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Heavy lepton production through vector boson fusion in e^+e^- collisions at high energies

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Abstract We study the production of heavy leptons belonging to a fourth generation, through the vector boson fusion mechanism in e^+e^- collisions at CLIC energies. The analysis of the cross sections shows that, for a considerable range of lepton masses, photon fusion is the most efficient mechanism for the production of heavy leptons. Only for very high masses the fusion of longitudinally polarized bosons becomes competitive with photon fusion.

1. Introduction

The standard model of the electroweak and strong interactions[1,2] has met remarkable experimental success in the last years. However, there are fundamental questions that are beyond the scope of the standard model whose answers might be within the reach of the future generation of accelerators. One of these questions is the number of fermionic families. The intriguing replication of leptons (and quarks) has led to a plentiful set of models where the existence of a fourth family is admitted[3]. We can also recall that some superstring models predict an even 'number of families, therefore we might find at least one extra lepton[4].

Admitting the existence of a fourth heavy lepton, we have recently shown that the most efficient process for the production of these leptons in hadronic colliders is

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the vector boson fusion **mechanism**[5]. This **result** was obtained within the **effective-vector-boson approximation**[6,7]. As happens for the **Higgs** boson sector, the physics of high energy **colliders** may be dominated by vector boson fusion processes[6], and many of **these** have been studied recently in the case of hadronic colliders[B], but not quite so **extensively** for e^+e^- **machines.**

In this paper we study the production of heavy leptons via vector boson fusion at CLIC energies. This **machine** is in study at **CERN** and is proposed to **operate** at $\sqrt{s} = 2$ TeV with a luminosity $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$ (or an integrated luminosity L $= 10^5$ **pb/year).** We **shall** compare the cross sections of photons and weak **(longitudinally and** transversally polarized) vector boson fusion giving a pair of charged leptons, or a heavy **lepton and** its neutrino, which will be computed within the effective-vector-boson approximation. Section 2 contains a discussion of this quoted approximation and **displays** the **basic tools** we **shall** deal with. In section 3 the **analytical** cross sections of each subprocess can be found, and we **leave** our results and conclusions to section 4.

2. The effective-vector-boson approximation

The effective-vector-boson approximation is an extension to massive weak gauge bosons of the **Weizsäcker-Williams** (or leading logarithmic) approximation. It is well known that this **method leads** to quite good results for the two-photon process, **i.e.,** $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-$ X, where in **the** limit of **parallel** momenta the photon distribution inside the electron is

$$A_f = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\ln\left(\frac{\hat{s}}{4m_e^2}\right) \tag{1}$$

and the full cross section for the two-photon process is the **product** of the photon distributions times the cross sections of the subprocess 7 7 $\to$ X.

The above procedure was generalized, in the case of weak vector hosons, by Mane et al. and Dawson[e], who determined the vector boson distributions inside a fermion for longitudinally and transversally polarized bosons. To leading order, they are respectively given by

$$V_f^L \cong \frac{\alpha}{\pi}\left(C_V^2 + C_A^2\right)\frac{1-x}{x} \tag{2a}$$

$$V_f^T \cong \frac{\alpha}{2\pi}\left(C_V^2 + C_A^2\right)\frac{1+(1-x)^2}{x}\ln\left(\frac{\hat{s}}{M_V^2}\right) \tag{2b}$$

where M_V is the gauge bosons mass, $\sqrt{\hat{s}}$ the subprocess invariant mass, and

$$C_V = -C_A = \frac{1}{2\sqrt{2}\sin\theta_W}$$

for charged (W*) weak bosons and

$$C_V = \frac{1}{\sin\theta_W \cos\theta_W} \qquad - Q\sin^2\theta_W\Big)$$

$$C^* = -\frac{1}{2\sin\theta_W \cos\theta_W}T_3$$

for the Z^0 boson.

