is 2%, determined from Run 2 data using the methods described in Ref. [31]. This uncertainty is propagated to the limits by shifting the dijet mass for signal events by ±2%. The uncertainty in the jet energy resolution translates into an uncertainty of 10% in the resolution of the dijet mass [31], and is propagated to the limits by increasing and decreasing by 10% the reconstructed width of the dijet mass shape for signal. The luminosity scale and its uncertainty are estimated from beam-beam scans utilizing the methods from Ref. [39]. The uncertainty in the integrated luminosity is 12%, and is propagated to the normalization of the signal. Changes in the values of the parameters describing the background introduce a change in the signal strength that is accounted for as a systematic uncertainty. The dependence of the signal mass distributions on the number of pileup interactions is negligible.

To set upper limits on signal cross sections we use a Bayesian formalism [40] with a uniform prior for a positive signal cross section; log-normal priors are used to model systematic uncertainties in the jet energy scale, jet energy resolution, and integrated luminosity, all treated as nuisance parameters to be integrated over. We calculate the likelihood, namely the posterior probability density as a function of resonance cross section, independently at each value of resonance pole mass from 1.5 to 7.2 TeV in 0.1 TeV steps. Resonances with masses less than 1.5 TeV are too close to the lower edge of our dijet mass spectrum to produce a peak distinguishable from the background and are therefore not considered. Examples of the resonance shapes used are shown in Fig. 2. The data are fitted with the background function plus a signal shape, with the signal cross section a fitted parameter. The resulting fitting function, with the signal cross section set to zero, is used as the background estimate. The likelihood is formed using as input the data, the background estimate from the best fit of the signal+background hypothesis to the data, and the resonance shape multiplied by the resonance cross section. The uncertainty in the background is incorporated through marginalization, i.e., by integrating the likelihood over the background parameters using uniform priors. The integration is performed for each of the background nuisance parameters in a range around the best-fit values, corresponding to a decrease in the likelihood by a factor of 1000 from its maximum value for each parameter independently.

Figure 3 shows the model-independent observed upper limits at 95% confidence level (CL) on $\sigma\, B\, A$, i.e., the product of the cross section (σ), the branching fraction (B), and the acceptance (A) for the kinematic requirements $|\Delta\eta_{\mathrm{jj}}| < 1.3$ and $|\eta| < 2.5$, for narrow qq, qg, and gg resonances. Figure 3 also shows the expected limits on the cross section and their bands of uncertainty. The expected limits are estimated with pseudo-experiments generated using background-only hypotheses. The generated mass spectra are fit with a background+signal model to extract expected upper limits. The difference in the limits for qq, qg, and gg resonances at the same resonance mass originates from the difference in their lineshapes. All upper limits presented are compared to the parton-level predictions of $\sigma\, B\, A$, without detector simulation, to determine mass limits on new particles. The model predictions shown in Fig. 3 are calculated in the narrow-width approximation [12] using the CTEQ6L1 [41] PDF at leading order, with a next-to-leading order correction factor of approximately 1.3 included for the W′ and Z′ models [42], and approximately 1.2 for the axigluon and coloron models [17]. The acceptance is evaluated at the parton level for the resonance decay to two partons. In the case of isotropic decays it is $A \approx 0.6$ independent of resonance mass.

For a given model, new particles are excluded at 95% CL in mass regions where the theoretical prediction lies at or above the observed upper limit for the appropriate final state of Fig. 3. The observed and expected mass limits reported in Table 1 represent significant extensions of the most stringent limits from LHC Run 1 [6, 11]. For string resonances, the observed mass limit of 7.0 TeV extends the previous CMS limit of 5.0 TeV; for scalar diquarks, the observed mass limit of 6.0 TeV extends the previous CMS limit of 4.7 TeV; for axigluons and colorons, the observed mass limit of 5.1 TeV extends the previous CMS limit of 3.6 TeV; for excited quarks, we set a mass limit of 5.0 TeV compared to the ATLAS limit of 4.06 TeV; for a color-octet scalar, the observed mass limit of 3.1 TeV improves the ATLAS limit of 2.7 TeV; and for a W′ boson, we exclude masses up to 2.6 TeV, just beyond the ATLAS limit of 2.45 TeV. With the current data sample we cannot set mass limits on Z′ bosons with standard-model-like couplings or on RS gravitons with dimensionless coupling less than 0.1.

In summary, a search for narrow resonances decaying into a pair of jets has been performed using a data sample of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ corresponding to an integrated luminosity of $2.4\,\mathrm{fb}^{-1}$. The dijet mass spectrum has been measured to be a smoothly falling distribution. In the analyzed data sample, there is no evidence for resonant particle production. We present generic upper limits on the product $\sigma\, B\, A$ that are applicable to any model of narrow dijet resonance production. This search is more sensitive than previous searches for dijet resonances for masses above 2 TeV. We set the most stringent limits to date on the masses of string resonances, scalar diquarks, axigluons, colorons, excited quarks, color-octet scalars, and W′ bosons.

