Bilepton Searches at the NLC

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ABSTRACT

We provide a general classification of bilepton fields carrying two units of lepton number which satisfy $SU(2)_L \otimes U(1)_Y$ gauge invariance and have renormalizable interactions. The discovery prospects of the NLC are discussed.

I. INTRODUCTION

In Ref. [1] we have studied in detail the the phenomenology of bosons carrying two units of lepton number. We call them *bileptons* here. The NLC will be a privileged experimental tool for probing such fields via their couplings to leptons and neutral gauge bosons. We summarize here the discovery prospects of this machine, assuming the following scaling relation for its luminosity:

$$\mathcal{L}_{e^+e^-}\ [\text{fb}^{-1}] = 200s\ [\text{TeV}^2] \ \text{ or } \mathcal{L}_{e^+e^-} \simeq 7.5 \times 10^7 s\ , \quad (1)$$

where s is the squared centre of mass energy.

A fascinating characteristic of the NLC is its ability to be also run in the e^-e^- mode [2] as well as the $e^-\gamma$ and $\gamma\gamma$ modes [3]. We shall take full advantage here of these new experimental degrees of freedom. For the e^-e^- mode, there will be some loss of luminosity due to the anti-pinch at the interaction point and we assume it can only achieve half the luminosity of the e^+e^- mode $\mathcal{L}_{e^-e^-} = \mathcal{L}_{e^+e^-}/2$ [4]. For the two modes involving back-scattered laser photon beams we use the polarized spectra of Ref. [5].

The most general renormalizable bilepton lagrangian consistent with the fundamental symmetries of the standard model involves

- two Lorentz scalar weak singlets L_1 and $\tilde{L}_1$,
- one Lorentz vector weak doublet $L_{2\mu}$,
- one Lorentz scalar weak triplet L_3.

The part of this lagrangian which is relevant at the NLC involves the interations with the leptons and the neutral gauge bosons: is

$$\begin{aligned}
\mathcal{L} &= \lambda_1 \bar{\ell}^c i\sigma_2 \ell L_1 + \text{ h.c.} + (D_\mu L_1)^\dagger (D^\mu L_1) \\
&+ \tilde{\lambda}_1 \bar{e}^c e \tilde{L}_1 + \text{ h.c.} + \left(D_\mu \tilde{L}_1\right)^\dagger \left(D^\mu \tilde{L}_1\right) \\
&+ \lambda_2 \bar{\ell}^c \gamma_\mu e L_2^\mu + \text{ h.c.} \\
&- 1/2 (D_\mu L^\nu - D_\nu L^\mu)^\dagger (D^\mu L_\nu - D^\nu L_\mu) \\
&- i(1-\kappa_\gamma) e Q_\gamma L_\mu^\dagger L_\nu (\partial^\mu A^\nu - \partial^\nu A^\mu) \\
&- i(1-\kappa_Z) e Q_Z L_\mu^\dagger L_\nu (\partial^\mu Z^\nu - \partial^\nu Z^\mu) \\
&+ \lambda_3 \bar{\ell}^c i\sigma_2 \vec{\sigma} \ell \cdot \vec{L_3} + \text{ h.c.} + (D_\mu L_3)^\dagger (D^\mu L_3)\ ,
\end{aligned} \quad (2)$$

where the covariant derivative is given in terms of the electric and weak charges Q_γ and Q_Z by

$$D_\mu = \partial_\mu - ieQ_\gamma A_\mu - ieQ_Z Z_\mu \quad (3)$$

and we use the notation where $\ell = (e_L, \nu_L)$ are left-handed $SU(2)_L$ lepton doublets and $e = e_R$ are right-handed charged singlet leptons. The flavour indices are suppressed but it should be borne in mind that the symbols λ denote 3×3 coupling matrices. The charge conjugate fields in $\mathcal{L}_{L=2}$ are defined to be $\bar{\ell}^c = (\ell^c)^\dagger \gamma^o = -\ell^T C^{-1}$. The subscript of the bilepton fields $L_{1,2,3}$ indicates their $SU(2)_L$ singlet, doublet or triplet nature, and the σs are Pauli matrices.

