Indirect search for lepton flavour violation at CERN LEP via doubly charged bileptons

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We search for lepton flavour violating couplings via doubly charged bilepton (or doubly charged Higgs) exchange in electron-positron annihilation process $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ using CERN LEP data at the center of mass energies between 189-207 GeV. Standard model program ZFITTER has been used to calculate radiative corrections. We find that $g_2^L/M_L^2 < O(10^{-6})$GeV$^{-2}$ at 95% C.L. for flavour violating scalar and vector bilepton couplings.

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I. INTRODUCTION

In the minimal Standard Model (SM) the usual Higgs mechanism responsible for the electroweak symmetry breaking implies the conservation of the lepton number separately for each generation. As is well known, the current low energy phenomenology of the SM is quite consistent with all present experiments. However, there has been no experimental evidence for the existence of the SM Higgs boson. This is one of the good reasons that other symmetry breaking mechanisms and extended Higgs sectors have not been excluded in the theoretical point of view. In addition, indication for neutrino oscillations necessarily violate lepton-flavour symmetry. In the theories beyond the SM, doubly charged, lepton flavour changing, exotic bosons may occur. Models with extended Higgs sectors include doubly charged Higgs boson. The supersymmetric extensions, such as SO(10) SUSY GUT model where supersymmetric lepton partners induce lepton flavour violation. The purpose of this paper is to study lepton flavour violation through the possible existence of doubly charged bileptons. Bileptons are defined as bosons carrying lepton number $L=2$ or $0$ which couple to two standard model leptons but not to quarks. Bileptons appear in models where SU(2)$_L$ gauge group is extended to SU(3) and also in models with extended Higgs sectors that contain doubly charged Higgs bosons. Grand unified theories, technicolor and composite models predict the existence of bileptons as well as other exotic particles. Classification and interactions of bileptons are provided by several works and a comprehensive review has been presented including low and high energy bounds on their couplings. Indirect constraints on the masses and couplings of doubly charged bileptons have been obtained from $\mu$ and $\tau$ physics, muonium-antimuonium conversion and Bhabha scattering experiments. Searches for doubly charged Higgs have been performed by DELPHI and OPAL collaborations at LEP.

At LEP, fermion pair production is the unique reaction to test the standard model at loop correction level. Therefore one needs precision calculations including QED and weak corrections for reliable comparison with experiments. ZFITTER is one of the standard model program developed to compute scattering cross sections and asymmetries for fermion pair production in $e^+e^-$ collision with QED and electroweak corrections. Using cross section calculations with ZFITTER realistic limits for new physics can be obtained from LEP data. Since QED corrections are model independent (well-defined if couplings, masses and widths of new particles are fixed), the usual convolution formulae can be applied for total cross section

$$\sigma(s) = \int dv \sigma^0(s') R(v)$$

with $v = 1 - s'/s$. For this reason, the flux factor $R(v)$ (radiator) is not influenced by new particles. Above equation can be straightforwardly generalized to different asymmetries $A_{FB}$, $A_{pol}$, $A_{LR}$ or to scattering angle distribution $d\sigma/\cos\theta$ with different effective Born terms and radiators. Final state acollinearity cut and minimum energy can also be applied. Contribution of doubly charged bileptons to $e^+e^-$ annihilation process is the subject of the present article

$$e^+e^- \rightarrow (\gamma, Z, L^-) \rightarrow \mu^+\mu^- (\gamma), \quad \tau^+\tau^- (\gamma)$$
where $L^{-}$ is the doubly charged bilepton giving flavour violating contribution. Here ($\gamma$) represents initial and final state radiations.

General effective lagrangian describing interactions of bileptons with the standard model leptons is generated by requiring $SU(2)_L \times U(1)_Y$ invariance. We consider the lagrangian involving the bilepton couplings to leptons only for $L=2$ bileptons as follows:

$$
\mathcal{L}_{L=2} = g_1^{ij} \bar{\ell}_i \gamma^2 \gamma_\mu \ell_j L^\mu_1 + \bar{g}_1^{ij} \bar{c} \gamma_\mu c_j R^\mu_1 \\
+ g_3^{ij} \bar{\ell}_i \gamma^2 \gamma_\mu \ell_j L^\mu_2 + \bar{g}_3^{ij} \bar{c} \gamma_\mu c_j R^\mu_2 + h.c.
$$

(3)

