Pairs of charged heavy fermions from an $SU(3)_L \otimes U(1)_N$ model at e^+e^- colliders

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We investigate the production, backgrounds, and signatures of pairs of charged heavy fermions using the $SU(3)_L \otimes U(1)_N$ electroweak model in e^+e^- colliders (Next Linear Collider and CERN Linear Collider). We also analyze the indirect evidence for a boson Z'.

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I. INTRODUCTION

Although the standard electroweak model is very successful in explaining experimental data up to order 100 GeV, there are experimental results on the muon anomalous magnetic moment [1] and (solar and atmospheric) neutrinos [2] which suggest no standard interpretation. Some other known experimental facts, such as the proliferation of the fermion generation and their complex pattern of masses and mixing angles, are not predicted in the framework of the standard model. There are no theoretical explanations for the existence of several generations and for the values of the masses. It was established at the CERN e^+e^- collider LEP that the number of light neutrinos is three [3].

Many models, such as composite models [4,5], grand unified theories [6], technicolor models [7], superstring-inspired models [8], and mirror fermions [9], predict the existence of new particles with masses of the scale of 1 TeV. All these models consider the possible existence of a new generation of fermions.

Heavy leptons are usually classified in four types: sequential leptons, paraleptons, ortholeptons, and long-lived penetrating particle [10]. In this work we will study the type of heavy leptons which does not belong to any one mentioned above. Consequently, the existing experimental bounds on heavy-lepton parameters do not apply to them. Particular kinds of heavy leptons considered here are predicted, for instance, by an electroweak model based on the $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (3-3-1 for short) semisimple symmetry group [11]. In this model we have only three generations, differently as we have in most of the heavy-lepton models [12,13]. It is a chiral electroweak model whose left-handed charged heavy leptons, which we denote by $P_a = E$, M, and T, together in association with the ordinary charged leptons and its respective neutrinos, are accommodated in $SU(3)_L$ triplets. So, we will study the production mechanism for these heavy-exotic leptons, together with the exotic quarks and exotic neutrinos, in e^-e^+ colliders such as the Next Linear Collider (NLC) ($\sqrt{s}=500$ GeV) and CERN Linear Collider (CLIC) ($\sqrt{s}=1000$ GeV).

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The outline of this paper is the following. In Sec. II we describe the relevant features of the model. The luminosities of $\gamma\gamma$, γZ, and ZZ for e^-e^+ colliders are given in Sec. III. In Sec. IV we study the production of a pair of exotic lepton. We summarize the results in Sec. V.

II. BASIC FACTS ABOUT THE 3-3-1 HEAVY-LEPTON MODEL

The most interesting feature of this class of models is the occurrence of anomaly cancellations, which is implemented only when the three fermion families are considered together, and not family by family as in the standard model. This implies that the number of families must be a multiple of the color number and, consequently, the 3-3-1 model suggests a route towards the answer of the flavor question [14]. The model has also a great phenomenological interest since the related new physics can be expected in a scale near the Fermi one [15,16].

Let us summarize the most relevant points of the model (for details, see Ref. [11]). The left-handed leptons and quarks transform under the $SU(3)_L$ gauge group as the triplets

$$\psi_{aL} = \begin{pmatrix} \nu_{\ell_a} \\ \ell'_a \\ P'_a \end{pmatrix}_L \sim (\mathbf{3},0), \quad Q_{1L} = \begin{pmatrix} u'_1 \\ d'_1 \\ J_1 \end{pmatrix}_L \sim \left(\mathbf{3},\frac{2}{3}\right),$$

$$Q_{\alpha L} = \begin{pmatrix} J'_\alpha \\ u'_\alpha \\ d'_\alpha \end{pmatrix}_L \sim \left(\mathbf{3}^*,-\frac{1}{3}\right), \tag{1a}$$

where $P'_a = E', M', T'$ are the new leptons, $\ell'_a = e', \mu', \tau'$, and $\alpha = 2, 3$. The J_1 exotic quark carries 5/3 units of elementary electric charge, while J_2 and J_3 carry $-4/3$ each. In Eqs. (1) numbers 0, 2/3, and $-1/3$ are the $U(1)_N$ charges. Each left-handed charged fermion has its right-handed counterpart transforming as a singlet in the presence of the $SU(3)_L$ group, i.e.,

$$\ell'_R \sim (\mathbf{1},-1), \quad P'_R \sim (\mathbf{1},1), \quad U'_R \sim (\mathbf{1},2/3), \tag{1b}$$

$$D'_R \sim (\mathbf{1},-1/3), \quad J_{1R} \sim (\mathbf{1},5/3), \quad J'_{2,3R} \sim (\mathbf{1},-4/3). \tag{1c}$$

We are defining $U=u,c,t$ and $D=d,s,b$. In order to avoid anomalies, one of the quark families must transform in a different way with respect to the two others. In Eqs. (1) all the primed fields are linear combinations of the mass eigenstates. The charge operator is defined by

$$\frac{Q}{e}=\frac{1}{2}(\lambda_3-\sqrt{3}\lambda_8)+N, \tag{2}$$

where λ's are the usual Gell-Mann matrices. We notice, however, that since $Q_{\alpha L}$ in Eqs. (1a) are in antitriplet representation of $SU(3)_L$, the antitriplet representation of the Gell-Mann matrices must also be used in Eq. (2) in order to get the correct electric charge for the quarks of the second and third generations.

