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Search for excited leptons in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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The ATLAS detector is used to search for excited leptons in the electromagnetic radiative decay channel $\ell^* \to \ell\gamma$. Results are presented based on the analysis of pp collisions at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of 2.05 fb^{-1}. No evidence for excited leptons is found, and limits are set on the compositeness scale Λ as a function of the excited lepton mass m_{ℓ^*}. In the special case where $\Lambda = m_{\ell^*}$, excited electron and muon masses below 1.87 TeV and 1.75 TeV are excluded at 95% C.L., respectively.

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I. INTRODUCTION

The standard model (SM) of particle physics is an extremely successful effective theory which has been extensively tested over the past 40 years. However, a number of fundamental questions are left unanswered. In particular, the SM does not provide an explanation for the source of the mass hierarchy and the generational structure of quarks and leptons. Compositeness models address these questions by proposing that quarks and leptons are composed of hypothetical constituents named preons [1]. In these models, quarks and leptons are the lowest-energy bound states of these hypothetical particles. New interactions among quarks and leptons should then be visible at the scale of the constituents' binding energies, and give rise to excited states. At the LHC, excited lepton ℓ^* production via four-fermion contact interactions can be described by the effective Lagrangian [2]

$$\mathcal{L}_{\text{contact}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu,$$

where g_*^2 is the coupling constant, Λ is the compositeness scale, and j_μ is the fermion current

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

For simplicity and consistency with recent searches, the following prescription is used: $g_*^2 = 4\pi$, $\eta_L = \eta'_L = \eta''_L = 1$, and $\eta_R = \eta'_R = \eta''_R = 0$ such that chiral symmetry is conserved [3,4]. The above ansatz ignores underlying preon dynamics and is valid as long as the mass of the excited leptons is below the scale Λ. In the well-studied case of the homodoublet-type ℓ^* [2,5,6], the relevant gauge-mediated Lagrangian describing transitions between excited and ground-state leptons is

$$\mathcal{L}_{\text{GM}} = \frac{1}{2\Lambda} \bar{\ell}^*_R \sigma^{\mu\nu} \left[g f \frac{\tau^a}{2} W^a_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] \ell_L + \text{H.c.},$$

where ℓ_L is the lepton field, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the $SU(2)_L$ and $U(1)_Y$ field strength tensors, g and g' are the respective electroweak couplings, and f and f' are phenomenological constants chosen to be equal to 1. The $\mathcal{L}_{\text{GM}}$ term allows the decay of excited leptons via the electromagnetic radiative mode $\ell^{*\pm} \to \ell^\pm \gamma$, a very clean signature which is exploited in this search. For a fixed value of Λ, the branching ratio $B(\ell^{*\pm} \to \ell^\pm\gamma)$ decreases rapidly with increasing ℓ^* mass. For $\Lambda = 2$ TeV, $B(\ell^{*\pm} \to \ell^\pm\gamma)$ is 30% for $m_{\ell^*} = 0.2$ TeV and decreases exponentially to about 2.3% for $m_{\ell^*} = 2$ TeV.

Previous searches at LEP [7], HERA [8], and the Tevatron [9] have found no evidence for such excited leptons. For the case where $\Lambda = m_{\ell^*}$, the CMS experiment has excluded masses below 1.07 TeV for e^* and 1.09 TeV for μ^* at the 95% credibility level (C.L.) [10].

II. ANALYSIS STRATEGY

This article reports on searches for excited electrons and muons in the $\ell^* \to \ell\gamma$ channel based on 2.05 fb^{-1} of 7 TeV pp collision data recorded in 2011 with the ATLAS detector [11]. The benchmark signal model considered is based upon theoretical calculations from Ref. [2]. In this model, excited leptons may be produced singly via $q\bar{q} \to \ell^*\bar{\ell}$ or in pairs via $q\bar{q} \to \ell^*\bar{\ell}^*$, due to contact interactions. As the cross section for pair production is much less than for single production, the search for excited leptons is based on the search for events with $\ell\bar{\ell}\gamma$ in the final state: three very energetic particles, isolated, and well separated from one another.

For both the e^* and μ^* searches, the dominant background arises from Drell-Yan (DY) processes accompanied either by a prompt photon from initial- or final-state radiation ($Z + \gamma$) or by a jet misidentified as a photon

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(Z + jets). The dominant irreducible $Z + \gamma$ background results in the same final state as the signal, whereas Z + jets background can be highly suppressed by imposing stringent requirements on the quality of the reconstructed photon candidate. Small contributions from $t\bar{t}$ and diboson (WW, WZ, and ZZ) production are also present in both channels. W + jets events, as well as semileptonic decays of heavy flavor hadrons, and multijet events can be heavily suppressed by requiring the leptons and photons to be isolated and thus have a negligible contribution to the total background.

The signature for excited leptons can present itself as a peak in the invariant mass of the $\ell + \gamma$ system because the width of the ℓ^* is predicted to be narrower than the detector mass resolution for excited lepton masses $m_{\ell^*} \lesssim 0.5\Lambda$. This peak could be easily resolved from the $Z + \gamma$ background. However, it is difficult to identify which of the two leading leptons in the event comes from the ℓ^* decay. To avoid this ambiguity, one can search for an excess in the $\ell\bar{\ell}\gamma$ invariant mass ($m_{\ell\ell\gamma}$) spectrum. This approach is effective for the whole $m_{\ell^*} - \Lambda$ parameter space probed, as one can search for an excess of events with $m_{\ell\ell\gamma} >$ 350 GeV, which defines a nearly background-free signal region. Optimization studies demonstrate that the observable $m_{\ell\ell\gamma}$ provides better signal sensitivity than $m_{\ell\gamma}$, particularly for lower ℓ^* masses. The analysis strategy therefore relies on $m_{\ell\ell\gamma}$ for the statistical interpretation of the results.