In the notations we have used $\ell$ is the left handed $SU(2)_L$ lepton doublet and $c_R$ is the right handed charged singlet lepton. Charge conjugate fields are defined as $\psi = 1^i j$ bilepton fields in left-right symmetric models \cite{6}. The subscript of bilepton fields $L_{1,2,3}$ and couplings $g_{1,2,3}$ denote $SU(2)_L$ singlets, doublets and triplets. We show flavour indices by $i, j = 1, 2, 3$. Here we are interested only in doubly charged bileptons. In order to express the lagrangian in terms of individual electron, bileptons and helicity projection operators $P_{R/L} = \frac{1}{2}(1 \pm \gamma_5)$ we expand the Pauli matrices and lepton doublets. Then we write the lagrangian as:

$$
\mathcal{L}_{L=2} = \bar{g}_1 \bar{L}^{++}_1 \gamma^2 \gamma_\mu L^\mu e + g_2 \bar{L}^{++}_2 \gamma^2 \gamma_\mu P_L e \\
-\sqrt{2}g_3 \bar{L}^{++}_3 \gamma^2 \gamma_\mu P_L e + h.c.
$$

(4)

where superscripts of bileptons stand for their electric charges. For simplicity, flavour indices have been skipped. If the scalar $L_{3}^{-}$ acquires a vacuum expectation value then it is a doubly charged Higgs boson that appears in the left-right symmetric models \cite{6}.

II. ELECTRON-POSITRON ANNIHILATION PROCESSES $e^{+} e^{-} \rightarrow \mu^{+} \mu^{-}, \tau^{+} \tau^{-}$

Including the doubly charged scalar bilepton $L_{3}^{-}$ exchange with lepton flavour changing couplings, the unpolarized differential cross section for the process $e^{+} e^{-} \rightarrow \ell^{+} \ell^{-}$ ($\ell = \mu, \tau$) in terms of mandelstam invariants $s, t$ and $u$ is given by

$$
\frac{d\sigma}{d\cos \theta} \equiv \frac{\pi \alpha^2}{8s} \left\{ 2 \frac{u^2}{s} + 2C_L^2 \frac{u}{s-M_Z^2} - \frac{g_1^2}{g_3^2} \frac{u}{u-M_L^2} \right\}^2 \\
+ \left\{ 2 \frac{u^2}{s} + 2C_R^2 \frac{u}{s-M_Z^2} \right\}^2 + 2 \left( \frac{2t}{s} + C_L C_R \frac{2t}{s-M_Z^2} \right)^2.
$$

(5)

With the flavour violating doubly charged vector bilepton couplings ($L_{2\mu}^{-}$ exchange with coupling $g_2$), the unpolarized differential cross section for the above process takes the form

$$
\frac{d\sigma}{d\cos \theta} \equiv \frac{\pi \alpha^2}{8s} \left\{ 2 \frac{u^2}{s} + 2C_L^2 \frac{u}{s-M_Z^2} \right\}^2 \\
+ \left\{ 2 \frac{u^2}{s} + 2C_R^2 \frac{u}{s-M_Z^2} \right\}^2 + \left\{ \frac{2t}{s} + C_L C_R \frac{2t}{s-M_Z^2} \right\}^2 \\
+ \left\{ \frac{2t}{s} + C_L C_R \frac{2t}{s-M_Z^2} + \frac{g_1^2}{g_3^2} \frac{2t}{u-M_L^2} \right\}^2.
$$

(6)

where the definition of mandelstam variables and $C_L, C_R$ are as follows:

$$
t = -\frac{s}{2}(1 - \cos \theta), \quad u = -\frac{s}{2}(1 + \cos \theta),
$$

(7)

$$
C_L = \frac{2\sin^2 \theta_W - 1}{2\sin \theta_W \cos \theta_W}, \quad C_R = \tan \theta_W.
$$

(8)
Bilepton couplings $\sqrt{2}g_3$ and $g_2$ in the lagrangian have been replaced by $g_L$ in the cross sections. Electromagnetic coupling $g_e$ is defined by $g_e^2 = 4\pi\alpha$.