The singlet and triplet fields are Lorentz scalars, whereas the members of the doublet are vectors. The electric and weak charges Q_γ and Q_Z are uniquely determined by gauge invariance. They are listed in Table I along with other quantum numbers.

	L	J	Y	T_3	Q_γ	Q_Z	lepton couplings
L_1^+	2	0	1	0	1	$-\frac{\sin\theta_w}{\cos\theta_w}$	$e_L\nu_L\ (\lambda_1)$
$\tilde{L}_1^{++}$	2	0	2	0	2	$-2\frac{\sin\theta_w}{\cos\theta_w}$	$e_R e_R\ (\tilde{\lambda}_1)$
$L_{2\mu}^{++}$	2	1	3/2	1/2	2	$-\frac{4\sin^2\theta_w - 1}{2\sin\theta_w\cos\theta_w}$	$e_R e_L\ (\lambda_2)$
$L_{2\mu}^{+}$				$-1/2$	1	$-\frac{2\sin^2\theta_w + 1}{2\sin\theta_w\cos\theta_w}$	$e_R\nu_L\ (\lambda_2)$
L_3^{++}	2	0	1	1	2	$-\frac{2\sin^2\theta_w - 1}{\sin\theta_w\cos\theta_w}$	$e_L e_L\ (\sqrt{2}\lambda_3)$
L_3^{+}				0	1	$-\frac{\sin\theta_w}{\cos\theta_w}$	$e_L\nu_L\ (\lambda_3)$
L_3^{0}				-1	0	$-\frac{1}{\sin\theta_w\cos\theta_w}$	$\nu_L\nu_L\ (-\sqrt{2}\lambda_3)$

Table I: Major quantum numbers and couplings of the bileptons.

For the vector bileptons there is an extra complication due to our *a priori* ignorance of their gauge nature. If they are gauge bosons the *anomalous couplings* κ_γ and κ_Z vanish at tree level. Finite values of these two parameters would generate electric quadrupole and anomalous magnetic dipole moments of the bileptons. The *minimal couplings* are obtained for $\kappa_\gamma = \kappa_Z = 1$, whereas for Yang-Mills bileptons $\kappa_\gamma = \kappa_Z = 0$.

More or less familiar examples of bileptons are the triplet Higgs, which occurs for instance in left-right symmetric models [6], as well as the doublet gauge bilepton, which occurs for instance in $SU(15)$ grand unification [7] or in the $(3,3,1)$ model [8].

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II. CURRENT LOW ENERGY LIMITS

Low-energy bounds on the bileptons can be derived from the good agreement between theory and experiment in processes expected in the standard model, such as polarized muon decays, the agreement between the different determination of the Fermi constant, *etc.*. Similarly, bounds can be derived from the non-observation of reactions which are forbidden or suppressed in the standard model, such as flavour violating muon or tau decays.

These experiments typically imply lower limits on the ratios m_L^2/λ^2 of the bilepton masses to their couplings to leptons. Unfortunately, these bounds vary greatly depending on the lepton generation indices carried by the λs. The 95% CL lower limits on the bilepton masses can be as large as

$$m_L \gtrsim 200\sqrt{\lambda^2}\ \text{[TeV]} \tag{4}$$

or as small as

$$m_L \gtrsim 2\sqrt{\lambda^2}\ \text{[TeV]}\ , \tag{5}$$

where the stronger bounds originate from flavour non-diagonal processes, in particular $\mu \to eee$ and $\mu \to e\gamma$ decays. In these cases, though, it may be natural to expect $\lambda \ll 1$. More details can be found in Ref. [1].

