Search for Narrow Trijet Resonances in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

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The first search for singly produced narrow resonances decaying to three well-separated hadronic jets is presented. The search uses proton-proton collision data corresponding to an integrated luminosity of 138 fb^{-1} at $\sqrt{s} = 13$ TeV, collected at the CERN LHC. No significant deviations from the background predictions are observed between 1.75 and 9.00 TeV. The results provide the first mass limits on a right-handed boson Z_R decaying to three gluons and on an excited quark decaying via a vector boson to three quarks, as well as updated limits on a Kaluza-Klein gluon decaying via a radion to three gluons.

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The standard model (SM) of particle physics has several well-established shortcomings, notably lacking explanations for the nonzero neutrino masses, the issue of dark matter, the matter-antimatter asymmetry of the universe, the hierarchy problem, and the proliferation of quarks and leptons. These shortcomings have motivated a comprehensive program of searches for beyond-the-SM physics at high-energy colliders. Searches for new particles coupled to quarks and/or gluons are especially compelling at hadron colliders, such as the CERN LHC, since these particles could potentially be produced with significant cross sections. Searches for new particles decaying to two hadronic jets (dijets) have been performed numerous times at past and current colliders [1–11]. Hadronic resonances with more complicated signatures have also been explored, including searches for the pair production of resonances decaying to two or more jets [12–19] and a search for resonances decaying to a jet and a boosted dijet resonance [20].

In this Letter, we present the first generic search for singly produced resolved three-jet (trijet) resonances (X) using proton-proton (pp) collision data recorded by the CMS experiment from 2016 to 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. Following techniques established by dijet resonance searches, the trijet invariant mass (m_{jjj}) spectrum is scrutinized for narrow excesses compatible with new resonances decaying to three hadronic jets. No assumptions are made on the structure of the decay, except for the requirement that the final state contain three resolved jets with large transverse momentum (p_{T}). The SM background consists of events containing three or more jets produced exclusively through quantum chromodynamics (QCD), and is estimated from data by fitting the m_{jjj} spectrum with smoothly falling empirical functions. The search for singly produced trijet resonances provides unique sensitivity for certain scenarios such as a spin-1 resonance dominantly produced via two off-shell gluons and decaying to three on-shell gluons. It also possesses complementary sensitivity to previous searches in scenarios such as a resonance decaying to another resonance (Y) in association with a gluon or quark. Sensitivity to these representative scenarios is probed using three specific signal benchmark models that could potentially address the aforementioned SM shortcomings: a right-handed Z boson, Z_R, decaying directly to three gluons (g) [21]; a Kaluza-Klein excitation of a gluon, g_{KK}, decaying via an intermediate radion to three gluons [22,23]; and an excited quark, q^*, decaying via an intermediate beyond-the-SM vector boson to three quarks (q) [24]. The latter two scenarios, which involve an initial resonance X and an intermediate resonance Y, are referred to as cascade decays and are characterized by the mass ratio $\rho_{\mathrm{m}} = m_Y/m_X$. Values of ρ_{m} between 0.2 and 0.8 that could lead to the resolved trijet signature are considered. At values of ρ_{m} lower than 0.2, the Y is produced with significant transverse momentum, and its decay products are reconstructed as a single jet; this scenario was explored in Ref. [20]. Supplemental information about the analysis is available in the Supplemental Material [25]. Tabulated results are provided as a HEPData record for this analysis [26].

The CMS apparatus [27] is a multipurpose, nearly hermetic detector, designed to trigger on [28,29] and identify electrons, muons, photons, and charged and neutral hadrons [30–32]. The "particle-flow" algorithm [33] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker, the crystal electromagnetic calorimeters (ECAL), and the

[*]Full author list given at the end of the Letter.

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brass-scintillator hadron calorimeters (HCAL), all operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum [34–36].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz with a fixed latency of about 4 μs [28]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [29].

The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone [37]. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti-k_{T} algorithm [38,39] with a distance parameter of 0.4 (AK4). Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5% to 10% of the true momentum over the entire p_{T} spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. *In situ* measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [35]. The jet energy resolution amounts typically to 15%–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [35]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [40]. Jets with $p_{\mathrm{T}} < 50$ GeV are further required to pass a multivariate pileup jet rejection algorithm, which has 99% efficiency for jets originating from the primary vertex of interest [41].

To mitigate the loss of resolution from QCD radiation outside the jet boundaries, a "wide-jet" algorithm introduced for previous CMS dijet searches [42] is used. Using the three leading jets with $p_{\mathrm{T}} > 100$ GeV as seeds, the four-vectors of additional jets in the event with $p_{\mathrm{T}} > 30$ GeV are added to the nearest seed jet within an optimized distance of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, where η is the pseudorapidity and ϕ is the azimuthal angle in radians. The wide jet algorithm improves the sensitivity of the search to the signal cross section by ∼10%–15% (50%–70%) compared to the use of AK8 (AK4) jets. The trijet invariant mass, m_{jjj}, is defined as the invariant mass of the three wide jets obtained with this algorithm.

Monte Carlo (MC) simulation is used to model the contributions from the production of new resonances that assume the Breit-Wigner line shape. The $Z_R \to ggg$ process is simulated at leading order (LO) in QCD with PYTHIA8.242 [43]. Two width scenarios are simulated: the nominal left-right symmetric scenario from Ref. [21] assuming SM-like couplings with a width of $\Gamma_{Z_R}/m_{Z_R} \sim 3\%$, and a narrow-width scenario with $\Gamma_{Z_R}/m_{Z_R} \sim 0.01\%$ that represents the cases where the width is negligible with respect to the jet energy resolution. The g_{KK} process is modeled at LO with MadGraph5_aMC@NLO2.7.3 [44], interfaced with PYTHIA for the parton shower. The excited quark process is also modeled at LO in QCD with PYTHIA. Simulated samples are also produced for the background QCD process, using MadGraph5_aMC@NLO2.6.5 at LO with up to four partons at the matrix element level. These background samples are used only for the development of the analysis strategy; the background estimation is performed using collision data. The NNPDF3.1 [45] parton distribution function (PDF) set at next-to-next-to-LO accuracy is used for all processes, along with the parton shower tune CP5 [46]. The interaction of particles with the detector is simulated using the GEANT4 toolkit [47]. The effects of pileup are incorporated by overlaying minimum bias events, simulated with PYTHIA, on the hard scattering interactions, with the multiplicity distribution matching that observed in data.

In the MC simulations, only signal events with a generated resonance mass greater than 85% of the mass point under consideration are used. This requirement is found to have negligible impact on the search while helping to avoid uncertainties that are associated with the exact description of the far-off-shell low-mass tails. The acceptance of this requirement, which depends on the width of the resonance, is denoted by $\mathcal{A}$.

