SLAC-PUB-4748
January 1989
(E)

SEARCHING FOR AN EXOTIC LEPTON AND GAUGE BOSON AT HIGH ENERGY e^+e^- COLLIDERS*

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ABSTRACT

The possibility of searching in high energy e^+e^- collisions for a singly produced heavy lepton with an ordinary light lepton, $e^+e^- \to L^+\ell^-$, has been investigated. The search is motivated mainly by its distinctive experimental signatures. In a data sample corresponding to an integrated luminosity of 30 fb^{-1} collected at a 1 TeV e^+e^- collider, the search is sensitive to a lepton of mass up to about 1 TeV/c^2 and a production cross section as low as 10% of the μ-pair point cross section. For the case where the process is mediated by an exotic gauge boson, sensitivity to a gauge boson of mass up to about 2 TeV/c^2 can be achieved.

1. INTRODUCTION

The search for a process that is beyond the standard model has long been the passion of high energy physics. One process that has not been explored in e^+e^- collisions is the single production of a heavy lepton together with an ordinary light lepton,[1] $e^+e^- \to L^+\ell^-$, where the heavy lepton has a mass greater than the beam energy and is not an excited state of the light lepton. For the case of an excited lepton there has been a profusion of searches, starting with the pioneering work at the fixed target experiments, and it will not be discussed here.[2] The search is motivated mainly by the distinctive experimental signatures. For example, the momentum spectrum of the light lepton exhibits a monochromatic peak. In the spirit of the Fermi's parameterization of the weak interaction, the production mechanism is assumed to be a four-fermion contact interaction, as shown in Fig. 1(a). Examples of the production mechanism are an exotic gauge boson Z' exchange [Fig. 1(b)] or a constituent exchange as in the composite model [Fig. 1(c)].

The unpolarized differential cross section for the process is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\chi^2(1+\cos\theta)\left(\frac{P_L}{P_b}\right)\left[\frac{1}{2}\left(\frac{m_L}{P_b}\right)^2 + (1+\cos\theta)\left(\frac{P_L}{P_b}\right)\right] , \tag{1}$$

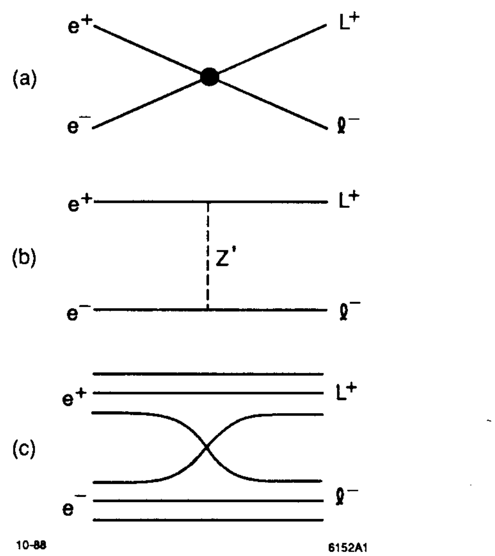

Fig. 1. The production of a heavy-light lepton pair through a four-fermion contact interaction (a). The interaction can be mediated by an exotic gauge boson exchange (b) or a constituent exchange (c).

where

$$\chi = \frac{\sqrt{2}Gs}{4\pi\alpha} , \tag{2}$$

G is the interaction coupling strength, m_L is the mass of the heavy lepton, θ is the polar angle of the light lepton, and P_b and P_L are the momentum of the beam and the heavy lepton, respectively. Integrating over the entire solid angle gives,

$$\sigma = \sigma^0 \cdot \chi^2\left(\frac{P_L}{P_b}\right)\left[\frac{3}{8}\left(\frac{m_L}{P_b}\right)^2 + \left(\frac{P_L}{P_b}\right)\right] , \tag{3}$$

where σ^0 is the μ-pair point cross section through the one-photon exchange. For the case of a Z' with mass $m_{Z'}$ being exchanged,

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

Contributed to the DPF Summer Study Snowmass '88
High Energy Physics in the 1990's, Snowmass, Colorado, June 27–July 15, 1988.

$$\chi = \frac{s}{4\pi\alpha} \cdot \frac{g^2}{4m_{Z'}^2} , \quad (4)$$

where g is the coupling strength of Z'.