III. LIMITS FROM Z^0 DECAYS

The Z^0 boson can decay into a pair of bileptons, if these are light enough. The resulting increases of the leptonic or invisible widths of the Z^0 cannot exceed the current experimental errors on these observables.

The couplings of the scalars are dictated by gauge invariance. The contribution of scalar bileptons to the Z^0 width is

$$\Gamma_{\text{scalar}} = \frac{\alpha Q_Z^2}{12} m_Z \beta^3\ , \tag{6}$$

where

$$\beta = \sqrt{1 - \frac{4m_L^2}{m_Z}}\ . \tag{7}$$

For the vector there remains an ambiguity due to the possible anomalous coupling κ_Z. The most conservative LEP bounds on vector bileptons are given for the value of κ_Z the minimizes the width, which then reads

$$\Gamma_{\text{vector}} = \frac{\alpha Q_Z^2}{12} m_Z \beta^3 \frac{1}{1-\beta^2} \frac{5 - 4\beta^2 + 3\beta^4}{2-\beta^2}\ . \tag{8}$$

We plot these widths in Fig. 1 as a function of the bilepton mass. The least constrained bilepton turns out to be $L_{2\mu}^{--}$, whose coupling to the Z^0 vanishes in the limit $\sin^2\theta_w = 1/4$. Any mass above *ca* 38 GeV is allowed. The other bileptons L_1^-, L_3^-, L_3^0 must lie above 44 GeV and $\tilde{L}_1^{--}, L_3^{--}, L_{2\mu}^-$ above 45 GeV.

Note that in the absence of other sources of new physics, this is the only reaction providing a direct bound for the neutral element of the triplet bilepton L_3^0.

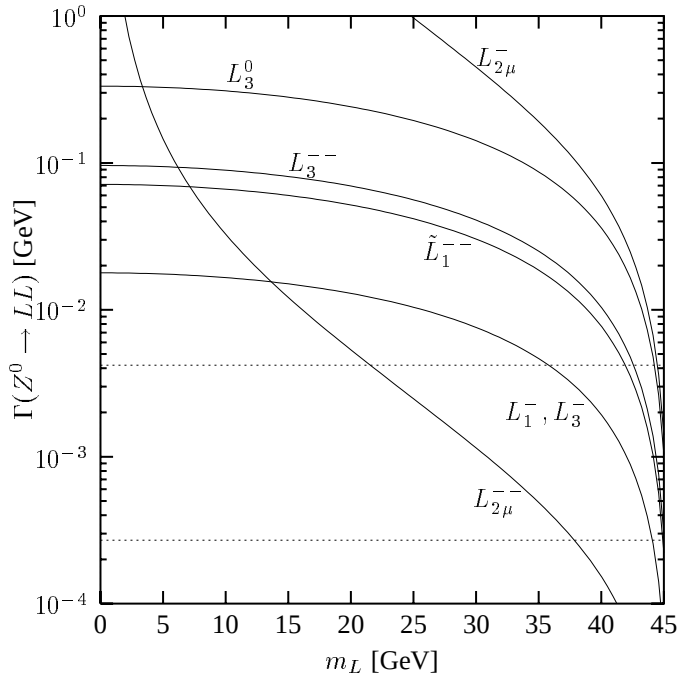

Figure 1: Partial decay widths of the Z^0 into pairs of bileptons as a function of the bilepton mass. The lower dotted line shows the largest partial width consistent with data for the charged bileptons, whereas the upper dotted line represents the same limit for the neutral bilepton L_3^0.