The three Higgs scalar triplets

$$\eta=\begin{pmatrix}\eta^0\\ \eta_1^-\\ \eta_2^+\end{pmatrix}\sim(\mathbf{3},0), \quad \rho=\begin{pmatrix}\rho^+\\ \rho^0\\ \rho^{++}\end{pmatrix}\sim(\mathbf{3},1),$$

$$\chi=\begin{pmatrix}\chi^-\\ \chi^{--}\\ \chi^0\end{pmatrix}\sim(\mathbf{3},-1), \tag{3}$$

generate the fermion and gauge boson masses in the model. The neutral scalar fields develop the vacuum expectation values (VEVs) $\langle\eta^0\rangle=v_\eta$, $\langle\rho^0\rangle=v_\rho$, and $\langle\chi^0\rangle=v_\chi$, with $v_\eta^2+v_\rho^2=v_W^2=(246\text{ GeV})^2$. Neutrinos can get their masses from η^0 scalar. A detailed scheme for Majorana mass generation for the neutrinos in this model is given in Ref. [17].

The pattern of symmetry breaking is

$$SU(3)_L\otimes U(1)_N \overset{\langle\chi\rangle}{\longmapsto} SU(2)_L\otimes U(1)_Y \overset{\langle\eta,\rho\rangle}{\longmapsto} U(1)_{em}$$

and so, we can expect $v_\chi \gg v_\eta, v_\rho$. The η and ρ scalar triplets give masses to the ordinary fermions and gauge bosons, while the χ scalar triplet gives masses to the new fermions and new gauge bosons.

Due to the transformation properties of the fermion and the Higgs fields under $SU(3)_L$ [see Eqs. (1) and (3)] the Yukawa interactions in the model are

$$\mathcal{L}_\ell^Y=-G_{ab}\overline{\psi}_{aL}\ell'_{bR}\rho-G'_{ab}\overline{\psi'}_{aL}P'_{bR}\chi+\text{H.c.}, \tag{4a}$$

$$\mathcal{L}_q^Y=\sum_a\Bigg[\overline{Q}_{1L}(G_{1a}U'_{aR}\eta+\tilde{G}_{1a}D'_{aR}\rho) + \sum_\alpha \overline{Q}_{\alpha L}(F_{\alpha a}U'_{aR}\rho^*+\tilde{F}_{\alpha a}D'_{aR}\eta^*)\Bigg] + \sum_{\alpha\beta}F^J_{\alpha\beta}\overline{Q}_{\alpha L}J'_{\beta R}\chi^*+G^J\overline{Q}_{1L}J_{1R}\chi+\text{H. c.} \tag{4b}$$

G's, F's, and $\tilde{F}$'s are Yukawa coupling constants with $a,b=1,2,3$ and $\alpha,\beta=2,3$. The interaction eigenstates, which appear in Eqs. (4), can be transformed into the corresponding physical eigenstates by appropriated rotations. However, since the cross-section calculations imply summation on flavors (see Sec. IV) and the rotation matrix must be unitary, the mixing parameters have no essential effects for our purpose here. So, hereafter we suppress the "prime" notation for the interaction eigenstates.

The gauge bosons consist of an octet $W_\mu^i(i=1,\ldots,8)$ associated with $SU(3)_L$ and a singlet B_μ associated with $U(1)_N$. The covariant derivatives are

$$\mathcal{D}_\mu\varphi_a=\partial_\mu\varphi_a+i\frac{g}{2}(\vec{W}_\mu\cdot\vec{\lambda})_a^b\varphi_b+ig'N_\varphi\varphi_aB_\mu, \tag{5}$$

where $\varphi=\eta,\rho,\chi$. The model predicts single-charged ($V^\pm$), double-charged ($U^{\pm\pm}$) vector bileptons and a new neutral gauge boson (Z') in addition to the charged standard gauge bosons $W^\pm$ and the neutral standard Z. We take from Ref. [15] the trilinear interactions of $Z'(k_1)$ with $V(k_2)^\pm$ and $U^{\pm\pm}(k_3)$, in the usual notation that all the quadrimoments are incoming in the vertex:

$$\mathcal{V}_{\lambda\mu\nu}=-i\frac{g}{2}\sqrt{\frac{3}{1+3t_W^2}}[(k_1-k_2)_\lambda g_{\mu\nu}+(k_2-k_3)_\mu g_{\nu\lambda} + (k_3-k_1)_\nu g_{\lambda\mu}], \tag{6}$$

where

$$t_W^2=\frac{\sin^2\theta_W}{1-4\sin^2\theta_W}. \tag{7}$$

The relevant neutral vector current interactions are

$$\mathcal{L}_Z=-\frac{g}{2\cos\theta_W}[a_L(f)\overline{f}\gamma^\mu(1-\gamma_5)f + a_R(f)\overline{f}\gamma^\mu(1-\gamma_5)f]Z_\mu, \tag{8a}$$

$$\mathcal{L}_{Z'}=-\frac{g}{2\cos\theta_W}[a'_L(f)\overline{f}\gamma^\mu(1-\gamma_5)f + a'_R(f)\overline{f}\gamma^\mu(1-\gamma_5)f]Z'_\mu, \tag{8b}$$

$$\mathcal{L}_{AP}=-e\overline{P}_a\gamma^\mu P_aA_\mu, \tag{8c}$$

$$\mathcal{L}_{ZP}=-g\sin\theta_W\tan\theta_W\overline{P}_a\gamma^\mu P_aZ_\mu, \tag{8d}$$

$$\mathcal{L}_{Z'P}=-\frac{g\tan\theta_W}{2\sqrt{3}t_W}\overline{P}_a\gamma^\mu[3t_W^2-1 + (3t_W^2+1)\gamma_5]P_aZ'_\mu, \tag{8e}$$

$$\mathcal{L}_{Zq}=-\frac{g}{4\cos\theta_W}\sum_a\overline{q}_a\gamma^\mu(v^a+a^a\gamma^5)q_aZ_\mu, \tag{8f}$$

$$\mathcal{L}_{Z'q} = -\frac{g}{4\cos\theta_W}\sum_a \bar{q}_a\gamma^\mu(v'^a + a'^a\gamma^5)q_a Z'_\mu, \tag{8g}$$

