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Search for excited leptons in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

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Abstract

A search for compositeness of electrons and muons is presented using a data sample of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$ collected with the CMS detector at the LHC and corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$. Excited leptons (ℓ^*) produced via contact interactions in conjunction with a standard model lepton are considered, and a search is made for their gauge decay modes. The decays considered are $\ell^* \to \ell\gamma$ and $\ell^* \to \ell\text{Z}$, which give final states of two leptons and a photon or, depending on the Z-boson decay mode, four leptons or two leptons and two jets. The number of events observed in data is consistent with the standard model prediction. Exclusion limits are set on the excited lepton mass, and the compositeness scale Λ. For the case $M_{\ell^*} = \Lambda$ the existence of excited electrons (muons) is excluded up to masses of 2.45 (2.47) TeV at 95% confidence level. Neutral current decays of excited leptons are considered for the first time, and limits are extended to include the possibility that the weight factors f and f', which determine the couplings between standard model leptons and excited leptons via gauge mediated interactions, have opposite sign.

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*See Appendix B for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics describes the observed phenomena very successfully, however it provides no explanation for the three generations of the fermion families. Attempts to explain the observed hierarchy have led to a class of models postulating that quarks and leptons may 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 Λ. Compositeness models predict the existence of excited states of quarks (q^*) and leptons (ℓ^*) at the characteristic scale of the new binding interaction. Since these excited fermions couple to the ordinary SM fermions, they could be produced via contact interactions (CI) in collider experiments, with subsequent decay to ordinary fermions through the emission of a $W/Z/\gamma$ boson, or via CI to other fermions.

Searches at LEP [10–13], HERA [14], and the Tevatron [15–18] have found no evidence for excited leptons. At the Large Hadron Collider (LHC) at CERN, previous searches performed by the CMS [19] and the ATLAS collaborations [20] have also found no evidence of excited leptons, obtaining a lower limit on the mass $M_{\ell^*} < 2.2\,\text{TeV}$ for the case $M_{\ell^*} = \Lambda$.

In this paper, a search for excited leptons (e^* and μ^*) is presented, using a data sample of pp collisions at a center-of-mass energy $\sqrt{s} = 8\,\text{TeV}$ collected with the CMS detector at the LHC in 2012 and corresponding to an integrated luminosity of $19.7 \pm 0.5\,\text{fb}^{-1}$ [21]. We consider the production of an excited lepton in association with an oppositely charged lepton of the same flavor, with subsequent radiative decays ($\ell\ell^* \to \ell\ell\gamma$) or neutral current decays ($\ell\ell Z$).

2 Theory and model assumptions

The composite nature of quarks and leptons, if it exists, will manifest itself, above a characteristic energy scale Λ, as a spectrum of excited states. Such excited fermions, f^*, may couple to SM leptons and quarks via a four-fermion CI that can be described by the effective Lagrangian

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

where Λ is the energy scale of the substructure, assumed to be equal to or larger than the excited fermion mass. The quantities $g_*^2 = 4\pi$, and j_μ, defined in Ref. [7], involve only left-handed currents by convention. In addition to the coupling via CI, excited fermions can also interact with SM fermions via gauge interactions. For excited leptons, the corresponding Lagrangian for the gauge-mediated (GM) interaction is given by

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

where $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field-strength tensors of the SU(2) and U(1) gauge fields, and $g = e/\sin\theta_W$. The quantity, $g' = e/\cos\theta_W$ represents the electroweak gauge coupling with the Weinberg angle θ_W, and Y and τ are the generators of the U(1) and SU(2) groups, respectively. The quantities f_R and f_L are the right and left-handed components of the lepton or excited lepton. The weight factors f and f' define the couplings between SM leptons and excited leptons via gauge interactions [7]. The compositeness scales contained in $\mathcal{L}_{\text{CI}}$ and $\mathcal{L}_{\text{GM}}$ are assumed to be the same.

The excited lepton, ℓ^*, can decay to a SM lepton via a CI $\ell^* \to \ell f\bar{f}$, where f is a fermion, or through the mediation of a gauge boson via a gauge interaction. The following gauge-interaction-mediated decays are possible: radiative decay $\ell^* \to \ell\gamma$, charged-current decay $\ell^* \to \ell' W$, and neutral-current decay $\ell^* \to \ell Z$. All four transitions, the CI and the three gauge interactions, are possible if $f = f'$, while $f = -f'$ forbids decays via photon emission. Since the exact relationship between the weight factors is unknown, the results are interpreted for two extreme values: $f = f' = 1$ and $f = -f' = 1$.

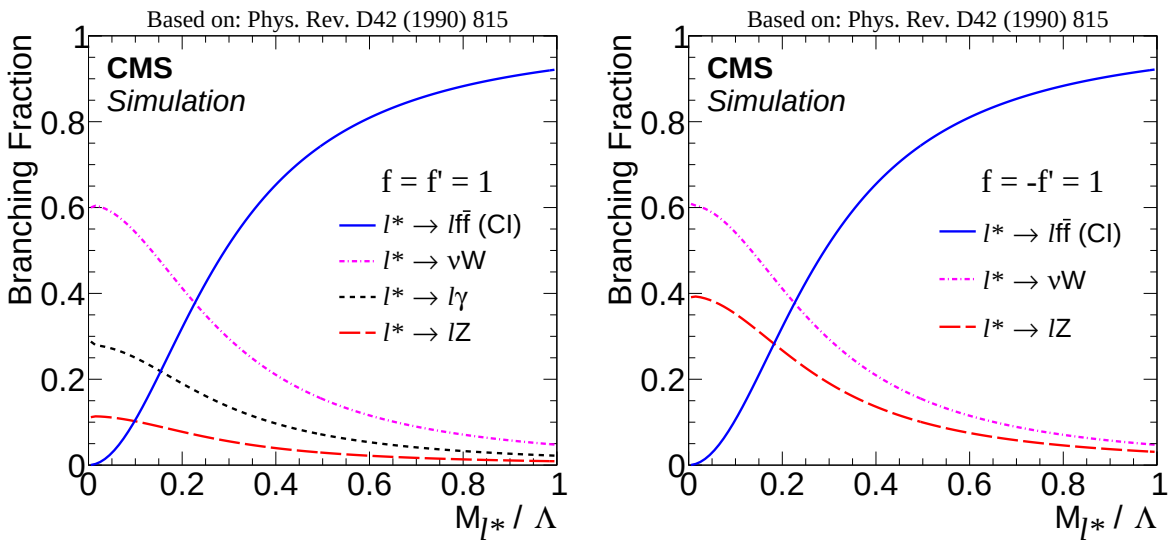

Figure 1: Branching fractions for the decay of excited leptons, as a function of the ratio M_{ℓ^*}/Λ of their mass to their compositeness scale, for the coupling weight factors $f = f' = 1$ (left) and $f = -f' = 1$ (right).

In the present analysis we search for the production of excited electrons and muons, e^* and μ^*, through a CI, which is dominant at the LHC for the model considered here. Excited leptons can also be produced via gauge interactions, but those processes involve electroweak couplings and contribute less than 1% to the cross section at the LHC; they have therefore been neglected here. For light ℓ^*, the decay of excited leptons via gauge interactions is dominant, while the decay via a CI becomes dominant at high masses, as shown in Fig. 1. The decay via a CI is not considered in the simulated samples used here.

The search channels considered in this analysis are summarized in Table 1. The $\ell\ell^* \to \ell\ell\gamma$ final state is represented by the Feynman diagram in Fig. 2 left. A second class of searches seeks decays via the emission of a Z boson (Fig. 2 right), with the Z boson decaying to either a pair of electrons, a pair of muons, or a pair of jets. This decay mode allows the phase space where $f = -f'$, unexplored by previous LHC searches, to be investigated. The transverse momentum (p_T) of the Z boson coming from the decay of the excited lepton is larger for heavier excited-lepton masses, and at high p_T the final-state particles are highly collimated. This characteristic is exploited in the $\ell\ell^* \to \ell\ell Z \to 2\ell 2j$ decay mode, in which jet substructure techniques are used to reconstruct a "fat jet" corresponding to the Z boson, and in the leptonic channels where the lepton isolation is modified.

Signal samples for both e^* and μ^* are produced using PYTHIA8.153 [22, 23], which uses the leading order (LO) compositeness model described in Ref. [7]. Thirteen ℓ^* mass points from 200 to 2600 GeV have been simulated for all channels except the $\ell\ell jj$ channels, which starts at 600 GeV

Table 1: Final states for excited lepton searches considered in this analysis, where $\ell = \mathrm{e}, \mu$. The notation for a specific channel is provided in the right most column. For neutral currents, the last two characters in this notation refer to particles from the decay of the Z boson.

Decay mode	Search channel	Notation
Radiative decay	$\mathrm{ee}^* \to \mathrm{ee}\gamma$	$\mathrm{ee}\gamma$
$\ell\ell^* \to \ell\ell\gamma$	$\mu\mu^* \to \mu\mu\gamma$	$\mu\mu\gamma$
	$\mathrm{ee}^* \to \mathrm{eeZ} \to 4\mathrm{e}$	4e
	$\mathrm{ee}^* \to \mathrm{eeZ} \to 2\mathrm{e}2\mu$	$2\mathrm{e}2\mu$
Neutral current	$\mathrm{ee}^* \to \mathrm{eeZ} \to 2\mathrm{e}2\mathrm{j}$	2e2j
$\ell\ell^* \to \ell\ell\mathrm{Z}$	$\mu\mu^* \to \mu\mu\mathrm{Z} \to 4\mu$	4μ
	$\mu\mu^* \to \mu\mu\mathrm{Z} \to 2\mu2\mathrm{e}$	$2\mu2\mathrm{e}$
	$\mu\mu^* \to \mu\mu\mathrm{Z} \to 2\mu2\mathrm{j}$	$2\mu2\mathrm{j}$

because of the analysis thresholds. Masses below 200 GeV are excluded by previous searches at 95% confidence level. All simulated events have been passed through the detailed simulation of the CMS detector based on GEANT4 [24] and have been re-weighted so that the distribution of pileup events (contributions from additional pp interactions in the same bunch crossing) matches that measured in data. The signal cross sections are calculated with PYTHIA8, and are corrected using the branching fraction to the 3-body decays via CI as predicted in Ref. [7], as this decay mode is not implemented in PYTHIA. The factorization and renormalization scales are set to the mass square of the excited lepton ($M^2_{\ell^*}$), Λ is set to 10 TeV, and the CTEQ6L1 [25] parametrization for the parton distribution functions (PDF) is used. This particular choice of the value of Λ has no impact on the resulting kinematic distributions. Only the width of the ℓ^* resonance and the ℓ^* production cross section depend on Λ. As long as the width of the ℓ^* is small compared to the mass resolution of the detector, the signal efficiency is independent of Λ. Mass-dependent next-to-leading order (NLO) k-factors ranging from 1.2 to 1.35 [26] are applied on the signal event yields. Production cross sections for the signals, as well as those of the different decay modes including the corresponding branching fractions are given in Table 2.

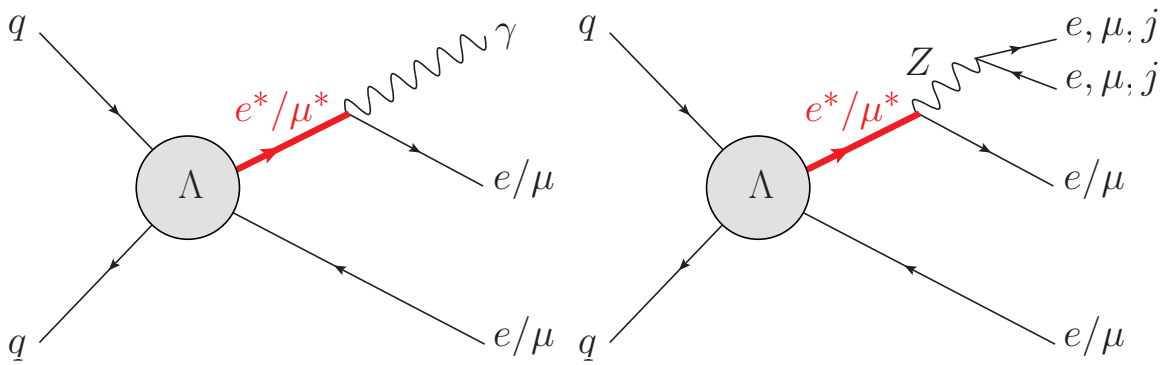

Figure 2: Illustrative diagrams for $\ell\ell^* \to \ell\ell\gamma$ (left) and $\ell\ell$Z (right), where $\ell = \mathrm{e}, \mu$. Decays of the Z boson to a pair of electrons, muons or jets are considered.

