Consequences of new-heavy-particle exchange in $e^+e^- \to W^+W^-$

Y. A. Coutinho, J. A. Martins Simões, and M. C. Pommot Maia*
Universidade Federal do Rio de Janeiro, Instituto de Física 21941, Rio de Janeiro, Brazil

(Received 6 May 1991)

In this paper we present an analysis of the contribution of new possible neutral current and heavy neutrino exchange for the process $e^+e^- \to W^+W^-$. The unitarity behavior is discussed for some extended models. Multi-TeV colliders are shown to be sensitive to new heavy neutrino masses at energies well below their mass thresholds

PACS number(s): 13.10.+q, 12.15.Cc, 14.60.Gh

I. INTRODUCTION

All the available experimental data confirm quite remarkably the predictions of the standard model of the electroweak interactions due to Salam, Weinberg, and Glashow [1]. But, as has been discussed exhaustively, the large number of parameters and unexplained structures seems to suggest that it is not a truly fundamental theory.

Trying to solve the problems left open by the standard model (SM) many candidates have been proposed as an extension of this model. But, as until now the success of the SM in describing the interactions of known matter is unquestionable, all these candidates must, necessarily, reproduce it at low energies. No signal of new physics is, so far, experimentally known up to a scale of 100 GeV.

The phenomenological agreement at low energies is not the only requirement we can impose. It is very important to have a theory that is self-consistent, renormalizable, and anomaly-free in order to do reliable estimates.

The advent of the new colliders, in addition to allowing the exploration of physics beyond the SM, will also permit us to test the remaining "problems:" the existence of the Higgs particle, the top quark and the Yang-Mills structure of the self-coupling of the electroweak vector bosons. W boson pair production [2] in electron-positron annihilation is a process whose acceptable behavior at high energies ($\sigma \simeq s^{-1}\ln s$) is given by gauge theory cancellations between the direct diagrams (γ and Z exchange) and the crossed-channel diagram (ν diagram). To emphasize we repeat that this gauge cancellation is vital for the renormalizability of the theory.

Almost all the proposed extensions of the SM present at least one new gauge boson. The effect of this new, and heavier than the now well-known Z_1 neutral gauge boson (hereafter named Z_2) in the process $e^+e^- \to W^+W^-$ has been studied by many authors in the superstring theory context [3]. Another characteristic of extended models (such as superstring inspired, mirror, composite) is the existence of new matter. As we do not have evidence of those particles today, if they exist they are heavier than the usually known particles. And we hope that with the new experimental facilities they will show themselves. A very unpleasant feature of extended models is the possibility of pushing away the mass scale of new particles well above experimental limits. One way to improve this situation is to consider the virtual effects of these particles and their phenomenological consequences at energy scales below their mass thresholds.

Our purpose in this paper is mainly to investigate the contribution of a new heavy neutral lepton N to W-boson pair production in e^+e^- collisions. For completeness we shall also include a second Z^0 contribution. Recently this problem was studied by Nagawat, Singh, and Sharma [4], but their analysis was limited to energies of the CERN e^+e^- collider LEP II.

This paper is organized in the following way. In Sec. II we give the general expression for the e^+e^- reaction and discuss the general conditions for a correct unitarity behavior. In Sec. III we briefly review the most usual extended model with heavy neutrinos and their unitarity behavior. Our result for the total cross section and angular distribution are given in Sec. IV. In Sec. V we discuss the main conclusions of our work.

II. THE $e^+e^- \to W^+W^-$ CROSS SECTION

To generalize we will consider that there is a new neutral gauge boson Z_2 and a heavy neutral particle in addition to the known ones contributing to this process. So, the most general interaction Lagrangian will be

$$L_{\text{int}} = -e\bar{e}\gamma^\mu e A_\mu + \sum_{a=1,2} \bar{e}\gamma^\mu (g_V^{(a)} - g_A^{(a)}\gamma^5) e Z_\mu^{(a)} + G_{VA}\bar{e}\gamma^\mu(a_1 + b_1\gamma^5)\nu W_\mu + G'_{VA}\bar{e}\gamma^\mu(a_2+b_2\gamma^5) N W_\mu \,, \quad (1)$$

where $g_V^{(a)}$ and $g_A^{(a)}$ are the $eZ_{(a)}$ couplings and will obviously depend on the particular model we use. G_{VA} is the usual SM $e\nu$ coupling and G'_{VA} the eN coupling.