Events are selected using a set of triggers requiring large hadronic activity, based on either the p_{T} of a single jet or

the event H_T, defined as the scalar sum of jet p_T for all jets with $p_T > 30$ GeV and $|\eta| < 3.0$. The typical thresholds deployed for H_T triggers were 900 (1050) GeV and 360 (500) GeV for the p_T triggers in 2016 (2017–2018). To avoid the phase space where the trigger is inefficient, we apply a selection of $m_{jjj} > 1.50$ TeV (2016) or $m_{jjj} > 1.76$ TeV (2017–2018). The trigger and m_{jjj} thresholds for 2016 data are lower because of the lower instantaneous luminosity. The fully reconstructed events are required to have at least three reconstructed jets with $p_T > 100$ GeV and $|\eta| < 2.5$, prior to the application of the wide-jet algorithm. The aforementioned jet identification criteria, which have an efficiency of more than 98%–99%, are applied to each jet used to construct the wide jet. Since the QCD background tends to have jets with higher values of $|\eta|$ than the signal processes, the sensitivity of the analysis is improved by requiring that the maximum difference in η between any two of the three wide jets, $\Delta\eta_{max}$, be less than 1.6. Similarly, the maximum difference in ΔR between any two wide jets must be less than 3.0. The efficiencies of the above selection requirements are calculated in simulation to be ∼30% for the Z_R process and between 23%–35% (26%–37%) for the g_{KK} (q^*) process for mass values between 2.0 and 9.0 TeV. For resonance masses below ∼2 TeV, the efficiencies decrease because the signal peaks are truncated by the lower m_{jjj} threshold, reaching ∼20% for the Z_R process, ∼15% for the g_{KK} process, and ∼25% for the q^* process at a mass of 1.75 TeV.

The background, dominantly arising from the QCD multijet process, is modeled by fitting the m_{jjj} distribution with smoothly falling, empirical functions that have been used in previous searches [19,20]. Three families of functions are considered:

$$f_A(x;N) = p_0 \frac{(1-x)^{p_1}}{x\sum_{i=2}^{N} p_i \log^{i-2}(x)},$$
$$f_B(x;N) = p_0 \frac{e^{-p_1 x}}{x\sum_{i=2}^{N} p_i \log^{i-2}(x)},$$
$$f_C(x;N) = p_0 x^{\sum_{i=1}^{N} p_i \log^{i-1}(x)}, \quad (1)$$

where $x = m_{jjj}/\sqrt{s}$, $p_i (i = 0, 1, \ldots, N)$ are free parameters, and N is the order of the fit function, which is determined using a Fisher F test [48]. It is found that the third-order yields the best fits to the data for all three families of functions. The p values obtained from a generalized χ^2 goodness-of-fit test [49] yield 0.62, 0.53, and 0.34 for the f_A, f_B, and f_C functions, respectively. The signal is extracted using a binned maximum-likelihood fit based on a profile likelihood ratio test statistic [50], with variable bin size approximating the m_{jjj} resolution. The signal component of the fit is taken from binned templates derived from simulation, while the background component corresponds to the integral of the fit function across each bin. The three

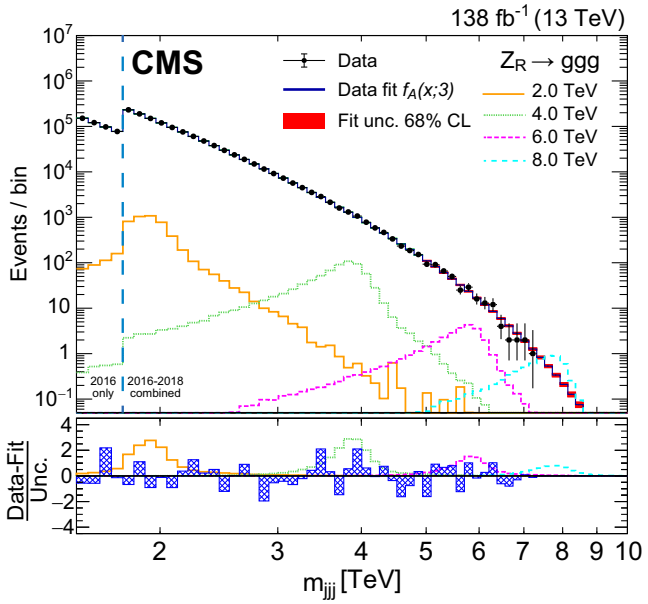


FIG. 1. The observed m_{jjj} distribution and the background-only fit to the data using the f_A fit function. Uncertainties in the fit that correspond to the 68% confidence level are depicted with the red band. The expected m_{jjj} distributions for Z_R signal masses of 2.0, 4.0, 6.0, and 8.0 TeV, with nominal width of ∼3%, are also shown. For illustration purposes, the normalizations correspond to $\sigma\mathcal{B}$ values of 200, 50, 20, and 20 fb, respectively. Only 2016 data are shown for $m_{jjj} < 1.76$ TeV because of the higher trigger thresholds in 2017 and 2018. In the bottom panel, the blue hatched bars show the difference between the observed data and the background prediction divided by the statistical uncertainty, along with expectations for the example Z_R signal points.

fit functions are incorporated into a single likelihood using a discrete nuisance parameter [51]. This parameter is profiled in an analogous way to continuous nuisance parameters to consider the extra uncertainty brought by the various possible choices of the background functional form. The background parameters are included as freely floating nuisance parameters. The three data-taking years are treated separately in the fit, in particular, with independent background parametrizations for each year, and are combined statistically into a single likelihood. The combined result of the background-only fits with the function $f_A(x;3)$ is shown in Fig. 1 as an example.

To gauge the systematic biases in the signal extraction, bias tests are performed using pseudodata produced from the background-only fits with injected signal events. The bias is found to be negligible. Systematic uncertainties in the signal are incorporated in the likelihood as constrained nuisance parameters. The jet energy resolution and scale uncertainties translate to ≈10% and ≈1% uncertainties in the width and the position of the trijet mass shape for the signal, respectively. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2%–2.5% individual uncertainties [52–54], while