III. ATLAS DETECTOR

ATLAS is a multipurpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. It consists of an inner tracking detector immersed in a 2 T solenoidal field, electromagnetic and hadronic calorimeters, and a muon spectrometer. Charged particle tracks and vertices are reconstructed in silicon-based pixel and microstrip tracking detectors that cover $|\eta| < 2.5$ and transition radiation detectors extending to $|\eta| < 2.0$ [12]. A hermetic calorimetry system, which covers $|\eta| < 4.9$, surrounds the superconducting solenoid. The liquid-argon electromagnetic calorimeter, which plays an important role in electron and photon identification and measurement, is finely segmented. It has a readout granularity varying by layer and cells as small as 0.025×0.025 in $\eta \times \phi$, and extends to $|\eta| <$ 2.5 to provide excellent energy and position resolution. Hadron calorimetry is provided by an iron-scintillator tile calorimeter in the central rapidity range $|\eta| < 1.7$ and a liquid-argon calorimeter with copper and tungsten as absorber material in the rapidity range $1.5 < |\eta| < 4.9$. Outside the calorimeter, there is a muon spectrometer which is designed to identify muons and measure their momenta with high precision. The muon spectrometer comprises three toroidal air-core magnet systems: one for the barrel and one per endcap, each composed of eight coils. Three layers of drift tube chambers and/or cathode strip chambers provide precision (η) coordinates for momentum measurement in the region $|\eta| < 2.7$. A muon trigger system consisting of resistive plate chambers in the barrel and thin-gap chambers for $|\eta| > 1$ provides triggering capability up to $|\eta| = 2.4$ and measurements of the ϕ coordinate.

IV. SIMULATED SAMPLES

The excited lepton signal samples are generated based on calculations from Ref. [2] at LO with COMPHEP 4.5.1 [13] interfaced with PYTHIA 6.421 to handle parton showers and hadronization [14,15], using MRST2007 LO* [16] parton distribution functions (PDFs). Only single production of excited leptons is simulated, with the ℓ^* decaying exclusively via the electromagnetic channel. The $Z + \gamma$ sample is generated with SHERPA 1.2.3 [17] using CTEQ6.6 [18] PDFs, requiring the dilepton mass to be above 40 GeV. To avoid phase-space regions where matrix elements diverge, the angular separation between the photon and leptons is required to be $R(\ell, \gamma) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} >$ 0.5 and the transverse momentum (p_T) of the photon is required to be $p_T^\gamma > 10$ GeV. To ensure adequate statistics at large $m_{\ell\ell\gamma}$, an additional $Z + \gamma$ sample is generated with $p_T^\gamma > 40$ GeV, and is equivalent to $\sim$300 fb^{-1} of data. The Z + jets background is generated with ALPGEN 2.13 [19], while the $t\bar{t}$ background is produced with MC@NLO 3.41 [20]. In both cases, JIMMY 4.31 [21] is used to describe multiple parton interactions and HERWIG 6.510 [22] is used to simulate the remaining underlying event and parton showers and hadronization. CTEQ6.6 PDFs are used for both backgrounds. To remove overlaps between the Z + jets and the $Z + \gamma$ samples, Z + jets events with prompt energetic photons are rejected if the photon-lepton separation is such that $R(\ell, \gamma) > 0.5$. The diboson processes are generated with HERWIG using MRST2007 LO* PDFs. For all samples, final-state photon radiation is handled via PHOTOS [23]. The generated samples are then processed through a detailed detector simulation [24] based on GEANT4 [25] to propagate the particles and account for the detector response. A large sample of MC minimum bias events is then mixed with the signal and background MC events to simulate pileup from additional pp collisions. Simulations are normalized on an event-by-event basis such that the distribution of the number of interactions per event agrees with the spectrum observed in data.

Although SHERPA includes higher-order QCD contributions beyond the $Z + \gamma$ Born amplitude, such as the real emission of partons in the initial state, it omits virtual corrections. For this reason, the $Z + \gamma$ cross section is calculated at next-to-leading order (σ_{NLO}) using MCFM [26] with MSTW2008 NLO PDFs [27]. The theoretical precision of the σ_{NLO} estimate is $\sim$6%, and the ratio $\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{SHERPA}}$ is used to determine a correction factor as a function of $m_{\ell\ell\gamma}$. The $Z+$ jets cross section is initially normalized to predictions calculated at next-to-next-to-leading order (NNLO) in perturbative QCD as determined by the FEWZ [28] program using MSTW2008 NNLO PDFs. Since the misidentification of jets as photons is not well modeled, the $Z+$ jets prediction is adjusted at the analysis level using data-driven techniques described below. Cross sections for diboson processes are known at NLO with an uncertainty of 5%, while the $t\bar{t}$ cross section is predicted at approximately NNLO, with better than 10% uncertainty [29,30].

V. DATA AND PRESELECTION

The data, which correspond to a total integrated luminosity of 2.05 fb^{-1}, were collected in 2011 during stable beam periods of 7 TeV pp collisions. For the e^* search, events are required to pass the lowest unprescaled single electron trigger available. For the first half of the data this corresponds to a p_T^e threshold of 20 GeV, and a p_T^e threshold of 22 GeV for the later runs. For the μ^* search, a single muon trigger with matching tracks in the muon spectrometer and inner detector with combined $p_T^\mu > 22$ GeV is used to select events. In addition, events with a muon with $p_T^\mu >$ 40 GeV in the muon spectrometer are also kept. Collision candidates are then identified by requiring a primary vertex with a z position along the beam line of $|z| <$ 200 mm and at least three associated charged particle tracks with $p_T > 0.4$ GeV.

