Search for narrow resonances using the dijet mass spectrum in pp collisions at s=8TeV
Search for narrow resonances using the dijet mass spectrum in $pp$ collisions at $\sqrt{s} = 8$ TeV

S. Chatrchyan et al.*
(CMS Collaboration)

(Received 19 February 2013; published 17 June 2013)

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.

DOI: 10.1103/PhysRevD.87.114015 PACS numbers: 13.85.Rm, 12.60.Cn, 13.87.Ce, 14.80.–j

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 $k/M_{Pl}$ = 0.1, where $k$ is related to the curvature of the fifth dimension and $M_{Pl}$ 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; $\phi$ is the azimuthal angle, $\theta$ is the polar angle, and the pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$. 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...
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 \( m_{jj} = \sqrt{(E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2} \), where \( E_i \) and \( \vec{p}_i \) (\( i = 1, 2 \)) are the energy and the momentum of a wide jet. We select events with \( m_{jj} > 890 \text{ GeV} \) 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 \( p_T > 40 \text{ GeV} \) 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 \( H_T > 650 \text{ GeV} \) or \( m_{jj} > 750 \text{ GeV} \) 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 ($\chi^2$) 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 2.3$\sigma$ and a global significance of 0.6$\sigma$ 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%
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 $\sigma$ 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 $\sim 15$ 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 $\sigma \times B \times A$, i.e. the product of the cross section ($\sigma$), the branching fraction ($B$) 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 $A = 0.6$, 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 $\sigma \times B \times A$ 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>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Upper limit on $\sigma \times B \times A$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$qq$</td>
</tr>
<tr>
<td>1000</td>
<td>0.62</td>
</tr>
<tr>
<td>1200</td>
<td>0.37</td>
</tr>
<tr>
<td>1400</td>
<td>0.18</td>
</tr>
<tr>
<td>1600</td>
<td>0.12</td>
</tr>
<tr>
<td>1800</td>
<td>0.16</td>
</tr>
<tr>
<td>2000</td>
<td>0.050</td>
</tr>
<tr>
<td>2200</td>
<td>0.036</td>
</tr>
<tr>
<td>2400</td>
<td>0.031</td>
</tr>
<tr>
<td>2600</td>
<td>0.019</td>
</tr>
<tr>
<td>2800</td>
<td>0.010</td>
</tr>
<tr>
<td>3000</td>
<td>0.012</td>
</tr>
<tr>
<td>3200</td>
<td>0.017</td>
</tr>
<tr>
<td>3400</td>
<td>0.016</td>
</tr>
<tr>
<td>3600</td>
<td>0.0090</td>
</tr>
<tr>
<td>3800</td>
<td>0.0039</td>
</tr>
<tr>
<td>4000</td>
<td>0.0026</td>
</tr>
<tr>
<td>4200</td>
<td>0.0021</td>
</tr>
<tr>
<td>4400</td>
<td>0.0020</td>
</tr>
<tr>
<td>4600</td>
<td>0.0017</td>
</tr>
<tr>
<td>4800</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

TABLE I. Observed upper limits at the 95% C.L. on $\sigma \times B \times A$ 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.
SEARCH FOR NARROW RESONANCES USING THE DIJET ...