The cross section for $e^+e^- \to V_iV_j \to$ X, where $V_{i(j)}$ is any of the electroweak bosons, can be written as

$$\sigma(e^+e^- \to V_iV_j \to X) = \frac{1}{1+\delta_{ij}}\int_{\tau_m}^{1} dx_1 \int_{\tau_m/x_1}^{1} dx_2 \left[V_i(x_1)V_j(x_2) + (i \leftrightarrow j)\right]\hat{\sigma}_{V_iV_j\to X}(x_1x_2s) \tag{3}$$

It is convenient to define the luminosities of bosons inside the fermion as

$$\frac{dL_{ij}}{d\tau} = \int_{\tau}^{1}\frac{dx_1}{x_1}\frac{1}{(1+\delta_{ij})}\left[V_i(x_1)V_j\left(\frac{\tau}{x_1}\right) + (i \leftrightarrow j)\right] \tag{4}$$

and eq.(3) is reduced to

$$\sigma = \int_{\tau_m}^{1} d\tau \frac{dL_{ij}}{d\tau}\hat{\sigma}_{V_iV_j\to X}(\tau s) \tag{5}$$

where $\tau = \hat{s}/s$, and $\hat{\sigma}_{V_iV_j\to X}$ is the cross section of the subprocess $V_iV_j \to$ X.

From eqs. (1), (2) and (4) we can easily show that

$$\frac{dL_{\gamma\gamma}}{d\tau} = \left[\frac{\alpha}{2\pi}\ln\left(\frac{\hat{s}}{4m_e^2}\right)\right]^2 \frac{(2+\tau)\ln\left(\frac{1}{\tau}\right) - 2(1-\tau)(3+\tau)}{\tau} \tag{6a}$$

$$\frac{dL_{V_T V_T}}{d\tau} = \left[\frac{\alpha}{2\pi}(C_V^2 + C_A^2)\ln\left(\frac{\hat{s}}{M_W^2}\right)\right]^2 \frac{(2+\tau)^2\ln\left(\frac{1}{\tau}\right) - 2(1-\tau)(3+\tau)}{\tau} \tag{6b}$$

$$\frac{dL_{V_L V_L}}{d\tau} = \left[\frac{\alpha}{\pi}(C_V^2 + C_A^2)\right]^2 \frac{(1+\tau)\ln\left(\frac{1}{\tau}\right) + 2(\tau-1)}{\tau} \tag{6c}$$

$$\frac{dL_{V_L V_L}}{d\tau} = \left[\frac{\alpha}{2\pi}(C_V^2 + C_A^2)\right]^2 \ln\left(\frac{\hat{s}}{M_T^2}\right)\frac{4(1+\tau)\ln\left(\frac{1}{\tau}\right) - (1-\tau)(7+\tau)}{\tau} \tag{6d}$$

where $M_T = M_V$ for W_T and Z_T, and $M_T = 2m_e$ for the photon.

The above luminosities are basically the quantity of vector bosons that can be found in the electron (or positron), and are plotted in fig.1. Notice that the electron (and positron) will mostly carry a cloud of transversally polarized bosons, whose luminosity is one order of magnitude larger than the others as can be observed in fig.1. As we shall verify, this difference may be compensated in the total cross section by the fact that the cross sections for subprocesses involving longitudinally polarized bosons are larger than the ones involving transversally polarized bosons by more than one order of magnitude.

3. Cross sections for the elementary process $V_iV_j \to$ leptons

The process we are interest in is $e^+e^- \rightarrow e^+e^-(\nu)V_iV_j \rightarrow e^+e^-(\nu)X$ where $V_{i(j)}$ can be a photon or a weak boson. In this last case, as we have distribution functions for longitudinally and transversally polarized bosons, we must compute the cross sections for each one of these polarizations. If the final state (X) is a pair L^+L−, the initial one (V_iV_j) may be; $\gamma\gamma$, W_TW_T, Z_TZ_T, W_LW_L, Z_LZ_L, γZ_T, γZ_L, W_LW_T and Z_LZ_T (where $(L(T)$ means longitudinal (transversal) polarization). When the final state is a lepton (L*) and its neutrino (ν_L), the possible V_iV_j contributions are

