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Search for excited leptons in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration[*]

Abstract

Results are presented of a search for compositeness in electrons and muons using a data sample of pp collisions at a center-of-mass energy $\sqrt{s}$ = 7 TeV collected with the CMS detector at the LHC and corresponding to an integrated luminosity of $5.0\,\text{fb}^{-1}$. Excited leptons (ℓ^*) are assumed to be produced via contact interactions in conjunction with a standard model lepton and to decay via $\ell^* \to \ell\gamma$, yielding a final state with two energetic leptons and a photon. The number of events observed in data is consistent with that expected from the standard model. The 95% confidence upper limits for the cross section for the production and decay of excited electrons (muons), with masses ranging from 0.6 to 2 TeV, are 1.48 to 1.24 fb (1.31 to 1.11 fb). Excited leptons with masses below 1.9 TeV are excluded for the case where the contact interaction scale equals the excited lepton mass. These are the best limits published to date.

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[*] See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics, albeit very successful, provides no explanation for the three generation structure of the fermion families. Attempts to explain the observed hierarchy have led to a family of models postulating that quarks and leptons might be composite objects of fundamental constituents [1–7]. The fundamental constituents are bound by an asymptotically free gauge interaction that becomes strong at a characteristic scale Λ. Compositeness models predict the existence of excited states of quarks (q^*) and leptons (ℓ^*) at this characteristic scale of the new binding interaction. Since these excited fermions couple to the ordinary SM fermions, they can be produced via contact interactions in collider experiments and subsequently decay radiatively to ordinary fermions through the emission of a $W/Z/\gamma$ boson or via contact interactions to other fermions. The excited leptons can also be produced via gauge-mediated interactions, but the cross sections for these are negligible for the range of parameters that are probed in this search and therefore this production mechanism is not considered. The effective Lagrangian describing the interaction of excited fermions [7] is parametrized by the scale Λ and by two factors f and f' representing the relative strength of the coupling between the excited fermions and isovector and isoscalar gauge fields, respectively. In this Letter the convention $f = f' = 1$ is adopted. The results for arbitrary $f = f' > 0$ can be simply obtained by a rescaling of the scale Λ to Λ/f.

Searches at LEP [8–11], HERA [12], and the Tevatron [13–16] found no evidence for excited leptons. At the Large Hadron Collider (LHC) [17] at CERN, previous searches performed by the CMS [18] and the ATLAS collaborations [19] have also shown no evidence for excited leptons. At a center-of-mass energy of $\sqrt{s}$ = 7 TeV, with 36 pb^{-1} of data [18], CMS has excluded cross sections for the production and decay of the $\ell^* \to \ell\gamma$ channels higher than 0.16 to 0.21 pb (0.14 to 0.19 pb) in the e^* (μ^*) channel for excited lepton masses ranging from 0.2 TeV to 2 TeV. In the same channels and with more integrated luminosity, ATLAS excluded cross sections higher than 2.3 (4.5) fb for excited electrons (muons) masses above 0.9 TeV, and excluded e^* (μ^*) with masses M_{ℓ^*} below 1.87 (1.75) TeV for the scale of contact interaction $\Lambda = M_{\ell^*}$ [19].

This Letter presents a search for excited leptons, e^* and μ^*, using a data sample of pp collisions at a center-of-mass energy $\sqrt{s}$ = 7 TeV collected with the CMS detector at the LHC in 2011 and corresponding to an integrated luminosity of $5.0 \pm 0.1\ \mathrm{fb}^{-1}$. The production of an excited lepton in association with an oppositely charged lepton of the same flavor, via four-fermion contact interactions, is considered. Thus when the excited lepton decays via $\ell^* \to \ell\gamma$, there are two oppositely charged leptons and a photon in the final state.

2 The CMS detector

The central feature of the Compact Muon Solenoid (CMS) detector is a superconducting solenoid, of 6 m internal diameter and 12.5 m in length, which provides an axial field of 3.8 T. Starting from the collision point, the first three detector components inside the solenoid are the silicon pixel and strip trackers; the lead-tungstate crystal electromagnetic calorimeter (ECAL), comprising a central (barrel) section and two forward (endcap) sections; and the brass/scintillator hadron calorimeter (HCAL). Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The tracker consists of 10 layers of silicon strip detectors in addition to the pixel detectors. Four stations of muon detectors are embedded in the steel yoke of the superconducting solenoid, including forward sections in order to extend the covered pseudorapidity region up to $|\eta| < 2.4$. The pseudorapidity (η) is defined as $\eta = -\ln[\tan(\theta/2)]$. The CMS detector uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane. The projection of the momentum on to the x-y plane is used to define the transverse momentum p_{T} and the transverse energy E_{T}. The details of the CMS detector are described elsewhere [20].

