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## Search for excited taus from $Z^0$ decays

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We have searched for excited taus from  $Z^0$  decay in the channels  $e^+e^- \rightarrow \tau^{*+}\tau^{*-} \rightarrow \tau^+\tau^-\gamma\gamma$  and  $e^+e^- \rightarrow \tau\tau^* \rightarrow \tau^+\tau^-\gamma$ , using the L3 detector at LEP. Using the  $\tau^*$  pair production channel, we can exclude a  $\tau^*$  up to a mass of 45.5 GeV at 95% confidence level. We have also determined upper limits on the  $\tau\tau^*Z^0$  and  $\tau\tau^*\gamma$  couplings as a function of  $m_{\tau^*}$  up to 89.3 GeV.

## 1. Introduction

The standard model [1] has been very successful in describing data on electroweak interactions; however, it leaves many fundamental questions unexplained such as the lepton-quark spectrum, mass generation, the Higgs mechanism, and the large number of arbitrary parameters. One possibility, which would explain the number of families and make the fermion masses and weak mixing angles calculable, would be to assume that quarks, leptons and gauge bosons are all composite [2] with an associated energy scale  $\Lambda$ . One natural consequence of compositeness models is the existence of excited states,  $q^*$ , of the known leptons  $l$ .

In this paper we describe a search for excited states of the heaviest known lepton, the tau, using the L3 detector at LEP. The excited tau,  $\tau^*$ , is assumed to

have spin  $\frac{1}{2}$  and to decay into an ordinary tau and a photon with a 100% branching ratio.

The  $e^+e^-$  collider, LEP, is ideal for the search of excited leptons [3–5] because the initial state consists of pointlike particles with known energy and the final state leptons and photons can be clearly identified. In  $e^+e^-$  collisions excited taus can be produced in pairs ( $e^+e^- \rightarrow \tau^{*+}\tau^{*-}$ ) or singly ( $e^+e^- \rightarrow \tau\tau^*$ ). In the first process obviously only  $\tau^*$  masses smaller than the beam energy can be explored. The signature is an acollinear tau pair and two hard photons. For the single  $\tau^*$  production mass limits close to the center of mass energy can be reached. The signature for this process is an acollinear tau pair with one hard photon.

## 2. $\tau^*$ Production models

In this analysis we assume that the  $Z^0$  and  $\gamma$  couple to spin  $\frac{1}{2}$  excited tau pairs the same as the standard tau pairs. The lowest order pair-production cross section can be found in refs. [6,7].

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For the single production the effective lagrangian [7] is written as:

$$L_{\text{eff}} = \sum_{\nu=e,\mu,\tau} \frac{e}{A} \bar{\Psi}_{\tau^*} \sigma^{\mu\nu} (C_V - D_V \gamma_5) \Psi_{\tau} \partial_{\mu} V_{\nu} + \text{h.c.},$$

where  $A$  is the composite mass scale and  $C_V$  and  $D_V$  the couplings constants. Assuming lepton universality, from precise  $g-2$  measurements it follows that  $|C_V| = |D_V|$ . The coupling constants can be written as  $C_V = -\frac{1}{4}(f+f')$  and  $C_{Z^0} = -\frac{1}{4}(f \cot \theta_w - f' \tan \theta_w)$ , where  $f$  and  $f'$  are respectively the free parameters for SU(2) and U(1). In this study we assume  $f=f'$ , so that the only free parameter in the lagrangian is  $f/A = \sqrt{2} \lambda / m_{\tau^*}$  [8]. The differential and total cross section formulae can be found in refs. [4,7].

For the generation of pair produced excited taus we have made a Monte Carlo program using the differential cross section as given in ref. [7]. We simulate the single production of excited taus with the Monte Carlo generator [9]. The subsequent decay of  $\tau$ -leptons is simulated with the Monte Carlo program [10]. Both for the single and pair production processes the effect of initial state radiations is taken into account in our calculations. All generated events have been passed through the L3 detector simulation [11] #1 which includes the effects of energy loss, multiple scattering, interactions and decays in the detector and the beam pipe.

### 3. Data

The L3 detector and its performance in the detection of muons, electrons and photons is described in detail elsewhere [13]. It consists of a central tracking and vertex chamber (TEC), a BGO electromagnetic calorimeter, a ring of plastic scintillation counters, a hadron calorimeter made of uranium and proportional wire chambers and a high precision muon chamber system. These detectors are installed inside a 12 m inner diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity is measured by detecting small angle Bhabha events. The BGO covers the polar angle from

42.3° to 137.7°, the muon chamber from 36° to 144°, and the hadron calorimeter from 5.5° to 174.5°.

The data used in these searches were taken with the L3 detector at LEP in 1990 during an energy scan of the  $Z^0$  resonance at center of mass energies between 88.3 and 94.3 GeV. The integrated luminosity used in this analysis is 2.2 pb<sup>-1</sup>.