IV. LIMITS FROM e^-e^- SCATTERING

The e^-e^- mode of a linear collider [2] is ideally suited for bilepton studies. If a doubly-charged bilepton is light enough, it can be produced as a s-channel resonance as depicted in Fig. 2. The signal to be tagged is a pair of like-sign leptons and the total number of events expected on any bilepton peak is of the order of

$$n \approx 10^9 \left(\frac{\lambda_{ee}\lambda_{\ell\ell'}}{\sum_{ij}\lambda_{ij}^2} \right)^2\ , \tag{9}$$

where the last factor is less or equal to one. If the leptonic couplings are so small, that the bilepton width drops below the beam energy spread, the signal will be attenuated accordingly. Still, the rates remain substantial, even for minute leptonic couplings [9]. This reaction is so spectacular and unavoidable, that we do not need to consider the on-shell production of doubly-charged bileptons in the other NLC modes.

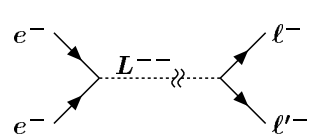

Figure 2: Lowest order Feynman diagram for the production of a doubly-charged bilepton L^{--} in e^-e^- collisions. The produced bilepton can be either a scalar $\tilde{L}_1^{--}, L_3^{--}$ or the vector $L_{2\mu}^{--}$.

Note also that the weak singlet, doublet or triplet nature of the bilepton can easily be determined by the polarization of the

beams.

If the doubly-charged bileptons are heavier than the collider's centre of mass energy, they cannot be produced on-shell in e^-e^- annihilations. Still, they may contribute sufficiently to Møller scattering to produce significant deviations from the standard model expectations. The differential cross sections involving $\tilde{L}_1^{--}$, $L_{2\mu}^{--}$ and L_3^{--} are given by

$$\frac{d\sigma_{\rm scalar}}{dt} = \frac{2\pi\alpha^2}{s^2} \tag{10}$$
$$\left\{ [RR] \left[\sum_i R_i^2 \left(\frac{s}{t-m_i^2} + \frac{s}{u-m_i^2} \right) - 2\frac{\tilde{\lambda}_1^2}{e^2} \frac{s}{s-m_L^2} \right]^2 \right.$$
$$+ [LL] \left[\sum_i L_i^2 \left(\frac{s}{t-m_i^2} + \frac{s}{u-m_i^2} \right) - 4\frac{\lambda_3^2}{e^2} \frac{s}{s-m_L^2} \right]^2$$
$$+ [LR] \left[\left(\sum_i L_i R_i \frac{t}{u-m_i^2} - \frac{\lambda_2^2}{e^2} \frac{t}{s-m_L^2} \right)^2 \right.$$
$$\left. \left. + \left(\sum_i L_i R_i \frac{u}{t-m_i^2} - \frac{\lambda_2^2}{e^2} \frac{u}{s-m_L^2} \right)^2 \right] \right\} ,$$

where e is the charge of the electron, $\alpha = e^2/4\pi$, $\lambda = \lambda_{ee}$ is the generic diagonal coupling of the bilepton and s, t and u are the Mandelstam variables. The dependence on the beam polarizations $P_{1,2}$ is contained in the factors

$$\begin{aligned} [RR] &= \frac{1+P_1+P_2+P_1P_2}{4} \\ [LL] &= \frac{1-P_1-P_2+P_1P_2}{4} \\ [LR] &= \frac{1-P_1P_2}{2} . \end{aligned} \tag{11}$$

The summation runs over $i = \gamma, Z^0$ and the standard model couplings of the photon and Z^0 boson to left- and right-handed leptons are given as a function of the weak mixing angle θ_w by

$$\left\{ \begin{array}{l} R_\gamma = 1 \\ L_\gamma = 1 \end{array} \right. \qquad \left\{ \begin{array}{l} R_{Z^0} = \dfrac{-\sin\theta_w}{\cos\theta_w} \\ L_{Z^0} = \dfrac{1-2\sin^2\theta_w}{2\sin\theta_w\cos\theta_w} . \end{array} \right. \tag{12}$$

To optimize the signal to background ratio, it is best to implemented a maximum likelihood fit. In the absence of deviation from the standard model, the 95% CL lower limits on the bilepton masses are of the order of

$$m_L \gtrsim \sqrt{s} \times 50\lambda_{ee} . \tag{13}$$

If the leptonic coupling matrix contains off-diagonal terms, lepton flavour violating processes such as $e^-e^- \to \mu^-\mu^-$ may be observed. In the absence of any signal, the corresponding limits are of the same order as in Eq. (13).

