SEARCH FOR NEW SEQUENTIAL LEPTONS IN e^+e^- ANNIHILATION AT PETRA ENERGIES

TASSO Collaboration

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We have searched for new heavy leptons produced in e^+e^- annihilations at c.m. energies up to 36.6 GeV. The existence of a sequential lepton with a mass less than 15.5 GeV can be excluded with 95% c.l. This conclusion is almost independent of the lepton's decay properties.

The discovery of a new sequential lepton would have far-reaching consequences. In the standard gauge theory of weak–electromagnetic interactions, the existence of a new heavy lepton $L^\pm$ would imply the presence of a fourth generation of fermions in analogy with (u, d, ν_e, e) [1].

The cross section for the production of a charged lepton in e^+e^- annihilation is

$$\sigma(e^+e^- \to L^+L^-) = (4\pi\alpha^2/3s)\beta_L[1 + (1-\beta_L^2)/2],$$

where β_L is the lepton's velocity and s is the centre of mass energy squared. Assuming the standard model for weak decay the L will have both leptonic and semi-leptonic decays:

$$L^\pm \to \ell^\pm \bar{\nu}_\ell \nu_L ,$$

$$\to (\text{hadrons})\, \nu_L ,$$

where ℓ represents e, μ or τ. The expected [2] decay branching ratios for V – A coupling are listed below[‡1].

$$L \to e\bar{\nu}_e\nu_L (= L \to \mu\bar{\nu}_\mu\nu_L = L \to \tau\bar{\nu}_\tau\nu_L) = 0.111 ,$$

$$L \to \bar{c}s\nu_L\ (= L \to \bar{u}d\nu_L) = 0.318 ,$$

$$L \to \bar{c}d\nu_L\ (= L \to \bar{u}s\nu_L) = 0.015 .$$

The leptonic branching ratios are sizeable, and thus L^+L^- production will lead, for example, to an excess of $e\mu$ events, which was the signal used in the discovery of the τ. However, from the branching ratios, the combined branching fraction into the $e\mu$ final state can be calculated to be only 0.035. Furthermore, the two-photon processes $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\tau^+\tau^-$ can cause considerable background [3]. This signature was therefore not considered in our analysis. In a previous publication on $\tau^+\tau^-$ production [4] we showed that at high energies the topology of τ events is quite different from multihadron events. One might therefore expect a method relying on event shapes to be useful in a search for heavy leptons. From the above branching ratios we would expect a significant number of eX and μX events, where X represents hadronic particles (these events contain a hard lepton recoiling against a number of hadrons). Accordingly we searched for heavy leptons in final states of the type eX, μX (method A), and in final states with a single unidentified charged particle recoiling against a group of particles (method B). Method B has the advantage that lepton identification is not required and therefore leads to higher event rates. It requires, however, a reliable estimate of the background produced by hadronic events.

The experiment was carried out at the DESY storage ring PETRA using the TASSO detector. The main features of the detector have been described previously [4,5]. We summarize briefly the properties of the lepton identifying components used for this analysis. Electrons are identified in two types of shower counters. The bottom part of the solenoid and the hadron arms ($\approx$40% of 4π) are covered by lead scintillator sandwich counters, nine radiation lengths thick, which are read out via wave length shifter bars. The counters have an energy resolution of σ_E/E = 14% averaged over $2 \leqslant E \leqslant 15$ GeV. Electrons with $E > 2$ GeV are identified by requiring that the difference between their measured shower energy and their momentum is less than three standard deviations. The probability that an isolated hadron is identified as an electron by this criterion varies from 2.2% for particles with E = 2 GeV to 0.5% for $E \geqslant 4$ GeV.

