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Search for excited leptons in $\ell\ell\gamma$ final states in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

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Abstract

A search is presented for excited electrons and muons in $\ell\ell\gamma$ final states at the LHC. The search is based on a data sample corresponding to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV, collected with the CMS detector in 2016. This is the first search for excited leptons at $\sqrt{s} =$ 13 TeV. The observation is consistent with the standard model background prediction, and the most stringent exclusion limits to date are set on the excited lepton mass and the compositeness scale, at 95% confidence level. Excited electrons and muons are excluded for masses below 3.9 and 3.8 TeV, respectively, under the assumption that the excited lepton mass equals the compositeness scale. The best observed limit on the compositeness scale is obtained with an excited lepton mass of around 1.0 TeV, excluding values below 25 TeV for both excited electrons and muons.

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*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) provides a very precise description of various phenomena in particle physics observed over the last half century. Notwithstanding its huge success, it does not explain the origin of the mass hierarchy and the number of generations of quarks and leptons. As an attempt to answer such fundamental questions, compositeness of quarks and leptons is introduced in many models [1–10]. These compositeness models suggest that quarks and leptons are themselves made of fundamental constituents that are bound by a new strong interaction with a characteristic energy scale Λ (called the compositeness scale).

An important prediction of compositeness models is the existence of excited states of quarks and leptons. In proton-proton (pp) collisions, excited fermions could be produced via contact interactions (CI) and decay either through SM gauge interactions or via CI to SM fermions.

This paper presents a search for excited leptons ($\ell^* = \mathrm{e}^*, \mu^*$) in $\ell\ell\gamma$ ($\ell = \mathrm{e}, \mu$) final states where the excited lepton decays to a SM lepton and a photon ($\ell^* \to \ell\gamma$) as illustrated in Fig. 1. A clear signature of a same-flavor (SF) lepton pair and a photon allows highly efficient signal selection. However, there is an ambiguity in reconstructing the excited lepton mass because of the two possible pairings of a lepton and the photon. For this search, information of both invariant masses is used to discriminate the excited lepton signal from SM background processes.

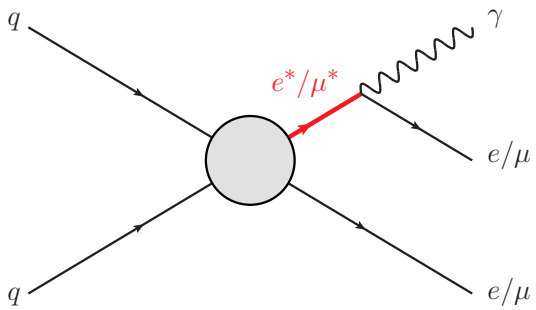

Figure 1: The Feynman diagram of the production of excited leptons in $\ell\ell\gamma$ final states.

We consider a benchmark model based on the formalism described in Ref. [8]. The effective Lagrangian of four-fermion CI, the main production mechanisms of excited leptons at the LHC, is given by

$$\mathcal{L}_{\mathrm{CI}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu, \tag{1}$$

where g_* is the coupling constant, which is set to be equal to $\sqrt{4\pi}$ in the model, and j_μ represents the fermion currents for SM fermions and their excited states, neglecting right-handed currents. In addition, excited lepton decays via SM gauge interactions are described by the corresponding Lagrangian

$$\mathcal{L}_{\mathrm{gauge}} = \frac{1}{2\Lambda} \bar{\ell}_R^* \sigma^{\mu\nu} \left(g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) \ell_L + \mathrm{h.c.}, \tag{2}$$

where ℓ and ℓ^* denote the lepton and excited lepton fields, and $W_{\mu\nu}$ and $B_{\mu\nu}$ are the SU(2) and U(1) gauge fields. The quantities $g = e/\sin\theta_W$ and $g' = e/\cos\theta_W$ represent the corresponding electroweak gauge couplings with the Weinberg mixing angle θ_W, and τ and Y are the generators of the SU(2) and U(1) groups. The symbols f and f' describe the couplings between SM leptons and excited leptons via gauge interactions and are chosen to be equal to 1 in the model.

Searches for excited leptons have been previously performed by the CMS Collaboration [11, 12], but no evidence for their existence was found, excluding $m_{\ell^*} < 2.5\,\mathrm{TeV}$ for the case $\Lambda =$

m_{ℓ^*}. Searches at the LEP [13–16], HERA [17], and Tevatron [18–21] colliders, and by the ATLAS Collaboration at $\sqrt{s} = 7$ TeV [22] and 8 TeV [23, 24] also found no evidence for the existence of excited leptons, setting lower mass limits of 2.2 and 2.8 TeV for excited electrons and muons, respectively, for the case $\Lambda = m_{\ell^*}$.

2 The CMS detector

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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [25]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of less than 100 kHz within a time interval of less than 4 μs. 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.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [26].

3 Data and simulated samples

The data used for this analysis correspond to an integrated luminosity of 35.9 fb^{-1}, recorded by the CMS detector in pp collisions at a center-of-mass energy of 13 TeV in 2016. Highly efficient triggers with 98–99% efficiency are used for this analysis, for events that satisfy the offline selection criteria. Events for the eeγ channel are selected using double-electron triggers that impose a transverse energy threshold of 33 GeV and online identification criteria for both electron candidates. For the $\mu\mu\gamma$ channel, events are selected using single-muon triggers with muon isolation criteria and a threshold of 24 GeV on the transverse momentum p_{T} of the muon.

