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Search for Excited Leptons in e^+e^- Annihilation at $\sqrt{s} = 172$ GeV

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Abstract

We have searched for excited leptons e^*, μ^*, τ^* and ν_e^* in e^+e^- collisions at $\sqrt{s}$ = 172 GeV using the 10.25 pb^{-1} of data collected by the L3 detector at LEP. No evidence has been found for their existence. From an analysis of the expected $\ell^*\ell^*$ pair production in the channels $\ell\ell\gamma\gamma$, $\ell\gamma\nu W(\ell = e, \mu, \tau)$ and $\nu\nu\gamma\gamma$, Excited states are excluded at 95% confidence level for mass up to 85.1 GeV for e^*, 85.0 GeV for μ^*, 84.1 GeV for τ^* and 78.9 GeV for ν_e^* assuming the same couplings as for standard leptons. From an analysis of the expected $\ell\ell^*$ single production in channels $ee\gamma$, $\mu\mu\gamma$, $\tau\tau\gamma$, $\nu_e eW$ and $\nu\nu\gamma$, the upper limits on the couplings λ/m_{ℓ^*} up to $m_{\ell^*} = 172$ GeV are determined.

1 Introduction

The importance of the existence of excited leptons and their experimental searches are summirized in our previou paper [1] and in other papers [2]. In this note we report a search based on the 10.25 pb^{-1} of data collected by the L3 experiment at the centre of mass energy of 172 GeV.

At $\mathrm{e^+e^-}$ colliders, excited leptons can be produced either in pairs ($\mathrm{e^+e^-} \longrightarrow \ell^*\ell^*$) or singly ($\mathrm{e^+e^-} \longrightarrow \ell\ell^*$). The lowest order pair production cross section can be found in ref. [3]. For single ℓ^* production, the effective Lagrangian [4] can be written as:

$$\mathcal{L}_{\mathrm{eff}} = \sum_{\mathrm{V}=\gamma,\mathrm{Z},\mathrm{W}} \frac{\mathrm{e}}{\Lambda} \bar{\Psi}_{\ell^*} \sigma^{\mu\nu} (\mathrm{C}_{\mathrm{V}\ell^*\ell} - \mathrm{D}_{\mathrm{V}\ell^*\ell}\gamma_5) \Psi_\ell \partial_\mu \mathrm{V}_\nu + \mathrm{h.c.}$$

where Λ is the composite mass scale and $\mathrm{C}_{\mathrm{V}\ell^*\ell}$ and $\mathrm{D}_{\mathrm{V}\ell^*\ell}$ are unknown coupling constants. The precise muon g-2 measurements impose $|\mathrm{C}_{\mathrm{V}\ell^*\ell}| = |\mathrm{D}_{\mathrm{V}\ell^*\ell}|$ [4,5]. The absence of the electric dipole moment of electrons suggests that both $\mathrm{C}_{\mathrm{V}\ell^*\ell}$ and $\mathrm{D}_{\mathrm{V}\ell^*\ell}$ are real. We assume that the excited lepton and its corresponding excited neutrino are a weak doublet, therefore the coupling constants satisfy $\mathrm{C}_{\mathrm{V}\ell^*\ell} = \mathrm{D}_{\mathrm{V}\ell^*\ell}$, and we have:

$$\mathrm{C}_{\gamma\ell^*\ell} = \frac{1}{2}(\mathrm{t}_3 f + \frac{\mathrm{Y}}{2} f'), \quad \mathrm{C}_{\mathrm{Z}\ell^*\ell} = \frac{1}{2}(\mathrm{t}_3 f \cot\theta_{\mathrm{W}} - \frac{\mathrm{Y}}{2} f' \tan\theta_{\mathrm{W}}), \quad \mathrm{C}_{\mathrm{W}\ell^*\ell} = \frac{f}{2\sqrt{2}\sin\theta_{\mathrm{W}}},$$

where f and f' are the free parameters for SU(2) and U(1) respectively, t_3 is the third component of weak isospin of ℓ^*, Y is the hypercharge of ℓ^*, and θ_{W} is the weak mixing angle. Throughout this paper we assume that t_3 and Y are the same for ℓ and ℓ^*.