The top part of the solenoid ($\approx$20% of 4π) is covered by a liquid argon shower calorimeter 14 radiation lengths thick. Lead plates 2 mm thick are used as showering material. The lead plates are highly segmented and form towers which are directed towards the interaction point. In order to increase electron–hadron separation the towers are longitudinally subsivided into front towers of 6 rl and back towers of 8 rl thickness, with sizes corresponding to $\Delta\Omega$ = 6 msr and 1.5 msr, respectively. At present the energy resolu-

‡1 These were computed assuming massless neutrinos. Differences in the available phase space due to fermion masses were neglected. This is a good approximation for $M_L > M_f$ (where f is either a quark or a lepton), and was found to be satisfactory in the case of the τ.

tion σ_E/E is $11\%/\sqrt{E(\mathrm{GeV})}$ for $1 \leqslant E \leqslant 4$ GeV and 5% for $E > 4$ GeV. The probability that an isolated hadron is misidentified as an electron is less than 0.3% for momenta greater than 1 GeV/c.

Muons are identified by signals in four layers of proportional tubes measuring two orthogonal coordinates behind iron absorber varying in thickness between 80 cm and 87 cm and covering 32% of the solid angle [‡2]. Muons also traverse shower counters which are equivalent to 10 cm of iron. The proportional tubes are 4 cm × 4 cm in cross section and the four layers are offset to give a resolution of 0.6 cm. Particles are tagged as muons if they produce hits in at least three proportional tube layers and these hits lie within three standard deviations of those predicted by extrapolating the track from the central detector. Muons of momentum less than approximately 1 GeV/c do not penetrate the iron. We restrict our muon identification to tracks with momenta >2 GeV/c where the tagging efficiency is greater than 99% and the pion contamination probability from decay in flight and punch-through is approximately 2% per track.

The data used in this analysis were taken in two main regions of centre of mass energy, at around W = 30 GeV and W = 35 GeV. The main details of our data reduction procedure have been reported previously [5]. The data used corresponds to luminosities of 2616 nb^{-1} at $W \approx 30$ GeV and 5308 nb^{-1} at $W \approx 35$ GeV. Tracks are accepted for polar angles $|\cos\theta| < 0.86$ and momentum transverse to the beam $p_T > 0.1$ GeV/c. In order to reduce the background from two-photon, Bhabha-scattering, and τ-pair processes to a negligible amount we require events to have ⩾5 charged tracks and charged energy ⩾8.0 GeV (9.3 GeV) at W = 30 GeV (35 GeV).

(A) The e–X, μ–X final states. The e–X, μ–X channels correspond individually to branching fractions of about 0.17. In order to increase our sensitivity to heavy lepton production we have required that an identified lepton should have an energy greater than 2 GeV/c and that the lepton candidate should be separated in space from all other charged tracks by an angle greater than 90°. A lepton with mass below 4 GeV would have an appearance very similar to the τ and our measurements of the τ cross section [4] exclude the existence of such a particle. The predictions for the number of events expected for a new lepton have been computed from a Monte Carlo program simulating the production and decay in our detector of a heavy lepton with branching ratios given above. The quark pairs produced from the hadronic decay of the heavy lepton have been hadronised using a modified Field–Feynman [6,7] fragmentation program. The total number of e–X and μ–X events expected from the data for a 4 GeV heavy lepton is 14.1 with a systematic uncertainty of 1.8, decreasing to 7.8 with a uncertainty of 1.2 for a lepton with mass 14 GeV. The number of e–X and μ–X events expected from hadronic events was found from a Monte Carlo program to be less than 0.5. We observe 2 events in the data, and therefore we exclude a new heavy lepton with a mass less than 14 GeV at 95% confidence level.

(B) The one charged + X topology. We define this topology by requiring an isolated charged particle with momentum $p > 1.5$ GeV/c separated by more than 90° from any other charged track. The momentum requirement takes advantage of the hard momentum spectrum expected from heavy lepton decays. Background due to beam gas and beam pipe interactions was found to be negligible. Bhabha-scattering events in which electrons and photons shower in the material before the track chambers constitute the major background. Most of it was removed by the requirement that at least 5 tracks be reconstructed for the event. The remaining background was removed by requiring that the effective mass of any pair of positive and negative particles when considered as electrons should be greater than 150 MeV.

