Search for excited leptons in $e^+e^-$ collisions at $\sqrt{s} = 188.6$ GeV

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Abstract

A search for the radiative decays of excited leptons $e^*$, $\mu^*$, $\tau^*$ and $\nu^*$, and for charged current weak decays of $e^*$, $\mu^*$, $\nu_e^*$ and $\nu_\mu^*$ was undertaken using a sample of 173.6 pb$^{-1}$ of data collected by ALEPH at 188.6 GeV. No evidence for a signal was found in single or pair production. Excluded mass limits from pair production are close to 94.2 GeV/c$^2$ for excited charged leptons and excited neutrinos. Limits on the couplings, $\lambda/m_\ell^*$, of excited leptons were derived from single production. For an excited lepton mass of 150 GeV/c$^2$, these limits are 0.0001, 0.001, 0.004, 0.006 and 0.01 GeV$^{-1}$, for $e^*$, $\mu^*$, $\tau^*$, $\nu_e^*$, $\nu_\mu^*$ and $\nu_\tau^*$ respectively.

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1 Introduction

Excited leptons arise naturally in models where the standard leptons are composite rather than elementary particles [1]. Their masses are determined by the compositeness scale and, if this is not too high, their production at LEP energies may be possible. Searches for excited leptons were already performed by ALEPH at centre of mass energies of 130–136 GeV [2]. Similar searches have been performed by other collaborations [3].

This paper presents an update of these searches performed on a data sample of 173.6 pb⁻¹ collected at a centre of mass energy of 188.6 GeV. Results are presented according to a phenomenological model [1] where the excited fermions are assumed to have spin and isospin \( \frac{1}{2} \). The large mass difference between the ground state and excited state is realised if the excited fermions acquire their masses prior to SU(2) \( \times \) U(1) breaking. Therefore both left- and right-handed components are in weak isodoublets \(^1\) and possess the full weak couplings to the gauge bosons. At LEP, excited leptons can be produced either singly \( (e^+e^- \rightarrow \ell\ell^*) \), or in pairs \( (e^+e^- \rightarrow \ell^*\ell^*) \). In the case of single production, the effective Lagrangian is given by [1]

\[
\mathcal{L}_{\text{eff}} = \sum_{V=\gamma,Z,W} \frac{e}{\Lambda} \bar{\ell}^* \sigma^{\mu\nu} (c_{V\ell\ell} - d_{V\ell\ell} \ell^*_\gamma) \ell \partial_{\mu} V_{\nu} + h.c.
\]

where \( c_{V\ell\ell} \) and \( d_{V\ell\ell} \) are couplings assuming magnetic transitions to ordinary leptons and \( \Lambda \) is the compositeness scale. The precision g-2 measurements imply \( |c_{\gamma\ell\ell}| = |d_{\gamma\ell\ell}| \) and the absence of electric dipole moments requires \( c_{\gamma\ell\ell} \) and \( d_{\gamma\ell\ell} \) to have the same phase [1, 4]. This means that only the right-handed (left-handed) part of the excited lepton (anti-lepton) is involved in the magnetic transition and in the model described in [1] all the couplings are assumed to satisfy \( c_{V\ell\ell} = d_{V\ell\ell} \) and can be written:

\[
\begin{align*}
c_{\gamma e^*e} &= -\frac{1}{4}(f + f') \\
c_{\gamma \nu^*\nu} &= \frac{1}{4}(f - f') \\
c_{Z e^*e} &= -\frac{1}{4}(f \cot \theta_W - f' \tan \theta_W) \\
c_{Z \nu^*\nu} &= \frac{1}{4}(f \cot \theta_W + f' \tan \theta_W) \\
c_{W e^*e} &= \frac{f}{2\sqrt{2}\sin \theta_W}.
\end{align*}
\]

The independent parameters in this model are \( f/\Lambda \) and \( f'/\Lambda \). By choosing a particular relationship between \( f \) and \( f' \), only one free parameter \( \lambda/m_{\ell} \) (defined as \( f/\sqrt{2}\Lambda \)), multiplying the cross-section remains. The scale, \( \Lambda \), need not be the same for the different lepton flavours. For pair production, mass limits are set for the case of point-like vector couplings to the gauge bosons. However the possibility of a form-factor [5] multiplying the couplings is also considered. The presence of magnetic couplings allows the excited leptons to decay to their ground state partners with the emission of a vector boson. Branching ratios are calculated according to [5].