We use the conventional approach to correcting the process $e^+e^- \rightarrow X \rightarrow f\bar{f}$ for radiative effects where $X$ represents an exchanged boson arising from new physics. For the new physics predictions of an observable $O'_{NP}$ with radiative effects, the tree level new physics predictions of an observable $O_{SM}$ is multiplied by a factor of the SM prediction including radiative corrections $O'_{SM}$ divided by the SM prediction at tree level $O_{SM}$.

$$O'_{NP} = O_{NP} \times \frac{O'_{SM}}{O_{SM}}$$

(9)

In order to estimate upper limits on $g_L$, one parameter, one sided $\chi^2$ analysis has been used by varying the $g_L^2$ for fixed bilepton mass between 100 GeV and 700 GeV. After 700 GeV bilepton coupling $g_L$ exceeds perturbative region, approaching unity. Total cross sections measured by OPAL detector at CERN LEP for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states are given in Table II and Table III with standard model values predicted by ZFITTER at energy region $\sqrt{s} = 189 - 207$ GeV [17]. The cross sections and errors shown on these tables are used in the following analysis has been used by varying the $g_L^2$ for fixed bilepton mass between 100 GeV and 700 GeV. After 700 GeV bilepton coupling $g_L$ exceeds perturbative region, approaching unity. Total cross sections measured by OPAL detector at CERN LEP for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states are given in Table II and Table III with standard model values predicted by ZFITTER at energy region $\sqrt{s} = 189 - 207$ GeV [17]. The cross sections and errors shown on these tables are used in the following.

$$\chi^2 = \sum_i \left( \frac{\sigma_i^{exp} - \sigma_i^{new}}{\Delta_i^{exp}} \right)^2$$

(10)

$$\Delta^{exp} = \sigma^{exp} \sqrt{\delta^2_{stat} + \delta^2_{sys}}$$

(11)

where $i$ represents energy index corresponding energy values, cross sections and experimental errors in Table I or Table II. Fig. 1 and Fig. 2 show the upper limits at 95% confidence level on the square of the scalar bilepton coupling $\chi^2/O_{SM}$ for $e \rightarrow \mu$ and $e \rightarrow \tau$ type lepton flavour violation as a function of bilepton mass. Upper limits on flavour changing vector bilepton couplings squared are shown in Fig. 3 and Fig. 4. For higher bilepton masses than LEP energies we take into account the approximation in the bilepton propagator:

$$\frac{g_L^2}{u - M^2_L} \approx -\frac{g_L^2}{M^2_L}$$

(12)

which reduces the number of parameters. Using the similar $\chi^2$ methods we obtain upper limits on the $g_L^2/M^2_L$ shown in Tables III- VI for the same kind of flavour violating cases as in the figures. From tables combined upper limit on $g_L^2/M^2_L$ is about $1 \times 10^{-6}$. We use the same ZFITTER version and the parameters as the ones used by the OPAL Collaboration in Ref. 17 for consistency in radiative corrections.

In conclusion previous limits in units of GeV$^{-2}$ from muon and tau physics for flavour violating doubly charged bilepton couplings are given below to compare with our results:

$$g_{ee}g_{e\mu}/M^2_L < 4.7 \times 10^{-11} \quad \mu \rightarrow e\bar{e}$$

(13)

$$g_{f\mu}g_{f\mu}/M^2_L < 2 \times 10^{-9} \quad \mu \rightarrow e\gamma$$

(14)

$$g_{f\tau}g_{f\mu}/M^2_L < 4 \times 10^{-4} \quad (g - 2)_\mu$$

(15)

$$g_{\tau\nu}g_{e\mu}/M^2_L < 4 \times 10^{-7} \quad \tau \rightarrow \ell\ell\ell$$

(16)

$$g_{\tau\nu}g_{e\tau}/M^2_L < 4 \times 10^{-6} \quad \tau \rightarrow e\gamma$$

(17)

$$g_{f\tau}g_{f\nu}/M^2_L < 7 \times 10^{-6} \quad \tau \rightarrow \mu\gamma$$

(18)

where the first constraint is from Ref. 8 at 90% C.L. and others are from Ref. 7 at 2$\sigma$. In $\mu$ and $\tau$ decays, the labels $\ell$ stand for $e$ or $\mu$ whereas the labels $f$ stand for all three lepton families.

Concerning the LEP experiments and new physics, two comments are in order. At LEP1 and LEP2 energies the forward-backward asymmetries have been accurately measured for two fermion final states [17, 18]. These measurements can also be used for the analysis of the new physics effect.

The upper limits on the cross sections for directly flavour violating events $e^+e^- \rightarrow e\mu, e\tau, \mu\tau$ were obtained at LEP2 energies [19]. The limits which were obtained range from 22 fb to 58 fb for $e\mu$ channel, from 78 fb to 144 fb for $e\tau$
channel. Such small cross sections should have direct impact on the natural values of flavour violating couplings.