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Final state</th>
<th>Observed excluded mass range [TeV]</th>
<th>Expected excluded mass range [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>String resonance</td>
<td>$qg$</td>
<td>[1.0, 4.78]</td>
<td>[1.0, 4.75]</td>
</tr>
<tr>
<td>Excited quark</td>
<td>$qg$</td>
<td>[1.0, 3.19]</td>
<td>[1.0, 3.47]</td>
</tr>
<tr>
<td>$E_6$ diquark</td>
<td>$qq$</td>
<td>[1.0, 4.28]</td>
<td>[1.0, 4.16]</td>
</tr>
<tr>
<td>Axigluon/coloron</td>
<td>$qg$</td>
<td>[1.0, 3.27]</td>
<td>[1.0, 3.60]</td>
</tr>
<tr>
<td>S8 resonance</td>
<td>$gg$</td>
<td>[1.0, 2.79]</td>
<td>[1.0, 2.54]</td>
</tr>
<tr>
<td>$W'$ boson</td>
<td>$qg$</td>
<td>[1.0, 1.73]</td>
<td>[1.0, 1.97]</td>
</tr>
<tr>
<td>$Z'$ boson</td>
<td>$qg$</td>
<td>[1.0, 1.62]</td>
<td>[1.0, 1.58]</td>
</tr>
<tr>
<td>RS graviton</td>
<td>$qg + gg$</td>
<td>[1.0, 1.45]</td>
<td>[1.0, 1.29]</td>
</tr>
</tbody>
</table>

particle production. Upper limits are set on the product $\sigma \times B \times A$ 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.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).


114015-11
SEARCH FOR NARROW RESONANCES USING THE DIIET . . .

PHYSICAL REVIEW D 87, 114015 (2013)

40 University of Athens, Athens, Greece
41 University of Ioannina, Ioannina, Greece
42 KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
43 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
44 University of Debrecen, Debrecen, Hungary
45 Panjab University, Chandigarh, India
46 University of Delhi, Delhi, India
47 Saha Institute of Nuclear Physics, Kolkata, India
48 Bhabha Atomic Research Centre, Mumbai, India
49 Tata Institute of Fundamental Research-EHEP, Mumbai, India
50 Tata Institute of Fundamental Research-HECR, Mumbai, India
51 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
52a INFN Sezione di Bari, Bari, Italy
52b Università di Bari, Bari, Italy
52c Politecnico di Bari, Bari, Italy
53a INFN Sezione di Bologna, Bologna, Italy
53b Università di Bologna, Bologna, Italy
54a INFN Sezione di Catania, Catania, Italy
54b Università di Catania, Catania, Italy
55a INFN Sezione di Firenze, Firenze, Italy
55b Università di Firenze, Firenze, Italy
56 INFN Laboratori Nazionali di Frascati, Frascati, Italy
57a INFN Sezione di Genova, Genova, Italy
57b Università di Genova, Genova, Italy
58a INFN Sezione di Milano-Bicocca, Milano, Italy
58b Università di Milano-Bicocca, Milano, Italy
59a INFN Sezione di Napoli, Napoli, Italy
59b Università di Napoli “Federico II”, Napoli, Italy
59c Università della Basilicata (Potenza), Napoli, Italy
59d Università G. Marconi (Roma), Napoli, Italy
60a INFN Sezione di Padova, Padova, Italy
60b Università di Padova, Padova, Italy
60c Università di Trento (Trento), Padova, Italy
61a INFN Sezione di Pavia, Pavia, Italy
61b Università di Pavia, Pavia, Italy
62a INFN Sezione di Perugia, Perugia, Italy
62b Università di Perugia, Perugia, Italy
63a INFN Sezione di Pisa, Pisa, Italy
63b Università di Pisa, Pisa, Italy
63c Scuola Normale Superiore di Pisa, Pisa, Italy
64a INFN Sezione di Roma, Roma, Italy
64b Università di Roma, Roma, Italy
65a INFN Sezione di Torino, Torino, Italy
65b Università di Torino, Torino, Italy
66a Università del Piemonte Orientale (Novara), Torino, Italy
66b INFN Sezione di Trieste, Trieste, Italy
66c Università di Trieste, Trieste, Italy
67 Kangwon National University, Chunchon, Korea
68 Kyungpook National University, Daegu, Korea
69 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
70 Korea University, Seoul, Korea
71 University of Seoul, Seoul, Korea
72 Sungkyunkwan University, Suwon, Korea
73 Vilnius University, Vilnius, Lithuania
74 Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
75 Universidad Iberoamericana, Mexico City, Mexico
76 Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
77 Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
78 University of Auckland, Auckland, New Zealand
79 University of Canterbury, Christchurch, New Zealand
80 National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
Universidad Autónoma de Madrid, Madrid, Spain
Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
CERN, European Organization for Nuclear Research, Geneva, Switzerland
Paul Scherrer Institut, Villigen, Switzerland
Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
Universität Zürich, Zurich, Switzerland
National Central University, Chung-Li, Taiwan
National Taiwan University (NTU), Taipei, Taiwan
Chaolalongkorn University, Bangkok, Thailand
Cukurova University, Adana, Turkey
Middle East Technical University, Physics Department, Ankara, Turkey
Bogazici University, Istanbul, Turkey
Istanbul Technical University, Istanbul, Turkey
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
University of Bristol, Bristol, United Kingdom
Rutherford Appleton Laboratory, Didcot, United Kingdom
Imperial College, London, United Kingdom
Brunel University, Uxbridge, United Kingdom
Baylor University, Waco, Texas, USA
The University of Alabama, Tuscaloosa, Alabama, USA
Boston University, Boston, Massachusetts, USA
Brown University, Providence, Rhode Island, USA
University of California, Davis, Davis, California, USA
University of California, Los Angeles, Los Angeles, California, USA
University of California, Riverside, Riverside, California, USA
University of California, San Diego, La Jolla, California, USA
University of California, Santa Barbara, Santa Barbara, California, USA
California Institute of Technology, Pasadena, California, USA
Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
University of Colorado at Boulder, Boulder, Colorado, USA
Cornell University, Ithaca, New York, USA
Fairfield University, Fairfield, Connecticut, USA
Fermi National Accelerator Laboratory, Batavia, Illinois, USA
University of Florida, Gainesville, Florida, USA
Florida International University, Miami, Florida, USA
Florida State University, Tallahassee, Florida, USA
Florida Institute of Technology, Melbourne, Florida, USA
University of Illinois at Chicago (UIC), Chicago, Illinois, USA
The University of Iowa, Iowa City, Iowa, USA
Johns Hopkins University, Baltimore, Maryland, USA
The University of Kansas, Lawrence, Kansas, USA
Kansas State University, Manhattan, Kansas, USA
Lawrence Livermore National Laboratory, Livermore, California, USA
University of Maryland, College Park, Maryland, USA
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
University of Minnesota, Minneapolis, Minnesota, USA
University of Mississippi, Oxford, Mississippi, USA
University of Nebraska-Lincoln, Lincoln, Nebraska, USA
SEARCH FOR NARROW RESONANCES USING THE DIJET \ldots