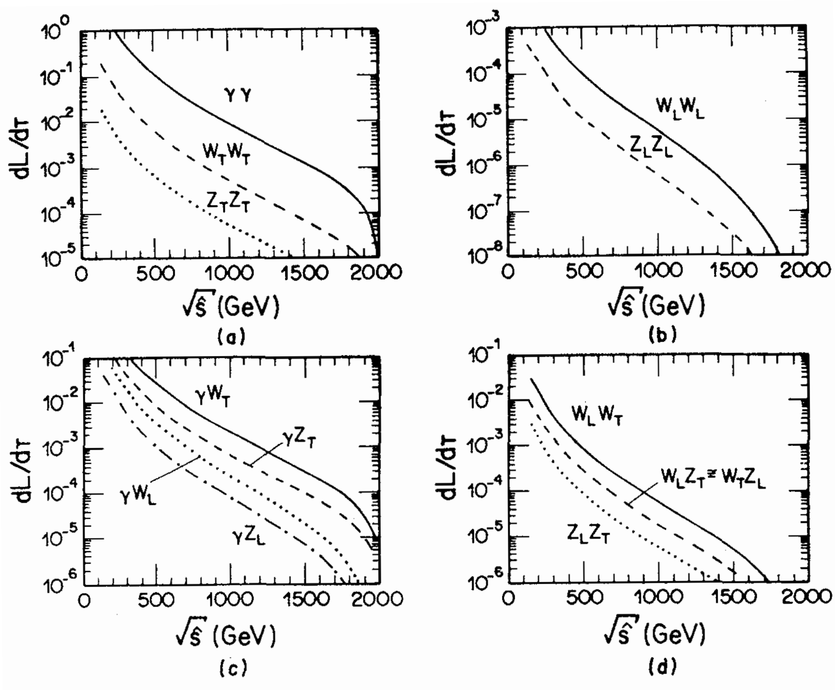

Fig.1 - (a) Luminosities for $\gamma\gamma, W_TW_T$ and Z_TZ_T fusion, (b) idem for W_LW_L and Z_LZ_L, (c) idem for $\gamma W_T, \gamma Z_T, \gamma W_L$ and γZ_L,, (d) idem for W_LW_T, Z_LZ_T and W_LZ_T.

γW_T, γW_L, W_LZ_T, W_TZ_L. In the following we shall present the main cross sections for the processes quoted above in the limit of high energies; for the complete expressions we refer the reader to refs. (10) and (5).

a) $W_L^+W_L^- \longrightarrow L+L-$

$$\hat{\sigma}_{WW\to LL}(\hat{s}) = \frac{\pi\alpha^2}{2\sin^4\theta_W}\left(\frac{M_L}{M_W}\right)^4\frac{\beta}{\hat{s}}\Big\{-1+\frac{\mathcal{L}}{\beta}+M_H^2(\hat{s}-M_H^2)\chi_H\left[-1+\frac{(1-\beta^2)}{2\beta}\mathcal{L}\right] + \frac{\beta^2}{(1-\beta^2)}M_H^4\chi_H\Big\} \tag{7}$$

where

$$\beta = \left(1-\frac{4M_L^2}{\hat{s}}\right)^{1/2}$$

$$\mathcal{L} \equiv \ln\frac{(1+\beta)}{(1-\beta)}$$

$$\chi_H = \frac{1}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2}$$

M_L and M_H are respectively the lepton and Higgs boson masses.

