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A search for excited leptons in pp collisions at $\sqrt{s} = 7$ TeV [☆]

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ABSTRACT

A search for excited leptons is carried out with the CMS detector at the LHC, using 36 pb^{-1} of pp collision data recorded at $\sqrt{s} = 7$ TeV. The search is performed for associated production of a lepton and an oppositely charged excited lepton $\mathrm{pp} \to \ell\ell^*$, followed by the decay $\ell^* \to \ell\gamma$, resulting in the $\ell\ell\gamma$ final state, where $\ell = \mathrm{e}, \mu$. No excess of events above the standard model expectation is observed. Interpreting the findings in the context of ℓ^* production through four-fermion contact interactions and subsequent decay via electroweak processes, first upper limits are reported for ℓ^* production at this collision energy. The exclusion region in the compositeness scale Λ and excited lepton mass M_{ℓ^*} parameter space is extended beyond previously established limits. For $\Lambda = M_{\ell^*}$, excited lepton masses are excluded below 1070 GeV/c^2 for e^* and 1090 GeV/c^2 for μ^* at the 95% confidence level.

1. Introduction

A fundamental question in the standard model (SM) of particle physics concerns the source of the mass hierarchy of quarks and leptons. A possible explanation for the three generations is a compositeness model in which the known leptons and quarks are bound states of either three fermions or a fermion–boson pair [1]. This substructure, if it exists, implies a large spectrum of excited states. Novel strong interactions would couple the excited fermions to ordinary quarks and leptons. These contact interactions can be described with an effective Lagrangian [2]:

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

where Λ is the compositeness or contact interaction scale, g^{*2} represents a coupling constant chosen to be 4π, and j_μ is the fermion current:

$$j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}^*_L \gamma_\mu f^*_L + \eta''_L \bar{f}^*_L \gamma_\mu f_L + \text{h.c.} + (L \to R).$$

The SM and excited fermions are denoted by f and f^*, respectively. The subscripts L (R) refer to left- (right-) handed fermions. The η factors for left-handed currents are conventionally set to one, and those for right-handed currents are set to zero. The excited fermions are assumed to have spin and isospin of 1/2. Gauge-mediated transitions between ordinary and excited fermions are described by an effective Lagrangian [2,3]:

$$\mathcal{L}_{\mathrm{GM}} = \frac{1}{2\Lambda} \bar{f}^*_R \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] f_L + \text{h.c.},$$

where $G^a_{\mu\nu}$, $W_{\mu\nu}$, and $B_{\mu\nu}$ are the field strength tensors of the gluon, SU(2), and U(1) gauge fields, respectively, and g_s, g, and g' are the corresponding gauge couplings. The scaling parameters f_s, f, and f' are assumed to be equal to one. Previous searches at LEP [4–7], HERA [8,9], and the Tevatron [10–13] have found no evidence for such excited leptons. Searches for $\ell\ell\mathrm{qq}$ contact interactions performed by studying the dilepton production at the Tevatron [14,15] and LHC [16] have resulted in lower limits on the compositeness or contact interaction scale Λ in the range of 3.3–4.5 TeV.

This Letter presents a search for excited leptons in pp collision data collected in 2010 at a centre-of-mass energy of 7 TeV with the Compact Muon Solenoid (CMS) [17] detector at the Large Hadron Collider (LHC). The data sample corresponds to an integrated luminosity of 36 pb^{-1}. The production of an excited lepton ℓ^* (μ^* or e^*) in association with an oppositely charged lepton of the same flavour via four-fermion contact interactions, followed by the electroweak decay $\ell^* \to \ell\gamma$, is considered. The production of excited leptons can also proceed via gauge-mediated interactions. However, the relative contribution of this production mechanism is below 0.5% for the range of excited lepton masses and compositeness scales considered in this search. The resulting final state, $\ell^+\ell^-\gamma$, is fully reconstructed. The dominant SM background for

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this search is the Drell–Yan production of $\ell^+\ell^-$ pairs, accompanied by a photon radiated either by an initial-state parton (ISR) or from one of the final-state leptons (FSR).

