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# A search for new leptons

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**Abstract.** A search for new leptons, charged and neutral, produced in $e^+e^-$ collisions at an average c.m. energy of 44.2 GeV, has been carried out with the CELLO detector at PETRA. No such particles have been observed: we exclude pair production of new charged leptons at the 95% C.L. in the mass range 1.5–22.0 GeV/c$^2$ and of neutral leptons in the mass range 3.1–18.0 GeV/c$^2$. Single production of a heavy neutrino together with a standard neutrino has also been studied; we exclude an electron-like neutral lepton in the mass ranges 0.6–34.6 GeV/c$^2$ for $V-A$ coupling to the $W$ boson, and 0.4–37.4 GeV/c$^2$ for $V+A$ coupling.

## 1 Introduction

We report results on a search for new leptons produced in $e^+e^-$ annihilation. We consider the case of new charged leptons, pair-produced like the presently known leptons, and the production of heavy neutral leptons (also called heavy neutrinos). In the latter case, both pair production through $\gamma(Z^0)$ annihilation and the production of a single heavy neutrino together with a standard massless neutrino through $t$-channel $W$ exchange are investigated. This analysis uses data collected with the CELLO detector at the $e^+e^-$ storage ring PETRA in 1983 and 1984.

## 2 The CELLO detector

CELLO [1] is a general purpose detector for $e^+e^-$ physics and is particularly well suited for lepton identification. Charged particles are detected in a set of interleaved cylindrical drift and proportional chambers, in a 1.3 T magnetic field produced by a thin-walled superconducting solenoid. The angular acceptance is 92% of $4\pi$ steradians and the momentum resolution is $0.013\sqrt{1+P_T^2}\cdot P_T$ ($P_T$ in GeV/c). A 20 radiation lengths thick cylindrical lead-liquid argon calorimeter with fine lateral and longitudinal segmentation covers a solid angle of 86% of $4\pi$ steradians. This barrel part is complemented by end-cap lead-liquid argon calorimeters in the polar angular range $0.92 \leqq |\cos\theta| \leqq 0.99$. The energy resolution for electromagnetic showers can be parametrized as $\delta E/E = 5\% + 10\%/\sqrt{E}$(GeV). The acceptance gap $0.86 \leqq |\cos\theta| \leqq 0.92$ between the barrel and the end cap regions is covered for part of the data taking with a lead scintillator sandwich. This 'hole tagger' was used primarily for vetoing purposes. Large planar drift chambers mounted outside the hadron absorber (80 cm iron) ensure muon identification over 92% of $4\pi$ steradians.

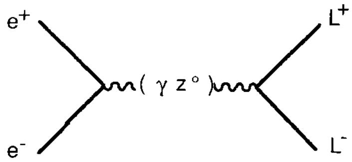


**Fig. 1.** Feynman diagram for $e^+e^- \to L^+L^-$

Electrons are identified by requiring the ratio of the energy deposited in the calorimeter to the reconstructed momentum to be greater than 0.5 and the longitudinal energy deposition in the calorimeter to be consistent with the pattern of electromagnetic showers.

Muons are identified as charged particles leaving a hit in the muon chambers associated to the extrapolated track as measured in the central track detector. The energy deposition in the calorimeter is required to agree with the expectation for a minimum ionizing particle.

The data were taken at centre of mass energies between 39.8 and 46.8 GeV. Part of the data were accumulated at a fixed energy while the rest came from an energy scan up to a maximum of 46.78 GeV. The overall accumulated luminosity was 21.4 pb$^{-1}$ at an average centre of mass energy of 44.2 GeV.

## 3 Search for new sequential charged leptons

We first describe the search for a new sequential charged lepton $L$, also sometimes referred to as charged heavy lepton to distinguish it from the tau lepton. This hypothetical new particle can be produced via ($\gamma, Z^0$) annihilation through the process

$$e^+e^- \to L^+L^-.$$

The corresponding lowest order Feynman diagram is shown in Fig. 1. At PETRA energies, contributions to the total cross-section due to the $Z^0$ exchange or to $\gamma - Z^0$ interference can be neglected. This cross-section can thus be written as a function of the centre of mass energy $\sqrt{s}$ and the mass of the heavy lepton $M_L$

$$\sigma(e^+e^- \to L^+L^-) \simeq \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \simeq \frac{43.4\,\beta(3-\beta^2)}{s(\mathrm{GeV}^2)}\,\mathrm{nb}$$

