A search for the resonant production of high-mass photon pairs is presented. The analysis is based on samples of proton-proton collision data collected by the CMS experiment at center-of-mass energies of 8 and 13 TeV, corresponding to integrated luminosities of 19.7 and 3.3 fb⁻¹, respectively. The interpretation of the search results focuses on spin-0 and spin-2 resonances with masses between 0.5 and 4 TeV and with widths, relative to the mass, between $1.4 \times 10^{-2}$ and $5.6 \times 10^{-2}$. Limits are set on scalar resonances produced through gluon-gluon fusion, and on Randall-Sundrum gravitons. A modest excess of events compatible with a narrow resonance with a mass of about 750 GeV is observed. The local significance of the excess is approximately 3.4 standard deviations. The significance is reduced to 1.6 standard deviations once the effect of searching under multiple signal hypotheses is considered. More data are required to determine the origin of this excess.

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Simulated signal samples of spin-0 and spin-2 resonances decaying to two photons are generated at leading order (LO) with the PYTHIA8.2 [28] event generator, using the NNPDF2.3 [29] parton distribution functions (PDFs), with values of the resonance mass $m_X$ in the range $0.5 < m_X < 4$ TeV and for three values of the relative width $\Gamma_X/m_X = 1.4 \times 10^{-4}$, $1.4 \times 10^{-2}$, and $5.6 \times 10^{-2}$. For the RS graviton model, where $\Gamma_X/m_X = 1.4k^2$ [6], this corresponds to dimensionless coupling values $k = 0.01$, 0.1, and 0.2. The chosen relative widths correspond, respectively, to resonances much narrower than, comparable to, and significantly wider than the detector resolution. The principal SM background processes, namely the direct production of two photons ($\gamma\gamma$), the production of $\gamma +$ jets events in which jet fragments are misidentified as photons, and the production of multijet events with misidentified jet fragments, are simulated with the SHERPA2.1 [30], MADGRAPH_AMC@NLO2.2 [31] (interfaced with PYTHIA8.2 for parton showering and hadronization), and PYTHIA8.2 generators, respectively. For all simulated samples, the detector response is modeled with the GEANT4 package [32]. The kinematic requirements and the identification criteria described below are determined using the simulated signal and background samples and are finalized prior to inspecting the diphoton mass data distribution in the search region.

For the 8 TeV data, the results of Ref. [8] are used in the present study to place limits on resonances with $m_X \leq 850$ GeV. In this Letter, we extend these 8 TeV limits to masses $m_X > 850$ GeV using an analysis similar to the 13 TeV one. In the following, we first describe the 13 TeV analysis, then the manner in which the 8 TeV analysis differs.

For the $B = 3.8$ (0) T data at 13 TeV, the trigger selection requires at least two photon candidates, each with transverse momentum $p_T$ above 60 (40) GeV. For each photon candidate, the ratio of the energy deposited in the hadron calorimeter to the photon energy ($H/E$ ratio) is required to be less than 0.15. For resonances with $m_X > 0.5$ TeV, the trigger selection is fully efficient.

In the subsequent analysis, photons are reconstructed by clustering spatially correlated energy deposits in the ECAL. To obtain the best energy resolution, the ECAL signals are calibrated and corrected for the variation of the crystal transparency during the data collection period [33]. The energies of the photon candidates are estimated with a multivariate regression technique [33]. For the 3.8 T data, the interaction vertex, i.e., the $pp$ collision point from which the photons are assumed to originate, is selected using the algorithm described in Ref. [34]. For resonances with $m_X > 500$ GeV, the fraction of events in which the interaction vertex is correctly assigned is estimated from simulation to be approximately 90%. For the 0 T data, the interaction vertex is identified as the reconstructed vertex with the largest number of charged tracks, yielding an estimated probability for the correct assignment of about 60%. The direction of a photon candidate’s momentum is computed taking as the origin the position of the chosen interaction vertex. Corrections to account for residual differences in the photon energy scale and resolution between the data and simulation are determined using $Z \rightarrow e^+e^-$ events, through the procedure described in Ref. [33]. For the 3.8 (0) T data, the energy scale and resolution corrections are derived in eight (four) bins defined in terms of the $R_0$ variable, which is the ratio of the energy deposited in the central 3 $\times$ 3 crystal matrix to the full cluster energy, and of the $|\eta|C$ variable, which is the absolute value of the pseudorapidity of the cluster with respect to the center of the detector. The energy scale correction factors measured for the 3.8 T data are found to be about 1% higher than the 0 T factors, while similar values are measured for the resolution corrections. The variation of the corrections in the EB (EE) region is assessed as a function of $p_T$ up to $p_T \approx 150$ (100) GeV using $Z \rightarrow e^+e^-$ data, and is found to be 0.5 (0.7)% or less for both the 3.8 and 0 T data.