To model the detector acceptance and event selection efficiency of signal events, simulated signal samples are generated with PYTHIA 8.205 [27] for excited lepton masses ranging from 0.25 to 5 TeV at intervals of 0.25 TeV up to 4 TeV and at intervals of 0.5 TeV between 4 and 5 TeV. The CUETP8M1 [28] underlying-event tune is used for all simulated samples. The signal samples are generated at the compositeness scale $\Lambda = 10$ TeV, but are also used for different compositeness scale interpretations since this parameter has a negligible impact on the kinematic distributions of final-state particles. The simulated signals are generated at leading order (LO) in perturbative quantum chromodynamics (QCD), and a mass-dependent K factor for next-to-leading-order (NLO) corrections is applied [29].

Major SM background processes such as DY+γ and $\mathrm{t\bar{t}}$+γ are generated at NLO using the MADGRAPH5_aMC@NLO 2.3.3 generator [30], while WW, WZ, and ZZ backgrounds are generated at LO with PYTHIA. The cross section for WW production is calculated at next-to-next-to-leading order [31] and the cross sections for WZ and ZZ production are computed at NLO [32].

The NNPDF3.0 [33] parton distribution function (PDF) set is used for all generated samples.

The generated events are processed through the full GEANT4 [34] simulation of the CMS detector. The effect of multiple pp interactions within the same bunch crossing or adjacent bunch crossings (pileup) is emulated by superimposing minimum bias events on the simulated events. The simulated events are weighted to match the pileup distribution observed in the data.

4 Event reconstruction and selection

The event selection uses a particle-flow algorithm [35] for optimal efficiency, kinematic resolution and purity in physics object reconstruction and identification. The particle-flow algorithm aims to reconstruct and identify individual particles in an event using an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly 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 momentum 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 zero-suppression effects and 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.

Events must have at least one primary vertex with at least four associated tracks, with the transverse (longitudinal) position within 2 (24) cm from the nominal collision point. The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp interaction vertex. Here the physics objects are the jets, clustered using a jet finding algorithm [36, 37] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$), taken as the negative vector sum of the p_{T} of those jets.

Electron candidates are reconstructed by matching clusters of ECAL energy deposits with tracks in the inner tracker. The momentum resolution ranges from 1.7 to 4.5% for electrons from Z boson decays, depending on the electron η and the bremsstrahlung energy emitted [38]. The electron candidates are required to have $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ and to be within the region $|\eta| < 2.5$. The barrel-endcap transition region $1.44 < |\eta| < 1.56$ is excluded. The electron candidates have to pass a set of identification requirements on the spatial distribution of energy deposits in the ECAL, on the ratio of the associated HCAL and ECAL energy deposits, on the isolation in the calorimeters, on the quality of the matching between the ECAL clusters and the associated track in the inner tracker, and on the agreement between the energy reconstructed in the ECAL and the momentum of the associated track.

Muon candidates are reconstructed as tracks in the muon detector that are matched to the tracks found in the inner tracker. The momentum resolution for muons with p_{T} up to 100 GeV is 1% in the barrel and 3% in the endcaps. The resolution in the barrel is better than 10% for muons with p_{T} up to 1 TeV [39]. The muon candidates must have $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ and be within $|\eta| < 2.4$. The muon candidates are required to pass identification criteria optimized for muons having large p_{T} [39] and to be isolated in the tracking systems.

Photon reconstruction starts from energy deposits in the ECAL, and photon candidates that have associated tracks are rejected. The photon energy resolution ranges from 1 to 5%, depending on photon η and showers in the ECAL [40]. The photon candidates are required to have $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ and $|\eta| < 2.5$, with those in the transition region $1.44 < |\eta| < 1.56$ being excluded from the analysis. A multivariate analysis (MVA) technique is used for photon iden-

tification, with shower shape variables and photon isolation sums in the ECAL and HCAL as inputs [40, 41].

Events are required to have two SF leptons and a photon. The two SF leptons are not required to be of opposite-sign charge because this would result in a signal efficiency loss of a few % at high lepton p_{T}, especially for the eeγ channel [42], whereas the background arising from events with same-sign dileptons is minimal. The selected leptons must be separated from the photon by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$, where ϕ is the azimuthal angle measured in radians. In addition, the invariant mass of the two SF leptons $m_{\ell\ell}$ is required to be larger than 116 GeV in order to suppress the dominant background contribution from Z boson production (Z boson veto criteria).

5 Background modeling

The major backgrounds in this search originate from SM processes with final states consisting of two prompt SF leptons and a prompt photon or a jet misidentified as a photon. The expected fraction of background events that have a jet misidentified as a lepton is less than 1% for both channels [43], therefore this background source is not considered in the analysis. Backgrounds associated with a prompt photon are estimated using simulation, while the yield of those associated with a jet is derived from the data.

The dominant background arises from Drell–Yan process accompanied by a prompt photon (DY+γ), which has a signature similar to the signal. Within the detector acceptance, Z boson production dominates the process, and its contribution is efficiently suppressed by applying the Z boson veto criteria described in Section 4. The fraction of DY+γ events after the event selection is approximately 70% of the background. Another prompt photon background comes from top quark pair production in association with a photon ($\mathrm{t\bar{t}}$+γ). These events form approximately 10% of the background. In addition, triboson processes such as WWγ, WZγ, and ZZγ (VVγ) also give rise to 5% of the background.

The other major background contribution consists of events with two prompt leptons and a photon that originates from a jet, hereafter referred to as the jet background. The estimation of this background is derived from data in a control region composed of events with two leptons and a photon passing all the kinematic requirements and lepton identification criteria defined in the event selection but failing the photon identification. The events in the control region, scaled by a weight factor derived from the misidentification rate of photon candidates from jets, provide the jet background prediction in the signal region.