3 Signal and background

The dominant, irreducible SM background in this search is Drell–Yan production of $\ell^+\ell^-\gamma$ where the final state photon is either radiated by an initial-state parton (initial-state radiation, ISR), or originates from one of the final-state leptons (final-state radiation, FSR). The second-most important background is due to Drell–Yan production associated with jets (Z+jets), where a jet is misidentified as a photon (see Section 5). Another important background in the e^* channel is due to W+jets events with an FSR or ISR photon where a jet is misidentified as an electron. In the μ^* channel, backgrounds from these W+jets processes that lead to one true, one misidentified muon, and a true photon in the final state have been estimated to be negligible. Other less significant backgrounds originate from diboson events (WW, WZ, ZZ), $\mathrm{t\bar{t}}$ production, and, for the electron channel, $\gamma\gamma$ production. These backgrounds are mainly suppressed by requiring high transverse momentum thresholds on the leptons and photon. Backgrounds arising from misidentified photons or misidentified electrons are estimated using a data-driven technique which is described in Section 5. The other backgrounds are estimated from the simulation.

Signal samples in both electron and muon channels are produced using PYTHIA 6.424 [21] (PYTHIA 8.145 [22]) based on the leading order (LO) compositeness model described in Ref. [7]. The signal cross sections are estimated with the Q^2 scale set to the square of the mass of the excited lepton ($M^2_{\ell^*}$).

Samples are obtained for different values of the excited lepton mass and $\Lambda = 4\,\mathrm{TeV}$, with the CTEQ6L1 [23] parametrization for the parton distribution functions. This particular choice of the value of Λ has no impact on the simulated kinematics and all results are presented independently of the value of Λ, except for the signal yield in Fig. 1 and Fig. 2. The SM background samples: $\mathrm{Z}+\gamma$, $\mathrm{W}+\gamma$, $\mathrm{t\bar{t}}$, $\mathrm{Z}+\mathrm{jets}$, $\mathrm{W}+\mathrm{jets}$, and WW are generated with MADGRAPH 4.5.1 [24]. PYTHIA has been used to perform the fragmentation and hadronization of samples generated with MADGRAPH. The diboson samples (WZ, ZZ) are generated using PYTHIA 6.424 [21]. For these SM background processes, the cross sections are scaled to the next-to-leading order (NLO) cross sections obtained from the parton level integrator MCFM [25]. All Monte Carlo events used in this analysis have been passed through the detailed simulation of the CMS detector based on GEANT4 [26].

4 Event reconstruction and selection

Candidate events for the electron (muon) channel are selected using triggers with the lowest possible thresholds on lepton transverse momentum. This corresponds to a transverse momentum threshold of 33 (24) GeV for the initial periods and 33 (40) GeV for the later periods of data collection in the electron (muon) channel. The trigger thresholds were raised in response to the increased mean instantaneous luminosity. For the leptons selected in the analysis, the trigger efficiencies are 100% (97%) in the electron (muon) channel. The two leptons and the photon in signal events are expected to be isolated from other particles in the event. This can be quantified by isolation variables, obtained by summing the energy deposits present inside a

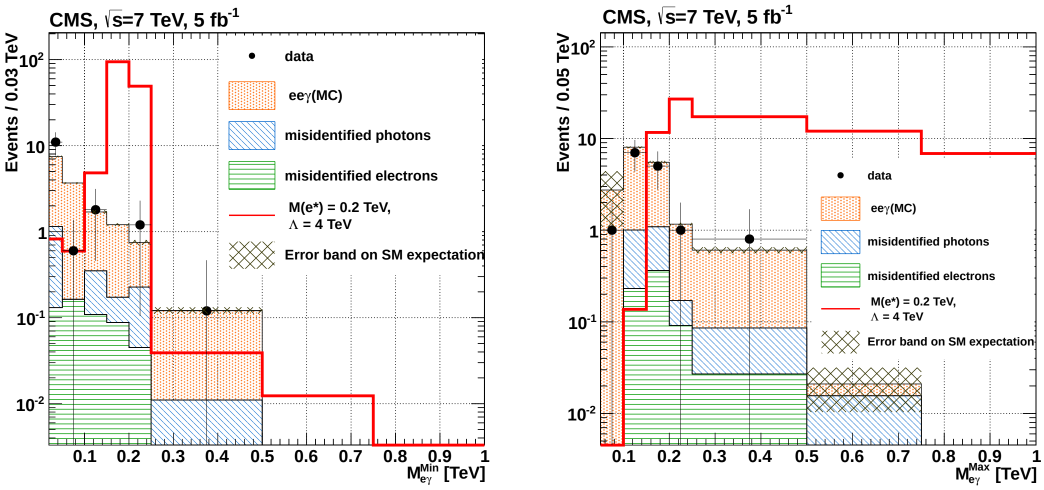

Figure 1: The distribution of events as a function of $M^{\min}_{\ell\gamma}$ (left) and $M^{\max}_{\ell\gamma}$ (right), expected in the presence of an excited electron with a mass of 0.2 TeV. The red dotted histogram corresponds to the contribution from the standard model backgrounds containing two real electrons and a real photon. The blue slanting hatched (green horizontal hatched) histograms correspond to the contribution from misidentified photon (electrons). The black solid circles correspond to the observed data. The red solid line histogram corresponds to the signal distribution for a mass of 0.2 TeV. The dark grey double hatched region shows the uncertainty in the SM expectation.