For excited charged leptons, the branching ratio for radiative decays as a function of the ratio \( f'/f \) and the excited lepton mass is shown in Fig. 1.

\(^1\)i.e. homodoublet type: \( \left( \begin{array}{c} \nu^*_L \\ \ell^*_L \end{array} \right), \left( \begin{array}{c} \nu^*_R \\ \ell^*_R \end{array} \right) \).
Figure 1: The branching ratio for radiative decays of excited charged leptons as a function of $f'/f$ and the excited lepton mass. The $\nu^*$ radiative branching ratios are obtained by the transformation $f'/f \rightarrow -f'/f$.

For $\ell^*$ masses below the W and Z, the branching ratio for the radiative decay, $\ell^* \rightarrow \ell \gamma$, is virtually 100% for most of the parameter space. For larger $\ell^*$ masses the decay channels involving W and Z open up, and for an $\ell^*$ of mass 140 GeV/c$^2$ the branching ratio is reduced to 43% when $f = f'$. For excited neutrinos the photonic branching ratios are obtained from Fig. 1 under the transformation $f'/f \rightarrow -f'/f$.

Throughout this paper, upper limits on the number of signal events, $\mu_s$, as a function of mass are calculated at 95% C.L. by comparing the number of data and expected background events (Poisson statistics) in mass bins four times as wide as the signal invariant mass resolution. Upper limits on the excited lepton couplings corresponding to $\mu_s$ expected events are presented.

## 2 Excited charged leptons decaying radiatively

In all radiative channels the default selection cuts require the polar angles of all identified charged tracks and photons to satisfy $|\cos \theta| < 0.95$ and the charged track momenta to be greater than 0.2 GeV/c. Event topologies are one, two, four or six charged tracks (excluding photon conversions), with no net charge for the multi-track cases. Events with four (six) charged tracks are required to contain exactly one (two) three-prong $\tau$ decay candidates. A three-prong $\tau$ candidate is defined as three tracks with net charge $\pm 1$ and invariant mass less than $m_{\tau}$ (assuming pion masses for the tracks). Charged jets are formed by adding to a charged track (or three-prong) all neutral particles within a cone of half-angle 5° (10°). Remaining neutral particles are clustered
to form neutral jets each with invariant mass less than 2 GeV/c² and regarded as photons. For events with two charged jets, the larger of the two jet momenta is required to be at least 5 GeV/c. The opening angle between the charged jets is required to be greater than 10° to reject events due to the γγℓ⁺ℓ⁻ process.

For ℓ⁺ masses below about 45 GeV/c², the data taken at the Z-peak is expected to provide more stringent constraints than the 188.6 GeV data; nevertheless, sensitivity to low masses is maintained in this analysis without degrading the search at higher masses.

The opening angle between the charged jets is required to be greater than 10° to reject events due to the process. For masses below about 4.5 GeV/c², the data taken at the Z-peak is expected to provide more stringent constraints than the 188.6 GeV data; nevertheless, sensitivity to low masses is maintained in this analysis without degrading the search at higher masses.

The energies of the final state particles were calculated by energy and momentum conservation using only the direction vectors. For ℓ⁺ℓ⁻γ events the calculation includes ISR effects assuming energy losses by only one of the beam particles along its initial direction. For the ℓ⁺ℓ⁻γγ topology the particle energies are calculated using the direction vectors assuming ISR losses by one of the beam particles. However, the energy loss in this case is estimated by minimizing the χ² formed from the measured and calculated energies of the final particles. The χ² minimization achieves a resolution of roughly 1 GeV for the ISR photon energy. When the estimated energy loss is less than 1 GeV it is set to zero thereby improving the mass resolution. In the τ⁺τ⁻γγ topology only the photons are used in the calculation.

The invariant mass resolution for e⁺ and µ⁺ is found to be about 75 MeV/c² which increases to 100 – 200 MeV/c² when the centre of mass energy spread of the LEP accelerator [6] is included. For τ⁺ the resolution is about 1.5 GeV/c².

The principle background for radiative decays is lepton pair production and Monte Carlo samples 3.6 times as large as the data for e⁺e⁻, and 200 times the data for µ⁺µ⁻ and τ⁺τ⁻ were used.