We consider a general mixing between Z_1 and Z_2 so that the mass eigenstates are related to the physical ones (Z, Z') by

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M \end{bmatrix} \begin{bmatrix} Z \\ Z' \end{bmatrix} .$$

*Present address: Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510.

The trilinear vector gauge boson couplings are

$$\gamma WW\colon \; eV_{\alpha\beta\delta} \,,$$
$$Z_1 WW\colon \; e\cos\theta_M \cot\theta_W V_{\alpha\beta\delta} \,, \tag{2}$$
$$Z_2 WW\colon \; -e\sin\theta_M \cot\theta_W V_{\alpha\beta\delta} \,,$$

with $V_{\alpha\beta\delta}$ the usual trilinear gauge boson vertex.

Using algebraic calculations we have the partial cross section for the Feynman diagrams of Fig. 1,

$$\frac{d\sigma}{dt}=\frac{2\pi\alpha^2}{s^2}\sum_{ij} B_{ij} \,, \tag{3}$$

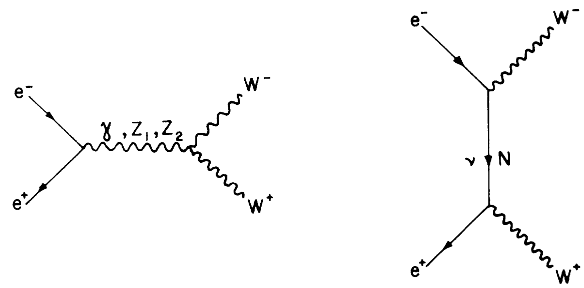

FIG. 1. Feynman diagrams for $e^+e^-\to W^+W^-$.

where the B_{ij} are given explicitly below and we keep terms proportional to M_N^2 and neglect terms such as m_e^2 and m_ν^2:

$$B_{\gamma\gamma}=A(s,t,u) \,, \tag{4a}$$

$$B_{Z_1Z_1}=\cos^2\theta_M\left[\frac{e_Z}{e^2}\right]^2[(g_V^{(1)})^2+(g_A^{(1)})^2]s^2{\Delta_{Z_1}}^2A(s,t,u) \,, \tag{4b}$$

$$B_{Z_2Z_2}=\sin^2\theta_M\left[\frac{e_Z}{e^2}\right]^2[(g_V^{(2)})^2+(g_A^{(2)})^2]sR_{Z_2}A(s,t,u) \,, \tag{4c}$$

$$B_{\gamma Z_1}=-2\cos\theta_M\left[\frac{e_Z}{e^2}\right]g_V^{(1)}s\Delta_{Z_1}A(s,t,u) \,, \tag{4d}$$

$$B_{\gamma Z_2}=2\sin\theta_M\left[\frac{e_Z}{e^2}\right]g_V^{(2)}{\Delta_{Z_2}}^{-1}R_{Z_2}A(s,t,u) \,, \tag{4e}$$

$$B_{Z_1Z_2}=-2\sin\theta_M\cos\theta_M\left[\frac{e_Z}{e^2}\right]^2(g_V^{(1)}g_V^{(2)}+g_A^{(1)}g_A^{(2)})sR_{Z_2}\Delta_{Z_1}{\Delta_{Z_2}}^{-1}A(s,t,u) \,, \tag{4f}$$

$$B_{\gamma\nu}=-2\frac{G_{VA}^2}{e^2}(a_1^2+b_1^2)I(s,t,u) \,, \tag{4g}$$

$$B_{\gamma N}=-2\frac{G_{VA}'^2}{e^2}(a_2^2+b_2^2)I_1(s,t,u) \,, \tag{4h}$$

$$B_{\nu\nu}=\frac{G_{VA}^4}{e^4}[a_1^4+b_1^4+6(a_1b_1)^2]E(s,t,u) \,, \tag{4i}$$