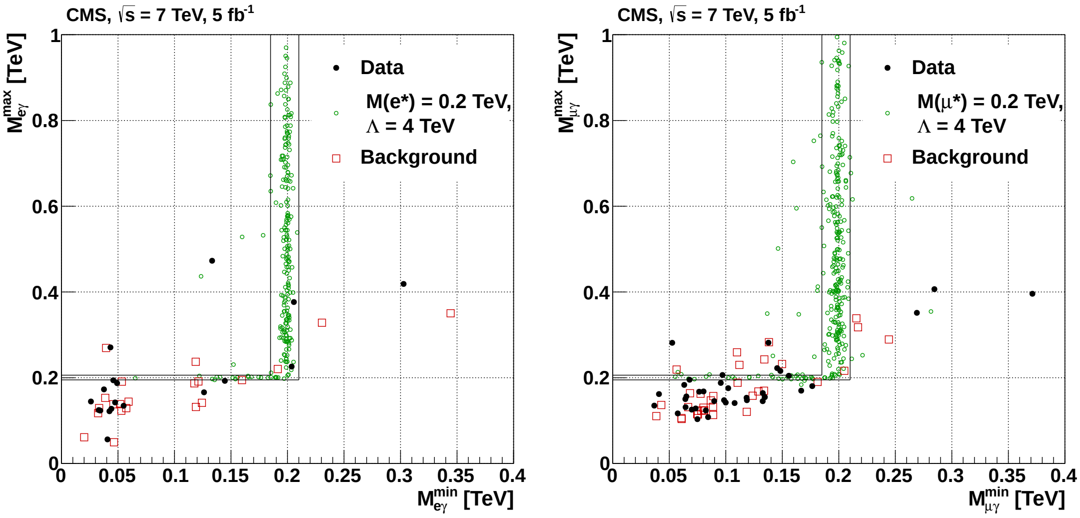

Figure 2: Distribution of $M^{\min}_{\ell\gamma}$ and $M^{\max}_{\ell\gamma}$ for the excited electron analysis (left) and excited muon analysis (right). The black solid circles, the red squares and the green open circles correspond to the observed data, the background distribution and the signal distribution, respectively. The optimized selection boundaries are shown for an excited lepton mass of 0.2 TeV. The sample is normalized to 5 fb^{-1} of integrated luminosity.

geometrical cone around the particle, in the tracker or in the calorimeters. Events with at least one well-reconstructed primary vertex, one isolated high-p_{T} photon, and two isolated high-p_{T} leptons are used in this analysis.

Electron identification is performed using clusters of localized energy deposits in the ECAL. An energy deposit in the ECAL due to an electron is identified by imposing requirements on shower shapes of the ECAL clusters and isolation variables as well as the ratio of the energies deposited in the hadron and electromagnetic calorimeters (H/E). A reconstructed track correctly associated with an ECAL cluster is also required. For the electron channel, the electrons are required to have a transverse energy $E_{\mathrm{T}} > 35$ (40) GeV in the ECAL barrel (endcap) and $|\eta| < 2.5$, excluding the transition region $1.4442 < |\eta| < 1.560$ between the ECAL barrel and endcap regions. The electron is required to be isolated both in the tracker and calorimeter within a cone of radius $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ around its direction. In the tracker, the sum of the p_{T}'s of the tracks, with track $p_{\mathrm{T}} > 0.7\,\mathrm{GeV}$ and excluding tracks within an inner cone of radius $\Delta R < 0.04$ relative to the electron, is required to be less than 5 GeV. For the isolation using the calorimeters, a variable $E_{\mathrm{T}}^{\mathrm{iso}}$ is introduced, defined as the total sum of transverse energy deposits excluding deposits associated with the electron. In the barrel, $E_{\mathrm{T}}^{\mathrm{iso}}$ is required to be less than $0.03E_{\mathrm{T}} + 2.0\,\mathrm{GeV}$, and in the endcap: for $E_{\mathrm{T}} < 50\,\mathrm{GeV}$, the total $E_{\mathrm{T}}^{\mathrm{iso}}$ is required to be $< 2.5\,\mathrm{GeV}$; for $E_{\mathrm{T}} > 50\,\mathrm{GeV}$, it is required to be $< 0.03E_{\mathrm{T}} + 1.0\,\mathrm{GeV}$.

For photons, identification criteria on the shower shapes, isolation variables and H/E are applied to energy clusters in the ECAL. Photon candidates are required to have clusters with $E_{\mathrm{T}} > 35\,\mathrm{GeV}$ and to be in the central region (barrel) of the ECAL with $|\eta| <1.4442$. The photon is also required to be isolated within a cone of radius $\Delta R < 0.4$ around its direction, both in the tracker and calorimeter. In the tracker, the sum of the transverse momenta of the tracks, excluding tracks within an inner cone of 0.04, is required to be less than $0.001p_{\mathrm{T}} + 2\,\mathrm{GeV}$. In the ECAL, the total $E_{\mathrm{T}}^{\mathrm{iso}}$ in the barrel, excluding deposits associated with the photon, is required to be $<0.006E_{\mathrm{T}} + 4.2\,\mathrm{GeV}$, whereas for the HCAL isolation, it is required to be $<0.0025E_{\mathrm{T}} + 2.2\,\mathrm{GeV}$.