The sensitivity of the search is studied using a Monte Carlo technique. The study assumes an e^+e^- linear collider operating at $\sqrt{s} = 1$ TeV with a luminosity of 3×10^{33} cm^{-2} s^{-1}. The effects of beamstrahlung[3] and initial state radiation[4] are included. A simple simulation of a generic detector is used.[5] In the Monte Carlo program, the heavy-light lepton pair is produced with an angular distribution according to Eq. (1). The heavy lepton is assumed to be a sequential lepton and decays into a weak vector boson W and a light neutrino ν_L. The W then decays according to the standard model. The width of the heavy lepton is given by

$$\Gamma = \frac{\alpha m_L}{16 \sin^2\theta_W} \left(\frac{m_L}{m_W}\right)^2 \left(1 + 2\frac{m_W^2}{m_L^2}\right) \left(1 - \frac{m_W^2}{m_L^2}\right)^2 , \quad (5)$$

where m_W is the W mass and θ_W is the Weinberg angle. The width is quite large as shown in Table I. Also shown is the cross section for the case of a Z' exchange that has a standard weak coupling strength and a mass of 1 TeV/c^2. The finite width dilutes some of the characteristics of the event signatures; however, it increases the cross section for the case of a very heavy lepton. The effects of beamstrahlung and initial state radiation decrease the cross section as expected since the cross section is proportional to s.

In searching for a heavy-light lepton pair, the light lepton candidate must first be identified. The identification depends not only on whether the light (primary) lepton is e, μ, or τ, but also on whether the W decays hadronically or leptonically. If the search is for an e or μ primary lepton with the W decaying hadronically, then the primary lepton is defined as the lepton with the highest momentum. Figure 2 shows the momentum spectrum of all the leptons in the events. (All kinematic plots shown here have passed all selection criteria described in this paper.) The primary lepton is clearly separated from the leptons from the W fragmentation. In the case that the W decays leptonically, no attempt is made to separate the primary lepton from the lepton from the W decay because the latter could be more energetic if the heavy lepton is very heavy.

Table I. Width of the heavy lepton and cross sections for the case of a Z' exchange with $m_{Z'} = 1$ TeV/c^2. Here σ is the lowest order cross section with zero width and σ^γ is the cross section with the standard model width, beamstrahlung, and initial state radiation.

m_L (GeV/c^2)	500	700	800	900
Γ_L (GeV/c^2)	38	103	154	219
$\sigma\,(fb)$	189	142	106	60
$\sigma^\gamma\,(fb)$	136	91	67	59

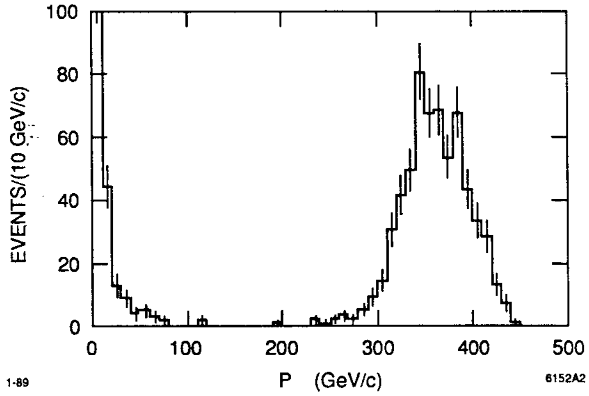

Fig. 2. The momentum spectrum of all the leptons in the heavy-light lepton candidates, with the light lepton being e or μ and the W decaying hadronically. The mass of the heavy lepton is 500 GeV/c^2.

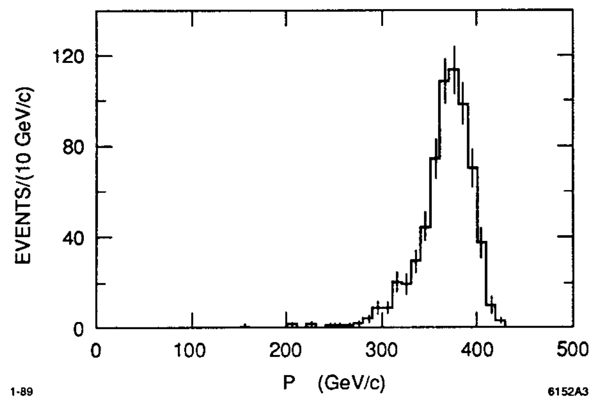

Fig. 3. The corrected momentum spectrum of the τ candidates in the heavy-light lepton events, with the light lepton being τ and the W decaying hadronically. The mass of the heavy lepton is 500 GeV/c^2.