The lepton selection consists of the same requirements used in the ATLAS search for new heavy resonances decaying to dileptons [31]. Electron candidates are formed from clusters of cells in the electromagnetic calorimeter associated with a charged particle track in the inner detector. For the e^* search, two electron candidates with $p_T^e >$ 25 GeV and $|\eta| < 2.47$ are required. Electrons within the transition region $1.37 < |\eta| < 1.52$ between the barrel and the endcap calorimeters are rejected. The *medium* electron identification criteria [32] on the transverse shower shape, the longitudinal leakage into the hadronic calorimeter, and the association with an inner detector track are applied to the cluster. The electron's reconstructed energy is obtained from the calorimeter measurement and its direction from the associated track. A hit in the first active pixel layer is required to suppress the background from photon conversions. To further suppress background from jets, the leading electron is required to be isolated by demanding that the sum of the transverse energies in the cells around the electron direction in a cone of radius $R < 0.2$ be less than 7 GeV. The core of the electron energy deposition is excluded, and the sum is corrected for transverse shower leakage and pileup from additional pp collisions to make the isolation variable essentially independent of p_T^e [33]. In cases where more than two electrons are found to satisfy the above requirements, the pair with the largest invariant mass is chosen. To minimize the impact of possible charge misidentification, the electrons are not required to have opposite electric charges.

Muon tracks are reconstructed independently in both the inner detector and the muon spectrometer, and their momenta are determined from a combined fit to these two measurements. For the μ^* search, two muons with $p_T^\mu >$ 25 GeV are required. To optimize the momentum resolution, each muon candidate is required to have a minimum number of hits in the inner detector and to have at least three hits in each of the inner, middle, and outer layers of the muon spectrometer. This requirement results in a muon fiducial acceptance of $|\eta| < 2.5$. Muons with hits in the barrel-endcap overlap regions of the muon spectrometer are discarded because of large residual misalignments. The effects of misalignments and intrinsic position resolution are otherwise included in the simulation. The p_T^μ resolution at 1 TeV ranges from 13% to 20%. To suppress background from cosmic rays, the muon tracks are required to have transverse and longitudinal impact parameters $|d_0| <$ 0.2 mm and $|z_0| < 1$ mm with respect to the primary vertex. To reduce background from heavy flavor hadrons, each muon is required to be isolated such that $\Sigma p_T(R < 0.3)/p_T^\mu < 0.05$, where only inner detector tracks with $p_T > 1$ GeV enter the sum. Muons are required to have opposite electric charges. In cases where more than two muons are found to satisfy the above requirements, the pair of muons with the largest invariant mass is considered.

The dielectron and dimuon distributions are inspected for consistency with background predictions to ensure that the resolution and efficiency corrections were adjusted properly in the simulation. Excellent agreement is found around the mass of the Z, in terms of both the peak position and width of the dilepton invariant mass distributions. For the mass range $70 < m_{\ell\ell} < 110$ GeV, the number of events observed in data agrees to within 1% of the background predictions for both the electron and muon channels. Furthermore, the tails of the p_T^e and p_T^μ distributions in the simulation are found to closely match the data.

The presence of at least one photon candidate with $p_T^\gamma >$ 20 GeV and pseudorapidity $|\eta| < 2.37$ is then necessary for the events to be kept. Photons within the transition region between the barrel and the endcap calorimeters are excluded. Photon candidates are formed from clusters of cells in the electromagnetic calorimeter. They include unconverted photons, with no associated track, and photons that converted to electron-positron pairs, associated with one or two tracks. All photon candidates are required to satisfy the *tight* photon definition [34]. This selection includes constraints on the energy leakage into the hadronic calorimeter as well as stringent requirements on the energy distribution in the first sampling layer of the electromagnetic calorimeter, and on the shower width in the second sampling layer. The *tight* photon definition is designed to increase the purity of the photon selection sample by rejecting most of the jet background, including jets with a leading neutral hadron (usually a π^0) that decays to a pair of collimated photons. To further reduce background from misidentified jets, photon candidates are required to be isolated by demanding that the sum of the transverse energies of the cells within a cone $R < 0.4$ of the photon be less than 10 GeV. As for the electron isolation, the core of the photon energy deposition is excluded and the sum is corrected for transverse shower leakage and pileup. Because no background predictions are simulated for $R(\ell, \gamma) < 0.5$, photons are required to be well separated from the leptons with $R(\ell, \gamma) > 0.7$. This requirement has a negligible impact on signal efficiency. Finally, if more than one photon in an event satisfies the above requirements, the one with the largest p_{T} is used in the search.

For the above selection criteria, the total signal acceptance times efficiency ($A \times \epsilon$) is ~56% in the e^* channel for masses $m_{e^*} > 600$ GeV. This value includes the acceptance of all selection cuts and the reconstruction efficiencies, and reflects the lepton and photon angular distributions. In comparison, $A \times \epsilon$ is ~32% for $m_{\mu^*} > 600$ GeV. The lower acceptance in the μ^* channel is due to the stringent selection on the muon spectrometer hits used to maximize the p_{T}^{μ} resolution, in particular, the limited geometrical coverage of the muon spectrometer with three layers of precision chambers.

VI. BACKGROUND DETERMINATION

All background predictions are evaluated with simulated samples. These include the dominant and irreducible $Z + \gamma$ background, as well as $Z +$ jets events where a jet is misidentified as a photon. The rate of jet misidentification is overestimated in the simulation so the $Z +$ jets predictions are adjusted to data as described below. Small contributions from $t\bar{t}$ and diboson production are also present at low $m_{\ell\ell\gamma}$. Background from multijet events and semileptonic decays of heavy flavor hadrons are heavily suppressed by the isolation requirements and are negligible in the signal region.