$$B_{NN}=\frac{G_{VA}'^4}{e^4}\{[a_2^4+b_2^4+6(a_2b_2)^2]E_2(s,t,u)+M_N^2(a_2^2-b_2^2)^2E_H(s,t,u)\} \,, \tag{4j}$$

$$B_{\nu N}=2\frac{G_{VA}^2}{e^2}\frac{G_{VA}'^2}{e^2}[(a_1^2+b_1^2)(a_2^2+b_2^2)+4a_1a_2b_1b_2]E_1(s,t,u) \,, \tag{4k}$$

$$B_{NZ_1}=2\cos\theta_M\frac{G_{VA}'^2}{e^2}\left[\frac{e_Z}{e_2}\right][g_V^{(1)}(a_2^2+b_2^2)-2a_2b_2g_A^{(1)}]s\Delta_{Z_1}I_1(s,t,u) \,, \tag{4l}$$

$$B_{NZ_2}=-2\sin\theta_M\frac{G_{VA}'^2}{e^2}\left[\frac{e_Z}{e^2}\right][g_V^{(2)}(a_2^2+b_2^2)-2a_2b_2g_A^{(2)}]R_{Z_2}{\Delta_{Z_2}}^{-1}I_1(s,t,u) \,, \tag{4m}$$

$$B_{\nu Z_1}=2\cos\theta_M\frac{G_{VA}^2}{e^2}\left[\frac{e_Z}{e^2}\right][g_V^{(1)}(a_1^2+b_1^2)-2a_1b_1g_A^{(1)}]s\Delta_{Z_1}I(s,t,u) \,, \tag{4n}$$

$$B_{\nu Z_2}=-2\sin\theta_M\frac{G_{VA}^2}{e^2}\left[\frac{e_Z}{e^2}\right][g_V^{(2)}(a_1^2+b_1^2)-2a_1b_1g_A^{(2)}]R_{Z_2}{\Delta_{Z_2}}^{-1}I(s,t,u) \,, \tag{4o}$$

where $e_Z=e\cot\theta_W$. The functions $A(s,t,u)$, $E(s,t,u)$, and $I(s,t,u)$ are given in the classical work of Brown and Mikaelian [2]:

$$A(s,t,u)=\left[\frac{ut}{M_W^4}-1\right]\left[\frac{1}{4}-\frac{M_W^2}{s}+3\frac{M_W^4}{s^2}\right]+\frac{s}{M_W^2}-4\ ,$$

$$I(s,t,u)=\left[\frac{ut}{M_W^4}-1\right]\left[\frac{1}{4}-\frac{1}{2}\frac{M_W^2}{s}-\frac{M_W^4}{st}\right]+\frac{s}{M_W^2}-2+2\frac{M_W^2}{t}\ , \tag{5}$$

$$E(s,t,u)=\left[\frac{ut}{M_W^4}-1\right]\left[\frac{1}{4}+\frac{M_W^4}{t^2}\right]+\frac{s}{M_W^2}\ .$$

The others are

$$E_1(s,t,u)=\frac{t}{t-M_N^2}E(s,t,u),\quad I_1(s,t,u)=\frac{t}{t-M_N^2}I(s,t,u),\quad E_2(s,t,u)=\left[\frac{t}{t-M_N^2}\right]^2E(s,t,u)\ ,$$

$$E_H(s,t,u)=\left[\frac{t}{t-M_N^2}\right]^2\left[\frac{M_W^2}{t^2}\left[\frac{ut}{M_W^4}-1\right]+\frac{s}{M_W^4}\left[\frac{1}{4}+\frac{M_W^4}{t^2}\right]\right]\ , \tag{6}$$

with

$$\Delta_{Z_{1,2}}=\frac{1}{s-M_{Z_{1,2}}^2} \tag{7}$$

and

$$R_{Z_{1,2}}=\frac{s}{(s-M_{Z_{1,2}}^2)^2+M_{Z_{1,2}}^2\Gamma_{Z_{1,2}}^2}\ . \tag{8}$$