However, the momentum spectrum still exhibits a peak (not shown). If the primary lepton is τ and the τ decays hadronically, all the decay products are combined into a single particle due to the limited calorimeter spatial resolution assumed. For the case that the W decays hadronically, the τ decay product is defined to be the most isolated particle. To reject soft particles ejected backward from the W fragmentation, an isolation criteria weighted by the particle momentum P is used:

$$\text{Weight} = P(1 - \cos\theta) ,$$

where θ is the opening angle between the two particles of interest. The particle with the largest weight is assumed to be from the τ decay. Since the τ is very energetic, its direction is well represented by that of the decay product. It is therefore possible to fully reconstruct the event by assuming energy and momentum conservation. Figure 3 shows the reconstructed τ momentum spectrum. The spectrum shows an asymmetric peak, a reflection of beamstrahlung. When the W decays leptonically, no attempt is made to identify the primary τ lepton candidate as in the case when the primary lepton is e or μ.

The selection criteria for heavy-light lepton candidates are designed to suppress the dominant background $e^+e^- \rightarrow$

W^+W^-. The candidate is required to have a minimum total visible energy of 250 GeV and transverse momentum of 180 GeV/c. The acollinearity and acoplanarity angles between the primary lepton and the W, defined as the hadronic jet or the lepton, are required to be greater than 25°. Both the primary lepton and the W are restricted to be in the angular region $|\cos\theta| < 0.9$, where θ is the polar angle of the particle. In order to reject $e^+e^- \rightarrow Z^0Z^0$ when one Z^0 decays into two neutrinos, the event mass is required to be greater than 100 GeV/c^2.

Additional criteria are applied when the W decays hadronically to further reduce the background from $e^+e^- \rightarrow W^+W^-$. The mass of the hadronic jet is required to be between 70 and 90 GeV/c^2. This eliminates the background from $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow e^+e^-q\bar{q}$, although it has little effect on $e^+e^- \rightarrow W^+W^-$. The background from $e^+e^- \rightarrow W^+W^-$ can be reduced by reconstructing the neutrino momentum using momentum conservation. The reconstructed neutrino is combined with the primary lepton candidate and if the mass of the combined system is less than 150 GeV/c^2, the event is rejected. In the case that the primary lepton is e or μ, the background is further suppressed by using the fact that the primary lepton momentum is related to the mass of the heavy lepton. The mass calculated from the momentum is compared with the mass calculated from the hadronic jet (W) and neutrino combination and if the mass difference is greater than 100 GeV/c^2, the event is discarded. This powerful cut is also effective in eliminating the remaining background from $e^+e^- \rightarrow e^+e^-q\bar{q}$ and $e^+e^- \rightarrow e^+\nu_eW^-$, with e^+e^- or $e^+\nu_e$ going down the beam pipe and a lepton from the fragmentation identified as the primary lepton. Unfortunately, this cut cannot be implemented when the primary lepton is τ because it is necessary to use both energy and momentum conservation in order to reconstruct the neutrino. Three new cuts are introduced to reduce the backgrounds in this case. The first cut eliminates the remaining background from $e^+e^- \rightarrow e^+e^-q\bar{q}$ and $e^+e^- \rightarrow e^+\nu_eW^-$ by requiring the opening angle between the primary lepton candidate and the hadronic jet to be greater than 10°. The second cut exploits the fact that, in the background from

$$e^+e^- \rightarrow W^+W^-$$
$$\quad W^- \rightarrow q\bar{q}'$$
$$\quad W^+ \rightarrow e^+\nu_e \text{ or } \mu^+\nu_\mu\,,$$

the reconstructed "τ" momentum discussed earlier in this paper is close to the "primary" lepton momentum, because there is only one missing neutrino. Therefore, if the reconstructed momentum is within 20% of the measured momentum the event is rejected. Finally, the lepton mass calculated from the reconstructed τ momentum is required to be greater than 400 GeV/c^2.