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FIG. 1: Upper limits on the scalar bilepton couplings squared against bilepton masses obtained from $e^+e^-\rightarrow \mu^+\mu^-$ process.

FIG. 2: Upper limits on the scalar bilepton couplings squared against bilepton masses obtained from $e^+e^-\rightarrow \tau^+\tau^-$ process.
FIG. 3: Upper limits on the vector bilepton couplings squared against bilepton masses obtained from $e^+e^- \rightarrow \mu^+\mu^-$ process.

FIG. 4: Upper limits on the vector bilepton couplings squared against bilepton masses obtained from $e^+e^- \rightarrow \tau^+\tau^-$ process.
TABLE I: Measured cross sections for $e^+ e^- \rightarrow \mu^+ \mu^-$ with OPAL detector at LEP for two different $s'/s$ cuts. The first error shown is statistical, the second systematic. The standard model cross sections are predicted by ZFITTER.

| $\sqrt{s}$ GeV | $\sigma$(pb) | $\sigma^M$(pb) | $\sigma$(pb) | $\sigma^M$(pb) |
|----------------|--------------|---------------|---------------|---------------|
|                | $s'/s > 0.01$ | $s'/s > 0.01$ | $s'/s > 0.7225$ | $s'/s > 0.7225$ |
| 189            | 7.85±0.25±0.09 | 7.75 | 3.14±0.15±0.03 | 3.21 |
| 192            | 7.40±0.61±0.09 | 7.47 | 2.86±0.34±0.03 | 3.10 |
| 196            | 7.08±0.37±0.08 | 7.13 | 2.93±0.22±0.03 | 2.96 |
| 200            | 6.67±0.36±0.08 | 6.80 | 2.77±0.21±0.03 | 2.83 |
| 202            | 5.63±0.48±0.07 | 6.64 | 2.36±0.28±0.03 | 2.77 |
| 205            | 6.53±0.35±0.08 | 6.41 | 2.88±0.21±0.03 | 2.67 |
| 207            | 6.81±0.28±0.08 | 6.29 | 2.77±0.16±0.03 | 2.63 |

TABLE II: Measured cross sections for $e^+ e^- \rightarrow \tau^+ \tau^-$ with OPAL detector at LEP for two different $s'/s$ cuts. The first error shown is statistical, the second systematic. The standard model cross sections are predicted by ZFITTER.

| $\sqrt{s}$ GeV | $\sigma$(pb) | $\sigma^M$(pb) | $\sigma$(pb) | $\sigma^M$(pb) |
|----------------|--------------|---------------|---------------|---------------|
|                | $s'/s > 0.01$ | $s'/s > 0.01$ | $s'/s > 0.7225$ | $s'/s > 0.7225$ |
| 189            | 8.17±0.39±0.21 | 7.74 | 3.45±0.21±0.09 | 3.21 |
| 192            | 7.74±0.95±0.20 | 7.47 | 3.17±0.50±0.08 | 3.10 |
| 196            | 7.21±0.57±0.19 | 7.12 | 2.89±0.30±0.07 | 2.96 |
| 200            | 7.04±0.56±0.18 | 6.80 | 3.14±0.30±0.08 | 2.83 |
| 202            | 7.69±0.84±0.20 | 6.63 | 2.95±0.43±0.07 | 2.77 |
| 205            | 6.84±0.55±0.18 | 6.40 | 2.72±0.28±0.07 | 2.67 |
| 207            | 6.39±0.41±0.17 | 6.28 | 2.78±0.22±0.07 | 2.63 |

TABLE III: Upper limits on the $e \rightarrow \mu$ type lepton flavor violating $g^L_2/M^2_L$ for doubly charged scalar bileptons at 95% C.L. Combination of results are also shown in the last row and masses are in units of GeV.

| $\sqrt{s}$ GeV | $g^L_2/M^2_L$ | $g^L_2/M^2_L$ |
|----------------|---------------|---------------|
|                | $s'/s > 0.01$ | $s'/s > 0.7225$ |
| 189            | $< 3.2 \times 10^{-6}$ | $< 1.7 \times 10^{-6}$ |
| 192            | $< 6.1 \times 10^{-6}$ | $< 3.1 \times 10^{-6}$ |
| 196            | $< 3.9 \times 10^{-6}$ | $< 2.4 \times 10^{-6}$ |
| 200            | $< 3.6 \times 10^{-6}$ | $< 2.2 \times 10^{-6}$ |
| 202            | $< 3.3 \times 10^{-6}$ | $< 1.8 \times 10^{-6}$ |
| 205            | $< 3.5 \times 10^{-6}$ | $< 2.2 \times 10^{-6}$ |
| 207            | $< 2.9 \times 10^{-6}$ | $< 1.7 \times 10^{-6}$ |
| Combination    | $< 1.6 \times 10^{-6}$ | $< 8.7 \times 10^{-7}$ |
TABLE IV: Upper limits on the $\epsilon \rightarrow \tau$ type lepton flavor violating $g_2^L/M^2_L$ for doubly charged scalar bileptons at 95% C.L. Combination of results are also shown in the last row and masses are in units of GeV.