Table 2: Excited lepton production cross section, and product of cross section and branching fraction for each of the three processes investigated, as a function of the mass of the excited lepton. The values of the k-factors are taken from Ref. [26]. The case $f = -f' = 1$ does not apply to the $\ell\ell^* \to \ell\ell\gamma$ channel.

Production cross sections for excited leptons

M_{ℓ^*} (GeV)	σ (pb)			NLO k-factor
	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV	
200	1.3×10^5	0.84	2.2×10^{-2}	1.30
1000	25.1	9.8×10^{-2}	2.5×10^{-3}	1.27
1800	0.28	1.1×10^{-2}	2.9×10^{-4}	1.28
2600	6.3×10^{-3}	1.1×10^{-3}	2.9×10^{-5}	1.35

$\sigma_{\mathrm{NLO}} \times$ B ($\ell\ell^* \to \ell\ell\gamma$) (pb)

M_{ℓ^*} (GeV)	$f = f' = 1$			$f = -f' = 1$		
	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV
200	3.9×10^3	0.36	9.4×10^{-3}	—	—	—
1000	0.70	2.0×10^{-2}	8.0×10^{-4}	—	—	—
1800	7.7×10^{-3}	1.2×10^{-3}	7.5×10^{-5}	—	—	—
2600	1.9×10^{-4}	7.1×10^{-5}	6.0×10^{-6}	—	—	—

$\sigma_{\mathrm{NLO}} \times$ B ($\ell\ell^* \to \ell\ell Z \to 2\ell 2j$) (pb)

M_{ℓ^*} (GeV)	$f = f' = 1$			$f = -f' = 1$		
	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV
200	772	7.2×10^{-2}	1.9×10^{-3}	2.7×10^3	0.28	7.3×10^{-3}
1000	0.20	5.7×10^{-3}	2.3×10^{-4}	0.68	2.0×10^{-2}	7.8×10^{-4}
1800	2.2×10^{-3}	6.8×10^{-4}	2.1×10^{-5}	7.5×10^{-3}	1.2×10^{-3}	7.4×10^{-5}
2600	5.3×10^{-5}	2.0×10^{-5}	1.7×10^{-6}	1.8×10^{-4}	7.0×10^{-5}	5.9×10^{-6}

$\sigma_{\mathrm{NLO}} \times$ B($\ell\ell^* \to \ell\ell Z \to 2\ell 2\ell'$ ($\ell' = e, \mu$)) (pb)

M_{ℓ^*} (GeV)	$f = f' = 1$			$f = -f' = 1$		
	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = 10$ TeV
200	73.5	6.8×10^{-3}	1.8×10^{-4}	256	2.6×10^{-2}	6.9×10^{-4}
1000	1.9×10^{-2}	5.4×10^{-4}	2.1×10^{-5}	6.5×10^{-2}	1.8×10^{-3}	7.4×10^{-5}
1800	2.1×10^{-4}	3.4×10^{-5}	2.0×10^{-6}	7.2×10^{-4}	1.1×10^{-4}	7.0×10^{-6}
2600	5.0×10^{-6}	1.9×10^{-6}	1.6×10^{-7}	1.7×10^{-5}	6.6×10^{-6}	5.7×10^{-7}

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) [27] coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about 1.3% up to $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [28]. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the ECAL and HCAL calorimeters alone are used. The electron momentum is determined by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \to ee$ decays ranges from 1.7% for non-showering electrons in the barrel region to 4.5% for showering electrons in the endcaps [29]. Muons are identified in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [30]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [27].

4 Event selections

4.1 Triggers

The selected trigger for each channel is summarized in Table 3. For all channels, except those with a $2e2\mu$ final state, dilepton triggers are exploited: the double electron trigger is used for events with electrons in the final state, while muon events are selected by the dimuon trigger. Both triggers have identical p_T thresholds, of 17 (8) GeV for the leading (subleading) lepton.

The two cross channels with 2e and 2μ in the final state exploit a muon–photon trigger with a p_T threshold of 22 GeV for both objects, where the photon trigger selects either electrons (as needed for this analysis) or photons, since the tracking information is not used at trigger level. The muon–photon trigger is chosen because the isolation requirements of the muon–electron trigger lead to an inefficiency when the two electrons from the Z boson decay are close together. The trigger efficiencies are close to one in all cases because of the large number of possible trigger objects. The offline p_T thresholds are set to 35 GeV for both electrons and muons, except for the 4-lepton channels, which require 25 GeV for each lepton.

Table 3: Trigger requirement, offline p_T and η-selection criteria, and event signature for all final state channels of the ℓ^* production and decay.

Channel	Trigger	Offline p_T	Offline $\lvert\eta\rvert$	Signature and object ID
eeγ	Dielectron with 17(8) GeV	$E_T^{e1} > 35$ GeV, $E_T^{e2} > 35$ GeV, $E_T^{\gamma} > 35$ GeV	$\lvert\eta_e\rvert < 1.44$, $1.56 < \lvert\eta_e\rvert < 2.5$, $\lvert\eta_\gamma\rvert < 1.44$	Two isolated high E_T electrons and one isolated high E_T photon
$\mu\mu\gamma$	Dimuon with 17(8) GeV	$p_T^{\mu 1} > 35$ GeV, $p_T^{\mu 2} > 35$ GeV, $E_T^{\gamma} > 35$ GeV	$\lvert\eta_\mu\rvert < 2.1$, $\lvert\eta_\gamma\rvert < 1.44$	Two isolated high p_T muons and one isolated high E_T photon
2e2j	Dielectron with 17(8) GeV	$E_T^{e1} > 35$ GeV, $E_T^{e2} > 35$ GeV, $E_T^{j} > 200$ GeV	$\lvert\eta_e\rvert < 1.44$, $1.56 < \lvert\eta_e\rvert < 2.5$, $\lvert\eta_j\rvert < 2.4$	Two isolated high E_T electrons and two jets that are merged from boosted Z boson decays
2μ2j	Dimuon with 17(8) GeV	$p_T^{\mu 1} > 35$ GeV, $p_T^{\mu 1} > 35$ GeV, $E_T^{j} > 200$ GeV	$\lvert\eta_\mu\rvert < 2.4$, $\lvert\eta_j\rvert < 2.4$	Two isolated high p_T muons and two jets that are merged from boosted Z boson decays
4e	Dielectron with 17(8) GeV	$E_T^{e} > 25$ GeV for all four electrons	$\lvert\eta_e\rvert < 1.44$, $1.56 < \lvert\eta_e\rvert < 2.5$	Two isolated high E_T electrons and two nearby high E_T electrons from boosted Z boson decay, using modified isolation for Z boson decay electrons
2e2μ	Muon-Photon with 22 GeV each	$p_T > 25$ GeV for all four leptons	$\lvert\eta_e\rvert < 1.44$, $1.56 < \lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$	Two isolated high E_T electrons and two nearby high p_T muons from boosted Z boson decay, using modified ID for one Z boson decay muon and modified isolation for both Z boson decay muons
2μ2e	Muon-Photon with 22 GeV each	$p_T > 25$ GeV for all four leptons	$\lvert\eta_e\rvert < 1.44$, $1.56 < \lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$	Two isolated high p_T muons and two nearby high E_T electrons from boosted Z boson decay, using modified isolation for both Z boson decay muons
4μ	Dimuon with 17(8) GeV	$p_T^{\mu} > 25$ GeV for all four muons	$\lvert\eta_\mu\rvert < 2.4$	Two isolated high p_T muons plus two nearby high p_T muons from boosted Z boson decay, using modified ID for one and modified isolation for both muons from Z boson decay

4.2 Object reconstruction and selection

4.2.1 Electrons

Electron candidates are identified as clusters of energy deposited in the ECAL, associated with tracks measured with the silicon tracker [29]. These candidates must be within the barrel or endcap fiducial regions with $|\eta| < 1.44$ or $1.56 < |\eta| < 2.50$, respectively and have a $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ ($25\,\mathrm{GeV}$ in the 4ℓ-searches). A set of identification requirements that are optimized for electrons with high transverse momenta [31], based on the profile of the energy deposition in the ECAL and the matching between the track and the cluster, are imposed to remove jets misidentified as electrons. The p_{T} sum of all other tracks (excluding the electron footprint) in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ (where ϕ is the azimutal angle in radians) around the track of the electron candidate must be less than $5\,\mathrm{GeV}$, a selection denoted as "tracker isolation". In computing the tracker isolation for electrons, tracks have to originate from within a distance $|d_{\mathrm{z}}| < 0.2\,\mathrm{cm}$ from the primary vertex. This requirement reduces the impact of pileup interactions vetoing candidate events. The sum of the transverse energy (E_{T}) of calorimeter energy deposits in the same cone, referred to as "calorimeter isolation", must be less than 3% of the candidate's transverse energy. The calorimeter isolation energy is corrected for pileup by the subtraction of the average energy per unit area of (η, ϕ), computed event by event using the FASTJET package [32].

For the two electrons from the Z boson decay (in the $\mathrm{ee}^* \to \mathrm{eeZ} \to 4\mathrm{e}$ and $\mu\mu^* \to \mu\mu\mathrm{Z} \to 2\mu 2\mathrm{e}$ channels), the tracker isolation and calorimeter isolation for each electron are modified to remove the contribution of the other electron [33].

4.2.2 Muons

The muon candidates have to pass identification (ID) criteria that are optimized for the reconstruction of muons with high transverse momenta [30, 31]. In the "global muon" reconstruction, muons are reconstructed within $|\eta| < 2.4$ by combining tracks from the inner tracker and the outer muon system. The following requirements are imposed: at least one hit in the pixel tracker; hits in more than five tracker layers; and the detection of the muon in at least two muon stations. Since the stations are separated by thick layers of iron, the latter requirement significantly reduces the probability of a hadron being misidentified as a muon. The relative uncertainty in the muon p_{T} measurement must not exceed 30%. In order to reduce the cosmic ray muon background, the transverse impact parameter of the muon track with respect to the primary vertex of the event is required to be less than $0.2\,\mathrm{cm}$. The primary vertex is chosen as the one with the highest Σp_{T}^2 of all charged tracks associated with that vertex. Furthermore, the muon is required to be isolated by demanding that the scalar sum of the transverse momenta of all tracks, excluding the muon itself, within a cone of $\Delta R < 0.3$ around its own track, be less than 5% of its p_{T}.

In the $\mathrm{ee}^* \to \mathrm{eeZ} \to 2\mathrm{e}2\mu$ and $\mu\mu^* \to \mu\mu\mathrm{Z} \to 4\mu$ channels, one oppositely charged muon pair comes from the decay of the boosted Z boson. The muons can be close enough that one muon is inside the isolation cone of the other. Therefore, for these muons, the isolation calculation is modified by removing the contribution of the other muon. After these modifications, the reconstruction and identification efficiency of nearby muons are found to be comparable to those of separated muons [33]. These two variations are referred to as "modified identification" and "relaxed isolation".

4.2.3 Photons

For photons, identification criteria from Ref. [28] are applied to clusters in the ECAL that include requirements on the shower shapes, isolation variables, and H/E (ratio of deposits in the HCAL and ECAL in a cone around the photon direction). A photon candidate is required to have a cluster with $E_{\mathrm{T}} > 35\,\mathrm{GeV}$ and to be in the barrel region of the ECAL, with $|\eta| < 1.44$. The photon is also required to be isolated within a cone of radius $\Delta R < 0.3$ both in the tracker and the calorimeter. The cone axis is taken to be the direction of the line joining the barycenter of the ECAL clusters to the primary vertex. The isolation criteria depend on the η of the photon, and distinguish between contributions from neutral and charged hadrons and electromagnetic particles. As with the electron isolation calculation, the sums do not include contributions from particles clearly associated with pileup vertices, and are adjusted for the estimated residual pileup.