Muons are reconstructed by combining tracks from the inner tracker and the outer muon system, requiring at least one hit in the pixel tracker, hits in more than 8 tracker layers and track segments reconstructed in at least two muon stations. Since the segments have multiple hits which typically occur in different muon detectors and are therefore separated by thick layers of iron, the latter requirement significantly reduces the probability of a hadron being misidentified as a muon. For the muon channel, two muons are required with each having $|\eta| < 2.1$; and the higher (lower) momentum muon must have $p_{\mathrm{T}} > 45$ (40) GeV. In order to reduce the cosmic-rays muon background, the transverse impact parameters of both muon tracks with respect to the primary vertex of the event are required to be less than 0.2 cm. Muon pairs which are back-to-back in the transverse plane are rejected, with the angle between two muon tracks $< \pi - 0.02$. Furthermore, the muon is required to be isolated such that the scalar sum of the transverse momenta of all tracks originating at the interaction vertex, excluding the muon itself, within a $\Delta R < 0.3$ cone around its direction is less than 10% of its p_{T}.

In order to reject Drell–Yan events with final state radiation, the distance in (η, ϕ) coordinates between the photon and the leading lepton, $\Delta R(\ell,\gamma)$ is required to be $\Delta R(\ell,\gamma) > 0.5$ for $\ell = \mathrm{e}$ and $\Delta R(\ell,\gamma) > 0.7$ for $\ell = \mu$. Two lepton-photon invariant masses can also be computed, because the final state is composed of two leptons and one photon. For the electron channel, the dielectron invariant mass is required to be above 60 GeV and each of the dielectron and electron-photon invariant masses are required to be outside a ±25 GeV window centered at the nominal Z mass (91.19 GeV). For the muon channel, the dilepton invariant mass is required to be 25 GeV above the nominal Z mass. Fig. 1 shows the distribution of $M_{\ell\gamma}^{\mathrm{min}}$ and $M_{\ell\gamma}^{\mathrm{max}}$, the lower and higher invariant mass respectively. In the case of a signal, the correct assignment peaks at the excited lepton mass. In the $M_{\ell\gamma}^{\mathrm{min}}$-$M_{\ell\gamma}^{\mathrm{max}}$ plane, the signal is distributed along two mutually perpendicular narrow bands. This shape determines the final selection cuts as outlined below and is illustrated in Fig. 2 for $M_{\ell^*} = 0.2\,\mathrm{TeV}$. Identical boundaries are used for the electron and muon channel. The only difference in the selection between the two channels is the Z veto, which, in the electron channel, is also applied on electron-photon invariant mass.

The background is located in the low invariant mass region, while the signal populates the higher invariant mass region. Using simulations, the boundaries of the signal region for a given mass have been chosen to optimize the expected limit. The final values for different excited lepton masses are shown in Table 1. For $M_{\ell^*} = 0.2\,\mathrm{TeV}$, the horizontal band is small, in order to reduce the background contamination. For $M_{\ell^*} = 0.4\,\mathrm{TeV}$, a larger horizontal band can be used, the increase of the background contamination being compensated by the gain in signal efficiency. For higher excited lepton masses, the horizontal band is large to improve the signal efficiency in regions where almost no background is present.

Table 1: Measured signal and expected background event numbers for the electron and muon channels as a function of the mass of the excited lepton. The signal efficiency with its corresponding uncertainty is given as $\epsilon_{\mathrm{signal}}$. The expected numbers of background events are reported as N_{bkgd} with Clopper–Pearson errors [27] along with the observed data N_{data}. The boundaries values for $M_{\ell\gamma}^{\mathrm{min}}$ and $M_{\ell\gamma}^{\mathrm{max}}$, which correspond to the signal region, are also given. The signal efficiencies shown with † symbol are obtained from a polynomial curve fitted to the reference mass points signal efficiencies.