2. Experimental setup and event simulation

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 field volume are the silicon pixel and strip trackers, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). The central tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules. It provides an impact parameter resolution of approximately 15 μm and a transverse momentum (p_T) resolution of 4% for 500 GeV/c charged particles. The ECAL has an energy resolution of better than 0.5% above 100 GeV. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ in the region $|\eta| < 1.74$ and 0.175×0.175 at higher values of η, where the pseudorapidity η is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, with θ being the polar angle with respect to the direction of the counterclockwise beam, and ϕ the azimuthal angle, both measured in radians. A preshower detector consisting of two planes of silicon sensors interleaved with a total of 3 radiation lengths of lead is located in front of the ECAL, covering $1.65 < |\eta| < 2.6$. Muons are measured in gas-ionization detectors embedded in the steel return yoke, with detection planes made of three technologies: drift tubes in the barrel region ($|\eta| < 1.2$), cathode strip chambers in the endcaps ($0.9 < |\eta| < 2.4$), and resistive plate chambers covering both the barrel and the endcap regions. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5% for p_T values up to 1 TeV/c. The CMS detector and its performance are described in detail in Ref. [17].

Monte Carlo (MC) samples of the signal process are produced with the Pythia [18] event generator, using the compositeness model described in [2,3], for different values of the ℓ^* mass. The signal production cross sections are calculated at the leading order. Decays of excited leptons via contact interactions, not implemented in Pythia, are taken into account for the signal expectation according to Ref. [2]. For $\Lambda = 1$ TeV (4 TeV), the branching fraction of the decay $\ell^* \to \ell\gamma$ normalized to all possible decay modes is 23% (33%) for $M_{\ell^*} = 200$ GeV/c^2 and 2.3% (17%) for $M_{\ell^*} = 1$ TeV/c^2. As a cross-check, samples of the signal process are also simulated using a customized version of the CompHEP [19] event generator. For the event selection criteria used in this analysis, event rates predicted by Pythia and CompHEP are found to agree to within about 2%. This difference is taken as a systematic uncertainty on the predicted signal rate. The dominant background process, the Drell–Yan production of $\ell^+\ell^-$ pairs with an ISR or FSR photon, is simulated with the MadGraph [20] event generator. The expectation for this process is corrected with the prediction of the next-to-leading order Baur generator [21]. The Pythia event generator is used to generate samples for other SM background processes, including WW, WZ, ZZ, $t\bar{t}$, and, for the electron channel, $\gamma\gamma$ production. All samples are generated using the CTEQ6L1 [22] parametrization for the parton distribution functions (PDF) and passed through a detailed simulation of the CMS detector response implemented with the GEANT4 package [23].

3. Event selection

This section describes the criteria used to select the events in the analysis. Trigger and particle identification efficiencies and their statistical uncertainties, determined via a tag-and-probe method [24] using samples of $Z \to \ell^+\ell^-$ events, will be discussed below.

Events are collected with single-muon and double-photon triggers. Double-photon triggers require two electromagnetic clusters above a p_T threshold, and thus can be satisfied both by photons and electrons. The trigger efficiency is about 99% for $\mu^+\mu^-\gamma$ and close to 100% for $e^+e^-\gamma$ events passing our final selection criteria. The analysis accepts events with one isolated photon, two isolated leptons with high p_T, and at least one reconstructed primary vertex. In events containing more than one photon or more than two leptons, the highest-p_T objects are chosen. Events containing particles from LHC machine-induced backgrounds, such as beam halo and beam gas, are rejected by requiring that the fraction of high quality tracks be at least 25% in events with more than 10 tracks [25].