The trigger for this analysis requires a total energy in the electromagnetic and hadronic calorimeters of at least 15 GeV in the central region ( $|\cos \theta| < 0.74$ ), or 20 GeV in the entire calorimeter, or at least one muon reconstructed in the muon chamber with momentum larger than 2 GeV.

Our analysis uses a cluster algorithm which groups neighbouring calorimeter energy depositions. The algorithm normally reconstructs one cluster for a single electron, photon, muon, jet or high energy tau. Photons are identified as energy clusters in the BGO calorimeter with an electromagnetic shower profile and which do not match tracks from the vertex chamber. The requirement on the shower profile is that the energy sum of 9 crystals divided by the energy sum of 25 crystals (centered around the shower maximum) is larger than 0.95.

We search for excited taus by requiring the following cuts:

(1) The total energy in the calorimeters must be larger than 22 GeV. No total energy requirement is made if the event contains a reconstructed muon with momentum larger than 2 GeV.

(2) The measured energy in the BGO calorimeter alone must be larger than 2 GeV and smaller than 80 GeV; this requirement rejects  $e^+e^- \rightarrow \mu^+\mu^-$  and  $e^+e^- \rightarrow e^+e^-$  events.

(3) There must be less than 16 shower peaks with  $E > 100$  MeV in the BGO calorimeter. This cut rejects hadron events.

(4) There must be at least one and at most eight reconstructed charged particle tracks in the vertex chamber with momentum larger than 100 MeV. This cut also rejects hadron events.

(5) There must be exactly two clusters with energies larger than 2 GeV, which are not compatible with photons.

(6) Each identified electron or muon must have an energy smaller than 35 GeV. An electron is identified as an electromagnetic shower profile with a matched track in the vertex chamber within 5° in the

#1 The GHEISHA program [12] is used to simulate hadronic events.

$r-\phi$  plane. This cut rejects  $e^+e^- \rightarrow e^+e^-$  and  $e^+e^- \rightarrow \mu^+\mu^-$  events.

After applying the above selection cuts, 1357 events remain. They are predominantly  $\tau^+\tau^-$  events and are used to search for excited taus. The trigger efficiency, which exceeds 99.5%, has been checked using redundant triggers.

**4. Search for  $ee^- \rightarrow \tau^{**}\tau^{*-}$**

From our previous measurement of  $\Gamma_{Z^0}$  and the standard model prediction [14], we can set a limit on  $\tau^*$  pair production which translate into  $m_{\tau^*}$  greater than 27 GeV at 95% confidence level (CL). This is comparable with the limits from other experiments using direct searches [15]. In the following, we will do the direct search starting from this mass limit.

For the selection of  $e^+e^- \rightarrow \tau^{**}\tau^{*-}$  we require, in addition to the above cuts (1)–(6), the following criteria to be satisfied:

- (a) There must be two identified photons with energies larger than 5 GeV. They must be separated from any other BGO calorimeter cluster by more than  $10^\circ$ .
- (b) The opening angle between the two recon-

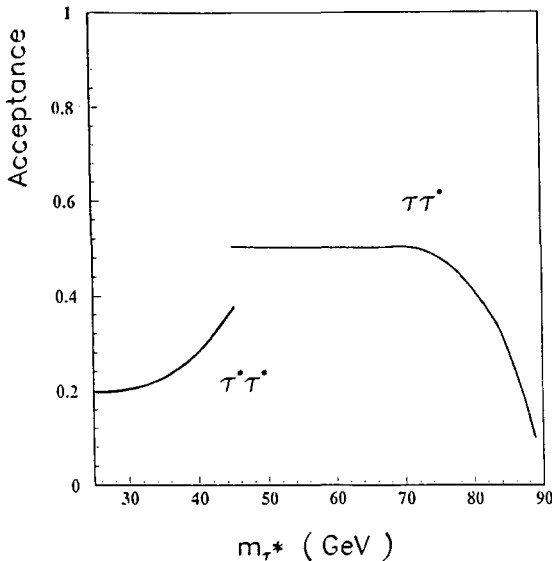


Fig. 1. The acceptance for  $\tau^*$  events both for single and pair production.

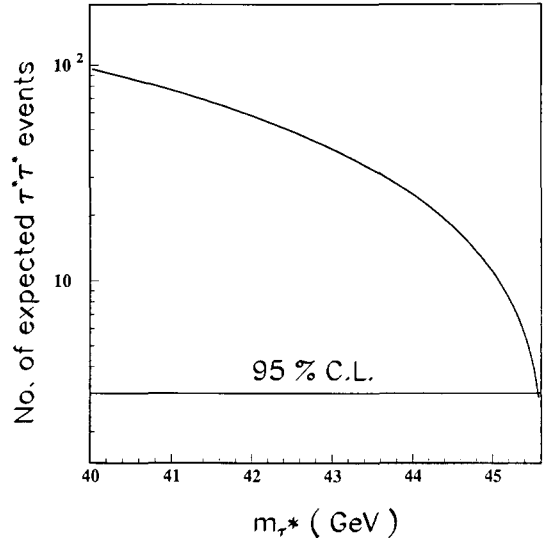


Fig. 2. Number of expected  $\tau^*\tau^*$  events from pair production.

structed clusters as defined in (5) must be smaller than  $170^\circ$ .