For excited charged leptons, we assume $f = f'$ in the above formula, so that $f/\Lambda (= \sqrt{2}\lambda/\mathrm{m}_{\ell^*})$ is the only free parameter in the Lagrangian [6]. An excited charged lepton is expected to decay immediately into its corresponding standard lepton and a photon with a 100% branching ratio if its mass is smaller than that of the W. For higher mass, the decays $\ell^* \to \mathrm{Z}\ell$ and $\ell^* \to \mathrm{W}\nu$ become important and the branching ratio of $\ell^* \to \ell\gamma$ is then a function of m_{ℓ^*} [7]. For the excited neutrino ν^*, both $f = f'$ and $f \neq f'$ cases, described in detail in [1], are studied. In the former case the $\gamma\nu\nu^*$ coupling vanishes and $\nu^* \longrightarrow \nu\mathrm{Z}$ and $\nu^* \longrightarrow \mathrm{eW}$ are the only decay modes allowed, whereas in the latter case the $\gamma\nu\nu^*$ coupling exists and $\nu^* \longrightarrow \nu\gamma$ decay would have a large branching ratio. In this analysis the searches are limited to the ν_{e}^*, which is assumed to be the lightest excited neutrino.

All the above processes have been generated by a Monte Carlo program according to the differential cross section of ref. [4] with an angular distribution of $1 + \cos\theta$ assigned to the ℓ^* decay. The relevant branching ratios of ℓ^* decays are taken from ref. [7]. The effect of initial state radiation is not included in the Monte Carlo generators but is taken into account in our cross section calculations. The generated events have been passed through the L3 detector simulation [8].

2 Pair Production of Excited Leptons

The identification of electrons, photons, muons, tau and hadron jets are described in ref. [1,9]. To get the tau momentum, we take the approximation that tau decay products follow its original tau direction due to the large Lorentz boost. Using this approximation and energy and momentum conservation, we can applying kinematic constraints to get tau momentum. To remove the background from two-photon collisions, in all channels except in the single photon final state, the visible energy of the event is required to be more than half of the beam energy.

2.1 Pair Production of Charged Excited Leptons

Event selection for the reaction $e^+e^- \longrightarrow \ell^*\ell^* \longrightarrow \ell\ell\gamma\gamma$ is based on the fact that these processes contain two leptons and two photons. The Standard Model background from lepton pair production with initial and final state radiation can be efficiently reduced by requiring two energetic photons.

Event with at least one identified lepton and exact two identified photons all with energy exceeding $0.2E_{\rm beam}$ are selected (muon energy is slightly different with 20 GeV cut), where $E_{\rm beam}$ is the beam energy; if the second lepton is missed out of the measurement region or beam pipe, the polar angle of both photons are required to be greater than 20° to seperate with the radiative background; for taus, the number of tracks is at least 2 and at most 6. The total energy deposited in the electromagnetic calorimeter for $\tau^*\tau^*$ candidates must be less than 85% of the centre of mass energy.

For two leptons and two photons, there are two possible ways of forming two lepton-photon mass combinations for each event, at least one of the two possible permutations, the mass difference must be less than 10 GeV and the average mass must be greater than 55 GeV. For one lepton and two photons, there are also two possible ways to combine one lepton with two photons, at least one of the two combinations must have an invariant mass between 55 and 105 GeV.

The reaction of $e^+e^- \longrightarrow \ell^*\ell^* \longrightarrow \ell\gamma\nu W$ is searched for with m_{ℓ^*} greater than the mass of W. Event selection requires the number of tracks is at least 2; the number of jet with energy greater than 2 GeV is at least 3; for $\ell = e, \mu$, the energy of the identified lepton and photon is between 20 GeV and $0.7E_{\rm beam}$, the polar angle both are greater than 20°, the acolinear angle between them is smaller than 60°, the sum of their energy is between $0.7E_{\rm beam}$ and $1.25E_{\rm beam}$, the polar angle of missing momentum of the event is greater than 25.8°. For $\ell = \tau$, the energy cut for photon is the same as for the electron and muon channels; the polar angle of the photon is greater than 25.8°, the sum of energy of the photon with the most energetic charged jet is smaller than $1.25E_{\rm beam}$, the sum of the first two energetic charged jet is smaller than $1.2E_{\rm beam}$; the polar angle of missing momentum of the event is in the barrel; the energy deposited in the hadron calorimeter should greater than 1 GeV to remove the Bhabha events; two tau should not both consistent with muons to remove the dimuon background. The branching ratio of reaction $e^+e^- \longrightarrow \ell^*\ell^* \longrightarrow \nu\nu WW$ is negligible and therefore this reaction is without being searched for.