2.1 Pair production

Excited charged lepton pair production is dominated by s-channel γ or Z exchange. The production rates are similar to those for standard, but heavy, leptons, and the radiative decay modes lead to a characteristic topology, ℓ⁺ℓ⁻γγ. The standard model background from lepton pair production with final state radiation can be efficiently reduced by imposing energy cuts and isolation angle cuts on the photons.

Events with two identified photons with energies of at least 15 and 8 GeV and two charged jets are selected. The average mass of the jet-photon combinations having the smaller mass difference is used to reconstruct the signal invariant mass. However for a signal mass near the kinematic limit, the events consist of two back-to-back jet-photon combinations. In this case the average mass of the high invariant mass pairing is chosen leading to a significant enhancement in the sensitivity of the search. A linear sliding cut on the minimum photon isolation angle, min(θ_{ℓ⁺γ₁},θ_{ℓ⁻γ₁},θ_{ℓ⁺γ₂},θ_{ℓ⁻γ₂}), is also applied. The isolation angle cut varies from 60° for a signal of mass 50 GeV/c² to 20° at the kinematic limit.

At this stage, six candidate data events remain. Channel selection cuts (described in section 2.2) to separate the e⁺, µ⁺ and τ⁺ contributions are applied and finally a cut on the mass difference is applied since this is peaked at zero for the signal. For a mass of 50 GeV/c² the mass difference is required to be less than 3 GeV/c² increasing to 5 GeV/c² at 75 GeV/c² and then up
to 10 GeV/$c^2$ near the kinematic limit. For a mass within 99.5% of the kinematic limit no cut is applied. For the $\tau^+\tau^-\gamma\gamma$ topology the mass difference cut is increased by a factor three. Finally, one $\tau^*$ pair candidate remains in the data with a mass of 75.5 GeV/$c^2$ and mass difference of 8 GeV/$c^2$.

The radiative Bhabha background is studied using the BHWIDE generator and radiative $\mu^+\mu^-$ and $\tau^+\tau^-$ events are generated with KORALZ. The expected numbers of background events are 1.7 $e^+e^*$, 0.3 $\mu^+\mu^*$ and 1.2 $\tau^+\tau^*$, with 14.4 events expected in total before the cut on mass differences. Signal events are generated using the KORALZ program modified to produce $\ell^+\bar{\ell}^*$ pairs decaying radiatively with the complete spin correlations implemented according to and fully simulated in the ALEPH detector Monte Carlo. Over the mass range 45–94.3 GeV/$c^2$ the signal efficiencies increase from 52%, 55% and 40% to 77%, 79% and 50% for $e^+e^*$, $\mu^+\mu^*$ and $\tau^+\tau^*$ respectively.

With no events observed near the kinematic limit, the 95% C.L. mass limits are set as shown in Fig. 2(a). Excited states with masses up to 94.3 GeV/$c^2$ for $e^*$, $\mu^*$ and $\tau^*$ are excluded at 95% confidence level. For masses below these, the 95% C.L. excluded form-factor as a function of mass is shown in Fig. 2b.

2.2 Single production

Excited charged leptons can also be produced singly, in association with their ground state partner. Masses close to the centre of mass energy can be probed this way, but the production
cross-section now involves the magnetic coupling, the magnitude of which is unknown. For all flavours, the production can take place via $s$-channel $\gamma$ or $Z$ exchange.

In single production, the final state usually consists of two leptons and a photon, but for excited electrons, the production cross section is dominated by the extremely forward peaked $t$-channel contribution. The topology is the same as for the quasi-real Compton scattering process, and since the spectator electron usually remains undetected in the beam pipe, the apparent topology, only one electron and a photon, is different. A dedicated analysis has therefore been performed for excited electrons in this configuration, as described in section 2.2.2.

2.2.1 $\ell^+\ell^-\gamma$ channel

To qualify, the events have to consist of a pair of charged jets with at least one photon of energy greater than 15 GeV and to fail the pair production selection. For each event there are two possible invariant mass combinations. The low mass combination is always accepted allowing the reconstruction of low mass signals. The high mass combination is also included provided that the photon isolation angle is greater than 40° which greatly reduces the background contribution.

For two charged jet events, channel selection cuts using particle identification and kinematic constraints are applied. An event is a candidate in the $e^*$ channel if both tracks are identified as electrons by the standard ALEPH algorithm [9] and the total measured energy of the charged jets is greater than 60% of the expected total charged energy (after subtraction of all isolated photons including the estimated energy of the ISR photon). If only one electron is identified and the other charged jet fails the standard muon identification, the cut is increased to 80%. Similarly cuts of 60% and 88% are applied for the $\mu^*$ channel. Events failing the above criteria are candidates for the $\tau^*$ channel unless the total charged track energy is found to be more than 95% of that expected. Events containing one or two three-prong charged jets are only considered for the $\tau^*$ search.