The misidentification rate is measured using data in a sideband ($50 < m_{\ell\ell} < 116$ GeV) of the dilepton mass distribution in the signal region ($m_{\ell\ell} > 116$ GeV). The photon identification is not required for events in the sideband, thereby the data in the sideband are enriched with Z boson events associated with a photon originating from a jet. To remove prompt photon contamination in the data, the distribution of the MVA variable used for the photon identification is employed, fitting the MVA variable distribution of the data events with template distributions for prompt photons and photons originating from jets. The MVA distribution of simulated prompt photon background events in the sideband is used as the template distribution for prompt photons. The template for photons originating from jets is obtained from a data sample enriched with W+jets events, where the W boson decays leptonically and a jet supplies a photon candidate. Events in the sample are required to have a muon of $p_{\mathrm{T}} > 35$ GeV, $p_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV, transverse mass $\sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\mu} [1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,\mu})]}$ between 50 and 110 GeV, and a photon candidate. The misidentification rate is evaluated in several photon p_{T} bins separately

for the barrel and endcaps of ECAL. The measured misidentification rate ranges from 2 (3)% at $p_{\mathrm{T}} = 35\,\mathrm{GeV}$ to 0.2 (0.4)% at $p_{\mathrm{T}} = 1\,\mathrm{TeV}$ in the barrel (endcaps). In the signal region, the estimated fraction of events arising from background with a jet misidentified as a photon is in the range 5–15%, depending on the photon p_{T}.

The kinematic distributions of the parent jets of the misidentified photons in the control region and those of the signal region are not identical in the same photon p_{T} range, owing to isolation requirements in the MVA identification. Consequently, the p_{T} distributions of leptons, which are correlated with the recoil of the jet in the same event, are different in the signal region and the control region. Therefore, an appropriate correction must be applied to the estimate of the lepton p_{T} distribution obtained by scaling the control region by a weight factor based on the misidentification rate. Using the p_{T} of the dilepton pair as a proxy of the jet recoil, the dilepton p_{T} distribution of the jet background estimate is reweighted to match the correct shape of the dilepton p_{T} distribution of the jet background events in the signal region. The shape is directly taken from data in the signal region, removing prompt photon contamination using simulated events. The reweighting is done for separate photon p_{T} bins used for the misidentification rate measurement, in order to retain the yield and the photon p_{T} spectrum obtained from the previous step. To validate the estimation procedures, closure tests are performed by applying the same method to derive background on simulated events, and the observed discrepancies are taken as estimates of the associated systematic uncertainties. After the correction, the lepton kinematic distributions from the total background prediction including the corrected jet background obtained from control samples in data are in good agreement with the distributions in data.

6 Signal modeling

The production of an excited lepton involves two SM leptons in the final state, one from the excited lepton decay and another from CI, and therefore there are two possible pairings of a lepton with the photon. The corresponding two invariant masses are referred to as $m_{\ell\gamma}^{\mathrm{min}}$ and $m_{\ell\gamma}^{\mathrm{max}}$. The $m_{\ell\gamma}^{\mathrm{min}}$ and $m_{\ell\gamma}^{\mathrm{max}}$ distributions of observed events along with the background prediction in the signal region are shown in Fig. 2.

A search window is set in the two-dimensional distribution of $m_{\ell\gamma}^{\mathrm{max}}$ versus $m_{\ell\gamma}^{\mathrm{min}}$. For ℓ^* events, either $m_{\ell\gamma}^{\mathrm{min}}$ or $m_{\ell\gamma}^{\mathrm{max}}$ corresponds to the reconstructed invariant mass of ℓ^*. Therefore, the mass resonance of the signal is concentrated in the shape of a reflected "L" as shown in Fig. 3. On the other hand, background events have no such correlation in $m_{\ell\gamma}^{\mathrm{min}}$ and $m_{\ell\gamma}^{\mathrm{max}}$ in the low mass region below 1 TeV. The distribution of the dominant DY+γ background is shown in Fig. 4. This clear distinction between signal and background events in the distribution of $m_{\ell\gamma}^{\mathrm{max}}$ versus $m_{\ell\gamma}^{\mathrm{min}}$ is used to define L-shaped search windows enhancing the discrimination between signal and background.

For low signal masses, $m_{\ell^*} \leq 1\,\mathrm{TeV}$, setting an L-shaped search window significantly improves a discrimination against the background with only a small loss in the signal acceptance. Therefore, the search window for $m_{\ell^*} \leq 1\,\mathrm{TeV}$ is set to be a narrow L-shape centered at m_{ℓ^*}, consisting of lower and upper thresholds of $m_{\ell\gamma}^{\mathrm{min}}$ and $m_{\ell\gamma}^{\mathrm{max}}$ as shown in Fig. 3. The thresholds are optimized for the best expected exclusion limit, which also provides the optimal discovery potential. The impact of the energy scale and resolution uncertainties on the signal acceptance is taken into account for the optimization. The optimized thresholds have values that are within $\pm 8\%$ of the simulated mass for e^*, and within ranges that vary from $\pm 4.5\%$ to $\pm 8\%$ of the simulated mass for μ^*.