The characteristic event signatures depend on the mass of the heavy lepton. The peak in the lepton momentum spectrum shown in Figs. 2 and 3 is for leptons of mass $\sim$ 500 GeV/c^2. The spectrum for a very heavy lepton is very broad. However, in the case when the primary lepton is e or μ and the W decays hadronically, the total visible energy spectrum also exhibits an asymmetric peak, as shown in Fig. 4. The peak is due to the very limited boost given by the heavy lepton to the monochromatic W.

The detection efficiency is quite good, as shown in Fig. 5. It could be as high as 20% when the primary lepton is e or μ and the W decays hadronically.

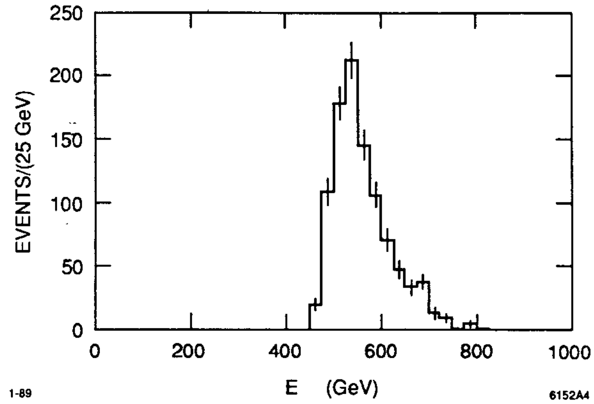

Fig. 4. The total visible energy spectrum of the heavy-light lepton candidates, with the light lepton being e or μ and the W decaying hadronically. The mass of the heavy lepton is 900 GeV/c^2.

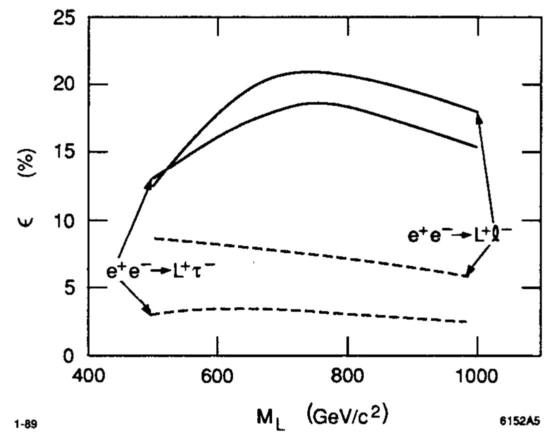

Fig. 5. The detection efficiency for the heavy-light lepton candidates. The solid lines are for the case when the W decays hadronically and the dash lines are for the leptonic decay. Here ℓ^- is either e^- or μ^-.

The sensitivity of the search is defined as the number of signal events required to see an excess of five standard deviations over the background. Since this is a Monte Carlo study and no attempt is made to estimate any systematic error, the standard deviation is calculated in the most conservative fashion: square root of the sum of the signal and background. The signal required for the search, together with the background, are summarized in Table II, for an integrated luminosity of 30 fb^{-1}, which may be collected over a period of three years. The sensitivity, in units of the μ-pair point cross section through one-photon exchange, is shown in Fig. 6. The hadronic decay of the W has better sensitivity to the heavy lepton than the leptonic decay. No attempt is made to calculate the combined sensitivity since the two decays may have different systematic errors in the real world. The search is sensitive to a lepton of mass up

Table II. The signal required to see a 5σ excess above the background for various search scenarios.

Search Scenario	$L^+ \to q\bar{q}'\bar{\nu}_L$ $\ell^- = e^-$ or μ^-	$L^+ \to q\bar{q}'\bar{\nu}_L$ $\ell^- = \tau^-$	$L^+ \to \ell^+\nu_\ell\bar{\nu}_L$ $\ell^- = e^-$, μ^- or τ^-
Signal	55	68	64
Background			
W^+W^-	64	97	90
Z^0Z^0	0	3	8
$e^+e^-W^+W^-$	3	16	3
Total	67	116	101