No events satisfy the above criteria. The background from radiative  $\tau^+\tau^-$  events has been found to be negligible from a Monte Carlo simulation [10]. The acceptance for  $\tau^*\tau^*$  events as a function of  $\tau^*$  mass is shown in fig. 1. The acceptance increases with the  $\tau^*$  mass because the photon becomes less collinear with the  $\tau$ . Fig. 2 shows the expected number of events from  $e^+e^- \rightarrow \tau^*\tau^*$  as a function of the excited tau mass. From this measurement we can exclude at 95% CL an excited tau for masses  $m_{\tau^*} < 45.5$  GeV.

**5. Search for  $e^+e^- \rightarrow \tau\tau^*$**

For the selection of  $e^+e^- \rightarrow \tau\tau^*$  we require, in addition to the above cuts (1)–(6), the following criteria to be satisfied:

- (a) There must be only one identified photon with energy larger than 5 GeV. The photon must be isolated as mentioned before.
- (b) The opening angle between the two reconstructed clusters as defined in cut (5) must be smaller than  $170^\circ$ .

Fig. 3 shows the photon energy distribution after cuts (1)–(6) compared with Monte Carlo simulations for  $e^+e^- \rightarrow \tau^+\tau^-$  and  $e^+e^- \rightarrow \tau\tau^*$  for a  $\tau^*$  mass of

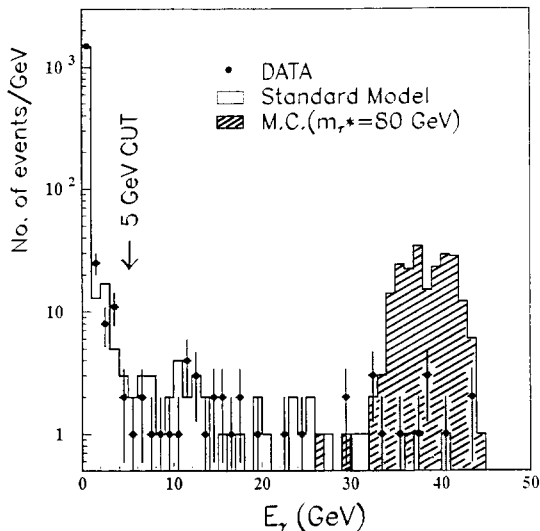


Fig.3. The measured photon energy spectrum compared with Monte Carlo. The unshaded area is the Monte Carlo prediction of standard model for  $\tau^+\tau^-$ . The shaded area is an example of the Monte Carlo prediction for  $\tau\tau^*$  with  $m_{\tau^*} = 80$  GeV and  $\lambda = 0.5$ .

80 GeV as an example. The acceptance for  $\tau\tau^*$  events for different  $\tau^*$  masses is shown in fig. 1.

After applying cuts (a) and (b), a total of 24 events

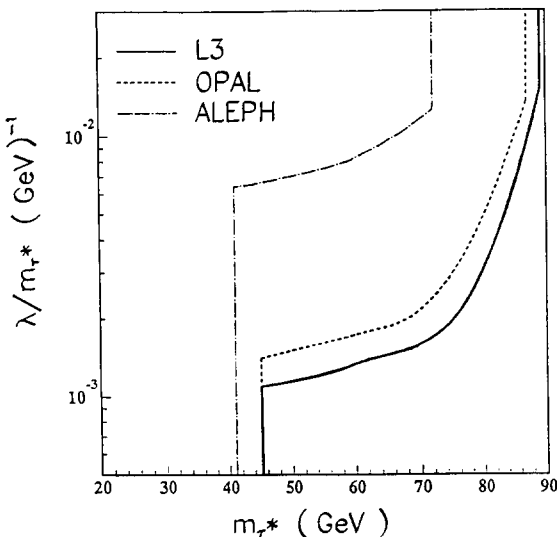


Fig. 4. The upper limit of the coupling constant  $\lambda/m_{\tau^*}$  at 95% CL as a function of  $m_{\tau^*}$ . The excluded region is above and left of the curves.

fulfill the above cuts. From a simulation [10] of the process  $e^+e^- \rightarrow \tau^+\tau^-\gamma$ ,  $22.3 \pm 4.2$  events are expected. Since it is not possible to reconstruct correctly the  $\tau\gamma$  invariant mass due to the undetected neutrinos from the  $\tau$  decay, we conservatively assume that all 24 events are seen at each value of  $\tau^*$  mass, with 22.3 background events expected. An excess of 12.5 events constitutes the 95% confidence level upper limit. For the cross section we use the analytic expression [4,7] including initial state radiative corrections. Fig. 4 shows the 95% CL upper limit of the coupling constant  $\lambda/m_{\tau^*}$  as a function of  $m_{\tau^*}$  together with results from other LEP experiments [5]. The beam energy and the energy cut for clusters limits our investigation to an  $m_{\tau^*}$  mass below 89.3 GeV.

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