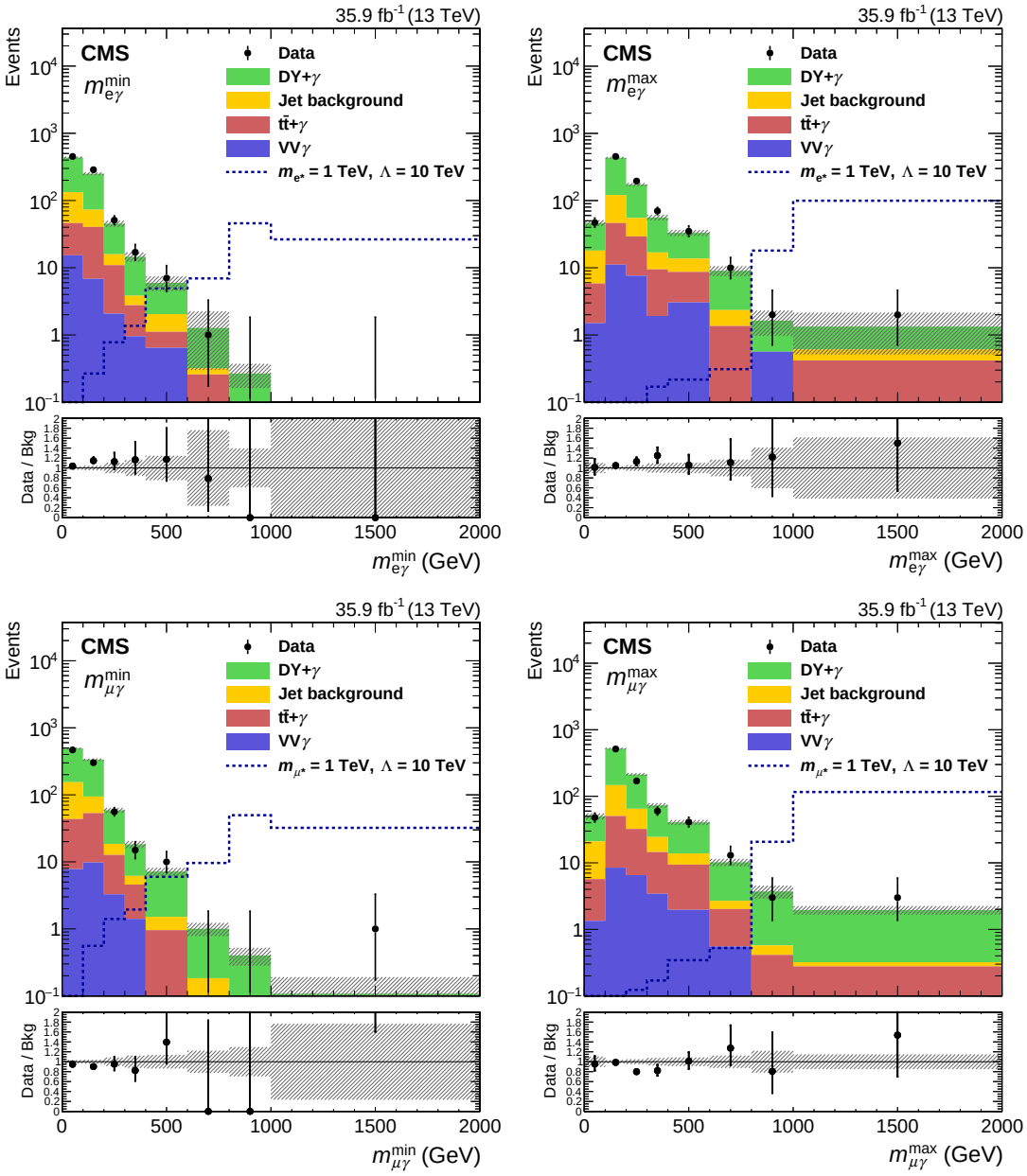

Figure 2: The distributions of $m_{\ell\gamma}^{\min}$ (left column) and $m_{\ell\gamma}^{\max}$ (right column) in the eeγ channel (upper row) and the $\mu\mu\gamma$ channel (lower row). The points with error bars denote the data and the stacked histograms show the predictions for each of the backgrounds. The uncertainty bands of the SM prediction includes only statistical uncertainties. Signal events for $m_{\ell^*} = 1$ TeV at $\Lambda = 10$ TeV are also shown as dotted lines. The last bin of each distribution includes overflow events.

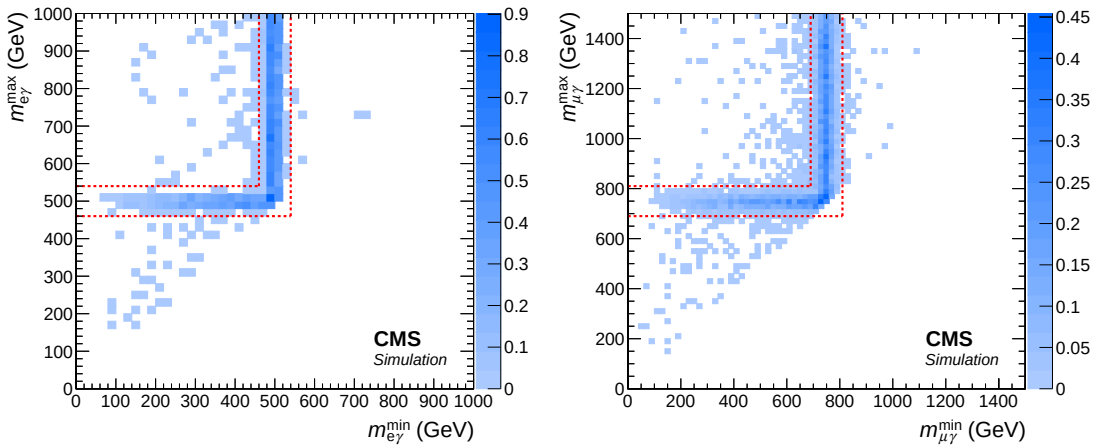

Figure 3: The two-dimensional distributions of $m_{\ell\gamma}^{\max}$ versus $m_{\ell\gamma}^{\min}$ of excited electrons with a mass of 500 GeV (left) and of excited muons with a mass of 750 GeV (right), after the event selection, normalized to the expected signal cross section at $\Lambda = 10$ TeV. The red dashed lines denote the boundary of the L-shaped search window.