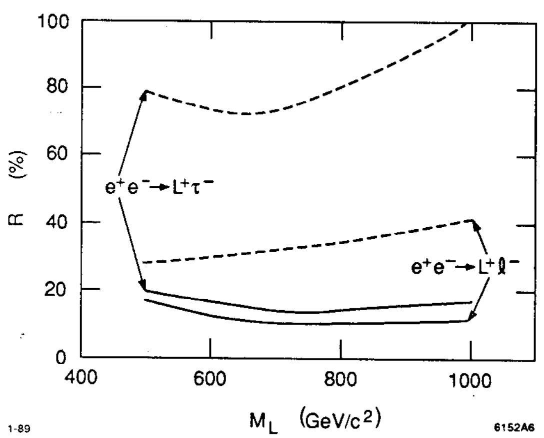

Fig. 6. The sensitivity of the search in units of the point cross section. The solid lines are for the case that the W decays hadronically and the dash lines are for the leptonic decay. Here ℓ^- is either e^- or μ^-.

to about 1 TeV/c^2 and a production rate as low as 10% of the point cross section. The sensitivity to an exotic Z' is shown in Fig. 7, for the case that the Z' couples to the leptons with the standard weak strength. The search is sensitive to a Z' with mass up to about 2 TeV/c^2.

The sensitivity for the case where the primary lepton is τ can be improved by the further use of the properties of the τ and the tracking information. The finite decay length of the τ would be a powerful discrimination against the background. For example, a τ with a momentum of 300 GeV/c has a decay length of 15 mm. A new search category can be created with the primary lepton candidate contains only three tracks and the three-track invariant mass is small. The background contamination in this category will be small. The only contamination from $e^+e^- \to W^+W^-$ is when one of the W's decays into τ which in turn decays into three charged particles. However, the search is limited by statistics because the three-charged-particle branching ratio of the τ is only $\sim 13\%$.

The search technique is not limited to the heavy lepton. The search is also sensitive to a massive particle that decays into a W and a light neutral particle. There is no need to

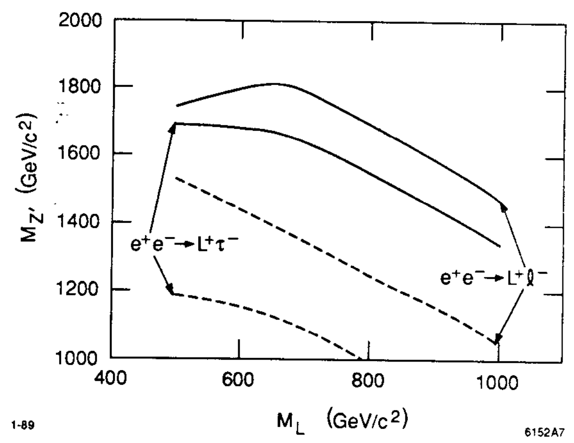

Fig. 7. The sensitivity of the search for an exotic Z'. The solid lines are for the case that the W decays hadronically and the dash lines are for the leptonic decay. Here ℓ^- is either e^- or μ^-.

restrict the search to the case where the hadronic jet is reconstructed to be W; a scan through all jet masses is highly desirable. In fact, the sensitivity could be much higher outside the W mass region because of the large cross section for $e^+e^- \to W^+W^-$. There is also no need to restrict the light "lepton" to be e, μ, or τ. The search with the light lepton being τ demonstrates that it can be a light particle that decays into one light charged particle and one light neutral particle. In fact, this is a general search technique for the production of a light-heavy particle pair! The search also should be conducted at PEP, PETRA, and TRISTAN colliders.

In conclusion, there is good sensitivity to the production of a heavy-light lepton pair in e^+e^- colliders. The event has distinctive signatures. At a 1 TeV e^+e^- collider, the search is sensitive to a lepton of mass up to about 1 TeV/c^2 and a production cross section as low as 10% of the μ-pair cross section. If the production is mediated by an exotic gauge boson, sensitivity to the gauge boson mass of up to about 2 TeV/c^2 can be achieved.

This work benefits greatly from the work of the SLAC group that studies the physic opportunities at a high-energy e^+e^- collider, in particular, the work of P. Rankin on $e^+e^- \to W^+W^-$. The author wishes to thank P. Burchat and D. Stoker for useful discussions.

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