The total cross section is obtained when we integrate (4) from $t_{\rm min}$ to $t_{\rm max}$:

$$t_{\rm min}=M_W^2-\frac{s}{2}(1+\beta),\quad t_{\rm max}=M_W^2-\frac{s}{2}(1-\beta)\ , \tag{9}$$

where β, the W velocity in the center-of-mass frame, is given by

$$\beta=\left[1-\frac{4M_W^2}{s}\right]^{1/2}\ . \tag{10}$$

When we let $s\to\infty$ there remains in the expression for the total cross section a term that is proportional to s and another that is constant in s. To guarantee unitarity we must verify if the coefficients of these terms vanish. In order to see how these coefficients look let us define

$$\mathcal{V}=\frac{e_Z}{e^2}(g_V^{(1)}\cos\theta_M-g_V^{(2)}\sin\theta_M)\ , \tag{11}$$

$$\mathcal{A}=\frac{e_Z}{e^2}(g_A^{(1)}\cos\theta_M-g_A^{(2)}\sin\theta_M)\ . \tag{12}$$

Doing so we get the relations for the linear term,

$$\begin{aligned}L=&(-1+\mathcal{V})^2+\mathcal{A}^2+\left[\frac{G_{VA}^2}{e^2}\right]^2(a_1^4+b_1^4+6a_1^2b_1^2)+\left[\frac{G_{VA}'^2}{e^2}\right]^2(a_2^4+b_2^4+6a_2^2b_2^2)\\&+2\frac{G_{VA}^2}{e^2}[(a_1^2+b_1^2)\mathcal{V}-2a_1b_1\mathcal{A}-(a_1^2+b_1^2)]\\&+2\frac{G_{VA}'^2}{e^2}[(a_2^2+b_2^2)\mathcal{V}-2a_2b_2\mathcal{A}-(a_2^2+b_2^2)]+2\frac{G_{VA}^2}{e^2}\frac{G_{VA}'^2}{e^2}[(a_1^2+b_1^2)(a_2^2+b_2^2)+4a_1b_1a_2b_2]\ ,\end{aligned} \tag{13}$$

and for the constant term,

$$C=\frac{1}{24M_W^2}\left[14[(-1+\mathcal{V})^2+\mathcal{A}^2]+18\left[\frac{G_{VA}^2}{e^2}\right]^2(a_1^4+b_1^4+6a_1^2b_1^2)+\left[\frac{G_{VA}'^2}{e^2}\right]^2(a_2^4+b_2^4+6a_2^2b_2^2)\left[\frac{18M_W^2-6M_N^2}{M_W^2}\right]\right.$$
$$+2\frac{G_{VA}^2}{e^2}\frac{G_{VA}'^2}{e^2}[(a_1^2+b_1^2)(a_2^2+b_2^2)+4a_1b_1a_2b_2]\left[\frac{18M_W^2-3M_N^2}{M_W^2}\right]$$
$$+32\frac{G_{VA}^2}{e^2}[(a_1^2+b_1^2)\mathcal{V}-2a_1b_1\mathcal{A}-(a_1^2+b_1^2)]$$
$$\left.+2\frac{G_{VA}'^2}{e^2}[(a_2^2+b_2^2)\mathcal{V}-2a_2b_2\mathcal{A}-(a_2^2+b_2^2)]\left[\frac{16M_W^2-3M_N^2}{M_W^2}\right]+6\left[\frac{G_{VA}'^2}{e^2}\right]^2(a_2^2-b_2^2)^2\frac{M_N^2}{M_W^2}\right] . \tag{14}$$

We can separate the linear term above in two independent equations:

$$-1+\mathcal{V}+\frac{G_{VA}^2}{e^2}(a_1^2+b_1^2)+\frac{G_{VA}'^2}{e^2}(a_2^2+b_2^2)=0 ,$$
$$\mathcal{A}-2\left[a_1b_1\frac{G_{VA}^2}{e^2}+a_2b_2\frac{G_{VA}'^2}{e^2}\right]=0 . \tag{15}$$