where θ_W is the Weinberg mixing angle, f is any fermion and q_a is any quark [11,14]. The coefficients in Eqs. (8a), (8b), (8f), and (8g) are

$$a_L(\nu'_a) = \frac{1}{2}, \quad a_R(\nu_a) = 0,$$

$$a'_L(\nu'_a) = \frac{1}{2}\sqrt{\frac{1-4\sin^2\theta_W}{3}}, \quad a'_R(\nu'_a) = 0, \tag{9a}$$

$$a_L(e'_a) = -\frac{1}{2} + \sin\theta_W, \quad a_R(e'_a) = \sin\theta_W,$$

$$a'_L(e'_a) = a'_L(\nu'_a), \quad a'_R(e'_a) = -\frac{\sin\theta_W}{2a'_L(\nu'_a)}, \tag{9b}$$

$$a_L(E'_a) = a_R(E'_a) = -\sin\theta_W,$$

$$a'_L(E'_a) = -\sqrt{\frac{1-4\sin\theta_W}{3}}, \quad a'_R(E'_a) = -a'_R(e'_a), \tag{9c}$$

$$v^U = \frac{3+4t_W^2}{f(t_W)}, \quad v^D = -\frac{3+8t_W^2}{f(t_W)},$$

$$-a^U = a^D = 1, \quad v'^u = -\frac{1+8t_W^2}{f(t_W)}, \tag{9d}$$

$$v'^c = v'^t = \frac{1-2t_W^2}{f(t_W)}, \quad v'^d = -\frac{1+2t_W^2}{f(t_W)},$$

$$v'^s = v'^b = \frac{f(t_W)}{\sqrt(3}, \quad a'^u = \frac{1}{f(t_W)}, \tag{9e}$$

$$a'^c = a'^t = -\frac{1+6t_W^2}{f(t_W)}, \quad a'^d = -a'^c, \quad a'^s = a'^b$$

$$= -a'^u \quad v'^{J_1} = \frac{2(1-7t_W^2)}{f(t_W)}, \tag{9f}$$

$$v'^{J_2} = v'^{J_3} = -\frac{2(1-5t_W^2)}{f(t_W)}, \quad a'^{J_2} = a'^{J_2} = a'^{J_2}$$

$$= a'^{J_1}$$

$$= -\frac{2(1+3t_W^2)}{f(t_W)}, \tag{9g}$$

with $f^2(t_W) = 3(1+4t_W^2)$. As we have commented in the introduction and by inspection of Eqs. (1), (8d), and (8e), we conclude that the heavy leptons P_a belong to another class of exotic particles different from the heavy-lepton classes usually considered in the literature. Thus, the present experimental limits do not apply directly to them [10] (see also Ref. [11]). Therefore, the 3-3-1 heavy-leptons phenomenology deserves more detailed studies.

III. LUMINOSITIES

Let us now analyze the case of elastic e^-e^+ scattering. The $\gamma\gamma$ differential luminosity is given by

$$\left(\frac{dL^{el}}{d\tau}\right)_{\gamma\gamma/\ell\ell} = \int_\tau^1 \frac{dx_1}{x_1} f_{\gamma/\ell}(x_1) f_{\gamma/\ell}(x_2 = \tau/x_1), \tag{10}$$

where $\tau = x_1x_2$ and $f_{\gamma/\ell}(x)$ is the effective photon approximation for the photon into the lepton, which is defined by

$$f_{\gamma/\ell}(x) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\ln\frac{s}{4m_e^2},$$

where x is the longitudinal momentum fraction of the lepton carried off by the photon, s is the center-of-mass energy of the e^-e^+ pair, and m_e is the electron mass.

The ZZ differential luminosity for elastic e^-e^+ scattering is given by

$$\left(\frac{dL^{el}}{d\tau}\right)_{ZZ/\ell\ell} = \int_\tau^1 \frac{dx_1}{x_1} f_{Z/\ell}(x_1) f_{Z/\ell}(x_2 = \tau/x_1),$$

where $f_{Z/\ell}(x)$ is the distribution function for finding a boson Z of transverse and longitudinal helicities in a fermion with energy $\sqrt{s}$ in the limit $\sqrt{s} \gg 2M_Z$ and which has the following forms:

$$f_{Z/}^{\pm T}\ell(x) = \frac{\alpha}{4\pi x\sin^2\theta_W\cos^2\theta_W}[(g_V\ell \mp g_A\ell)^2 + (g_V\ell \pm g_A\ell)^2(1-x)^2]\ln\frac{s}{M_Z^2},$$

$$f_{Z/}^{L}\ell(x) = \frac{\alpha}{\pi\sin^2\theta_W\cos^2\theta_W}[(g_V\ell)^2 + (g_A\ell)^2]\frac{1-x}{x},$$

where g_V^ℓ and g_A^ℓ are the vector and the axial-vector coupling, respectively.

For the $Z\gamma$ differential luminosity for elastic e^-e^+ scattering we have the expression

$$\left(\frac{dL^{el}}{d\tau}\right)_{Z\gamma/\ell\ell} = \int_\tau^1 \frac{dx_1}{x_1} f_{Z/\ell}(x_1) f_{\gamma/\ell}(x_2 = \tau/x_1).$$

IV. CROSS SECTION PRODUCTION

A. $e^-e^+ \to P^-P^+$

Pair production of exotic particles is, to a very good approximation, a model-independent process, since it proceeds through a well-known electroweak interaction. This production mechanism can be studied through the analysis of the reactions $e^-e^+ \to P^-P^+$, provided that there is enough available energy ($\sqrt{s} \geqslant 2M_P$). We will analyze the following processes for pair production of exotic heavy leptons: $e^-e^+ \to P^-P^+$, $e^-e^+ \to \gamma\gamma \to P^-P^+$, $e^-e^+ \to Z\gamma \to P^-P^+$, and $e^-e^+ \to ZZ \to P^-P^+$, the first process takes place through the exchange of a photon, a boson Z^0 and $Z^{0\prime}$ in the s channel, while the other processes take place through the exchange of heavy lepton in the t and u channels.