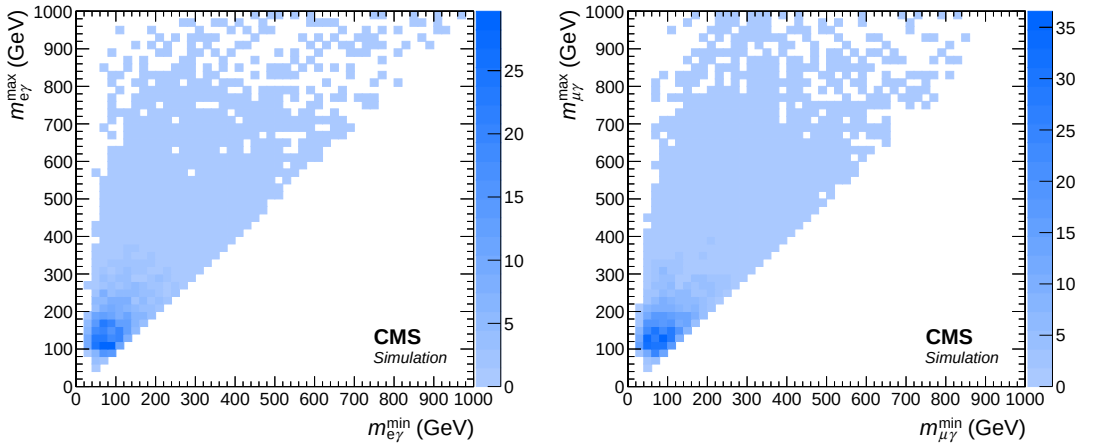

Figure 4: The two-dimensional distributions of $m_{\ell\gamma}^{\max}$ versus $m_{\ell\gamma}^{\min}$ of DY+γ background events in the eeγ (left) and $\mu\mu\gamma$ (right) channels, after the event selection, normalized to the cross section for DY+γ production.

The search windows defined for $m_{\ell^*} > 1$ TeV, where the background contribution is expected to be negligible, only impose the lower $m_{\ell\gamma}^{\max}$ threshold of 1 TeV, thereby maximizing the signal acceptance.

The product of signal acceptance and efficiency ($A\,\epsilon_{\text{sig}}$) has been measured from the simulated signal samples, and ranges from 30 to 49% and from 33 to 59% for excited electrons and muons, respectively. The relatively low values of $A\,\epsilon_{\text{sig}}$ at low masses mainly result from lepton and photon p_{T} thresholds. To determine $A\,\epsilon_{\text{sig}}$ for mass points other than those of the simulated samples, a polynomial fit to the dependence on m_{ℓ^*} is used for interpolation, as shown in Fig. 5.

7 Systematic uncertainties

The systematic uncertainties in the signal and the background yields are summarized in Table 1. The statistical uncertainties in the data and the simulated samples used for the back-

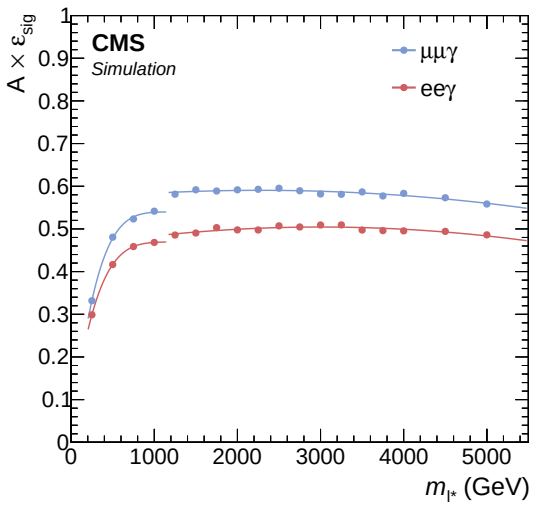

Figure 5: The product of signal acceptance and efficiency as a function of the generated resonance mass for the eeγ (lower) and $\mu\mu\gamma$ (upper) channels. Each marker denotes the value measured from the simulated signal sample at a given mass point, and the lines represent polynomial fits to the measured values.

ground estimation are dominant. These uncertainties are expected to be reduced in future by producing simulated samples enriched with high p_{T} photons. The statistical uncertainties in the simulated signal samples used to measure $A\,\epsilon_{\mathrm{sig}}$ are negligible and therefore not considered in the analysis. The values of the systematic uncertainties for the jet background estimate coming from control samples in data are also large compared to other systematic uncertainties, but their impact on the sensitivity of the search is small since the jet background makes up only 5–15% of the total background.

Table 1: Summary of the systematic uncertainties (in %) in the signal yield, the prompt photon background prediction, and the jet background prediction.