No events pass the selection. For the reaction of $e^+e^- \longrightarrow \ell^*\ell^* \longrightarrow \ell\ell\gamma\gamma$, the main background from radiative processes is estimated to be 0.5 events for e^*e^* and to be less than 0.1 events for $\mu^*\mu^*$ and $\tau^*\tau^*$. The detection efficiency for the signal is estimated from Monte Carlo to be 60% for e^*e^*, 58% for $\mu^*\mu^*$ and 42% for $\tau^*\tau^*$. For the reaction of $e^+e^- \longrightarrow \ell^*\ell^* \longrightarrow \ell\gamma\nu W$, the main background from $q\bar{q}$ [11] and W pair production [12] is estimated to be negligible for e^*e^*, 0.2 for $\mu^*\mu^*$ and 0.6 events for $\tau^*\tau^*$. The detection efficiency for the signal is estimated from Monte Carlo to be 31%, 34% and 23% for these three decay channels respectively.

Taking into account the luminosity, the efficiency, the decay branching ratio and the production cross section, we obtain the number of expected ℓ^* as a function of m_{ℓ^*}. The small effects due to the systematic errors on the luminosity and selection efficiency are incorpotated into each limit [10]. The luminosity error is taken as 0.6% and the selection efficiency is about

2% with another about 2% statistical errors. From Poisson statistics, we determine the lower mass limit for e*, μ^* and τ^* at 95% Confidence Level (C.L.) to be 85.1 GeV, 85.0 GeV and 84.1 GeV respectively.

2.2 Pair Production of Excited Electron Neutrinos

Event selection for the excited electron neutrinos follows the analysis of ref. [1]. For the reaction $\mathrm{e}^+\mathrm{e}^- \longrightarrow \nu_\mathrm{e}^*\nu_\mathrm{e}^* \longrightarrow \nu_\mathrm{e}\nu_\mathrm{e}\gamma\gamma$, the change is to require two photons in the barrel region each with energy greater than $0.2E_\mathrm{beam}$ instead of 20 GeV. For the reaction $\mathrm{e}^+\mathrm{e}^- \longrightarrow \nu_\mathrm{e}^*\nu_\mathrm{e}^* \longrightarrow$ eeWW, the change is to require the isolated electron with energy greater than 4 GeV instead of 5 GeV.

No events pass the selection of $\nu\nu\gamma\gamma$ decay mode. Same number of 0.3 events are predicted from KORALZ [13] and NNGSTR [14] Monte Carlo generator, they are consistent with each other. Background predicted from GGG generator [15] is negligible. However due to the insufficient tools of our private ntuple, three events passed the selection of eeWW decay mode. These three events are consistent with the background prediction of 1.4 events from hadronic events and 1.8 events from W pair production.

The detection efficiency is estimated from Monte Carlo to be 51% for the $\nu\gamma$ decay mode and 39% for the eW decay mode. The lower mass limit for excited electron neutrinos at 95% C.L., combined with our previous data [1], is determined to be 78.9 GeV. Due to the low cross section, it is unable to give a mass limit in eW decay mode.

3 Single Production of Excited Leptons

3.1 Single Production of Charged Excited Leptons

Event selection for the reaction of $\mathrm{e}^+\mathrm{e}^- \longrightarrow \ell\ell^* \longrightarrow \ell\ell\gamma$ is based on the fact that these processes contain one energetic photon plus leptons. The photon is required to be in the barrel region and to have an energy more than $0.2E_\mathrm{beam}$ and no other photons to be present.

Events are selected with at least one lepton with energy greater than $0.2E_\mathrm{beam}$(muon energy is slightly different with 15 GeV cut); the number of tracks is one for electron due to its t-channe contributions, at most 2 for muon decay channel, at lease 2 and at most 6 for tau decay channel; the total energy deposited in the hadron calorimeter is less than $0.2E_\mathrm{beam}$ for electron and 25 GeV for muon channel, the total visible energy is less than $1.85E_\mathrm{beam}$ for tau channel. For electron decay channel, if the second electron is missing in the beam pipe, the thrust axis of the event is required to be within the barrel region; for muon decay channel, the polar angle of the missing momentum is greater than 18°; fot tau decay channel, the thrust axis of the event is in the barrel region, the number of clusters must be less than 15 is required to remove the hadronic events.

