SEARCHES FOR COMPOSITENESS IN LEP

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Resonant masses for excited fermions have been searched for by all the LEP collaborations. No signals have been found at LEP I or at 130–140 GeV centre of mass energy. Pair produced excited fermions are excluded close to the kinematic limit E_{beam} for leptons at the higher energy, and for quarks up to $m_Z/2$. New limits have been set on the couplings required for the single production of excited fermions, up to the corresponding kinematic limit close to $2E_{beam}$. The decays $Z \to ggg$, $Z \to gg\gamma$ and $Z \to \gamma S$, for scalar S, have not been observed, and limits have been set on branching ratios into these channels.

1 Introduction

Excited fermions are natural corollaries of models where the Standard Model fermions themselves are composite particles rather than being elementary ones [1]. The mass gap is determined by the compositeness scale, and, for a not too large value of the latter, may be bridged by the LEP energy. Looking for these new fermions provides a probe of possible new physics beyond the SM.

As the spectrum of the excited fermions depends crucially on the dynamics of the particular theory in question, the lowest lying excited states are allowed a wide range of spins and isospins. The studies reported here are restricted to spin 1/2 and isospin 1/2 (other cases have been discussed by Kühn and P.M. Zerwas [2]). If we assume that the excited states acquire mass above the electroweak breaking scale (so as to motivate the rather large mass gap), they necessarily would have vector-like couplings [3].

Apart from the gauge couplings (governed by the quantum numbers), these particles would also couple with the ground states. As the relevant piece of the interaction Lagrangian has the structure of a magnetic form factor, (and hence is of dimension 5), its strength is determined by f_i/Λ, where Λ is the compositeness scale and f_i are dimensionless coupling constants that may differ for the different gauge bosons. The presence of such couplings allow the excited fermions to decay to their ground state partners and a photon or a Z boson (or gluon in case of quarks), or to the isospin partners of the corresponding ground state and a $W^\pm$ boson.

The pair production cross sections are dominated by s-channel diagrams involving γ or the Z. While e^* or ν_e^* production can receive contributions from the magnetic piece of the Lagrangian, for the allowed range of f_i, $\sqrt{s} \sim \Lambda$ is required to make these terms significant [4].

In another possible compositeness scenario, the Z boson is the excited particle, being the spin-parallel bound state of two more elementary particles (preons), whose ground state is the spin-antiparallel scalar,S. The natural decay mode is now $Z \to \gamma S$, where the S boson decays to some (or all) of the same channels as Z, plus perhaps the no longer forbidden $\gamma\gamma$ and gg.

The two main sections of this article are (1) reports from LEP I, mostly using the whole data set, and (2) results from the high energy LEP runs in November 1995 [6,7,8,9,10,11]. With one partial exception, all searches are for mass resonances.

2 Searches using LEP I data

2.1 Rare Decays

Underlying compositeness can result in an enhanced rate for rare decays, such as those arising from anomalous 4-boson vertices. Two new limits are reported on the branching ratios for such decays,

(1) $BR(Z \to gg\gamma) < 2.5 \times 10^{-5}$, based on 2-jet, one photon event rates [5],

(2) $BR(Z \to ggg) < 1.5 \times 10^{-2}$, based on statistical gluon/quark-jet discriminators [12].

Standard Model rates are still below these limits, but (1) above now excludes some compositeness enhancement scenarios [13].

2.2 Radiative decays of excited fermions

Here are included all decays of excited charged leptons via photons and excited quarks via photons or gluons. The signatures of the signals are tracks (jets in the quark case) with one photon or two (pair production) or extra jets (for $q^* \to qg$). Photon energy cuts are generally high, at around 10 GeV. Background comes from electroweak radiative corrections, except for the jets only case, where it comes from higher order QCD. No signals are seen. Mass limits are now superceded by higher energy data (see later), although form factors are still more stringent (not shown). Coupling limits for single production [5], ($c_{Z\ell^*\ell} = -\frac{1}{4}(f \cot\theta_W - f' \tan\theta_W)$, etc[1]) are shown in Fig. 1, where for each channel separately the branching ratio for the radiative decay is assumed to be 100%.

A study of the QED 2γ final state events[5], excludes an enhancement due to the exchange of a virtual e^*, for $m_{e^*} < 162\,\mathrm{GeV}/c^2$.

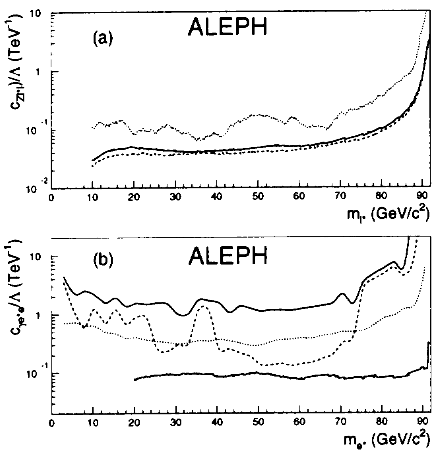

Figure 1: Coupling limits for single f* production as a function of f* mass; (a) s-channel: solid, dashed and dotted lines denote e^*, μ^* and τ^* respectively; (b) left hand label; lower solid line is t-channel e^*: right hand label; $q^* \to q\gamma$ (dotted line), $q^* \to qg$ (dashed line) and (upper solid line) branching ratio independent limit. Values above the lines are excluded at 95% c.l.

2.3 Weak decays of excited leptons

Here are included all W- and Z-mediated decays of all excited leptons, charged and neutral, with all the possible decays of the bosons. Most channels are characterized by missing momentum and/or mass, and are relatively free of background. No signals are seen, and the limits on the coupling for single production [5], obtained by combining all the channels are shown in Fig. 2.