M_{ℓ^*}	$M_{\ell\gamma}^{\mathrm{min}}$	$M_{\ell\gamma}^{\mathrm{max}}$	Electron channel			Muon channel		
(TeV)	(TeV)	(TeV)	$\epsilon_{\mathrm{signal}}$ (%)	N_{bkgd}	N_{data}	$\epsilon_{\mathrm{signal}}$ (%)	N_{bkgd}	N_{data}
0.2	0.19-0.21	0.20-0.21	24.8 ± 1.8	$1.0\,^{+1.1}_{-0.5}$	2	28.2 ± 1.3	$1.2^{+1.7}_{-0.6}$	2
0.3	0.23-0.37	0.29-0.31	$30.0 \pm 2.2^{\dagger}$	$1.2\,^{+2.1}_{-0.8}$	1	$34.4 \pm 1.6^{\dagger}$	$5.4^{+2.6}_{-1.8}$	2
0.4	0.28-0.52	0.38-0.41	32.7 ± 2.4	$0.1\,^{+1.4}_{-0.1}$	1	39.1 ± 1.8	$1.6^{+2.0}_{-0.9}$	3
0.5	0.35-0.65	0.47-0.53	$34.8 \pm 2.6^{\dagger}$	$0.0\,^{+1.4}_{-0.0}$	1	$42.1 \pm 1.9^{\dagger}$	$0.0^{+1.4}_{-0.0}$	1
0.6	0.42-0.78	0.55-0.64	36.6 ± 2.6	$0.0\,^{+1.4}_{-0.0}$	0	45.4 ± 2.0	$0.0^{+1.4}_{-0.0}$	0
0.7	0.49-0.91	0.65-0.76	$37.8 \pm 2.7^{\dagger}$	$0.1\,^{+1.4}_{-0.0}$	0	$45.9 \pm 2.1^{\dagger}$	$1.0^{+1.7}_{-0.6}$	0
0.8	0.56-1.04	0.75-0.88	37.8 ± 2.7	$0.0\,^{+1.4}_{-0.0}$	0	45.3 ± 2.0	$0.0^{+1.4}_{-0.0}$	0
1.0	0.70-1.30	0.75-1.08	40.4 ± 2.8	$0.0\,^{+1.4}_{-0.0}$	0	48.5 ± 2.1	$0.0^{+1.4}_{-0.0}$	0
1.2	0.84-1.56	0.75-1.34	41.1 ± 2.9	$0.0\,^{+1.4}_{-0.0}$	0	50.0 ± 2.2	$0.0^{+1.4}_{-0.0}$	0
1.5	1.05-1.95	0.75-1.67	41.7 ± 2.9	$0.0\,^{+1.4}_{-0.0}$	0	50.8 ± 2.2	$0.0^{+1.4}_{-0.0}$	0
2.0	1.40-2.60	0.75-2.23	43.5 ± 3.1	$0.0\,^{+1.4}_{-0.0}$	0	50.4 ± 2.2	$0.0^{+1.4}_{-0.0}$	0

5 Background due to particle misidentification

Hadronic jets in which a π^0 carries a significant fraction of the energy may be misidentified as isolated photons. Thus Z+jets events are a potential background for this search. The photon misidentification rate is measured directly from a data sample dominated by jets, with a photon-like candidate cluster embedded inside, which can potentially be misidentified as a photon. The misidentification rate is defined as the ratio of the number of photon candidates passing all the photon selection criteria (numerator) to the number of photon candidates that pass a loose set of shower shape requirements but fail one of the photon isolation criteria (denominator). The misidentification rate is estimated in bins of photon E_{T}. The numerator sample can have a contribution from isolated true photons. The probability distribution of the energy-weighted shower width ($\sigma_{\eta\eta}$) computed in units of crystal size of isolated true photons is different from that of non-isolated photons. The true photon fraction in the numerator is estimated by fitting these two different shower shapes to the shower shape distribution of the numerator sample, and subtracted from the numerator. In order to estimate the contribution of misidentified photons in the analysis, this corrected misidentification rate is applied to a subsample of data events containing one photon candidate and satisfying all other selection criteria. This rate is calculated in photon E_{T} bins of (0.03–0.05, 0.05–0.075, 0.075–0.09, 0.09–0.2) TeV. Fig. 3 shows the E_{T} dependence of the photon misidentification rate. The calculated misidentified photon rate is found to be 0.28, 0.07, 0.06 and 0.09 for the above mentioned E_{T} bins.

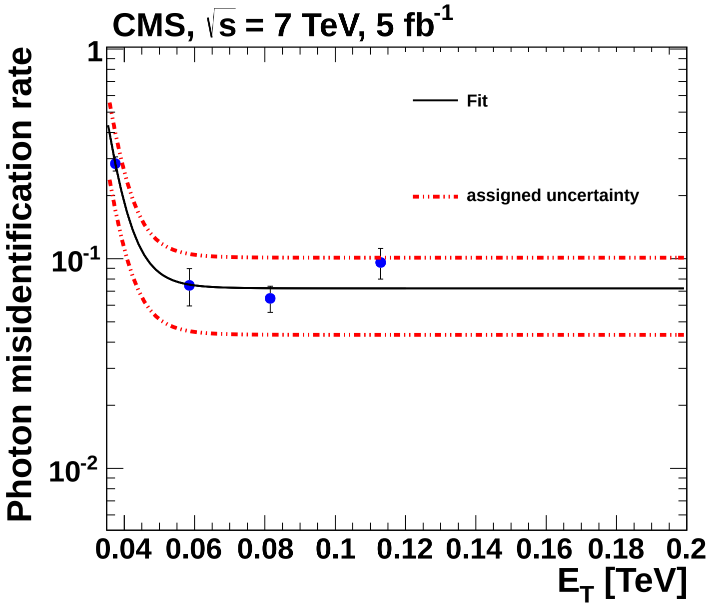

Figure 3: The jet-to-photon misidentification rate as a function of E_{T}. The dashed line is the 40% uncertainty band.