V. LIMITS FROM $e^-\gamma$ SCATTERING

Singly-charged bileptons can be produced in $e^-\gamma$ scattering as depicted in Fig. 3. Since these bileptons decay into a charged lepton and a neutrino, the signal to be tagged is a lepton and missing energy. The analysis is more complex than in e^-e^- scattering, because

- there is no resonance and the signal is hence weak at threshold;
- the initial photons have a hard but continuous energy and polarization spectrum [5];
- the standard model backgrounds from W^- or Z^0 production and subsequent leptonic or invisible decays are substantial.

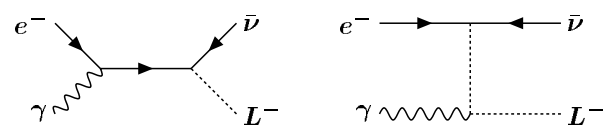

Figure 3: Lowest order Feynman diagrams for the associate production of a singly-charged bilepton L^- and an anti-neutrino in $e^-\gamma$ collisions. The produced bilepton can be either a scalar L_1^-, L_3^- or the vector $L_{2\mu}^-$. In the case of the L_1^-, the neutrino cannot be of the electron type.

The polarized differential cross sections for the production of scalar, vector or Yang-Mills fields are given by

$$\frac{d\sigma_{\rm scalar}}{dt} = \frac{2\pi\alpha^2}{s^2}\frac{\lambda^2}{e^2}\frac{1-P_e}{2}\frac{-u}{s(t-m_L^2)^2} \left[\frac{1-P_\gamma}{2}t^2 + \frac{1+P_\gamma}{2}m_L^4 \right] \tag{14}$$

$$\frac{d\sigma_{\rm vector}(\kappa_\gamma=1)}{dt} = \frac{2\pi\alpha^2}{s^2}\frac{\lambda^2}{e^2}\frac{1+P_e}{2}\frac{1}{4m_L^2 s(t-m_L^2)^2} \left\{ \frac{1-P_\gamma}{2}u\left[8um_L^4 - tu(s-8m_L^2) - 2m_L^2(s-2m_L^2)^2\right] - \frac{1+P_\gamma}{2}\left[s^3t + 2m_L^2(s-2m_L^2)^2\right] \right\} \tag{15}$$

$$\frac{d\sigma_{\rm vector}(\kappa_\gamma=0)}{dt} = \frac{2\pi\alpha^2}{s^2}\frac{\lambda^2}{e^2}\frac{1+P_e}{2}\frac{-2u}{s(t-m_L^2)^2} \left[\frac{1-P_\gamma}{2}(s-m_L^2)^2 + \frac{1+P_\gamma}{2}(u-m_L^2)^2 \right] . \tag{16}$$

To optimize the signal to background ratio, it is best to implemented a maximum likelihood fit. To gauge the discovery potential of $e^-\gamma$ collisions, we have plotted in Fig.4 for the scalar bilepton L_1^- and several collider centre of mass energies the resulting observable one standard deviation boundary in the (λ, m_L) plane.