Using the interaction Lagrangians (8a), (8b), and (8c), it is easy to evaluate the cross section for the process $e^+e^- \to P^+P^-$, involving a neutral current, from which we obtain

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{P^+P^-} = \frac{\beta\alpha^2\pi}{s^3}\Bigg([2sM_P^2+(M_P^2-t)^2+(M_P^2-u)^2] + \frac{1}{2\sin^2\theta_W\cos^2\theta_W(s-M_{Z,Z'}^2+iM_{Z,Z'}\Gamma_{Z,Z'})}\{2sM_P^2 g'^{PP}_V g_V^\ell + g'^{PP}_V g_V^\ell[(M_P^2-t)^2+(M_P^2-u)^2] + g'^{PP}_A g_A^\ell[(M_P^2-u)^2-(M_P^2-t)^2]\}\Bigg)$$
$$+ \frac{\beta\pi\alpha^2}{16\cos^4\theta_W\sin^4\theta_W}\frac{1}{s(s-M_{Z,Z'}^2+iM_{Z,Z'}\Gamma_{Z,Z'})^2}\{[(g'^{PP}_V)^2+(g'^{PP}_A)^2][(g_V^\ell)^2+(g_A^\ell)^2][(M_P^2-u)^2+(M_P^2-t)^2] + 2sM_P^2[(g'^{PP}_V)^2-(g'^{PP}_A)^2][(g_V^\ell)^2+(g_A^\ell)^2] + 4g'^{PP}_V g'^{PP}_A g_V{}^\ell g_A^\ell[(M_P^2-u)^2-(M_P^2-t)^2]\}$$
$$+ \frac{\beta\pi\alpha^2}{8\sin^4\theta_W\cos^4\theta_W s(s-M_Z^2+iM_Z\Gamma_Z)(s-M_{Z'}^2+iM_{Z'}\Gamma_{Z'})}(2sM_P^2(g_V^\ell+g_A^\ell)(g_V^{PP}g'^{PP}_V - g_A^{PP}g'^{PP}_A) + (M_P^2-t)^2\{[(g_V^\ell)^2+(g_A^\ell)^2]g_V^{PP}g'^{PP}_V + g_A^{PP}g'^{PP}_A - 2g_V{}^\ell g_A{}^\ell g_V^{PP}g'^{PP}_A - 2g_V^\ell g_A^\ell g_A^{PP}g'^{PP}_V\} + (M_P^2-u)^2\{[(g_V^\ell)^2+(g_A^\ell)^2](g_V^{PP}g'^{PP}_V + g_A^{PP}g'^{PP}_A) + 2g_V^\ell g_A^\ell g_V^{PP}g'^{PP}_A + 2g_V^\ell g_A^\ell g_A^{PP}g'^{PP}_V\}), \quad (11)$$

where

$$g_{V,A}^{PP} = \frac{a_L \pm a_R}{2}, \quad g'^{PP}_{V,A} = \frac{a'_L \pm a'_R}{2}.$$

The prime ($'$) is for the case when we take a boson Z', $\Gamma_{Z,Z'}$ are the total width of boson Z and Z' [15], $\beta = \sqrt{1-4M_P^2/s}$ is the velocity of the heavy lepton in the c.m. of the process, α is the fine structure constant, which we take equal to $\alpha = 1/128$, $g_{V,A}^\ell$ are the standard coupling constants, M_Z is the mass of the Z boson, $\sqrt{s}$ is the center of mass energy of the e^-e^+ system, $t = M_P^2 - (1-\beta\cos\theta)s/2$ and $u = M_P^2 - (1+\beta\cos\theta)s/2$, where θ is the angle between the heavy-lepton and the incident electron, in the c.m. frame. For Z' boson we take $M_{Z'} = (0.6-3)$ TeV, since $M_{Z'}$ is proportional to the VEV v_χ [14,18]. For the standard model parameters we assume Particle Data Group (PDG) values, i.e., $M_Z = 91.02$ GeV, $\sin^2\theta_W = 0.2315$, and $M_W = 80.33$ GeV [10]. In Figs. 1 and 2, we show the cross sections $\sigma(e^-e^+ \to P^-P^+)$ for the NLC and the CLIC.

Another way to produce a pair of heavy-exotic leptons is through the elastic reactions of types $e^-e^+ \to \gamma\gamma \to P^-P^+$, $e^-e^+ \to Z\gamma \to P^-P^+$, and $e^-e^+ \to ZZ \to P^-P^+$. These three processes take place through the exchange of the exotic lepton in the t and u channels. So the cross section for the production of a pair of P^-P^+ in the e^-e^+ collision can be obtained by convoluting the cross section for the subprocesses $\gamma\gamma \to P^-P^+$, $Z\gamma \to P^-P^+$, and $ZZ \to P^-P^+$, with the two photon, Zγ and ZZ luminosities in these collisions, that is,

$$\sigma = \int_{\tau_{min}}^1 \frac{dL}{d\tau} d\tau \hat{\sigma}(\hat{s} = x_1x_2s)$$
$$= \int_{\tau_{min}}^1 \int_{\ln\sqrt{(\tau)}}^{-\ln\sqrt{(\tau)}} \frac{dx_1}{x_1} f_{V/\ell}(x_1) f_{V/\ell}(x_2) \int \frac{d\hat{\sigma}}{d\cos\theta} d\cos\theta$$

where $V = \gamma, Z$. The subprocess cross section for two photon P^-P^+ production via elastic collisions of electron-positron is

