Search for Narrow Resonances in Dijet Final States at $\sqrt{s} = 8$ TeV with the Novel CMS Technique of Data Scouting

V. Khachatryan et al.*
(CMS Collaboration)
(Received 29 April 2016; published 14 July 2016)

A search for narrow resonances decaying into dijet final states is performed on data from proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $18.8 \text{ fb}^{-1}$. The data were collected with the CMS detector using a novel technique called data scouting, in which the information associated with these selected events is much reduced, permitting collection of larger data samples. This technique enables CMS to record events containing jets at a rate of 1 kHz, by collecting the data from the high-level-trigger system. In this way, the sensitivity to low-mass resonances is increased significantly, allowing previously inaccessible couplings of new resonances to quarks and gluons to be probed. The resulting dijet mass distribution yields no evidence of narrow resonances. Upper limits are presented on the resonance cross sections as a function of mass, and compared with a variety of models predicting narrow resonances. The limits are translated into upper limits on the coupling of a leptophobic resonance $Z'_{\ell}$ to quarks, improving on the results obtained by previous experiments for the mass range from 500 to 800 GeV.

DOI: 10.1103/PhysRevLett.117.031802

Deep inelastic proton-proton ($pp$) collisions often result in the production of two or more jets of particles, emitted with large transverse momentum $p_T$ relative to the incoming beams. Within the framework of the standard model, the distribution of the invariant mass of the pair of jets having the largest values of $p_T$ (the dijet) is expected to decrease smoothly with increasing mass. Many proposed extensions of the standard model predict the existence of new states coupling to quarks and gluons, which would manifest themselves as resonances in the dijet mass spectrum. The first results on this topic were presented by the UA1 [1] and UA2 [2,3] experiments, collecting data at the Sp$ar{p}$S at a center-of-mass energy of 630 GeV. These results were later extended to larger values of resonance masses, by the Fermilab experiments CDF [4–8] and D0 [9] with $\sqrt{s} = 1.8$ and 1.96 TeV proton-antiproton ($p\bar{p}$) collisions at the Tevatron, and then by the CERN experiments ATLAS [10–14] and CMS [15–19] with $\sqrt{s} = 7$ and 8 TeV $pp$ collisions at the LHC. Searches for dijet resonances with mass above $\sim 1.2$ TeV were recently performed by ATLAS [20] and CMS [21] using $pp$ collisions at $\sqrt{s} = 13$ TeV. No significant excess was found in any of these searches. A review of the results below 8 TeV can be found in Ref. [22].

Results obtained at different collider energies can be compared by translating the upper limits on the quark-quark resonance cross sections into upper bounds on the coupling constants $g$ of the new resonance to a pair of partons for a given model, as reported in Ref. [23]. That study shows that these searches are not sensitive to the presence of low-mass ($\lesssim 1$ TeV) resonances with small couplings ($g \lesssim 1$) to quarks. Similar conclusions can be obtained for quark-gluon and gluon-gluon resonances. The main experimental difficulties originate from the large cross section of multijet events at low dijet mass and the limited resources for processing and storing this data. Thus, the experiments are forced to increase the thresholds of their triggers, in order to keep an acceptable data volume despite the increasing collision rate. Since the ultimate technical limitation is the available bandwidth at which events can be recorded on disk, an alternative strategy is reducing the event size in order to increase the recorded event rate. This approach, first implemented at the LHC by the CMS experiment in 2011, is referred to as data scouting [24]. A similar data collection strategy has also been recently introduced by the LHCb experiment [25].

This Letter presents a search for narrow resonances decaying into two jets using $pp$ interactions at $\sqrt{s} = 8$ TeV. The study is performed on the scouting data collected with the CMS detector during 2012. The data set corresponds to an integrated luminosity of $18.8 \text{ fb}^{-1}$.

The analysis strategy follows a similar search performed on the standard data streams [19], which is only sensitive to resonance masses above 1200 GeV. Using data scouting, the present study extends the results of Ref. [19] down to 500 GeV.
The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeters, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, its coordinate system, and the main kinematic variables used in the analysis can be found in Ref. [26].