Similar plots can be obtained for the other bileptons. The lines osculating these curves can be rescaled to other luminosities and used to define the 95% CL lower limits on the bilepton masses

$$\text{scalar:} \qquad m_L \gtrsim \sqrt{s} \times \min\left(0.6, 20\sqrt{\sum_\ell \lambda_{e\ell}^2} \right) \tag{17}$$

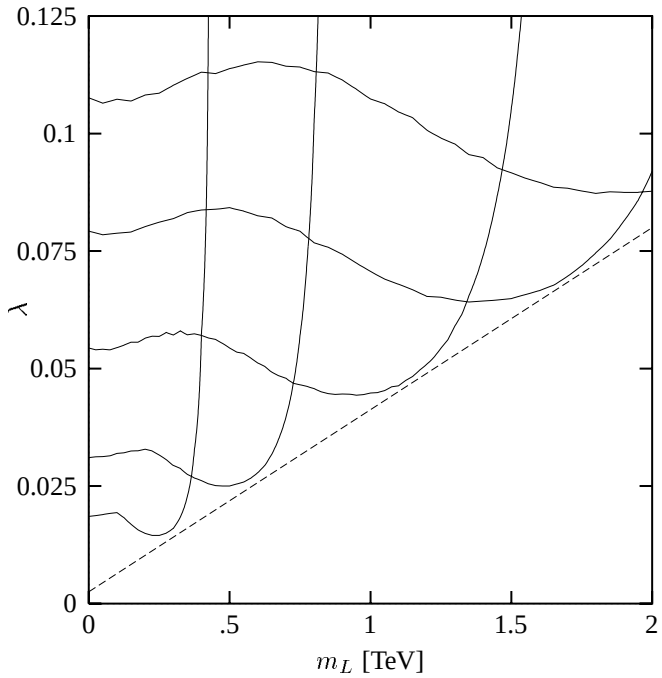

Figure 4: Smallest observable scalar bilepton L_1^- couplings to leptons at the one standard deviation level. as a function of the bilepton mass in $e^-\gamma$ collisions. The collider's e^+e^- luminosity is 20 fb^{-1} and its e^+e^- centre of mass energies are .5, 1, 2, 3 and TeV from left to right.

$$\text{vector:} \qquad m_L \gtrsim \sqrt{s} \times \min\left(0.3, 40\sqrt{\sum_\ell \lambda_{e\ell}^2}\right) \ . \quad (18)$$

Since the flavour of the neutrinos cannot be determined Although the relations (14,15) are only valid for bilepton masses lighter than 60% or 30% of the collider energy, heavier bileptons with stronger couplings can of course also be probed up to the kinematical limit $m_L \simeq .91\sqrt{s_{ee}}$.

VI. LIMITS FROM e^+e^- SCATTERING

The pair-production of singly-charged bileptons may become interesting if their couplings to leptons turn out to be too small to be observed in $e^-\gamma$ scattering. Indeed, as depicted in the Feynman diagram of Fig. 5, bileptons can still be produced thanks to their couplings to the neutral gauge bosons.

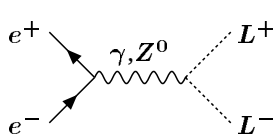

Figure 5: Lowest order Feynman diagrams contributing to $e^+e^- \to L^+L^-$ scattering, where the final state bileptons can be either the scalars L_1^-, L_3^- or the vector $L_{2\mu}^{--}$.

The signal consists of events with two charged leptons and missing energy. The standard model backgrounds from W pair production are substantial, but may be rendered harmless in e^+e^- scattering with right-handed electron beams.

Assuming the bileptons couple so weakly to leptons that their discovery is precluded in $e^-\gamma$ scattering, we can ignore the t-channel lepton exchange in the e^+e^- reaction. Whatever the charge of the produced bileptons, the integrated scalar cross sections are then

$$\sigma_{\rm scalar} = \frac{2\pi\alpha^2}{3s}\beta^3\Sigma \ , \quad (19)$$

where β is the velocity of the bileptons

$$\beta = \sqrt{1 - \frac{4m_L^2}{s}} \quad (20)$$

and

$$\begin{aligned} \Sigma &= [LL]\left(\sum_{i=\gamma,Z^0} \frac{s}{(s-m_i^2)} Q_i L_i\right)^2 \quad (21) \\ &+ [RR]\left(\sum_{i=\gamma,Z^0} \frac{s}{(s-m_i^2)} Q_i R_i\right)^2 \ . \end{aligned}$$