A total of 18 events for e*, 2 events for μ^* and 4 events for τ^* pass the selection. A Monte Carlo calculation utilizing the TEE program [16] predicts 14.2 background events for electron channel, utilizing KORALZ program predicts 5.9 for muon and 4.1 events for tau channel respectively. Fig. 1a shows the invariant mass, $m_{\ell\gamma}$, of all combinations together with the background. No significant structure is observed. The mass resolution for e* is about 1 GeV for e*, 3 GeV for μ^* and 2 GeV for τ^* which estimated from Monte Carlo events. We use the mass resolution in calculating the upper limit.

The detection efficiency is estimated from Monte Carlo to be 46% for e*, 59% for μ^* and 49% for τ^* from m_{ℓ^*} = 90 GeV to m_{ℓ^*} = 170 GeV. The decay branching ratio of $\ell^* \rightarrow \ell\gamma$ changes from 88% at m_{ℓ^*} = 90 GeV to 38% at m_{ℓ^*} = 170 GeV. Combining our present data with that of previous data [1] and taking into account the luminosity, the efficiency and the branching ratio, the upper limits of the coupling constant λ/m_{ℓ^*} at 95% C.L. as a function of m_{ℓ^*} is shown in Fig. 2.

It has to be noted that the decay branching ration in the reaction of $e^+e^- \longrightarrow \ell\ell^* \longrightarrow \ell\nu W$ increase from 12% at m_{ℓ^*} = 90 GeV to 54% at m_{ℓ^*} = 170 GeV. Therefore this decay channel should be combined with that of the leptonic decay channel to get a lower coupling constant limit. But the background subtraction of $q\bar{q}$ evnets and W pair is complicated and sufficient tools are needed.

3.2 Single Production of Excited Electron Neutrinos

Event selection for the reaction $e^+e^- \longrightarrow \nu_e\nu_e^* \longrightarrow \nu_e\nu_e\gamma$ uses the same criteria as in ref. [1]. A total of 28 events pass the selection. The background is mainly due to radiative neutrino events $e^+e^- \longrightarrow \nu\nu\gamma$, and $e^+e^- \longrightarrow \gamma\gamma$ with one γ missing in the beam pipe. For radiative neutrino events there are 19.5 events predicted from NNGSTR consistent with the 20.3 events predicted from KORALZ. The number of events predicted for $e^+e^- \longrightarrow \gamma\gamma$ background is 1.1 using the GGG generator. We conclude that all events are compatible with the expected background.

The detection efficiency is estimated to be 71%. Taking into account the luminosity, the decay branching ratio, an upper limit is obtained for the coupling constant $\lambda/m_{\nu_e^*}$ at 95% C.L. as a function of $m_{\nu_e^*}$ for both $f = 0$ and $f' = 0$. The result is shown in Fig. 3, in which $\lambda = f$ if $f' = 0$, and $\lambda = f'$ if $f = 0$.

Event selection for the reaction $e^+e^- \longrightarrow \nu_e\nu_e^* \longrightarrow \nu_e eW$ uses the same criteria as in ref. [1]. A total of 6 events pass the section. Backgroud are predicted to be 6.3 events from W pair production and 2.0 events from hadronic events.

The detection efficiency is estimated to be 33% from $m_{\nu_e^*}$ = 90 GeV to $m_{\nu_e^*}$ = 170 GeV. The decay branching ratio of $\nu_e^* \rightarrow eW$ is more than 95% at $m_{\nu_e^*}$ = 90 GeV and decreases to 64% at $m_{\nu_e^*}$ = 170 GeV. Combined with our previous data [1], we obtain an upper limit at 95% C.L. for the coupling constant $\lambda/m_{\nu_e^*}$ as a function of $m_{\nu_e^*}$, as shown in Fig. 2.

