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

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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 [1–9]. The fundamental constituents are bound by an asymptotically free gauge interaction that becomes strong at a characteristic scale $\Lambda$. Compositeness models predict the existence of excited states of quarks ($q^*$) and leptons ($\ell^*$) 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/γ 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 $\Lambda$. Additionally, for decay via gauge mediated interaction, two factors $f$ and $f'$ represent 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 $\Lambda$ to $\Lambda/f$.

Searches at LEP [10–13], HERA [14], and the Tevatron [15–18] found no evidence for excited leptons. At the Large Hadron Collider (LHC) [19] at CERN, previous searches performed by the CMS [20] and the ATLAS Collaborations [21] 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 [20], 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 $e^*$ ($\mu^*$) 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 leptons (muons) masses above 0.9 TeV, and excluded $e^*$ ($\mu^*$) with masses $M_{\ell^*}$ below 1.87 (1.75) TeV for the scale of contact interaction $\Lambda = M_{\ell^*}$ [21].

This Letter presents a search for excited leptons, $e^*$ and $\mu^*$, 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 $5.0 \pm 0.1$ 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
Drell–Yan production of $Z$. Signal and background samples are described elsewhere \cite{22}. Produced using 	extsc{pythia} the transverse energy $E_T$ and the pseudorapidity $\eta$ are expected to be isolated from other particles in the event. This corresponds to a transverse momentum $p_T$ and the transverse energy $E_T$. The details of the CMS detector are described elsewhere \cite{22}.

### 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 ($Z\gamma$ radiation, FSR). The second-most important background is due to ISR, or originates from one of the final-state leptons (final-state $\gamma$ production). The polar angle $\theta$ is measured from the positive $z$ axis and the azimuthal angle $\phi$ 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 \cite{22}.

### 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 trigger thresholds were raised in response to the increased mean instantaneous luminosity.
can be quantified by isolation variables, obtained by summing the energy deposits present inside a 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 $E_T > 35$ (40) GeV in the ECAL barrel (endcap) and $|\eta| < 1.4442$ 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 $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.3$ around its direction. In the tracker, the scalar sum of the $p_T$ of the tracks, that are at least 0.7 GeV in $p_T$ and lie outside a 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 $E_T^{\text{iso}}$ is introduced, defined as the total sum of transverse energy deposits excluding deposits associated with the electron. In the barrel, $E_T^{\text{iso}}$ is required to be less than 0.03$E_T + 2.0$ GeV, and in the endcap: for $E_T < 50$ GeV, the total $E_T^{\text{iso}}$ is required to be below 2.5 GeV; for $E_T > 50$ GeV, it is required to be below 0.03$E_T + 1.0$ GeV.

For photons, identification criteria on the shower shapes, isolation variables and $H/E$ are applied to energy clusters in the ECAL [29]. Photon candidates are required to have clusters with $E_T > 35$ 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. The cone axis is taken to be the direction of the line joining the barycenter of the energy cluster to the primary vertex. In the tracker, the scalar sum of the transverse momenta of the tracks, excluding tracks within an inner cone of 0.04, is required to be less than 0.001$p_T + 2$ GeV. In the ECAL, the total $E_T^{\text{iso}}$ in the barrel, excluding deposits associated with the photon, is required to be below 0.006$E_T + 4.2$ GeV, whereas for the HCAL isolation, it is required to be below 0.0025$E_T + 2.2$ 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 that 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 $p_T > 45$ (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 and muon pairs that are back-to-back in the transverse plane are rejected, with the angle between two muon tracks below $\pi - 0.02$. 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 $(\eta, \phi)$ coordinates between the photon and the leading lepton, $\Delta R(\ell, \gamma)$ is required to be $> 0.5$ for $\ell = e$ 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 $\pm 25$ 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 $M_{\ell\gamma}^{\text{min}}$ and $M_{\ell\gamma}^{\text{max}}$, the lower and higher invariant mass respectively. In the case of a signal, the correct assignment peaks at the excited lepton mass. In the $M_{\ell\gamma}^{\text{min}}$–$M_{\ell\gamma}^{\text{max}}$ 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 $M_X = 0.2$ 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
prove the signal efficiency in regions where almost no background contamination is compensated by the gain in signal efficiency. For horizontal band can be used, the increase of the background shower width \( \sigma_{\eta\eta} \) to the number of photon candidates that pass a loose set of photon identification criteria to the number of photon candidates that pass one of the photon identification criteria and passes instead the selection requirements, except a requirement that the photon candidate fails one of the photon isolation criteria (denominator). The misidentification rate is therefore corrected by using the probability distribution of energy-weighted shower width \( \sigma_{\eta\eta} \) of isolated true photons computed in units of crystal size, which 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, the 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 \( 0.03\text{–}0.05, 0.05\text{–}0.075, 0.075\text{–}0.09, 0.09\text{–}0.1, 0.1\text{–}0.2, 0.2\text{–}0.3, 0.3\text{–}0.4\text{–}0.5, \ldots \text{TeV} \). 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.