The $Z +$ jets estimates are adjusted to data in a control region defined by $m_{\ell\ell\gamma} < 300$ GeV. This region represents less than 1% of the signal parameter space for $m_{\ell^*} \geq 200$ GeV. The nominal strategy consists of counting the number of events in data in this control region and comparing it to the MC background predictions. The excess of background events found in the simulation is attributed to the mismodeling of the rate of jets misidentified as photons, and the number of $Z +$ jets events is scaled down accordingly. As a result, the number of events in the control region is the same in the MC simulations as in data, as shown in Table I. The $Z +$ jets estimates are validated using various data-driven methods, notably by using misidentification rates evaluated in jet-enriched samples, and applying these rates to $Z +$ jets data samples using an approach similar to the one described in Ref. [34]. The main reason for the overestimation of the jet misidentification rate in the simulation is due to the mismodeling of the jet shower shapes. A $Z +$ jets enriched sample was used to correct the shower shapes of jets in the simulations, such that the efficiency for jets to pass the *tight* photon requirement in the MC simulation is comparable to the rate measured in data. This correction depends strongly on the generator used (e.g. PYTHIA vs ALPGEN) and results in a 15% uncertainty in the $Z +$ jets background estimate.

The largest difference between the nominal $Z +$ jets background determination and the alternative estimates is

TABLE I. Data yields and background expectations inside ($m_{\ell\ell\gamma} < 300$ GeV) and outside the $m_{\ell\ell\gamma}$ control region after adjusting the $Z +$ jets background. The uncertainties shown are purely statistical, except for the $Z +$ jets background for which the total uncertainty is dominated by systematic uncertainties.

Region (GeV)	$Z + \gamma$	$Z +$ jets	Diboson	tt	Data
$m_{ee\gamma} < 300$	306 ± 8	138 ± 38	8.3 ± 0.8	2.4 ± 0.5	455
$m_{ee\gamma} > 300$	25 ± 2	8.1 ± 1.6	0.8 ± 0.2	0.5 ± 0.2	29
$m_{\mu\mu\gamma} < 300$	255 ± 8	89 ± 31	4.9 ± 0.6	0.9 ± 0.3	350
$m_{\mu\mu\gamma} > 300$	14 ± 1	5.4 ± 1.4	0.9 ± 0.3	0.1 ± 0.1	19

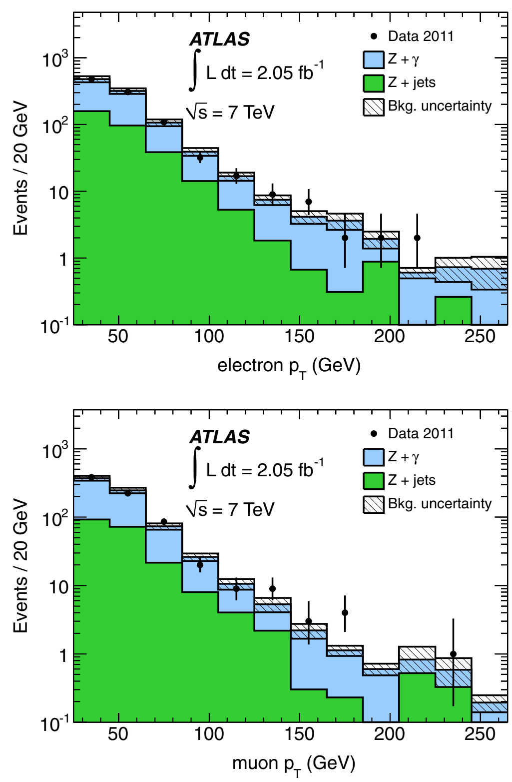

FIG. 1 (color online). Lepton p_{T} distributions for the e^* (top panel) and μ^* (bottom panel) channels. The expected background uncertainties shown correspond to the sum in quadrature of the statistical uncertainties as well as the uncertainty in the $Z +$ jets normalization measured in the control region.

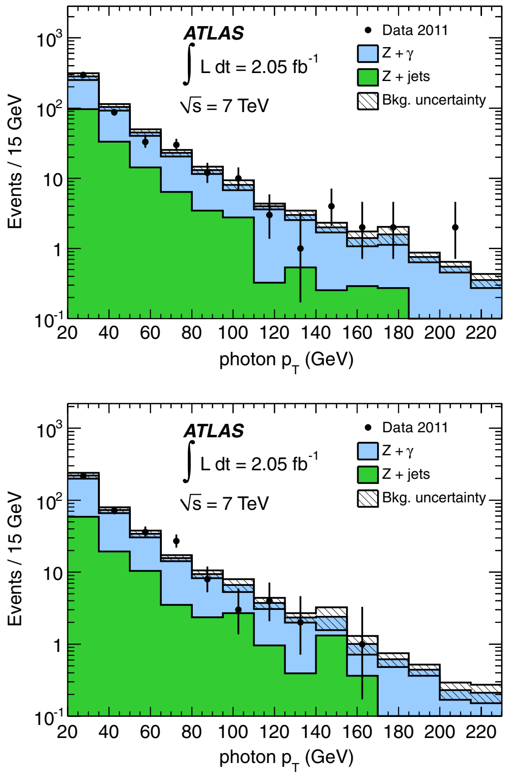

FIG. 2 (color online). Photon p_{T} distributions for the e^* (top panel) and μ^* (bottom panel) channels. The expected background uncertainties shown correspond to the sum in quadrature of the statistical uncertainties as well as the uncertainty in the Z + jets normalization measured in the control region.