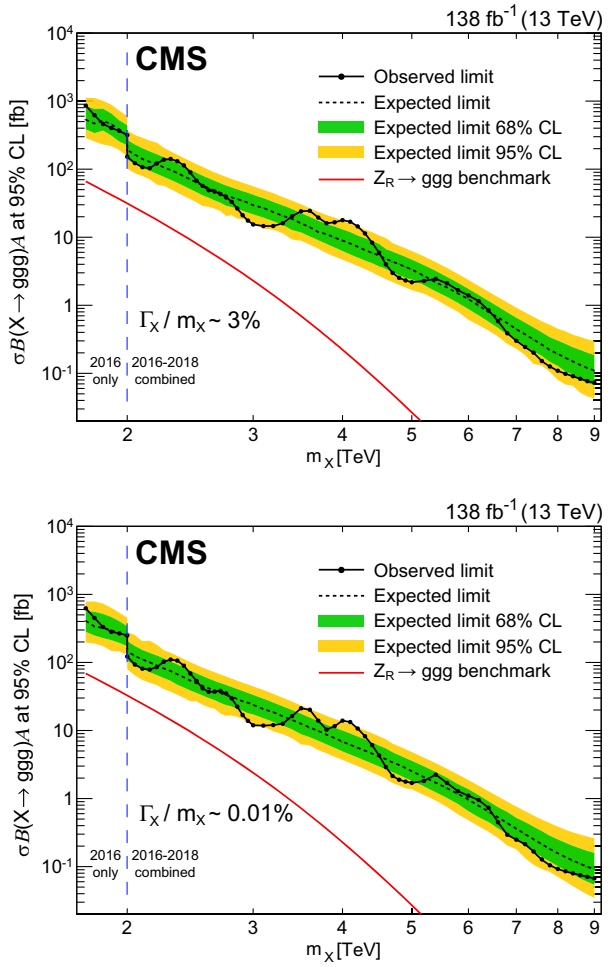


FIG. 2. Limits at 95% CL on $\sigma\mathcal{B}(X \to ggg)\mathcal{A}$ for the nominal (upper) and narrow-width (lower) scenarios. Only 2016 data are used to derive limits below 2.0 TeV because of the higher trigger thresholds in 2017 and 2018. Theoretical predictions assuming SM-like couplings are depicted with red curves.

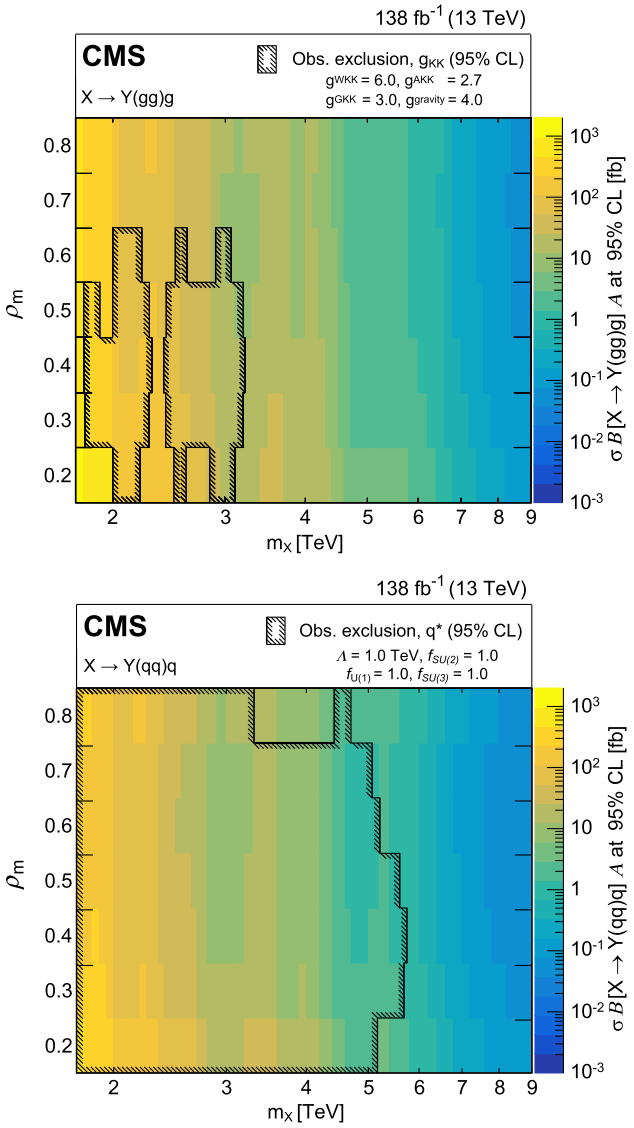


FIG. 3. Observed limits at 95% CL as a function of m_X and ρ_m on $\sigma\mathcal{B}[X \to Y(gg)g]\mathcal{A}$ (upper) and $\sigma\mathcal{B}[X \to Y(qq)q]\mathcal{A}$ (lower). Only 2016 data are used to derive limits below 2.0 TeV because of the higher trigger thresholds in 2017 and 2018. The legend shows the model parameters that are defined in [23,24] for the chosen benchmark, and their corresponding mass exclusion ranges are depicted with areas inside the black hatched contours.

the overall uncertainty for the 2016–2018 period is 1.6%. Finally, the uncertainty in the predicted signal yield that stems from the pileup reweighting procedure is ≈3% for the three years, and is uncorrelated between years. The most significant uncertainties are those associated with background fit parameters in the background prediction, which are evaluated to have an impact on the fitted signal strength of ≈10% over the entire search range.

No significant excesses compatible with the signal hypotheses are observed. For the $X \to ggg$ signal scenario, the largest deviation is observed at $m_X = 4.1$ TeV, corresponding to local significance values of 2.1 and 2.2 standard deviations for the nominal and narrow width hypotheses, respectively. Taking into account the look-elsewhere effect [55], the global significance values are 0.2 and 0.3 standard deviations, respectively. For the $X \to Y(gg)g$ cascade decay scenario, the largest deviation is observed for $\rho_m = 0.3$ and $m_X = 4.1$ TeV, with a local (global) significance of 2.2 (0.4) standard deviations. For the $X \to Y(qq)q$ cascade decay scenario, the largest deviation is observed at $\rho_m = 0.7$ and $m_X = 3.9$ TeV, and corresponds to a local (global) significance of 2.1 (0.3) standard deviations.

Limits are set for the first time at 95% confidence level (CL) on the product of the signal process production cross section, branching fraction, and acceptance ($\sigma\mathcal{B}\mathcal{A}$) to three resolved jets using the asymptotic CL_s procedure [56–58] in the mass range between 1.75 and 9.00 TeV. Only 2016 data are used to derive limits below 2.0 TeV because of the higher trigger thresholds deployed in 2017 and 2018. Limits are shown in Fig. 2 for the three-body decay of

new resonances, ranging from 0.073 (0.067) fb to 0.86 (0.62) pb for the nominal (narrow) width hypotheses. Theoretical predictions of $\sigma\mathcal{BA}$ assuming SM-like couplings are depicted with red curves. The current dataset does not provide sufficient sensitivity to constrain the Z_R model. Limits on the cascade decay of new resonances into ggg (qqq) are presented in Fig. 3, which range from 0.061 (0.047) fb to 1.2 (0.49) pb. Benchmark model coupling parameters [23,24] are shown in the legend, and their corresponding mass exclusion ranges are depicted with areas inside the black hatched contours. At $\rho_{\mathrm{m}} = 0.2$, this search achieves a similar level of sensitivity to that of the previous search [20] for the ggg decay mode.