with

$$\beta = \left[1 - \frac{4M_L^2}{s}\right]^{\frac{1}{2}}$$

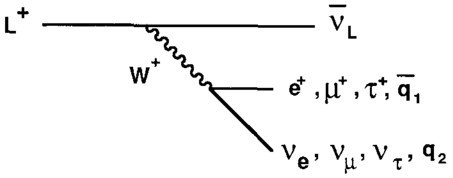


**Fig. 2.** Decay diagram for a new sequential charged lepton $L$

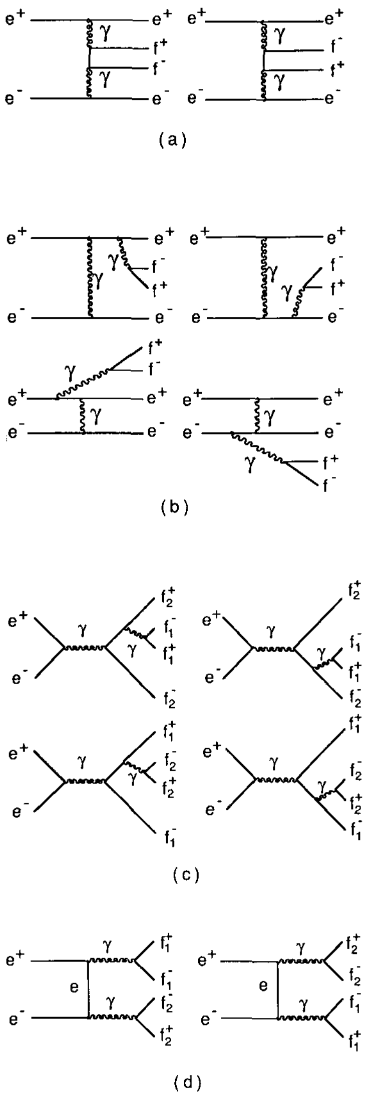


**Fig. 3a–d.** Lowest order diagrams ($\alpha^4$) producing four charged fermion final states ($f_1, f_2 = e, \mu, \tau, q$): **a** DIS, **b** IC, **c** virtual bremsstrahlung correction to single $\gamma$ annihilation, **d** virtual two photon production

The lepton is assumed to decay via the weak interaction $L^+ \to \bar{\nu}_L + (e\nu_e, \mu\nu_\mu, \tau\nu_\tau, \bar{d}u$ or $\bar{s}c)$ where $\nu_L$ is assumed to be massless (see Fig. 2). For $L$ masses up to a few GeV the semileptonic decay would proceed as in the case of the $\tau$ lepton mainly through hadronic resonances. However, for large $M_L$ the decay is essentially to the $\bar{q}q$ continuum followed by quark fragmentation to hadrons. For $M_L = 21$ GeV/c$^2$, the branching ratios to leptons and quarks (assuming two accessible quark generations) are estimated to be [2]:

$B(\nu_L \nu_\mu \mu) \simeq B(\nu_L \nu_e e) \simeq 10.7\%.$

$B(\nu_L \nu_\tau \tau) \simeq 10.1\%.$

$B(\nu_L u\bar{d}) \simeq B(\nu_L c\bar{s}) \simeq 32\%.$

$B(\nu_L u\bar{s}) \simeq B(\nu_L c\bar{d}) \simeq 2\%.$

In this analysis we select events where one of the charged heavy leptons decays to $e\nu_e(\mu\nu_\mu)$ and $\nu_L$, and the other decays semileptonically to hadrons. We therefore look for event signatures such as $e^+e^- \to e(\mu)$ + hadrons and missing energy, with the lepton recoiling against the hadrons ("one-lepton" signature). Each of these modes represents about 14% of all $L^+L^-$ pairs. In view of the strong background expected from ordinary multihadronic events we do not attempt to look for signatures arising from semihadronic decays of both heavy leptons. We also examine the acoplanar $e-\mu$ events, which give the classical and cleanest signature for new charged lepton pair-production; this mode has a probability of only slightly more than 2%.

### *3.1 Data selection and backgrounds*

*3.1.1 One-lepton signature.* For the one-lepton signature, the main selection criteria were:

1) at least 5 charged particles,

2) one of these being an isolated electron (muon) positively identified by the liquid argon calorimeter (muon chambers) with momentum greater than 4 GeV/c. "Isolated" means that there is no other charged particle within a cone of $\theta_{min} = 18°$ half angle around the direction of the lepton.

3) total energy of charged particles greater than $0.15\sqrt{s}$

4) for the $e^+(e^-)$ signature only, $-\cos\theta(+\cos\theta) \leqq 0.5$, where $\theta$ is the angle of the scattered $e^+$ (or $e^-$).

Cuts 1 and 2 suppress the tau pairs and the radiative Bhabhas and muon pairs, as well as most of the $2\gamma$ events with four fermions in the final state (Fig. 3a, d). Cut 3 eliminates most $2\gamma$ events with a hadronic final state. Order $\alpha^4$ processes with four fermions in the final state nearly always lead to events having an electron and/or a positron emitted at a small angle, which then escapes detection. Such events are also suppressed by cut 1. Cut 4 is applied to reject an important fraction of the large background coming from deep inelastic electron photon scattering (DIS)

(Fig. 3a, where $f^+$ and $f^-$ represent quarks) and from inelastic Compton scattering (IC), also called virtual bremsstrahlung (Fig. 3b). In both these processes the positron (or electron) is scattered mainly in the forward direction. The contamination due to order $\alpha^4$ processes was studied by Monte Carlo, using the event generators described in [3, 4].

A further source of background is due to $e^+e^- \to q\bar{q}(g)$ events with multihadronic final states leading to punchthrough particles simulating muons, or to the production of electrons or muons coming from the decay of light mesons or the semileptonic decays of heavy quarks. This contamination was studied using the LUND generator [5] with a full detector simulation.