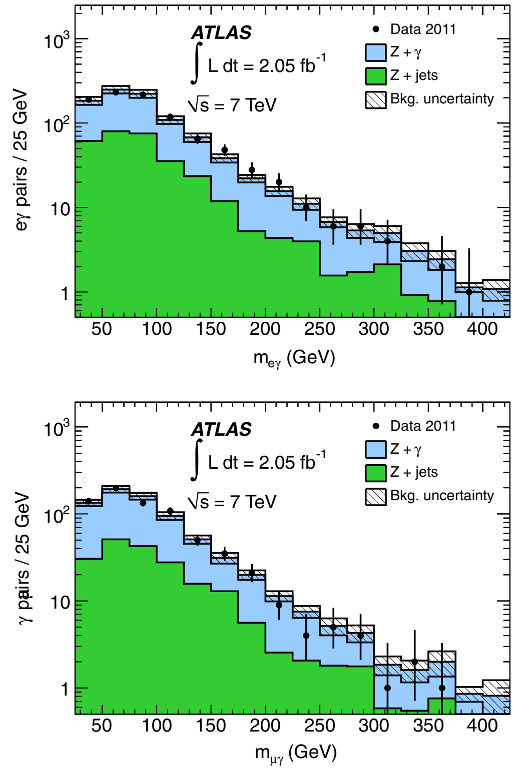

FIG. 3 (color online). Distributions of the invariant mass of the $\ell\gamma$ systems for the e^* (top panel) and μ^* (bottom panel) channels. Combinations with both the leading and subleading leptons are shown. The expected background uncertainties shown correspond to the sum in quadrature of the statistical uncertainties as well as the uncertainty in the Z + jets normalization measured in the control region. For both channels, one event lies outside the mass range shown.

assigned as a systematic uncertainty and dominates the total error in the Z + jets estimates presented in Table I. The corresponding scaling factors applied to the Z + jets simulation are 0.51 ± 0.14 and 0.61 ± 0.21 for the e^* and μ^* channels, respectively, i.e. within uncertainties of one another. Furthermore, the ratio of the number of Z + jets events outside the control region to the number of events inside is found to be the same in the MC simulations as in the data-driven techniques: 0.06 for both the e^* and μ^* channels. This finding indicates that the jet p_{T} misidentification rate as a function of the jet is modeled properly.

Comparisons between data and the resulting background expectations for the p_{T}^{ℓ}, p_{T}^{γ}, $m_{\ell\gamma}$, and $m_{\ell\ell\gamma}$ distributions are shown in Figs. 1–4. No significant discrepancies are observed between data and the simulations. In particular, the background prediction for the photon p_{T} shape matches the data for both the e^* and μ^* searches, which suggests that the tuning of the jet misidentification rate for the Z + jets background is adequate.

VII. SIGNAL REGION OPTIMIZATION

The signal search region is optimized as a function of m_{ℓ^*} using simulated events by determining the lower bound on $m_{\ell\ell\gamma}$ that maximizes the significance defined as

$$S_L = \sqrt{2\ln[(1 + S/B)^{S+B}e^{-S}]},$$

where S and B are the number of signal and background events, respectively. The optimum threshold value is found to be $m_{\ell\ell\gamma} = m_{\ell^*} + 150$ GeV. Additionally, to improve the sensitivity, particularly at low m_{ℓ^*}, background contributions from DY processes are suppressed further by requiring events to satisfy $m_{\ell\ell} > 110$ GeV. The signal efficiency for these two additional requirements is >99% for $m_{\ell^*} \geq 200$ GeV.

Because few events survive the complete set of requirements, the shapes of the $Z + \gamma$ and Z + jets backgrounds are individually fitted using an exponential function $\exp(P_0 + P_1 \times m_{\ell\ell\gamma})$ over the mass range $250\ \mathrm{GeV} < m_{\ell\ell\gamma} < 950$ GeV. The sum of these two fits is then used to obtain the total background prediction for $m_{\ell\ell\gamma} > 350$ GeV. The resulting background estimates and data yields are shown in Table II for the e^* and μ^* searches, as well as in Figs. 5 and 6.

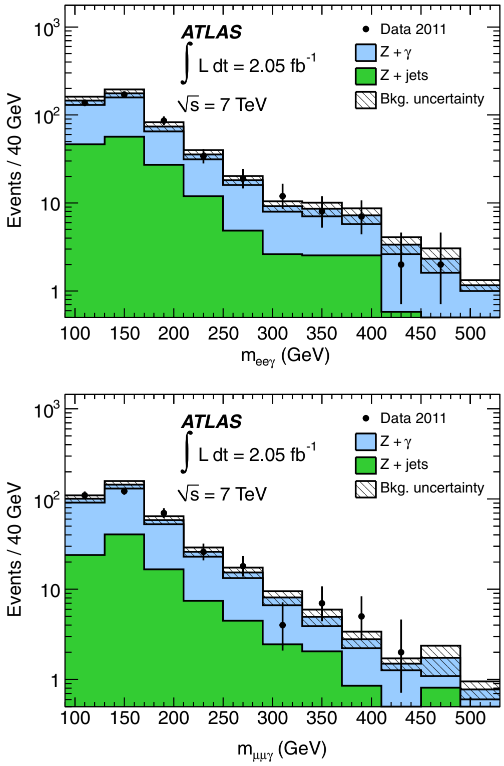

FIG. 4 (color online). Distributions of the invariant mass for the $\ell\ell\gamma$ system for the e^* (top panel) and μ^* (bottom panel) channels. The expected background uncertainties shown correspond to the sum in quadrature of the statistical uncertainties as well as the uncertainty in the $Z+$ jets normalization measured in the control region. For both channels, one event lies outside the mass range shown.