Details of the muon reconstruction and identification are given elsewhere [26,27]. When a track is found in the muon chambers (standalone muon), a matching track in the central detector is required. A fit combining hits from these two matching tracks is performed, resulting in a "global-muon track". Alternatively, a track in the central detector, loosely matching with hits in the muon detectors after extrapolation to the muon chambers, results in a "tracker muon". The tracker muons, together with the corresponding global-muon tracks, are selected for the analysis. Cosmic rays, muons from decay in flight of hadrons, and hadrons misidentified as muons are rejected using requirements on the quality of the global-muon fit, number of detector layers with hits in the muon chambers, and transverse impact parameter of the track. Two isolated muons with $p_T > 20$ GeV/c and $|\eta| < 2.4$ are used in the analysis. The reconstruction and identification efficiency for muons with $p_T > 20$ GeV/c is (96 ± 1)%.

Electrons and photons are detected in the ECAL as localized clusters [28,29]. The electron and photon identification procedures exploit the ECAL shower shape and isolation variables, the relative energy fraction deposited in the hadronic and electromagnetic calorimeters (H/E), and, for electrons, the presence of a track matching the ECAL cluster. Applying different selection criteria to these variables separates clusters originating from electrons, photons, and hadrons.

For electrons, a central-detector track matching the ECAL cluster is required. The track parameters are extrapolated to ECAL; the energy and extrapolated positions are required to be consistent with those of the ECAL cluster. Electrons are identified both in the ECAL barrel ($|\eta| < 1.44$) and endcaps ($1.57 < |\eta| < 2.5$), which are the regions covered by both the tracker and ECAL. Events in the $e^+e^-\gamma$ channel are required to contain at least two electrons with $p_T > 25$ GeV/c. This threshold excludes p_T regions with lower trigger efficiency. Electrons are selected with an average efficiency of (91.4 ± 0.3)% in the barrel and (90.6 ± 0.6)% in the endcaps.

Photons are selected as clusters in the ECAL barrel. To accept converted photons, no additional requirement based on the presence of matching tracks is applied. Only ECAL clusters that have not been previously matched to either of the two highest-p_T electrons can be identified as photons. Isolated photons with $p_T > 20$ GeV/c are used.

The photon should be separated from each of the selected leptons in the η–ϕ plane by $\Delta R > 0.5$, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences between the photon and the lepton. Only events with dilepton invariant mass $M_{\ell\ell} > 60$ GeV/c^2 are selected for further analysis.

Of the two possible lepton–photon invariant mass combinations in each event, the higher value, $M_{\mu\gamma}^{\max}$ or $M_{e\gamma}^{\max}$, is used as the search variable. The use of the second mass combination does not improve the search sensitivity for the range of excited lepton masses probed.

Table 1

Predicted and observed numbers of events passing all the selection criteria for the muon and electron final states. Columns 2–4 list separately the numbers of background events from the following sources: final states containing two leptons and one photon, including the dominant process, Drell–Yan with ISR or FSR; final states with two leptons accompanied by a jet misidentified as a photon; and final states with one genuine lepton and one genuine photon, accompanied by a jet misidentified as a lepton. Contributions from final states with two or three misidentified jets are found to be negligible. Statistical and systematic uncertainties are summed in quadrature.

Final state	$\ell^+\ell^-\gamma$	$\ell^+\ell^- + \text{jet}$	$\ell\gamma + \text{jet}$	Total	Observed
$\mu^+\mu^-\gamma$	19.1 ± 1.4	5.5 ± 2.1	0.7 ± 0.9	25.3 ± 2.7	25
$e^+e^-\gamma$	11.0 ± 1.0	1.4 ± 0.8	1.0 ± 0.4	13.4 ± 1.4	7

4. Background estimation

Irreducible backgrounds from SM processes and instrumental backgrounds from events in which jets are mis-reconstructed as leptons or photons are evaluated separately. The contribution from SM processes with real leptons and photons, dominated by Drell–Yan with ISR/FSR production, is estimated from MC simulation. The predicted background yields are corrected to account for the difference in the efficiencies measured from data and simulated events. The scale factors are 0.967 ± 0.025 for photons, 0.989 ± 0.010 for muons, 0.978 ± 0.004 for electrons in the barrel, and 0.994 ± 0.006 for electrons in the endcaps.