\textit{PHYSICAL REVIEW D} 87, 114015 (2013)

\textsuperscript{142}State University of New York at Buffalo, Buffalo, New York, USA
\textsuperscript{143}Northeastern University, Boston, Massachusetts, USA
\textsuperscript{144}Northwestern University, Evanston, Illinois, USA
\textsuperscript{145}University of Notre Dame, Notre Dame, Indiana, USA
\textsuperscript{146}The Ohio State University, Columbus, Ohio, USA
\textsuperscript{147}Princeton University, Princeton, New Jersey, USA
\textsuperscript{148}University of Puerto Rico, Mayaguez, Puerto Rico
\textsuperscript{149}Purdue University, West Lafayette, Indiana, USA
\textsuperscript{150}Purdue University Calumet, Hammond, Indiana, USA
\textsuperscript{151}Rice University, Houston, Texas, USA
\textsuperscript{152}University of Rochester, Rochester, New York, USA
\textsuperscript{153}The Rockefeller University, New York, New York, USA
\textsuperscript{154}Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
\textsuperscript{155}University of Tennessee, Knoxville, Tennessee, USA
\textsuperscript{156}Texas A&M University, College Station, Texas, USA
\textsuperscript{157}Texas Tech University, Lubbock, Texas, USA
\textsuperscript{158}Vanderbilt University, Nashville, Tennessee, USA
\textsuperscript{159}University of Virginia, Charlottesville, Virginia, USA
\textsuperscript{160}Wayne State University, Detroit, Michigan, USA
\textsuperscript{161}University of Wisconsin, Madison, Wisconsin, USA