Like events in the standard data stream, data scouting events selected by the Level-1 (L1) trigger are processed online in the high-level trigger (HLT) computer farm. Jets are reconstructed from the energy deposits in the calorimeters. A momentum value is assigned to every calorimeter energy deposit from the jet energies using an event-by-event and jet-area based correction[30]. All jets in this analysis are required to have $p_T > 30$ GeV and $|\eta| < 2.5$ and to pass a jet quality selection, based on the transverse distribution and magnitude of the energy deposits in the electromagnetic and hadron calorimeters. Additional requirements are applied to remove events where electronic noise mimics jets. Finally, the azimuthal angle between the two highest $p_T$ jets is required to be $\Delta \phi > \pi/3$. The latter requirement enforces the dijet event topology and suppresses the instrumental background originating in the calorimeters.

As in previous CMS dijet searches [16–19], geometrically close jets are combined into “wide jets.” In this process, the two leading jets are used as seeds and the four-momenta of all other jets are then added to the closest leading jet, if they satisfy the condition $|\Delta \eta| > 1.3$. This requirement maximizes the search sensitivity for isotropic decays of dijet resonances in the presence of QCD multijet background. We select events with $m_{jj} > 390$ GeV, for which the combined L1 trigger and HLT are found to be fully efficient.

Figure 1 shows the measured differential cross section as a function of dijet mass in bins of variable width
corresponding to the dijet mass resolution \[15\]. The plot is limited to the mass range relevant for this study. To test the smoothness of the measured cross section, a binned maximum likelihood fit to the data is performed with the parametrization:

\[
\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{xP_x+p_1ln(x)},
\]

where \(x = m_{jj}/\sqrt{s}\) and \(P_i\) \((i = 0, 1, 2, 3)\) are free parameters. This functional form was used previously to describe both data and QCD predictions \[8,10–19\]. The fit to data yields a \(\chi^2\) of 31 for 22 degrees of freedom. The difference between the data and the best fit function is shown at the bottom of Fig. 1, normalized to the statistical uncertainty of the data in each bin. No significant excess of events above the background fit is observed.

This search focuses on narrow resonances with intrinsic widths smaller than the dijet mass resolution. Three varieties of narrow resonances associated with representative simplified models are considered: Randall–Sundrum (RS) gravitons \[33\] coupling either to quark-antiquark (q\(\bar{q}\)) or to gluon-gluon (\(gg\)) pairs with coupling \(k/M_{Pl} = 0.1\), and excited quarks \[34,35\] coupling to quark-gluon (\(qg\)) pairs with compositeness scales that are equal to the excited quark masses. The distribution of the dijet mass for signal events is modeled using the PYTHIA 8.2 \[36\] generator with tune 4C \[37\] for the description of the underlying event. The generated events are processed through a GEANT4 \[38\] model of the CMS detector. The jet energies in the simulated signal samples are corrected in order to match the energy scale observed in the online reconstruction in the following way: a small fraction of the scouting data, corresponding approximately to one million events, is also saved in the standard data record, to allow a jet-by-jet comparison of the offline and online reconstruction performances. The corrections are derived from this subset of the data sample by comparing the energy of jets reconstructed offline with the energy of the corresponding jets reconstructed at the HLT, calculated as a function of \(p_T\) and \(\eta\) of the offline reconstructed jet. The energies of online and offline reconstructed jets agree within ~2% in the kinematic phase-space of this analysis. Figure 2 shows the \(qq\), \(qg\), and \(gg\) signal shapes for a resonance with mass of 900 GeV. The predicted mass distributions have Gaussian cores due to both QCD radiation and jet energy resolution and tails towards lower mass values primarily from QCD radiation. The contribution of this low-mass tail to the line shape depends on the parton content of the resonance. Resonances containing gluons, which emit QCD radiation more strongly than quarks, have a more pronounced tail. Neglecting the tails, the approximate width of the reconstructed dijet mass peak varies with resonance mass from 11% at 500 GeV to 7% at 1600 GeV.