From a fit, the measured rate is parametrized by a function, $f_{\gamma}^{\mathrm{misid}}(E_{\mathrm{T}})$, as given in the equation (1) with a, b and c being the fit parameters:

$$f_{\gamma}^{\mathrm{misid}}(E_{\mathrm{T}}) = a + \frac{b}{(E_{\mathrm{T}})^c} \quad (1)$$

An uncertainty of 40% is assigned to this function which envelopes the spread of data points relative to the fit . From this method, after applying cuts as given in Table 1 to the lowest mass point of 0.2 TeV, the contribution of photon misidentification background in the full selection is found to be $0.07^{+0.16}_{-0.07}$ events for both the electron and the muon channels. It is negligible for higher mass points.

Table 2: Details of the expected background compositions for several masses, showing contributions from $Z+\gamma$ MC sample, misidentified γ and misidentified electron estimated from data. The uncertainties are reported as the quadratic sum of statistical and systematic errors.

M_{ℓ^*}	Electron channel			Muon channel	
(TeV)	$\mathrm{Z}+\gamma$ MC	misid γ	misid electron	$\mathrm{Z}+\gamma$ MC	misid γ
0.2	$0.8^{+1.1}_{-0.5}$	$0.07^{+0.16}_{-0.07}$	$0.08^{+0.17}_{-0.07}$	$1.0\,^{+1.7}_{-0.6}$	$0.07\,^{+0.16}_{-0.07}$
0.4	$0.0^{+1.4}_{-0.0}$	$0.07^{+0.16}_{-0.07}$	$0.01^{+0.02}_{-0.01}$	$1.6\,^{+1.9}_{-0.9}$	$0.00\,^{+0.45}_{-0.00}$
$\geq$0.8	$0.0^{+1.4}_{-0.0}$	$0.00^{+0.45}_{-0.00}$	$0.00^{+0.08}_{-0.00}$	$0.0\,^{+1.4}_{-0.0}$	$0.00\,^{+0.45}_{-0.00}$

Backgrounds with zero or one real electron can contribute to the e* search. The largest contributions come from processes such as $\mathrm{W}(\to \mathrm{e}\nu)$ + jet + γ where the jet in the event is misidentified as an electron. Misidentification can occur when photons coming from π^0s inside a jet convert to an $\mathrm{e}^+\mathrm{e}^-$ pair and are misidentified as electrons. Other possible sources include when a charged particle within a jet provides both the track in the tracker and an electromagnetic cluster that together fake an electron signature, or when a track from a charged particle matches with a nearby energy deposition in the calorimeter from another particle. The misidentification rate is calculated as the ratio between the number of candidates passing the electron selection criteria with respect to those satisfying looser selection criteria. The looser selection criteria require only that the first tracker layer contributes a hit to the electron track and that offline emulations of the online trigger requirements ("loose identification requirements") on shower shape $\sigma_{\eta\eta}$ and the ratio H/E are satisfied. This ratio is estimated as a function of E_T in bins of η ($f^{\text{misid}}_{\text{electron}}(E_\mathrm{T},\eta)$) using a data sample selected with single-photon triggers [28]. The jet to electron misidentified background in e* is estimated by applying this misidentification rate to a sample passing all our selection requirements, including triggers, except requiring one of the electron candidates to fail the electron identification criteria and pass instead the loose identification requirements. The systematic uncertainty on $f^{\text{misid}}_{\text{electron}}(E_\mathrm{T},\eta)$ is determined using a sample of events containing two reconstructed electrons as in [28]. The contribution from jet events to the dielectron mass spectrum can be determined either by applying the misidentification rate twice on events with two loose electrons or by applying the misidentification rate once on events with one fully identified electron and one loose electron. The first estimate lacks contributions from W + jets and γ + jets events while the second estimate is contaminated by Drell–Yan events. These effects are corrected using simulated samples. If the misidentification rate method is correct, the two corrected estimations should agree. Both estimates are found to agree well and the residual difference of 40% is taken as a systematic uncertainty on the jet to electron misidentification rate. The contribution from events which have zero or one real electron is $0.08^{+0.17}_{-0.07}$ for the lowest mass point of 0.2 TeV and is negligible for higher mass points.

