30 / 7/5/89 JS ②

SLAC-PUB--4985

DE89 014591

REVIEW OF "CLOSE-MASS" HEAVY LEPTON SEARCHES*

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Abstract

Results from recent searches in e^+e^- annihilation at PEP($\sqrt{s}$ = 29 GeV) for a fourth-generation charged lepton associated with a slightly lighter neutrino partner are presented. Some emphasis is given to the most recent search, which uses a novel approach based on radiative tagging, an approach that holds promise as a general tool in searching for exotic events characterized by very low visible energy. Prospects for upcoming sequential lepton searches at SLC and LEP experiments are also discussed.

Invited talk presented at the XXIV Rencontres de Moriond: Electroweak Interactions and Unified Theories, Les Arcs, France, March 5 12, 1989.

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* Work supported by the Department of Energy under contract DE-AC03-76SF00515

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CONF-8903132--1

1. Introduction

It was pointed out in 1986[1] that previous searches for a fourth-generation sequential lepton had been insensitive to lepton doublets where the charged lepton is only slightly heavier than the neutral lepton. Dubbed "close mass" leptons, these particles would give rise in e^+e^- annihilation data to events with low visible energy (assuming the heavy neutrino lives long enough to escape detection). Such leptons might easily have eluded discovery because low energy events are typically discarded in conventional searches, in order to suppress two-photon backgrounds.

Three separate searches have been conducted recently for close-mass leptons in experiments at the PEP e^+e^- storage ring($\sqrt{s} = 29\,\mathrm{GeV}$), two on the Mark II experiment[2,3] and one on the TPC experiment.[4] These searches will be reviewed, with some emphasis on the second Mark II analysis, which uses an unusual radiative-tagging technique to look for nearly degenerate lepton doublets. At the end, consideration will be given to upcoming sequential lepton searches at SLC and LEP experiments. In particular, strategies for detecting close-mass leptons will be discussed in detail.

2. Close-Mass Leptons

Although measurements indicate that neutrinos from the first three generations are much lighter than their charged partners, if not massless, our poor understanding of lepton generations precludes any definitive statement concerning the mass of any fourth-generation neutrino. Cosmological considerations[5] currently allow a stable Dirac neutrino with mass greater than $\approx 4\ \mathrm{GeV}/c^2$. In addition, a model proposed by Raby and West[6] suggests that a close mass sequential lepton doublet with a stable neutrino of mass 4–10 GeV/c^2 could solve both the solar neutrino puzzle and the dark matter problem.

Close-mass lepton events in e^+e^- annihilation give rise to low visible energy because the undetected heavy neutrinos carry away a large fraction of the available energy. The low momenta of the detected heavy lepton decay products lead to two major problems in conventional sequential lepton searches. The first is that electron identification from calorimetry measurements and muon identification from penetration through dense material become difficult at lower momenta. The second problem

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is that at lower visible energies, conventional two-photon backgrounds, especially those from the process $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$, provide a serious contamination. The mass difference ($\delta_M \equiv M_L - M_{\nu_L}$) constrains heavy lepton search strategies in another way: the branching ratios for various charged lepton decay modes depend quite sensitively upon δ_M, as shown in the following table.

Table 1. Shown are dominant decay modes for different ranges in the lepton mass difference δ_M.

Range in Mass Difference	Branching Ratios (%)			
	$L \rightarrow (e, \mu, \tau)$	$L \rightarrow \pi$	$L \rightarrow \rho$	$L \rightarrow$ other
$\delta_M < M_\pi$	100	0	0	0
$M_\pi < \delta_M < 600$ MeV	5 30	Dominant	< 5	0·1
600 MeV < δ_M < 4 GeV	≈ 30	Falling	Max ≈ 40	1 → 60
4 GeV < δ_M	→ 33	→ 0	→ 0	→ 67

For very low mass differences, phase space suppression of available decay modes can impart a substantial lifetime to the charged heavy lepton. Since single charged particle decay modes dominate at low δ_M, the resulting events typically have two detected charged particles, neither of which extrapolates back to the beam collision point. In principle, this makes a useful signal, but in practice, such events have poor trigger efficiency because of experimental filters against cosmic ray and beampipe-related backgrounds. This reduced trigger efficiency can severely limit an experiment's sensitivity to very low δ_M doublets.