A Bayesian analysis \[39\] is used to set upper limits on the signal cross section. A uniform prior for the positive signal cross section is assumed. We calculate the posterior probability density as a function of the resonance cross section for resonance masses between 500 and 1600 GeV, in 100 GeV steps. At each considered mass value, a signal-plus-background fit to the data is performed, with the signal production cross section left as a free parameter. The contribution of the background is taken to be the distribution given by the background component of the fitted function. The likelihood is formed using the following inputs: the reconstructed dijet mass distribution in data, the background estimate from the best fit of the background hypothesis to the data, and the simulated \(m_{jj}\) distribution for the resonance that is a histogram normalized to the resonance cross section.

The dominant sources of systematic uncertainty are the jet energy scale and resolution, the luminosity, and the estimation of the background. The uncertainty of 5% in the jet energy scale is derived from the results reported in Ref. \[29\] and from dedicated studies performed for the data scouting analysis. This uncertainty is propagated to the limits by scaling the dijet signal distribution by 5% up and down. The observed limits change by few percent when varying the jet energy scale uncertainty from 5% to 1%. The uncertainty in the jet energy resolution translates into an uncertainty of \(\pm 10\%\) in the resolution of the signal distribution \[29\], and is propagated to the limits by increasing and decreasing the width of the simulated dijet mass distribution shape for the signal by 10%. The uncertainty in the normalization of the signal resulting
from the uncertainty in the integrated luminosity is $\pm 2.6\%$ [40]. Uncertainties in the values of the parameters describing the background also contribute to the uncertainty in the signal strength and are taken into account in the limit setting procedure, as described below.

The above systematic uncertainties are incorporated in the limit calculation as nuisance parameters. Log-normal priors are used to model the jet energy scale, jet energy resolution, and luminosity uncertainties, while uniform priors are used for the parameters of the background function. The posterior function for the signal cross section is obtained by marginalizing over these nuisance parameters. The integration is performed independently for each of the background nuisance parameters in a range around the best-fit values that is large enough to accommodate a decrease in the likelihood by a factor of 1000 from its maximum value.

Figure 3 shows the observed model-independent upper limits at 95% confidence level (CL) on $\sigma BA$, i.e. the product of the signal cross section ($\sigma$), the branching fraction to jets (B), and the acceptance (A) for the kinematic requirements $|\Delta \eta_{jj}| < 1.3$ and $|\eta| < 2.5$. The effect of the $m_{jj} > 390$ GeV requirement has been taken into account by correcting the limits, and therefore does not appear in the acceptance. In Table I, the limits are reported separately for narrow $qq$, $qg$, and $gg$ resonances, in the mass range between 500 and 1600 GeV. The data scouting exclusions for masses between 1200 and 1600 GeV overlap with those from the high-mass search performed with the standard data stream [19]. In the overlapping mass interval, the sensitivity of the data scouting search is found to be almost identical with the high-mass search sensitivity, and the results are found to be compatible with those of the high-mass search within $\pm 2$ standard deviations.

Additionally, we apply our search results to the following models of s-channel dijet resonances: excited quarks [34,35]; axigluons [41,42]; scalar diquarks [43]; new gauge bosons ($W'$ and $Z'$) [44]; and RS gravitons [33]. More details on the specific choices of couplings for the models considered can be found in Ref. [17]. The upper limits presented are compared to the parton-level predictions of $\sigma BA$ without any detector simulation, in order to determine mass limits on new particles. The model predictions shown in Fig. 3 are calculated in the narrow-width approximation [22] using CTEQ6L1 PDFs [45] at leading order and a next-to-leading-order $k$ factor is included for the $W'$, $Z'$, and axigluon models [42]. New particles are excluded at 95% CL in mass regions for which the theoretical curve lies at or above the observed upper limit for the appropriate final state in Fig. 3. The RS graviton cross section can be compared to the average of the upper limits for $qq$ and $gg$ final states.

We exclude excited quarks, axigluons, scalar diquarks, $W'$ and $Z'$ bosons, and RS gravitons with masses between 500 and 1600 GeV. These limits cover regions not excluded by previous dijet resonance searches at hadron colliders, as follows: scalar diquarks with masses between 630 and 970 GeV [22]; $W'$ bosons with masses between 840 and 1000 GeV [22]; $Z'$ bosons with masses between 740 and 1000 GeV [17,22]; RS gravitons with masses between 500 and 1000 GeV [22].