In summary, the first generic search for singly produced new particles decaying to three hadronic jets has been presented. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. The three-jet invariant mass spectrum is scanned for narrow peaks corresponding to new particles. No significant excesses above the standard model background expectations are observed. Limits are set on the product of the production cross section, branching fraction, and acceptance to three resolved jets. The results are interpreted in the context of a new right-handed boson Z_R decaying to three gluons, a Kaluza-Klein gluon g_{KK} decaying via an intermediate radion to three gluons (ggg), and an excited quark decaying via a vector boson to three quarks (qqq). This is the first search for the three-body decay of singly produced high-mass resonances X into three resolved jets at the LHC, and also the first search for X that decays into three resolved jets through an intermediate resonance Y with a mass ratio m_Y/m_X within 0.3–0.8 for the ggg decay mode and 0.2–0.8 for the qqq decay mode, significantly extending the model parameter space explored by a previous search [20].

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Valuev,[142] R. Clare,[143] M. Gordon,[143] G. Hanson,[143] W. Si,[143] S. Wimpenny,[143,a] J. G. Branson,[144] S. Cittolin,[144] S. Cooperstein,[144] D. Diaz,[144] J. Duarte,[144] L. Giannini,[144] J. Guiang,[144] R. Kansal,[144] V. Krutelyov,[144] R. Lee,[144] J. Letts,[144] M. Masciovecchio,[144] F. Mokhtar,[144] M. Pieri,[144] M. Quinnan,[144] B. V. Sathia Narayanan,[144] V. Sharma,[144] M. Tadel,[144] E. Vourliotis,[144] F. Würthwein,[144] Y. Xiang,[144] A. Yagil,[144] A. Barzdukas,[145] L. Brennan,[145] C. Campagnari,[145] G. Collura,[145] A. Dorsett,[145] J. Incandela,[145] M. Kilpatrick,[145] J. Kim,[145] A. J. Li,[145] P. Masterson,[145] H. Mei,[145] M. Oshiro,[145] J. Richman,[145] U. Sarica,[145] R. Schmitz,[145] F. Setti,[145] J. Sheplock,[145] D. Stuart,[145] S. Wang,[145] A. Bornheim,[146] O. Cerri,[146] A. Latorre,[146] J. M. Lawhorn,[146] J. Mao,[146] H. B. Newman,[146] T. Q. Nguyen,[146] M. Spiropulu,[146] J. R. Vlimant,[146] C. Wang,[146] S. Xie,[146] R. Y. Zhu,[146] J. Alison,[147] S. An,[147] M. B. Andrews,[147] P. Bryant,[147] V. Dutta,[147] T. Ferguson,[147] A. Harilal,[147] C. Liu,[147] T. Mudholkar,[147] S. Murthy,[147] M. Paulini,[147] A. Roberts,[147] A. Sanchez,[147] W. Terrill,[147] J. P. Cumalat,[148] W. T. Ford,[148] A. Hassani,[148] G. Karathanasis,[148] E. MacDonald,[148] N. Manganelli,[148] F. Marini,[148] A. Perloff,[148] C. Savard,[148] N. Schonbeck,[148] K. Stenson,[148] K. A. Ulmer,[148] S. R. Wagner,[148] N. Zipper,[148] J. Alexander,[149] S. Bright-Thonney,[149] X. Chen,[149] D. J. Cranshaw,[149] J. Fan,[149] X. Fan,[149] D. Gadkari,[149] S. Hogan,[149] J. Monroy,[149] J. R. Patterson,[149] J. Reichert,[149] M. Reid,[149] A. Ryd,[149] J. Thom,[149] P. Wittich,[149] R. Zou,[149] M. Albrow,[150] M. Alyari,[150] O. Amram,[150] G. Apollinari,[150] A. Apresyan,[150] L. A. T. Bauerdick,[150] D. Berry,[150] J. Berryhill,[150] P. C. Bhat,[150] K. Burkett,[150] J. N. Butler,[150] A. Canepa,[150] G. B. Cerati,[150] H. W. K. Cheung,[150] F. Chlebana,[150] G. Cummings,[150] J. Dickinson,[150] I. Dutta,[150] V. D. Elvira,[150] Y. Feng,[150] J. Freeman,[150] A. Gandrakota,[150] Z. Gecse,[150] L. Gray,[150] D. Green,[150] A. Grummer,[150] S. Grünendahl,[150] D. Guerrero,[150] O. Gutsche,[150] R. M. Harris,[150] R. Heller,[150] T. C. Herwig,[150] J. Hirschauer,[150] L. Horyn,[150] B. Jayatilaka,[150] S. Jindariani,[150] M. Johnson,[150] U. Joshi,[150] T. Klijnsma,[150] B. Klima,[150] K. H. M. Kwok,[150] S. Lammel,[150] D. Lincoln,[150] R. Lipton,[150] T. Liu,[150] C. Madrid,[150] K. Maeshima,[150] C. Mantilla,[150] D. Mason,[150] P. McBride,[150] P. Merkel,[150] S. Mrenna,[150] S. Nahn,[150] J. Ngadiuba,[150] D. Noonan,[150] V. Papadimitriou,[150] N. Pastika,[150] K. Pedro,[150] C. Pena,[150,nnnn] F. Ravera,[150] A. Reinsvold Hall,[150,oooo] L. Ristori,[150] E. Sexton-Kennedy,[150] N. Smith,[150] A. Soha,[150] L. Spiegel,[150] S. Stoynev,[150] J. Strait,[150] L. Taylor,[150] S. Tkaczyk,[150] N. V. Tran,[150] L. Uplegger,[150] E. W. Vaandering,[150] I. Zoi,[150] C. Aruta,[151] P. Avery,[151] D. Bourilkov,[151] L. Cadamuro,[151] P. Chang,[151] V. Cherepanov,[151] R. D. Field,[151] E. Koenig,[151] M. Kolosova,[151] J. Konigsberg,[151] A. Korytov,[151] K. H. Lo,[151] K. Matchev,[151] N. Menendez,[151] G. Mitselmakher,[151] K. Mohrman,[151] A. Muthirakalayil Madhu,[151] N. Rawal,[151] D. Rosenzweig,[151] S. Rosenzweig,[151] K. Shi,[151] J. Wang,[151] T. Adams,[152] A. Al Kadhim,[152] A. Askew,[152] N. Bower,[152] R. Habibullah,[152] V. Hagopian,[152] R. Hashmi,[152] R. S. Kim,[152] S. Kim,[152] T. Kolberg,[152] G. Martinez,[152] H. Prosper,[152] P. R. Prova,[152] O. Viazlo,[152] M. Wulansatiti,[152] R. Yohay,[152] J. Zhang,[152] B. Alsufyani,[153] M. M. Baarmand,[153] S. Butalla,[153] T. Elkafrawy,[153,fff] M. Hohlmann,[153] R. Kumar Verma,[153] M. Rahmani,[153] M. R. Adams,[154] C. Bennett,[154] R. Cavanaugh,[154] S. Dittmer,[154] R. Escobar Franco,[154] O. Evdokimov,[154] C. E. Gerber,[154] D. J. Hofman,[154] J. h. Lee,[154] D. S. Lemos,[154] A. H. Merrit,[154] C. Mills,[154] S. Nanda,[154] G. Oh,[154] B. Ozek,[154] D. Pilipovic,[154] T. Roy,[154] S. Rudrabhatla,[154] M. B. Tonjes,[154] N. Varelas,[154] X. Wang,[154] Z. Ye,[154] J. Yoo,[154] M. Alhusseini,[155] D. Blend,[155] K. Dilsiz,[155,pppp] L. Emediato,[155] G. Karaman,[155] O. K. Köseyan,[155] J.-P. Merlo,[155] A. Mestvirishvili,[155,qqqq] J. Nachtman,[155] O. Neogi,[155] H. Ogul,[155,rrrr] Y. Onel,[155] A. Penzo,[155] C. Snyder,[155] E. Tiras,[155,ssss] B. Blumenfeld,[156] L. Corcodilos,[156] J. Davis,[156] A. V. Gritsan,[156] L. Kang,[156] S. Kyriacou,[156] P. Maksimovic,[156] M. Roguljic,[156] J. Roskes,[156] S. Sekhar,[156] M. Swartz,[156] T. Á. Vámi,[156] A. Abreu,[157] L. F. Alcerro Alcerro,[157] J. Anguiano,[157] P. Baringer,[157] A. Bean,[157] Z. Flowers,[157] D. Grove,[157] J. King,[157]