*3.1.2 $e-\mu$ signature.* For the electron-muon final state, we applied the following cuts:

1) 2 charged particles, each with $|\cos\theta|$ less than 0.85 and momentum greater than 2 GeV/c, one of them identified as an electron and the other one as a muon

2) acoplanarity greater than 100 mrad, where the acoplanarity is defined as:

$$\cos\theta_{acop} = -(\mathbf{p}_e x \mathbf{z})\cdot(\mathbf{p}_\mu x \mathbf{z})/(|\mathbf{p}_e x \mathbf{z}|\cdot|\mathbf{p}_\mu x \mathbf{z}|)$$

with $\mathbf{z}$ a unit vector along the electron beam

3) sum of the absolute values of the two momenta greater than $\sqrt{s}/8$

4) 2-particle invariant mass greater than 0.2 GeV/c$^2$

5) no neutral energy cluster greater than 500 MeV.

Cut 2 is needed to suppress the large background from $\tau$-pair production with the same signature. Cut 4 reduces the contamination from Bhabhas, $\mu$-pairs and $\tau$-pairs recoiling against a very hard but undetected radiative photon. Cut 5 suppresses the background from radiative $\tau$-pair production.

*3.2 Results*

*3.2.1 Isolated lepton signature.* For the isolated electron signature, 27 events were found to fulfil the selection criteria. Table 1 shows for this case the expected background due to DIS, IC and 1 or $2\gamma$ annihilation, amounting to $25.1\pm2.2$ events. For the isolated muon signature, 9 events were found for an expected background of $7.8\pm1.5$ events. The background can be reduced further by applying cuts on the invariant mass of the charged particles excluding the isolated electron (muon). Figure 4 shows the expected charged particle invariant mass distribution for hadronic decays of a heavy lepton of mass $M_L = 21$ GeV/c$^2$ obtained by using the Lund Monte Carlo with the fragmentation function of Peterson et al. [6]. In order to reduce multiparticle background from sources other than $L^+L^-$ production, we require the invariant mass of charged particles, excluding the isolated electron (muon), to be less than 11 GeV/c$^2$. For events with the electron signature, we require in addition this mass to be larger than 2 GeV/c$^2$ in order to reduce the background from IC events.

**Table 1.** Expected number of background events for the $e$-hadrons signature in the search for pair-production of a new charged lepton

| Reaction | Number of expected events |
|---|---|
| DIS | $4.0\pm0.8$ |
| IC | $8.1\pm1.1$ |
| $1-\gamma$ annihilation | $13.0\pm1.7$ |
| Total | $25.1\pm2.2$ |

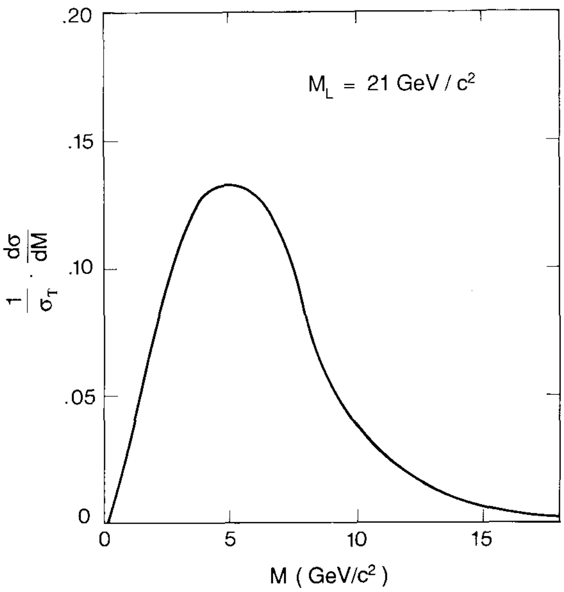


**Fig. 4.** Monte Carlo generated invariant mass spectrum of charged particles in new charged lepton decays

After applying these cuts on the invariant mass, we are left with 18 (3) events with an isolated electron (muon) signature for an estimated background of $17.8\pm1.4$ ($5.2\pm1.2$) events. The numbers of observed events are used to derive 95% C.L. upper limits for the total number of events (signal plus background), assuming Poisson statistics. This limit is shown as a horizontal line in Figs. 5 and 6. The curve in these figures shows, versus the new lepton mass, the lower limit of the sum of the possible new lepton signal and the various backgrounds, computed using the MC simulation. This limit is obtained by taking into account the systematic error due to the uncertainty

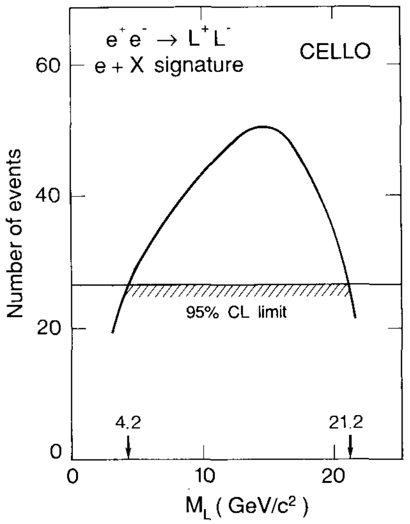


**Fig. 5.** Expected number of events versus the new lepton mass for the case of an electron-hadron signature

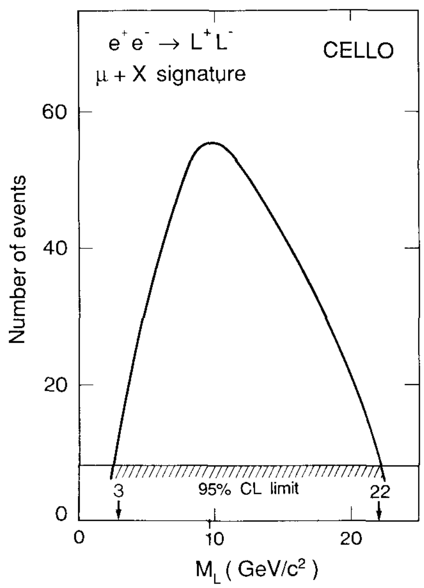


**Fig. 6.** Expected number of events versus the new lepton mass for the case of a muon-hadron signature

on luminosity ($\pm 2\%$), track reconstruction ($\pm 1\%$), lepton identification efficiency ($\pm 1\%$) and background estimate ($\pm 1\%$), all added linearly to be on the safe side*. From these figures a new charged lepton can be excluded in the mass range between 4.2 and 22 GeV/$c^2$ for the isolated electron or muon signatures respectively. The same method to obtain mass limits has been applied throughout this paper.

* The systematic error on the acceptance has not been taken into account, but comparison of MC distributions such as lepton isolation angle $\theta_{min}$ or lepton momentum from $B$ meson decay show good agreement with our data [7]

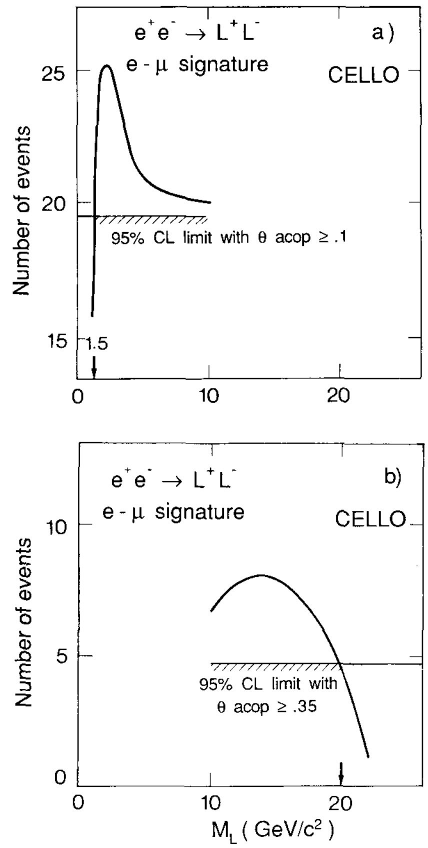


**Fig. 7a, b.** Expected number of events versus the new lepton mass for the case of an electron-muon signature with an acoplanarity cut of: **a** 100 mrad, **b** 350 mrad

*3.2.2 $e-\mu$ signature.* For the $e-\mu$ signature, 12 events are observed, while the background is expected to be 10.8 events from tau pairs. By applying a more stringent acoplanarity cut of 350 mrad, we are left with one event for a background of 0.13, and can thus improve the sensitivity for high mass leptons. From Fig. 7 showing the expected counting rates, one observes that new charged lepton masses are excluded between 1.5 and 20 GeV/$c^2$ at the 95% C.L.

*3.2.3 Combined results.* Combining the previous results we conclude that a new charged lepton is excluded at the 95% C.L. in the mass range 1.5–22 GeV/$c^2$. This result is similar to those of other experiments at PETRA and PEP [8]. Recent analyses of experiments at TRISTAN [9] and of the UA1 Collaboration [10] set more stringent lower limits of 25 GeV/$c^2$ (95% C.L.) and 41 GeV/$c^2$ (90% C.L.), respectively, to the mass of a new charged lepton.

## 4 Search for new neutral leptons

We now discuss the search for new neutral leptons $N$, also sometimes referred to as neutral heavy leptons

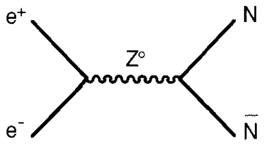


**Fig. 8.** Feynman diagram for $e^+e^- \to N\bar{N}$

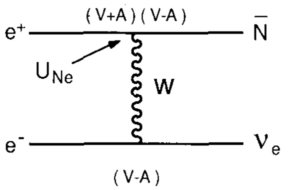


**Fig. 9.** Feynman diagram for $e^+e^- \to \bar{N}\nu_e$

or heavy neutrinos. The two possibilities considered are $N\bar{N}$ pair production through $Z^0$ annihilation (Fig. 8) and the production of a single new neutral heavy lepton together with a light neutrino through $W$ exchange (Fig. 9). With the latter mechanism, one is sensitive to new neutral leptons up to the total available centre of mass energy, in contrast to the first mechanism which is sensitive to masses up to half the centre of mass energy. The associated production of light and heavy neutrinos is possible with massive neutrinos. In this case, the mass eigenstate and weak eigenstate need not coincide and one can have mixing between the various generations, just as in the quark sector. There, the mixing is parametrized by a Kobayashi-Maskawa type unitary matrix. In analogy, one can write the weak eigenstate of the electron neutrino as a mixture of the mass eigenstates $\nu_i$ [11]:

$$\nu_e = \sum_i U_{ei}\,\nu_i$$

where the sum is taken over 4 generations. For reviews on previous searches see [11].

The total cross section of the annihilation mechanism into two new neutral leptons is given by the Standard Model formula:

$$\sigma = \frac{G^2 s}{96\pi}\left[\frac{M_z^2}{s-M_z^2}\right]^2 \beta(3+\beta^2)(1-4\sin^2\theta_w+8\sin^4\theta_w)$$

with $G$ the Fermi constant, $\theta_w$ the electroweak mixing angle and

$$\beta = \left[1-\frac{4M_N^2}{s}\right]^{\frac{1}{2}}.$$

The energy dependence of this cross-section for several new neutral lepton masses is shown in Fig. 10. The cross section for the production of a single neutral heavy lepton can be calculated using a $V-A$ (left-handed) or a $V+A$ (right-handed) current at the vertex $eWN$ (Fig. 9), [12, 7].

$$\sigma_{(V-A)} = \frac{G^2}{4\pi}\left(1-\frac{M_N^2}{s}\right)^2 |U_{Ne}|^2 (a-1)^2 \cdot\left[\frac{s}{a-1}+(s-M_N^2)+\tfrac{1}{2}[s+a(s-M_N^2)]\ln\frac{a-1}{a+1}\right]$$

$$\sigma_{(V+A)} = \frac{G^2}{4\pi}\left(1-\frac{M_N^2}{s}\right)^2 |U_{Ne}|^2\, 2s \cdot\left(\frac{M_W^2}{M_W^2+s-M_N^2}\right)$$

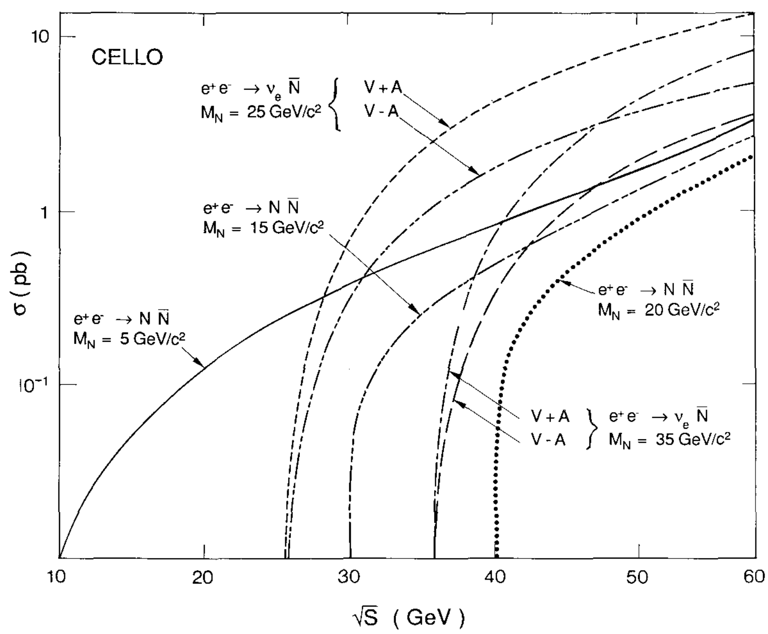


**Fig. 10.** Total cross section versus centre of mass energy for several neutral heavy lepton masses for the reactions of Figs. 8 and 9

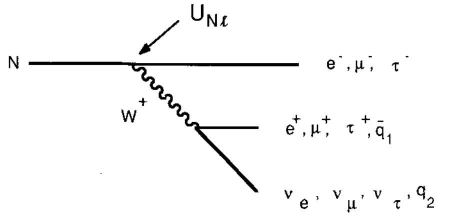


**Fig. 11.** Decay diagram for a new neutral lepton $N$

where

$$a=\frac{s+2M_W^2-M_N^2}{(s-M_N^2)}$$

and $U_{Ne}$ is the $e-N$ mixing parameter. For an $e$-type neutral lepton this mixing parameter is equal to 1. The magnitude of various cross-sections is displayed in Fig. 10.

It is generally assumed that a new neutral lepton decays in the same way as a charged lepton through a $W$ boson (Fig. 11), leading to a lifetime of:

$$\tau_N=\frac{M_\mu^5}{M_N^5}\tau_\mu\frac{B(N\to l\nu_e e)}{\sum_l |U_{Nl}|^2}.$$

Thus, in order to observe the decay in our detector, the value of $M_N^5\sum|U_{Nl}|^2$ has to be sufficiently large.

The decay channels depend upon the mass of the heavy neutrino. The semi-leptonic decays of a light neutrino ($\sim 2$ GeV/c$^2$) proceed through hadronic resonances in the same way as for the tau lepton [13] while a heavy neutrino will decay into the $q\bar{q}$ continuum [2] with branching ratios to leptons and quarks as for the charged lepton decays (see Sect. 3).

### *4.1 Pair production of new neutral leptons*

*4.1.1 Data selection.* For new neutral lepton pair production the final state contains at least 2 oppositely charged leptons. We require:

– at least 4 charged particles with $|\cos\theta|$ less than 0.92 with at least one isolated and identified lepton with momentum greater than 2 GeV/c having no charged particle within a cone of 18° half angle about the direction of the lepton

– a further identified lepton of the same type, with opposite charge.

Depending on the charged particle multiplicity, we distinguish 2 cases:

a) 4 particles in the final state with the following requirements:

– zero total charge of the event

– The invariant mass of any pair of opposite charged particles greater than 1 GeV/c$^2$.

The last cut is very efficient for rejecting radiative lepton pair production where the photon is converted in the beam pipe, off-momentum particles interacting in the beam pipe and $\alpha^4$ QED processes. The events satisfying these cuts are then fitted with 3 or 4 constraints (3 $C$ allows for the radiation of a photon along the beam direction). This fit [7] allows us to distinguish between events with 3 or 4 leptons coming from $N$ pair production and those with 4 lepton final states from order $\alpha^4$ QED processes. Since the purely leptonic decay of a new neutral lepton always produces at least one neutrino, only those 4 prong events which fail to give a good fit because of the missing energy are kept.

b) $\geqq 5$ charged particles in the final state, with:

– momenta of the leptons larger than 4 GeV/c

– The invariant mass of an electron and the nearest charged particle greater than 200 MeV/c$^2$.

The lepton momentum cut rejects DIS and IC interactions while the cut on the invariant mass rejects events with an electron interacting in the beam pipe or with conversion of a photon. The overall efficiency of these cuts varies from 3.6% for $M_N=2$ GeV/c$^2$ to 51.5% for $M_N=20$ GeV/c$^2$.

*4.1.2 Results.* We are finally left with 2 events (one for each of the cases a) and b)): a 4 prong event with 3 identified electrons, and a high multiplicity event with 2 identified muons and 2 jets [14]. If we assume that these events come from $e^+e^-\to N\bar{N}$, the smallest possible mass for $N$ can be calculated by assigning the observed particles to one or the other heavy neutral lepton. We find respectively 8 and 13 GeV/c$^2$ for this smallest mass.

Two sources of background were studied: $\alpha^4$ QED processes (Fig. 3) leading to final states containing at least two leptons. the background for the event with 2 muons for example comes from the conversion of a virtual photon into a $mu$-pair (Fig. 3c, d). A further source of contamination is from single photon annihilation into $q\bar{q}$. Since in this case the leptons are produced close to the quark-jets, this contribution is negligible within our cuts. Table 2 summarizes the different types of candidates found and the expected background.

We consider two cases for the decay of the new lepton:

### *a) Short lifetimes*

Let us now suppose that the mixing matrix element $U_{Ne}$ or $U_{N\mu}$ is large enough for the decay to occur close to the interaction region ($\lesssim 2$ cm). Figs. 12a and

Table 2. Observed number of events and expected background for each of the signatures studied in the search for pair-production of a new neutral lepton

| Signature | Number of events seen | Expected background |
|---|---|---|
| 4 charged particles including $\geq 2$ leptons | 1 | $0.74 \pm 0.07$ |
| $\geq 5$ charged particles including 2 electrons | 0 | $1.4 \pm 0.3$ |
| $\geq 5$ charged particles including 2 muons | 1 | $0.13 \pm 0.03$ |

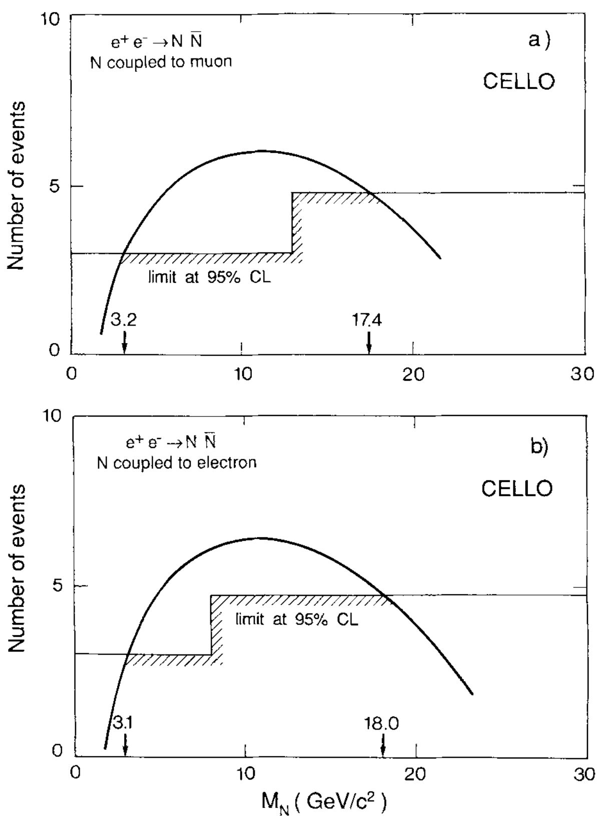


Fig. 12a, b. Expected number of events versus the mass of the new neutral lepton $N$ pair-produced with a dominant coupling **a** to muons **b** to electrons

b show that at the 95% C.L. neutral heavy lepton pair production is excluded in the mass range 3.2–17.4 GeV/c$^2$ for dominant $N-\mu$ coupling, and in the range 3.1–18.0 GeV/c$^2$ for dominant $N-e$ coupling.

*b) Long lifetimes*

Limits on $|U_{Ne}|^2$ or $|U_{N\mu}|^2$ were obtained from investigation of events in which the neutral leptons were required to have decayed far from the interaction point. The efficiency of this selection has been studied by generating MC events where the heavy neutrinos decay at different distances from the interaction point. As a typical example, the acceptance for an event with 2 neutral leptons of mass 15 GeV/c$^2$, both decaying at 5 cm is 55%, decreasing to 19% at 20 cm. The data were thus searched for events with a secondary vertex, by requiring:
– at least 4 charged particles
– the average impact parameter of the tracks (in the plane normal to the beam direction) to be greater than 1 cm
– impact parameters greater than 1 cm for more than 50% of the tracks.

The events which were not accepted by these cuts had to satisfy the previous selection criteria. All the events fulfilling the secondary vertex cuts were visually scanned to search for candidates having 2 separate vertices. To eliminate events with interactions in the beam pipe, vertices in a region of $\pm 1$ cm around the vacuum tube were discarded. No additional candidate was found. We calculated the expected number of events with two heavy neutrinos decaying in the central detector at distances $X_1$ and $X_2$ from the interaction point by folding the detection efficiencies $\varepsilon(X_1, X_2)$ with the decay probability for given $|U_{Nl}|^2$ and $M_N$. This determines a 95% C.L. exclusion contour in the plane defined by the mixing matrix element and the mass of the new lepton (Fig. 13). The slightly better limits for new neutral leptons decaying away from the interaction point ($\geq 2$ cm) are mainly due to the fact that no event of this type was found. In

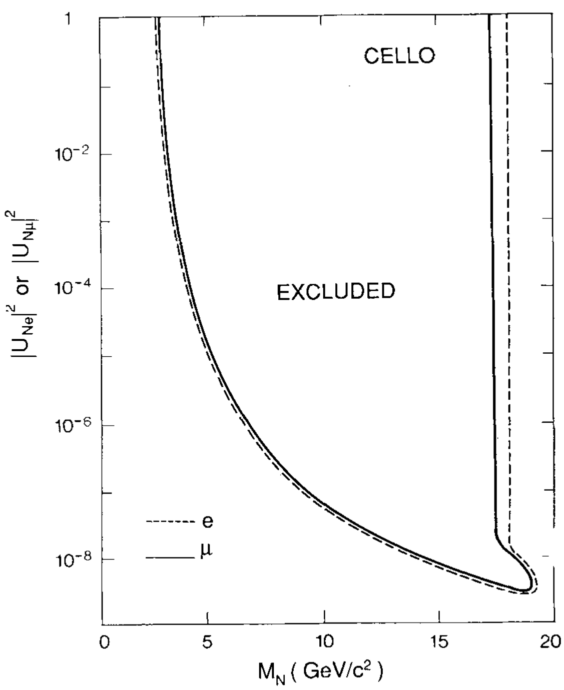


Fig. 13. 95% C.L. exclusion contours of new neutral lepton mass $M_N$ versus $|U_{Nl}|^2, l=e, \mu$

the high mass region our analysis improves the existing limits from other searches [15].

### 4.2 *Single new neutral lepton production*

We finally discuss single new neutral lepton production. It is clear from Fig. 9 that this production mechanism leads to events with large missing momentum since a neutrino is produced back to back with the heavy neutral lepton. Thus for example, at an energy of 44 GeV in the centre of mass, a neutral lepton mass of 25 GeV/c$^2$ implies a momentum of 14.9 GeV/c for the $\nu_e$ opposite to the heavy lepton momentum.

*4.2.1 Data selection.* Two signatures were studied:

a) $e-\mu$ events, selected in the same way as for the new charged lepton search (see Sect. 3.1).

b) electron + multihadron events, selected by requiring:

– at least 5 charged particles with $|\cos\theta|$ less than 0.92, including 1 identified electron with momentum above 4 GeV/c