VIII. SYSTEMATIC UNCERTAINTIES

In this section, the dominant systematic uncertainties in the $Z+\gamma$ and $Z+$ jets background predictions are first described, followed by a description of the experimental systematic uncertainties that affect both the background and signal yields, and by a discussion of the theoretical uncertainties which affect both the e^* and μ^*.

The dominant systematic uncertainty in the irreducible $Z+\gamma$ background comes from the fit of its background shape and normalization due to the limited number of events with $m_{\ell\ell} > 110$ GeV. This uncertainty increases with m_{ℓ^*} from about 20% at 200 GeV to 100% for $m_{\ell^*} >$ 800 GeV. The second largest uncertainty in the $Z+\gamma$ background is of theoretical nature and arises from the NLO computations. This uncertainty is obtained by varying the renormalization and factorization scales by factors of 2 around their nominal values and combining with uncertainties arising from the PDFs and values of the strong coupling constant α_s. For $m_{\ell^*} = 200$ GeV ($m_{\ell^*} >$ 800 GeV), the resulting theoretical uncertainty in the number of $Z+\gamma$ background events in our signal region is 7% (10%) for both channels.

The uncertainty in the $Z+$ jets normalization is determined to be 38% (35%) for the e^* (μ^*) channel, which covers the range of values obtained by the different estimates as well as their uncertainties in the $m_{\ell\ell\gamma} < 300$ GeV control region. Uncertainties in the $Z+$ jets prediction from the shape of the fitted distribution are added in quadrature to the normalization uncertainty.

Experimental systematic uncertainties that affect both signal and background yields include the uncertainty from the luminosity measurement of 3.7% [35] and uncertainties in particle reconstruction and identification as described below.

A 3% systematic uncertainty is assigned to the photon efficiency. This value is obtained by comparing the signal efficiency with and without photon shower shape corrections (2%), by studying the impact of material mismodeling in the inner detector (1%), and by determining the reconstruction efficiency for various pileup conditions (1%) [36].

The electron trigger and reconstruction efficiency is evaluated in data and in MC simulations in several $\eta \times \phi$ bins to high precision. Correction factors are applied to the simulations accordingly and have negligible uncertainties. A 1% systematic uncertainty in the electron efficiency at high p_{T} is assigned. This uncertainty is

TABLE II. Data yields and background expectation as a function of a lower bound on $m_{\ell\ell\gamma} = m_{\ell^*} + 150$ GeV. The uncertainties represent the sum in quadrature of the statistical and systematic uncertainties. The probability for the background-only hypothesis (p value) is also provided.

	e^* search				μ^* search			
$m_{\ell\ell\gamma}$ region (TeV)	$Z+\gamma$	Total bkg	Data	p value	$Z+\gamma$	Total bkg	Data	p value
>0.35	10.1 ± 1.9	11.5 ± 2.2	8	0.92	5.2 ± 1.4	6.0 ± 1.6	6	0.40
>0.45	4.6 ± 1.0	5.1 ± 1.2	2	0.83	3.1 ± 0.8	3.4 ± 0.9	3	0.42
>0.55	2.1 ± 0.7	2.3 ± 0.8	1	0.80	1.8 ± 0.6	2.0 ± 0.7	1	0.72
>0.65	0.98 ± 0.47	1.02 ± 0.49	1	0.32	1.09 ± 0.49	1.14 ± 0.51	1	0.72
>0.75	0.45 ± 0.29	0.46 ± 0.30	1	0.16	0.65 ± 0.39	0.67 ± 0.39	1	0.28
>0.85	0.20 ± 0.16	0.21 ± 0.17	1	0.11	0.39 ± 0.29	0.39 ± 0.29	1	0.17
>0.95	0.09 ± 0.09	0.10 ± 0.09	1	0.03	0.23 ± 0.21	0.23 ± 0.21	0	0.78
>1.05	0.05 ± 0.05	0.05 ± 0.05	0	0.81	0.14 ± 0.14	0.14 ± 0.14	0	0.92

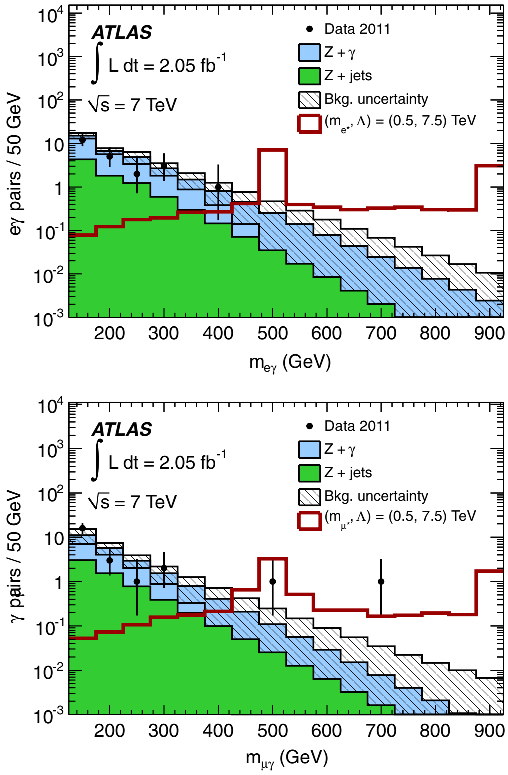

FIG. 5 (color online). Distributions of the invariant mass of the $\ell\gamma$ systems for the e^* (top panel) and μ^* (bottom panel) channels after requiring $m_{\ell\ell} > 110$ GeV. Combinations with both the leading and subleading leptons are shown. The expected background uncertainties shown correspond to the sum in quadrature of the statistical uncertainties as well as the uncertainty in the $Z +$ jets normalization measured in the control region. Note that the last bin contains the sum of all entries with $m_{\ell\gamma} >$ 950 GeV.