G. Krintiras,[157] M. Lazarovits,[157] C. Le Mahieu,[157] C. Lindsey,[157] J. Marquez,[157] N. Minafra,[157] M. Murray,[157] M. Nickel,[157] M. Pitt,[157] S. Popescu,[157,tttt] C. Rogan,[157] C. Royon,[157] R. Salvatico,[157] S. Sanders,[157] C. Smith,[157] Q. Wang,[157] G. Wilson,[157] B. Allmond,[158] A. Ivanov,[158] K. Kaadze,[158] A. Kalogeropoulos,[158] D. Kim,[158] Y. Maravin,[158] K. Nam,[158] J. Natoli,[158] D. Roy,[158] G. Sorrentino,[158] F. Rebassoo,[159] D. Wright,[159] A. Baden,[160] A. Belloni,[160] A. Bethani,[160] Y. M. Chen,[160] S. C. Eno,[160] N. J. Hadley,[160] S. Jabeen,[160] R. G. Kellogg,[160] T. Koeth,[160] Y. Lai,[160] S. Lascio,[160] A. C. Mignerey,[160] S. Nabili,[160] C. Palmer,[160] C. Papageorgakis,[160] M. M. Paranjpe,[160] L. Wang,[160] J. Bendavid,[161] W. Busza,[161] I. A. Cali,[161] Y. Chen,[161] M. D'Alfonso,[161] J. Eysermans,[161] C. Freer,[161] G. Gomez-Ceballos,[161] M. Goncharov,[161] P. Harris,[161] D. Hoang,[161] D. Kovalskyi,[161] J. Krupa,[161] L. Lavezzo,[161] Y.-J. Lee,[161] K. Long,[161] C. Mironov,[161] C. Paus,[161] D. Rankin,[161] C. Roland,[161] G. Roland,[161] S. Rothman,[161] Z. Shi,[161] G. S. F. Stephans,[161] J. Wang,[161] Z. Wang,[161] B. Wyslouch,[161] T. J. Yang,[161] B. Crossman,[162] B. M. Joshi,[162] C. Kapsiak,[162] M. Krohn,[162] D. Mahon,[162] J. Mans,[162] B. Marzocchi,[162] S. Pandey,[162] M. Revering,[162] R. Rusack,[162] R. Saradhy,[162] N. Schroeder,[162] N. Strobbe,[162] M. A. Wadud,[162] L. M. Cremaldi,[163] K. Bloom,[164] M. Bryson,[164] D. R. Claes,[164] C. Fangmeier,[164] F. Golf,[164] G. Haza,[164] J. Hossain,[164] C. Joo,[164] I. Kravchenko,[164] I. Reed,[164] J. E. Siado,[164] W. Tabb,[164] A. Vagnerini,[164] A. Wightman,[164] F. Yan,[164] D. Yu,[164] A. G. Zecchinelli,[164] G. Agarwal,[165] H. Bandyopadhyay,[165] L. Hay,[165] I. Iashvili,[165] A. Kharchilava,[165] M. Morris,[165] D. Nguyen,[165] S. Rappoccio,[165] H. Rejeb Sfar,[165] A. Williams,[165] E. Barberis,[166] Y. Haddad,[166] Y. Han,[166] A. Krishna,[166] J. Li,[166] M. Lu,[166] G. Madigan,[166] R. Mccarthy,[166] D. M. Morse,[166] V. Nguyen,[166] T. Orimoto,[166] A. Parker,[166] L. Skinnari,[166] A. Tishelman-Charny,[166] B. Wang,[166] D. Wood,[166] S. Bhattacharya,[167] J. Bueghly,[167] Z. Chen,[167] K. A. Hahn,[167] Y. Liu,[167] Y. Miao,[167] D. G. Monk,[167] M. H. Schmitt,[167] A. Taliercio,[167] M. Velasco,[167] R. Band,[168] R. Bucci,[168] S. Castells,[168] M. Cremonesi,[168] A. Das,[168] R. Goldouzian,[168] M. Hildreth,[168] K. W. Ho,[168] K. Hurtado Anampa,[168] C. Jessop,[168] K. Lannon,[168] J. Lawrence,[168] N. Loukas,[168] L. Lutton,[168] J. Mariano,[168] N. Marinelli,[168] I. Mcalister,[168] T. McCauley,[168] C. Mcgrady,[168] C. Moore,[168] Y. Musienko,[168,q] H. Nelson,[168] M. Osherson,[168] R. Ruchti,[168] A. Townsend,[168] M. Wayne,[168] H. Yockey,[168] M. Zarucki,[168] L. Zygala,[168] A. Basnet,[169] B. Bylsma,[169] M. Carrigan,[169] L. S. Durkin,[169] C. Hill,[169] M. Joyce,[169] A. Lesauvage,[169] M. Nunez Ornelas,[169] K. Wei,[169] B. L. Winer,[169] B. R. Yates,[169] F. M. Addesa,[170] H. Bouchamaoui,[170] P. Das,[170] G. Dezoort,[170] P. Elmer,[170] A. Frankenthal,[170] B. Greenberg,[170] N. Haubrich,[170] S. Higginbotham,[170] G. Kopp,[170] S. Kwan,[170] D. Lange,[170] A. Loeliger,[170] D. Marlow,[170] I. Ojalvo,[170] J. Olsen,[170] A. Shevelev,[170] D. Stickland,[170] C. Tully,[170] S. Malik,[171] A. S. Bakshi,[172] V. E. Barnes,[172] S. Chandra,[172] R. Chawla,[172] S. Das,[172] A. Gu,[172] L. Gutay,[172] M. Jones,[172] A. W. Jung,[172] D. Kondratyev,[172] A. M. Koshy,[172] M. Liu,[172] G. Negro,[172] N. Neumeister,[172] G. Paspalaki,[172] S. Piperov,[172] V. Scheurer,[172] J. F. Schulte,[172] M. Stojanovic,[172] J. Thieman,[172] A. K. Virdi,[172] F. Wang,[172] W. Xie,[172] J. Dolen,[173] N. Parashar,[173] A. Pathak,[173] D. Acosta,[174] A. Baty,[174] T. Carnahan,[174] K. M. Ecklund,[174] P. J. Fernández Manteca,[174] S. Freed,[174] P. Gardner,[174] F. J. M. Geurts,[174] A. Kumar,[174] W. Li,[174] O. Miguel Colin,[174] B. P. Padley,[174] R. Redjimi,[174] J. Rotter,[174] E. Yigitbasi,[174] Y. Zhang,[174] A. Bodek,[175] P. de Barbaro,[175] R. Demina,[175] J. L. Dulemba,[175] C. Fallon,[175] A. Garcia-Bellido,[175] O. Hindrichs,[175] A. Khukhunaishvili,[175] P. Parygin,[175,q] E. Popova,[175,q] R. Taus,[175] G. P. Van Onsem,[175] K. Goulianos,[176] B. Chiarito,[177] J. P. Chou,[177] Y. Gershtein,[177] E. Halkiadakis,[177] A. Hart,[177] M. Heindl,[177] D. Jaroslawski,[177] O. Karacheban,[177,ee] I. Laflotte,[177] A. Lath,[177] R. Montalvo,[177] K. Nash,[177] H. Routray,[177] S. Salur,[177] S. Schnetzer,[177] S. Somalwar,[177] R. Stone,[177] S. A. Thayil,[177] S. Thomas,[177] J. Vora,[177] H. Wang,[177] H. Acharya,[178] D. Ally,[178] A. G. Delannoy,[178] S. Fiorendi,[178] T. Holmes,[178] N. Karunarathna,[178] L. Lee,[178] E. Nibigira,[178] S. Spanier,[178] D. Aebi,[179] M. Ahmad,[179] O. Bouhali,[179,uuuu] M. Dalchenko,[179] R. Eusebi,[179] J. Gilmore,[179] T. Huang,[179] T. Kamon,[179,vvvv] H. Kim,[179] S. Luo,[179] S. Malhotra,[179] R. Mueller,[179] D. Overton,[179] D. Rathjens,[179] A. Safonov,[179] N. Akchurin,[180] J. Damgov,[180] V. Hegde,[180] A. Hussain,[180] Y. Kazhykarim,[180] K. Lamichhane,[180] S. W. Lee,[180] A. Mankel,[180] T. Mengke,[180] S. Muthumuni,[180] T. Peltola,[180] I. Volobouev,[180] A. Whitbeck,[180] E. Appelt,[181] S. Greene,[181] A. Gurrola,[181] W. Johns,[181] R. Kunnawalkam Elayavalli,[181] A. Melo,[181] F. Romeo,[181] P. Sheldon,[181] S. Tuo,[181] J. Velkovska,[181] J. Viinikainen,[181] B. Cardwell,[182] B. Cox,[182] J. Hakala,[182] R. Hirosky,[182] A. Ledovskoy,[182] A. Li,[182] C. Neu,[182] C. E. Perez Lara,[182] P. E. Karchin,[183] A. Aravind,[184] S. Banerjee,[184] K. Black,[184] T. Bose,[184] S. Dasu,[184] I. De Bruyn,[184]