Backgrounds from processes in which jets are misreconstructed as leptons or photons are measured with data samples selected to contain predominantly jets [29,30]. For each jet-enriched data sample, the misidentification rate is measured as the ratio of the number of objects passing all selection cuts (numerator) to the number of potentially misidentifiable objects (denominator). For the muon misidentification rate estimation, the denominator corresponds to the number of tracker muons with $|\eta| < 2.4$. For electrons, the denominator is the number of ECAL clusters with $H/E < 0.05$ and $p_T > 20$ GeV/c. For photons, the denominator is the number of photon candidates obtained by relaxing the isolation or shower-shape criterion.

Signal search samples containing one or more potentially misidentifiable objects are selected and used together with the measured misidentification rates in order to predict the number of background events with misidentified objects. A closure test of the misidentification-rate method was done using MC simulation. Good agreement between the expected and observed number of events is found. The background prediction is also tested by comparing the observed and expected numbers of events in several data control regions: samples where only one lepton and one photon are selected, and samples containing two leptons and a photon selected with a looser sets of criteria.

Table 1 compares the predicted and observed numbers of events passing all selection requirements. Because of the lower efficiency for particle identification and the stricter p_T requirement, yields in the electron channel are lower than in the muon channel.

Fig. 1 (left) shows the photon transverse momentum distributions in the electron (top) and muon (bottom) channels, and (right) the maximum lepton–photon invariant mass distributions for data, along with the predictions for a signal with $M_{\ell^*} = 200$ GeV/c^2, $\Lambda = 2$ TeV, and for the SM background processes. The background prediction describes the data well in these as well as in other kinematic variables.

5. Systematic uncertainties

The normalization and shape of the invariant mass distributions used to establish a possible excited lepton signal are subject to uncertainties from both experimental and theoretical sources. The normalizations of the spectra are based on the integrated luminosity of the data sample, which is known to a precision of 4% [31]. The theoretical calculations of background process cross sections are affected by uncertainties in parton distribution functions [22] and the choice of factorization and renormalization scales. The uncertainties on the PDFs are evaluated using a reweighting technique with the CTEQ6M parametrization [22], while the uncertainties on the factorization and renormalization scales are estimated by varying them simultaneously from half to twice their central values. The resulting uncertainty on the background expectation is found to be 5%. In this section, all quoted uncertainties are obtained after requiring $M_{\ell\gamma}^{\max} > 180$ GeV/c^2.

The uncertainty on the number of background events from jets misidentified as leptons or photons is estimated by comparing misidentification rates measured in jet-enriched samples collected with different trigger requirements. Another source of uncertainty, estimated using MC simulations, is the difference between the misidentification rate observed in the jet-triggered samples, where it is measured, and the photon- or muon-triggered samples, where it is applied. The photon misidentification-rate uncertainty increases from 20% to 50% with photon p_T. This results in an uncertainty of 10% (7%) on the background prediction in the muon (electron) channel. The electron misidentification rate is known with a 25% (40%) uncertainty in the ECAL barrel (endcaps), resulting in a 10% uncertainty on the background prediction in the electron channel. The uncertainty on the muon misidentification rate is estimated to be 50%, and the resulting effect on the background expectation is 1%.

The uncertainties on the efficiency correction factors used in simulated events are included in the systematic uncertainties. They are 0.6% (1.1%) for electrons measured in the ECAL barrel (endcaps), 1% for muons, and 2.5% for photons. The effect on signal and background yields due to the particle identification uncertainties is smaller than 2% for the leptons and about 2.5% for the photons. The uncertainty on the photon and electron energy scale translates into an additional uncertainty of 0.5% for signal and 1.2% for background predictions.

Considering all sources of uncertainties mentioned above, the selection efficiencies for excited leptons are known to a precision of 3–4%, in both the electron and muon channels.