b) $Z_L^0 Z_L^0 \longrightarrow L^+ L^-$

$$\underset{ZZ\to LL}{\hat{\sigma}(\hat{s})} = \frac{\pi\alpha^2}{2\sin^4\theta_W\cos^4\theta_W}\left(\frac{M_L}{M_Z}\right)^4\frac{\beta}{\hat{s}}\Big\{\Big[1+2M_H^2(\hat{s}-M_H^2)\chi_H\Big]\Big(-1+\frac{1}{2\beta}\mathcal{L}\Big) + \frac{\beta^2}{(1-\beta^2)}M_H^4\chi_H\Big\} \tag{8}$$

c) $\gamma Z_L^0 \longrightarrow L^+ L^-$

$$\underset{\gamma Z\to LL}{\hat{\sigma}(\hat{s})} = \frac{\pi\alpha^2}{\sin^2\theta_W\cos^2\theta_W}(1-4\sin^2\theta_W)^2\left(\frac{M_L}{M_Z}\right)^2\frac{\beta}{\hat{s}}\Big(-2+\frac{1}{\beta}\mathcal{L}\Big) \tag{9}$$

d) $\gamma W_L^{\mp} \longrightarrow L^{\mp}\overset{(-)}{\nu}_L$

$$\underset{\gamma W\to L\nu}{\hat{\sigma}(\hat{s})} = \frac{\pi\alpha^2}{2\sin^2\theta_W}\left(\frac{M_L}{M_W}\right)^2\frac{1}{\hat{s}}\{-(1-\eta)(1-4\eta)+[1-2\eta(1+\eta)]\mathcal{L}\} \tag{10}$$

where

$$\eta = M_L^2/\hat{s}$$

We would like to recall that the cross sections eq.(7) to (eq. (10) are the resul of a sum of diagrams, and some of these separately violate unitarity although the complete sum is well behaved at high energia. It is also important to remember that the above cross sections show an enhancement factor $(M_L/M_V)^4$ for those involving the fusion of two longitudinaily polarized bosons, or $(M_L/M_V)^2$ when only one longitudinal boson appears. Obviously, for $M_L << M_V$ there is no enhancement, and we expect that procases originated by transversally polarized bosons dominate, since their luminosity in the fermion is larger.

The enhancement factor $(M_L/M_W)^2$ arises from the high energy behavior of the longitudinal polarization of the weak bosons (ϵ_L^μ), whose dominant term is given by k_μ/M_V. When this polarization vector **acts** on nonconserved **axial** currents it introduces a factor M_L/M_V in the amplitude for **each** longitudinal boson.

4. Results and conclusions

Our numerical **results** are shown in figs. 2 and 3. In fig. 2 the curve labelled *77* is the contribution of the process $e{+}e^- \to e{+}e^- 77 \to e{+}e^-$ L+L-, whose **subprocess** cross section $\gamma\gamma \to$ L+L^- is

$$\hat{\sigma}(\hat{s})_{\gamma\gamma\to LL} = \frac{4\pi\alpha^2}{\hat{s}}\beta\left[\frac{(3-\beta^4)}{2\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)-2+\beta^2\right] \tag{11}$$

which, among **all** the process of fusion of vector bosons, is the dominant up to $M_L \approx 300$ **GeV.** For **larger** lepton **masses**[11] the processes involving longitudinally polarized bosons start being more important than the *77* one.

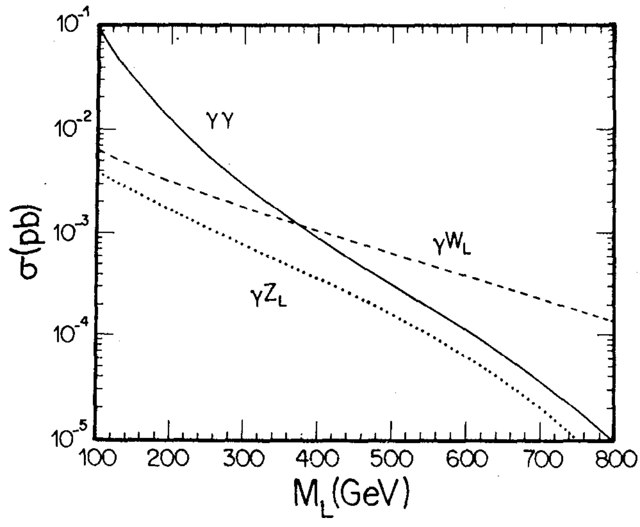

Fig.2 - Cross sections for the process $e^+e^- \to e^+e^- L{+}L-$ through *77* and γZ_L fusion, and for $e{+}e^- \to e^{(\bar{\nu})}L^{(\bar{\nu})}$ via γW_L fusion.