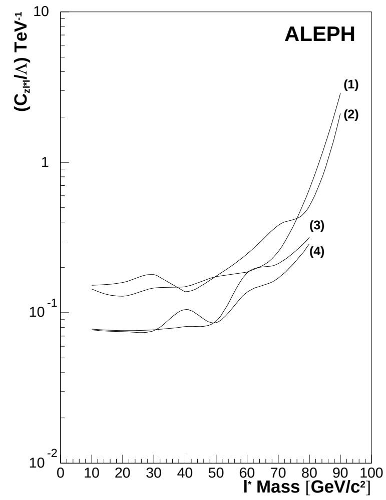

Figure 2: Lower limits on the compositeness parameters after combining all weak decay channels:(1)μ^*, (2) e^*_e, (3)ν^*_e and (4)ν^*_μ.

2.4 Composite $Z \to \gamma S$

Using data sets from the radiative decay channels above, but extending the photon energy limit down to 3 GeV, no signal is seen in any S-decay channel, and limits [5] are set as shown in Fig. 3. Note that the curve labelled 'q' applies to any one quark flavour or gg.

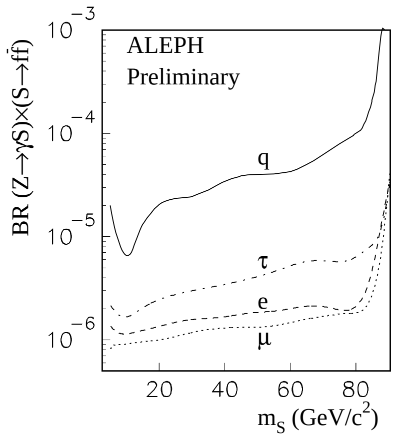

Figure 3: ALEPH: Limits on the branching ratio product $BR(Z \to S\gamma) \times BR(S \to f\bar{f})$ for various fermions.

3 Searches at 130–140 GeV

Approximately 5.5pb^{-1} of data were taken in this higher energy range by the LEP collaborations in November 1995. All the collaborations have conducted searches in many of the excited lepton channels discussed previously.

3.1 Pair produced excited charged leptons

The signal required was $Z/\gamma \rightarrow \ell^*\ell^* \rightarrow \ell^+\ell^-\gamma\gamma$, i.e. the radiative decay channel. No signals were seen and the best mass limits (by a few 100 MeV/c^2) were those of OPAL [10]: $m_{e^*} > 66.5\,\mathrm{GeV}/c^2, m_{\mu^*} > 66.8\,\mathrm{GeV}/c^2$ and $m_{\tau^*} > 65.8\,\mathrm{GeV}/c^2$. Their analysis used very low cuts on track momentum (1.5 GeV/c) and photon energy (1 GeV/c^2), included 3-prong τ-decays, and used a typical algorithm to recover the τ momentum from the direction of its decay products. The final analysis step is shown in Fig.4 for $\tau^*\tau^*$: the invariant masses of the possible track-photon combinations are compared, to find the one giving the smaller difference between its members. A cut is made on this difference (dashed box in the figure) at values related to the resolution of the invariant mass; it can be seen that one candidate (at very high mass) would gave survived a less severe cut.

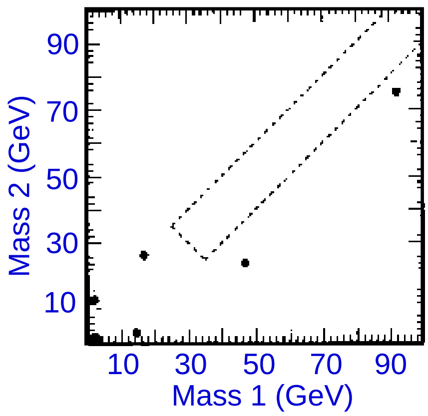

Figure 4: OPAL: $\tau^*\tau^*$ candidates, showing the tolerance on the mass equality of the τ^*-s (dashed box).

3.2 Pair produced excited neutrinos

In the radiative channel ($Z \rightarrow \nu^*\nu^* \rightarrow \nu\nu\gamma\gamma$) ALEPH [6],Opal [11] and L3 [9] have limits, based on searches for acoplanar photon pairs, close to $m_{\nu^*} > 64\,\mathrm{GeV}/c^2$. L3 and OPAL, however, have other analyses which search for the weak charged current decays, which can be expected to have a significant branching ratio, for ν^*-masses above the W-mass, and to dominate (71%) the weak decays. For example, L3, who are searching only for e^+e^-WW, accommodate all W decay channels, by requiring at least 1 isolated electron, momentum $> 2\,\mathrm{GeV}/c$, with at least 4 tracks and electromagnetic energy below 95% of the centre of mass energy, but at least 20% of this energy visible. Now they require 5 jets or 3 jets and a second electron $> 1\,\mathrm{GeV}/c$ and estimate a signal efficiency of 59%. No signal is seen and the limit is $m_{\nu_e^*} > 57.3\,\mathrm{GeV}/c^2$, at 95% confidence level.

3.3 Singly produced excited charged leptons

Searches were performed for events comprising 2 tracks and one photon (including the 3-prong τ-decay), but best limits were obtained from the t-channel electron search, with one electron invisible. Limits are shown, interpreted in the previously discussed Hagiwara model [1], with the f_i set equal, in Fig. 5, where three of the four LEP collaborations are seen to agree very substantively.