\textsuperscript{a}Deceased.
\textsuperscript{b}Also at Vienna University of Technology, Vienna, Austria.
\textsuperscript{c}Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
\textsuperscript{d}Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
\textsuperscript{e}Also at Universidade Estadual de Campinas, Campinas, Brazil.
\textsuperscript{f}Also at California Institute of Technology, Pasadena, CA, USA.
\textsuperscript{g}Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
\textsuperscript{h}Also at Suez Canal University, Suez, Egypt.
\textsuperscript{i}Also at Zewail City of Science and Technology, Zewail, Egypt.
\textsuperscript{j}Also at Cairo University, Cairo, Egypt.
\textsuperscript{k}Also at Fayoum University, El-Fayoum, Egypt.
\textsuperscript{l}Also at British University in Egypt, Cairo, Egypt.
\textsuperscript{m}Now at Ain Shams University, Cairo, Egypt.
\textsuperscript{n}Also at National Centre for Nuclear Research, Swierk, Poland.
\textsuperscript{o}Also at Université de Haute Alsace, Mulhouse, France.
\textsuperscript{p}Also at Joint Institute for Nuclear Research, Dubna, Russia.
\textsuperscript{q}Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
\textsuperscript{r}Also at Brandenburg University of Technology, Cottbus, Germany.
\textsuperscript{s}Also at The University of Kansas, Lawrence, KS, USA.
\textsuperscript{t}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
\textsuperscript{u}Also at Eötvös Loránd University, Budapest, Hungary.
\textsuperscript{v}Also at Tata Institute of Fundamental Research-HECR, Mumbai, India.
\textsuperscript{w}Now at King Abdulaziz University, Jeddah, Saudi Arabia.
\textsuperscript{x}Also at University of Visva-Bharati, Santiniketan, India.
\textsuperscript{y}Also at Sharif University of Technology, Tehran, Iran.
\textsuperscript{z}Also at Isfahan University of Technology, Isfahan, Iran.
\textsuperscript{aa}Also at Shiraz University, Shiraz, Iran.
\textsuperscript{bb}Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
\textsuperscript{cc}Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
\textsuperscript{dd}Also at Università degli Studi di Siena, Siena, Italy.
\textsuperscript{ee}Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
\textsuperscript{ff}Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
\textsuperscript{gg}Also at University of California, Los Angeles, CA, USA.
\textsuperscript{hh}Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
\textsuperscript{ii}Also at INFN Sezione di Roma, Roma, Italy.
\textsuperscript{jj}Also at University of Athens, Athens, Greece.
Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at Paul Scherrer Institut, Villigen, Switzerland.

Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

Also at Gaziosmanpasa University, Tokat, Turkey.

Also at Adiyaman University, Adiyaman, Turkey.

Also at Izmir Institute of Technology, Izmir, Turkey.

Also at The University of Iowa, Iowa City, IA, USA.

Also at Mersin University, Mersin, Turkey.

Also at Ozyegin University, Istanbul, Turkey.

Also at Kafkas University, Kars, Turkey.

Also at Suleyman Demirel University, Isparta, Turkey.

Also at Ege University, Izmir, Turkey.

Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

Also at Kahramanmaras Sütçü Imam University, Kahramanmaras, Turkey.

Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.

Also at Utah Valley University, Orem, UT, USA.

Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom.

Also at Institute for Nuclear Research, Moscow, Russia.

Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

Also at Argonne National Laboratory, Argonne, IL, USA.

Also at Erzincan University, Erzincan, Turkey.

Also at Kyungpook National University, Daegu, Korea.