Photon candidates are subject to additional identification requirements. The $H/E$ ratio of the candidates must lie below 0.05. For the 3.8 (0) T data, the size of the electromagnetic clusters in $\eta$ ($\eta$ and $\phi$) [33] is required to be compatible with that expected for a prompt photon, i.e., a photon produced directly in a hard-scattering process. For candidates in the 3.8 T sample, the scalar $p_T$ sum of additional photons in a cone of radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$ around the photon direction, corrected to account for the contributions from extraneous $pp$ collisions in the same or nearby proton bunch crossing, must be less than 2.5 GeV. For the 0 T sample, the analogous sum must be less than 3.6 (3.0) GeV for the EB (EE) candidates. For the 3.8 T data, we additionally require the scalar $p_T$ sum of the charged hadrons within a cone of radius $R = 0.3$ around the photon direction to be less than 5 GeV and for the 0 T data the number of charged hadrons within this cone, excluding an inner cone of radius $R = 0.05$, to be 3 or less. The photon isolation requirement for the 0 T data is less stringent than that for the 3.8 T data to compensate for the additional selection criterion for the 0 T data based on the size of the shower profile in the azimuthal direction. Photon candidates associated with an electron track that itself is not consistent with a photon conversion are rejected.

For the 3.8 T data, the efficiency of the identification criteria for prompt isolated photon candidates in the barrel (endcaps) is above 90 (85)% for the kinematic range considered in the analysis. For the 0 T data, the corresponding efficiency exceeds 85 (70)%. The identification and trigger efficiencies are measured, as a function of $p_T$, using data events containing a Z boson decaying to a pair of electrons, or to a pair of electrons or muons in association

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with a photon [33]. The efficiencies from data are found to be consistent with those from simulation.

In each event, photon candidates with $p_T > 75$ GeV are grouped in all possible pairs. We require $|\eta| < 2.5$ for each candidate in the pair and $|\eta| < 1.44$ for at least one of them. Candidates in the region $1.44 < |\eta| < 1.57$ are rejected because of difficulties in modeling the photon reconstruction efficiency in the transition region between the barrel and endcap detectors. The invariant mass $m_{\gamma\gamma}$ of the pair is required to exceed 230 GeV. For events in which one photon candidate is reconstructed in an endcap, $m_{\gamma\gamma}$ must exceed 330 GeV. The fraction of events in which more than one photon pair satisfies all the selection criteria is roughly 1%. In these cases, only the pair with the largest photon scalar $p_T$ sum is retained.

Photon pairs are divided into two categories, denoted by “EBEB” when both photons are reconstructed in the ECAL barrel and by “EBEE” when one of the two photons is reconstructed in an ECAL endcap. Each category is further divided into events recorded at 3.8 and 0 T.

For the 3.8 (0) T analysis, the overall signal selection efficiency varies between 0.5–0.7 (0.4–0.5), depending on the signal hypothesis. Because of the different angular distribution of the decay products, the kinematic acceptance for the RS graviton resonances is lower than for scalar resonances; for $m_X < 1$ TeV the reduction is approximately 20%. The two acceptances become similar for $m_X > 3$ TeV. About 90 (80)% of the background events in the EBEB (EBEE) sample arises from the $\gamma\gamma$ process. These results, estimated from simulation, are validated for the 3.8 T analysis using the method described in Ref. [35].