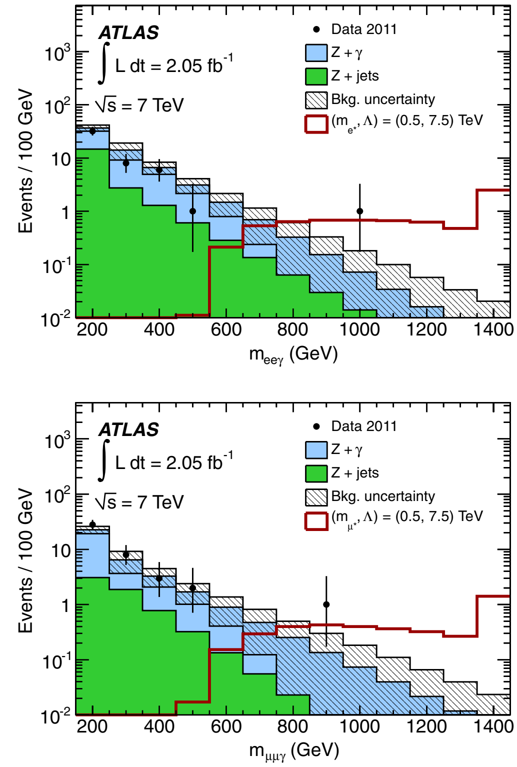

FIG. 6 (color online). Distributions of the invariant mass for the $\ell\ell\gamma$ system for the e^* (top panel) and μ^* (bottom panel) searches after requiring $m_{\ell\ell} > 110$ GeV. The $Z +$ jets and $Z + \gamma$ backgrounds were fitted, and the total uncertainties from the fit as well as the uncertainty in the $Z +$ jets normalization measured in the control region are displayed as the shaded area. Note that the last bin contains the sum of all events with $m_{\ell\ell\gamma} > 1450$ GeV.

estimated by studying the electron efficiency as a function of the calorimeter isolation criteria.

The calorimeter energy resolution is dominated at high $p_{\rm T}$ by a constant term which is 1.1% in the barrel and 1.8% in the endcaps. The simulation is adjusted to reproduce this resolution at high energy, and the uncertainty in this correction has a negligible effect on $p_{\rm T}^{\rm e}$ and $p_{\rm T}^{\gamma}$. The calorimeter energy scale is corrected by studying $J/\psi \to ee$ and $Z \to ee$ events. Calibration constants are obtained for several η regions and deviate at most by 1.5% of unity, and have small uncertainties. Thus, uncertainties on the calorimeter energy scale and resolution result in negligible uncertainties in the background and signal yields.

The combined uncertainty in yields arising from the trigger and reconstruction efficiency for muons is estimated to increase linearly as a function of $p_{\rm T}^{\mu}$ to about 1.5% at 1 TeV. This uncertainty is dominated by a conservative estimate of the impact of large energy loss from muon bremsstrahlung in the calorimeter, which can affect reconstruction in the muon spectrometer. The uncertainty from the resolution due to residual misalignments in the muon spectrometer propagates to a change in the number of events passing the $m_{\mu\mu\gamma}$ cut and affects the sensitivity of the search. The muon momentum scale is calibrated with a statistical precision of 0.1% using the $Z \to \mu\mu$ mass peak. Thus, uncertainties on the muon momentum scale and resolution result in negligible uncertainties in the background and signal yields.

An additional 1% systematic uncertainty is assigned to the e^* and μ^* signal efficiencies to account for the fact that the dependence on Λ is neglected in this analysis. This uncertainty is obtained by studying the signal $A \times \epsilon$ for various excited lepton masses and compositeness scales. Theoretical uncertainties from renormalization and factorization scales and PDFs have a negligible impact on the signal efficiency and are not included in the results presented below.

IX. RESULTS

A summary of the data yields and background expectations as a function of a lower bound on $m_{\ell\ell\gamma}$ is shown in Table II for the e^* and μ^* searches. The uncertainties displayed correspond to the sum in quadrature of the statistical and systematic uncertainties. The significance for an excited lepton signal is estimated by means of a p value, the probability of observing an outcome at least as signal-like as the one observed in data, assuming that a signal is absent. The lowest p values obtained are 3% in the e^* channel (for $m_{ee\gamma} > 950$ GeV) and 17% in the μ^* channel (for $m_{\mu\mu\gamma} > 850$ GeV), which indicates that the data are consistent with the background hypothesis.

Given the absence of a signal, an upper limit on the ℓ^* cross section times branching ratio σB is determined at the 95% C.L. using a Bayesian approach [37] with a flat, positive prior on σB. Systematic uncertainties are incorporated in the limit calculation as nuisance parameters. The limits are translated into bounds on the compositeness scale as a function of the mass of the excited leptons by comparing them with theoretical predictions of σB for various values of Λ.

The expected exclusion limits are determined using simulated pseudoexperiments (PE) containing only SM processes, by evaluating the 95% C.L. upper limits for each PE for each fixed value of m_{ℓ^*}. The median of the distribution of limits represents the expected limit. The ensemble of limits is used to find the 1σ and 2σ envelopes of the expected limits as a function of m_{ℓ^*}.