P. Everaerts,[184] C. Galloni,[184] H. He,[184] M. Herndon,[184] A. Herve,[184] C. K. Koraka,[184] A. Lanaro,[184] R. Loveless,[184] J. Madhusudanan Sreekala,[184] A. Mallampalli,[184] A. Mohammadi,[184] S. Mondal,[184] G. Parida,[184] D. Pinna,[184] A. Savin,[184] V. Shang,[184] V. Sharma,[184] W. H. Smith,[184] D. Teague,[184] H. F. Tsoi,[184] W. Vetens,[184] A. Warden,[184] S. Afanasiev,[185] V. Andreev,[185] Yu. Andreev,[185] T. Aushev,[185] M. Azarkin,[185] A. Babaev,[185] A. Belyaev,[185] V. Blinov,[185,q] E. Boos,[185] V. Borshch,[185] D. Budkouski,[185] V. Bunichev,[185] M. Chadeeva,[185,q] V. Chekhovsky,[185] M. Danilov,[185,q] A. Dermenev,[185] T. Dimova,[185,q] D. Druzhkin,[185,wwww] M. Dubinin,[185,nnnn] L. Dudko,[185] G. Gavrilov,[185] V. Gavrilov,[185] S. Gninenko,[185] V. Golovtcov,[185] N. Golubev,[185] I. Golutvin,[185] I. Gorbunov,[185] Y. Ivanov,[185] V. Kachanov,[185] L. Kardapoltsev,[185,q] V. Karjavine,[185] A. Karneyeu,[185] V. Kim,[185,q] M. Kirakosyan,[185] D. Kirpichnikov,[185] M. Kirsanov,[185] V. Klyukhin,[185] O. Kodolova,[185,xxxx] D. Konstantinov,[185] V. Korenkov,[185] A. Kozyrev,[185,q] N. Krasnikov,[185] A. Lanev,[185] P. Levchenko,[185,yyyy] N. Lychkovskaya,[185] V. Makarenko,[185] A. Malakhov,[185] V. Matveev,[185,q] V. Murzin,[185] A. Nikitenko,[185,zzzz,xxxx] S. Obraztsov,[185] V. Oreshkin,[185] V. Palichik,[185] V. Perelygin,[185] M. Perfilov,[185] S. Petrushanko,[185] S. Polikarpov,[185,q] V. Popov,[185] O. Radchenko,[185,q] M. Savina,[185] V. Savrin,[185] V. Shalaev,[185] S. Shmatov,[185] S. Shulha,[185] Y. Skovpen,[185,q] S. Slabospitskii,[185] V. Smirnov,[185] A. Snigirev,[185] D. Sosnov,[185] V. Sulimov,[185] E. Tcherniaev,[185] A. Terkulov,[185] O. Teryaev,[185] I. Tlisova,[185] A. Toropin,[185] L. Uvarov,[185] A. Uzunian,[185] A. Vorobyev,[185,a] G. Vorotnikov,[185] N. Voytishin,[185] B. S. Yuldashev,[185,aaaaa] A. Zarubin,[185] I. Zhizhin,[185] and A. Zhokin[185]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Sun Yat-Sen University, Guangzhou, China*
[19]*University of Science and Technology of China, Hefei, China*
[20]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China*
[21]*Zhejiang University, Hangzhou, Zhejiang, China*
[22]*Universidad de Los Andes, Bogota, Colombia*
[23]*Universidad de Antioquia, Medellin, Colombia*
[24]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[25]*University of Split, Faculty of Science, Split, Croatia*
[26]*Institute Rudjer Boskovic, Zagreb, Croatia*
[27]*University of Cyprus, Nicosia, Cyprus*
[28]*Charles University, Prague, Czech Republic*
[29]*Escuela Politecnica Nacional, Quito, Ecuador*
[30]*Universidad San Francisco de Quito, Quito, Ecuador*
[31]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[32]*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
[33]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