The principal difference between the 8 TeV analysis described in Ref. [8] (used here in the search for resonances with $m_X \leq 850$ GeV) and the 13 TeV analysis described above is that, in the former, the events are further categorized according to the $R_0$ value of the photon candidates. Specifically, events are categorized as having either $\min(R_0) > 0.94$ or $\min(R_0) \leq 0.94$, where $\min(R_0)$ is the smaller of the two $R_0$ values in the photon pair. To search for resonances with $m_X > 850$ GeV in the 8 TeV data, we select photons with $p_T > 80$ GeV that satisfy the “loose” identification criteria of Ref. [33] and require that there be an EBEB photon pair with $m_{\gamma\gamma} > 300$ GeV. We do not include EBEE photon pairs in this case for reasons of simplicity, because such events would have improved the analysis sensitivity by at most a few percent.

The $m_{\gamma\gamma}$ distributions of the events selected in the 13 TeV analysis are shown in Fig. 1. The corresponding 8 TeV results used for the $m_X \leq 850$ GeV search are shown in Fig. 2 [8]. The $m_{\gamma\gamma}$ distributions of 8 TeV events used for the $m_X \leq 850$ GeV search are available in the Supplemental Material [36].

The results of the search are interpreted in the framework of a composite statistical hypothesis test. For each signal hypothesis, a simultaneous unbinned extended maximum likelihood fit to the $m_{\gamma\gamma}$ spectra observed in all categories is performed and the likelihood function used to construct the test statistic. The modified frequentist method [37,38] is utilized to set upper limits on the production of diphoton resonances, following the prescription described in Ref. [39]. The compatibility of the observation with the background-only hypothesis is evaluated by computing the background-only $p$ value [39], denoted $p_0$ in the following. Asymptotic formulas [40] are used in the calculations. The accuracy of the formulas in the estimation of limits and significance is studied for a subset of the hypothesis tests and is found to be about 10%. Thus the upper limits on the production cross section times branching fraction for the resonant production of two photons could be up to 10% higher, and the significance of an excess over the SM up to 10% lower, than the results presented below.

The shape of the $m_{\gamma\gamma}$ signal distribution in the likelihood function is given by the convolution of the intrinsic shape, taken from the PYTHIA generator, with a function characterizing the CMS detector response. The normalization is a free parameter of the fit. The intrinsic shape is generated for various $m_X$ values. The detector response is derived from a PYTHIA sample including GEANT4 modeling using a coarser spacing in $m_X$, assuming a small intrinsic width, and incorporating corrections derived from $Z \rightarrow e^+ e^-$ data. The intrinsic width and detector response are interpolated to intermediate points using the “moment morphing” technique of Ref. [41]. At 13 TeV, the signal mass resolution, defined as the ratio of the full width at half maximum (FWHM) of the distribution, divided by 2.35, to the peak position, is roughly 1.0 (1.5)% for the EBEB (EBEE) categories.

The background $m_{\gamma\gamma}$ spectra are described by parametric functions of $m_{\gamma\gamma}$. The coefficients are obtained from a fit to the data events, and considered as unconstrained nuisance parameters in the fit. In this manner, the description of the background is derived from data. For the 13 TeV data and for the 8 TeV data in the $m_X > 850$ GeV search, a parametrization of the form $f(m_{\gamma\gamma}) = a + b \log(m_{\gamma\gamma})$ is chosen, where $a$ and $b$ are parameters determined independently for each of the five event categories: the four shown in Fig. 1 plus that of the 8 TeV $m_X > 850$ GeV search. The validity of the procedure is tested, using simulated background samples, by examining the difference between the true and predicted numbers of background events in 14 contiguous intervals in $m_{\gamma\gamma}$ within the search region. For each interval, a sampling distribution of the pull variable is constructed using pseudoexperiments with the same sample size as the data. Background-only fits are performed on the pseudoexperiments using the same $m_{\gamma\gamma}$ ranges employed in data. In each region, the pull is defined as the difference between the true and estimated numbers of events divided by the estimated statistical uncertainty. If the absolute
value $|m|$ of the median of the sampling distribution exceeds 0.5 in any interval, the statistical uncertainty in the predicted number of background events is increased by an additional term, denoted the "bias term," which is parametrized as a continuous function of $m_{\gamma\gamma}$. The bias term is tuned in such a manner that the sampling distribution of a pull variable that includes the bias term yields $|m| < 0.5$ for all intervals. The additional uncertainty is then included in the likelihood function by adding to the background model a component having the same shape as the signal, with a normalization coefficient distributed as a Gaussian of mean zero and width equal to the integral of the bias term over the FWHM of the tested signal shape. The inclusion of the additional component, whose magnitude is comparable to the 1 standard deviation band shown in Fig. 1, has the effect of avoiding falsely positive or negative tests that could be induced by a mismodeling of the background shape, and it degrades the analysis sensitivity by 5% or less.