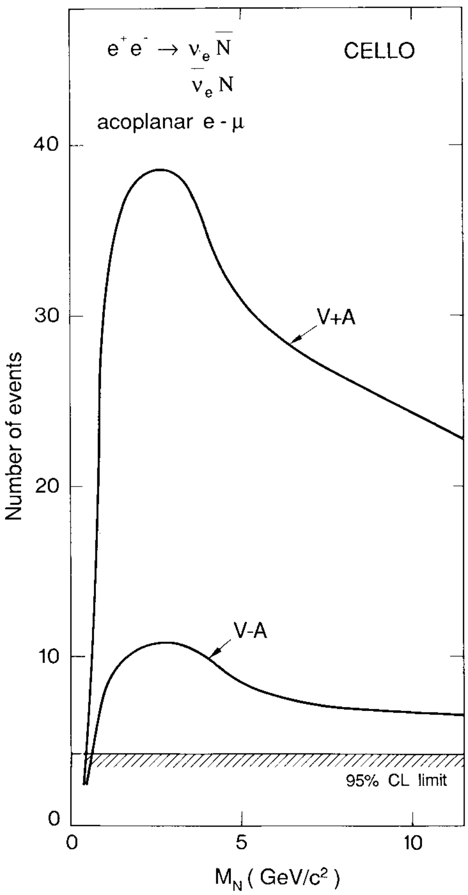


**Fig. 14.** Expected number of events versus the mass of new neutral lepton $N$ produced via the diagram of Fig. 9, with an $e-\mu$ final state

**Table 3.** Expected number of background events for the $e$-hadrons signature in the search for associated production of a new neutral lepton

| Reaction | Number of expected events |
|---|---|
| DIS | $4.9 \pm 0.9$ |
| IC | $1.2 \pm 0.5$ |
| $1-\gamma$ annihilation | $0.7 \pm 0.1$ |
| Total | $6.8 \pm 1.1$ |

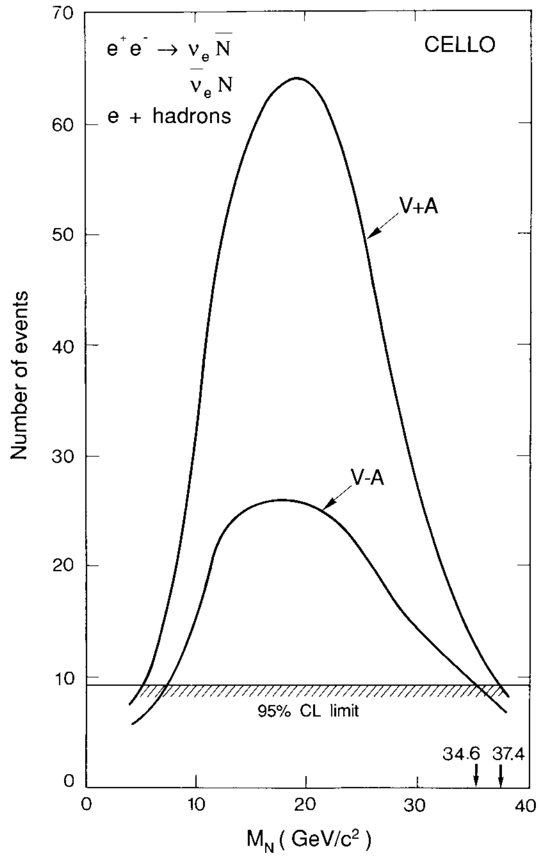


**Fig. 15.** Expected number of events versus the mass of new neutral lepton $N$ produced via the diagram of Fig. 9 with an $e$ + hadrons final state

– sum of absolute values of all momenta greater than 10 GeV/c.

– No charged particles within a cone of half-angle of 18° ($\cos\theta = 0.95$) around the thrust axis of the events.

*4.2.2 Results.* For the electron-muon signature, one candidate event is found with a background of 0.13 events from $\tau$ production, as stated in Sect. 3.2, for an acoplanarity cut of 350 mrad. This it can be concluded that there is no evidence for an anomalous production of $e-\mu$ events. Given the one observed candidate, we exclude at 95% C.L. the existence of singly produced new heavy leptons above 600 MeV/c$^2$ for a $V-A$ coupling and above 400 MeV/c$^2$ for $V+A$ coupling in the low mass region (Fig. 14). These limits are safe upper limits obtained as explained in Sect. 3.2. The sensitivity to errors is in fact lower because of the steep rise in the low mass region.

In the case of the electron + hadrons signature, 4 events are found with an estimated background of $6.8 \pm 1.1$ mainly due to the DIS process described above. Table 3 gives the expected numbers of events of this reaction together with those of the IC process and annihilation to $q\bar{q}$. We exclude a neutral heavy lepton at 95% C.L. with a mass lower than 34.6 GeV/c$^2$ for $V-A$ coupling and 37.4 GeV/c$^2$ for $V+A$ (Fig. 15). This last search only applies for an electron-like neutral lepton assuming that $|U_{Ne}|^2=1$.

The present result improves earlier limits from PEP and PETRA [16].

## 5 Summary

We have searched for new lepton production in $e^+e^-$ annihilation. No evidence has been found neither for pair-production of a new charged lepton nor for production of a neutral lepton, whether in pairs of singly in association with a standard neutrino. From the non-observation of pair production a new charged lepton is excluded at the 95% C.L. in the mass range 1.5–22.0 GeV/c$^2$, and a new neutral one in the range 3.1–18.0 GeV/c$^2$. Our limits on associated production of a heavy neutral lepton together with a standard massless neutrino exclude electron-like neutral leptons in the mass range 0.6–34.6 GeV/c$^2$ for a $V-A$ current at the $eWN$ vertex and 0.4–37.4 GeV/c$^2$ for $V+A$.

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