For the vector there remains an ambiguity due to the possible anomalous coupling κ_γ and κ_Z. For simplicity, we assume here that $\kappa_\gamma = \kappa_Z = \kappa$ The most conservative bounds on vector bileptons are given for the value of κ the minimizes the cross section, which then reads

$$\sigma_{\rm vector} = \frac{\pi\alpha^2}{6s}\beta^3\Sigma\frac{5-4\beta^2+3\beta^4}{2-\beta^2} \ . \quad (22)$$

It is only for simplicity, that we assume the electric and weak anomalous coupling to be equal. It must be borne in mind that some unfortunate combinations may suppress the vector cross sections even further, but we discard this possibility here.

It is easy to check in the limit where $m_Z^2 \ll s$, that for the singly-charged bileptons the cross sections with left-polarized electrons are suppressed with respect to those with right-polarized electrons. Assuming the luminosity scaling law (1) and all bilepton decay channels to be observed, we plot in Fig. 6 the number of expected bilepton events in right-polarized e^+e^- collisions as a function of the ratio of bilepton mass to the centre of mass energy. Clearly, a significant signal is expected, even close to the kinematical limit.

If the bileptons are heavier than half the collider's centre of mass energy, they cannot be pair-produced in e^+e^- annihilations. Still, the doubly-charged bileptons may contribute sufficiently to Bhabha scattering to produce significant deviations from the standard model expectations. The scalar and vector differential cross sections are given by

$$\begin{aligned} \frac{d\sigma}{dt} &= \frac{4\pi\alpha^2}{s^2} \quad (23) \\ &\left\{[RR]\left[\left(\sum_i R_i^2\left(\frac{u}{s-m_i^2}+\frac{u}{t-m_i^2}\right) - 2\frac{\tilde{\lambda}_1^2}{e^2}\frac{u}{u-m_L^2}\right)^2\right.\right. \\ &+ \left(\sum_i L_i R_i \frac{t}{s-m_i^2}\right)^2 - 2\frac{\lambda_2^2}{e^2}\frac{t}{u-m_L^2}\sum_i L_i R_i \frac{t}{s-m_i^2} \end{aligned}$$

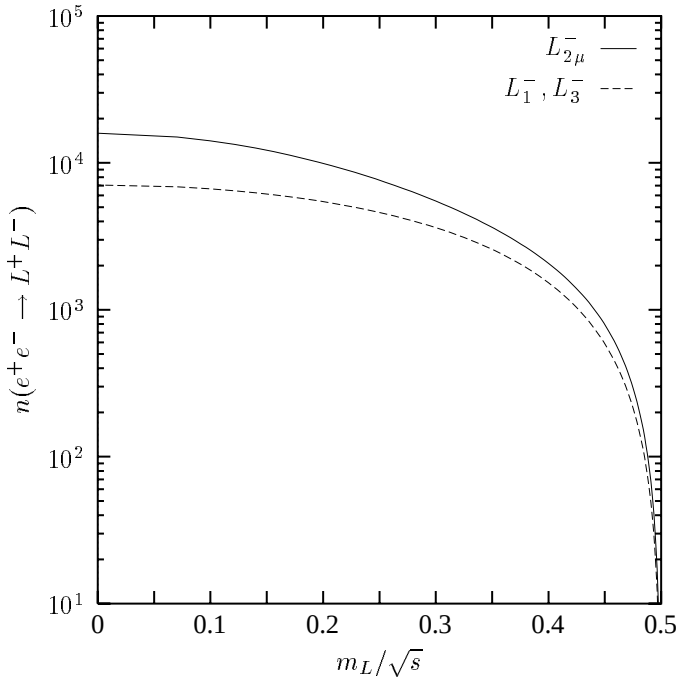

Figure 6: Mass dependence of the number of pair-produced singly-charged bileptons in e^+e^- annihilations, assuming the luminosity scaling law (1).