3. Mark II Results (charged particle identification)

The first Mark II[7] analysis relies upon charged particle identification to extract heavy lepton events from conventional backgrounds. Nine distinct event classifications are defined:

electron *vs* muon

electron *vs* pion (0γ)
electron *vs* pion (> 0γ)
muon *vs* pion (0γ)
muon *vs* pion (> 0γ)

electron *vs* 3 charged
electron *vs* > 3 charged
muon *vs* 3 charged
muon *vs* > 3 charged

These are further subdivided: for the two-prong events according to whether t acoplanarity (acollinearity in plane transverse to beam) is less than or greater tha 25°; and for the multi prong events according to whether all particles opposite the isolated lepton have a total invariant mass less than or greater than 2.5 GeV/c^2. The number of events expected to fall into one of the final 18 classifications is calculated for the following background processes:

$$e^+e^- \to \tau^+\tau^- \qquad\qquad e^+e^- \to q\bar{q}$$
$$e^+e^- \to e^+e^-\tau^+\tau^- \qquad\qquad e^+e^- \to e^+e^-q\bar{q}$$
$$e^+e^- \to \mu^+\mu^-q\bar{q}$$

and compared with that observed in the data (integrated luminosities for data samples vary from 108 to 205 pb^{-1}). Electrons are identified from calorimetry and muons from penetration through up to four layers of steel. Single pions are charged particles identified as both non-electrons and non-muons, according to similar criteria.

The total number of events found in all categories is expected to be 1217 ± 47, while the number observed in the data is 1233. The χ^2 for the number of events distributed in each category is 23.4 for 18 degrees of freedom. Limits are placed on the existence of close mass leptons by calculating the ratio R_i for each classification:

$$R_i \equiv \frac{\mathrm{Prob}_i(\mathrm{Background} \to \mathrm{Observed})}{\mathrm{Prob}_i(\mathrm{Background} + \mathrm{Signal} \to \mathrm{Observed})}$$

where Gaussian differential probability distributions are used. The product R_{tot} of these 18 values of R_i is then a measure of whether the background alone or the background plus a hypothetical signal is favored by the observed data. Monte Carlo samples have been generated for various combinations of (M_L,M_{ν_L}). By interpolation in the M_L, M_{ν_L} plane of calculated R_{tot} values for each combination, a contour is derived that encloses the region where $R_{tot} > 99$. The result is shown in fig. 1.

4. TPC Results

The TPC[8] search too relies upon charged particle identification through $\frac{dE}{dx}$ measurement. This allows good discrimination of electrons from non-electrons at lower momenta than attainable with calorimetry measurements, hence providing better sensitivity to low δ_M lepton doublets. Only one event topology is considered in the analysis:

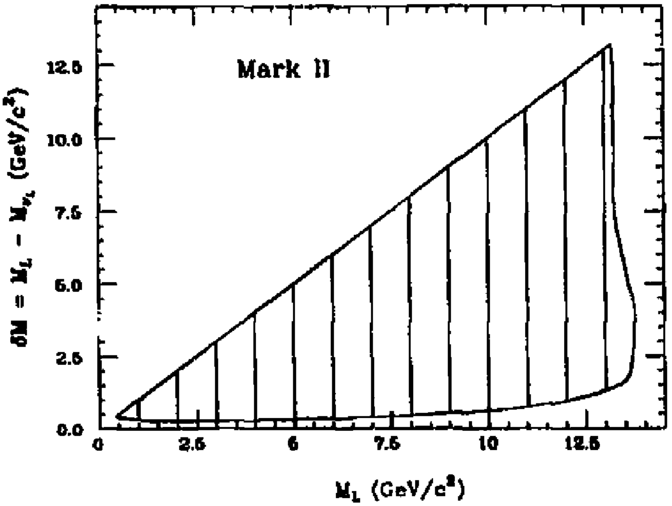

Figure 1. Region excluded by first Mark II search, based on charged particle identification.

