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Publicação IF - 1349/99

IFUSP-DFN/99-020

Study of the Process $e^+e^- \to W^+W^-$ in a Model with Four Majorana Neutrinos

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(To be published in the Proceedings of the 8th Mexican School of Particles and Fields 98)

Abstract. *We investigate the process* $e^+e^- \to W^+W^-$*, currently being studied at LEP, in the context of the simplest extension of the Stantard Model of electroweak interactions, where a singlet right-handed neutrino is added to the matter content of the model.*

INTRODUCTION

The Standard Model of electroweak interactions (SM) [1] has passed all the high-precision tests performed at LEP and SLC up to now. Nevertheless its neutrino sector is still very much open to theoretical speculation. Are neutrinos really massless even though there is no underlying principle of nature to prevent them to acquire mass ? The fact that neutrinos are the only known electrically neutral elementary fermions means that they could be Majorana particles. Why should they be considered Dirac particles ? We believe these questions will only eventually be answered by the confront of experimental data with theoretical assumptions.

In this work, we consider an extension of the standard electroweak model, where a singlet right-handed neutrino is added to the particle content of SM and study the possible consequences of this model to the process $e^+e^- \to W^+W^-$ as a function of the free mixing parameters. We have calculated the total cross-section considering on-shell W boson production at three level. This is a first attempt to estimate the maximal deviations from the SM that can be consistent with the LEP data and its consequences in terms of the model free parameters.

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The excitation curve of W-pair production near threshold is dominated by the neutrino exchange t-channel diagram. As this increase depends strongly on the value of the W boson mass, M_W, and as the LEP experiments promise a very accurate determination of M_W by direct reconstruction of W bosons through their decay products as well as the scan of the production cross-section, we may hope that in the near future these data will impose very strong constraints in mixing in the leptonic sector.

We do not discuss here the inclusion of finite-width effects for the off-shell W-pair production which is clearly very important and will be addressed in the near future.

BRIEF DESCRIPTION OF THE MODEL

In the minimal extension of the SM considered here, which we will call Minimal Model (MM), where one right-handed singlet neutral fermion is added to the particle content of the SM, the most general form of the neutrino mass term is [2]

$$\mathcal{L}_\nu^M = -\sum_{j=e,\mu,\tau} a_j \overline{\nu}'_{jL}\nu'_R - \frac{1}{2}M\overline{\nu}'^C_R\nu'_R + H.c., \tag{1}$$

where the primed fields are not yet the physical ones. The diagonalization of the neutrino mass matrix will result in four physical neutrinos fields ν_1, ν_2, ν_P and ν_F; the first two massless and the last two massive Majorana neutrinos with masses

$$m_P = \frac{1}{2}\left(\sqrt{M^2+4a^2} - M\right) \quad \text{and} \quad m_F = \frac{1}{2}\left(\sqrt{M^2+4a^2} + M\right), \tag{2}$$

where $a^2 = {a_e}^2 + {a_\mu}^2 + {a_\tau}^2$.

In terms of the physical fields the charged-current interactions ($\mathcal{L}^{CC}$) is proportional to the factor

$$CC = \left(\begin{array}{c} \overline{\nu}_1\overline{\nu}_2\overline{\nu}_P\overline{\nu}_F \end{array}\right)_L \gamma^\mu \Phi R \left(\begin{array}{c} e \\ \mu \\ \tau \\ 0 \end{array}\right)_L W_\mu^+ + H.c., \tag{3}$$

where $\Phi = diag\,(1,1,i,1)$ and R is the matrix

$$\left[\begin{array}{cccc} c_\beta & -s_\beta s_\gamma & -s_\beta c_\gamma & 0 \\ 0 & c_\gamma & -s_\gamma & 0 \\ c_\alpha s_\beta & c_\alpha c_\beta s_\gamma & c_\alpha c_\beta c_\gamma & -s_\alpha \\ s_\alpha s_\beta & s_\alpha c_\beta s_\gamma & s_\alpha c_\beta c_\gamma & c_\alpha \end{array}\right]. \tag{4}$$

In Eq. (4) c and s denote the cosine and the sine of the respective arguments. The angles α, β, e γ lie in the first quadrant and are related to the mass parameter as follows:

$$s_\alpha = \sqrt{\frac{m_P}{m_P + m_F}}, \quad s_\beta = \frac{a_e}{a}, \quad c_\beta s_\gamma = \frac{a_\mu}{a}, \quad c_\beta c_\gamma = \frac{a_\tau}{a}. \tag{5}$$

W-PAIR PRODUCTION IN THE MM

At the Born level the $e^+e^- \to W^+W^-$ process can take place not only via γ and Z^0 formation, but also through t-channel neutrino exchange. This last process dominates the counting rate at LEP 200 energies. The Higgs-exchange diagram which is suppressed by a factor m_e/m_W is completely negligible and can be omitted from our calculation.