When we substitute these equations in the expression for the coefficient of the constant term we automatically have cancellations among them, except for the term

$$C=\frac{M_N^2}{4M_W^2}(a_2^2-b_2^2)^2 . \tag{16}$$

Let us briefly review the SM case. The γ, Z, ν exchanges cancel naturally the linear and constant contribution to the total cross section. This is a consequence of the renormalizability of the theory. But if terms of order m_e are considered then one must include the Higgs boson exchange in order to recover the exact cancellation. This last point suggests a deeper connection between fermion mass generation and a good unitarity behavior. In the SM one can include Dirac neutrino masses different from zero, which implies mixing between them of $V-A$ type. Here again relations (13) and (14) are identically zero. We can also apply our calculation to light $q\bar{q}\to W^+W^-$ and consider heavy-quark exchange (bottom and top). Here again Eqs. (15) are automatically satisfied and Eq. (16) is also satisfied because of the $V-A$ structure of the Kobayashi-Maskawa mixing. We turn now our attention to extended models.

III. NEW-NEUTRINO EXCHANGE

In practically all the extensions of the SM, we have new fermionic degrees of freedom and in particular new heavy neutrinos. In this section we briefly review some aspects of the most popular extensions which are relevant for our purposes.

A. Vector singlet models (VSM)

The upper experimental bound on neutrino masses of many orders of magnitude smaller than their corresponding charged leptons finds a simple explanation in the seesaw mechanism. Two neutrinos are introduced: one very light and the other very heavy. An elegant realization of this mechanism [5] is given by new heavy neutrino singlets N_L, N_R. New heavy electron singlets E_L, E_R are also included in the model. After rotation we have the parameters

$$g_V=\frac{g}{4\cos\theta_W}(\cos^2\theta_L^e-4\sin^2\theta_W) ,$$
$$g_A=\frac{g}{4\cos\theta_W}(\cos^2\theta_L^e) ,$$
$$a_1=-b_1=\cos\theta_L^e\cos\theta_L^\nu ,$$
$$a_2=-b_2=\cos\theta_L^e\sin\theta_L^\nu , \tag{17}$$

and $G_{VA}=G'_{VA}=g/2\sqrt{2}$.

With these parameters we can easily verify that equations (15) and (16) are automatically satisfied and unitarity is satisfied at the order considered in this paper for arbitrary mixing angles.

B. Fermion–mirror-fermion models (FMF)

The asymmetry between right and left fermion components in the SM can be restored [6] by introducing new fermions with opposite R, L assignments: $(N,E)_R;E_L;N_L$. With the same notation for right and left rotations as in the previous case we have

$$g_V=\frac{g}{4\cos\theta_W}(\cos^2\theta_L^e+\sin^2\theta_R^e-4\sin^2\theta_W) ,$$
$$g_A=\frac{g}{4\cos\theta_W}(\cos^2\theta_L^e-\sin^2\theta_R^e) ,$$
$$a_1=\cos\theta_L^e\cos\theta_L^\nu+\sin\theta_R^e\sin\theta_R^\nu ,$$
$$b_1=\sin\theta_R^e\sin\theta_R^\nu-\cos\theta_L^e\cos\theta_L^\nu ,$$
$$a_2=\cos\theta_L^e\sin\theta_L^\nu-\sin\theta_R^e\cos\theta_R^\nu ,$$
$$b_2=-\cos\theta_L^e\sin\theta_L^\nu-\sin\theta_R^e\cos\theta_R^\nu . \tag{18}$$

Returning to Eqs. (15) and (16), we have two solutions for a good unitarity behavior in first order: $\sin\theta_R^e=0$ and $\sin\theta_L^\nu=0$.