(electron) *vs* (muon or pion)

where no attempt is made to distinguish muons from pions. The acollinearity of the two detected tracks is required to be at least 3°, while the acoplanarity must be at least 2°, or, if the two-track invariant mass is less than 1.5 GeV/c^2, at least 10°. Events are then classified as to whether the two tracks have the same or opposite charges. The same-sign events allow a direct subtraction of backgrounds from two-photon processes where two or more additional charged particles escape detection.

Additional subtractions are performed to account for calculated backgrounds from the processes $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$. The resulting spectrum in measured electron candidate momentum(integrated luminosity is 68 pb^{-1}), which ideally should be uniform and consistent with zero, is used to set limits on the existence of close-mass leptons. A χ^2 is calculated for the consistency between the observed spectrum and that expected from the presence of a hypothetical heavy lepton signal, where Gaussian error distributions are assumed. The actual observed final spectrum shows a small excess of events, but one consistent with estimated systematic and statistical errors, allowing useful limits to be derived with 99% confidence level, as shown in fig. 2.

TPC has also attempted to explore significantly lower mass differences with

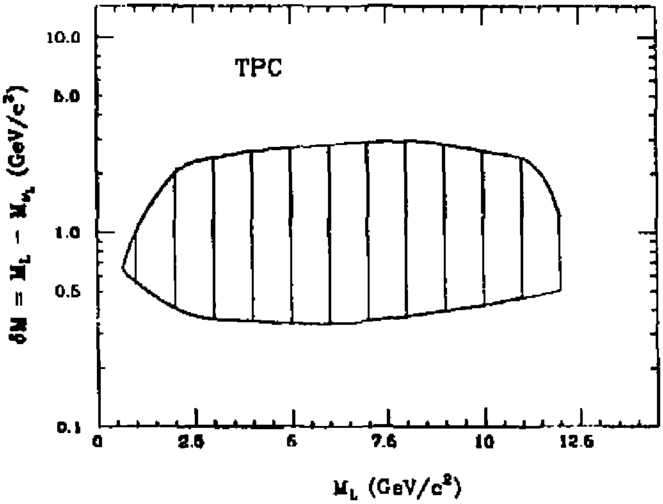

Figure 2. Region excluded with 99% C.L. by TPC search, based on charged particle identification.

three additional techniques. The first approach uses $\frac{dE}{dx}$ measurements to search for pair-production of heavy, pseudo-stable charged particles, corresponding to the very low mass differences where charged lepton lifetimes are long. The second approach searches for direct evidence of heavy lepton decays within the time-projection-chamber itself, decays visible as kinks in reconstructed charged tracks. The third approach searches for indirect evidence of heavy lepton decays by demanding two low energy reconstructed pion tracks that do not extrapolate back to the beam collision point. In order, these three methods are sensitive to regions of increasing mass differences, that is, to decreasing charged lepton lifetimes. All three appear quite promising, but at the moment, systematic uncertainties in trigger efficiency and in detector acceptance preclude the placing of confident limits on close-mass lepton production.

5. Mark II Results (radiative tagging)

Because it depends upon electron and muon identification, the first Mark II analysis suffers in the very low δ_M region, where that identification is unreliable and two-photon backgrounds severe. To solve this problem, a second approach has been explored, in which one requires the presence of an isolated, energetic photon, as a tag for initial state radiation during pair production of the heavy charged leptons. This idea is a variation on the well known single photon tag used in neutrino counting experiments.[9] The radiative tag suppresses conventional two-photon backgrounds by many orders of magnitude, avoiding the necessity of electron or muon identification.

Briefly, the event selection criteria in the radiative tag analysis demand: 1) two oppositely charged, well measured tracks with energy less than 4 GeV; 2) at least one photon with energy greater than 1 GeV and that makes an angle with the beam directions greater than 45°; and 3) no charged particles within 45° of the tagging photon and no other photons within 30°. In addition, the missing transverse momentum of the event must be greater than 1 GeV/c and greater than the missing longitudinal momentum. The opening angle between the two charged particles is restricted to the range 20–160°, while the acoplanarity must be greater than 20 mrad. Further cuts are imposed to suppress an unusual background from the coincidence of a cosmic-ray-induced electromagnetic shower with two-photon production of electron pairs.