6. Results and discussion

In order to enhance the sensitivity of the analysis, the search is restricted to the high invariant mass region by applying a selection on $M_{\ell\gamma}^{\max}$ that depends on the excited lepton mass hypothesis. For each excited lepton mass, the entire analysis is repeated using various search regions and the region giving the best expected limits is taken. For excited lepton masses above 600 GeV/c^2, where almost no background is expected, the search region $M_{\ell\gamma}^{\max} > 500$ GeV/c^2 is used. The number of observed events, and the predicted numbers from SM backgrounds and from an excited lepton signal, as well as the selection efficiency, are listed in Table 2 for the two search channels with various excited lepton mass hypotheses and fixed $\Lambda = 2$ TeV. The uncertainties on the number of predicted background events and the signal efficiencies are the statistical and systematic uncertainties summed in quadrature. No excited lepton candidate events are found in any of the search regions. This lack of events is consistent with the SM background predictions.

Considering the production of excited leptons via a four-fermion contact interaction as an alternative hypothesis to the SM, upper limits on the ℓ^* production cross section times branching fraction of the $\ell^* \to \ell\gamma$ decay are set using a Bayesian method with a flat prior [32]. A log-normal prior is used for the integration over

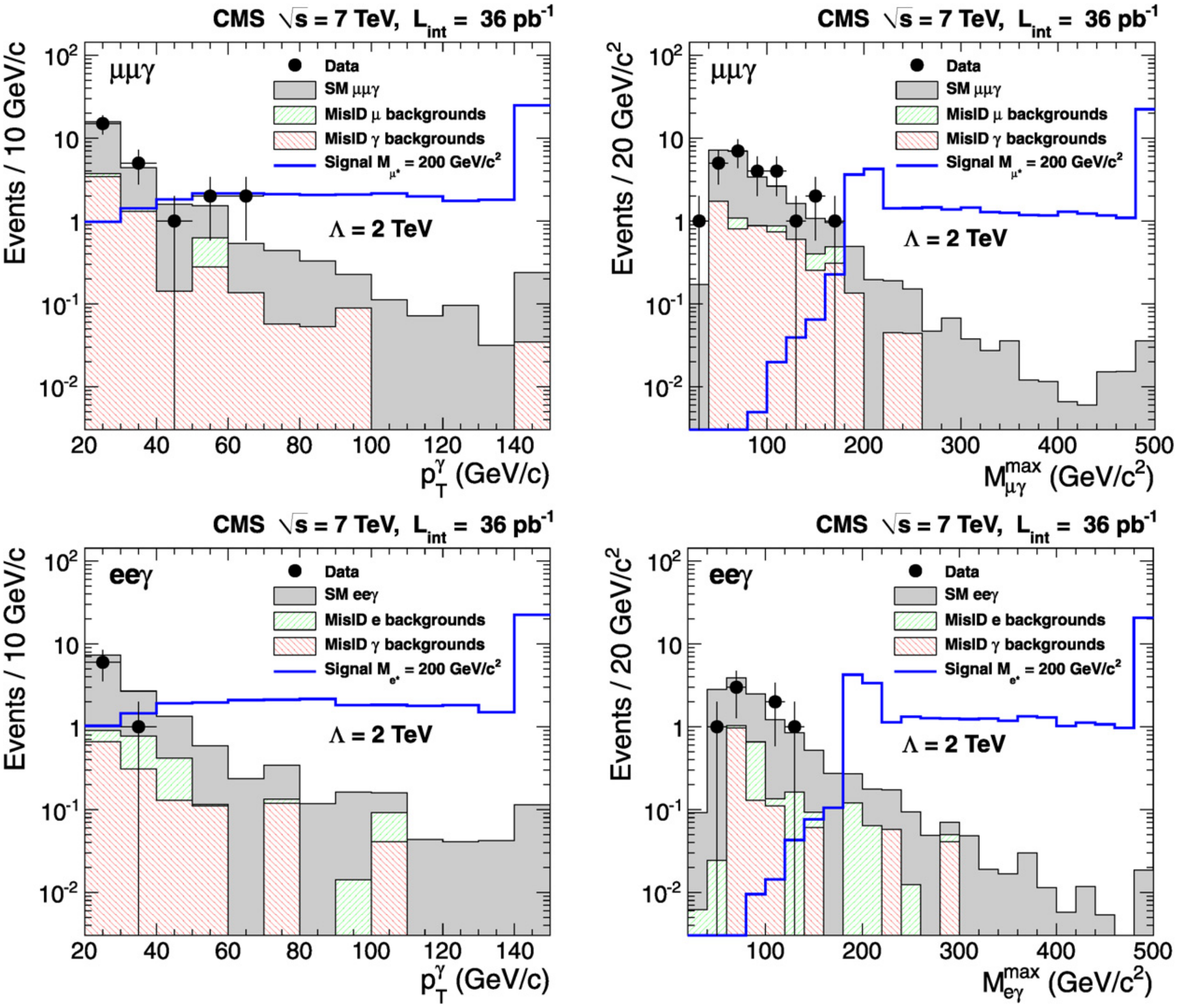

Fig. 1. Photon transverse momentum distributions (left) and maximum invariant mass distributions of the lepton–photon pair (right) in the muon (top) and electron (bottom) channels. The data are shown as solid circles with error bars and the expected SM background distributions are shown as hatched histograms. The solid-line histogram displays the expected excited lepton signal for $M_{\ell^*} = 200$ GeV/c^2, $\Lambda = 2$ TeV. For this particular M_{ℓ^*}, the search region is restricted to $M_{\ell\gamma}^{\mathrm{max}} > 180$ GeV/c^2. In each histogram, the last bin includes the overflows.

Table 2
Minimum requirement on the highest invariant mass pair $M_{\ell\gamma}^{\mathrm{cut}}$, number of events observed in data and expected SM background, signal efficiency, observed (expected) upper limits $\sigma_{\mathrm{obs}}^{\mathrm{lim}}$ ($\sigma_{\mathrm{exp}}^{\mathrm{lim}}$) on the ℓ^* production cross section times the branching fraction of the $\ell^* \to \ell\gamma$ decay, and expected numbers of signal events, for various excited lepton masses M_{ℓ^*}, assuming $\Lambda = 2$ TeV. Invariant masses are given in GeV/c^2 and $\sigma_{\mathrm{obs}}^{\mathrm{lim}}$ ($\sigma_{\mathrm{exp}}^{\mathrm{lim}}$) in pb. The statistical and systematic uncertainties on signal efficiency are summed in quadrature.