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{\gamma\gamma} = \frac{\beta\alpha^2\pi}{s}\Bigg(\frac{1}{(t-M_P^2)^2}(-M_P^4 - 3M_P^2 t - M_P^2 u + tu) + \frac{1}{(u-M_P^2)^2}(-M_P^4 - M_P^2 t - 3M_P^2 u + tu) + \frac{2}{(t-M_P^2)(u-M_P^2)}(-2M_P^4 - M_P^2 t - M_P^2 u)\Bigg), \quad (12)$$

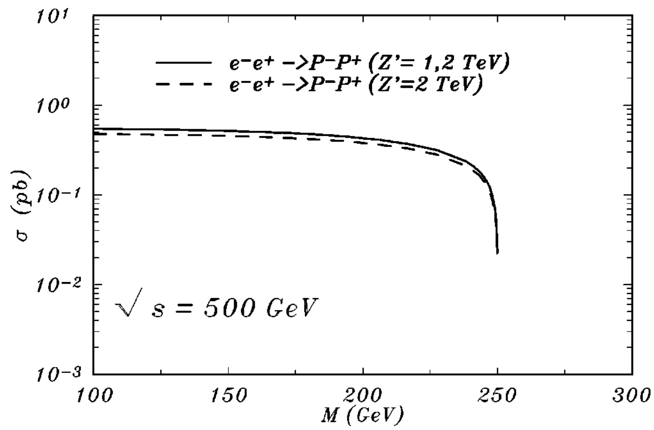

FIG. 1. Total cross section for the process $e^-e^+ \to P^-P^+$ as a function of M_P at $\sqrt{s}=500$ GeV: (a) $M_{Z'}=1200$ GeV (solid line), and (b) 2000 GeV(dashed line).

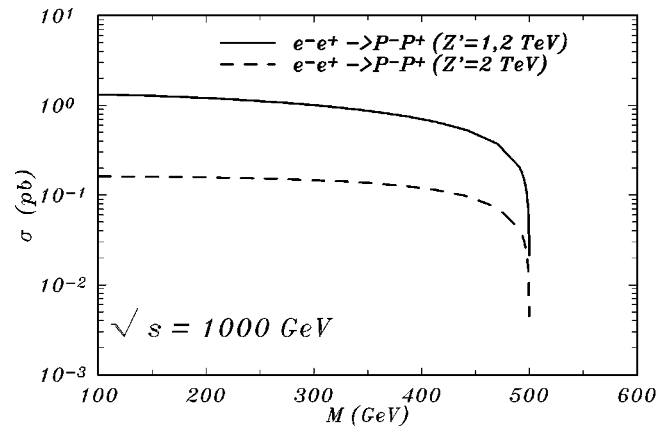

FIG. 2. Total cross section for the process $e^-e^+ \to P^-P^+$ as a function of M_P at $\sqrt{s}=1000$ GeV: (a) $M_{Z'}=1200$ GeV (solid line) and (b) $M_{Z'}=2000$ GeV (dashed line).

where M_P is the mass of the exotic lepton, $\hat{t}=M_P^2-(\hat{s}/2)(1-\beta\cos\theta)$ and $\hat{u}=M_P^2-(\hat{s}/2)(1+\beta\cos\theta)$ refer to the exchanged momenta squared, corresponding to the direct and crossed diagrams for the two photons, with β being the P velocity in the subprocess c.m. and θ its angle with respect to the incident electron in this frame.

The contribution of the subprocess cross sections for $Z\gamma$ and ZZ luminosities to the total cross section can be shown to be very small; therefore, we do not show here the explicit calculation for them, but we present their results in Fig. 3 for the CLIC.

B. $e^-e^+ \to Q\bar{Q}$

The production of exotic quarks was already studied by both of the authors [13,19], so that in this subsection we will restrict its study through the analysis of the reaction $e^-e^+ \to Q\bar{Q}$ in the case that there is enough available energy ($\sqrt{s} \geqslant 2M_Q$). This process takes place through the exchange of a photon, Z and Z' in the s channel.

Using the interaction Lagrangians given in Sec. II, we can evaluate the cross section involving a neutral current to obtain

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{Q\bar{Q}}=\frac{N_c\beta_Q\alpha^2\pi}{s^3}\Bigg(\{c_q^2[2sM_Q^2+(M_Q^2-t)^2+(M_Q^2-u)^2]\}$$
$$+\frac{c_q}{2\sin^2\theta_W\cos^2\theta_W(s-M_{Z,Z'}^2+iM_{Z,Z'}\Gamma_{Z,Z'})}\{2sM_Q^2g'^{Q\bar{Q}}_Vg_V^\ell+g'^{Q\bar{Q}}_Vg_V^\ell[(M_Q^2-t)^2+(M_Q^2-u)^2]$$
$$+g'^{Q\bar{Q}}_Ag_A^\ell[(M_Q^2-u)^2-(M_Q^2-t)^2]\Big\}+\frac{\beta\pi\alpha^2}{16\cos^4\theta_W\sin^4\theta_W}\frac{1}{s(s-M_{Z,Z'}^2+iM_{Z,Z'}\Gamma_{Z,Z'})^2}\{[(g'^{Q\bar{Q}}_V)^2+(g'^{Q\bar{Q}}_A)^2]$$
$$\times[(g_V^\ell)^2+(g_A^\ell)^2][(M_Q^2-u)^2+(M_Q^2-t)^2]+2sM_Q^2[(g'^{Q\bar{Q}}_V)^2-(g'^{Q\bar{Q}}_A)^2][(g_V^\ell)^2+(g_A^\ell)^2]$$
$$+4g'^{Q\bar{Q}}_Vg'^{Q\bar{Q}}_Ag_V^\ell g_A^\ell[(M_Q^2-u)^2-(M_Q^2-t)^2]\}$$
$$+\frac{\beta\pi\alpha^2}{8\sin^4\theta_W\cos^4\theta_W s(s-M_Z^2+iM_Z\Gamma_Z)(s-M_{Z'}^2+iM_{Z'}\Gamma_{Z'})}(2sM_Q^2(g_V^\ell+g_A^\ell)(g_V^{Q\bar{Q}}g'^{Q\bar{Q}}_V-g_A^{Q\bar{Q}}g'^{Q\bar{Q}}_A)+(M_Q^2$$
$$-t)^2\{[(g_V^\ell)^2+(g_A^\ell)^2]g_V^{Q\bar{Q}}g'^{Q\bar{Q}}_V+g_A^{Q\bar{Q}}g'^{Q\bar{Q}}_A-2g_V^\ell g_A^\ell g_V^{Q\bar{Q}}g'^{Q\bar{Q}}_A-2g_V^\ell g_A{}^\ell g_A^{Q\bar{Q}}g'^{Q\bar{Q}}_V\}+(M_Q^2-u)^2\{[(g_V^\ell)^2$$
$$+(g_A^\ell)^2](g_V^{Q\bar{Q}}g'^{Q\bar{Q}}_V+g_A^{Q\bar{Q}}g'^{Q\bar{Q}}_A)+2g_V^\ell g_A^\ell g_V^{Q\bar{Q}}g'^{Q\bar{Q}}_A+2g_V^\ell g_A^\ell g_A^{Q\bar{Q}}g'^{Q\bar{Q}}_V\}), \tag{13}$$