For the 8 TeV data in the $m_X \leq 850$ GeV search, the background shape is parametrized as $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{-c}e^{-dm_{\gamma\gamma}}$, where $c$ and $d$ are parameters fit independently for each event category of Fig. 2, and different $m_{\gamma\gamma}$ intervals are used for each $m_X$. The intervals are chosen by comparing the results of the nominal parametrization with those obtained using alternative parametrizations of the background, with the intervals determined to minimize differences in the predicted background yields [8]. The method used for 13 TeV and the one of Ref. [8] yield similar levels of uncertainty in the background estimation. The latter approach, however, is not easily applicable when only a small number of events populate the $m_{\gamma\gamma} > m_X$ region, which is why this approach is not adopted for the 13 TeV analysis or for the 8 TeV search with $m_X > 850$ GeV.
We evaluate systematic uncertainties in the signal model predictions. For the 8 TeV data, these are discussed in Ref. [8]. For the 13 TeV analysis they are as follows. For 3.8 (0) T, a 2.7 (12)% uncertainty is due to the limited knowledge of the total integrated luminosity [42]. An 8 (16)% uncertainty is attributed to the selection efficiency and a 6 (6)% uncertainty to the PDFs. An uncertainty of 1% is assigned to the absolute photon energy scale, with an additional 1% to account for possible differences between the energy scales of the 3.8 and 0 T samples. An uncertainty in the signal mass resolution is assessed by varying the photon energy resolution corrections derived from $Z \rightarrow e^+e^-$ events by $\pm 0.5\%$. Energy resolution uncertainties are taken to be uncorrelated between the 8 and 13 TeV data, while a linear correlation of 0.5 is assumed for the energy scale. Taking the value of the linear correlation to be 0 or 1 leads to negligible changes in the results. Other systematic uncertainties are taken to be uncorrelated between the two data sets, except for the one associated with the PDFs, which is taken to be fully correlated.

The ratio of the 8 TeV to the 13 TeV production rates is determined from simulation and is held constant in the fit. For the scalar (RS graviton) resonance, this ratio decreases from 0.27 (0.29) at $m_X = 500$ GeV to 0.03 (0.04) at $m_X = 4$ TeV and equals 0.22 (0.24) for $m_X = 750$ GeV. The uncertainty in this ratio, determined by varying the PDFs, is found to have a negligible impact on the results and is therefore ignored.