Source	eeγ channel (%)			$\mu\mu\gamma$ channel (%)		
	Signal	Prompt γ bkg	Jet bkg	Signal	Prompt γ bkg	Jet bkg
Integrated luminosity	2.5	2.5	—	2.5	2.5	—
Pileup	1	1	—	1	1	—
Trigger	1	1	—	2	2	—
Lepton efficiency	2.5	2.5	—	2	2	—
Photon efficiency	1.5	1.5	—	1.5	1.5	—
e/γ energy scale & resolution	2	2	—	2.5	2.5	—
μ momentum scale & resolution	—	—	—	2	2	—
PDF & scales	2	10	—	2	10	—
Jet bkg estimate	—	—	54–90	—	—	54–90
Sample size	—	8–44	5–47	—	10–25	6–58

The integrated luminosity has been measured with a precision of 2.5% [44]. The effect of pileup modeling on the selection efficiency is measured to be less than a percent over all mass points, and a 1% uncertainty is assigned for it. Systematic uncertainties in the signal selection efficiency include uncertainties arising from the trigger selection, lepton identification [39] and photon identification [40, 41]. Various sources of potential biases in the selection efficiency measurements are considered to determine such uncertainties. Uncertainties in the e/γ energy scale and resolution, and muon momentum scale and resolution translate into uncertainties in the signal acceptance. The effect on the signal acceptance is evaluated by shifting and smear-

ing the p_T of each object by ± 1 standard deviation. Although the fraction of energy affected by the e/γ energy scale and resolution uncertainties is larger for eeγ events than for $\mu\mu\gamma$ events, because the mass window is narrower and the mass resolution is worse, the impact on the acceptance is measured to be stronger in the latter case.

Systematic uncertainties in the signal acceptance and background cross sections due to the PDF choice have been estimated by following the PDF4LHC prescription [45]. Renormalization and factorization scale uncertainties are evaluated by varying the scales up and down by a factor of 2, both simultaneously and independently. The maximum change observed among the corresponding variations in the signal and the background yields is taken as an estimate of the associated systematic uncertainty. Uncertainties of 2 and 10% are assigned for the PDF and scale uncertainties in the signal acceptance and the background yields, respectively.

For the jet background estimate, the following uncertainties are taken into account: statistical uncertainties in the jet-to-photon misidentification rate measurement (8–72%), systematic uncertainties in the template distributions used for the misidentification rate measurement (20%), and systematic uncertainties based on the discrepancies observed in the closure tests for the jet background determination procedure performed on simulated samples (50%). The total systematic uncertainty in the jet background prediction is evaluated by summing these uncertainties in quadrature and amounts to 54%, increasing to 90% for masses above 1 TeV.

8 Results

Within the uncertainties, the data are found to be consistent with the background prediction as summarized in Tables 2 and 3. We set 95% confidence level (CL) upper limits on the production cross sections of excited electrons and excited muons, and corresponding lower limits on the compositeness scale Λ, as a function of the excited lepton mass using a single-bin counting method [46]. The limits are computed with the modified frequentist CL_s method [47, 48], with a likelihood ratio used as a test statistic. The systematic uncertainties are treated as nuisance parameters with log-normal priors. The limits are set in the mass range between 0.25 and 5.0 TeV.

Figure 6 shows the 95% CL upper limits on the product of the signal cross section and branching fraction to $\ell\ell\gamma$ final states, $\sigma\,\mathcal{B}(\ell^* \to \ell\gamma)$ and lower limits on Λ, as a function of the resonance mass. The observed limits are denoted by the solid black lines and the expected limits for the background-only hypothesis are represented by the dashed black lines. The 68 and 95% CL ranges are shown with the green and yellow bands, respectively. The observed limits on the signal cross section range from 3.7 to 0.2 fb as a function of m_{ℓ^*} and are consistent with the expected limits. The fluctuations of the expected limits and the uncertainty bands, which appear for $m_{\ell^*} < 1$ TeV, are consequences of the statistical fluctuations from the limited number of simulated events passing the event selection. The dashed lines in the left plots in Fig. 6 represent the theoretical cross sections including the NLO QCD correction factors for $\Lambda = m_{\ell^*}$, 10, 15, and 25 TeV, in the sequence on the plot from bottom to top.

The lower limit on m_{ℓ^*} depends on Λ since both m_{ℓ^*} and Λ are free parameters in the reference model. The observation excludes $m_{\ell^*} < 3.9$ (3.8) TeV for excited electrons (muons) in the case where $\Lambda = m_{\ell^*}$. The exclusion on Λ ranges from 15 to 25 TeV in the mass range m_{ℓ^*} between 0.25 and 1.0 TeV, and decreases with increasing mass up to approximately 4 TeV for $m_{\ell^*} >$ 1.0 TeV. The best observed limit on Λ is obtained in the mass range between 0.5 and 1.0 TeV, excluding Λ below 25 TeV for both excited electrons and muons. A summary of representative exclusion limits is given in Table 4.

Table 2: The observed yield and the SM prediction in the search window of the given m_{ℓ^*} in the eeγ channel. The symbols N_{data}, N_{prompt}, and N_{jet} represent the number of events in data, the prompt photon background prediction, and the jet background estimate, respectively, together with statistical and systematical uncertainties.