Muon channel						
M_{μ^*}	$M_{\mu\gamma}^{\mathrm{cut}}$	N_{data}	$N_{\mathrm{predicted\ SM}}$	Signal eff. (%)	$\sigma_{\mathrm{obs}}^{\mathrm{lim}}$ ($\sigma_{\mathrm{exp}}^{\mathrm{lim}}$)	$N_{\mathrm{predicted\ signal}}$
200	180	0	$1.35 \pm 0.15 \pm 0.14$	44.8 ± 1.8	0.19 (0.28)	47
400	350	0	$0.11 \pm 0.08 \pm 0.03$	51.0 ± 1.9	0.16 (0.17)	18.6
600	500	0	$0.04 \pm 0.08 \pm 0.03$	53.9 ± 2.0	0.15 (0.15)	7.3
800	500	0	$0.04 \pm 0.08 \pm 0.03$	55.6 ± 2.1	0.15 (0.15)	2.8
1000	500	0	$0.04 \pm 0.08 \pm 0.03$	56.9 ± 2.1	0.15 (0.15)	1.1
1200	500	0	$0.04 \pm 0.08 \pm 0.03$	56.9 ± 2.1	0.15 (0.15)	0.4
1500	500	0	$0.04 \pm 0.08 \pm 0.03$	58.5 ± 2.1	0.14 (0.14)	0.1
Electron channel						
M_{e^*}	$M_{e\gamma}^{\mathrm{cut}}$	N_{data}	$N_{\mathrm{predicted\ SM}}$	Signal eff. (%)	$\sigma_{\mathrm{obs}}^{\mathrm{lim}}$ ($\sigma_{\mathrm{exp}}^{\mathrm{lim}}$)	$N_{\mathrm{expected\ signal}}$
200	180	0	$1.00 \pm 0.12 \pm 0.10$	38.7 ± 1.5	0.21 (0.30)	40
400	350	0	$0.10 \pm 0.07 \pm 0.02$	44.6 ± 1.7	0.19 (0.19)	16
600	500	0	$0.01 \pm 0.06 \pm 0.02$	47.0 ± 1.7	0.18 (0.18)	6.4
800	500	0	$0.01 \pm 0.06 \pm 0.02$	49.3 ± 1.8	0.17 (0.17)	2.5
1000	500	0	$0.01 \pm 0.06 \pm 0.02$	50.9 ± 1.8	0.16 (0.16)	1.0
1200	500	0	$0.01 \pm 0.06 \pm 0.02$	51.3 ± 1.8	0.16 (0.16)	0.4
1500	500	0	$0.01 \pm 0.06 \pm 0.02$	52.9 ± 1.8	0.16 (0.16)	0.1