C. Vector doublet models (VDM)

Another possible way to introduce new heavy leptons is through the assignment $\binom{N}{E}_L;\binom{N}{E}_R$. The most usual scenario for this representation is the E_6 superstring model [7]. In this case one can have a low-energy group larger than the standard SU (2)⊗U(1) with new neutral Z^{0}'s. The simple rotation of two Z^0, as done in the beginning of Sec. II, can be easily shown to satisfy the unitarity conditions Eqs. (13) and (14). As will be shown in the next section the Z_2 and N diagrams in $e^+e^- \to W^+W^-$ show significant contributions in different kinematical regions. We consider then the Z_2 and N contributions separately. The new neutrino representation implies

$$\begin{aligned} g_V &= \frac{g}{4\cos\theta_W}(1+\sin^2\theta_R^e - 4\sin^2\theta_W)\ , \\ g_A &= \frac{g}{4\cos\theta_W}(\cos^2\theta_R^e)\ , \\ a_1 &= \cos(\theta_L^\nu - \theta_L^e) + \sin\theta_R^e \sin\theta_R^\nu\ , \\ b_1 &= -\cos(\theta_L^\nu - \theta_L^e) - \sin\theta_R^e \sin\theta_R^\nu\ , \\ a_2 &= \sin(\theta_L^\nu - \theta_L^e) - \sin\theta_R^e \cos\theta_R^\nu\ , \\ b_2 &= -\sin(\theta_L^\nu - \theta_L^e) - \sin\theta_R^e \cos\theta_R^\nu\ . \end{aligned} \tag{19}$$

From Eqs. (15) and (16) we have two solutions: $\theta_L^\nu = \theta_L^e$ and $\sin\theta_R^e = 0$.

IV. RESULTS

The large number of mixing angles which appear in extended models (in addition to the new-lepton masses) make the experimental bounds depend on combinations of angles and masses. In the regions where $M_{L,N} > 45$ GeV these mixing angles can be very large [8]. In this paper we will consider small mixings, all of the order of $\sin^2\theta_i \simeq 0.05$.

Our analysis shows that for arbitrary mixing [see Eq. (16)] unitarity will be violated for heavy neutrinos. A similar result was found in Ref. [9] for a heavy fourth-generation neutrino and implies bounds on M_N in the TeV region.

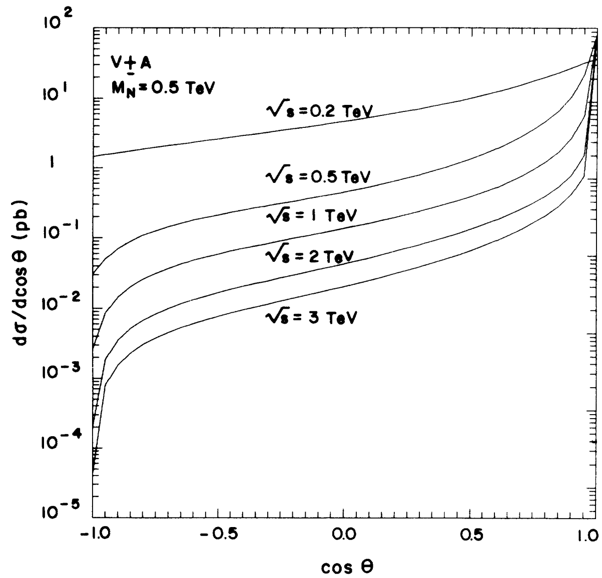

FIG. 3. Angular distribution for $e^+e^- \to W^+W^-$ with $M_N = 0.5$ TeV and the same mixing angle as in Fig. 2.

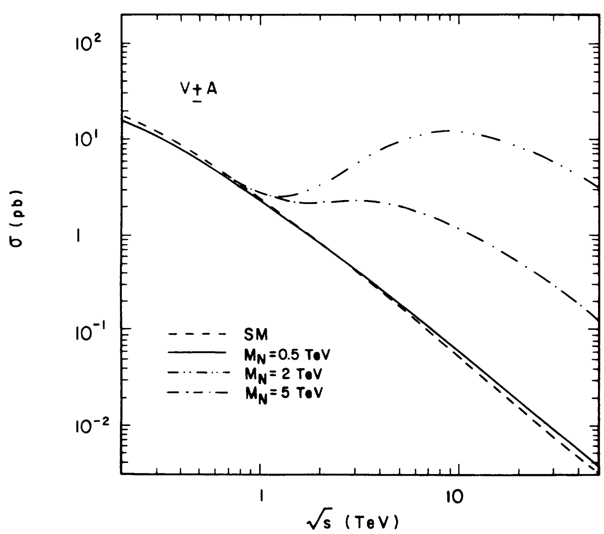

FIG. 2. Total cross section for $e^+e^- \to W^+W^-$, with $M_N = 0.5$, 2, and 5 TeV, and a mixing angle in the neutral sector $\sin^2\theta_i = 0.05$.