m_{e^*} (GeV)	Window (GeV)	N_{data}	N_{prompt}	N_{jet}	$A\,\epsilon_{\text{sig}}$
250	230–270	84	$74.4 \pm 6.8 \pm 8.0$	$12.5 \pm 0.7 \pm 6.9$	0.30
275	253–297	80	$50.9 \pm 6.0 \pm 5.4$	$10.0 \pm 0.6 \pm 5.5$	0.32
300	276–324	68	$44.7 \pm 5.5 \pm 4.8$	$7.6 \pm 0.5 \pm 4.2$	0.33
330	304–356	51	$40.4 \pm 4.7 \pm 4.3$	$5.9 \pm 0.5 \pm 3.3$	0.35
360	331–389	39	$28.1 \pm 3.8 \pm 3.0$	$4.0 \pm 0.4 \pm 2.2$	0.36
400	368–432	27	$19.4 \pm 3.0 \pm 2.1$	$3.3 \pm 0.3 \pm 1.8$	0.38
450	414–486	17	$15.8 \pm 2.5 \pm 1.7$	$2.8 \pm 0.4 \pm 1.6$	0.40
500	460–540	16	$12.3 \pm 1.9 \pm 1.3$	$2.3 \pm 0.3 \pm 1.3$	0.42
550	506–594	15	$8.2 \pm 1.7 \pm 0.9$	$1.6 \pm 0.2 \pm 0.9$	0.43
600	552–648	10	$7.6 \pm 1.8 \pm 0.8$	$1.2 \pm 0.2 \pm 0.7$	0.44
650	598–702	6	$4.9 \pm 1.3 \pm 0.5$	$0.8 \pm 0.2 \pm 0.5$	0.45
700	644–756	9	$3.6 \pm 1.4 \pm 0.4$	$0.5 \pm 0.1 \pm 0.3$	0.45
750	690–810	5	$3.4 \pm 1.3 \pm 0.4$	$0.3 \pm 0.1 \pm 0.2$	0.46
800	736–864	1	$2.9 \pm 1.1 \pm 0.3$	$0.3 \pm 0.1 \pm 0.2$	0.46
900	828–972	1	$1.5 \pm 0.6 \pm 0.2$	$0.1 \pm 0.1 \pm 0.1$	0.47
1000	920–1080	1	$0.8 \pm 0.8 \pm 0.1$	$0.1 \pm 0.1 \pm 0.1$	0.47
> 1000	≥ 1058	1	$1.4 \pm 0.5 \pm 0.2$	$0.1 \pm 0.1 \pm 0.1$	0.49

Table 3: The observed yield and the SM prediction in the search window of the given m_{ℓ^*} in the $\mu\mu\gamma$ channel. The symbols N_{data}, N_{prompt}, and N_{jet} represent the number of events in data, the prompt photon background prediction, and the jet background estimate, respectively, together with statistical and systematical uncertainties.

m_{μ^*} (GeV)	Window (GeV)	N_{data}	N_{prompt}	N_{jet}	$A\,\epsilon_{\text{sig}}$
250	238–262	41	$43.8 \pm 4.9 \pm 4.9$	$8.7 \pm 0.6 \pm 4.8$	0.33
275	261–289	38	$42.8 \pm 5.0 \pm 4.8$	$6.8 \pm 0.5 \pm 3.8$	0.35
300	284–316	47	$35.4 \pm 4.6 \pm 4.0$	$6.5 \pm 0.6 \pm 3.6$	0.37
330	312–348	23	$33.1 \pm 3.9 \pm 3.7$	$5.1 \pm 0.5 \pm 2.8$	0.39
360	340–380	24	$25.8 \pm 3.0 \pm 2.9$	$3.7 \pm 0.4 \pm 2.0$	0.41
400	376–424	26	$22.8 \pm 3.0 \pm 2.6$	$2.2 \pm 0.3 \pm 1.2$	0.44
450	422–478	17	$15.1 \pm 2.3 \pm 1.7$	$1.8 \pm 0.3 \pm 1.0$	0.46
500	467–533	14	$9.8 \pm 1.6 \pm 1.1$	$1.8 \pm 0.3 \pm 1.0$	0.48
550	512–588	11	$10.8 \pm 1.8 \pm 1.2$	$1.0 \pm 0.2 \pm 0.5$	0.49
600	556–644	8	$5.8 \pm 1.2 \pm 0.7$	$0.7 \pm 0.2 \pm 0.4$	0.51
650	600–700	10	$6.8 \pm 1.1 \pm 0.8$	$0.6 \pm 0.1 \pm 0.3$	0.52
700	644–756	5	$5.8 \pm 1.0 \pm 0.7$	$0.4 \pm 0.1 \pm 0.2$	0.52
750	690–810	6	$5.1 \pm 1.0 \pm 0.6$	$0.3 \pm 0.1 \pm 0.2$	0.53
800	736–864	3	$4.5 \pm 1.0 \pm 0.5$	$0.2 \pm 0.1 \pm 0.1$	0.53
900	828–972	2	$3.1 \pm 0.8 \pm 0.4$	$0.1 \pm 0.1 \pm 0.1$	0.54
1000	920–1080	0	$1.1 \pm 0.3 \pm 0.1$	$0.1 \pm 0.0 \pm 0.1$	0.54
> 1000	≥ 1058	3	$1.5 \pm 0.3 \pm 0.2$	$0.0 \pm 0.0 \pm 0.0$	0.59