Finally to reduce the background from “$Z$-return events”, the invariant mass of the dilepton system (calculated with the rescaled momenta) is required to differ from $M_Z$ by at least 5 GeV/$c^2$ (7 GeV/$c^2$ for the $\tau^*$ search). 976 events are predicted in the $e^*$ channel, 67.6 in the $\mu^*$ channel and 107 in the $\tau^*$ channel, while 974, 50 and 126 events respectively, are selected in data.

For the signal, a generator based on the model of [1] with complete spin effects implemented according to [5] is used, with initial state radiation and with tau decays implemented. The efficiency for $\mu^*$ is in the range 60-70% (50-60% for $\tau^*$) for the high mass combinations. The $e^*$ efficiency for this topology is about 10%; the combination of this channel with the dominant $e\gamma$ channel results in an overall $e^*$ efficiency of about 60%.

Limits for the $\mu^*$ and $\tau^*$ couplings are shown in Fig. 3.

2.2.2 Single production of excited electrons ($e\gamma$ channel)

The main backgrounds come from:

- radiative Bhabha scattering with one of the final state electrons remaining undetected in
the beam pipe;

- Bhabha scattering with one of the final state electrons transferring practically all of its energy to a photon through hard bremsstrahlung in the detector material, producing mostly back-to-back events;

- Bhabha scattering where the ionization trail of one of the electrons escapes through a TPC crack resulting in a fake photon.

- $\gamma\gamma$ final states with one of the photons converting in the detector material into an $e^+e^-$ pair asymmetric enough for one of the electrons to escape detection.

The Monte Carlo generators TEEGG7 [10], BHWIDE and GGG [11] are used to study these backgrounds.

Events are selected containing exactly one good track and one photon both with energies greater than 15 GeV. Previously, ALEPH analyses [2] required the detected track and photon to be coplanar with the beam to exploit the very sharply forward peaked distribution for the undetected particle. This has been found to lead to an unnecessary loss of signal efficiency, particularly for values of the parameters $f$ and $f'$ which reduce the sharpness of the forward peak ($f \approx -f'$). At polar angles between $1.4^\circ$ and $18.2^\circ$ with respect to the beam axis, the low angle particle is usually detected by the luminosity calorimeters with excellent angular resolution. These events are now retained. For the case where the low angle particle remains undetected, it is assumed to lie along a trajectory of closest approach to the beam-axis whilst being coplanar with the visible photon and track. The $z$-component of the low angle particle is required to be opposite in direction to $\beta$, the boost of the system formed by the detected photon and track.

Figure 3: 95% C.L. exclusion limits ($f = f'$) from 130–189 GeV data in the mass-coupling plane for singly produced $\ell^*$ decaying radiatively.
A track passing through the inner tracker typically produces 8 hits. Hence requiring the number of hits in the inner tracker to be less than a total of 13 for opening angles above 175°, removes misidentified back-to-back Bhabha events. Requiring the number of such hits to be at least four removes the background from asymmetric photon conversion.

In the e* centre of mass frame, the decay photon is preferentially scattered forward [1], whereas the quasi-real Compton process favours backscattered photons. This effect is exploited to enhance signal sensitivity by introducing a cut on the photon scattering angle varying with the reconstructed eγ mass calculated using the rescaling method of the ℓ+ℓ−γ topology. Only events satisfying θ_{scatter} < 170 - 500π/γ degrees are retained. In order to reject events with additional low angle photons, the total energy in the event including the calculated energy of the low angle particle was required to be more than 0.9√s.

The charged track must be identified as an electron by the standard ALEPH identifiers, and the sign of its charge has to be consistent with the quasi-real Compton scattering topology which requires that −qβ > 0 where q is the track charge.

1336 events are expected while 1372 events are selected in the data, with no evidence of signal. The ℓ+ℓ−γ and eγ datasets are added and the resulting exclusion limit is shown in Fig. 3.

3 Radiative decays of excited neutrinos

The radiative single and pair production topologies are characterised by events with one and two energetic photons respectively. In order to eliminate the considerable background from wrongly interpreted cosmic muon events, the analysis [12] is employed. The principle background (ντγ(γ)) has been simulated with twenty times more Monte Carlo luminosity than data.

3.1 Pair production

Two photons above 15 and 8 GeV are required in the event, the acoplanarity of the photons is required to be less than 175° (eliminating e+e− → γγ QED events), and the missing mass must lie outside the range 80–102 GeV/c², removing events containing the neutrino-pair decay of an on-shell Z. Finally requiring at least one of the photons to be in the polar angle range |cos θ| < 0.73 further reduces the background with minimal signal efficiency losses. Eight acoplanar photon pair events are found, against a background estimate of 9.6. The kinematically allowed mass range for the ν* candidates is taken into account when computing limits. The efficiency of the analysis for the fully simulated Monte Carlo signal increases smoothly from 47%, for a ν* of 45 GeV/c² mass, to 78% at the kinematic limit. No evidence for a signal was found, and the mass limit for ν* is 94.2 GeV/c². Form-factor limits associated with ν* production are shown in Fig. 2.

3.2 Single production

Single ν* production in association with a standard neutrino occurs in e+e− annihilation and additionally via t-channel W-exchange for νe*. 7
Events with one photon of energy greater than 20 GeV and all other photons having energy less than 5 GeV are selected. The missing mass of the event is required to exclude $Z \rightarrow \nu \bar{\nu}$, in the mass range 80–102 GeV/$c^2$. Background events detected only by initial state radiation tagging favour low polar angles, so $|\cos \theta| < 0.73$ is imposed as a final cut. 101 events are expected, largely from $\nu \bar{\nu} \gamma(\gamma)$ background, and 81 are observed. Signal events are generated according to the model of Ref. [1] with spin effects implemented according to [5]. Efficiencies for $\nu_e^*$ are between 40% and 70% for the mass range above 90 GeV/$c^2$. For $\nu_\mu^*$ and $\nu_\tau^*$ the efficiencies vary between 45% and 70%. With no evidence of signal, the limits on the $\nu^*$ couplings are shown in Fig. 4. The observed deficit in the data results in a coupling limit smaller than the expected limit by a factor of about 1.4. For $\nu_{e,\mu}^*$ the limit obtained results from a combination of the radiative and weak decay limits. For $\nu_\tau^*$ only the radiative limit is shown.

Figure 4: 95% C.L. exclusion limits from 189 GeV data in the mass-coupling plane for singly produced $\nu^*$ as a function of $\nu^*$ mass. The values $f = 1, f' = 0$ have been used. The $\nu_e^*$ and $\nu_\mu^*$ curves are the combined limits from the radiative and weak decay channels. For $\nu_\tau^*$ the radiative limit only is shown.

4 Weak decays

In this section we consider the weak decay channels $e^+e^- \rightarrow \nu_e\nu_e^* \rightarrow \nu_e eW, e^+e^- \rightarrow \nu_\mu\nu_\mu^* \rightarrow \nu_\mu \mu W$ (the most important) and also $e^+e^- \rightarrow e\bar{\nu} eW, e^+e^- \rightarrow \mu\bar{\nu} \mu W$.

The weak decays of singly produced excited leptons are characterised by topologies where a lepton and neutrino are accompanied by the decay products of a W. Such topologies, where the W decays hadronically, are selected by requiring that an isolated charged lepton be identified
Figure 5: 95% C.L. exclusion limits ($f = -f'$) for charged current decays of $e^*$ and $\mu^*$ in the mass-coupling plane for single production using the 189 GeV data.

in events with at least 8 charged tracks and a total visible energy greater than 80 GeV. The main standard model background for these topologies comes from $W$ pair production, where one $W$ decays hadronically and the other decays semileptonically. The principle suppression of background relies on avoiding the on-shell boson mass region for the lepton-neutrino invariant mass (hereafter called the ‘leptonic $W$-mass’). The missing momentum vector serves to identify the neutrino momentum.

If an electron is found by the standard ALEPH identifiers it is required to have no other charged track within a cone of half-angle $10^\circ$, and neutral energy within the same cone is added to the electron, to compensate for bremsstrahlung losses. For an identified muon the same cone is used, but no bremsstrahlung loss is added. The hadronic boson mass (mass of the hadronic part of the event, excluding identified isolated particles) is required to agree with that of the $W$ to within $15 \text{ GeV}/c^2$, and the ‘leptonic $W$-mass’ must disagree with the $W$ mass to within the same limits.