Since our perturbative calculation shows an agreement with unitarity for $V \pm A$ couplings, we consider only these two cases. The VSM fits naturally in this situation and the VDM and FMF mixings can be included in both $V \pm A$ cases as shown in the previous section. For these mixings, we have the same total cross section and angular distribution. In Fig. 2–4 the curves represent the tree mixings FMF, VDM, and VSM.

The role of N exchange can be seen in Fig. 2. For a 500-GeV heavy neutrino the total cross section is almost the same as the SM total cross section. This implies that a heavy neutrino exchange in the t channel will be difficult to observe at LEP II energies. The increase in the total cross section is a clear t-channel effect. The

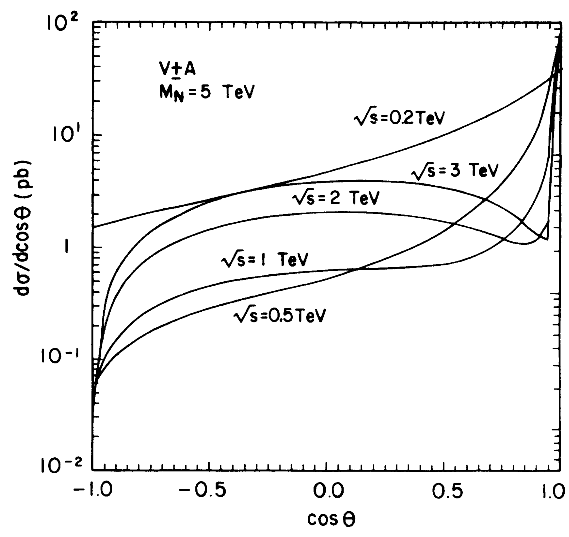

FIG. 4. The same as Fig. 3 but $M_N = 5$ TeV.

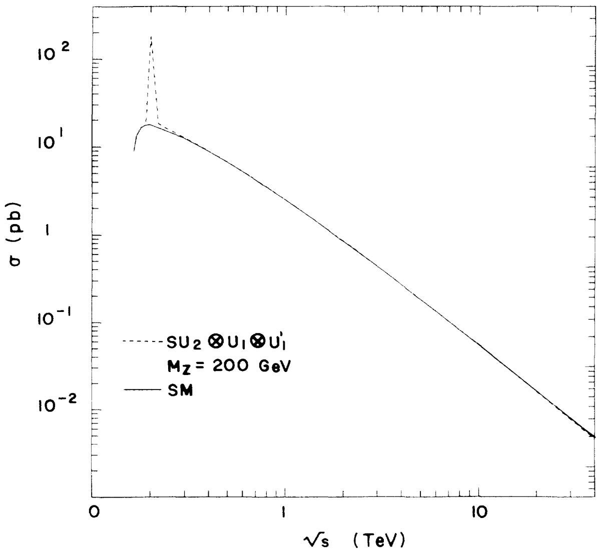

FIG. 5. Total cross section for $e^+e^- \to W^+W^-$ in SU(2)⊗U(1)⊗U′(1). Input parameters: $M_{Z_2}=200$ GeV, $\Gamma_{Z_2}=2$ GeV, and a mixing angle $\sin^2\theta_M=0.01$.