Figure 7 shows the 95% C.L. expected and observed limits on $\sigma B(\ell^* \to \ell\gamma)$ for the e^* and μ^* searches. For $m_{\ell^*} > 0.9$ TeV, the observed and expected limits on σB are 2.3 fb and 4.5 fb for the e^* and μ^*, respectively. The green and yellow bands show the expected 1σ and 2σ contours of the expected limits. When the expected number of background events is zero, there is an effective quantization of the expected limits obtained from the PE, and no downward fluctuation of the background is possible. These effects explain the behavior of the 1σ and 2σ contours of the expected limits for large ℓ^* masses. Theoretical predictions of σB for three different values of Λ are also displayed in Fig. 7, as well as the theoretical uncertainties from renormalization and factorization scales and PDFs for $\Lambda = 2$ TeV. These uncertainties are shown for illustrative

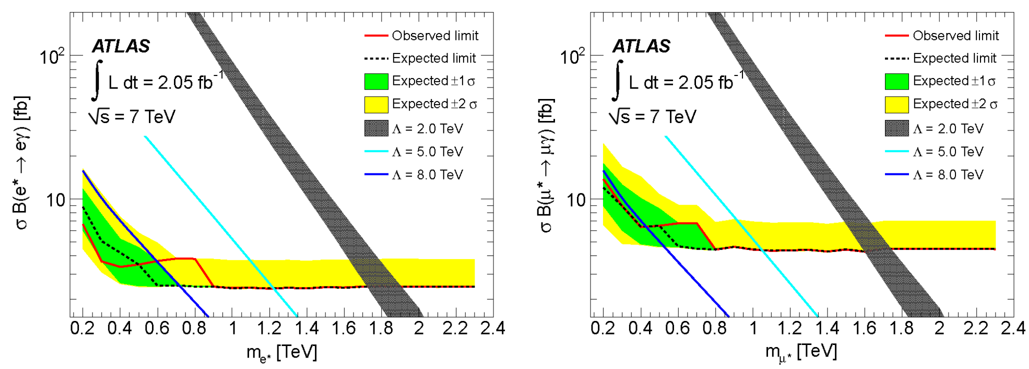

FIG. 7 (color online). Limits at 95% C.L. on the cross section times branching ratio as a function of e^* and of μ^* mass. Theoretical predictions for excited leptons produced for three different compositeness scales are shown, as well as the theoretical uncertainties from renormalization and factorization scales and PDFs for $\Lambda = 2$ TeV. For $m_{\ell^*} > 0.9$ TeV, the observed limit on σB is 2.3 fb (4.5 fb) for e^* (μ^*).

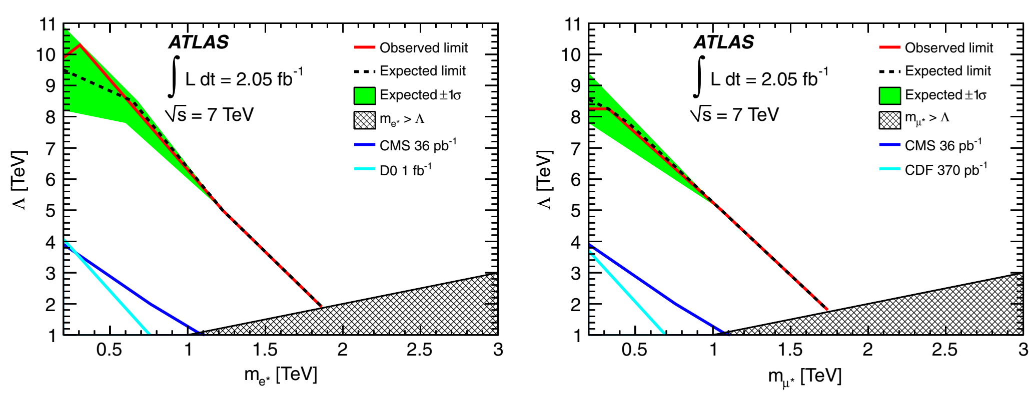

FIG. 8 (color online). Exclusion limits in the $m_{\ell^*} - \Lambda$ parameter space for e^* and μ^*. Regions to the left of the experimental limits are excluded at 95% C.L. No limits are set for the hashed region, as the approximations made in the effective contact interaction model do not hold for $m_{\ell^*} > \Lambda$. The best limits from the Tevatron experiments as well as from the CMS experiment based on 36 pb^{-1} are also shown.

purposes only and are not included in determining mass limits. The mass limits obtained for various Λ values are used to produce exclusion limits on the $m_{\ell^*} - \Lambda$ plane as shown in Fig. 8. In the special case where $\Lambda = m_{\ell^*}$, masses below 1.87 TeV and 1.75 TeV are excluded for excited electrons and muons, respectively.

X. CONCLUSIONS

The results of a search for excited electrons and muons with the ATLAS detector are reported, using a sample of $\sqrt{s} = 7$ TeV pp collisions corresponding to an integrated luminosity of 2.05 fb^{-1}. The observed invariant mass spectra are consistent with SM background expectations. Limits are set on the cross section times branching ratio $\sigma B(\ell^* \rightarrow \ell\gamma)$ at 95% C.L. For $m_{\ell^*} > 0.9$ TeV, the observed upper limits on σB are 2.3 fb and 4.5 fb for the e^* and μ^* channels, respectively. The limits are translated into bounds on the compositeness scale Λ as a function of the mass of the excited leptons. In the special case where $\Lambda = m_{\ell^*}$, masses below 1.87 TeV and 1.75 TeV are excluded for e^* and μ^*, respectively. These limits are the most stringent bounds to date on excited leptons for the parameter-space region with $m_{\ell^*} \geq 200$ GeV.

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