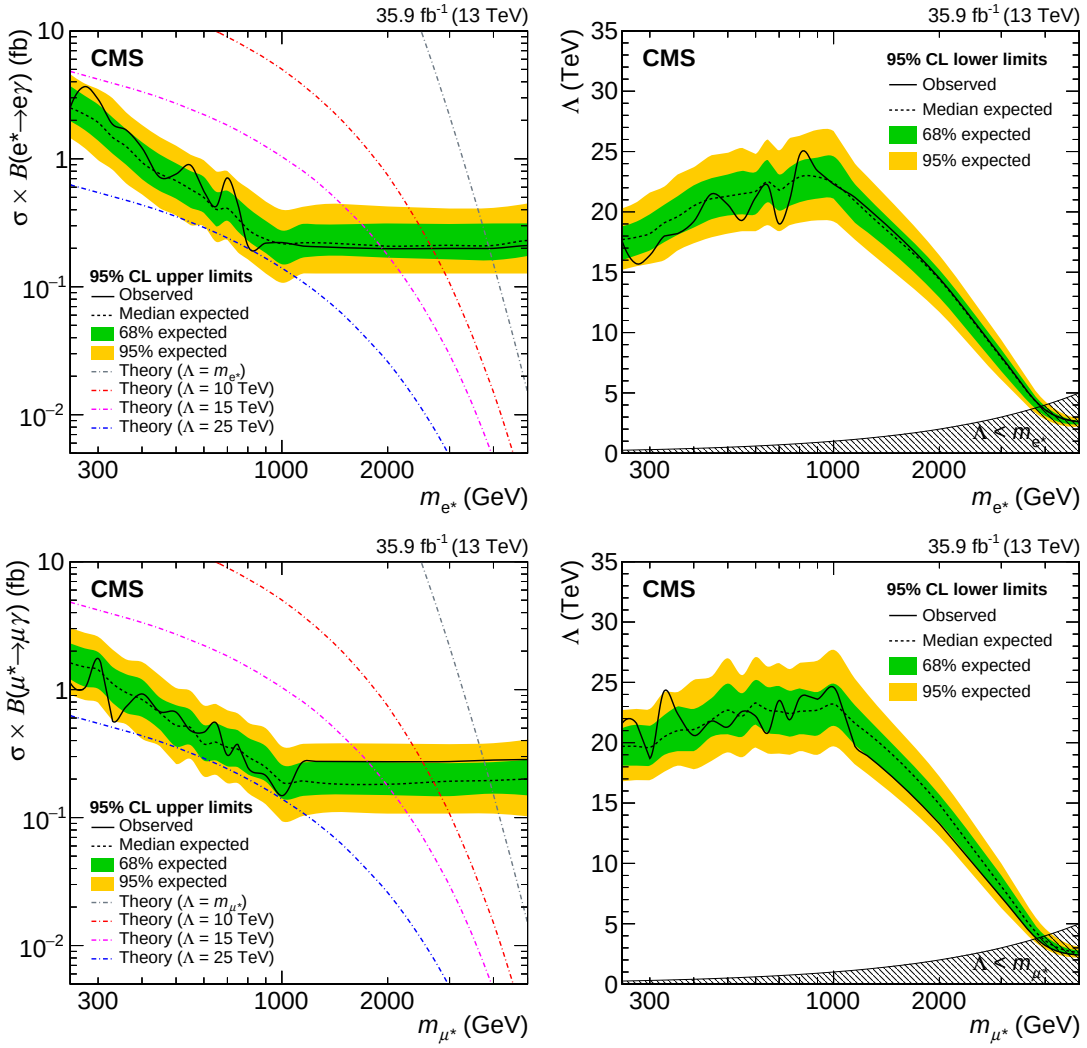

Figure 6: Observed (solid) and expected (dashed) 95% CL upper limits on the product of the production cross section and branching fraction (left column) and lower limits on the compositeness scale (right column) as a function of signal mass m_{ℓ^*}, together with the 68% (green, inner) and 95% (yellow, outer) quantiles of the expected limit, for e* (upper row) and μ^* (lower row).

Table 4: Summary of the observed (expected) lower limits on m_{ℓ^*}, assuming $\Lambda = m_{\ell^*}$, and the best observed (expected) lower limits on Λ in the mass range 0.5–1.0 TeV.

Channel	Observed (expected) limit on m_{ℓ^*} for $m_{\ell^*} = \Lambda$, TeV	Observed (expected) limit on Λ for $m_{\ell^*} \approx 1$ TeV, TeV
eeγ	3.9 (3.8)	25 (23)
$\mu\mu\gamma$	3.8 (3.9)	25 (23)

9 Summary

A search has been presented for excited electrons and muons in $\ell\ell\gamma$ final states at the LHC. The search is based on a data sample corresponding to an integrated luminosity of 35.9 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV, collected with the CMS detector in 2016. No significant excess over the standard model prediction is observed in the data, and 95% confidence level upper and lower limits are set on the product of the signal production cross section and branching fraction to $\ell\ell\gamma$ final states and the compositeness scale, respectively, as a function of the excited lepton mass. The observed limits on the product of the signal cross section and the branching fraction range from 3.7 to 0.2 fb as a function of m_{ℓ^*}. Excited electrons and muons are excluded for masses below 3.9 and 3.8 TeV, respectively, under the assumption that the excited lepton mass equals the compositeness scale. The best observed limit on the compositeness scale is obtained with an excited lepton mass of around 1.0 TeV, excluding a compositeness scale below 25 TeV for both excited electrons and muons. These are the first results of a search at $\sqrt{s} = 13$ TeV for excited leptons and also the most stringent limits on the excited lepton mass and the compositeness scale to date.

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19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
31: Also at Kyunghee University, Seoul, Korea
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, USA
40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
41: Also at California Institute of Technology, Pasadena, USA
42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
44: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Adiyaman University, Adiyaman, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
64: Also at Monash University, Faculty of Science, Clayton, Australia
65: Also at Bethel University, St. Paul, USA
66: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
67: Also at Utah Valley University, Orem, USA

68: Also at Purdue University, West Lafayette, USA
69: Also at Beykent University, Istanbul, Turkey
70: Also at Bingol University, Bingol, Turkey
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea