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Search for Excited Leptons at $\sqrt{s} = 192 - 202$ GeV

The L3 Collaboration

Abstract

We report on a search for excited electrons, muons, taus and neutrinos in e^+e^-collisions at centre-of-mass energies from 192 GeV up to 202 GeV, using the L3 detector at LEP. No evidence has been found for their existence. From a search for pair produced excited leptons, we determine lower mass limits for excited electrons, muons, taus, and neutrinos. From a search for singly produced excited leptons we derive upper limits on their coupling constants.
All results are preliminary.

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1 Introduction

The existence of excited leptons would provide clear evidence for fermion substructure. Composite models could explain the number of families and make the fermion masses and weak mixing angles calculable [1]. The excited leptons e^*, μ^*, τ^* and ν^* have been extensively searched for at the LEP $e^+e^-$and at the HERA ep colliders [2].

Excited leptons are assumed to have both spin and isospin $\frac{1}{2}$ and the same electroweak SU(2) and U(1) gauge coupling constants to the vector bosons as the standard leptons, but are expected to be grouped into both left and right handed weak isodoublets. An excited lepton, ℓ^* or ν^*, is expected to decay immediately into its ground state, ℓ or ν, by radiating a photon or a massive vector boson, W or Z.

At e^+e^- colliders, excited leptons can be produced either in pairs ($e^+e^- \rightarrow \ell^*\ell^*$ or $e^+e^- \rightarrow \nu^*\nu^*$) or singly ($e^+e^- \rightarrow \ell\ell^*$ or $e^+e^- \rightarrow \nu\nu^*$). For pair production, the coupling of the excited leptons to the gauge bosons is described by the Lagrangian [3]

$$\mathcal{L}_{\ell^*\ell^*} = \bar{L}^*\gamma^\mu \left(g\frac{\vec{\tau}}{2}\vec{W}_\mu + g'YB_\mu \right) L^*.$$

The cross section for pair production depends on the mass of the excited lepton [1, 4], and is shown in Figure 1(a).

Single production as well as magnetic de-excitation can be described by an effective Lagrangian [3] of the form

$$\mathcal{L}_{\ell^*\ell} = \frac{gf}{\Lambda}\bar{L}^*\sigma^{\mu\nu}\frac{\vec{\tau}}{2}l_L\partial_\mu\vec{W}_\nu + \frac{g'f'}{\Lambda}\bar{L}^*\sigma^{\mu\nu}Yl_L\partial_\mu B_\nu + h.c.,$$

where Λ is the compositeness scale and f and f' are the coupling constants associated with SU(2) and U(1) respectively. They determine the production rate of single excited leptons and their branching ratio into standard leptons plus gauge bosons [4]. Figures 1(b) and 1(c) show the cross section for single production for $\Lambda = 1$ TeV.

Excited leptons may be produced in pairs up to masses close to the beam energy. The cross section is fixed by the model and is of the order of a few picobarns. Single production of excited leptons may occur up to masses close to $\sqrt{s}$. Thus, the search for singly produced excited leptons extends the sensitivity above the mass region accessible to pair production.

Table 1 and Figures 2(a) and 2(b) show the excited leptons decay branching ratios for two relative values of f and f'.

We search for pair produced excited leptons (with a mass below $\frac{\sqrt{s}}{2}$) in the radiative $\ell^* \rightarrow \ell\gamma$ and $\nu^* \rightarrow \nu\gamma$, and charged current decays, $\ell^* \rightarrow \nu$W and $\nu^* \rightarrow \ell$W, which are dominant for every value of the coupling constants, f and f'. Thus, with the combined search for radiative decays, $\ell^* \rightarrow \ell\gamma$, $\nu^* \rightarrow \nu\gamma$, and charged current decays $\ell^* \rightarrow \nu$W, $\nu^* \rightarrow \ell$W, we are sensitive to the whole parameter space.

In the search for singly produced excited leptons (with masses up to $\sqrt{s}$) all the possible decays are considered, namely radiative, charged and neutral current decays.

We derive lower mass limits for every flavour of excited lepton independently of the coupling constants. Moreover, we derive limits on the mass and the coupling constant for two particular scenarios often considered in this search: $f = f'$ and $f = -f'$. In these cases, only $\frac{|f|}{\Lambda}$ remains as a free parameter in the Lagrangian.

Decay Channel	$m^* = 95$ GeV		$m^* = 190$ GeV	
	$f = f'$	$f = -f'$	$f = f'$	$f = -f'$
$\ell^* \to \ell\gamma$	81	0	36	0
$\ell^* \to \nu$W	19	93	55	63
$\ell^* \to \ell$Z	0	7	9	37
$\nu^* \to \nu\gamma$	0	81	0	36
$\nu^* \to \ell$W	93	19	63	55
$\nu^* \to \nu$Z	7	0	37	9

Table 1: Predicted branching ratios in % for excited lepton decays, for two chosen values of excited lepton mass m^*. Upper part corresponds to charged excited leptons, lower part corresponds to excited neutrinos.

In the case of single production, the excited lepton polar angle distribution depends on the ratio of the coupling constants $\frac{f}{f'}$. This is critical for e^* production; if $f = f'$, the t channel photon exchange gives a large contribution at low polar angle (with the standard electron escaping through the beam pipe); if $f = -f'$, the $e^*e\gamma$ vertex is not allowed, and only the Z mediated s and t channels contribute, giving rise to events with an electron visible in the detector. Thus, the efficiency for e^* selection is calculated for both scenarios: $f = f'$ and $f = -f'$. For all other flavours of excited lepton, the detection efficiency depends slightly on the coupling assumption.

2 Monte Carlo and data samples

The data sample analysed was collected in 1999 by the L3 detector [5] at centre-of-mass energies in the range from 192 GeV to 202 GeV, and amounts to a total luminosity of 233.2 pb^{-1}. The breakdown of the luminosity in four energies is the following: 29.7 pb^{-1} at 191.6 GeV, 83.7 pb^{-1} at 195.5 GeV, 82.8 pb^{-1} at 199.5 GeV and 37.0 pb^{-1} at 201.7 GeV.

For the simulation of background from Standard Model processes different Monte Carlo programs were used. Radiative Bhabha events were generated using BHWIDE [6] and TEEGG [7]. For other radiative dilepton events, $\mu\mu\gamma$, $\tau\tau\gamma$ and $\nu\nu\gamma$, the KORALZ [8] generator was used. The GGG [9] Monte Carlo was used for final states with only photons. KORALW [10] was used for the $e^+e^- \to$ WW process. KK2F [11] was used for $q\bar{q}$ production. PYTHIA [12] was used for ZZ and Zee production and EXCALIBUR [13] was used for the 4-fermion final states with non negligible contribution from processes other than resonant ZZ and WW production.

The generation of excited leptons signal and their decay was done according to the differential cross section of reference [3]. For signal efficiency estimation, pair excited leptons were generated with 95 GeV of mass and single excited leptons were generated with three different masses: 100, 150 and 195 GeV. Initial state radiation is not implemented in the generation, but its effect in the cross section is taken into account for calculation of limits.

All the Monte Carlo events have been simulated in the L3 detector using the GEANT3 program [14], which takes into account the effects of energy loss, multiple scattering and showering in the materials.

3 Event selection

Table 2 shows the final states considered in the search for excited leptons produced in pairs.

Signal	Final State		
e^*e^*	$ee\gamma\gamma$		$e\gamma\nu W$
$\mu^*\mu^*$	$\mu\mu\gamma\gamma$	$\nu\nu WW$	$\mu\gamma\nu W$
$\tau^*\tau^*$	$\tau\tau\gamma\gamma$		$\tau\gamma\nu W$
$\nu_e^*\nu_e^*$		$eeWW$	$\nu\gamma eW$
$\nu_\mu^*\nu_\mu^*$	$\nu\nu\gamma\gamma$	$\mu\mu WW$	$\nu\gamma\mu W$
$\nu_\tau^*\nu_\tau^*$		$\tau\tau WW$	$\nu\gamma\tau W$

Table 2: Final states considered in the search for excited leptons produced in pairs.

Table 3 shows the final states considered in the search for single production of excited leptons.

Signal	Final State		
ee^*	$ee\gamma$	$e\nu W$	eeZ
$\mu\mu^*$	$\mu\mu\gamma$	$\mu\nu W$	$\mu\mu Z$
$\tau\tau^*$	$\tau\tau\gamma$	$\tau\nu W$	$\tau\tau Z$
$\nu_e\nu_e^*$		νeW	
$\nu_\mu\nu_\mu^*$	$\nu\nu\gamma$	$\nu\mu W$	$\nu\nu Z$
$\nu_\tau\nu_\tau^*$		$\nu\tau W$	

Table 3: Final states considered in the search for excited leptons produced singly.

Excited leptons decaying radiatively give rise to final states with low multiplicity and high energy photons in the detector. A dedicated selection is used for each final state topology: $ee\gamma\gamma$, $\mu\mu\gamma\gamma$, $\tau\tau\gamma\gamma$, $\nu\nu\gamma\gamma$, $ee\gamma$, $\mu\mu\gamma$, $\tau\tau\gamma$ and $\nu\nu\gamma$.

In the case of pair production of excited leptons decaying through charged current, a basic WW selection which searches for two W bosons is used for the final states $\nu\nu$WW and $\tau\tau$WW. For the eeWW and $\mu\mu$WW final states, the WW selection is complemented with the search for two isolated electrons or muons. For WW identification we consider the fully hadronic, $WW \rightarrow q\bar{q}q\bar{q}$, and the semileptonic, $WW \rightarrow q\bar{q}\ell\nu$, decays.

In the case of pair production with one excited lepton decaying radiatively and the other decaying through charged current, events with one energetic photon, and the decay products of a W are selected. The hadronic, $W \rightarrow q\bar{q}$, and the leptonic, $W \rightarrow \ell\nu$, decays are considered. Four dedicated selections are used for the topologies $e\gamma\nu W$, $\mu\gamma\nu W$, $\tau\gamma\nu W$ and $\nu\gamma\ell W$.

For single production of excited leptons decaying through charged or neutral current, both the hadronic, $W \rightarrow q\bar{q}$ and $Z \rightarrow q\bar{q}$, and the leptonic decays, $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$ and $Z \rightarrow \nu\nu$, are considered.

3.1 Particle identification

The L3 detector measures accurately the energy and direction of photons, leptons and hadronic jets.

- **Hadronic jets** are defined as angular associations of energy depositions in the electromagnetic and hadronic calorimeters, and charged tracks measured in the central tracking chamber (TEC). Different algorithms are used to optimise the performance of jet reconstruction depending on the final state topology searched for. For final states with two visible jets, the Durham algorithm is used to force the event into two jets. In low multiplicity events containing photons, tau identification is based on jets constructed from calorimetric clusters, tracks and muons, with invariant mass below 3 GeV and at least one associated track. For the rest of the events, jets are reconstructed using the algorithm described in Ref. [15].

- **Photons** and **electrons** are identified as clusters with energy above 1 GeV in the electromagnetic calorimeter, and electromagnetic shape (more than 95% of its energy contained in a 3x3 matrix of BGO crystals). Photons must be isolated whereas electrons must be matched to a charged track. In order to be well inside the angular acceptance of the central tracking chamber (TEC), the polar angle (angle with the beam axis) of electrons and photons must satisfy $|\cos\theta| < 0.95$.

- **Muons** are measured by the muon chamber system surrounding the calorimeters. In addition, an algorithm is used to find **minimum ionising particles**, to increase efficiency in muon detection. The criteria is to ask for calorimetric clusters with more hits than one third of the expected number of hits for a minimum ionising particle. Moreover, the calorimetric energy must be smaller than 10 GeV, and either they must have an associated TEC track or they must be at low polar angle, $|\cos\theta| > 0.95$.

- Low multiplicity hadronic jets as well as electrons and muons are also identified as **tau candidates**.

Particle identification is slightly different depending on the event topology. In low multiplicity events, lepton and photon identification relays on a set of loose cuts which provide a high efficiency. In events containing hadronic jets, some tighter cuts are applied to identify leptons and photons keeping a low rate of misidentification.

3.2 Cosmic background rejection

To reject background from cosmic rays, in low multiplicity events, every muon track is required to be identified as a muon coming from the vertex (if it has an associated track in the TEC, its distance of closest approach is required to be less than 2 mm in the transverse direction, and 40 mm in the longitudinal direction; otherwise, the distance of closest approach of the muon track must be less than 200 mm both in the transverse and the longitudinal directions). Moreover, all the events are required to have at least one scintillator hit within 5 ns from beam crossing.

3.3 Pair production

For $\ell^*\ell^*$ and $\nu^*\nu^*$ production, we consider the radiative decay ($\ell\ell\gamma\gamma$ and $\nu\nu\gamma\gamma$), the charged current decay ($\nu\nu$WW and $\ell\ell$WW), and the mixed decay modes ($\ell\nu$Wγ).

3.3.1 Radiative decays

Event selection for the reactions $e^+e^- \rightarrow \ell^*\ell^* \rightarrow \ell\ell\gamma\gamma$ and $e^+e^- \rightarrow \nu^*\nu^* \rightarrow \nu\nu\gamma\gamma$ are based on the fact that these processes contain two leptons and two photons.

A preselection of leptonic events with hard photons is performed according to the following cuts:

- To reject hadronic events, the number of tracks in the central tracking chamber is required to be less than 8.
- The selected events are required to have two identified photons with energy greater than 15 GeV. At least one them must be in the barrel region ($|\cos\theta| < 0.75$). This criterion reduces efficiently the background from Standard Model processes where the photons are mainly due to initial state radiation, and are emitted predominantly at low angle.

In the case of charged excited leptons, the final state leptons are visible in the detector, and the invariant mass of the excited lepton is reconstructed after performing a kinematical fit which imposes conservation of energy and momentum. The resolution in the reconstruction of the invariant mass of charged excited leptons is shown in Table 4.

Signal	Resolution
$e^*e^* \rightarrow ee\gamma\gamma$	0.8 GeV
$\mu^*\mu^* \rightarrow \mu\mu\gamma\gamma$	1.1 GeV
$\tau^*\tau^* \rightarrow \tau\tau\gamma\gamma$	1.3 GeV

Table 4: Invariant mass resolution of $\ell\gamma$ pairs for pair produced excited leptons. The estimate is based on Monte Carlo (the reconstructed mass is fitted to a Gaussian distribution).

In the case of excited neutrinos, the energies and angles of the two final state photons are compatible with a certain range of masses of the excited neutrino. The background from $\nu\nu\gamma\gamma$ and $\gamma\gamma(\gamma)$ processes can be efficiently reduced requiring two energetic acoplanar photons.

Our selection is sensitive to excited leptons from 50 GeV to the kinematical limit $\frac{\sqrt{s}}{2}$.

$ee\gamma\gamma$ Selection

Event selection for the reaction $e^+e^- \rightarrow e^*e^* \rightarrow ee\gamma\gamma$ requires the following additional criteria:

- Two identified electrons and no other tracks with momentum greater than 1 GeV in the event.
- After kinematical fit, the difference of the two electron-photon masses is required to be smaller than 10 GeV and their sum greater than 100 GeV.

The detection efficiency for e^* is estimated from Monte Carlo to be 46%, independent from the e^* mass. The main background is from radiative Bhabha events $e^+e^- \rightarrow ee\gamma\gamma$. A total of 0.8 events is expected from Standard Model.

$\mu\mu\gamma\gamma$ Selection

Event selection for the reaction $e^+e^- \to \mu^*\mu^* \to \mu\mu\gamma\gamma$ requires the following additional criteria:

- Two TEC tracks with momentum greater than 1 GeV. At least one of them associated to a track in the muon chambers.
- After kinematical fit, the difference of the two muon-photon masses is required to be smaller than 10 GeV and their sum greater than 100 GeV.

The detection efficiency for μ^* is estimated from Monte Carlo to be 44%, independent from the μ^* mass. The main background is from radiative dimuon events $e^+e^- \to \mu\mu\gamma\gamma$. A total of 0.5 events is expected from Standard Model.

$\tau\tau\gamma\gamma$ Selection

Event selection for the reaction $e^+e^- \to \tau^*\tau^* \to \tau\tau\gamma\gamma$ requires the following additional criteria:

- At least two charged jets.
- The visible decay products from the taus carry just a fraction of the energy of the taus, due to the presence of undetected neutrinos. We require that after the kinematical fit (assuming two photons and two taus in the event), at least one of the tau candidates must have a fitted energy exceeding its visible energy more than 10 GeV. Moreover, its visible energy must be greater than 10 GeV and must be contained in the acceptance of the electromagnetic calorimeter (BGO).
- After kinematical fit, the difference of the two tau-photon masses is required to be smaller than 10 GeV and their sum greater than 100 GeV.

The detection efficiency for τ^* is estimated from Monte Carlo to be 43%, independent from the τ^* mass. The main background is from radiative $e^+e^- \to \tau\tau\gamma\gamma$ and $e^+e^- \to ee\gamma\gamma$ events when the energy of one of the electrons is mismeasured. A total of 0.2 events is expected from Standard Model.

$\nu\nu\gamma\gamma$ Selection

Event selection for the reaction $e^+e^- \to \nu^*\nu^* \to \nu\nu\gamma\gamma$ requires the following additional criteria:

- Two photons with energies in the range from 0.2 to 0.8 times the beam energy and acoplanarity greater than 10°. The photons must be in the barrel region, $|\cos\theta| < 0.75$.
- No other particles detected, neither in central tracking system, nor in muon chambers. The energy of any other calorimetric cluster should be less than 5 GeV.

The detection efficiency for ν^* is estimated from Monte Carlo to be 45%, independent from the ν^* mass. The main background is from radiative $\nu\nu$ events, $e^+e^- \to \nu\nu\gamma\gamma$. A total of 1.9 events is expected from Standard Model.

3.3.2 Charged current decays

The reaction $e^+e^- \rightarrow \ell^*\ell^* \rightarrow \nu\nu WW$ gives rise to events with two W bosons and some missing energy. However, the missing energy depends on the mass of the excited lepton, and does not provide an unambiguous experimental signature. In events where both W bosons decay hadronically the resolution of the hadronic calorimeter is around 10%. In events where one W decays leptonically, the undetected neutrino carries around half the energy of the W. Thus in order to have a high signal efficiency independent of the mass of the excited lepton, a basic WW selection is used.

In the reaction $e^+e^- \rightarrow \nu^*\nu^* \rightarrow \ell\ell WW$, the final state contains two W bosons and two charged leptons. In the case of $\nu^*_\tau\nu^*_\tau$ production, the decay products of the taus are often immersed into the hadronic jets from W decay. Thus the bare WW selection is also used. In the case of $\nu^*_e\nu^*_e$ or $\nu^*_\mu\nu^*_\mu$ production the final state contains two electrons or two muons which provide a clean experimental signature. In this case, the WW selection is complemented with a search for two isolated leptons of the same flavour.

In the WW selection the fully hadronic decay, $WW \rightarrow q\bar{q}q\bar{q}$, and the semileptonic decays, $WW \rightarrow q\bar{q}e\nu$, $WW \rightarrow q\bar{q}\mu\nu$ and $WW \rightarrow q\bar{q}\tau\nu$, are considered. Thus, the WW selection is the combination of four different selections: qqqq, qqeν, qq$\mu\nu$ and qq$\tau\nu$. These are explained below. The detection efficiency for ℓ^* and ν^* is estimated from Monte Carlo to be above 65%, slightly dependent on the mass and flavour of the excited lepton. The main background source is from WW and $q\bar{q}$ production. A total of 2993 events is expected from Standard Model.

qqqq Selection

The criteria for the qqqq selection are:

- The number of charged tracks must be greater than 20, and the number of calorimetric clusters must be greater than 40.
- The calorimetric energy must be greater than 140 GeV.
- To reject the $q\bar{q}\gamma$ background, with a photon escaping through the beam pipe, the polar angle θ of the missing momentum must be in the range $18° < \theta < 162°$, or the missing momentum must be smaller than 30 GeV. No calorimetric clusters with electromagnetic shape and energy greater than 50 GeV.
- At least three jets with energy greater than 10 GeV, and more than one associated track. For at least one pair of these jets, their invariant mass must be in the range from 50 GeV to 110 GeV, the recoiling mass against these two jets must be greater than 50 GeV and the sum of invariant plus recoil masses must be greater than 120 GeV.

qq$\ell\nu$ Selection

The basic criteria for the qq$\ell\nu$ selection are:

- The number of charged tracks must be greater than 4, and the number of calorimetric clusters must be greater than 15.
- The calorimetric energy must be greater than 60 GeV.
- The missing momentum must be greater than 20 GeV.

- The visible energy must be smaller than $0.8 * \sqrt{s}$.
- The polar angle θ of the missing momentum must be in the range $18^\circ < \theta < 162^\circ$.
- Additionally there must be an isolated lepton in the event according to the criteria explained below.

qqeν Selection
The qqeν selection requires the qq$\ell\nu$ criteria and in addition:

- An electron with energy greater than 5 GeV, more than 90% of its total calorimetric energy contained in the electromagnetic calorimeter and a matching track with momentum greater than 1 GeV within 0.5° in the $r\phi$ projection. This track must be isolated from any other track more than 10°. The polar angle θ of the electron must be in the range $18^\circ < \theta < 162^\circ$, and either its energy must be greater than 20 GeV, or the distance to the closest jet must be greater than 15°.
- The invariant mass of the rest of the event (excluding the identified electron) must be in the range from 40 GeV to 120 GeV.

qq$\mu\nu$ Selection
The qq$\mu\nu$ selection requires the qq$\ell\nu$ criteria and in addition:

- A muon track with momentum greater than 5 GeV. Its distance of closest approach to the interaction vertex, must be smaller than 200 mm in the transverse and the longitudinal directions. It must be matched to a track with momentum greater than 1 GeV within 0.5° in the $r\phi$ projection. The polar angle θ of the muon must be in the range $26^\circ < \theta < 154^\circ$, and either its momentum must be greater than 20 GeV, or the distance to the closest jet must be greater than 15°.
- The invariant mass of the rest of the event (excluding the identified muon) must be in the range from 40 GeV to 120 GeV.

qq$\tau\nu$ Selection
The qq$\tau\nu$ selection requires the qq$\ell\nu$ criteria and in addition:

- At least three charged jets with energy greater than 8 GeV. One of these jets must be compatible with the decay products of a tau; it must have an associated track with momentum greater than 1.5 GeV, and must accomplish at least two of the following conditions: number of tracks is less than four, number of calorimetric clusters is less than five, jet invariant mass is smaller than 2 GeV, and at least 70% of its energy is contained in a 5° half-opening cone.
- The invariant mass of the rest of the event (excluding the identified tau) must be in the range from 50 GeV to 110 GeV.
- The missing momentum along the longitudinal direction must be smaller than 55 GeV.

- The number of calorimetric clusters must be smaller than 70.
- No calorimetric clusters with electromagnetic shape and energy greater than 72 GeV.
- No calorimetric clusters with electromagnetic shape and energy greater than 25 GeV, not contained in the jet identified as a tau, and isolated more than 30° from the rest of the jets.

eeWW Selection

Event selection for the reaction $e^+e^- \rightarrow \nu_e^* \nu_e^* \rightarrow$ eeWW is based on the WW selection, which is complemented with the search for two isolated electrons. These additional electrons must satisfy the following criteria:

- The energy should be in the range from 3 GeV to 25 GeV.
- The electron candidate must have more than 90% of the energy contained in the electromagnetic calorimeter.
- The electron should be isolated from any other calorimetric cluster more than 10°.
- The electron must be matched to a track with momentum greater than 1 GeV, within 0.5° in the $r\phi$ projection.
- This track should be isolated from any other track more than 10°.

The detection efficiency for ν_e^* is estimated from Monte Carlo to be 19%. The background is mainly from WW and $q\bar{q}$ production. A total of 0.2 events is expected from Standard Model.

$\mu\mu$WW Selection

Event selection for the reaction $e^+e^- \rightarrow \nu_\mu^* \nu_\mu^* \rightarrow \mu\mu$WW is based on the WW selection, which is complemented with the search for two isolated muons. These additional muons must satisfy the following criteria:

- The momentum should be in the range from 3 GeV to 25 GeV.
- The distance of closest approach to the interaction vertex must be smaller than 200 mm in the transverse and the longitudinal directions.
- One good track (momentum greater than 1 GeV and distance of closest approach to the interaction vertex smaller than 2 mm in the transverse direction and 40 mm in the longitudinal direction) in a 10° half-opening cone around the muon track. Moreover, the calorimetric energy in this cone must be less than 10 GeV.

The detection efficiency for ν_μ^* is estimated from Monte Carlo to be 22%. The background is mainly from WW and $q\bar{q}$ production. A total of 0.7 events is expected from Standard Model.

3.3.3 Mixed decays

The reactions $e^+e^- \rightarrow \ell^*\ell^* \rightarrow \ell\gamma\nu W$ and $e^+e^- \rightarrow \nu^*\nu^* \rightarrow \nu\gamma\ell W$ give rise to events with an energetic photon, a lepton, and the decay products of a W boson. Both the hadronic decay and the leptonic decay of the W are considered.

In the case of e^*e^* and $\mu^*\mu^*$ production, the invariant mass of the excited lepton is reconstructed from the final state lepton and photon. Moreover, this invariant mass must be equal to the invariant mass recoiling against the lepton-photon system. The resolution in the mass reconstruction is shown in Table 5.

Signal	Mass resolution	
	$\ell-\gamma$ Invariant Mass	$\ell-\gamma$ Recoil Mass
$e^*e^* \rightarrow e\gamma\nu W$	1.0 GeV	1.2 GeV
$\mu^*\mu^* \rightarrow \mu\gamma\nu W$	2.7 GeV	3.6 GeV

Table 5: Invariant mass and recoil mass resolution of $\ell\gamma$ pairs for pair production of excited leptons. The estimate is based on Monte Carlo (the reconstructed mass is fitted to a Gaussian distribution).

In the case of $\tau^*\tau^*$ and $\nu^*\nu^*$ production, if the W decays hadronically, the invariant mass of the hadronic jets must be compatible with the mass of the W. Moreover, in the case of $\nu^*\nu^*$ production, the visible energy of the event, excluding the photon, must be equal to the beam energy if the W decays hadronically, or smaller if the W decays leptonically.

A general preselection is performed according to the following criteria:

- There must be one photon with energy in the range from 30 GeV to 65 GeV in the angular region $|\cos\theta| < 0.90$.
- The missing momentum must not point at low angle, $|\cos\theta_{\rm miss}| < 0.95$. This cut reduces most of the background from two photon physics, and the radiative return to the Z.

$e\gamma\nu W$ Selection

Event selection for the reaction $e^+e^- \rightarrow e^*e^* \rightarrow e\gamma\nu W$ requires the following additional criteria:

- There must be an electron with energy greater than 30 GeV.
- The sum of the invariant and recoil masses of the electron-photon system must be greater than 160 GeV, and its difference must be smaller than 10 GeV.

The detection efficiency for e^*e^* is estimated from Monte Carlo to be 57%.

The main background source is from radiative events $e^+e^- \rightarrow ee\gamma$, $e^+e^- \rightarrow \tau\tau\gamma$ and $e^+e^- \rightarrow q\bar{q}\gamma$. A total of 11 events is expected from Standard Model.

$\mu\gamma\nu$W Selection

Event selection for the reaction $e^+e^- \rightarrow \mu^*\mu^* \rightarrow \mu\gamma\nu W$ requires the following additional criteria:

- There must be a muon with momentum greater than 30 GeV.
- The sum of the invariant and recoil masses of the muon-photon system must be greater than 160 GeV, and its difference must be smaller than 20 GeV.

The detection efficiency for $\mu^*\mu^*$ is estimated from Monte Carlo to be 43%.

The main background source is from radiative events $e^+e^- \rightarrow \mu\mu\gamma$ and $e^+e^- \rightarrow \tau\tau\gamma$ and the process $e^+e^- \rightarrow WW$. A total of 8 events is expected from Standard Model.

$\tau\gamma\nu$W Selection

Event selection for the reaction $e^+e^- \rightarrow \tau^*\tau^* \rightarrow \tau\gamma\nu W$ requires the following additional criteria:

- There must be at least three jets in the event with energy greater than 5 GeV. The photon can be one of these jets.
- At least one of these jets must have less than 5 calorimetric clusters, and between 1 and 3 charged tracks. This jet is considered as a tau candidate.
- The recoil mass of the tau-photon system must be greater than 80 GeV. This is calculated from the centre of mass energy and the tau-photon quadrimomenta.
- Excluding the photon and the tau, the visible energy of the event must be smaller than 120 GeV.
- If the W boson decays leptonically, the event must have low multiplicity (no more than 8 charged tracks) and the invariant mass of the event, excluding the photon and the tau, must be smaller than 20 GeV.
- If the W boson decays hadronically, the event must have high multiplicity (at least 9 charged tracks) and the invariant mass of the event, excluding the photon and the tau, must be in the range from 60 GeV to 100 GeV.

The detection efficiency for $\tau^*\tau^*$ is estimated from Monte Carlo to be 37%.

The main background source is from radiative events $e^+e^- \rightarrow ee\gamma$, $e^+e^- \rightarrow \tau\tau\gamma$ and $e^+e^- \rightarrow q\bar{q}\gamma$, and the process $e^+e^- \rightarrow WW$. A total of 45 events is expected from Standard Model.

$\nu\gamma\ell$W Selection

Event selection for the reaction $e^+e^- \rightarrow \nu^*\nu^* \rightarrow \nu\gamma\ell W$ requires the following additional criteria:

- There must be one photon with energy in the range from 30 GeV to 65 GeV in the angular region $|\cos\theta| < 0.75$.
- There must be at least three jets in the event with energy greater than 5 GeV. The photon can be one of these jets.

- At least one of these jets must have less than 5 calorimetric clusters, and between 1 and 3 charged tracks. This jet is considered as a lepton candidate.
- In low multiplicity events (no more than 8 charged tracks), the invariant mass of the event, excluding the photon and the lepton, must be smaller than 20 GeV and the visible energy of the event, excluding the photon, must be smaller than 70 GeV.
- In high multiplicity events (at least 9 charged tracks), the invariant mass of the event, excluding the photon and the lepton, must be in the range from 60 GeV to 100 GeV and the visible energy of the event, excluding the photon, must be smaller than 120 GeV.

The detection efficiency for $\nu^*\nu^*$ is estimated from Monte Carlo to be 38% for $\nu_e^*\nu_e^*$, 28% for $\nu_\mu^*\nu_\mu^*$ and 19% for $\nu_\tau^*\nu_\tau^*$.

The main background source is from radiative events $e^+e^-\to ee\gamma$, $e^+e^-\to \tau\tau\gamma$ and $e^+e^-\to q\bar{q}\gamma$, and the process $e^+e^-\to$ WW. A total of 12 events is expected from Standard Model.

3.4 Single production

For $\ell\ell^*$ and $\nu\nu^*$ production, we consider the radiative decay ($\ell\ell\gamma$ and $\nu\nu\gamma$), the charged current decay ($\ell\nu$W and $\nu\ell$W), and the neutral current decay modes ($\ell\ell$Z and $\nu\nu$Z). In the case of charged and neutral current decays, both the hadronic, $W\to q\bar{q}$ and $Z\to q\bar{q}$, and the leptonic decays, $W\to\ell\nu$, $Z\to\ell\ell$ and $Z\to\nu\nu$, are considered.

3.4.1 Radiative decays

Event selection for the reactions $e^+e^-\to \ell\ell^* \to \ell\ell\gamma$ and $e^+e^-\to \nu\nu^* \to \nu\nu\gamma$ is based on the fact that these processes contain two leptons and a photon. In the case of charged excited leptons a kinematical fit is performed to improve the resolution in the energy of leptons and the photon (it is essential to calculate the energy of taus). The resolution in the reconstruction of the invariant mass of charged excited leptons is shown in Table 6. The Standard Model background comes from lepton pair production with initial and final state radiation.

Signal	Selection	Resolution for different m_* (GeV)		
		100	150	195
$ee^*\to ee\gamma$	$ee\gamma$	0.9 GeV	1.3 GeV	1.1 GeV
$\mu\mu^*\to\mu\mu\gamma$	$\mu\mu\gamma$	0.8 GeV	1.1 GeV	0.7 GeV
$\tau\tau^*\to\tau\tau\gamma$	$\tau\tau\gamma$	1.2 GeV	1.2 GeV	1.7 GeV
$ee^*\to e\nu_e W$	$qqe\nu$	6.3 GeV	1.4 GeV	1.4 GeV
$\mu\mu^*\to\mu\nu_\mu W$	$qq\mu\nu$	9.0 GeV	2.6 GeV	8.5 GeV
$\nu_e\nu_e^*\to\nu_e eW$	$qqe\nu$	11 GeV	12 GeV	13 GeV
$\nu_\mu\nu_\mu^*\to\nu_\mu\mu W$	$qq\mu\nu$	11 GeV	13 GeV	17 GeV

Table 6: Invariant mass resolution of excited leptons for single production. The estimate is based on Monte Carlo (the reconstructed mass is fitted to a Gaussian distribution).

A preselection of leptonic events with a hard photon is performed according to the following cuts:

- To reject hadronic events, the number of tracks in the central tracking chamber is required to be less than 8.
- The selected events are required to have an identified photon with energy greater than 20 GeV, in the barrel region, $|\cos\theta| < 0.75$.

eeγ Selection

In the reaction $e^+e^- \rightarrow ee^* \rightarrow ee\gamma$ there is a large contribution from the t channel diagram. Thus, for a large fraction of signal events, one electron is lost in the beam pipe and only the electron and photon from the decay of the excited electron are visible in the detector. The following additional criteria are required:

- One or two tracks with momentum greater than 1 GeV. At least one identified electron.
- After kinematical fit, at least one eγ pair must have an invariant mass above 70 GeV.

The detection efficiency for e^* is estimated from Monte Carlo to be 61%, slightly dependent on the e^* mass. The main background is from $e^+e^- \rightarrow ee\gamma$. A total of 714 events is expected from Standard Model.

$\mu\mu\gamma$ Selection

Event selection for the reaction $e^+e^- \rightarrow \mu\mu^* \rightarrow \mu\mu\gamma$ requires the following additional criteria:

- One or two tracks with momentum greater than 1 GeV.
- One identified muon. In case there is only one track in the muon spectrometer, a minimum ionising particle is searched for around the second track measured in the central tracker, or in the direction of the missing momentum.
- After kinematical fit, at least one pair $\mu\gamma$ must have an invariant mass above 70 GeV.

The detection efficiency for μ^* is estimated from Monte Carlo to be 61%, slightly dependent on the μ^* mass. The main background is from radiative events $e^+e^- \rightarrow \mu\mu\gamma$. A total of 67 events is expected from Standard Model.

$\tau\tau\gamma$ Selection

Event selection for the reaction $e^+e^- \rightarrow \tau\tau^* \rightarrow \tau\tau\gamma$ requires the following additional criteria:

- At least two charged jets.
- No calorimetric cluster with energy greater than 5 GeV, excluding those associated to the photon and the two charged jets.
- After the kinematical fit (assuming one photon and two taus in the event), at least one of the tau candidates must have a fitted energy exceeding its visible energy more than 10 GeV. Moreover, its visible energy must be greater than 10 GeV. This jet must be inside the acceptance of the electromagnetic calorimeter.

- At least one pair $\tau\gamma$ must have an invariant mass above 70 GeV.

The detection efficiency for τ^* is estimated from Monte Carlo to be 42%, slightly dependent on the τ^* mass. The main background is from $e^+e^- \rightarrow \tau\tau\gamma$ and $e^+e^- \rightarrow ee\gamma$ events. There is also a little contribution from radiative dimuon events $e^+e^- \rightarrow \mu\mu\gamma$. A total of 69 events is expected from Standard Model.

$\nu\nu\gamma$ Selection

Event selection for the reaction $e^+e^- \rightarrow \nu\nu^* \rightarrow \nu\nu\gamma$ is based on the fact that this process contains one energetic photon and no other visible particle. The following criteria are applied:

- One photon in the barrel region, $|\cos\theta| < 0.75$, with energy greater than 0.3 times the beam energy.
- No other particles detected, neither in central tracking system, nor in muon chambers. The energy of any calorimetric cluster should be less than 5 GeV, excluding the photon. To reduce the background from cosmic rays, there are must be less than eight calorimetric clusters in the event.

The detection efficiency for ν^* is estimated from Monte Carlo to be 64%, slightly dependent on the ν^* mass. The background is mainly from radiative neutrino events $e^+e^- \rightarrow \nu\nu\gamma$. A total of 232 events is expected from Standard Model. It has been taken into account that the trigger is not 100% efficient in events with a single photon in the detector. From the Monte Carlo simulation, this efficiency is 97%. For all the other selections described in this note, the trigger inefficiency is negligible.

3.4.2 Charged current decays

The reactions $e^+e^- \rightarrow \ell\ell^* \rightarrow \ell\nu W$ and $e^+e^- \rightarrow \nu\nu^* \rightarrow \nu\ell W$ give rise to final states similar to Standard Model W pair production.

$W \rightarrow q\bar{q}$

If the W boson decays hadronically, we use the $qq\ell\nu$ selections described in Section 3.3.2. However, in order to be sensitive to excited neutrinos with mass close to $\sqrt{s}$, and charged excited leptons with mass close to the W mass, where the final state neutrino carries low momentum, the cuts on minimum missing momentum and maximum visible energy are not applied in the single production searches.

qqX Selection

When the charged lepton escapes through the beam pipe, or its energy is very low, it is not detected. For this situation, the $qq\ell\nu$ selections are complemented with a qqX selection which requires the following criteria:

- The number of charged tracks (with distance of closest approach to the interaction vertex smaller than 2 mm in the transverse direction) must be greater than 4, and the number of calorimetric clusters must be greater than 15.
- The polar angle θ of the missing momentum must be in the range $18^\circ < \theta < 162^\circ$.

- The event is forced into two jets with a Durham algorithm. To reject events with three or more jets the $YCUT_{23}$ is required to be less than 0.02. To reject $q\bar{q}$ background, the acoplanarity between the two jets must be greater than 10°.

- The invariant mass of the two jets must be in the range from 60 GeV to 100 GeV and the visible energy must be smaller than 150 GeV.

- To reject WW background with one W decaying hadronically, and an undetected lepton from the other W, the recoiling mass is required to be smaller than 70 GeV.

$\mathbf{W} \rightarrow \boldsymbol{\ell\nu}$

If the W boson decays leptonically, the event contains two charged leptons and two neutrinos, $e^+e^- \rightarrow \ell\ell^* \rightarrow \ell\nu W \rightarrow \ell\nu\ell\nu$ or $e^+e^- \rightarrow \nu\nu^* \rightarrow \nu\ell W \rightarrow \nu\ell\ell\nu$.

A preselection of leptonic events is performed according to the following criteria:

- To reject hadronic events and cosmic background, events are required at least 1 track (closer than 2 mm to the interaction vertex in the transverse direction) and no more than 8 tracks.

- The missing momentum must not point at low angle, $|\cos\theta_{\mathrm{miss}}| < 0.9$.

- To reject dilepton background, events must not contain any cluster in the electromagnetic calorimeter or track in the muon chambers with energy greater than $0.85 * E_{beam}$.

- The missing momentum in the transverse direction must be greater than 10 GeV.

- The event must contain two charged jets with energy greater than 20 GeV and 3 GeV respectively, and acoplanarity between 10° and 170°. These jets are identified as charged leptons.

In addition the following criteria are applied:

• Events with at least one identified electron are considered as candidates for the reactions $e^+e^- \rightarrow ee^* \rightarrow e\nu W \rightarrow e\nu\ell\nu$ and $e^+e^- \rightarrow \nu_e\nu_e^* \rightarrow \nu e W \rightarrow \nu e\ell\nu$.

• Events with at least one identified muon are considered as candidates for the reactions $e^+e^- \rightarrow \mu\mu^* \rightarrow \mu\nu W \rightarrow \mu\nu\ell\nu$ and $e^+e^- \rightarrow \nu_\mu\nu_\mu^* \rightarrow \nu\mu W \rightarrow \nu\mu\ell\nu$.

• All events are considered as candidates for the reactions $e^+e^- \rightarrow \tau\tau^* \rightarrow \tau\nu W \rightarrow \tau\nu\ell\nu$ and $e^+e^- \rightarrow \nu_\tau\nu_\tau^* \rightarrow \nu\tau W \rightarrow \nu\tau\ell\nu$.

The combined detection efficiency for ℓ^* and ν^* (with W decaying hadronically or leptonically) as it is shown in Table 9 depends on the mass and flavour of the excited lepton. The quoted efficiencies for e^* correspond to the $f = -f'$ scenario. If $f = f'$ the e^* efficiency in the charged current decay is significantly smaller (due to the forward peaked differential cross section), but this is not a problem, as in that case the radiative decay channel provides a clean signature, see last paragraph of Section 1. The number of expected events from Standard Model for each flavour of excited lepton selection is: 764 for e^* and ν_e^*, 694 for μ^* and ν_μ^*, and 1377 for τ^* and ν_τ^*.

3.4.3 Neutral current decays

The reactions $e^+e^- \to \ell\ell^* \to \ell\ell Z$ and $e^+e^- \to \nu\nu^* \to \nu\nu Z$ where the Z boson may decay either hadronically or leptonically are considered.

$Z \to q\bar{q}$

If the Z boson decays hadronically, single production of charged excited leptons gives rise to final states with jets and visible leptons, $e^+e^- \to \ell\ell^* \to \ell\ell Z \to \ell\ell q\bar{q}$. Single production of neutral excited leptons gives rise to final states with a pair of jets and missing energy, $e^+e^- \to \nu\nu^* \to \nu\nu Z \to \nu\nu q\bar{q}$. In this case, we have not designed a dedicated selection algorithm. However the $qq\ell\nu$ and qqX selections used in the search for singly produced excited leptons decaying through charged currents (Section 3.3.2) are sensitive to this signal. The $qq\ell\nu$ are used in the search for $\ell\ell q\bar{q}$ final states, whereas the qqX selection is used in the search for $\nu\nu q\bar{q}$ final states.

$Z \to \ell\ell$ and $Z \to \nu\nu$

If the Z boson decays leptonically, single production of charged excited leptons gives rise to final states with two or four charged leptons, $e^+e^- \to \ell\ell^* \to \ell\ell Z \to \ell\ell\ell\ell$, or $e^+e^- \to \ell\ell^* \to \ell\ell Z \to \ell\ell\nu\nu$. For single production of neutral excited leptons we consider the case in which the Z boson decays into a pair of charged leptons, $e^+e^- \to \nu\nu^* \to \nu\nu Z \to \nu\nu\ell\ell$, giving rise to a final state with a pair of leptons visible in the detector. Thus, we have experimental signatures with either two or four charged leptons in the final state.

In case of two charged leptons in the final state, we use the preselection used in the search for $\ell\ell^* \to \ell\nu W \to \ell\nu\ell\nu$, described in Section 3.4.2. In addition, the following criteria are applied:

• Events with at least one identified electron are considered as candidates for the reaction $e^+e^- \to ee^* \to eeZ \to ee\nu\nu$.

• Events with at least one identified muon are considered as candidates for the reaction $e^+e^- \to \mu\mu^* \to \mu\mu Z \to \mu\mu\nu\nu$.

• All events are considered as candidates for the reaction $e^+e^- \to \tau\tau^* \to \tau\tau Z \to \tau\tau\nu\nu$.

In the search for events with four charged leptons in the final state, a preselection is performed according to the following cuts:

- There must be at least 1 track closer than 2 mm to the interaction vertex in the transverse direction and no more than 8 tracks.
- The missing momentum must not point at low angle, $|\cos\theta_{\mathrm{miss}}| < 0.9$.
- The event must contain at least three charged jets with energy greater than 3 GeV. These are identified as charged leptons.
- For at least one of the combinations, the invariant mass of a pair of jets must be in the range from 80 GeV to 100 GeV.

In addition to the preselection the following criteria are applied:

• Events with at least one identified electron are considered as candidates for the reaction $e^+e^- \to ee^* \to eeZ \to ee\ell\ell$.

• Events with at least one identified muon are considered as candidates for the reaction $e^+e^- \to \mu\mu^* \to \mu\mu Z \to \mu\mu\ell\ell$.

• All the events satisfying the preselection cuts are considered as candidates for the reaction $e^+e^- \rightarrow \tau\tau^* \rightarrow \tau\tau Z \rightarrow \tau\tau\ell\ell$.

The combined detection efficiency for ℓ^* and ν^* (with Z decaying hadronically or leptonically) as it is shown in Table 9 depends on the mass and flavour of the excited lepton. The quoted efficiencies for e^* correspond to the $f = -f'$ scenario. The number of expected events from Standard Model for each flavour of excited lepton selection is: 692 for e^*, 617 for μ^*, 1308 for τ^* and 357 for ν^*.

4 Results and limits

The number of candidates observed in data is compared with the expected background from Standard Model, searching for an excess indicating the existence of excited leptons. However, no such excess has been found.

From pair production searches, taking into account the number of candidates found and expected, the luminosity, the branching ratio and the efficiency, upper limits on the cross section are set at 95% confidence level, using Bayesian statistics and assuming a flat *a priori* distribution for the signal. The results are shown in terms of lower limits on the mass of the excited leptons.

From single production searches, the invariant mass of excited lepton may be calculated in the reactions $\ell\ell^* \rightarrow \ell\ell\gamma$, $\ell\ell^* \rightarrow \ell\nu W \rightarrow \ell\nu q\bar{q}$ and $\nu\nu^* \rightarrow \nu\ell W \rightarrow \nu\ell q\bar{q}$. The resolution of the invariant mass reconstruction depends on the final state topology and is shown in Table 6. In these selections, each event is a candidate for excited lepton with mass compatible with the reconstructed invariant mass, whereas in the other selections, each event is considered as a candidate for excited lepton of any mass. For each flavour of excited lepton, a scan on the mass is performed. For each mass, the number of candidates observed and expected is calculated, and taking into account the luminosity, the branching ratio and the efficiency, an upper limit on the cross section is obtained, using Bayesian statistics and assuming a flat *a priori* distribution for the signal. The result is plotted in terms of an upper limit on the coupling constant (which determines the cross section for single production) as a function of the mass of excited lepton. The results are presented for two particular scenarios often used in excited lepton searches, $f = f'$ and $f = -f'$. For each scenario and flavour of excited lepton, the results of all selections corresponding to the allowed decay channels are combined to calculate an upper limit on the coupling constant, $|f|/\Lambda$. In the cases of charged excited lepton with $f = f'$ and excited neutrinos with $f = -f'$ the radiative decay is allowed and provides most of the experimental sensitivity, allowing to set a low upper limit to the coupling constant. In the complementary cases, the radiative decay is forbidden, and the limits are calculated from the weak decay searches.

Results from pair production searches are summarised in Table 7.

Figure 3(a) shows the sum of invariant plus recoil mass of two hadronic jets, in the $WW \rightarrow q\bar{q}q\bar{q}$ selection. Figure 3(b) shows the invariant mass of two hadronic jets, in the $WW \rightarrow q\bar{q}\ell\nu$ selection. These results have been combined to derive lower limits on the mass of excited leptons in both scenarios, $f = f'$ and $f = -f'$. Moreover, mass limits have been derived independently of the coupling constants f and f'. A scan has been performed for all the possible ratios of the two coupling constants: $\frac{f}{f'} = \tan\theta$ with $\theta \in (0, \pi)$. For each value of $\frac{f}{f'}$, the corresponding decay fractions $\ell^*\ell^* \rightarrow \ell\ell\gamma\gamma$, $\ell^*\ell^* \rightarrow \nu\nu WW$ and $\ell^*\ell^* \rightarrow \ell\gamma\nu W$ ($\nu^*\nu^* \rightarrow \nu\nu\gamma\gamma$, $\nu^*\nu^* \rightarrow \ell\ell WW$

Signal	Data	Bkg (S.M.)	Eff
$e^*e^* \to ee\gamma\gamma$	1	0.8	46.4%
$\mu^*\mu^* \to \mu\mu\gamma\gamma$	1	0.5	44.4%
$\tau^*\tau^* \to \tau\tau\gamma\gamma$	0	0.2	43.1%
$\nu^*\nu^* \to \nu\nu\gamma\gamma$	2	1.9	44.9%
$\ell^*\ell^* \to \nu\nu WW$	2978	2993	64.9%
$\nu_e^*\nu_e^* \to eeWW$	0	0.2	19.1%
$\nu_\mu^*\nu_\mu^* \to \mu\mu WW$	0	0.7	21.8%
$\nu_\tau^*\nu_\tau^* \to \tau\tau WW$	2978	2993	69.1%
$e^*e^* \to e\gamma\nu W$	13	11	56.8%
$\mu^*\mu^* \to \mu\gamma\nu W$	5	8	42.7%
$\tau^*\tau^* \to \tau\gamma\nu W$	56	45	36.6%
$\nu_e^*\nu_e^* \to \nu\gamma eW$			38.1%
$\nu_\mu^*\nu_\mu^* \to \nu\gamma\mu W$	18	12	28.5%
$\nu_\tau^*\nu_\tau^* \to \nu\gamma\tau W$			18.6%

Table 7: Results from the searches for pair produced excited leptons. The second column shows the number of selected events, whereas the third one shows the number of expected events from Standard Model. The fourth column shows the percentage of Monte Carlo signal events that were selected as candidates.

and $\nu^*\nu^* \to \nu\gamma\ell W$ in the case of excited neutrinos), have been calculated, and taking into account the number of observed and expected candidates in each selection, as well as the luminosity, the efficiencies and the cross section, lower limits on the mass of excited leptons have been set. For each flavour of excited lepton, the lowest limit is considered as an absolute limit, independent of the coupling constants. In Table 8 the mass limits are shown.

Excited Lepton	95% CL Mass Limit (GeV)		
Coupling	$f = f'$	$f = -f'$	Coup. Indep.
e^*	100.1	96.2	96.0
μ^*	100.3	96.2	96.2
τ^*	99.9	96.2	94.9
ν_e^*	99.3	99.5	98.5
ν_μ^*	99.4	99.5	98.5
ν_τ^*	93.9	99.4	92.7

Table 8: 95% confidence level lower mass limits for excited leptons. These limits are derived from the combined searches for pair produced excited leptons decaying radiatively and weakly.

Results from searches for single production of excited leptons are summarised in Table 9.

Figures 4(a), 4(b) and 4(c) show all combinations of invariant mass $m_{e\gamma}$, $m_{\mu\gamma}$ and $m_{\tau\gamma}$ above 70 GeV, together with the expected background from Standard Model. No significant structure is observed. Figure 4(d) shows the energy of the photon in the single photon selection.

Figures 5(a), 5(b) and 5(c) show the recoil mass against the identified lepton in the qqeν, qq$\mu\nu$ and qq$\tau\nu$ selections; in the reaction $\ell\ell^* \to \ell\nu W \to \ell\nu q\bar{q}$ the recoil mass against the

Signal	Data	Bkg (S.M.)	Efficiency for different m_* (GeV)		
			100	150	195
$ee^* \to ee\gamma$	682	714	51.6%	64.7%	66.0%
$\mu\mu^* \to \mu\mu\gamma$	72	67	59.6%	63.3%	59.8%
$\tau\tau^* \to \tau\tau\gamma$	50	69	44.3%	44.1%	38.7%
$\nu\nu^* \to \nu\nu\gamma$	230	232	53.1%	67.9%	70.0%
$ee^* \to e\nu_e W$	728	764	75.8%	74.0%	51.6%
$\nu_e\nu_e^* \to \nu_e eW$			59.5%	68.9%	66.2%
$\mu\mu^* \to \mu\nu_\mu W$	684	694	61.1%	64.6%	55.6%
$\nu_\mu\nu_\mu^* \to \nu_\mu\mu W$			67.8%	64.5%	62.8%
$\tau\tau^* \to \tau\nu_\tau W$	1365	1377	55.8%	54.5%	54.2%
$\nu_\tau\nu_\tau^* \to \nu_\tau\tau W$			46.4%	60.6%	61.4%
$ee^* \to eeZ$	663	692	70.9%	26.4%	75.6%
$\mu\mu^* \to \mu\mu Z$	608	617	62.3%	40.3%	52.9%
$\tau\tau^* \to \tau\tau Z$	1307	1308	42.5%	21.6%	37.7%
$\nu\nu^* \to \nu\nu Z$	350	357	31.9%	13.9%	40.2%

Table 9: Number of candidates for excited leptons obtained from the searches for singly produced excited leptons. The second column shows the number of selected events, whereas the third one shows the number of expected events from Standard Model. The columns 4-6 show the percentage of Monte Carlo signal events that were selected as candidates for different masses of excited leptons.

visible lepton corresponds to the excited lepton mass. No significant structure is observed. Figures 5(d), 5(e) and 5(f) show the event invariant mass for the qqeν, qq$\mu\nu$ and qq$\tau\nu$ selections; in the reaction $\nu\nu^* \to \nu\ell W \to \nu\ell q\bar{q}$ the event invariant mass corresponds to the excited neutrino mass. Figure 3(c) shows the visible energy of the qqX selected events.

Figure 6 shows the limits on the coupling constant derived from single production searches.

Conclusion

A search for pair produced excited electrons, muons, taus and neutrinos has been performed for radiative $\ell^* \to \ell\gamma$, $\nu^* \to \nu\gamma$, and charged current decays $\ell^* \to \nu\mathrm{W}$, $\nu^* \to \ell\mathrm{W}$. The reactions $\ell^*\ell^* \to \ell\gamma\nu\mathrm{W}$ and $\nu^*\nu^* \to \nu\gamma\ell\mathrm{W}$ have been searched for the first time in the L3 experiment.

A search for singly produced excited leptons has been performed for radiative $\ell^* \to \ell\gamma$, $\nu^* \to \nu\gamma$, charged current $\ell^* \to \nu\mathrm{W}$, $\nu^* \to \ell\mathrm{W}$, and neutral current decays $\ell^* \to \ell\mathrm{Z}$, $\nu^* \to \nu\mathrm{Z}$. The searches for weak decays with the W or Z boson decaying leptonically are performed for the first time in the L3 experiment.

We see no evidence for excited electrons, muons, taus or neutrinos. The observed candidate events are consistent with Standard Model expectations. From pair production searches lower mass limits at 95% confidence level are set up to the kinematical limit. Mass limits independent of the coupling constants f and f' have been derived.

From single production searches, limits on the coupling constants $\frac{|f|}{\Lambda}$ are set in the range from 10^{-4} GeV^{-1} to 1 GeV^{-1} for ℓ^* and ν^* masses up to 200 GeV. These results considerably extend our previous limits [16]. All results are preliminary.

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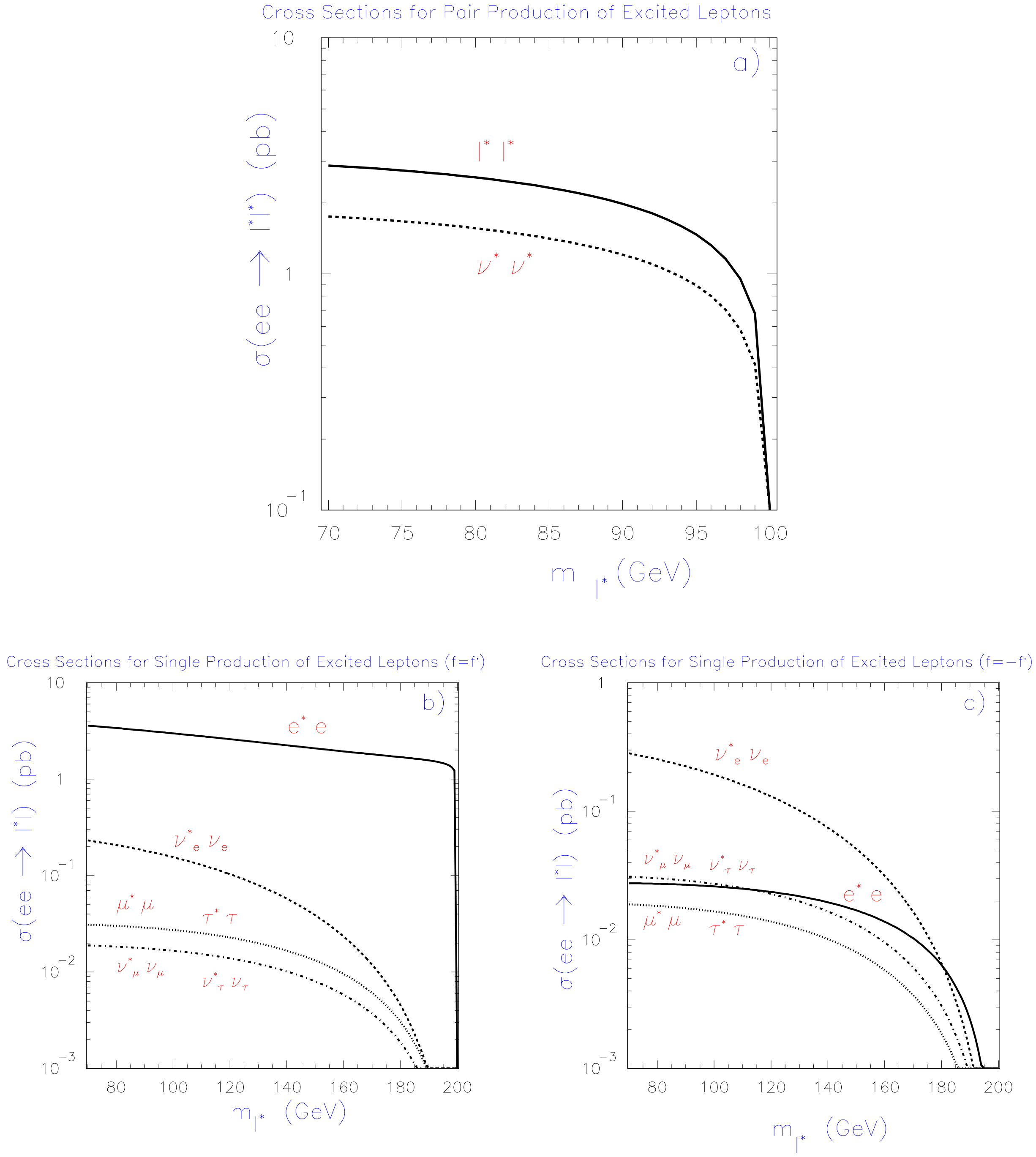

Figure 1: Cross section at $\sqrt{s} = 200$ GeV, for: (a) pair production of excited leptons, ($e^+e^- \rightarrow \ell^*\ell^*$ and $e^+e^- \rightarrow \nu^*\nu^*$); (b) single production of excited leptons ($e^+e^- \rightarrow \ell\ell^*$ and $e^+e^- \rightarrow \nu\nu^*$) for $f = f'$ and $\Lambda = 1$ TeV; (c) single production of excited leptons for $f = -f'$ and $\Lambda = 1$ TeV.

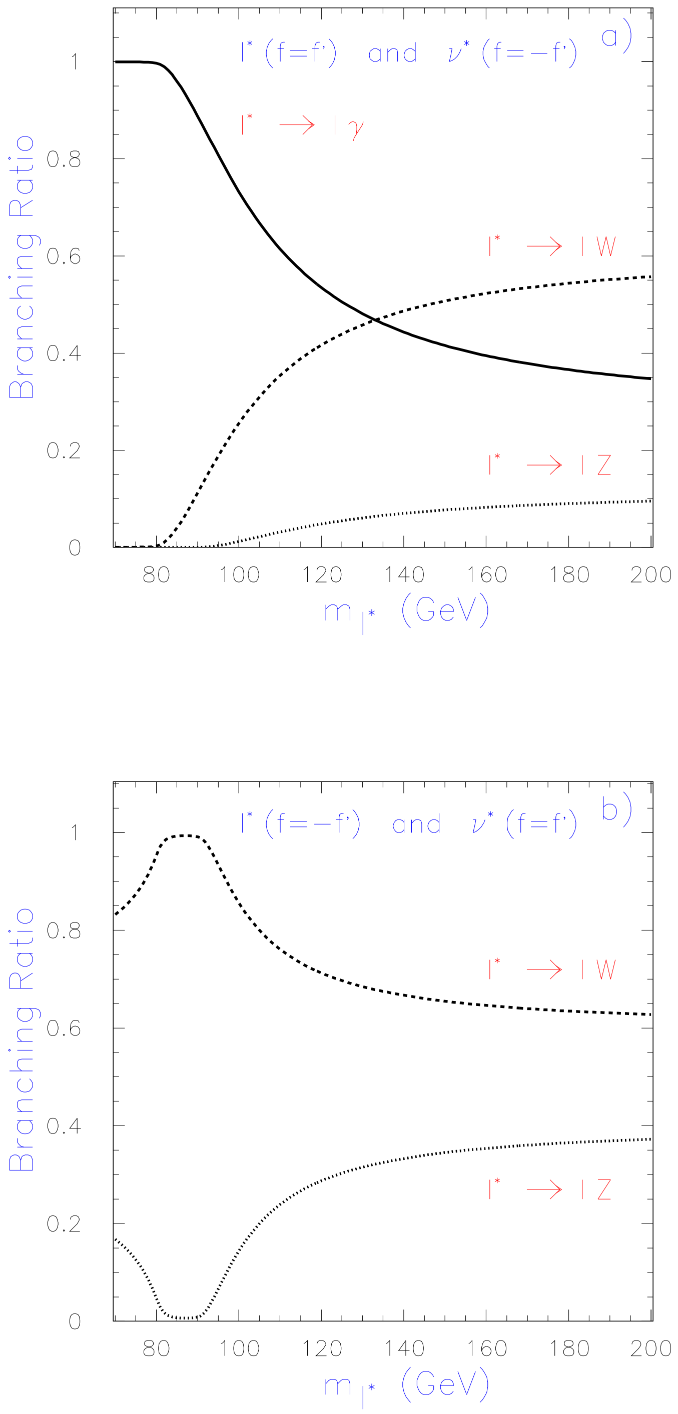

Figure 2: Branching ratios of: (a) charged excited leptons with $f = f'$ and excited neutrinos with $f = -f'$; (b) charged excited leptons with $f = -f'$ and excited neutrinos with $f = f'$.

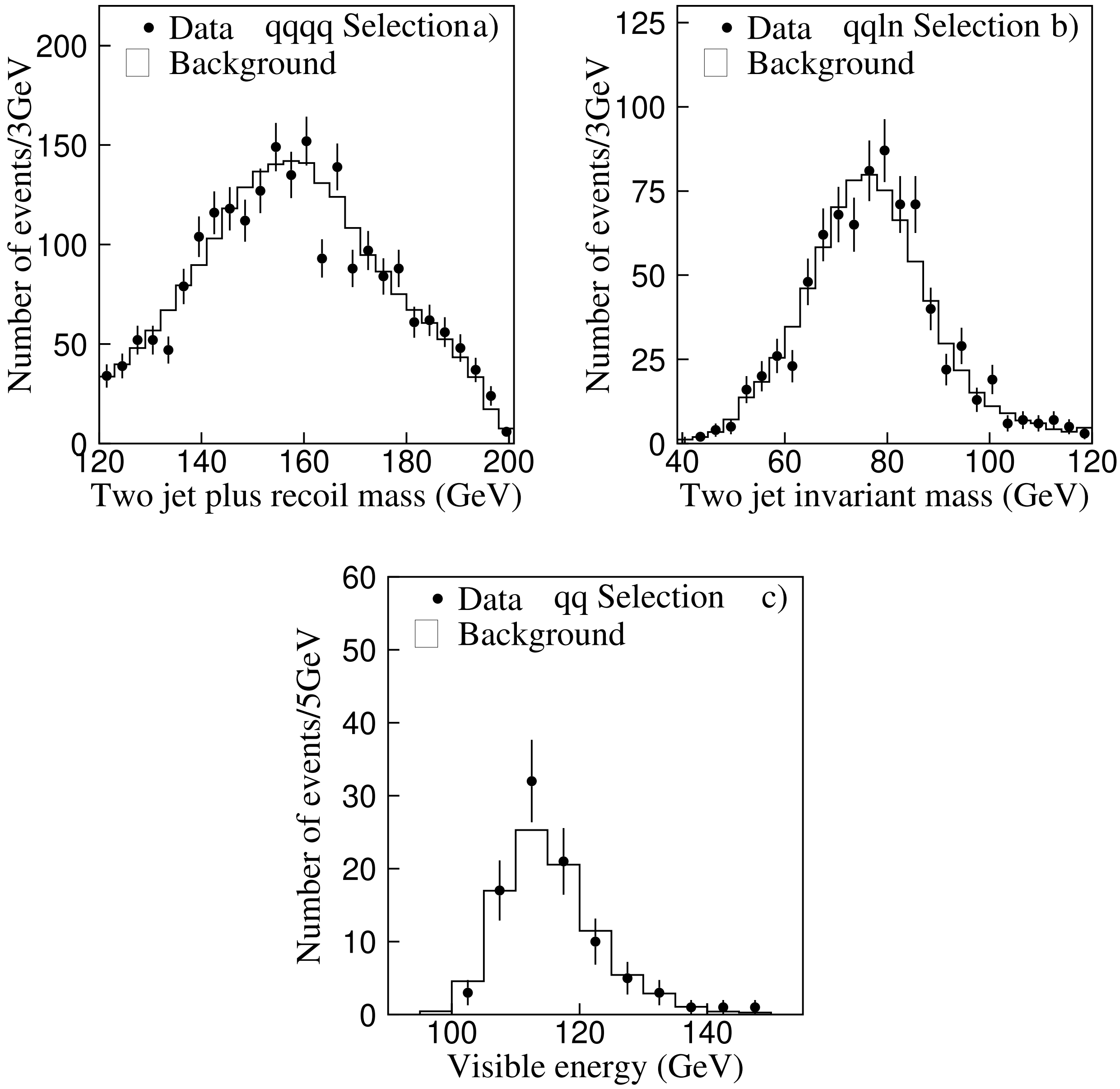

Figure 3: (a): Sum of invariant plus recoil mass of two hadronic jets, in the WW $\to$ $q\bar{q}q\bar{q}$ selection. (b): Invariant mass of two hadronic jets, in the WW $\to$ $q\bar{q}\ell\nu$ selection. (c): Visible energy of the qqX selected events. The solid line is the Standard Model expected background, and the dots are the data.

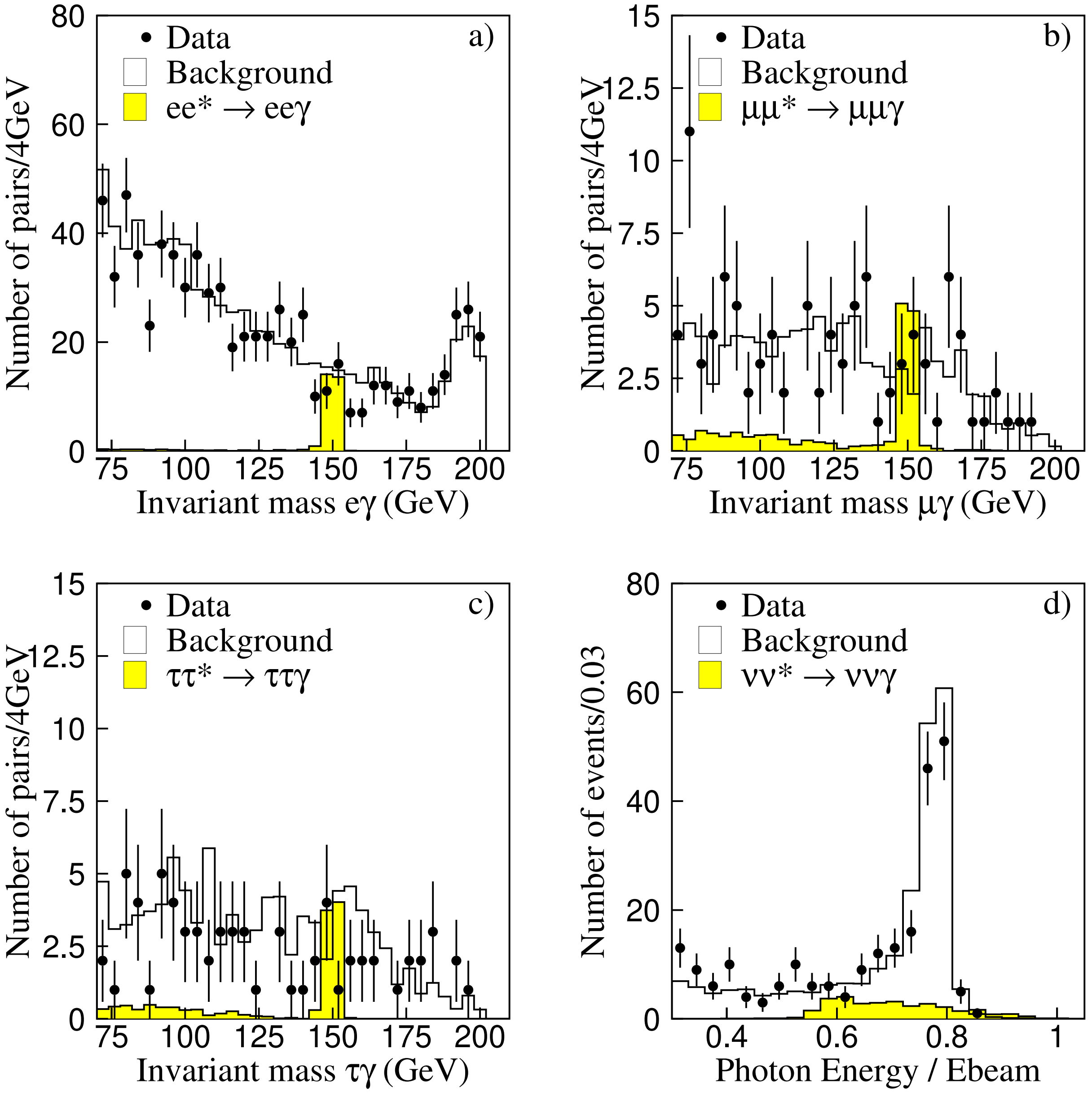

Figure 4: The invariant mass distributions for: (a) eγ, (b) $\mu\gamma$, and (c) $\tau\gamma$ pairs, in $\ell\ell\gamma$ selection. Energy of single photon divided by the beam energy, (d) for single γ selection. The expected signal for an excited lepton with a mass of 150 GeV (arbitrary normalised) is shown together with data and Standard Model background.

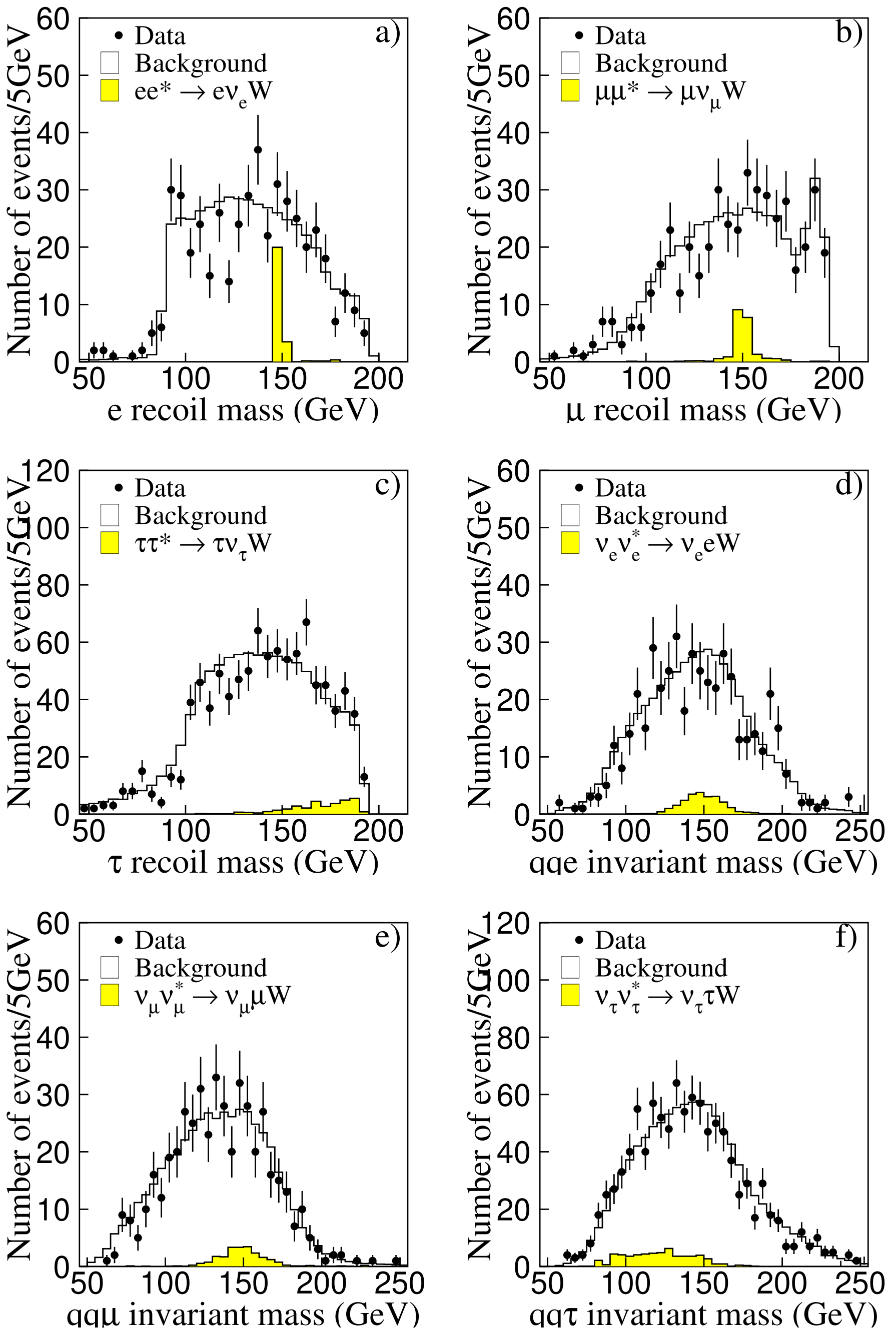

Figure 5: Recoil mass distributions for (a) electron, (b) muon, and (c) tau, in the qq$\ell\nu$ selections. Invariant mass distributions for: (d) qqeν, (e) qq$\mu\nu$, and (f) qq$\tau\nu$, selected events. The expected signal for an excited lepton with a mass of 150 GeV (arbitrary normalised) is shown together with data and Standard Model background.

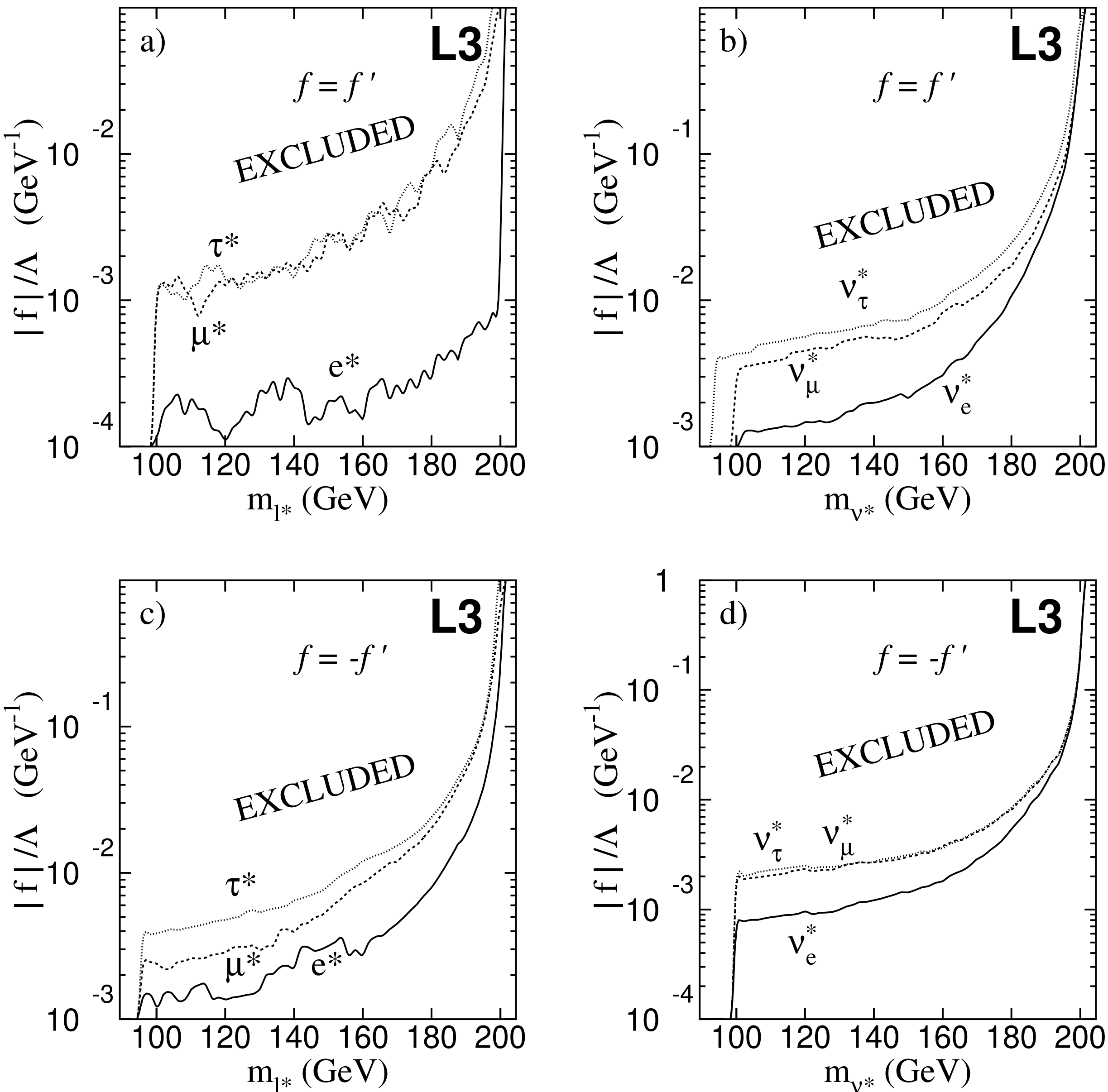

Figure 6: 95% confidence level upper limit on the coupling constant $|f|/\Lambda$, as a function of the excited lepton mass with $f = f'$: (a) e^*, μ^* and τ^* , (b) ν_e^*, ν_μ^* and ν_τ^*, and with $f = -f'$: (c) e^*, μ^* and τ^*, (d) ν_e^*, ν_μ^* and ν_τ^*.