In fig. 1 we show the distribution of the angle between the lone track and its nearest neighbour for the data at 35 GeV. Also shown are the expectations calculated by Monte Carlo [7] for $e^+e^- \to$ hadrons alone together with the contribution from heavy lepton production for m_L = 10 GeV.

Clearly our description of hadronic final states produced via normal quark–antiquark production will strongly affect the isolation of any possible heavy lepton signal. We have used Monte Carlo programs

‡2 The end-cap chambers, covering an additional 13% of the solid angle, have not been used in this analysis.

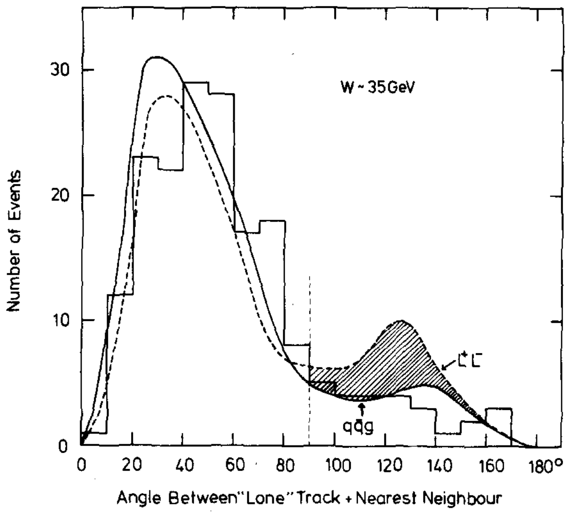

Fig. 1. Distribution of the angle between the lone track (method B) and its nearest neighbour at 35 GeV: for the data (histogram); predicted for hadronic events (solid curve); and predicted for hadronic events plus the heavy lepton contributions with m_L = 10 GeV (dashed curve).

following the procedures both of Hoyer et al. [8] and Ali et al. [9] to describe quark–antiquark production with the possibility of hard gluon bremsstrahlung. Radiative corrections were included following the prescription of Berends and Kleiss [10].

We have investigated the sensitivity of the Monte Carlo prediction to the parameters of the model used to describe the hadronic final state. We point out that in a previous analysis [7] by fitting the four parameters listed below we obtained a good description of the hadronic final states. The parameters and their fit values are:

(i) $a = 0.57 \pm 0.20$, where a determines the fragmentation of a quark q into a quark q′ plus a hadron: $f^h(z) = 1 - a + 3a(1-z)^2$, for u, d, s quarks, where $z = (E + p_\parallel)_h/(E + p_\parallel)_q$.

(ii) $P/(P + V) = 0.56 \pm 0.15$, where P/V is the ratio of primordial pseudo-scalar to vector mesons produced in the fragmentation process.

(iii) $\sigma_q = 0.32 \pm 0.04$ GeV/c, where σ_q governs the distribution of transverse momentum k_T of the quarks in the jet cascade, which is assumed to be of the form $\exp(-k_T^2/2\sigma_q^2)$.

(iv) $\alpha_s = 0.17 \pm 0.02$, where α_s is the strong coupling constant at $W \approx 30$ GeV.

We have varied each of these parameters to within one standard deviation of the measured values while maintaining reasonable agreement with the characteristics of the data. Within these conditions the smallest and largest predictions for the number of "1 + X" events produced from purely hadronic processes have been taken as estimates of the systematic uncertainty on this prediction. This uncertainty was found to be approximately 20%.

The number of "1 + X" events predicted from the hadronic production process alone, 30.5 ± 5.5 (statistical) with a systematic uncertainty of 6.7 agrees well with the 34 events observed in the data. For a heavy lepton of mass m_L = 12 GeV, on the other hand, the expected number of events is 60.3. In order to calculate the confidence level against the production of a new heavy lepton we have subtracted the systematic uncertainty from the predictions. The data then exclude the production of a new heavy lepton with mass ⩽12 GeV, with 95% confidence.