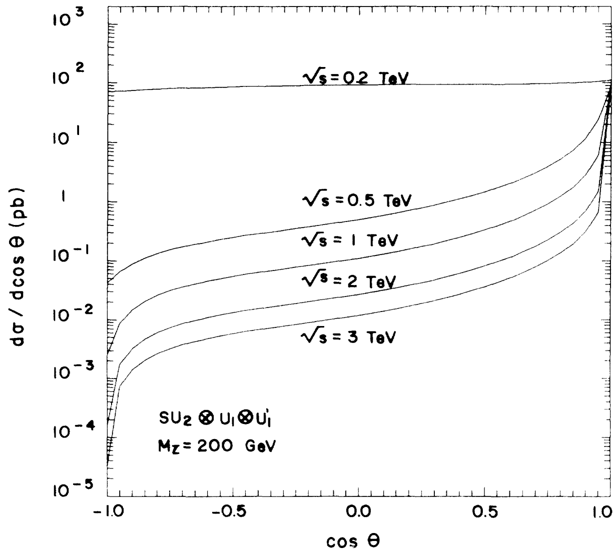

FIG. 6. Angular distribution for $e^+e^- \to W^+W^-$ in SU(2)⊗U(1)⊗U′(1) with the same parameters as in Fig. 5.

"dip" starts to be important for energies higher than 1 TeV and for $M_N > 1$ TeV. For a 2-TeV collider the contribution for masses of 5 TeV are clearly shown.

We stress the fact that these ultraheavy masses are allowed only in the very particular $V \pm A$ situation. Our conclusion agrees with the analysis done for the processes $E^+E^- \to E^+E^-$ and $e^+E^- \to$ boson-boson for the VDM [10] where no mass bounds can be put on the new heavy leptons. This "dip" effect can be employed as a precise mechanism for establishing upper bounds for masses and mixings of possible new heavy neutrinos. In the angular distribution of Fig. 3, when M_N is small the curves falls, but as M_N increases we enter the dip region and the angular distributions show a very characteristic behavior. In Fig. 4 we have a 5-TeV heavy neutrino contribution.

For SU(2)⊗U(1)⊗U′(1) mixing, a possible Z_2 exchange is shown in Fig. 5, it behaves as a peak above the SM and can be easily separated from N exchange. The Z_2 angular distribution is shown in Fig. 6. It shows an increase only at energies around the Z_2 peak.

V. CONCLUSIONS

In this paper we have shown that the first-order calculation for $e^+e^- \to W^+W^-$ satisfies unitarity for a limited class of mixing between neutrinos and heavy neutral leptons. This was the case for vector-doublet models and the fermion-mirror-fermion model. The vector singlet model is well behaved at this level. Following the standard model, our result shows that the mass generation mechanism must be included in order to recover good unitarity behavior.

The other important point that is raised in our work is the possibility of detecting very-high-mass effects of new heavy neutrinos ($M_N \cong 5$ TeV) at e^+e^- colliders in the region of 1–2 TeV. If no contribution of this type is found, our results can be used to show bounds on masses and mixing angles.

ACKNOWLEDGMENTS

This work was supported partially by FAPERJ and CNPq.

[1] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)* edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968); S. L. Glashow, Nucl. Phys. **22**, 579 (1961).

[2] R. W. Brown and K. O. Mikaelian, Phys. Rev. D **19**, 922 (1979); K. Hagiwara *et al.*, Nucl. Phys. **B282**, 253 (1987); G. Barbiellini *et al.*, in *Physics at LEP,* LEP Jamboree, Geneva, Switzerland, 1985, edited by J. Ellis and R. Peccei (CERN Report No. 86-02, Geneva, 1986).

[3] R. Nagima and S. Wakaizumi, Phys. Lett. B **184**, 410 (1987); R. Nagima, Prog. Theor. Phys. **77**, 926 (1987); S. Nandi *et al.*, Phys. Lett. B **188**, 159 (1987).

[4] A. K. Nagawat *et al.*, Phys Rev. D **42**, 2984 (1990).

[5] M. C. Gonzalez-Garcia, A. Santamaria, and J. W. F. Valle, Nucl. Phys. **B342**, 108 (1990).

[6] J. Maalampi and M. Roos, Phys. Rep. C **186**, 53 (1990).

[7] T. G. Rizzo, Phys. Rev. D **34**, 2076 (1986).

[8] P. Langacker and D. London, Phys. Rev. D **38**, 886 (1988).

[9] M. S. Chanowitz, M. A. Furman, and I. Hinchliffe, Nucl. Phys. **B153**, 402 (1979).

[10] D. London, G. Bélanger, and J. N. Ng, Phys. Rev. D **37**, 799 (1988).