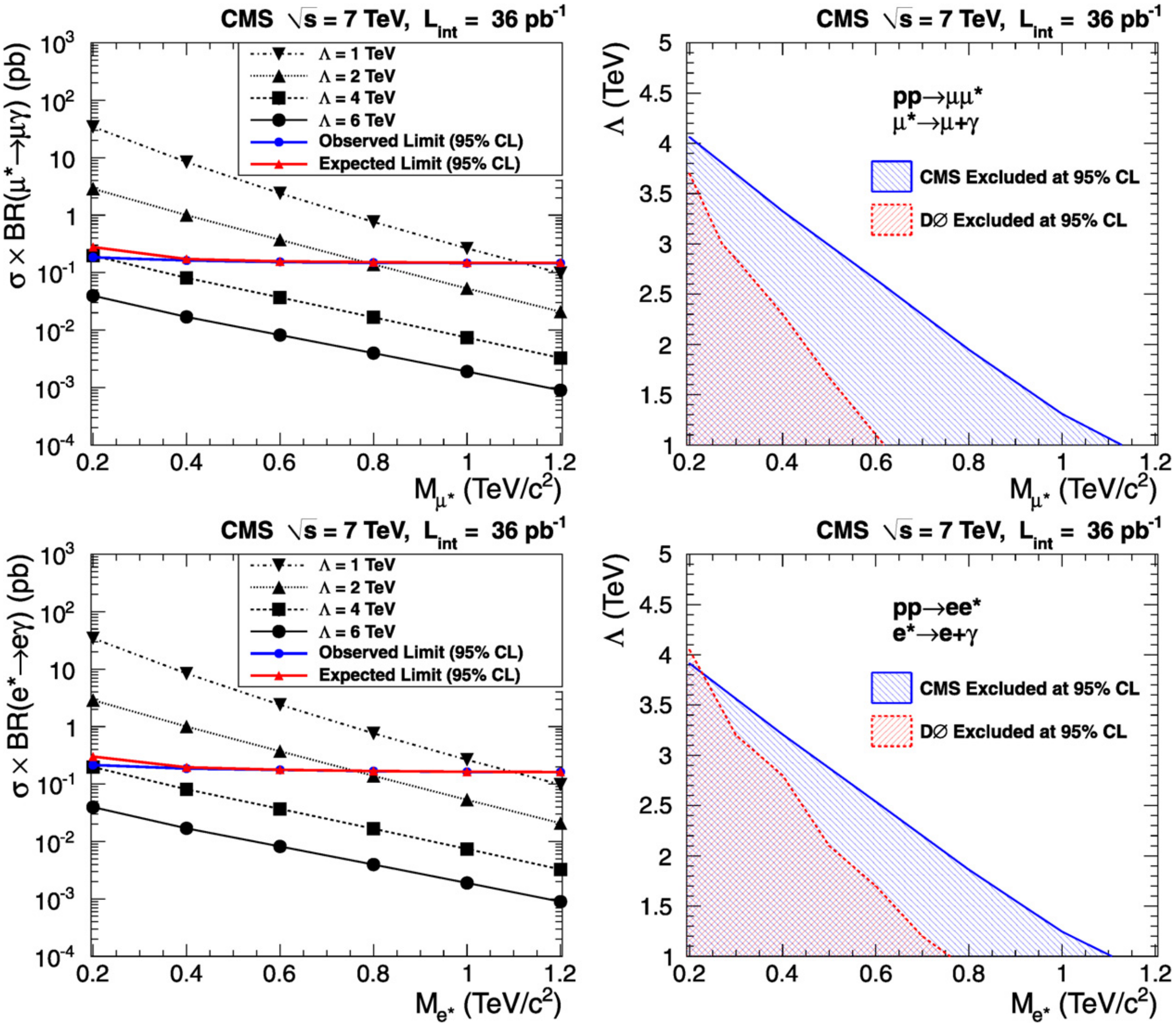

Fig. 2. Left: Observed and expected limits on the excited muon (top) and electron (bottom) production cross section times branching fraction at 95% CL, as functions of the excited lepton mass. The predictions for different Λ values are also shown. Right: The region in the (Λ, M_{ℓ^*}) plane excluded at the 95% CL by the present search, both for muons (top) and electrons (bottom). The previous most stringent limits from the D0 Collaboration [11,13] are also displayed.

the nuisance parameters. The corresponding expected limit is computed as the weighted average of limits over all possible numbers of observed events, where the weight is the Poisson probability to observe a given number of events in data assuming background-only hypothesis. The systematic uncertainties discussed in the previous section are taken into account in the statistical analysis. Cross sections higher than 0.16 pb to 0.21 pb for e^* production and higher than 0.14 pb to 0.19 pb for μ^* production are excluded at the 95% confidence level (CL) for excited lepton masses ranging from 200 GeV/c^2 to 1500 GeV/c^2, as shown in Fig. 2 (left) and given in Table 2. At a contact interaction scale of $\Lambda = M_{\ell^*}$, excited lepton masses are excluded below 1070 GeV/c^2 for electrons and 1090 GeV/c^2 for muons. If a higher contact interaction scale $\Lambda = 2$ TeV is considered, excited lepton masses are excluded below 760 GeV/c^2 for electrons and 780 GeV/c^2 for muons. Fig. 2 (right) displays the exclusion regions in the (Λ, M_{ℓ^*}) plane obtained from these limits, showing an improvement with respect to the previous most stringent limits established at hadron colliders [11,13].

7. Summary

We have searched for evidence of lepton compositeness in proton–proton collisions by looking for production of excited leptons followed by decay to a lepton and a photon at $\sqrt{s} = 7$ TeV. The data sample corresponds to an integrated luminosity of 36 pb^{-1} collected with the CMS detector. No excess of events in the $\ell^+\ell^-\gamma$ final state was found above the SM expectation in the electron or muon channel. We report the first upper limits on ℓ^* production at this collision energy and exclude a new region of the $\Lambda - M_{\ell^*}$ parameter space. At a contact interaction scale of $\Lambda = 2$ TeV, excited lepton masses are excluded at the 95% CL below 760 GeV/c^2 for electrons and 780 GeV/c^2 for muons. Assuming $\Lambda = M_{\ell^*}$ instead, excited lepton masses are excluded below 1070 GeV/c^2 for electrons and 1090 GeV/c^2 for muons, representing the most stringent limits to date.

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