If we set the convention $e^+(q_+,\kappa_+) + e^-(q_-,\kappa_-) \to W^+(p_+,\lambda_+) + W^-(p_-,\lambda_-)$, where the arguments are the momenta and helicities of incoming and outgoing particles, one can write the total three level helicity amplitude $\mathcal{M}_{\rm Born}$ as

$$\mathcal{M}_{\rm Born}\left(\kappa,\lambda_+,\lambda_-,s,t\right) = \sum_{\alpha=\nu,\gamma,Z^0} \mathcal{M}_\alpha\left(\kappa,\lambda_+,\lambda_-,s,t\right), \tag{6}$$

where $s = (q_+ + q_-)^2$ and $t = (q_+ - p_+)^2$ are the usual Mandelstam variables and $\mathcal{M}_\nu$, $\mathcal{M}_\gamma$ and $\mathcal{M}_{Z^0}$ can be calculated in accordance to the helicity amplitude prescription found in refs. [3–5]. We have neglected the electron mass, so the helicity of the positron will be opposite to that of the electron , i.e. $\kappa_- = -\kappa_+ = \kappa$. Imposing CP conservation instead of 36 amplitudes we only have to calculate 12 independent ones.

In the MM only the neutrino amplitude is modified with respect to the SM results. To calculate this amplitude in terms of the SM one we will write the electron neutrino (ν_e) eigenstate in terms of the physical neutrinos of the model. For this purpose, we use the lepton mixing matrix and then ν_e can be write as follows $|\nu_e\rangle = c_\beta\,|\nu_1\rangle - i s_\alpha c_\beta\,|\nu_P\rangle + s_\alpha s_\beta\,|\nu_F\rangle$.

Therefore the invariant amplitude do ν_e in MM can be obtained directly from its expression in the SM by

$$\mathcal{M}_\nu^{\rm MM}\left(\kappa,\lambda_+,\lambda_-,s,t\right) = \frac{e^2}{2s_W^2}\left[\frac{c_\beta^2}{t^2} + \frac{c_\alpha^2 s_\beta^2}{t_P^2} + \frac{s_\alpha^2 s_\beta^2}{t_F^2}\right]^{\frac{1}{2}} \mathcal{M}_1^\kappa(\lambda_+,\lambda_-)\delta_{\kappa-}, \tag{7}$$

where t_P and t_F are given by $t_i = t-(m_i)^2, \quad i = P, F$ and the index MM indicates that the Minimal Model was used for its calculation. Also $\delta_{\kappa-}$ is equal to 1 for left-handed electrons or 0 for right-handed ones and the expression for $\mathcal{M}_1^\kappa(\lambda_+,\lambda_-)$ are the SM ones that can be found in ref. [3].

In this way we can now study the differences between the results of differential and total cross-sections for W^+W^- production in the SM and in the MM in terms of the model free parameters. Before doing so let us revise the constrains on masses and mixing angles of the MM imposed by the measured Z^0 invisible width [6]. Three mass regions can be considered for the massive neutrinos: **(1)** $m_P, m_F < \frac{M_Z}{2}$; **(2)** $m_P < \frac{M_Z}{2}$ and $\frac{M_Z}{2} < m_F < M_Z$ and **(3)** $m_P < \frac{M_Z}{2}$ and $m_F > M_Z$.

In the region **(1)**, as showed in ref. [6], there is a constraint on the masses, i.e. $m_F > 18.2\ m_P$. This implies for our present calculation no visible discrepancy from the SM cross-section even is one consider maximal mixing. In the case of

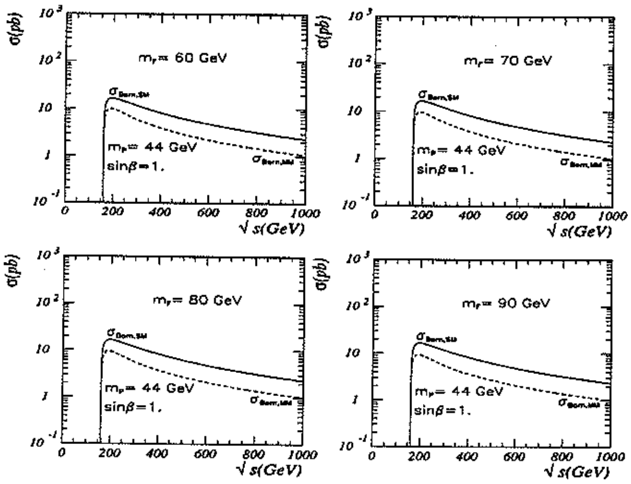

FIGURE 1. Region (2): Total cross-section in the MM and SM for several values of m_F.

region (2) all masses in the kinematic region are allowed. Here we have found, as exemplified by the plots in Fig. 1, that one expect that not all mixing values will be allowed by the LEP data. In region (3) the constraint is that the lightest neutrino (m_P) has been smaller than 9 GeV and again no visible discrepancy from the SM cross-section can be observed even is one consider maximal mixing.

CONCLUSIONS

In conclusion we have : **(i)** in the region (1) and (3) the total cross-section for on-shell W-pair production in MM is not distinguishable from the SM one. Therefore, in these regions, it seems that LEP data will not help much in constraining the model parameters. This may change when we perform the off-shell W-pair calculation; **(ii)** we can hope to experimentally constrain the MM parameters in region (2) and **(iii)** since the difference in the cross-section between the SM and the MM calculation vary dependent on $\sqrt{s}$ and the maximal discrepancy occurs near the W^+W^- pair production threshold because the t-channel dominates at this energy, we see that finite-width of the W will has really to be taken into account before any fit with experimental data can be performed.

ACKNOWLEDGMENTS

We thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for financial support.

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