The mass of the excited particle ($e^*, \nu_e^*, \mu^*$ or $\nu_\mu^*$) can be deduced from the event configuration: if the identified isolated lepton is a decay product in the searched-for channel, then the invariant mass of the lepton and the boson taken together provides the right value ($\nu_\mu^* \to \mu W$, etc), and if the isolated lepton is the recoil particle as in $\mu^* \to \nu_\mu W$, then the invariant mass of the boson together with the missing momentum is appropriate. Alternatively in the decay case the mass recoiling from the missing momentum works and in the recoil case the mass recoiling from the lepton is appropriate. In practice, in the decay channels the two appropriate values are taken for each analysis and compared and the event is discarded if the larger value exceeds the smaller value by more than 20%. The values are then averaged. In the recoil channels the recoil from the
Table 1: Weak decays: the final number of events selected and signal efficiencies after all cuts.

<table>
<thead>
<tr>
<th>Channel</th>
<th>f,f’</th>
<th>WW MC</th>
<th>Other MC</th>
<th>Data</th>
<th>Efficiency distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e \to eW$</td>
<td>1,0</td>
<td>55.6</td>
<td>28.6</td>
<td>71</td>
<td>32-64% rising with mass</td>
</tr>
<tr>
<td>$\nu_\mu \to \mu W$</td>
<td>1,0</td>
<td>54.0</td>
<td>1.3</td>
<td>47</td>
<td>30-66% rising with mass</td>
</tr>
<tr>
<td>$e^+ \to \nu_\tau W$</td>
<td>1,-1</td>
<td>59.0</td>
<td>13.8</td>
<td>66</td>
<td>19-52% rising until 180 GeV/c²</td>
</tr>
<tr>
<td>$\mu^+ \to \nu_\mu W$</td>
<td>1,-1</td>
<td>57.1</td>
<td>1.2</td>
<td>50</td>
<td>19-57% rising until 180 GeV/c²</td>
</tr>
</tbody>
</table>

lepton is found to be a much more reliable and this value is taken alone, the 20% comparison being made with the other algorithm on a sliding scale, from a 10 GeV excess at 100 GeV down to zero for values above 150 GeV. An additional algorithm is applied which reduces the mass-resolution to around ±2.5 GeV/c²: events with large missing mass (i.e. more than one source of missing momentum comparable to the neutrino) are discarded. Table 1 shows these lepton plus neutrino channels, the number of events predicted by background studies and the number found in data, and briefly describes their efficiencies as measured by radiatively corrected Monte Carlos. The ‘other’ Monte Carlos are the sum of e⁺e⁻ → q̅q, Zee, ZZ, Weν and Zνν.

For the e⁺ channel, a slight complication arises from the values of $f$ and $f’$ where the very forward peaked f-channel contribution is dominant for values much different from $f = -f’$. For $f = f’$, for instance, the electron not involved in the e⁺-decay usually remains undetected at low angle with respect to the beam (the efficiency is negligible and isn’t given in table 1). For the e⁺ channel the limits from the weak decays and radiative decays have been combined over the full parameter space as shown in Fig. 6. Each contour corresponds to a particular mass. The interior of each contour forms the non-excluded region for that particular mass.

5 Conclusion

Excited leptons were searched for in the data collected by ALEPH at 188.6 GeV. No evidence for a signal was found. Excited states were excluded at 95% confidence level for masses close to 94.2 GeV/c² for e⁺, $\mu^+$, and $\tau^+$ and $\nu^+$. For single production, the 95% C.L. exclusion limits on the couplings, $\lambda/m_{l^*}$, for an excited lepton mass of 150 GeV/c² are 0.0001 GeV⁻¹ for e⁺, 0.001 GeV⁻¹ for $\mu^+$, 0.004 GeV⁻¹ for $\tau^+$ and below 0.01 GeV⁻¹ for $\nu^+$.

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It is a pleasure to thank our colleagues from the accelerator divisions for the excellent performance of LEP. Thanks are also due to all the technical personnel of collaborating institutions for their contributions to the success of ALEPH. Those of us from non-member states thank CERN for its hospitality.
Figure 6: The 95% C.L. limits for $e^+$ production at 188.6 GeV over the full $f^+f^-$ parameter space. Each mass corresponds to a contour, the interior of which is the non-excluded region for that mass.

References

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