[34]Department of Physics, University of Helsinki, Helsinki, Finland
[35]Helsinki Institute of Physics, Helsinki, Finland
[36]Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
[37]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[38]Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
[39]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[40]Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[41]Georgian Technical University, Tbilisi, Georgia
[42]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[43]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[44]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[45]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[46]University of Hamburg, Hamburg, Germany
[47]Karlsruher Institut fuer Technologie, Karlsruhe, Germany
[48]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
[49]National and Kapodistrian University of Athens, Athens, Greece
[50]National Technical University of Athens, Athens, Greece
[51]University of Ioánnina, Ioánnina, Greece
[52]HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[53]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[54]Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[55]Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[56]Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[57]Panjab University, Chandigarh, India
[58]University of Delhi, Delhi, India
[59]Saha Institute of Nuclear Physics, HBNI, Kolkata, India
[60]Indian Institute of Technology Madras, Madras, India
[61]Tata Institute of Fundamental Research-A, Mumbai, India
[62]Tata Institute of Fundamental Research-B, Mumbai, India
[63]National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
[64]Indian Institute of Science Education and Research (IISER), Pune, India
[65]Isfahan University of Technology, Isfahan, Iran
[66]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[67]University College Dublin, Dublin, Ireland
[68a]INFN Sezione di Bari, Bari, Italy
[68b]Università di Bari, Bari, Italy
[68c]Politecnico di Bari, Bari, Italy
[69a]INFN Sezione di Bologna, Bologna, Italy
[69b]Università di Bologna, Bologna, Italy
[70a]INFN Sezione di Catania, Catania, Italy
[70b]Università di Catania, Catania, Italy
[71a]INFN Sezione di Firenze, Firenze, Italy
[71b]Università di Firenze, Firenze, Italy
[72]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[73a]INFN Sezione di Genova, Genova, Italy
[73b]Università di Genova, Genova, Italy
[74a]INFN Sezione di Milano-Bicocca, Milano, Italy
[74b]Università di Milano-Bicocca, Milano, Italy
[75a]INFN Sezione di Napoli, Napoli, Italy
[75b]Università di Napoli 'Federico II', Napoli, Italy
[75c]Università della Basilicata, Potenza, Italy
[75d]Università G. Marconi, Roma, Italy
[76a]INFN Sezione di Padova, Padova, Italy
[76b]Università di Padova, Padova, Italy
[76c]Università di Trento, Trento, Italy
[77a]INFN Sezione di Pavia, Pavia, Italy
[77b]Università di Pavia, Pavia, Italy
[78a]INFN Sezione di Perugia, Perugia, Italy
[78b]Università di Perugia, Perugia, Italy
[79a]INFN Sezione di Pisa, Pisa, Italy

[79b]Università di Pisa, Pisa, Italy
[79c]Scuola Normale Superiore di Pisa, Pisa, Italy
[79d]Università di Siena, Siena, Italy
[80a]INFN Sezione di Roma, Roma, Italy
[80b]Sapienza Università di Roma, Roma, Italy
[81a]INFN Sezione di Torino, Torino, Italy
[81b]Università di Torino, Torino, Italy
[81c]Università del Piemonte Orientale, Novara, Italy
[82a]INFN Sezione di Trieste, Trieste, Italy
[82b]Università di Trieste, Trieste, Italy
[83]Kyungpook National University, Daegu, Korea
[84]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[85]Hanyang University, Seoul, Korea
[86]Korea University, Seoul, Korea
[87]Kyung Hee University, Department of Physics, Seoul, Korea
[88]Sejong University, Seoul, Korea
[89]Seoul National University, Seoul, Korea
[90]University of Seoul, Seoul, Korea
[91]Yonsei University, Department of Physics, Seoul, Korea
[92]Sungkyunkwan University, Suwon, Korea
[93]College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
[94]Riga Technical University, Riga, Latvia
[95]University of Latvia (LU), Riga, Latvia
[96]Vilnius University, Vilnius, Lithuania
[97]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[98]Universidad de Sonora (UNISON), Hermosillo, Mexico
[99]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[100]Universidad Iberoamericana, Mexico City, Mexico
[101]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[102]University of Montenegro, Podgorica, Montenegro
[103]University of Canterbury, Christchurch, New Zealand
[104]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[105]AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
[106]National Centre for Nuclear Research, Swierk, Poland
[107]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[108]Warsaw University of Technology, Warsaw, Poland
[109]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[110]Faculty of Physics, University of Belgrade, Belgrade, Serbia
[111]VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[112]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[113]Universidad Autónoma de Madrid, Madrid, Spain
[114]Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
[115]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[116]University of Colombo, Colombo, Sri Lanka
[117]University of Ruhuna, Department of Physics, Matara, Sri Lanka
[118]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[119]Paul Scherrer Institut, Villigen, Switzerland
[120]ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
[121]Universität Zürich, Zurich, Switzerland
[122]National Central University, Chung-Li, Taiwan
[123]National Taiwan University (NTU), Taipei, Taiwan
[124]High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[125]Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
[126]Middle East Technical University, Physics Department, Ankara, Turkey
[127]Bogazici University, Istanbul, Turkey
[128]Istanbul Technical University, Istanbul, Turkey
[129]Istanbul University, Istanbul, Turkey
[130]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
[131]National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
[132]University of Bristol, Bristol, United Kingdom