From a fit, the measured rate is parametrized by a function,

\[
 f_{\gamma}^{\text{misid}}(E_T) = a + \frac{b}{(E_T)^c}. \tag{1}
\]

![CMS, (8 TeV, 5 fb^-)](image)

Fig. 3. The jet-to-photon misidentification rate as a function of \( E_T \). The dashed line is the 40% uncertainty band.

An uncertainty of 40% is assigned to this function which envelopes the spread of data points relative to the fit. The jet to photon misidentification rate is estimated by applying this misidentification rate to a sample passing all our selection requirements, including triggers, except a requirement that the photon candidate fails one of the photon identification criteria and passes instead the loose identification requirements. Applied 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.

Backgrounds with zero or one real electron can contribute to the e+ search. The largest contributions come from processes such as \( W(\rightarrow e\nu) + \text{jet} + \gamma \) where the jet in the event is misidentified as an electron. Misidentification can occur when photons coming from \( \pi^0\)'s inside a jet convert to an \( e^+e^- \) 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.

mass have been chosen to optimize the expected limit. The final values for different excited lepton masses are shown in Table 1. For \( M_{\ell^*} = 0.2 \) TeV, the horizontal band is small, in order to reduce the background contamination. For \( M_{\ell^*} = 0.4 \) 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.

### 5. Background due to particle misidentification

Hadronic jets in which a \( \pi^0 \) carries a significant fraction of the energy may be misidentified as isolated photons. Thus \( Z + \text{jet} \) 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. This misidentification rate is therefore corrected by using the probability distribution of energy-weighted shower width \( \sigma_{\eta\eta} \) of isolated true photons computed in units of crystal size, which 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, the 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 \( 0.03\text{–}0.05, 0.05\text{–}0.075, 0.075\text{–}0.09, 0.09\text{–}0.1, 0.1\text{–}0.2, 0.2\text{–}0.3, 0.3\text{–}0.4\text{–}0.5, \ldots \text{TeV} \). 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.

From a fit, the measured rate is parametrized by a function,

\[
 f_{\gamma}^{\text{misid}}(E_T) = a + \frac{b}{(E_T)^c}. \tag{1}
\]
The looser selection criteria require only that the first tracker layer contributes a hit to the electron track and that offline simulations of the online trigger requirements (“loose identification requirements”) on shower shape $σ_{\text{sh}}$ and the ratio $H/E$ are satisfied. This ratio is estimated as a function of $E_T$ in bins of $\eta$ ($f_{\text{missid electron}} (E_T, \eta)$) using a data sample selected with single-photon triggers [31]. The jet to electron misidentified background in $e^*$ is estimated by applying one of the electron candidates to fail the electron identification criteria and pass instead the loose identification requirements. The systematic uncertainty on $f_{\text{missid electron}} (E_T, \eta)$ is determined using a sample of events containing two reconstructed electrons as in [31]. 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 $W + \text{jets}$ and $\gamma + \text{jets}$ 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 $40\%$ between the two estimates is taken as the 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 $0.2 \text{ TeV}$ and is negligible for higher mass points.