6 Results

After all selection steps the expected background for $M_{\ell^*} > 0.7\,\mathrm{TeV}$ is found to be $0^{+1.4}_{-0.0}$ event in the simulated sample. The signal efficiency increases with the mass of the excited lepton, from 25% to 44% in the electron channel and 28% to 50% in the muon channel. All numbers are summarized in Table 1. The expected numbers of signal events and irreducible background events are evaluated from simulation while the contribution of misidentified particles is derived from data. The background composition for several mass points, 0.2 TeV, 0.4 TeV and $\geq$ 0.6 TeV for both channels is shown in Table 2. The uncertainties in the description of the detector performance, such as lepton energy or momentum resolution, lepton and photon energy scales, have been included in the systematic uncertainties. The impact on the signal yield corresponds to an uncertainty of $\pm 2\%$ and $\pm 3.5\%$, for each of the channels respectively. Effects caused by the increase in the typical number of additional pp interactions ('pileup') per LHC bunch crossing are modeled by adding to the generated events multiple collisions with a multiplicity distribution matched to the luminosity profile of the collision data. To evaluate the systematic uncertainty associated with the pileup simulation, the mean of the distribution of the pileup interactions is varied by 5%, leading to a variation of 3.0% (0.6%) in the simulated backgrounds and 1.0% (1.5%) in signal yields in the electron (muon) channel. An additional systematic uncertainty of 10% is assigned to the background to account for uncertainties associated with the choice of parton distribution functions. The uncertainty in the luminosity normalization is 2.2% [29].

As seen in Table 1, for masses above 0.5 TeV, no data events pass the criteria designed to select excited lepton signatures. Using a single bin counting method, upper limits are provided on the production cross section times branching fraction of excited electrons and excited muons at the 95% confidence level. The method is implemented in the statistical package developed by the Higgs study group [30]. The computation has been performed using both a Bayesian [31, 32] and a $\mathrm{CL_s}$ [33, 34] approach; the results are found to be consistent with each other. The results presented here are from the frequentist $\mathrm{CL_s}$ approach, without the use of the asymptotic approximation [30]. The background and signal uncertainties are dominated by completely uncorrelated uncertainties. The integrated luminosity normalization uncertainty is considered separately, with 100% correlation between signal and background. The nuisance parameters related to the uncertainties on the background are treated according to gamma probability distribution functions. The uncertainties on the signal yield and the integrated luminosity normalization are taken into account via a lognormal treatment of nuisance parameters. The observed limits for the electron and the muon channels are shown in Fig. 4. Production cross sections higher than 1.48 to 1.24 fb (1.31 to 1.11 fb) are excluded at the 95% confidence limit (CL) for e^* (μ^*) masses ranging from 0.6 to 2 TeV. The structure observed in the expected and observed limits results from the limited sizes of the simulated background samples. The optimization of the invariant masses selecting the $M_{\ell\gamma}^{\min}$–$M_{\ell\gamma}^{\max}$ signal region has been determined from simulation of signal reference mass points, ranging from $M_{\ell^*} = 0.2$ TeV to 2.0 TeV in steps of 0.2 TeV. For lower masses, the selected signal regions do not overlap. For continuous coverage, additional mass points for $M_{\ell^*} < 0.6$ TeV, have been added by interpolating the cut thresholds and the signal efficiencies. Limits for masses between 0.2 and 0.4 TeV are less stringent because of the presence of background in this region.

In the excited muon channel, as visible in Table 1, the bump at $M_{\mu^*} \sim 0.5$ TeV corresponds to a region where the background is found to be $0.0^{+1.4}_{-0.0}$ in the simulated sample while one data event is observed. Also in this channel, the shape of the uncertainty bands at $M_{\mu^*} = 0.7$ TeV corresponds to a region where the background is found to be $1.0^{+1.7}_{-0.6}$ in the simulated sample while zero data events are observed. The muon channel cross section limit is slightly lower compared to the electron channel because of the difference in the acceptance.

The set of $\Lambda - M_{\ell^*}$ values for which the theoretical cross section times branching fraction is higher than the 95% upper limit on cross section, is considered as excluded region of the pa-