4 Conclusion

We see no evidence for excited electrons, muons, taus or electron neutrinos; the observed events are consistent with Standard Model expectations. From pair production searches the lower mass limits at 95% C.L. are found to be 85.1 GeV for e*, 85.0 GeV for μ^*, 84.1 GeV for τ^*, and 78.9 GeV ($\nu_e\gamma$ decay mode) for ν_e^*. From single production searches, we derived upper limits on the couplings λ/m_{ℓ^*} in the range of $(10^{-4} - 1)$ GeV^{-1} for ℓ^* masses up to 172 GeV.

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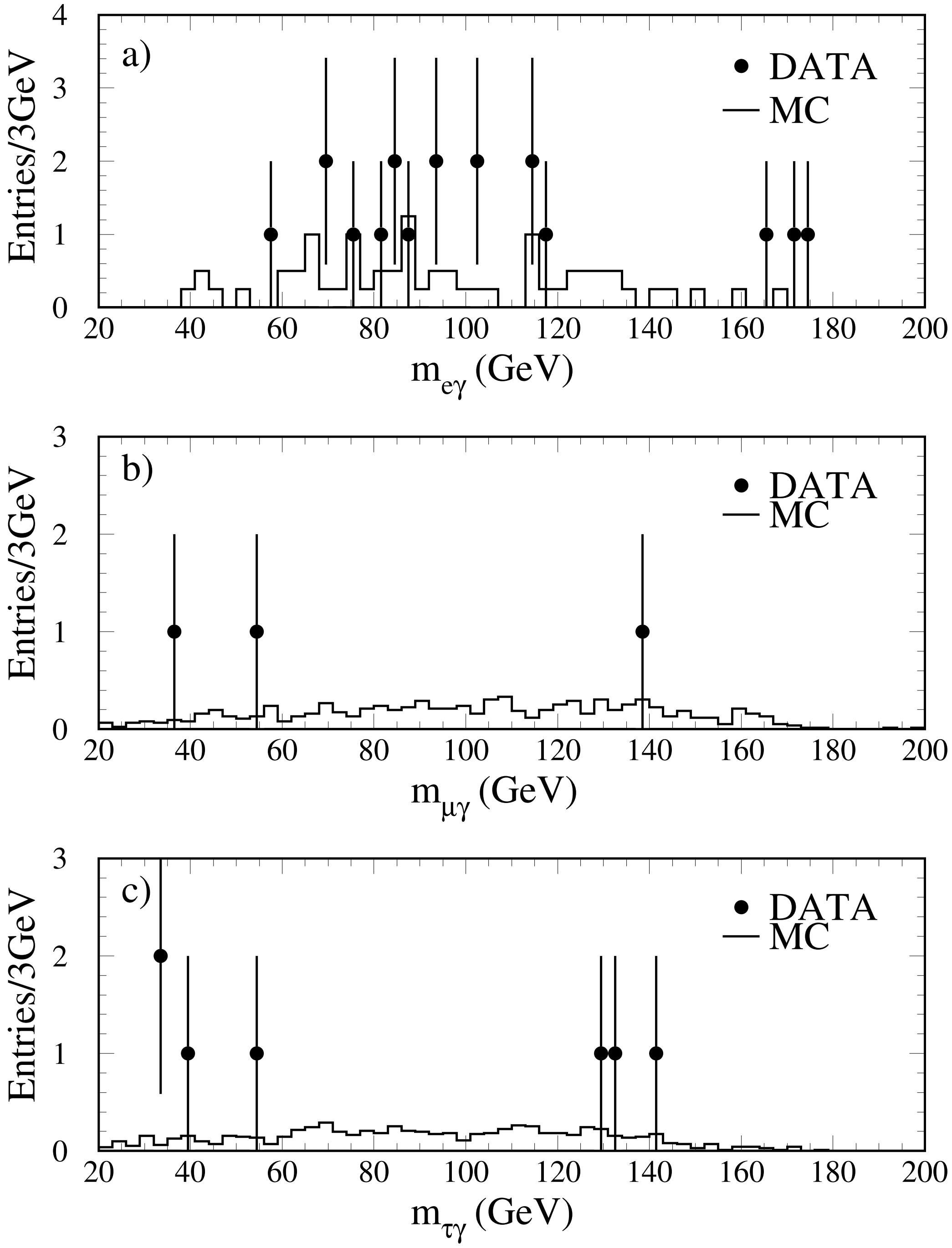

Figure 1: Selected events in single production searches: a) invariant mass of all $e\gamma$ combinations; b) invariant mass of all $\mu\gamma$ combinations; c) invariant mass of all $\tau\gamma$ combinations.