### 6. Results

After all selection steps the expected background for $M_{\ell^*} > 0.7 \text{ TeV}$ is found to be $0.14^{+0.03}_{-0.02}$ 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 $\geq 0.6 \text{ TeV}$ 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 the electron and muon 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 $2.2\%$ [32].

As seen in Table 1, for masses above $0.5 \text{ TeV}$, 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 [33]. The computation has been performed using both a Bayesian [34,35] and a $\text{CL}_S$ [36,37] approach; the results are found to be consistent with each other. The results presented here are from the frequentist $\text{CL}_S$ approach, without the use of the asymptotic approximation [33]. 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 $1.24 \text{ fb}$ ($1.31$ to $1.11 \text{ fb}$) are excluded at the $95\%$ confidence level (CL) for $e^*$ ($\mu^*$) 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 $M_{\ell^*} - M_{\ell^*}^{\text{max}}$ signal region has been determined from simulation of signal reference mass points, ranging from $M_{\ell^*} = 0.2 \text{ TeV}$ to $2.0 \text{ TeV}$ in steps of $0.2 \text{ TeV}$. For lower masses, the selected signal regions do not overlap. For continuous coverage, additional mass points for $M_{\ell^*} < 0.6 \text{ TeV}$ 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 $M_{\mu^*} \sim 0.5 \text{ TeV}$ corresponds to a region where the background is found to be $0.0^{+1.4}_{-0.6}$ in the simulated sample while one data event is observed. Also in this channel, the shape of the uncertainty bands at $M_{\mu^*} = 0.7 \text{ TeV}$ 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. For high excited lepton masses, the muon channel cross section limit is slightly lower than the electron channel limit because of the difference in the acceptance. For lower excited lepton masses, the sensitivity of the electron channel is also reduced because of misidentification of photons and electrons.

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 parameter 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 region is theoretically excluded, where $M_{\ell^*} > \Lambda$. The signal cross sections are estimated with the $Q^2$ scale set to the square of the mass of excited lepton ($M_{\ell^*}^2$). If the $Q^2$ scale is varied to $M_{\ell^*}^2 / 2$, the limit for $\Lambda = M_{\ell^*}$ increases by $1.5\%$ and if it is varied to $2M_{\ell^*}^2$, the limit for $\Lambda = M_{\ell^*}$ decreases by $2.4\%$. The impact of the parton distribution functions (PDF) uncertainties on the signal is smaller than $1\%$.

Assuming the same masses for $e^*$ and $\mu^*$, the two counting experiments have been combined using the $\text{CL}_S$ approach, improving the excluded cross section limit to $0.73$ to $0.60 \text{ fb}$ for masses from $0.2 \text{ TeV}$ to $2.0 \text{ TeV}$.
Fig. 4. Expected and observed 95% CL upper limits on the cross section of the studied channel for the different excited electron (top) and muon (bottom) mass points, using the CLs method. The excluded region is above the curve. The black solid lines correspond to the excited lepton LO cross sections times branching ratio for different $\Lambda$ scales. The one (two) standard deviation uncertainty bands are shown in green (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

0.6 to 2 TeV. Allowing $e^*$ and $\mu^*$ to have different masses, the excluded cross sections would also be within this range. 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 $Z+\gamma$ normalization uncertainty, and the $Z+\gamma$ 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 ($pp \rightarrow ee^* \rightarrow ee\gamma$) and muon ($pp \rightarrow \mu\mu^* \rightarrow \mu\gamma\gamma$) channels. For each excited lepton mass, the excluded cross section can be associated with a value for the new interaction scale $\Lambda$. 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 $e^*$ ($\mu^*$) masses ranging from 0.6 to 2 TeV. The slightly better sensitivity in the muon channel is due to its better acceptance and efficiency, and also, for lower $\ell^*$ masses, to the fact that there is a higher background in the electron channel arising from particle misidentification. These limits are the most stringent published to date.

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