where $\beta_Q=\sqrt{1-4M_Q^2/s}$ is the velocity of the exotic quark in the c.m. of the process, c_q is the charge of the quark, Q is the exotic quark and $\overline{Q}$ the exotic antiquark, $\sqrt{s}$ is the center of mass energy of the e^-e^+ system, $t=M_Q^2-(s/2)(1-\beta\cos\theta)$ and $u=M_Q^2-(s/2)(1+\beta\cos\theta)$, where θ is the angle between the exotic quark and the incident eletron, in the c.m. frame and the couplings g_V^{QQ} and g_A^{QQ} are given in Sec. II.

In order to analyze the indirect evidence for a boson Z', we compute the production of the quarks as in the standard model as in the 3-3-1 model. As a result we find that in the 3-3-1 model at high energies there will be many more dijets than expected in the scope of the standard model. In Fig. 4, we show the result for the cross section $\sigma[e^-e^+\to q\overline{q}(Q\overline{Q})]$ as a function of center of mass energy for different values of the boson mass $M_{Z'}$.

C. $e^-e^+\to N_1N_2$

Given the recent indications of the existence of massive neutrinos, in this section we will also study them. Some examples of the relevance of their study are the deficit of solar electron neutrinos whose flux falls below that predicted by the standard solar model [20], the neutrino oscillations, where the electron neutrinos partially convert to muon neutrinos within the interior of the sun [21] and the need for explications concerning hot dark matter in cosmology [22].

We study the production of massive neutrinos through the analysis of the reaction $e^-e^+\to N_1N_2$. This process takes place through the exchange of the bosons Z,Z' in the s channel. Using the interaction Lagrangians given by Eqs. (8a) and (8b), we evaluate the cross section, obtaining

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{N_1N_2}=\frac{\beta_N\alpha^2\pi}{32s\sin^4\theta_W\cos^4\theta_W}\Bigg(\frac{1}{(s-M_{Z,Z'}^2+iM_{Z,Z'}\Gamma_{Z,Z'})}[2M_N^4(g_V{}^{\ell 2}+g_A^{\ell 2})-2M_N^2t(g_V^\ell-g_A^\ell)^2-2M_N^2u(g_V^\ell+g_A^\ell)^2$$
$$+t^2(g_V^\ell-g_A^\ell)^2+u^2(g_V^\ell+g_A^\ell)^2]+\frac{2}{(s-M_Z^2+iM_Z\Gamma_Z)(s-M_{Z'}^2+iM_{Z'}\Gamma_{Z'})}[2M_N^4(g_V^\ell g_V^{\ell\prime}+g_A^\ell g_A^{\ell\prime})$$
$$-2M_N^2g_V^\ell(g_V^{\ell\prime}-g_A^{\ell\prime})(t-u)+2M_N^2g_A^\ell t(g_V^{\ell\prime}-g_A^{\ell\prime})-2M_N^2g_A^\ell u(g_V^{\ell\prime}+g_A^{\ell\prime})+t^2(g_V^{\ell\prime}-g_A^{\ell\prime})(g_V^\ell-g_A^\ell)$$
$$+u^2(g_V^{\ell\prime}+g_A^{\ell\prime})(g_V^\ell+g_A^\ell)]\Bigg), \tag{14}$$

where $\beta_N=\sqrt{1-4M_N^2/s}$ is the velocity of exotic neutrino in the c.m. of the process and $M_{Z,Z'}$ is the mass of the boson $Z(Z')$.

V. RESULTS AND CONCLUSIONS

In the following we present the cross section for the process $e^+e^-\to P^+P^-,(\overline{Q}Q),(N_1N_2)$ for the NLC and CLIC. In all calculations we take $\sin^2\theta_W$=0.2315, $M_Z=91.188$ GeV, and the mass of the heavy exotic lepton equal to 200 GeV.

In Fig. 1, we show the cross section $\sigma(e^-e^+\to P^-P^+)$ as a function of M_P. Taking into account that the expected integrated luminosity for the NLC will be of the order of 6×10^4 pb^{-1}/yr, there will be a total of $\simeq2.5\times10^4$ heavy-exotic lepton pairs produced per year, considering $M_Z'=1200$ GeV, while for $M_{Z'}=2000$ GeV the production will be of the order of 2.2×10^4.