The median expected and observed 95% confidence level (C.L.) exclusion limits on the product of the 13 TeV signal production cross section and decay branching fraction, $\sigma_{13\text{ TeV}}B_{\gamma\gamma}$, are presented in Fig. 3 for the combined analysis. The upper (lower) plot shows the results for a narrow (broad) resonance width,
The results for $\Gamma_X/m_X = 1.4 \times 10^{-2}$ are shown in the middle plot. The blue-grey (darker) and green (lighter) solid curves indicate the observed limits for a scalar resonance and an RS graviton. The corresponding dashed curves show the expected limits, with their one standard deviation intervals. Using the LO cross sections from PYTHIA8.2, RS gravitons with masses below 1.6, 3.3, and 3.8 TeV are excluded for $k = 0.01$, 0.1, and 0.2, respectively, corresponding to $\Gamma_X/m_X = 1.4 \times 10^{-4}$, $1.4 \times 10^{-2}$, and $5.6 \times 10^{-2}$. The observed value of $p_0$ as a function of $m_X$ is shown in Fig. 4 for the scalar narrow-width hypothesis ($\Gamma_X/m_X = 1.4 \times 10^{-3}$). The largest excess, observed for $m_X \approx 750$ GeV, has a local significance of approximately 3.4 standard deviations. Similar values are obtained for the two spin hypotheses, while lower values of the local significance are obtained for wider signal hypotheses. For $\Gamma_X/m_X = 5.6 \times 10^{-2}$ a local significance of 2.3 standard deviations is estimated.

Trial factors associated with the test of several mass hypotheses are estimated for fixed width and spin assumptions by counting the number of times the value of $p_0$ observed in data crosses the level corresponding to 0.5 standard deviations and applying the asymptotic formulas of Ref. [43], where a trial factor refers to the ratio of the probability to observe an excess at a given $m_X$ value to the probability to observe it anywhere in the examined $m_X$ range. To account for the different width and spin hypotheses tested, a correction factor is estimated using the 13 TeV event categories, as follows. A sampling distribution of the minimum value of $p_0$ is generated from an ensemble of background-only pseudoexperiments, testing for all examined spin, width, and mass hypotheses. The correction factor is given by the ratio of the trial factors obtained varying only the signal mass to those obtained also varying the width and spin. A global significance for the 750 GeV excess, taking into account the effect of testing all the signal hypotheses considered, is thereby estimated to be approximately 1.6 standard deviations. The estimated global significance increases by about 5% if the spin hypothesis is not varied and by an additional 5% if only narrow-width signal hypotheses are considered. A statistical uncertainty of roughly 10% in the estimated global significance is associated with the counting of $p_0$ crossings in data.

The excess is primarily due to events in which both photons are in the ECAL barrel. The shape of the associated ECAL clusters is in agreement with the expectation for high-$p_T$ prompt photons. In particular, the $R_9$ value exceeds 0.94 for more than 80% of the photon pair candidates in the 13 TeV data in the region corresponding to the excess, i.e., the showers are compact, with lateral shapes like those of unconverted photons at lower energy, in agreement with the expectation for a sample of prompt high energy photon pairs. Within the limited statistical precision currently available, the kinematic distributions of the diphoton candidates in the $m_{\gamma\gamma}$ region corresponding to...
the largest excess, as well as the multiplicity and kinematic distributions of the hadronic jets reconstructed in the same events, do not exhibit significant deviations from the distributions expected for SM processes.

In summary, a search for the resonant production of high-mass photon pairs is presented. The analysis is based on 19.7 and 3.3 fb$^{-1}$ of proton-proton collisions collected at $\sqrt{s} = 8$ and 13 TeV, respectively, by the CMS experiment. Limits on the production cross section for resonance masses 0.75 < $m_X < 4$ TeV and relative widths 1.4 × 10$^{-4}$ < $\Gamma_X/m_X < 5.6 \times 10^{-2}$ are determined. Using leading-order cross sections for RS graviton production, RS gravitons with masses below about 1.6, 3.3, and 3.8 TeV are excluded at 95% confidence level for gravitons with masses below about 1.6, 3.3, and 3.8 TeV, respectively, corresponding to $\approx 10^8$, $\approx 10^7$, and $\approx 10^6$ photons. The signficance of the excess is reduced to about 1.6 standard deviations once the effect of searching under multiple hypotheses is taken into account. More data are required to determine the origin of this excess. A similar analysis is presented by the ATLAS Collaboration [44].

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: BMWWF and FWF (Austria); FNRS and FWO (Belgium); CNEP, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); NRF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFS, 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); MOE 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); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[14] ATLAS Collaboration, Search for resonant diboson production in the $WW$/$WZ \rightarrow \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV, Phys. Rev. D 87, 112006 (2013).