After all selection cuts, 14 events remain from 104 pb^{-1} of data, while 12.3 ± 1.7 are expected from the backgrounds $e^+e^- \to \tau^+\tau^-\gamma$, $e^+e^- \to e^+e^-\tau^+\tau^-$, and $e^+e^- \to e^+e^-\pi^+\pi^0\pi^-\pi^0$. An additional background of 1.7 events is predicted from a sample of 10^5 annihilation hadronic events generated by the Lund Monte Carlo.[10] Because of the very low particle multiplicity of the surviving events and because of uncertainties in simulating neutral hadron interactions in the electromagnetic calorimeter, no systematic error is assigned to this value and the estimate is not used in setting limits on heavy lepton production.

For a hypothetical heavy lepton signal, the confidence level for exclusion is calculated from

$$\mathrm{C.L.} \quad \equiv \quad 1 - \frac{\mathrm{Prob}(\mathrm{Bkg} + \mathrm{Sig} \to N_{\mathrm{Obs}} \leq 14)}{\mathrm{Prob}(\mathrm{Bkg} \to N_{\mathrm{Obs}} \leq 14)}$$

where the probabilities are convolutions of Gaussian error distributions for the expectation values with Poissonian distributions for the fluctuations in observed numbers of events. The region excluded with 95% confidence level by the radiative tagging analysis is shown in fig. 3.

One severe handicap in the second Mark II analysis is its necessary reliance upon a charged particle trigger. For δ_M below $\approx 200\ \mathrm{MeV}/c^2$, where detected decay product

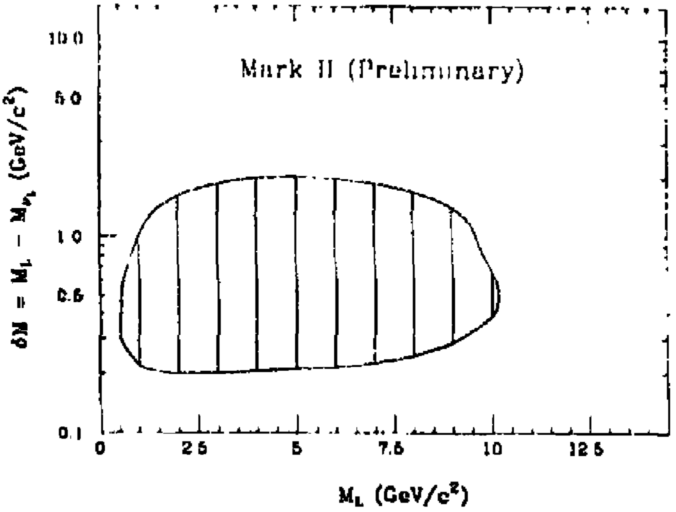

Figure 3. Region excluded with 95% C.L. by second Mark II analysis, based on radiative tagging.

tracks often do not extrapolate back to the beam collision point, trigger efficiency is usually poor and difficult to measure directly. In the future, similar experiments would be wise to trigger directly upon the tagging photon. It deserves mention that single photon triggers contemplated at SLC and LEP experiments for neutrino counting should be as inclusive as allowed by accelerator backgrounds. Event vetoes based on the presence of charged particles could easily discard close mass leptons or other exotic low-visible-energy processes.

6. Conclusions and Prospects

The three experimental searches reviewed here offer no evidence for the existence of close-mass leptons. Little room remains for the Raby and West model, although it cannot yet be completely ruled out. Figure 4 shows the currently[4] excluded regions in the M_L-M_{ν_L} plane, including other experimental results. Despite great progress, much work remains before close mass leptons can be ruled out for masses accessible at SLC and LEP energies.