[133]Rutherford Appleton Laboratory, Didcot, United Kingdom
[134]Imperial College, London, United Kingdom
[135]Brunel University, Uxbridge, United Kingdom
[136]Baylor University, Waco, Texas, USA
[137]Catholic University of America, Washington, DC, USA
[138]The University of Alabama, Tuscaloosa, Alabama, USA
[139]Boston University, Boston, Massachusetts, USA
[140]Brown University, Providence, Rhode Island, USA
[141]University of California, Davis, Davis, California, USA
[142]University of California, Los Angeles, California, USA
[143]University of California, Riverside, Riverside, California, USA
[144]University of California, San Diego, La Jolla, California, USA
[145]University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
[146]California Institute of Technology, Pasadena, California, USA
[147]Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
[148]University of Colorado Boulder, Boulder, Colorado, USA
[149]Cornell University, Ithaca, New York, USA
[150]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[151]University of Florida, Gainesville, Florida, USA
[152]Florida State University, Tallahassee, Florida, USA
[153]Florida Institute of Technology, Melbourne, Florida, USA
[154]University of Illinois Chicago, Chicago, USA, Chicago, USA
[155]The University of Iowa, Iowa City, Iowa, USA
[156]Johns Hopkins University, Baltimore, Maryland, USA
[157]The University of Kansas, Lawrence, Kansas, USA
[158]Kansas State University, Manhattan, Kansas, USA
[159]Lawrence Livermore National Laboratory, Livermore, California, USA
[160]University of Maryland, College Park, Maryland, USA
[161]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[162]University of Minnesota, Minneapolis, Minnesota, USA
[163]University of Mississippi, Oxford, Mississippi, USA
[164]University of Nebraska-Lincoln, Lincoln, Nebraska, USA
[165]State University of New York at Buffalo, Buffalo, New York, USA
[166]Northeastern University, Boston, Massachusetts, USA
[167]Northwestern University, Evanston, Illinois, USA
[168]University of Notre Dame, Notre Dame, Indiana, USA
[169]The Ohio State University, Columbus, Ohio, USA
[170]Princeton University, Princeton, New Jersey, USA
[171]University of Puerto Rico, Mayaguez, Puerto Rico, USA
[172]Purdue University, West Lafayette, Indiana, USA
[173]Purdue University Northwest, Hammond, Indiana, USA
[174]Rice University, Houston, Texas, USA
[175]University of Rochester, Rochester, New York, USA
[176]The Rockefeller University, New York, New York, USA
[177]Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
[178]University of Tennessee, Knoxville, Tennessee, USA
[179]Texas A&M University, College Station, Texas, USA
[180]Texas Tech University, Lubbock, Texas, USA
[181]Vanderbilt University, Nashville, Tennessee, USA
[182]University of Virginia, Charlottesville, Virginia, USA
[183]Wayne State University, Detroit, Michigan, USA
[184]University of Wisconsin - Madison, Madison, Wisconsin, USA
[185]An institute or international laboratory covered by a cooperation agreement with CERN

[a]Deceased.
[b]Also at Yerevan State University, Yerevan, Armenia.
[c]Also at TU Wien, Vienna, Austria.
[d]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[e]Also at Ghent University, Ghent, Belgium.

[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[h]Also at UFMS, Nova Andradina, Brazil.
[i]Also at Nanjing Normal University, Nanjing, China.
[j]Also at Henan Normal University, Xinxiang, China.
[k]Also at The University of Iowa, Iowa City, Iowa, USA.
[l]Also at University of Chinese Academy of Sciences, Beijing, China.
[m]Also at China Center of Advanced Science and Technology, Beijing, China.
[n]Also at University of Chinese Academy of Sciences, Beijing, China.
[o]Also at China Spallation Neutron Source, Guangdong, China.
[p]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[q]Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
[r]Also at British University in Egypt, Cairo, Egypt.
[s]Also at Cairo University, Cairo, Egypt.
[t]Also at Birla Institute of Technology, Mesra, Mesra, India.
[u]Also at Purdue University, West Lafayette, Indiana, USA.
[v]Also at Université de Haute Alsace, Mulhouse, France.
[w]Also at Department of Physics, Tsinghua University, Beijing, China.
[x]Also at Tbilisi State University, Tbilisi, Georgia.
[y]Also at The University of the State of Amazonas, Manaus, Brazil.
[z]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[aa]Also at University of Hamburg, Hamburg, Germany.
[bb]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[cc]Also at Isfahan University of Technology, Isfahan, Iran.
[dd]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[ee]Also at Brandenburg University of Technology, Cottbus, Germany.
[ff]Also at Forschungszentrum Jülich, Juelich, Germany.
[gg]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[hh]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[ii]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[jj]Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[kk]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[ll]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[mm]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[nn]Also at Punjab Agricultural University, Ludhiana, India.
[oo]Also at University of Hyderabad, Hyderabad, India.
[pp]Also at University of Visva-Bharati, Santiniketan, India.
[qq]Also at Indian Institute of Science (IISc), Bangalore, India.
[rr]Also at IIT Bhubaneswar, Bhubaneswar, India.
[ss]Also at Institute of Physics, Bhubaneswar, India.
[tt]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[uu]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[vv]Also at Sharif University of Technology, Tehran, Iran.
[ww]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[xx]Also at Helwan University, Cairo, Egypt.
[yy]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[zz]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[aaa]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[bbb]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[ccc]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[ddd]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[eee]Also at Università di Napoli 'Federico II', Napoli, Italy.
[fff]Also at Ain Shams University, Cairo, Egypt.
[ggg]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[hhh]Also at Riga Technical University, Riga, Latvia.
[iii]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[jjj]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[kkk]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[lll]Also at Saegis Campus, Nugegoda, Sri Lanka.
[mmm]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.

[nnn]Also at National and Kapodistrian University of Athens, Athens, Greece.
[ooo]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[ppp]Also at University of Vienna Faculty of Computer Science, Vienna, Austria.
[qqq]Also at Universität Zürich, Zurich, Switzerland.
[rrr]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[sss]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[ttt]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[uuu]Also at Konya Technical University, Konya, Turkey.
[vvv]Also at Izmir Bakircay University, Izmir, Turkey.
[www]Also at Adiyaman University, Adiyaman, Turkey.
[xxx]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[yyy]Also at Marmara University, Istanbul, Turkey.
[zzz]Also at Milli Savunma University, Istanbul, Turkey.
[aaaa]Also at Kafkas University, Kars, Turkey.
[bbbb]Also at stanbul Okan University, Istanbul, Turkey.
[cccc]Also at Hacettepe University, Ankara, Turkey.
[dddd]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[eeee]Also at Yildiz Technical University, Istanbul, Turkey.
[ffff]Also at Vrije Universiteit Brussel, Brussel, Belgium.
[gggg]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[hhhh]Also at University of Bristol, Bristol, United Kingdom.
[iiii]Also at IPPP Durham University, Durham, United Kingdom.
[jjjj]Also at Monash University, Faculty of Science, Clayton, Australia.
[kkkk]Also at Università di Torino, Torino, Italy.
[llll]Also at Bethel University, St. Paul, Minnesota, USA.
[mmmm]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[nnnn]Also at California Institute of Technology, Pasadena, California, USA.
[oooo]Also at United States Naval Academy, Annapolis, Maryland, USA.
[pppp]Also at Bingol University, Bingol, Turkey.
[qqqq]Also at Georgian Technical University, Tbilisi, Georgia.
[rrrr]Also at Sinop University, Sinop, Turkey.
[ssss]Also at Erciyes University, Kayseri, Turkey.
[tttt]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[uuuu]Also at Texas A&M University at Qatar, Doha, Qatar.
[vvvv]Also at Kyungpook National University, Daegu, Korea.
[wwww]Also at Universiteit Antwerpen, Antwerpen, Belgium.
[xxxx]Also at Yerevan Physics Institute, Yerevan, Armenia.
[yyyy]Also at Northeastern University, Boston, Massachusetts, USA.
[zzzz]Also at Imperial College, London, United Kingdom.
[aaaaa]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.