Following the theoretical framework of Ref. [23], the model-independent upper limits on the cross section of $qq$ resonances are translated into 95% CL upper limits on the coupling $g_B$ of a hypothetical leptophobic resonance.

### Table I. Observed upper limits at 95% C.L. on $\sigma BA$ for resonances decaying to $qq$, $qg$, and $gg$ final states as a function of the resonance mass.

| Mass [GeV] | $qq$ Upper limit on $\sigma BA$ [pb] | $qg$ Upper limit on $\sigma BA$ [pb] | $gg$ Upper limit on $\sigma BA$ [pb] |
|-----------|-------------------------------------|-------------------------------------|-------------------------------------|
| 500       | 5.0                                | 11                                  | 11                                  |
| 600       | 4.3                                | 3.4                                  | 3.7                                  |
| 700       | 3.6                                | 1.1                                  | 1.5                                  |
| 800       | 1.0                                | 1.5                                  | 2.1                                  |
| 900       | 0.5                                | 1.4                                  | 2.2                                  |
| 1000      | 0.4                                | 0.65                                 | 0.85                                 |
| 1100      | 0.4                                | 0.66                                 | 1.0                                  |
| 1200      | 0.25                               | 0.49                                 | 0.70                                 |
| 1300      | 0.19                               | 0.30                                 | 0.40                                 |
| 1400      | 0.10                               | 0.19                                 | 0.29                                 |
| 1500      | 0.07                               | 0.10                                 | 0.14                                 |
| 1600      | 0.05                               | 0.07                                 | 0.10                                 |
FIG. 4. Observed 95% CL upper limits on the coupling $g_B$ of a hypothetical leptophobic resonance $Z_B' \rightarrow q\bar{q}$ as a function of its mass. The $Z_B'$ production cross section scales with the square of the coupling $g_B$. Figure 4 shows the upper limits obtained with the data scouting technique in the mass region from 500 to 1200 GeV, extending the coverage of previous CMS searches to below 1200 GeV. Previous exclusions obtained with similar searches at various collider energies are also shown. As a result of the large data set collected by the data scouting stream, the bound on $g_B$ is improved by up to a factor of 3 for resonance masses between 500 and 800 GeV, compared to previous searches. This corresponds to an order-of-magnitude improvement in the cross section limit.

In summary, a search for narrow resonances decaying into two jets was performed using data from proton-antiproton collisions recorded by the CMS experiment at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 18.8 fb$^{-1}$. The novel technique of data scouting was used; by reducing the information stored per event, multijet events could be collected in sufficiently large samples that a sensitive search for dijet resonances down to masses as low as 500 GeV was possible. No evidence for a narrow resonance is found. Model-independent upper limits on production cross sections are derived for quark-quark, quark-gluon, and gluon-gluon resonances. Based on these results, new limits are set on an extensive selection of narrow $s$-channel resonances over mass ranges not excluded by previous searches at hadron colliders. Bounds on the coupling of a hypothetical leptophobic resonance decaying to quark-antiquark are also provided, as a function of the resonance mass. The limits obtained are the most stringent to date in the dijet final state for narrow resonance masses between about 500 and 800 GeV.

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: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MCI and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); SFI (Dublin); CERN; STFC (United Kingdom); DOE and NSF (USA).