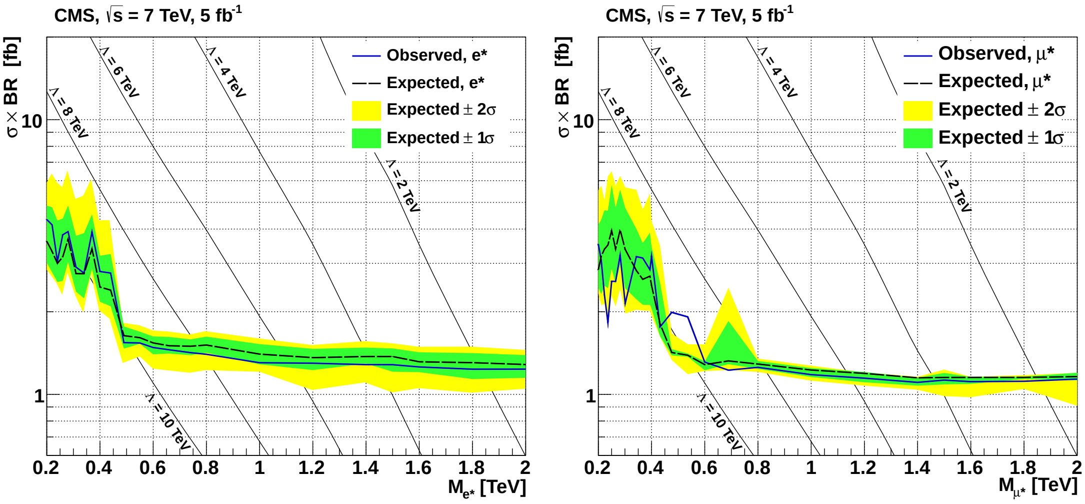

Figure 4: Expected and observed 95% CL upper limits on the cross section of the studied channel for the different excited electron (left) and muon (right) mass points given in Table 1, using the $\mathrm{CL_s}$ method. The black solid lines correspond to the excited lepton LO cross sections times branching ratio for different Λ scales. The one (two) standard deviation uncertainty bands are shown in green (yellow).

rameter space. The exclusion region in the $\Lambda - M_{\ell^*}$ plane is shown in Fig. 5. The displayed uncertainty band corresponds to the uncertainty on the cross section limits, and does not take into account uncertainties on the theoretical signal cross section. The signal cross sections are estimated with the Q^2 scale set to the square of the mass of excited lepton ($M^2_{\ell^*}$). If the Q^2 scale is varied to $M^2_{\ell^*}/2$, the limit for $\Lambda = M_{\ell^*}$ increases by 1.5% and if it is varied to $2M^2_{\ell^*}$, the limit for $\Lambda = M_{\ell^*}$ decreases by 2.4%.

Assuming the same masses for e^* and μ^*, the two counting experiments have been combined using the $\mathrm{CL_s}$ approach, improving the excluded cross section limit to 0.73 to 0.60 fb for masses from 0.6 to 2 TeV. The following uncertainties have been considered as completely correlated between the two channels: the photon scale factor uncertainties in signal and background, the photon misidentification rate systematic uncertainty not related to statistics, the luminosity uncertainty, the pileup simulation uncertainty, the $\mathrm{Z} + \gamma$ normalization uncertainty, and the $\mathrm{Z} + \gamma$ PDF uncertainty. The other uncertainties are considered as 100% uncorrelated.

7 Summary

A search has been performed with the CMS detector for excited leptons in the electron ($\mathrm{pp} \to \mathrm{ee}^* \to \mathrm{ee}\gamma$) and muon ($\mathrm{pp} \to \mu\mu^* \to \mu\mu\gamma$) channels. For lower ℓ^* masses the electron channel is less sensitive as it is more affected by misidentification of photons and electrons. For each excited lepton mass, the excluded cross section can be associated with a value for the new interaction scale Λ. Excited leptons (electrons or muons) with masses below 1.9 TeV are excluded for the scale of contact interaction $\Lambda = M_{\ell^*}$. Production cross sections higher than 1.48 to 1.24 fb (1.31 to 1.11 fb) are excluded at the 95% CL for e^* (μ^*) masses ranging from 0.6 to 2 TeV. These limits are the most stringent published to date.

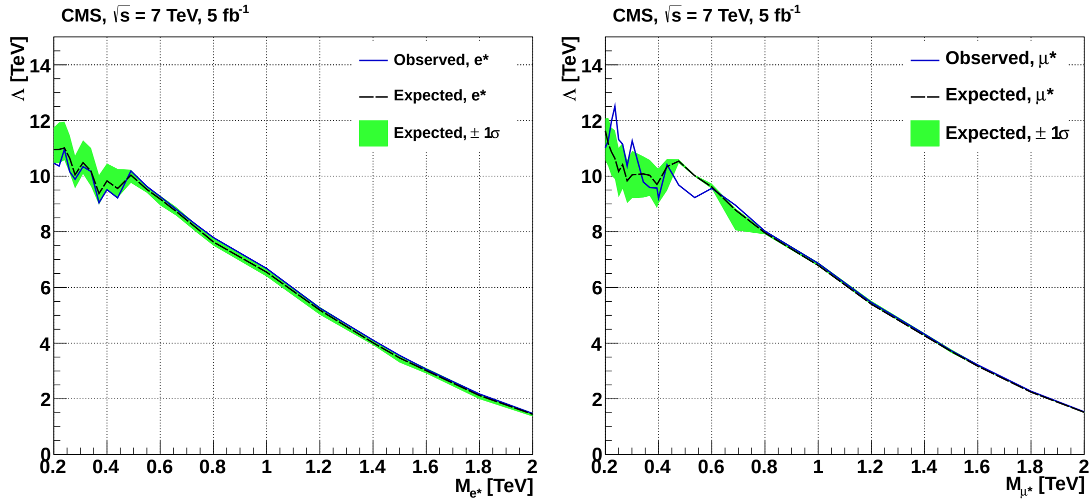

Figure 5: Expected and observed 95% CL lower limits on the Λ scale for the different excited electron (left) and muon (right) mass points given in Table 1, using the CL$_s$ method. These limits are computed with the LO signal cross section obtained from PYTHIA 6.424. The one standard deviation uncertainty band is shown in green. The bands do not include the uncertainty on signal cross section.

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