4.2.4 Jets and $\mathrm{Z} \to \mathrm{jj}$ tagging

Hadronic jets are reconstructed from the list of particle flow (PF) candidates that are obtained with the PF algorithm [34], which reconstructs and identifies single particles by combining information from all sub-detectors. Charged PF constituents not associated to the primary vertex are not used in the jet clustering procedure. Good PF candidates are clustered into jets using the Cambridge-Aachen (CA) algorithm [35] with a distance parameter $R = 0.8$. An area-based correction is applied, to take into account the extra energy clustered in jets from neutral particles in pileup interactions, using the FASTJET software package [32]. Jet energy corrections are derived from the simulation, and are validated with in-situ measurements using the energy balance of dijet, photon+jet, and Z+jets events [36]. Additional quality criteria are applied to the jets in order to remove spurious jet-like features originating from isolated noise patterns from the calorimeters or the tracker. These jet quality requirements are found to be 99% efficient for signal events. The jets are required to have $p_{\mathrm{T}} > 200\,\mathrm{GeV}$ and $|\eta| < 2.4$. Jets must also be separated from any well-identified lepton (passing selections of Sections 4.2.2 and 4.2.1) by a cone of radius $\Delta R > 0.8$.

In the $2\ell 2\mathrm{j}$ channels, the search is optimized for high-mass excited leptons that produce a boosted, hadronically decaying Z boson. When such a highly boosted Z decays to two quarks, their separation is often so small that they are reconstructed as a single jet with a mass larger than that of a typical Quantum ChromoDynamics (QCD) jet. To achieve the best possible mass resolution for this single jet, a *jet pruning* algorithm [37, 38] is applied, which is also used by the CMS collaboration for several other physics analyses with hadronic decays of boosted W and Z bosons [33, 39–42]. This pruning procedure involves reclustering the constituents of the original jet and applying additional requirements to eliminate soft QCD radiation and large-angle QCD radiation coming from sources other than the Z boson. The kinematic distributions of the resultant jet are a closer reflection of the hard process. In particular, the pruned jet mass is closer to the mass of the parent Z boson.

In addition, to further discriminate against jets from gluon and single-quark hadronization, a quantity called N-subjettiness is used [43–45]. Before the pruning procedure is applied, the jet constituents are re-clustered with the k_{T} algorithm [46, 47], until N joint objects, called "subjets", remain in the iterative combination procedure of the k_{T} algorithm. The N-subjettiness, τ_N, is then defined as:

$$\tau_N = \frac{1}{\sum_k p_{\mathrm{T},k} R_0} \sum_k p_{\mathrm{T},k} \min(\Delta R_{1,k}, \Delta R_{2,k} ... \Delta R_{N,k}), \tag{3}$$

where the index k runs over the jet constituents and the distances $\Delta R_{n,k}$ are calculated with respect to the axis of the nth subjet. The quantity R_0 is set equal to the jet radius of the original jet. The τ_N variable measures the capability of clustering the reconstructed particles in the jet in exactly N-subjets: if it has a small value then it represents a configuration that is more compatible with the N-subjettiness hypothesis. In particular, the variable that is best able to discriminate between the jets from a boosted Z boson decay and standard QCD jets is the ratio of 2- to 1-subjettiness, $\tau_{21} = \tau_2/\tau_1$. If the jet has $\tau_{21} < 0.5$ and if its pruned mass falls in the range between 70–110 GeV, the jet is tagged as originating from a Z boson, and is referred to as a "fat jet" in this paper.

The mismodeling of the τ_{21} variable can bias the signal efficiency estimated from the simulated samples. A discrepancy between data and simulation has been observed in the identification efficiency measured in events containing merged jets produced by boosted W-bosons from top decays that pass the same V-tag selections as the ones in this $\ell\ell$jj analysis [33]. Correction factors obtained from this sample are found to be 0.9 ± 0.1. These corrections are applied to the signal efficiencies obtained from simulation.

4.3 Signal selection

In addition to the trigger and object identification requirements, signal-candidate events are selected and SM backgrounds suppressed, sequentially as follows:

1. Selection of final state objects (see Section 4.3.1) and reconstruction of the boosted Z boson in those channels containing a Z boson.
2. Rejection of backgrounds with Z bosons (see Section 4.3.2) with an invariant mass requirement.
3. Rejection of other backgrounds using a dedicated search window (see Section 7.1) that uses two calculations of M_{ℓ^*}.

4.3.1 Preselection

As a first step, the final state objects are selected in the various search channels.

- $\ell\ell^* \to \ell\ell\gamma$: Selection of two same flavor isolated leptons and one isolated high E_{T} photon within the acceptance and p_{T} thresholds given in Table 3. In the case of $\mu\mu\gamma$, muon pairs that are back-to-back are rejected by removing those with an angle above $\pi - 0.02$ to avoid contributions from cosmic ray muons. Additionally, the muons are required to have opposite charges. Selected photons must be separated from the leptons by $\Delta R > 0.7$ to reduce the contribution from final state radiation.
- $\ell\ell^* \to \ell\ell\mathrm{Z} \to 2\ell 2\mathrm{j}$: Selection of two isolated same flavor leptons and one fat jet (as defined in Section 4.2.4) satisfying the acceptance and p_{T} thresholds given in Table 3. If more than one fat jet is found, the one with the highest p_{T} is used. In the channel with muons, the muons are required to have opposite charges.
- $\ell\ell^* \to \ell\ell\mathrm{Z} \to 4\ell$: Selection of exactly four isolated leptons (four electrons, four muons or two electrons and two muons) within the acceptance and p_{T} thresholds given in Table 3. First, the relaxed ID (for muons) and isolation are used for all leptons. Next, the boosted Z boson is reconstructed. In the 2μ2e (2e2μ) channel, the electron (muon) pair defines the reconstructed Z boson. In the 4e and 4μ channels, the same flavor lepton pair with its invariant mass closest to the Z pole mass is

chosen. As a final step, the requirements on the leptons are tightened. In channels with the boosted Z boson decaying to muons, an additional charge requirement is applied to both muons, and one of the muons originating from the Z boson decay is allowed to fulfill the relaxed ID only; all other leptons need to pass the full ID.

The invariant mass of the two leptons (in the 4ℓ channels, of the two leptons that are not used to reconstruct the Z boson) is denoted as $M_{\ell\ell}$ in what follows. This di-lepton mass is used to reduce backgrounds that include Z bosons not associated with the decay of putative heavy leptons.

4.3.2 Invariant mass requirement

The invariant mass $M_{\ell\ell}$ is required to be above 106 GeV in the $\ell\ell\gamma$ and 4ℓ channels, and above 200 GeV for the 2ℓ2j channels, to reduce backgrounds containing Z bosons. This cut efficiently removes contributions from Zγ (ZZ) to the $\ell\ell\gamma$ and the 2ℓ2j backgrounds. For the eeγ channel, there is an additional Z-veto on the two possible electron-photon invariant masses to remove electron pairs coming from a Z decay, where one electron is misidentified as a photon. Events are removed where any of the electron-photon invariant masses is within $\pm$25 GeV of the nominal Z boson mass.

5 Modeling of the background

5.1 Sources of background

Several SM processes contribute to the expected background for the various channels. Those contributions are discussed in the following.

- $\ell\ell^* \to \ell\ell\gamma$ channels: Drell-Yan (DY) production is the most important background for the $\ell\ell^* \to \ell\ell\gamma$ channels, mostly originating from production of a photon in association with a Z, which has a very similar signature to the signal. It is simulated using SHERPA1.4 [48] and its production cross section is normalized using a NLO cross section calculated with the Monte Carlo (MC) program MCFM6.1&6.6 [49, 50].

  Subleading contributions to the background arise from diboson events with an additional high energy photon or events in which an electron is misidentified as a photon. Such events are simulated using PYTHIA6.4 [23]. Background contributions also arise from events in which an additional prompt photon is produced together with a top pair ($t\bar{t}$+γ). These events are simulated with MADGRAPH5.1 [51] using a LO cross section. All these irreducible backgrounds arising from two prompt leptons and a prompt photon are estimated using MC simulation. Smaller contributions due to events with two genuine leptons and a jet which has been misidentified as a photon are estimated from data (see Section 5.2). For the eeγ channel, jets faking electrons may contribute, although at a negligible level (see Section 5.2.2 for details). The contribution of muons faked by jets is negligible.
- $\ell\ell^* \to \ell\ell$Z $\to 2\ell$2j channels: The production of a Z boson (decaying to leptons) plus additional jets is the dominant background followed by the production of two top quarks and diboson events. These contributions have been estimated from data, using simulation to validate the exclusion methodology (see Section 5.2.3). All background contributions from simulation ($t\bar{t}$, diboson and DY+jets) are simulated using MADGRAPH with NLO cross sections that were calculated using MCFM.
- $\ell\ell^* \to \ell\ell$Z $\to 4\ell$ channels: The production of ZZ (including Zγ^*), with both bosons

decaying leptonically, is the main background to the four-lepton channel and contributes about 90% of the total background expected. An additional smaller contribution arises from the production of three vector bosons where some of the leptons escape detection. The production of two top quarks, $t\bar{t}$, with or without an additional vector boson, can contribute to each channel. The background due to Higgs boson production is negligible in the phase space considered here. In the four lepton channels, all the backgrounds have been estimated using predictions from simulations. The $ZZ \to 4\ell$ background is described with GG2ZZ [52] for production via gluon fusion and in the case of $q\bar{q}$ annihilation at NLO with POWHEG1.0 [53–56]. Processes involving $t\bar{t}$+X (X = W, Z, γ) and triple boson samples are simulated with MADGRAPH. It has been checked that the simulation describes correctly a sample of 4-lepton events selected as in Section 4.3, but relaxing the Z-vetoes to increase the number of events.

Table 4 summarizes the simulated background samples with the corresponding NLO cross sections, and the channels where these samples are used. PYTHIA has been used to perform the fragmentation and hadronization of samples generated with MADGRAPH. All simulated events have been passed through the detailed simulation of the CMS detector based on GEANT4 [24]. The pileup simulation has been re-weighted so that the distribution of pileup events matches that measured in data. Correction factors are also applied to allow for differences between the simulated and measured reconstruction efficiencies of the physics objects.

5.2 Data-driven backgrounds

5.2.1 Misidentification of electrons

Backgrounds with zero or one real electron can contribute to the $ee\gamma$ candidate sample. The largest contributions come from processes such as $W(\to e\nu)$+jet+γ where the jet in the event is misidentified as an electron. Misidentification can occur when photons coming from π^0 or η mesons inside a jet convert to an e^+e^- pair. Other possible sources include processes with a charged particle within a jet providing a track in the tracker and an electromagnetic cluster that together fake an electron signature, or a track from a charged particle that matches 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 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 the shower shape $\sigma_{\eta\eta}$ and the ratio H/E are satisfied.

This ratio H/E is estimated as a function of E_T in bins of η ($f^{\text{misid}}_{\text{electron}}(E_T, \eta)$) using a data sample selected with single-photon triggers [31].

In order to estimate the contribution of misidentified electrons to the selected events, the misidentification rate is applied to a subsample of data events containing one electron passing good electron criteria and a second one passing a loose set of criteria. This loose set of criteria includes cuts on shower shape and the ratio H/E, but allows one of the electron selection criteria to be missed. The events are required to satisfy all other selection criteria of the analysis.

The systematic uncertainty in $f^{\text{misid}}_{\text{electron}}(E_T, \eta)$ is determined using a sample of events containing two reconstructed electrons as in [31]. The contribution from jet events to the inclusive 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

Table 4: Background samples with the corresponding generator and cross sections used for the various channels. Specific generator selections are shown where important for the interpretation of the quoted cross sections.