| $\sqrt{s}$ GeV | $g_2^L/m^2_L$ | $s'/s > 0.01$ | $s'/s > 0.7225$ |
|----------------|---------------|----------------|-----------------|
| 189            | $< 4.9 \times 10^{-6}$ | $< 2.8 \times 10^{-6}$ | 
| 192            | $< 8.8 \times 10^{-6}$ | $< 5.3 \times 10^{-6}$ | 
| 196            | $< 5.8 \times 10^{-6}$ | $< 3.1 \times 10^{-6}$ | 
| 200            | $< 5.5 \times 10^{-6}$ | $< 3.31.1 \times 10^{-6}$ | 
| 202            | $< 7.5 \times 10^{-6}$ | $< 4.2 \times 10^{-6}$ | 
| 205            | $< 5.2 \times 10^{-6}$ | $< 2.9 \times 10^{-6}$ | 
| 207            | $< 4.4 \times 10^{-6}$ | $< 2.3 \times 10^{-6}$ | 
| Combination    | $< 2.4 \times 10^{-6}$ | $< 1.3 \times 10^{-6}$ | 

TABLE V: Upper limits on the $\epsilon \rightarrow \mu$ type lepton flavor violating $g_2^L/M^2_L$ for doubly charged vector bileptons at 95% C.L. Combination of results are also shown in the last row and masses are in units of GeV.

| $\sqrt{s}$ GeV | $g_2^L/m^2_L$ | $s'/s > 0.01$ | $s'/s > 0.7225$ |
|----------------|---------------|----------------|-----------------|
| 189            | $< 2.7 \times 10^{-6}$ | $< 2.1 \times 10^{-6}$ | 
| 192            | $< 7.4 \times 10^{-6}$ | $< 4.2 \times 10^{-6}$ | 
| 196            | $< 6.0 \times 10^{-6}$ | $< 2.3 \times 10^{-6}$ | 
| 200            | $< 5.5 \times 10^{-6}$ | $< 2.2 \times 10^{-6}$ | 
| 202            | $< 4.1 \times 10^{-6}$ | $< 3.0 \times 10^{-6}$ | 
| 205            | $< 2.8 \times 10^{-6}$ | $< 1.8 \times 10^{-6}$ | 
| 207            | $< 2.2 \times 10^{-6}$ | $< 1.4 \times 10^{-6}$ | 
| Combination    | $< 1.5 \times 10^{-6}$ | $< 1.0 \times 10^{-6}$ | 

TABLE VI: Upper limits on the $\epsilon \rightarrow \tau$ type lepton flavor violating $g_2^L/M^2_L$ for doubly charged vector bileptons at 95% C.L. Combination of results are also shown in the last row and masses are in units of GeV.

| $\sqrt{s}$ GeV | $g_2^L/m^2_L$ | $s'/s > 0.01$ | $s'/s > 0.7225$ |
|----------------|---------------|----------------|-----------------|
| 189            | $< 3.7 \times 10^{-6}$ | $< 2.2 \times 10^{-6}$ | 
| 192            | $< 5.9 \times 10^{-6}$ | $< 4.0 \times 10^{-6}$ | 
| 196            | $< 4.3 \times 10^{-6}$ | $< 5.2 \times 10^{-6}$ | 
| 200            | $< 4.0 \times 10^{-6}$ | $< 2.4 \times 10^{-6}$ | 
| 202            | $< 4.7 \times 10^{-6}$ | $< 3.1 \times 10^{-6}$ | 
| 205            | $< 3.6 \times 10^{-6}$ | $< 2.4 \times 10^{-6}$ | 
| 207            | $< 3.1 \times 10^{-6}$ | $< 1.9 \times 10^{-6}$ | 
| Combination    | $< 2.0 \times 10^{-6}$ | $< 1.2 \times 10^{-6}$ |