[1] C. Albajar et al. (UA1 Collaboration), Two-jet mass distributions at the CERN proton-antiproton collider, Phys. Lett. B 209, 127 (1988).
[2] J. Alitti et al. (UA2 Collaboration), A measurement of two jet decays of the W and Z bosons at the CERN $p\bar{p}$ collider, Z. Phys. C 49, 17 (1991).
[3] J. Alitti et al. (UA2 Collaboration), A search for new intermediate vector bosons and excited quarks decaying to two-jets at the CERN $p\bar{p}$ collider, Nucl. Phys. B400, 3 (1993).
[4] F. Abe et al. (CDF Collaboration), Two-jet mass distribution at $\sqrt{s} = 1.8$ TeV, Phys. Rev. D 41, 1722 (1990).
[5] F. Abe et al. (CDF Collaboration), Search for Quark Compositeness, Axiqgluons and Heavy Particles Using the Dijet Invariant Mass Spectrum Observed in $p\bar{p}$ Collisions, Phys. Rev. Lett. 71, 2542 (1993).
[6] F. Abe et al. (CDF Collaboration), Search for New Particles Decaying to Dijets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. Lett. 74, 3538 (1995).
[7] F. Abe et al. (CDF Collaboration), Search for new particles decaying to dijets at CDF, Phys. Rev. D 55, R5263 (1997).
[8] T. Aaltonen et al. (CDF Collaboration), Search for new particles decaying into dijets in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 79, 112002 (2009).
51 Panjab University, Chandigarh, India
52 University of Delhi, Delhi, India
53 Saha Institute of Nuclear Physics, Kolkata, India
54 Indian Institute of Technology Madras, Madras, India
55 Bhabha Atomic Research Centre, Mumbai, India
56 Tata Institute of Fundamental Research-A, Mumbai, India
57 Tata Institute of Fundamental Research-B, Mumbai, India
58 Indian Institute of Science Education and Research (IISER), Pune, India
59 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
60 University College Dublin, Dublin, Ireland
61a INFN Sezione di Bari, Bari, Italy
61b Università di Bari, Bari, Italy
61c Politecnico di Bari, Bari, Italy
62a INFN Sezione di Bologna, Bologna, Italy
62b Università di Bologna, Bologna, Italy
63a INFN Sezione di Catania, Catania, Italy
63b Università di Catania, Catania, Italy
64 INFN Sezione di Firenze, Firenze, Italy
64a Università di Firenze, Firenze, Italy
65 INFN Laboratori Nazionali di Frascati, Frascati, Italy
66a INFN Sezione di Genova, Genova, Italy
66b Università di Genova, Genova, Italy
67a INFN Sezione di Milano-Bicocca, Milano, Italy
67b Università di Milano-Bicocca, Milano, Italy
68a INFN Sezione di Napoli, Roma, Italy
68b Università di Napoli 'Federico II', Roma, Italy
68c Università della Basilicata, Roma, Italy
68d Università G. Marconi, Roma, Italy
69a INFN Sezione di Padova, Trento, Italy
69b Università di Padova, Trento, Italy
69c Università di Trento, Trento, Italy
70a INFN Sezione di Pavia, Pavia, Italy
70b Università di Pavia, Pavia, Italy
71a INFN Sezione di Perugia, Perugia, Italy
71b Università di Perugia, Perugia, Italy
72a INFN Sezione di Pisa, Pisa, Italy
72b Università di Pisa, Pisa, Italy
72c Scuola Normale Superiore di Pisa, Pisa, Italy
73a INFN Sezione di Roma
73b Università di Roma
74a INFN Sezione di Torino, Novara, Italy
74b Università di Torino, Novara, Italy
74c Università del Piemonte Orientale, Novara, Italy
75a INFN Sezione di Trieste, Trieste, Italy
75b Università di Trieste, Trieste, Italy
76 Kyungpook National University, Daegu, Korea
77 Chonbuk National University, Jeonju, Korea
77 Hanyang University, Seoul, Korea
78a Korea University, Seoul, Korea
78b Seoul National University, Seoul, Korea
81 University of Seoul, Seoul, Korea
82 Sungkyunkwan University, Suwon, Korea
83 Vilnius University, Vilnius, Lithuania
84 National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
85 Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
86 Universidad Iberoamericana, Mexico City, Mexico
87 Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
88 Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
89 University of Auckland, Auckland, New Zealand
90 University of Canterbury, Christchurch, New Zealand
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
National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), 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
University 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
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
Cukurova University, Adana, Turkey
Middle East Technical University, Physics Department, Ankara, Turkey
Bogazici University, Istanbul, Turkey
Istanbul Technical University, Istanbul, Turkey
Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
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, 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 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, 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
\textsuperscript{151}Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
\textsuperscript{152}University of Minnesota, Minneapolis, Minnesota, USA.
\textsuperscript{153}University of Mississippi, Oxford, Mississippi, USA.
\textsuperscript{154}University of Nebraska-Lincoln, Lincoln, Nebraska, USA.
\textsuperscript{155}State University of New York at Buffalo, Buffalo, New York, USA.
\textsuperscript{156}Northeastern University, Boston, Massachusetts, USA.
\textsuperscript{157}Northwestern University, Evanston, Illinois, USA.
\textsuperscript{158}University of Notre Dame, Notre Dame, Indiana, USA.
\textsuperscript{159}The Ohio State University, Columbus, Ohio, USA.
\textsuperscript{160}Princeton University, Princeton, New Jersey, USA.
\textsuperscript{161}University of Puerto Rico, Mayaguez, Puerto Rico.
\textsuperscript{162}Purdue University, West Lafayette, Indiana, USA.
\textsuperscript{163}Purdue University Calumet, Hammond, Indiana, USA.
\textsuperscript{164}Rice University, Houston, Texas, USA.
\textsuperscript{165}University of Rochester, Rochester, New York, USA.
\textsuperscript{166}Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA.
\textsuperscript{167}University of Tennessee, Knoxville, Tennessee, USA.
\textsuperscript{168}Texas A&M University, College Station, Texas, USA.
\textsuperscript{169}Texas Tech University, Lubbock, Texas, USA.
\textsuperscript{170}Vanderbilt University, Nashville, Tennessee, USA.
\textsuperscript{171}University of Virginia, Charlottesville, Virginia, USA.
\textsuperscript{172}Wayne State University, Detroit, Michigan, USA.
\textsuperscript{173}University of Wisconsin—Madison, Madison, Wisconsin, USA.

\textsuperscript{a}Deceased.
\textsuperscript{b}Also at Vienna University of Technology, Vienna, Austria.
\textsuperscript{c}Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
\textsuperscript{d}Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
\textsuperscript{e}Also at Universidade Estadual de Campinas, Campinas, Brazil.
\textsuperscript{f}Also at Centre National de la Recherche Scientifique (CNRS)-IN2P3, Paris, France.
\textsuperscript{g}Also at Université Libre de Bruxelles, Bruxelles, Belgium.
\textsuperscript{h}Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
\textsuperscript{i}Also at Joint Institute for Nuclear Research, Dubna, Russia.
\textsuperscript{j}Also at British University in Egypt, Cairo, Egypt.
\textsuperscript{k}Also at Zewail City of Science and Technology, Zewail, Egypt.
\textsuperscript{l}Also at Fayoum University, El-Fayoum, Egypt.
\textsuperscript{m}Also at Ain Shams University, Cairo, Egypt.
\textsuperscript{n}Also at Université de Haute Alsace, Mulhouse, France.
\textsuperscript{o}Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
\textsuperscript{p}Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
\textsuperscript{q}Also at Tbilisi State University, Tbilisi, Georgia.
\textsuperscript{r}Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
\textsuperscript{s}Also at University of Hamburg, Hamburg, Germany.
\textsuperscript{t}Also at Brandenburg University of Technology, Cottbus, Germany.
\textsuperscript{u}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
\textsuperscript{v}Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University.
\textsuperscript{w}Also at University of Debrecen, Debrecen, Hungary.
\textsuperscript{x}Also at Indian Institute of Science Education and Research, Bhopal, India.
\textsuperscript{y}Also at Institute of Physics, Bhubaneswar, India.
\textsuperscript{z}Also at University of Visva-Bharati, Santiniketan, India.
\textsuperscript{aa}Also at University of Ruhuna, Matara, Sri Lanka.
\textsuperscript{ab}Also at Isfahan University of Technology, Isfahan, Iran.
\textsuperscript{ac}Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
\textsuperscript{ad}Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
\textsuperscript{ae}Also at Università degli Studi di Siena, Siena, Italy.
\textsuperscript{af}Also at Purdue University, West Lafayette, IN, USA.
\textsuperscript{ag}Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
\textsuperscript{ah}Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
\textsuperscript{ai}Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