Process	Selection	Generator	NLO cross section (pb)	Channel
Z+jets $\to \ell\ell$+jets	$p_{\mathrm{T}}^{\mathrm{Z}} = 70$–$100\,\mathrm{GeV}$	MADGRAPH	5.30×10^4	$2\ell 2$j
Z+jets $\to \ell\ell$+jets	$p_{\mathrm{T}}^{\mathrm{Z}} > 100\,\mathrm{GeV}$	MADGRAPH	3.92×10^4	$2\ell 2$j
W+jets $\to \ell\nu$+jets	—	MADGRAPH	3.63×10^4	$2\ell 2$j
$\mathrm{Z}\gamma \to \ell\ell\gamma$	$\Delta R(\gamma, \ell) > 0.6$	SHERPA	14.9	$\ell\ell\gamma$
$\mathrm{t\bar{t}}$+jets	—	MADGRAPH	23.9	$2\ell 2$j
$\mathrm{t\bar{t}}\gamma$	$E_{\mathrm{T}}(\gamma) > 10\,\mathrm{GeV}$	MADGRAPH	1.44(LO)	$\ell\ell\gamma$
$\mathrm{t\bar{t}Z}$	—	MADGRAPH	0.208	4ℓ
$\mathrm{t\bar{t}W}$	—	MADGRAPH	0.232	4ℓ
$\mathrm{WW} \to 2\ell 2\nu$	—	MADGRAPH	6.03	$2\ell 2$j
WW	—	PYTHIA6	54.8	$\ell\ell\gamma$
$\mathrm{WZ} \to 2\ell 2\mathrm{q}$	—	MADGRAPH	2.32	$2\ell 2$j, 4ℓ
$\mathrm{WZ} \to 3\ell\nu$	—	MADGRAPH	1.00	$2\ell 2$j, 4ℓ
WZ	—	PYTHIA6	33.2	$\ell\ell\gamma$
$\mathrm{ZZ} \to 2\ell 2\mathrm{q}$	—	MADGRAPH	2.47	$2\ell 2$j, 4ℓ
$\mathrm{ZZ} \to 2\ell 2\nu$	—	MADGRAPH	0.71	$2\ell 2$j
$\mathrm{ZZ} \to 4\ell$	—	MADGRAPH	0.177	$2\ell 2$j
ZZ inclusive	—	PYTHIA6	17.7	$\ell\ell\gamma$
$\mathrm{ZZ} \to 4\ell$	—	POWHEG	0.077	4ℓ
$\mathrm{ZZ} \to 2\ell 2\ell'$	—	POWHEG	0.176	4ℓ
$\mathrm{gg} \to \mathrm{ZZ} \to 4\ell$	—	GG2ZZ	0.005	4ℓ
$\mathrm{gg} \to \mathrm{ZZ} \to 2\ell 2\ell'$	—	GG2ZZ	0.012	4ℓ
WWZ	—	MADGRAPH	0.063	4ℓ
WZZ	—	MADGRAPH	0.020	4ℓ
ZZZ	—	MADGRAPH	0.005	4ℓ

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 with DY events. These effects are corrected for using simulated samples. The observed difference of 30% between the two estimates is taken as the systematic uncertainty in the jet-to-electron misidentification rate.

5.2.2 Misidentification of photons

Hadronic jets in which a π^0 or η meson carries a significant fraction of the energy may be misidentified as isolated photons. Thus Z+jet(s) events are a potential background for the $\ell\ell\gamma$ search. The photon misidentification rate is measured directly from data using a data set collected using a single photon trigger. To avoid trigger biases, the events must contain at least one reconstructed super-cluster (energy deposit in the ECAL) besides the one that fired the trigger. In addition, the ratio of hadronic energy to the energy of that super-cluster is required to be less than 5%. The misidentification rate is defined as the ratio of the number of photon candidates that pass all the photon selection criteria (numerator) to the ones that pass a loose set of shower shape requirements but fail one of the photon isolation criteria (denominator). The numerator sample can have a contribution from isolated true photons. The contamination is estimated using the distribution of energy-weighted shower width computed in units of crystal lateral dimension. The shower shape for isolated true photons is obtained from a simulated sample. The shape of non-isolated photons is obtained from data by considering a background dominated region (side-band region) of the photon isolation variable. The true photon fraction in the numerator is estimated by fitting these two different shower shapes (signal and background templates) to the shower shape distribution of the numerator sample. The photon misidentification rate is calculated in photon E_{T} bins. It decreases with increasing photon E_{T} and is at most of the order of a few percent.

In order to estimate the contribution of misidentified photons to the selected events, the misidentification rate is applied to a subsample of data events that satisfy all selection criteria listed in Section 4.3 except that the photon candidate must pass a looser set of shower shape requirements and fail one of the photon isolation criteria.

There are two main sources of uncertainties in the determination of jet to photon misidentification rate. First, the shower shape of non-isolated photons is obtained from data in the side band region: changing the side band region results in some change in the template for non-isolated photons. Second, the probability for a jet to fake a photon is different for quark and gluon jets and the fraction of jets due to quarks may not be the same in the sample used to obtain the fake rate and in the sample where this fake rate is applied. Considering these two sources of uncertainties, a conservative systematic uncertainty of 50% is assigned, independently of the photon E_{T}.

5.2.3 Data-driven background in $2\ell 2$j

The backgrounds due to DY+jets, $\mathrm{t\bar{t}}$ and di-boson production are estimated using the "ABCD" method, which relies on two variables to separate the signal from the background. The two-dimensional plane of these two variables is divided in four disjoint rectangular regions A, B, C, and D, so that the region A is the signal region, while B, C, and D are the control regions, dominated by backgrounds. If the ratio of the backgrounds in regions A and B is the same as that for C and D (which holds if the two variables are independent), i.e.: $N_{\mathrm{A}}/N_{\mathrm{B}} = N_{\mathrm{C}}/N_{\mathrm{D}}$, then the background in the signal region A, N_{A} can be estimated as:

$$N_{\mathrm{A}} = N_{\mathrm{C}} \frac{N_{\mathrm{B}}}{N_{\mathrm{D}}}, \tag{4}$$

where N_{A}, N_{B}, N_{C}, and N_{D} are the background events in regions A, B, C, and D, respectively. The variables exploited in this analysis are the dilepton invariant mass $M_{\ell\ell}$ and N-subjettiness τ_{21}. The region A is defined by the selection cut given in Sections 4.2.4 and 4.3. The regions B, C and D correspond to a similar selection but with reversed requirements on $M_{\ell\ell}$ and/or on the subjettiness ratio τ_{21} of the selected highest p_{T} fat jet. These four regions are indicated in Fig. 3 (upper-left) along with the borders of the regions (shown as solid lines) corresponding to the invariant mass $M_{\ell\ell}$ being either above (for signal) or below (for background) 200 GeV and τ_{21} being either above (background) or below (signal) 0.5.

For the 2μ2j final state, Fig. 3 shows the invariant mass of the pair of isolated muons as a function of the N-subjettiness ratio, τ_{21}, of the fat jet but without selection on τ_{21}. The background events displayed are from simulated samples of DY+jets, $\mathrm{t\bar{t}}$+jets, and diboson production, while the signal events are from a sample simulated at $M_{\ell^*} = 1.2$ TeV. In the signal region A, about 20 background events are expected, with ∼50% originating from DY+jets and ∼40% due to $\mathrm{t\bar{t}}$+jets.

Several tests were performed using simulated samples to verify that the ABCD method using these variables reliably predicts the background yield. The relation given in Equation 4 is expected to be independent of the choice of boundaries for the control regions. This assumption has been tested by applying the ABCD method to simulated samples of DY+jets, tt+jets and di-boson events. Moving the boundaries of regions B, C and D changed the calculated number of events in region A (whose definition is kept fixed) only slightly, as shown in Table 5.

Table 5: Events estimated in the region A by applying the ABCD method to simulated samples of DY+jets, $\mathrm{t\bar{t}}$+jets, and di-boson events, as well as to data: each time with a different set of defining boundaries for regions B, C and D. The true number of events in region A is 19.2 ± 1.3 and 15.0 ± 1.1 for the muon and electron channel, respectively.

Thresholds ($M_{\ell\ell}$, τ_{21})	From simulation estimated N_A	From data estimated N_A
muon channel		
(200, 0.50)	19.3 ± 1.4	20.9 ± 5.6
(180, 0.52)	19.8 ± 1.6	23.9 ± 6.4
(160, 0.54)	20.2 ± 1.8	20.4 ± 6.4
electron channel		
(200, 0.50)	16.6 ± 1.3	22.1 ± 5.9
(180, 0.52)	16.3 ± 1.3	24.2 ± 6.8
(160, 0.54)	16.6 ± 1.5	23.9 ± 7.2

6 Systematic uncertainties

Three types of systematic uncertainties are considered:

- **Overall uncertainties in the simulation:** These include the uncertainty in the luminosity [21], the simulation of pileup and uncertainties in the cross sections used.

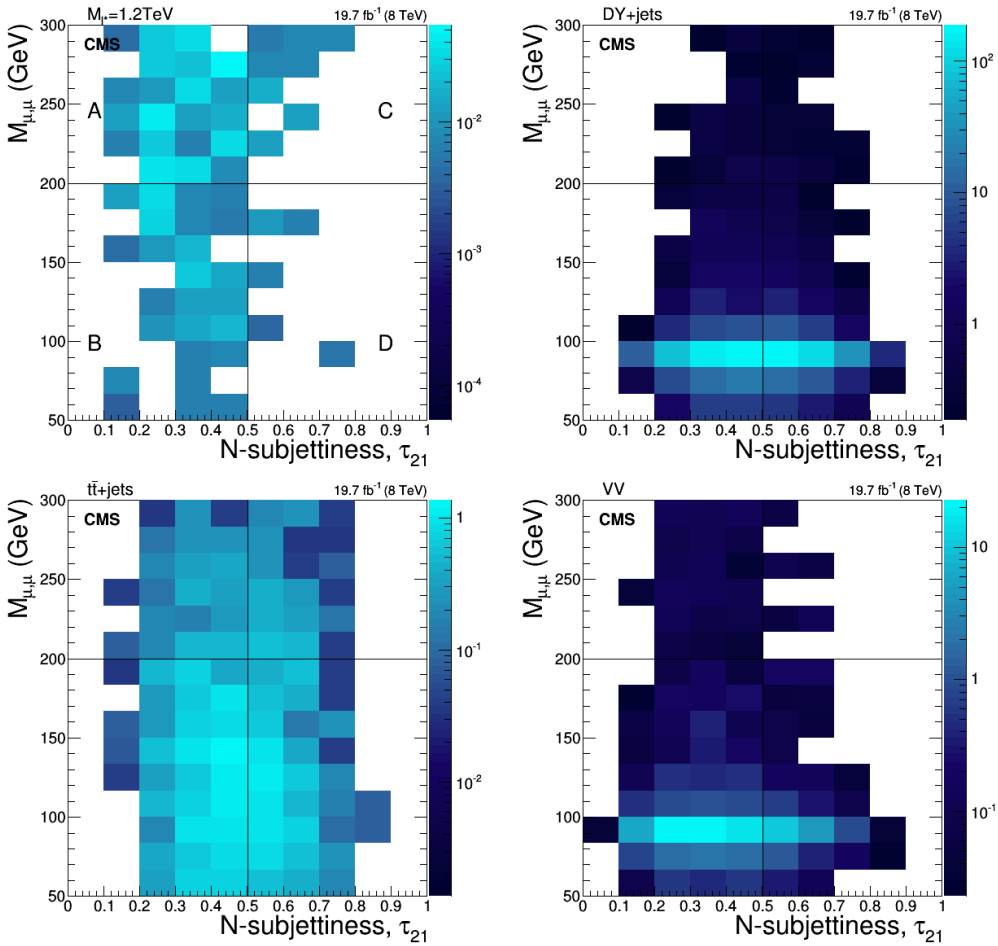

Figure 3: Invariant mass of the pair of isolated muons vs. the N-subjettiness ratio, τ_{21}, of the selected fat jet, for events passing the selection criteria given in Section 4.3, but with the cuts on $M_{\ell\ell}$ and τ_{21} relaxed for signal with $M_{\ell^*} = 1.2\,\text{TeV}$ (top left), Drell-Yan+jets (top right), $\text{t}\bar{\text{t}}$+jets (bottom left) and diboson events (bottom right). The right hand scale corresponds to a weighted number of events.

These uncertainties affect the normalization and are treated similarly for all background- and signal simulations.

- **Object simulation uncertainties:** These depend on the final state of the respective analysis and are applied to the simulation of signal and background events. They consist, for example, of uncertainties in the energy or momentum scale and resolution of the various particles, or in correction factors that were applied to account for differences between the simulated and the actual performance of the detector.
- **Uncertainties in background estimations from data:** These uncertainties are applied to background components that were estimated from data and are only relevant to the $\ell\ell^* \to \ell\ell\gamma$ and $\ell\ell^* \to \ell\ell\text{Z} \to 2\ell 2\text{j}$ channels.

The sources of these systematic uncertainties are discussed in Section 6.1 and their implications for signal and background in Section 6.2.

6.1 Object-specific simulation uncertainties

Electron uncertainties

For electrons, uncertainties exist for the electron energy scale and electron identification efficiency. In both the barrel and the endcap, the scale uncertainties are determined by shifting the transverse energy of the electrons by 1%. [31]. Systematic uncertainteis due to electron identification are 2% and 4% [31] for very high energy electrons in barrel and endcap, respectively.

Muon uncertainties

There are three sources of uncertainties for muons: uncertainties in the muon momentum scale; the muon momentum resolution; and the efficiency of the muon selection. As described in Ref. [30] the uncertainty in the muon momentum scale is estimated from the effect of changing the p_{T} of each muon by $5\% \times p_{\mathrm{T}}/\,\mathrm{TeV}$. For the momentum resolution, the uncertainty is estimated by smearing the p_{T} of the muon by 0.6%. The uncertainty in the selection efficiency is 0.5% for the identification criteria, and 0.2% for the isolation criterion for each muon.

Photon uncertainties

The energy scale and resolution uncertainties for photons are very small compared to those of the other objects. The energy scale uncertainties are determined by shifting the transverse energies of the photons by 0.6% in the barrel section of the calorimeter[29].

Jet-energy scale

Jet-energy corrections are applied to account for the response function of the combined calorimeter system and other instrumental effects, based on in situ measurements using dijet, Z+jet, and photon+jet data samples [36]. Uncertainties due to these corrections are evaluated by shifting the jet energies by the calibration uncertainties ($\pm 1\sigma$). The effect on signal yield was found to be less than 1%.

6.2 Implications of uncertainties on signal and background yield

The above sources of uncertainties are specifically associated with the simulation of the various objects. To quantify each uncertainty on the signal and background, the relevant quantity is varied by $\pm 1\sigma$, relative to the best estimate. Subsequently all kinematic selections are reapplied and the impact on the analysis is determined by calculating the difference of the result from that of the original parametrization.

For all channels, the impact of pileup uncertainties was estimated by shifting the mean number of additional interactions and the inelastic cross section by 5%. The uncertainty in the signal yield cross section is taken to be 10%, following Ref. [26].

In the case of the four lepton final states, the dominant uncertainty in the background is the uncertainty in the cross section of the ZZ background, which is conservatively assumed to be 15% ([57]). Additional uncertainties with a large impact on the background yield are the electron energy scale (with impact on background yield of 12%), the electron selection efficiency (6%), and the uncertainty in the electron resolution (2.5%). The mixed channels suffer large effects from the electron energy scale (8%), electron efficiencies (5%), and muon efficiencies (3%). In the four muon channel, the second largest uncertainty is associated with the muon selection efficiency (4%) followed by that on the muon momentum scale (1.6%). In this channel the uncertainties in the signal yield are completely dominated by the corresponding cross section uncertainty.

In the $\ell\ell^* \to \ell\ell\gamma$ channel, the dominant systematic uncertainty in the background is the uncertainty in the production cross section arising from the parametrization of the parton distribution functions in the main background ($Z\gamma$), which was determined to be 10% by changing the choice of PDF set in the simulation according to Ref. [58, 59]. Although the uncertainty in the data-derived background was determined to be 50%, its impact is rather small (4%), as the total contribution of this background is rather small. The impact of the photon energy scale and resolution are negligible. One of the dominant systematic uncertainties for the signal in the $\mu\mu^* \to \mu\mu\gamma$ channel is that in the muon momentum scale [30], which rises with increasing p_{T}. As a result, the impact on the final event yield is rather small in case of the background, containing muons of moderate momenta, but reaches more than 5% in the high-mass signal samples.

In the $\ell\ell^* \to \ell\ell\mathrm{Z} \to 2\ell2\mathrm{j}$ channel, the dominant systematic uncertainty in the background is that associated with the background estimation method, mainly the signal contamination in control regions B, C and D of the ABCD matrix. This depends on the M_{ℓ^*} parameter; the lowest mass point represents the worst-case scenario where such contamination is maximal, and the highest mass point is the best-case scenario. The effect of the signal leakage in the control regions was estimated for various mass points between $M_{\ell^*} = 0.6$ and 2.6 TeV, and found to be of the order of 30% in the worst cases. It should be noted that the signal leakage here does not include the contributions from the CI-mediated decays of the excited lepton, they are rather considered as part of the background that is automatically estimated through the data-based background estimation method. Another source of systematic uncertainties arises from the Z tagging, since there is a discrepancy between the Z tagging efficiency in data and simulation, as discussed in Section 4.2.4. Based on the correction factors measured, a 10% uncertainty is assigned the estimated signal efficiency.

7 Final selection and results

Table 6 summarizes the event yield for all channels after applying the selections for the leptons, photon or Z boson, and the invariant mass cuts given in Section 4.3. Data agree with the SM expectation and no evidence for new physics is seen.

In the photon channels the main background ($Z\gamma$) contributes almost 90% of the total. The remaining contributions are $t\bar{t}\gamma$ ($\lesssim$7%) and jet/ photon misidentification (estimated from data to be $\lesssim$3%), and are rather small in comparison. Similarly in the four lepton channels, about 90% of the backgound arises from ZZ. The jet channels have mixed composition. The main background (Z+Jets) contributes about 50%. The second largest contribution ($t\bar{t}$) contributes 40% of the expected background. The description of the background is based on the data driven approach described above, but the composition is estimated using simulation, since this information cannot be obtained from the data.

Table 6: Expected background events, measured data events and expected signal yields for various channels before the L-shape optimization. Quoted uncertainties are the quadratic sum of statistical and systematic errors. The signal yields are presented for different values of Λ, for the cases $f = f' = 1$ and $f = -f' = 1$. No signal is expected in $\ell\ell^* \to \ell\ell\gamma$ for $f = -f' = 1$.

Channel	N_{bg}	N_{data}	N_{signal} $M_{\ell^*} = 0.6$ TeV $f{=}f'{=}1$ ($f{=}{-}f'{=}1$)		N_{signal} $M_{\ell^*} = 2$ TeV $f{=}f'{=}1$ ($f{=}{-}f'{=}1$)	
			$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV	$\Lambda = M_{\ell^*}$	$\Lambda = 4$ TeV
eeγ	70.4 ± 7.9	62	1.1×10^5 (0)	5.7×10^2 (0)	25 (0)	5.1 (0)
2e2j	22.1 ± 6.0	25	1.3×10^4 (4.6×10^4)	69 (2.4×10^2)	4.7 (16)	1.0 (3.3)
4e	3.0 ± 0.6	0	1.4×10^3 (5.0×10^3)	7.5 (26)	0.3 (1.1)	0.1 (0.2)
2e2μ	2.9 ± 0.5	4	1.8×10^3 (6.2×10^3)	9.3 (32)	0.4 (1.5)	0.1 (0.3)
$\mu\mu\gamma$	119 ± 15	150	1.2×10^5 (0)	6.4×10^2 (0)	26 (0)	5.4 (0)
2μ2j	20.9 ± 5.6	25	1.6×10^4 (5.6×10^4)	85 (2.9×10^2)	5.9 (20)	1.2 (4.1)
2μ2e	2.5 ± 0.4	2	1.7×10^3 (6.0×10^3)	9.0 (31)	0.4 (1.3)	0.1 (0.3)
4μ	4.0 ± 0.6	4	2.3×10^3 (7.9×10^3)	12.1 (42)	0.5 (1.8)	0.1 (0.4)

7.1 L-shape search window

After reconstruction of the intermediate boson (photon or Z-boson), two leptons remain to reconstruct the excited lepton, either as $\ell\gamma$ or ℓZ. Thus, both possible lepton+boson invariant masses are calculated, referred to in the following as M^X_{min} and M^X_{max} where X is the channel

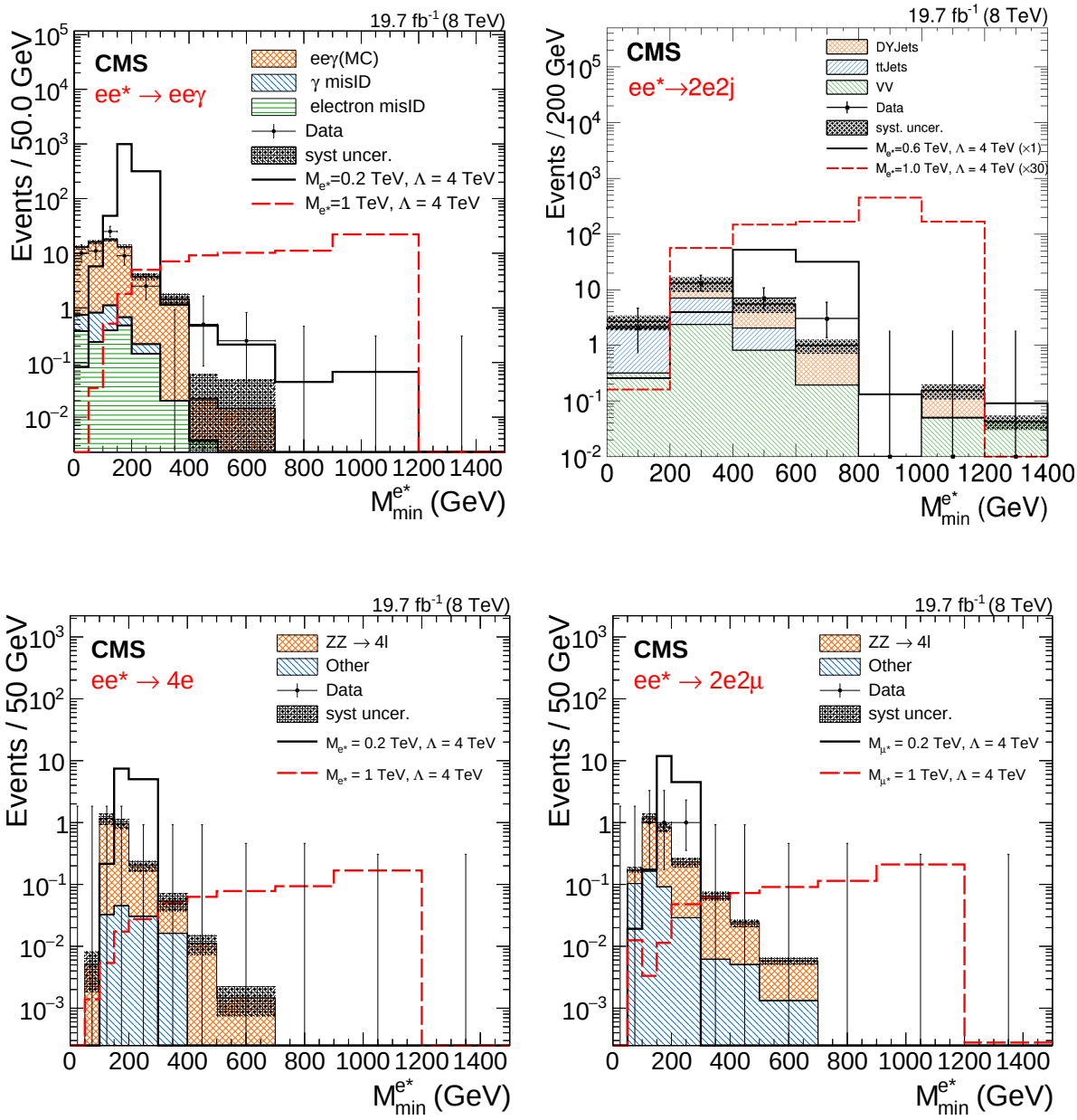

Figure 4: Reconstructed minimum invariant mass from the vector boson (γ, Z) plus one electron for the four excited electron channels. Top left: eeγ, top right: 2e2j, bottom left: 4e, bottom right: 2e2μ. Two signal distributions are shown for M_{ℓ^*} = 0.2 and 1 TeV, except the 2e2j channel where the trigger threshold only allows searches for $M_{\ell^*} > 0.5$ TeV. The asymmetric error bars indicate the central confidence intervals for Poisson-distributed data and are obtained from the Neyman construction as described in Ref. [60].

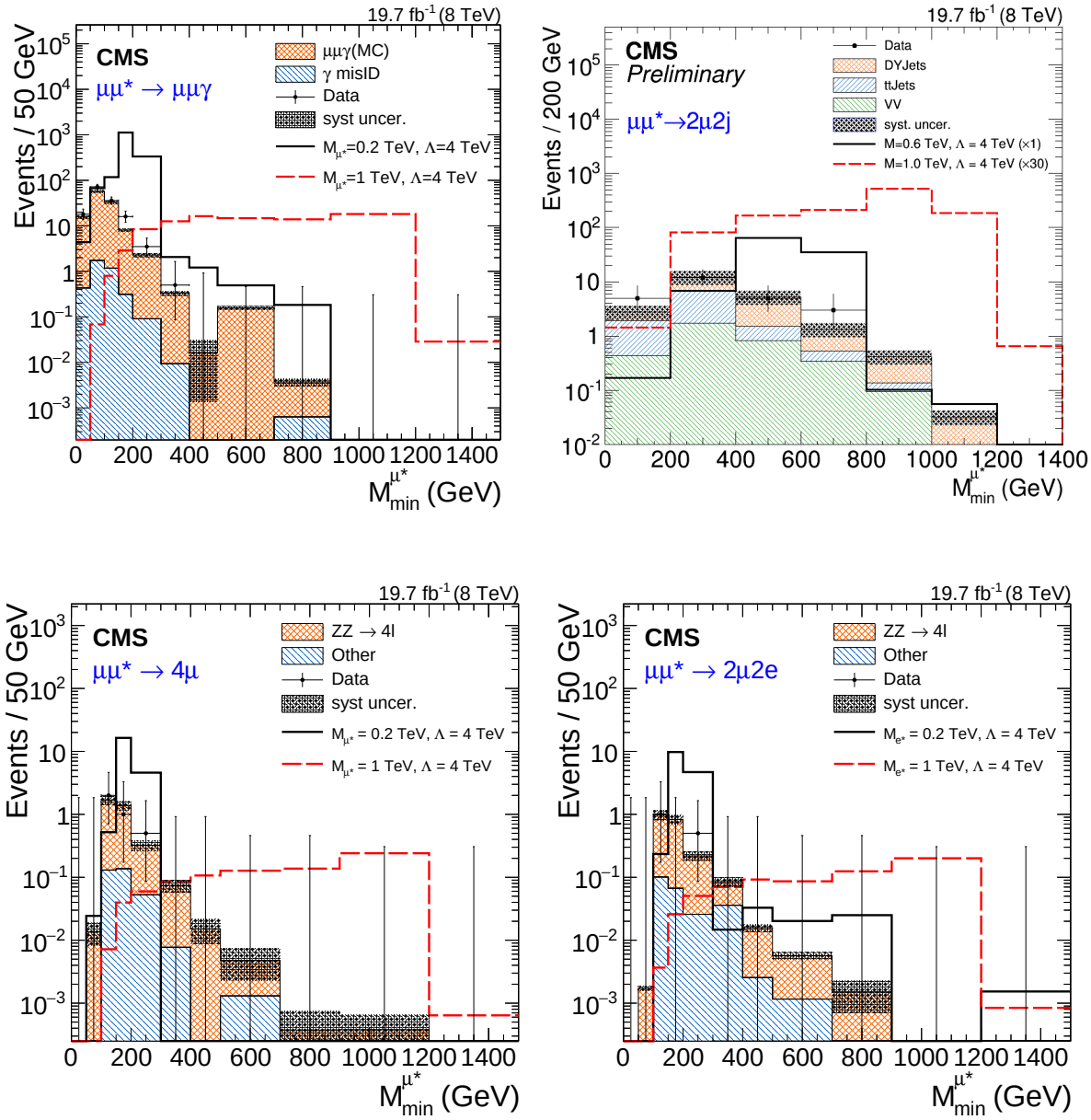

Figure 5: Reconstructed minimum invariant mass from the vector boson (γ, Z) plus one muon for the four excited muon channels. Top left: $\mu\mu\gamma$, top right: 2μ2j, bottom left: 4μ, bottom right: 2μ2e. Two signal distributions are shown for $M_{\ell*} = 0.2$ and 1 TeV, except the 2μ2j channel where the trigger threshold only allows searches for $M_{\ell*} > 0.5$ TeV. The asymmetric error bars indicate the central confidence intervals for Poisson-distributed data and are obtained from the Neyman construction as described in Ref. [60].

considered, e* or μ^*. Figures 4 and 5 show M^X_{min} for all excited electron and muon channels with the background and systematic uncertainties described previously.

An illustrative plot of M^X_{min} versus M^X_{max} is given in Fig. 6. While the expected background tends to be at low invariant masses, a potential signal has the form of an inverted "L" around the excited lepton mass. Defining such a search window discriminates efficiently against background and is referred to in the following as the "final selection" or the "L-shape cut" when defining the final search regions.

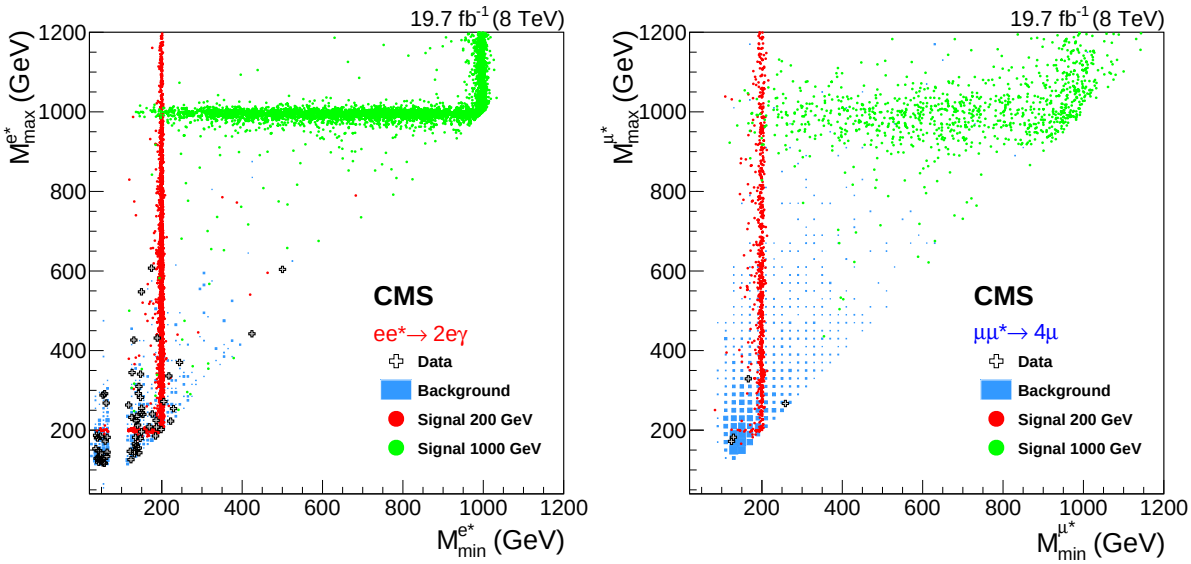

Figure 6: Illustrative two dimensional minimal-versus-maximal invariant-mass distribution for the ee* $\rightarrow$ eeγ (left) and the 4μ channel (right). It can be seen that the resolution worsens with increasing signal mass and that the channels have different resolutions. The left plot clearly shows the effect of the additional Z-veto that is applied in this channel.

The width of these L-shaped search regions depends on the channel and the ℓ^* mass. Detailed values for all channels are given in the Appendix. In the muon channels, the mass resolution worsens with increasing energy and the widths of the search windows need to become broader. This can be achieved without affecting the sensitivity of the search, since the high-mass regions are practically background-free. In the electron channels, the improving relative resolution of the electromagnetic calorimeter with increasing energy allows a more precise energy measurement at high masses. As a consequence, the width of the L-shaped windows is chosen individually for the different channels and mass points (by optimizing with respect to the best expected limit). Shown in Fig. 7 is a comparison of the width of search window with the intrinsic excited lepton width as a function of the excited lepton mass, for representative values of the compositeness scale Λ. This figure shows that the mass windows are in general much wider than the intrinsic width of the excited lepton, unless both its mass and Λ are small. The size of the mass window has a negligible effect on the final result, as will be discussed in Section 7.2.

The product of acceptance and efficiency as a function of ℓ^* mass for all channels is shown in Fig. 8. The decreasing efficiency at high masses in the 2ℓ2j channels results from the subjettiness algorithm, which loses ability to resolve the constituents of the fat jets, which overlap more and more with increasing ℓ^* mass.

The selected L-shaped search regions with positions given by the simulated signal masses do

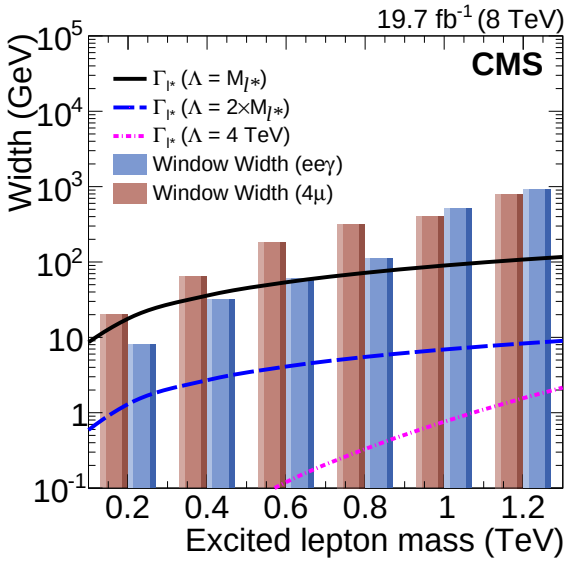

Figure 7: Width of the widest search window (4μ channel) and of a narrow one (eeγ) compared with the intrinsic decay width of the excited lepton, as a function of the ℓ^* mass and for different values of Λ.

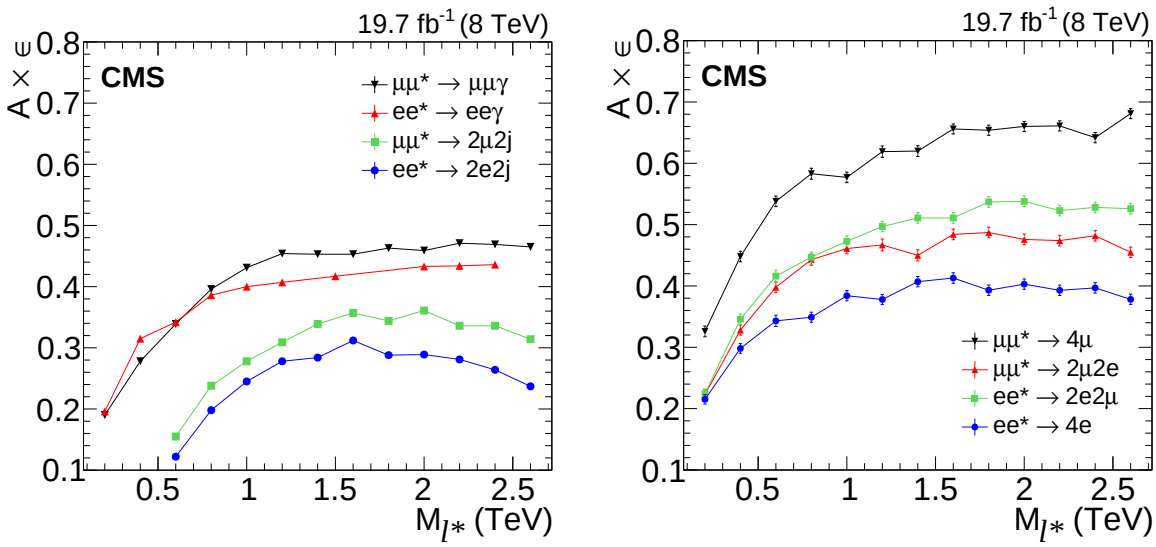

Figure 8: The product of acceptance and efficiency after L-shape selection. In the left panel, the efficiencies for the $\ell\ell^* \to \ell\ell\gamma$ and 2ℓ2j channels are shown while the right panel gives the efficiencies of the four-lepton channels. For the 2ℓ2j and 4ℓ channels, the values do not include the branching fractions for the specific Z boson decay channel.

not cover the complete M_{min} -M_{max} plane in the low mass region, where the search windows are narrow. To avoid simulating more mass points, those regions are covered with additional L-shaped search regions based on a linear interpolation of the signal expectation between the two closest available simulated signal masses. In the 4e channel a common window position is defined for all channels. There, the widths are estimated by linear interpolation between two consecutive masses such that the boundaries of all the search regions are connected. The central positions of these resulting interpolated search windows are then applied in all channels, while the corresponding widths are estimated for each channel individually.

The data, as well as the background expectation, in these newly defined L-shaped search regions can be derived from the distributions. As there are no corresponding signal samples simulated for all these search regions (compare Section 2), this information is not available for the signal. The signal is therefore estimated by a fit to the signal expectation of the available simulated mass points including the systematic uncertainties.

7.2 Limits on cross section and compositeness scale Λ

The resulting cross section limits are shown in Fig. 9. They range from 0.3 fb to 3 fb as a function of M_{ℓ^*}. The four lepton final states: 4e and 2e2μ, 4μ and 2μ2e, differing only in the decay of the SM Z boson, are combined. The other channels are shown individually. The black lines represent the theoretical cross sections including the NLO correction factors for different values of Λ. Solid lines are for the case $f = f' = 1$ while the dashed lines are for $f = -f' = 1$. The 95% confidence level (CL) upper limit on the excited lepton production cross section times branching fraction has been set using a single-bin counting method [61]. The computation has been performed using a Bayesian [62] approach.

The uncertainty bands have interesting behavior in some regions. They become asymmetric and in some cases the 1σ band disappears. Both effects have their origin in the low background expectation in the corresponding search window. In such cases, fluctuations of the limit to lower values are not possible. Unstable behavior of both expected and observed limits is due to the limited number of (background) events in the search regions, with the consequence that the presence of a single event leads to a considerable upward fluctuation of the observed limit (see also tables in the appendix).

The corresponding observed limits on the compositeness scale Λ are displayed in Fig. 10(left) for the case of SM-like couplings ($f = f' = 1$) and in Fig. 10(right) for couplings of opposite sign ($f = -f' = 1$). In the latter case, $\ell\ell^* \to \ell\ell\gamma$ cannot contribute. For low M_{ℓ^*} masses compositeness scales up to 16 TeV can be excluded. The sensitivity to Λ decreases with increasing M_{ℓ^*}. For the representative assumption of $M_{\ell^*} = \Lambda$, the resulting limits are summarized in Table 7 and Fig. 11. Although, the assumption that the signal efficiency is independent of Λ is not valid for the phase space where Λ and M_{ℓ^*} are small (lower left corner of Figs. 10), the behaviours of the cross section, $\sigma \sim 1/\Lambda^4$ is such that the complete region under the curves is nonetheless excluded.

Because of its considerably larger cross section times branching fraction, the $\ell\ell^* \to \ell\ell\gamma$ final state provides the maximum sensitivity for excluding excited leptons with masses up to 2.45 TeV. This limit improves upon the existing ATLAS limit for single ℓ^* production based on a partial 8 TeV data set [20] and exceeds significantly the limits of searches for single excited lepton production at previous colliders. The $\ell\ell^* \to \ell\ell\gamma$ channel shows no sensitivity for the case $f = -f' = 1$, which is therefore studied with Z boson radiation, with the $\ell\ell^* \to \ell\ell\text{Z} \to 2\ell2\text{j}$ channel being dominant. The excited muon channels are slightly more sensitive than those of the excited electron channels, even though the resolution and thus the signal separation ability

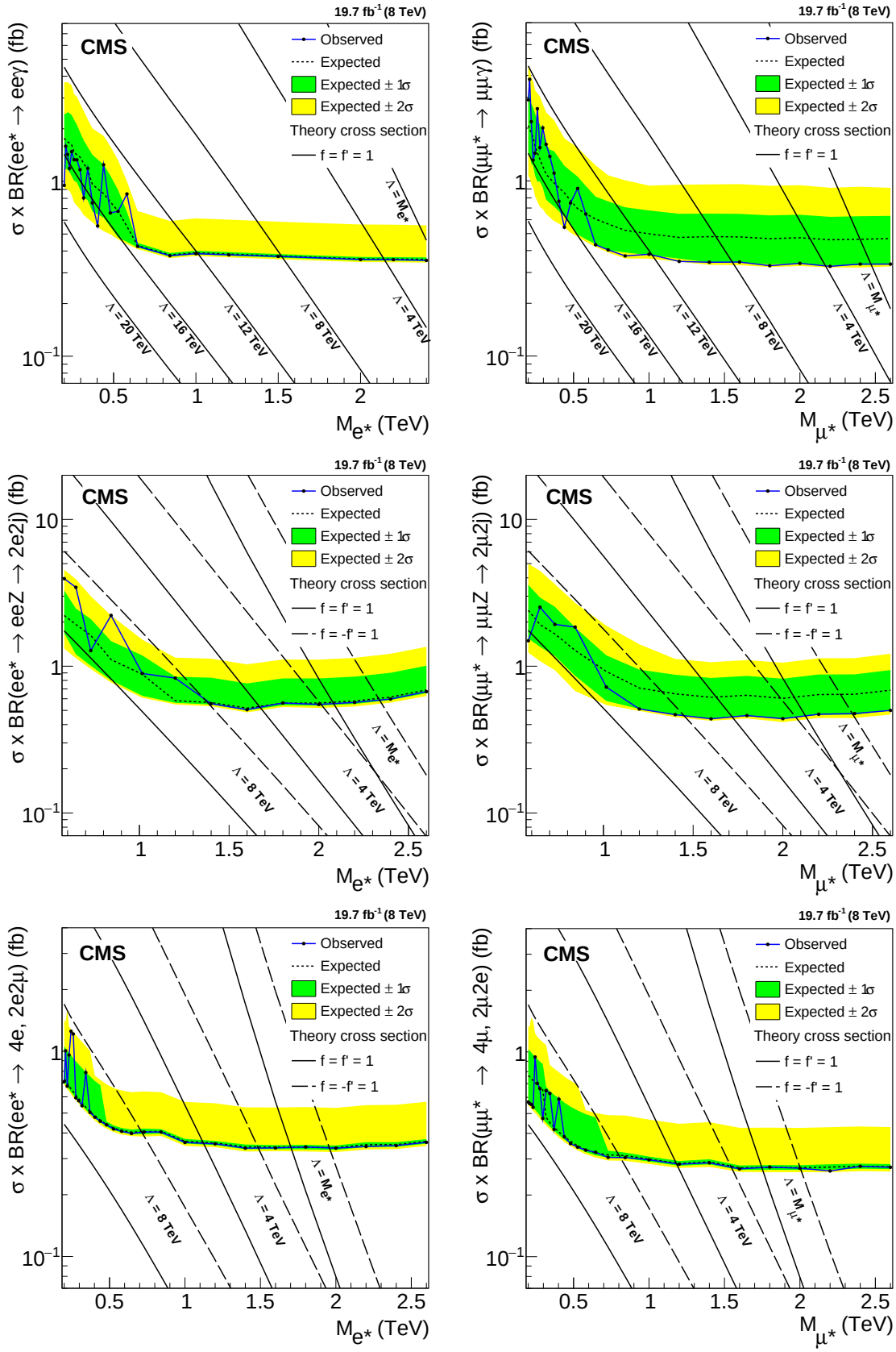

Figure 9: Upper limits at 95% CL on the product of the production cross section and branching fraction for excited electrons (left) and excited muons (right). First row: $\ell\ell^* \to \ell\ell\gamma$, second row: $\ell\ell^* \to \ell\ell Z \to 2\ell 2j$, last row: combined four-lepton results. It is assumed that the signal efficiency is independent of Λ. Theory curves are shown as solid or dashed lines.

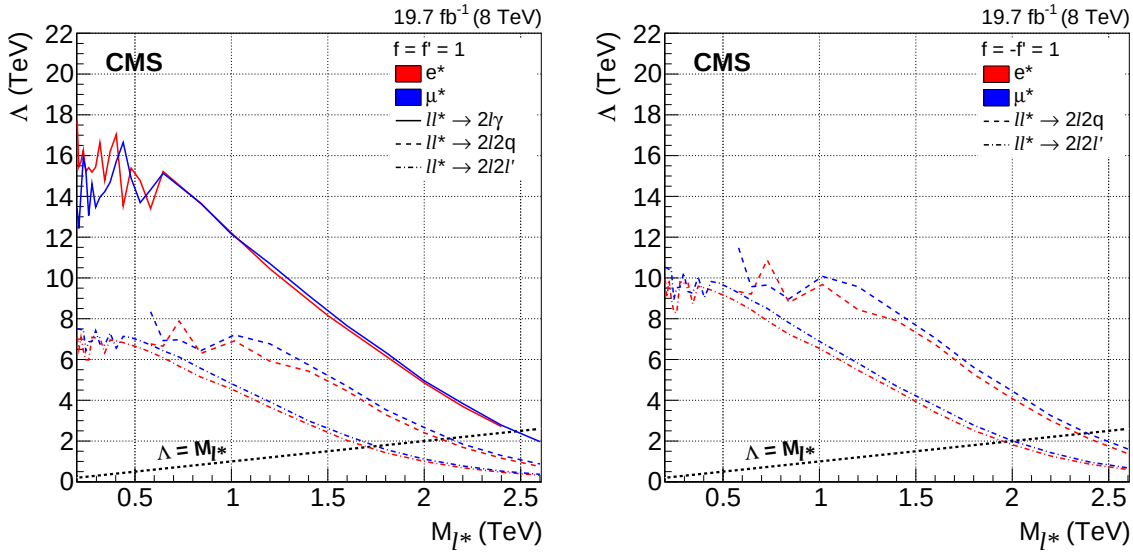

Figure 10: Observed 95% CL limits on the compositeness scale Λ for the cases $f = f' = 1$ and $f = -f' = 1$, as a function of the excited lepton mass for all channels. The excluded values are below the curves.

of electron final states is higher than that of the muon channels. The higher exclusion power is due to the better muon reconstruction efficiency, which leads to an overall higher signal selection efficiency.

Table 7: Summary of the observed (expected) limits on ℓ^* mass, assuming $M_{\ell^*} = \Lambda$, for the cases $f = f' = 1$ and $f = -f' = 1$. The latter case is not applicable to $\ell\ell^* \to \ell\ell\gamma$.

Search channel	$M_{\ell^*} = \Lambda$, values in TeV	
	$f = f' = 1$	$f = -f' = 1$
$ee^* \to ee\gamma$	2.45 (2.45)	—
$ee^* \to eeZ \to 2e2j$	2.08 (2.07)	2.34 (2.33)
$ee^* \to eeZ \to 4e$	1.55 (1.55)	1.78 (1.78)
$ee^* \to eeZ \to 2e2\mu$	1.58 (1.58)	1.84 (1.84)
$ee^* \to eeZ \to 2e2\ell$	1.70 (1.70)	1.96 (1.96)
$\mu\mu^* \to \mu\mu\gamma$	2.47 (2.40)	—
$\mu\mu^* \to \mu\mu Z \to 2\mu 2j$	2.11 (2.05)	2.37 (2.31)
$\mu\mu^* \to \mu\mu Z \to 4\mu$	1.64 (1.64)	1.89 (1.89)
$\mu\mu^* \to \mu\mu Z \to 2\mu 2e$	1.58 (1.58)	1.83 (1.83)
$\mu\mu^* \to \mu\mu Z \to 2\mu 2\ell$	1.75 (1.75)	2.00 (2.00)

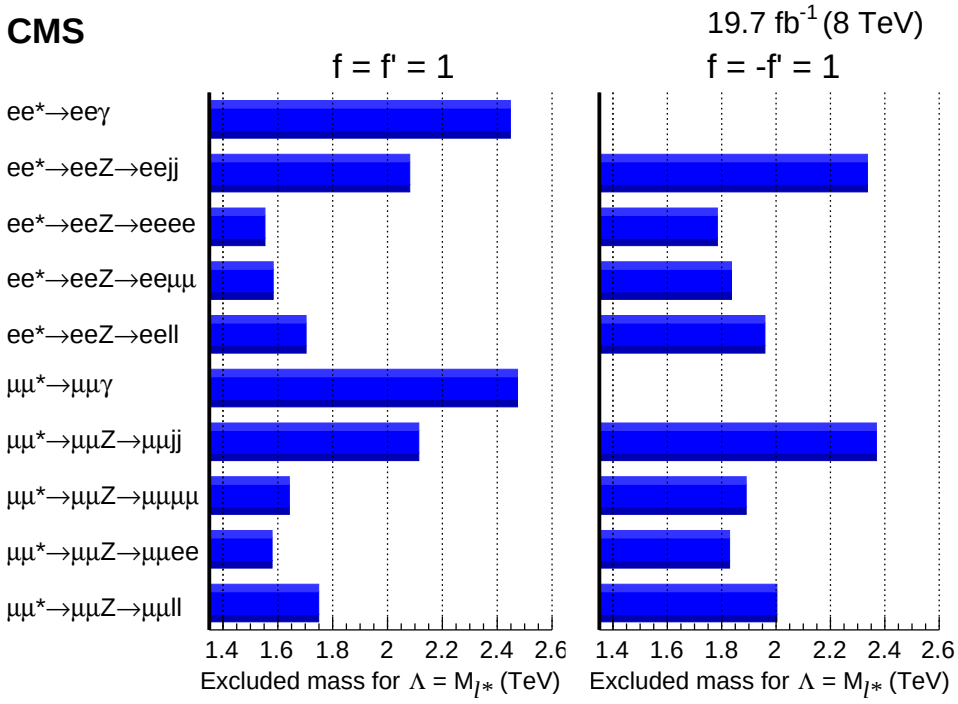

Figure 11: Summary of all mass limits for the various channels and, including the combination of the four lepton channels, for $M_{\ell^*} = \Lambda$.

8 Summary

A comprehensive search for excited leptons, e^* and μ^*, in various channels has been performed using 19.7 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV. The excited lepton is assumed to be produced via contact interactions in conjunction with the corresponding standard model lepton. Decaying to its ground state, the excited lepton may emit either a photon or a Z boson. No evidence of excited leptons is found and exclusion limits are set on the compositeness scale Λ as a function of the excited lepton mass M_{ℓ^*}.

The $\ell\ell^* \to \ell\ell\gamma$ final state has the largest production cross section and has therefore previously been used for searches. Following convention, the limits for the assumption $\Lambda = M_{\ell^*}$ are included here. This final state yields the best limits, excluding excited electrons up to 2.45 TeV and excited muons up to 2.47 TeV, at 95% confidence level. These limits place the most stringent constraints to date on the existence of excited leptons.

The $\ell^* \to \ell Z$ decay channel has been examined for the first time at hadron colliders, allowing the case where couplings between standard model leptons and excited leptons $f = -f = 1$ can be studied. The leptonic and hadronic (2-jet) final states of the Z boson are used in this search; these final states are Lorentz boosted, requiring a dedicated reconstruction strategy. The observed 95% exclusion limits extend to 2.34 (2.37) TeV for excited electrons (muons), for $f = -f' = 1$.

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A Appendix

Final numbers used to calculate the expected and observed cross section limits for the various excited lepton channels are shown in Tab. A.1– A.4. In all tables, "window" refers to the interval between the upper and lower invariant mass boundaries of the search windows for the given mass points. The interpolated search windows are not shown. The signal efficiency after all selection steps including the search window is ϵ_{signal}. The expected number of events for the SM background and the number of observed data events are N_{bg} and N_{data}, respectively.

Table A.1: Final numbers used to calculate the cross section limits for the excited lepton channels resulting in photon emission, $\mu\mu^* \to \mu\mu\gamma$ and $\text{ee}^* \to \text{ee}\gamma$.

M_{ℓ^*}	$\mu\mu^* \to \mu\mu\gamma$				$\text{ee}^* \to \text{ee}\gamma$			
(GeV)	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}
200	194–206	19.0%	6.95 ± 1.64	10	196–204	19.6%	4.57 ± 1.21	1
400	384–416	27.8%	1.27 ± 0.60	1	384–416	31.5%	1.19 ± 0.61	0
600	564–636	33.9%	0.64 ± 0.48	0	570–630	34.2%	0.40 ± 0.31	2
800	720–880	39.6%	0.29 ± 0.28	0	744–856	38.6%	0.01 ± 0.01	0
1000	720–1280	43.1%	0.29 ± 0.28	0	744–1256	40.0%	0.05 ± 0.04	0
1200	720–1680	45.4%	0.57 ± 0.40	0	744–1656	40.7%	0.05 ± 0.04	0
1400	720–2080	45.3%	0.57 ± 0.40	0	—	—	—	—
1500	—	—	—	—	744–2256	41.7%	0.05 ± 0.04	0
1600	720–2480	45.3%	0.57 ± 0.40	0	—	—	—	—
1800	720–2880	46.3%	0.57 ± 0.40	0	—	—	—	—
2000	720–3280	45.9%	0.57 ± 0.40	0	744–3256	43.3%	0.05 ± 0.04	0
2200	720–3680	47.1%	0.57 ± 0.40	0	744–3656	43.4%	0.05 ± 0.04	0
2400	720–4080	46.9%	0.57 ± 0.40	0	744–4056	43.6%	0.05 ± 0.04	0
2600	720–4480	46.5%	0.57 ± 0.40	0	—	—	—	—

Table A.2: Final numbers used to calculate the cross section limits for the excited lepton channels resulting in the emission of a Z boson that decays to two jets, $\mu\mu^* \to \mu\mu\text{Z} \to 2\mu2\text{j}$ and $\text{ee}^* \to \text{eeZ} \to 2\text{e}2\text{j}$.

M_{ℓ^*}	$\mu\mu^* \to \mu\mu\text{Z} \to 2\mu2\text{j}$				$\text{ee}^* \to \text{eeZ} \to 2\text{e}2\text{j}$			
(GeV)	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}
600	558–642	15.5%	4.69 ± 1.58	3	570–630	12.2%	3.19 ± 1.11	3
800	728–872	23.8%	3.35 ± 1.15	4	728–856	19.8%	2.49 ± 0.88	3
1000	900–1100	27.8%	1.75 ± 0.63	1	900–1100	24.5%	1.47 ± 0.55	1
1200	1068–1332	30.9%	0.94 ± 0.37	0	1068–1332	27.8%	0.50 ± 0.26	1
1400	1100–1700	33.9%	0.70 ± 0.30	0	1200–1600	28.4%	0.50 ± 0.23	0
1600	1100–2100	35.7%	0.70 ± 0.30	0	1200–2000	31.2%	0.50 ± 0.23	0
1800	1100–2500	34.4%	0.70 ± 0.30	0	1200–2400	28.8%	0.50 ± 0.23	0
2000	1100–2900	36.1%	0.70 ± 0.30	0	1200–2800	28.9%	0.50 ± 0.23	0
2200	1100–3300	33.6%	0.70 ± 0.30	0	1200–3200	28.1%	0.50 ± 0.23	0
2400	1100–3700	33.6%	0.70 ± 0.30	0	1200–3600	26.4%	0.50 ± 0.23	0
2600	1100–4100	31.4%	0.70 ± 0.30	0	1200–4000	23.7%	0.50 ± 0.23	0

Table A.3: Final numbers used to calculate the cross section limits for the two excited muon channels in the 4ℓ final states.

M_{μ^*}	$\mu\mu^* \to \mu\mu Z \to 4\mu$				$\mu\mu^* \to \mu\mu Z \to 2\mu 2e$			
(GeV)	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}
200	190–210	32.6%	0.77 ± 0.12	0	196–204	22.3%	0.23 ± 0.05	0
400	368–432	44.8%	0.23 ± 0.04	0	376–424	32.8%	0.14 ± 0.03	1
600	510–690	53.8%	0.13 ± 0.02	0	540–660	39.8%	0.07 ± 0.03	0
800	640–960	58.3%	0.06 ± 0.01	0	720–880	44.3%	0.04 ± 0.01	0
1000	800–1200	57.7%	0.03 ± 0.01	0	850–1150	46.1%	0.01 ± 0.01	0
1200	800–1600	61.9%	0.04 ± 0.01	0	1000–1400	46.7%	0.00 ± 0.00	0
1400	800–2000	62.0%	0.04 ± 0.01	0	1200–1800	45.0%	0.01 ± 0.01	0
1600	800–2400	65.6%	0.04 ± 0.01	0	1200–2200	48.4%	0.01 ± 0.01	0
1800	800–2800	65.4%	0.04 ± 0.01	0	1200–2600	48.7%	0.01 ± 0.01	0
2000	800–3200	66.0%	0.04 ± 0.01	0	1200–3000	47.6%	0.01 ± 0.01	0
2200	800–3600	66.1%	0.04 ± 0.01	0	1200–3400	47.4%	0.01 ± 0.01	0
2400	800–4000	64.2%	0.04 ± 0.01	0	1200–3800	48.2%	0.01 ± 0.01	0
2600	800–4400	68.1%	0.04 ± 0.01	0	1200–4200	45.5%	0.01 ± 0.01	0

Table A.4: Final numbers used to calculate the cross section limits for the two excited electron channels in the 4ℓ final states.

M_{e^*}	$ee^* \to eeZ \to 4e$				$ee^* \to eeZ \to 2e2\mu$			
(GeV)	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}	Window (GeV)	ϵ_{signal}	N_{bg}	N_{data}
200	196–204	21.5%	0.23 ± 0.05	0	196–204	22.4%	0.24 ± 0.05	0
400	384–416	29.8%	0.08 ± 0.02	0	384–416	34.6%	0.09 ± 0.02	0
600	570–630	34.3%	0.03 ± 0.01	0	552–648	41.6%	0.08 ± 0.02	0
800	744–856	34.9%	0.01 ± 0.00	0	728–872	44.7%	0.02 ± 0.01	0
1000	900–1100	38.4%	0.01 ± 0.00	0	860–1140	47.3%	0.02 ± 0.01	0
1200	1000–1200	37.8%	0.01 ± 0.01	0	860–1540	49.7%	0.02 ± 0.01	0
1400	1000–1600	40.7%	0.01 ± 0.01	0	860–1940	51.1%	0.02 ± 0.01	0
1600	1000–2000	41.3%	0.01 ± 0.01	0	860–2340	51.1%	0.02 ± 0.01	0
1800	1000–2400	39.3%	0.01 ± 0.01	0	860–2740	53.7%	0.02 ± 0.01	0
2000	1000–2800	40.3%	0.01 ± 0.01	0	860–3140	53.8%	0.02 ± 0.01	0
2200	1000–3200	39.3%	0.01 ± 0.01	0	860–3540	52.3%	0.02 ± 0.01	0
2400	1000–3800	39.7%	0.01 ± 0.01	0	860–3940	52.8%	0.02 ± 0.01	0
2600	1000–4200	37.8%	0.01 ± 0.01	0	860–4340	52.6%	0.02 ± 0.01	0

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