CMS Collaboration, Search for Narrow Resonances in Dijet Final States at $\sqrt{s} = 8$ TeV with the Novel CMS Technique of Data Scouting, arXiv:1604.08907.


CMS Collaboration, Search for massive resonances in dijet systems containing jets tagged as $W$ or $Z$ boson decays in $pp$ collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 08 (2014) 173.


See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.117.051802 for figures illustrating the $m_{\gamma\gamma}$ spectrum at 8 TeV for $m_X > 500$ GeV, the background composition, and further aspects of the statistical analysis.


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<td>165</td>
<td>Purdue University Calumet</td>
<td>Hammond, Indiana, USA</td>
</tr>
</tbody>
</table>
aDeceased.
bAlso at Vienna University of Technology, Vienna, Austria.
cAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
dAlso at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
eAlso at Universidade Estadual de Campinas, Campinas, Brazil.
fAlso at Universidade Federal de Pelotas, Pelotas, Brazil.
gAlso at Université Libre de Bruxelles, Bruxelles, Belgium.
hAlso at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
iAlso at Joint Institute for Nuclear Research, Dubna, Russia.
jAlso at Suez University, Suez, Egypt.
kAlso at British University in Egypt, Cairo, Egypt.
lAlso at Ain Shams University, Cairo, Egypt.
mAlso at Helwan University, Cairo, Egypt.
nAlso at Université de Haute Alsace, Mulhouse, France.
oAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
pAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
qAlso at Tbilisi State University, Tbilisi, Georgia.
rAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
sAlso at University of Hamburg, Hamburg, Germany.
tAlso at Brandenburg University of Technology, Cottbus, Germany.
uAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
viAlso at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University.
viiAlso at University of Debrecen, Debrecen, Hungary.
viiiAlso at Indian Institute of Science Education and Research, Bhopal, India.
ixAlso at Institute of Physics, Bhubaneswar, India.
xiAlso at University of Visva-Bharati, Santiniketan, India.
xiiAlso at University of Ruhuna, Matara, Sri Lanka.
xiiiAlso at Isfahan University of Technology, Isfahan, Iran.
xivAlso at University of Tehran, Department of Engineering Science, Tehran, Iran.
xvAlso at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
xviAlso at Università degli Studi di Siena, Siena, Italy.
xviiAlso at Purdue University, West Lafayette, IN, USA.
xviiiAlso at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
ixixAlso at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
xxAlso at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
xxiAlso at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
xxiiAlso at Institute for Nuclear Research, Moscow, Russia.
xxiiiAlso at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.
xxivAlso at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
xxvAlso at University of Florida, Gainesville, FL, USA.
xxviAlso at P.N. Lebedev Physical Institute, Moscow, Russia.
xxviiAlso at California Institute of Technology, Pasadena, CA, USA.
xxviiiAlso at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
xxixAlso at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
xxxAlso at INFN Sezione di Roma, Università di Roma, Roma, Italy.
xxxiAlso at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
xxxiAlso at National and Kapodistrian University of Athens, Athens, Greece.
xxxivAlso at Riga Technical University, Riga, Latvia.
Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
Also at Adiyaman University, Adiyaman, Turkey.
Also at Mersin University, Mersin, Turkey.
Also at Cag University, Mersin, Turkey.
Also at Piri Reis University, Istanbul, Turkey.
Also at Ozyegin University, Istanbul, Turkey.
Also at Izmir Institute of Technology, Izmir, Turkey.
Also at Marmara University, Istanbul, Turkey.
Also at Kafkas University, Kars, Turkey.
Also at Istanbul Bilgi University, Istanbul, Turkey.
Also at Yildiz Technical University, Istanbul, Turkey.
Also at Hacettepe University, Ankara, Turkey.
Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
Also at Argonne National Laboratory, Argonne, IL, USA.
Also at Erzincan University, Erzincan, Turkey.
Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
Also at Texas A&M University at Qatar, Doha, Qatar.
Also at Kyungpook National University, Daegu, Korea.