Sequential leptons could manifest themselves in several ways on the Z^0 resonance. For example, there is the direct evidence of events with two acoplanar jets and large missing energy or events with one massive jet opposite an isolated lepton. In addition, one has the indirect evidence from the difference between the measured total Z^0 width

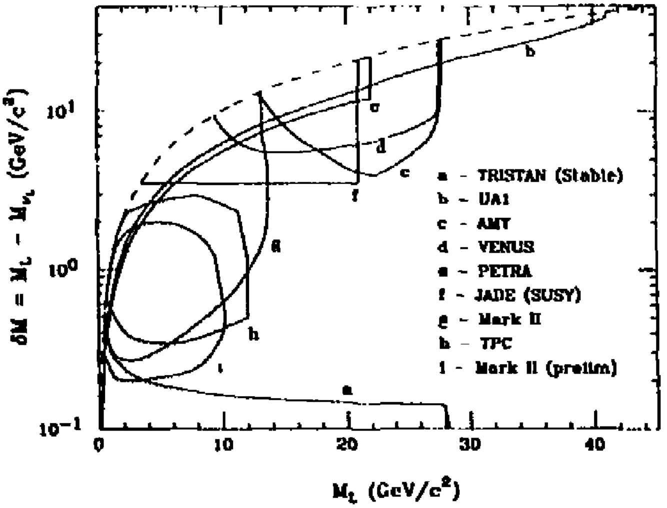

Figure 4. Currently excluded regions in the M_L, M_{ν_L} plane for $\delta_M > 0$.

and that expected from the standard model. Similarly, one can measure the single photon cross section, making visible the "invisible" Z^0 decays to neutrinos.

Which of these approaches are useful depends on the mass difference δ_M. For δ_M greater than ≈ 5 GeV/c^2 and a charged lepton mass not too close to half the Z^0 mass, all should apply. Detection of such a fourth generation lepton doublet should be straightforward and relatively easy.

A slightly harder case occurs for large δ_M, with M_L nearly equal to $M_{Z^0}/2$; the direct signatures are severely suppressed by phase space, but the signature are unmistakable, requiring only large integrated luminosities to identify. Moreover, the extra invisible width should be measurable.

Another somewhat difficult case occurs when δ_M is smaller than a few GeV/c^2, but greater than ≈ 350 MeV/c^2. The hadronic jet decay modes are less useful than exclusive modes, such as to the pion or rho. Visible energy is low, but electron and muon identification is still feasible. Again, the extra invisible width should be measurable for neutrino masses not too close to $M_{Z^0}/2$.

Much more difficult is the case when δ_M is in the range ≈ 150 350 MeV/c^2. The dominant decay mode is through a single charged pion, thus taking away the powerful tools of electron and muon identification. Visible energies are low enough that two-photon backgrounds become serious. Worse, substantial charged lepton lifetimes produce decay products with large impact parameters, leading to poor trigger efficiency.

In this regime, radiative tagging would again be useful, given a suitable trigger, as discussed above. Ideally, a close mass lepton search would be conducted in parallel with a single photon measurement at a center-of-mass energy somewhat above the Z^0 resonance peak,[11] to ensure an appreciable signal for photons with energy greater than ≈ 1 GeV. This case becomes extremely difficult, though, when $M_L \approx M_{Z^0}/2$. Phase space suppresses both the direct signature and the invisible Z^0 width; large integrated luminosities are necessary to explore this possibility.

Finally, for $\delta_M < 130$ MeV/c^2, life becomes much easier. The heavy charged lepton lives long enough to be detected directly. For nearly all charged lepton masses below $M_{Z^0}/2$, the characteristic $\frac{dE}{dx}$ deposition makes this process simple to identify. Some care would be necessary in the $\frac{dE}{dx}$ cross-over region with electron and muon pairs. For electrons, calorimetry information should readily resolve the ambiguity. Distinguishing "stable" heavy charged leptons from muons in the cross-over region would be more difficult without accurate time-of-flight measurement, but even in this case, the increase in total apparent muon pair cross section is easily measurable. For charged leptons with intermediate lifetimes such that most decay before reaching the outer detector regions and thus do not fully mimic muons, the search strategy would depend sensitively on detector design. An analysis exploiting visibly kinked tracks, as in the TPC search, might be appropriate in this case.

I would like to acknowledge the valuable assistance of my co-workers on the Mark II experiment. In particular, Martin Perl has been a rich source of ideas and advice, while David Stoker furnished a sophisticated and robust Monte Carlo program for simulating heavy lepton production and decay

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