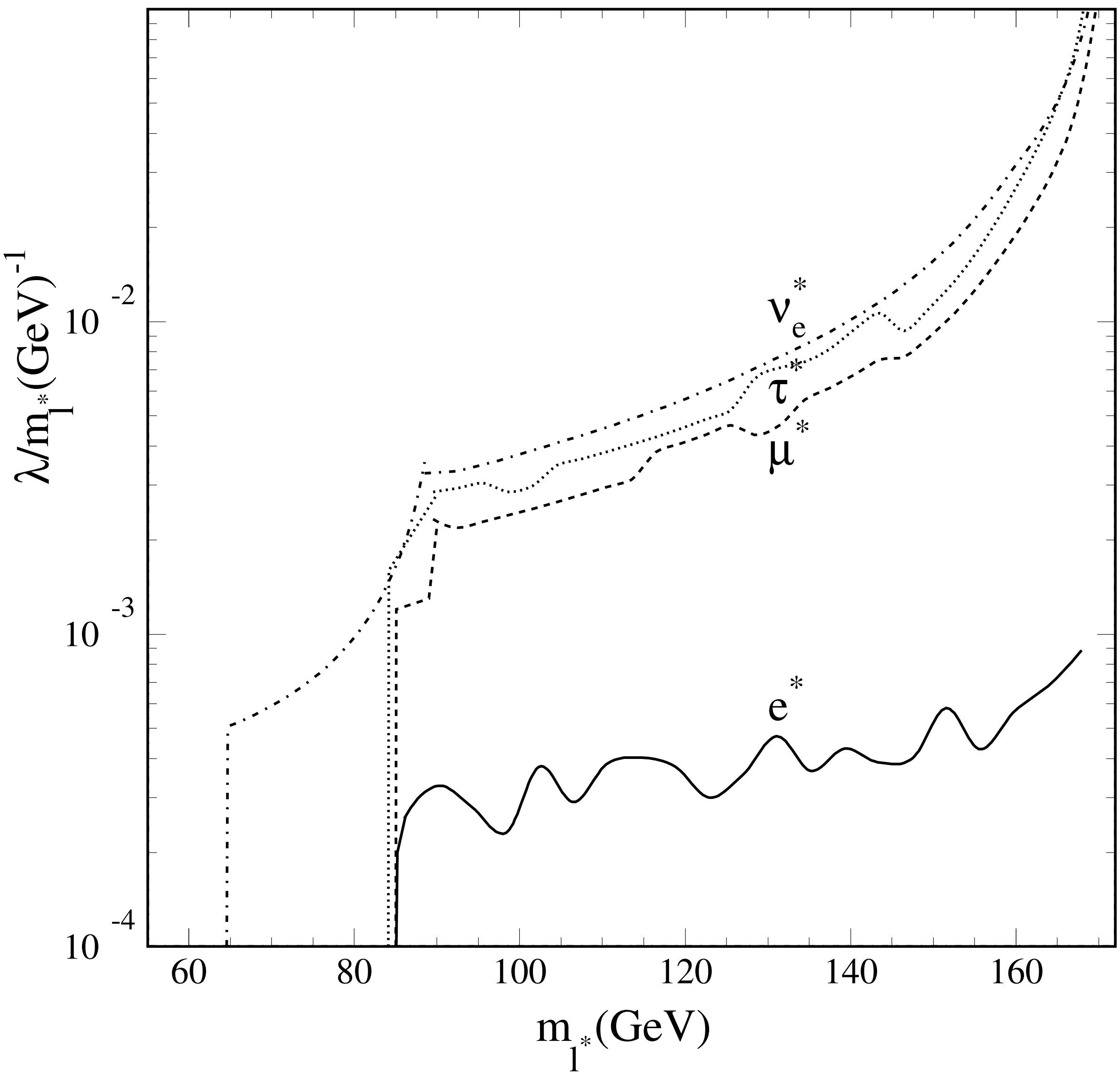

Figure 2: The upper limit of the coupling constant λ/m_{ℓ^*} at 95% C.L. as a function of m_{ℓ^*} for excited leptons with $f = f'$. The excluded region is above and to the left of the curves.