In Fig. 2, taking into account that the integrated luminosity for the CLIC will be of the order of 2×10^5 pb^{-1}/yr, then the statistics that we can expect for this collider is a little larger. So for the process $e^-e^+\to P^-P^+$, considering the mass of the boson Z' equal to 1200 GeV, we will have a total of $\simeq2\times10^5$ lepton pairs produced per year, while for $M_{Z'}=2000$ GeV the production will be $\simeq3\times10^4$. For both Figs. 1 and 2 we considered $M_{J_1}=300$ GeV, $M_{J_2}=400$ GeV, $M_{J_3}=600$ GeV, and $M_V=800$ GeV.

In Fig. 3, we show the pair production of exotic heavy leptons through the elastic reactions, so the statistics that we

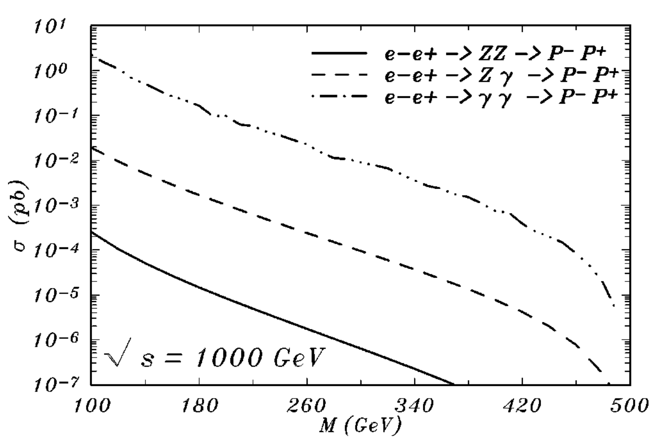

FIG. 3. Total cross section for the process $e^-e^+\to P^-P^+$ as a function of M_P at $\sqrt{s}=1000$ GeV for different elastic production mechanisms: (a) $\gamma\gamma$ (dot-dot-dashed line), (b) $Z\gamma$ (dashed line), (c) ZZ (solid).

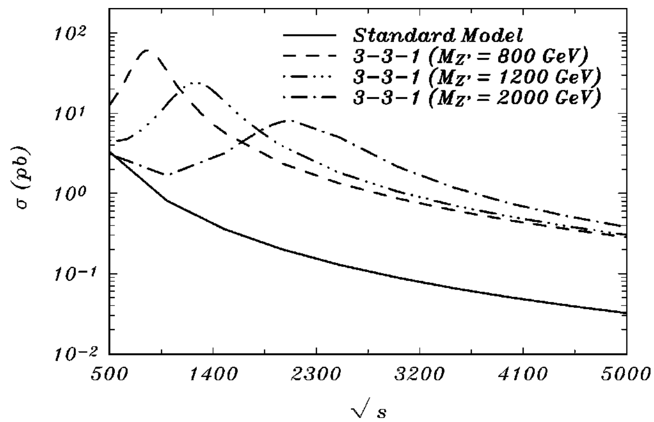

FIG. 4. Total cross section vs the total c.m. energy $\sqrt{s}$ for the following masses of the gauge boson Z': (a) $M_{Z'}=800$ GeV (dashed line), (b) $M_{Z'}=1200$ GeV (dot-dot-dashed line), (c) $M_{Z'}=2000$ GeV (dot-dashed line), (d) standard model (solid line).

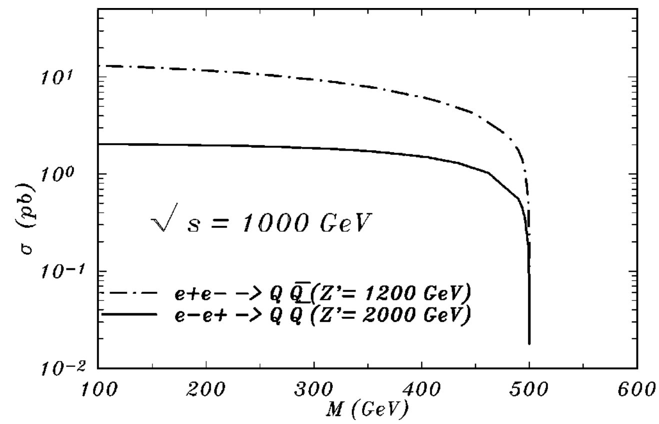

FIG. 6. Total cross section for the process $e^-e^+\to Q\bar{Q}$ as a function of M_Q at $\sqrt{s}=1000$ GeV: (a) $M_{Z'}=1200$ GeV (dot-dashed line), (b) $M_{Z'}=2000$ GeV (solid line).

can expect for the CLIC collider, for photon-photon P^-P^+ production, will be of the order of $\simeq 2\times 10^4$ lepton pairs produced per year, while for $Z\gamma$ the production will be of $\simeq 200$ events per year and for ZZ it will be very small. It should be noted that here we have taken only the transverse helicity of the boson Z, since the longitudinal one gives a small contribution.

In Fig. 4, we compare the standard cross section $\sigma(e^-e^+\to q\bar{q})$ with the production cross section $\sigma(e^-e^+\to q\bar{q}+Q\bar{Q})$, when the 3-3-1 model is applied. We see from these results that using the 3-3-1 model we will have more dijets than using the standard model at high energies. This figure was obtained imposing the cut $|\cos\theta|<0.95$ and assuming three bosons Z' with masses equal to 800, 1200, and 2000 GeV. This figure still show the resonance peaks associated with the boson Z'. We have also considered for this figure $M_{J_1}=200$ GeV, $M_{J_2}=220$ GeV, $M_{J_3}=245$ GeV, whose masses would be accessible to the NLC.

In Figs. 5 and 6 we show the cross sections for the production of exotic quarks $e^+e^-\to\bar{Q}Q$, in the colliders NLC and CLIC. We see from these results that we can expect for the first collider a total of $\simeq 3.6\times 10^5$ heavy quark pairs produced per year, considering the mass of the boson Z' equal to 1.2 and 2 TeV. We see that the cross section for both masses of the boson Z' is not different from one another. For the second collider, the CLIC, we expect a total of $\simeq 2.4\times 10^6$ exotic quarks for the mass of the boson Z' equal to 1.2 TeV, while for $M'_Z=2$ TeV we obtain 4×10^5 events per year. Here the cross sections are different from one another, which is not the case for the NLC; this is due to the propagator, that for the CLIC is larger than for the NLC.