$$
\begin{aligned}
&+\left(\frac{\lambda_2^2}{e^2}\frac{s}{u-m_L^2}\right)^2 - 2\frac{\lambda_2^2}{e^2}\frac{s}{u-m_L^2}\sum_i L_iR_i\frac{s}{t-m_i^2}\Bigg] \\
&+[LL]\Bigg[\left(\sum_i L_i^2\left(\frac{u}{s-m_i^2}+\frac{u}{t-m_i^2}\right) - 4\frac{\lambda_3^2}{e^2}\frac{u}{u-m_L^2}\right)^2 \\
&+\left(\sum_i L_iR_i\frac{t}{s-m_i^2}\right)^2 - 2\frac{\lambda_2^2}{e^2}\frac{t}{u-m_L^2}\sum_i L_iR_i\frac{t}{s-m_i^2} \\
&+\left(\frac{\lambda_2^2}{e^2}\frac{s}{u-m_L^2}\right)^2 - 2\frac{\lambda_2^2}{e^2}\frac{s}{u-m_L^2}\sum_i L_iR_i\frac{s}{t-m_i^2}\Bigg] \\
&+[LR]\Bigg[\left(\sum_i L_iR_i\frac{s}{t-m_i^2}\right)^2 + \left(\frac{\lambda_2^2}{e^2}\frac{t}{u-m_L^2}\right)^2\Bigg]\Bigg\} \ .
\end{aligned}
$$

To optimize the signal to background ratio, it is best to implemented a maximum likelihood fit. In the absence of deviation from the standard model, the 95% CL lower limits on the bilepton masses are of the order of

$$m_L \gtrsim \sqrt{s} \times 50\lambda_{ee} \ . \tag{24}$$

If the leptonic coupling matrix contains off-diagonal terms, lepton flavour violating processes such as $e^+e^- \to e^+\mu^-$ may be observed. In the absence of any signal, the corresponding limits are of the same order as in Eq. (24).

VII. LIMITS FROM $\gamma\gamma$ SCATTERING

In principle bileptons can also be pair-produced in $\gamma\gamma$ collisions However, the doubly-charged bileptons will be much better observed in e^-e^- scattering. Similarly, $e^-\gamma$ collisions or e^+e^- annihilations with a right-handed electron beam will offer a better signal to background ratio. Moreover, the $\gamma\gamma$ centre of mass energy cannot exceed *ca* 83% of the e^+e^- collider energy. For all these reasons, $\gamma\gamma$ collisions are only of marginal interest for discovering bileptons, and we do not consider these reactions here.

Still, it must be borne in mind that these processes may be interesting when it comes to studying the gauge nature of vector bileptons, and provide an accurate measurement of the anomalous photon coupling κ_γ.

VIII. CONCLUSIONS

Defining *bileptons* to be bosons carrying lepton number 2, we have derived their most general renormalizable lagrangian consistent with the $SU(2)_L \otimes U(1)_Y$ symmetry.

The strongest current bounds from low-energy experiments involve the off-diagonal elements of the matrix coupling the bileptons to leptons. The diagonal elements of the leptonic coupling matrix will be much better constrained by high-energy Bhabha and Møller scattering experiments at the NLC.

Given sufficient centre of mass energy, the NLC will provide the opportunity to test the direct production of bileptons, and hence determine unambiguously the leptonic coupling matrix. Doubly-charged bileptons would show up as an unmistakable resonance in the e^-e^- mode, whereas singly-charged bileptons would be discovered via their pair-production in the e^+e^- mode. If their couplings to leptons are sufficiently large, singly-charged bileptons would also be observed below the pair-production threshold in the $e^-\gamma$ mode. The $\gamma\gamma$ mode of the NLC is not well suited for discovering bileptons, but may well provide additional insight as to their nature.

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