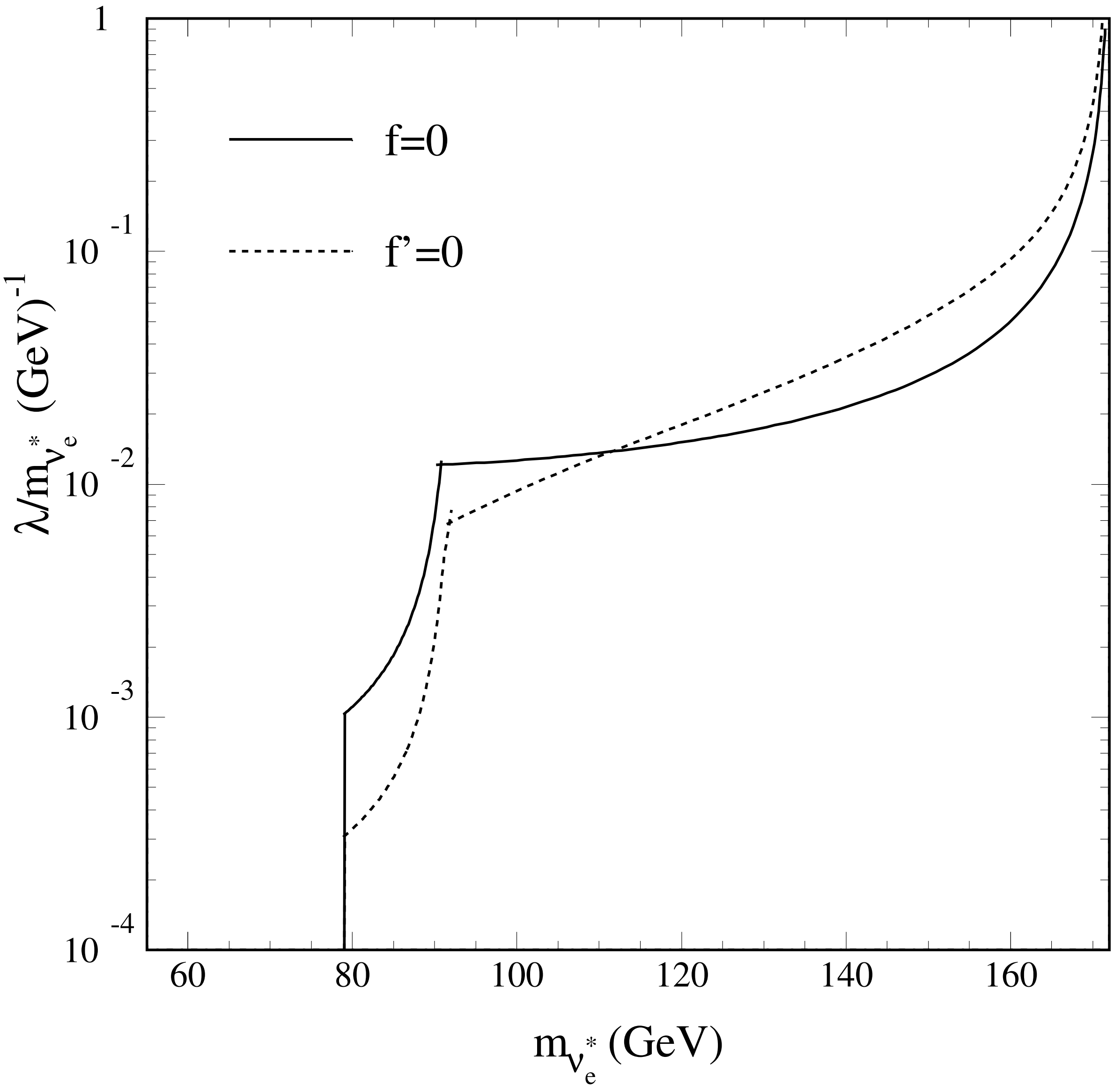

Figure 3: The upper limit of the coupling constant λ/m_{ℓ^*} at 95% C.L. as a function of m_{ℓ^*} for excited electron neutrinos with $\lambda = f$ ($f' = 0$) and $\lambda = f'$ ($f = 0$). The excluded region is above and to the left of the curves.