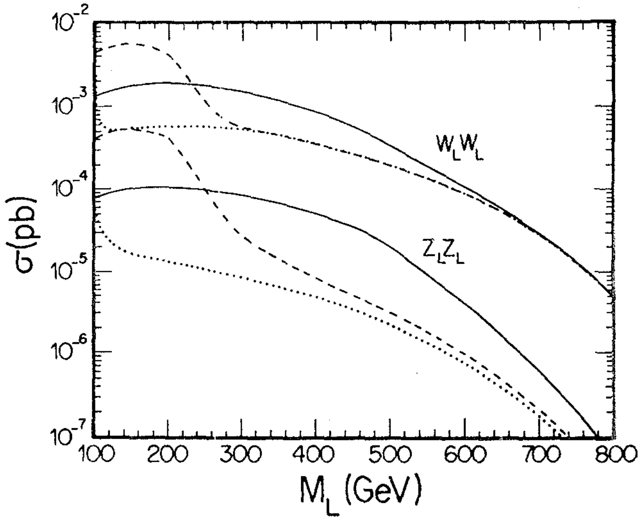

Fig.3 - Cross section for the process $e^+e^- \rightarrow e^+e^-L^+L^-$ via WW and ZZ fusion at $\sqrt{s}$ = **2** TeV for M_H = 1 TeV (solid curves), M_H = 500 GeV (dashed curves), and M_H = 200 GeV (dotted curves).

Notice that the introduction of at least one longitudinal boson (γW_L), producing a heavy lepton and its neutrino (fig. 2) overcomes the 77 production of a pair of heavy leptons. There are two main factors justifying this behavior. Firstly the enhancement factor $(M_L/M_V)^2$ and secondly the larger phase space for the pair $L\nu$.

The fact that electrons and positrons do not contain too many W's and Z's is also reflected in fig. 3, where we have an enhancement factor $(M_L/M_V)^4$ for W_LW_L and Z_LZ_L, but these are not enough to overcome the larger 7 Iuminosity and a smaller enhancement $(M_L/M_V)^2$ of the process γW_L.

In fig. 3 we also notice the effect of Higgs boson exchange diagrams. However, larger or smaller masses for the Higgs bosons will not modify the results, because their effects appear in a region where the two-photon process is clearly dominant.

In conclusion, for very heavy leptons, the fusion of a longitudinally polarized charged boson and a photon producing an $L\nu$ pair do win over any other vector boson fusion process, although it is not the main mechanism for heavy lepton production. If such leptons exist they can be better found in the direct annihilation of e^+e^- through the γ and Z^0. The events containing a heavy lepton and its neutrino from vector boson fusion can be detected looking for a jet plus missing energy, although at CLIC energies and for a lepton mass in the range 400 - 500 MeV we shall not have more than $O(10^2)$ events.

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11. There are experimental constraints on the splitting of a new fermion generation, which for a light Higgs boson can be quite stringent, for example $|M_L - M_\nu| < 310$ GeV for $M_H = 100$ GeV (U. Amaldi et al., Phys. Rev. D36, 1385 (1987); however, these constraints are overcomed in some extensions of the standard model.

Resumo

Estudamos a produção de leptons pesados, e pertencentes a uma quarta geração, através do mecanismo de fusão de bosons vetoriais em colisões e^+e^- a energias do CLIC. A análise tias seções de choque mostra que, dentro de um extenso domínio para a massa dos isptons, a fusão de fótons é o mecanismo mais eficiente para a produção de leptons pesados. Somente para massas muito grandes é que o processo de fusão de bosons, polarizados longitudinalmente, se torna competitivo com aquele envolvendo a fusão de fótons.