(C) "1 + X" or "0 + X" events defined via the sphericity axis. Method B is very sensitive to lower lepton masses since the boost between the lepton rest frame and the laboratory frame results in a large separation between the decay products of one lepton and those of the other. However, as the lepton mass increases this boost diminishes and method B becomes less sensitive. In order to be more sensitive to larger lepton masses we use the sphericity axis to define two hemispheres (rather than the "lone" track as in method B). This method finds more of these events where the single track from the decay of one of the leptons is emitted at a large angle to the original lepton direction.

Because large angles are possible between the initial lepton direction and that of its decay products for lepton masses close to threshold, there is an increase in the number of events where one lepton decay into our detector acceptance while the other decays outside it. These events are characterized by a jet of particles in one hemisphere with zero tracks in the other. We call these "0 + X" events.

In method C we divide each event into two hemispheres via the plane normal to the sphericity axis and count the number of events with either 0 or 1 track in a hemisphere. In contrast to method B, we make no cut on the lone track momentum. All other cuts are as before.

The systematic uncertainty on the prediction from hadronic processes was estimated as described in the previous section. For a lepton mass of 4 GeV we expect a total (sum of the contributions from heavy lepton pairs and $e^+e^- \to$ hadrons) of 102.2 "0 + X" and "1 + X" events with a systematic uncertainty of 9.5. We expect 55.9 events of this type from $e^+e^- \to$ hadrons events and observe 53 events in the data. For a lepton mass of 15.5 GeV the total number of "0 + X" and "1 + X" events expected is 48.5 with uncertainty 4.2. The expected number from $e^+e^- \to$ hadrons is 30.4: we observe 32 in the data. A heavy lepton with mass $m_L \leqslant 15.5$ GeV can therefore be excluded with 95% confidence.

We have attempted to ascertain to what extent our conclusions depend on the details of the heavy lepton decay. Fig. 2 shows the 95% confidence level contour excluding a new lepton plotted against mass and leptonic branching ratio, $B_e + B_\mu + B_\tau$ (all of which have been assumed to be equal). It was calculated using method C. It can be seen that we are able to exclude a new lepton over a wide range of possible leptonic branching ratios. We have also varied the assumptions on the weak decay. While we have assumed a V − A current throughout, large variations in the proportions of vector and axial vector currents have little effect on our results. We have also modified the Field–Feynman model to arbitrarily decrease by two the average number of primary particles produced in the fragmentation of the heavy lepton. Under these circumstances we would still be able to exclude a new heavy lepton with mass between 5 and 14 GeV with 95% confidence.

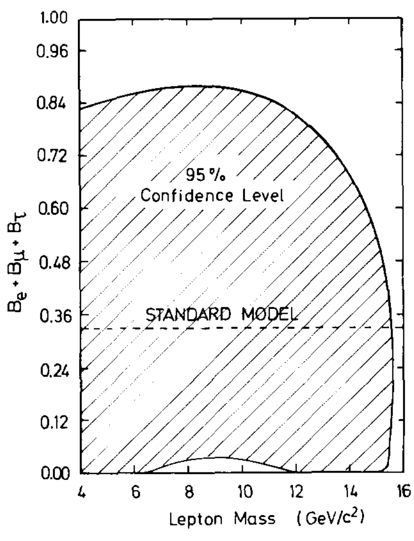

Fig. 2. 95% confidence level contour against the existence of a new heavy lepton plotted as a function of the leptonic branching fraction and lepton mass. The branching fraction into μ, e and τ has been assumed to be equal. The contour was determined from the data using method C.

In conclusion, if we assume the standard model we are able to exclude the existence of a new heavy lepton with a mass less than 15.5 GeV to 95% confidence level, in agreement with other experiments at PETRA [11]. Further, we have shown that our conclusion would still hold true if the properties of the hypothetical lepton differed substantially from those assumed in the standard model.

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