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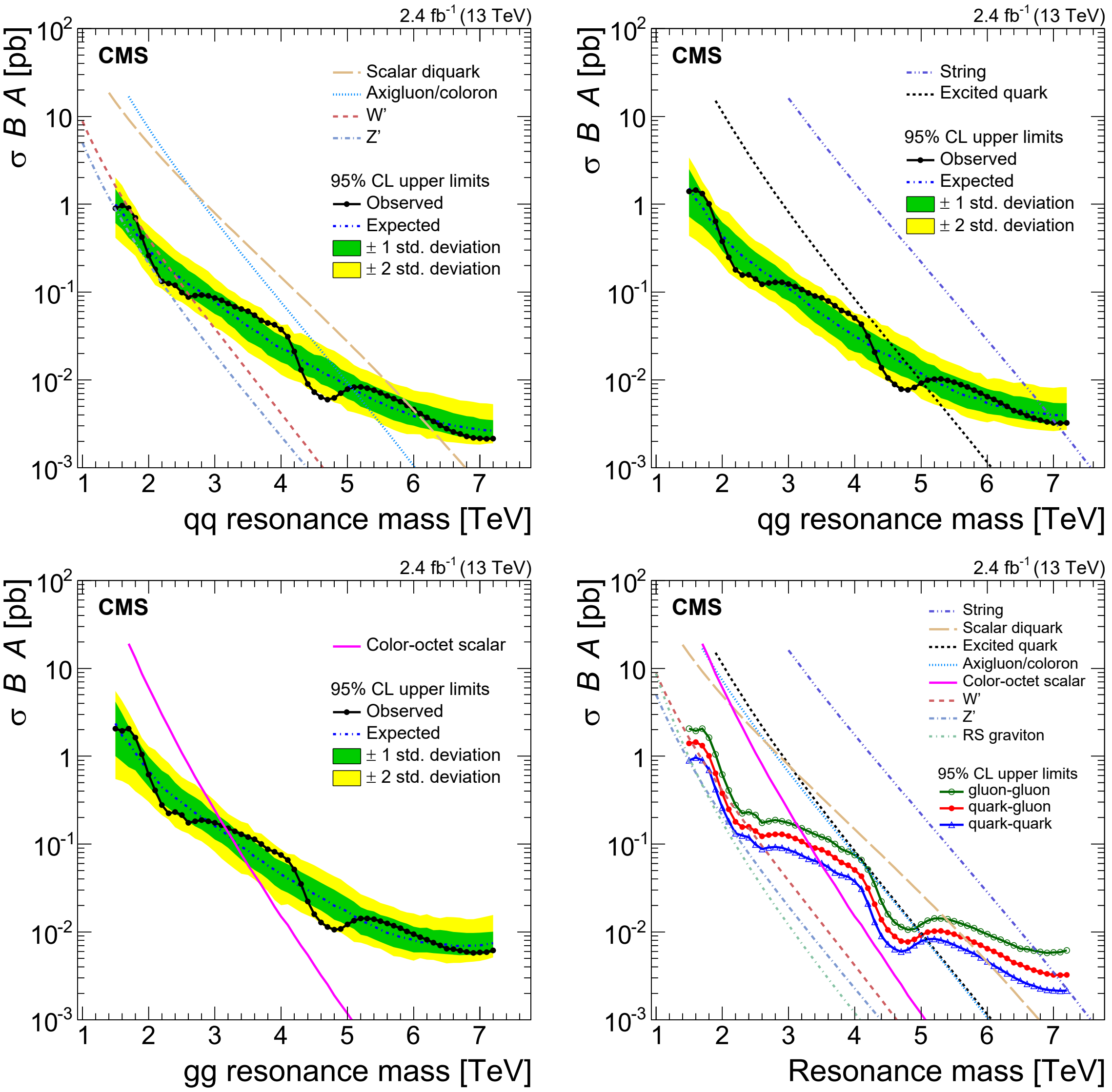

Figure 3: The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance for quark-quark (top left), quark-gluon (top right), and gluon-gluon (bottom left) type dijet resonances, shown as symbols connected by solid curves, and a comparison of all types (bottom right). The corresponding expected limits (dash-dotted curves) and their variation at the 1 and 2 standard deviation levels (shaded bands) are also shown. The limits are compared to the predicted cross sections of string resonances [13, 14], scalar diquarks [15], excited quarks [19, 20], axigluons [16, 17], colorons [17, 18], color-octet scalars [21], new gauge bosons W′ and Z′ [22], and RS gravitons [23].

Table 1: Observed and expected mass limits for analyses that exclude the listed models at 95% CL for a resonance mass from 1.5 TeV up to the indicated values.

Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	$q\overline{q}$	5.1	5.1
Excited quark (q^*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy *PW* (W')	$q\overline{q}$	2.6	2.3

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