In Figs. 7 and 8 we show the cross sections for the production of exotic neutrinos, $e^+e^-\to N_1N_2$, in the colliders NLC and CLIC. We see from these results that we can expect, in the NLC, a total of around 1.5×10^3 heavy neutrino pairs produced per year for the mass of the boson Z' equal to 1.2 TeV, while for the mass equal to $M'_Z=2$ TeV, the total of events is 1.3×10^3. We see that the cross sections are nearly equal. We also have that the CLIC can produce a total of 2×10^4 pairs of exotic neutrinos for the mass of the boson Z' equal to 1200 GeV, while for $M'_Z=2$ TeV the number of events will be 5.8×10^3. The discrepancy between these

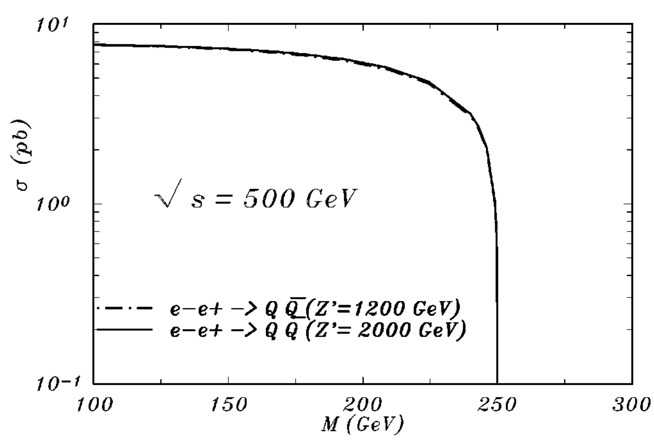

FIG. 5. Total cross section for the process $e^-e^+\to Q\bar{Q}$ as a function of M_Q at $\sqrt{s}=500$ GeV: (a) $M_{Z'}=1200$ GeV (dot-dashed line), (b) $M_{Z'}=2000$ GeV (solid line).

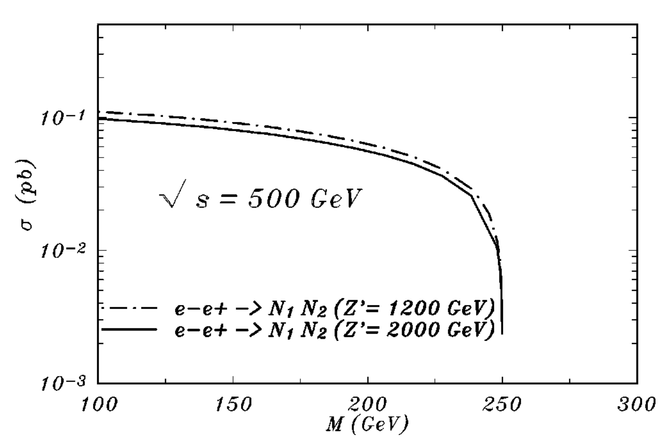

FIG. 7. Total cross section for the process $e^-e^+\to N_1N_2$ as a function of M_N at $\sqrt{s}=500$ GeV: (a) $M_{Z'}=1200$ GeV (dot-dashed line), (b) $M_{Z'}=2000$ GeV (solid line).

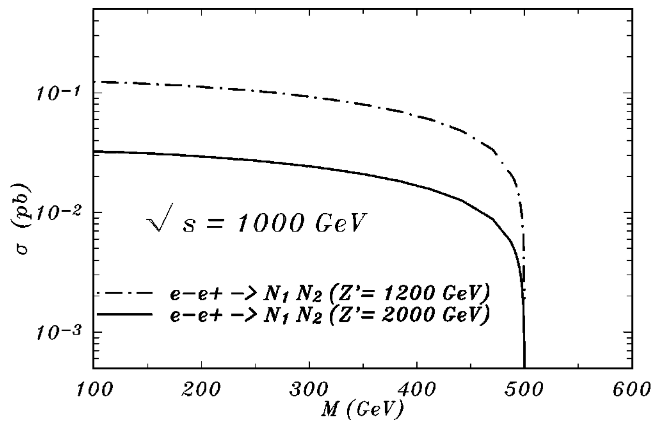

FIG. 8. Total cross section for the process $e^-e^+\to N_1N_2$ as a function of M_N at $\sqrt{s}=1000$ GeV: (a) $M_{Z'}=1200$ GeV (dot-dashed line), (b) $M_{Z'}=2000$ GeV (solid line).

cross sections in both colliders has the same reason as above. Here, for both figures, we considered $M_{J_1}=300$ GeV, $M_{J_2}=400$ GeV, $M_{J_3}=600$ GeV, and $M_V=800$ GeV.

The main background for the signal, $e^-e^+\to P^-P^+\to\overline{\nu u}J_1(\nu\overline{uJ_1})$, can be found, e.g., in Ref. [15]. The backgrounds for the signal, $e^-e^+\to Q\overline{Q}\to q\ell^-\ell^-(\overline{q}\ell^+\ell^+)$, are shown in Ref. [19], and the backgrounds for heavy neutrinos are determined in Ref. [23]. Here it is to remark that even so a detailed simulation of Monte Carlo must be done in all cases to extract the signal from the background, due to the possibility of production of additional jets, the balances of energy that may occur if the missing energy may be averaged out, and other small backgrounds, for example, for the signal $q\ell^-\ell^-(\overline{q}\ell^+\ell^+)$, such as HZZ, WZZ, and $q\overline{q}ZZ$.

In summary, we have shown in this work that in the context of the 3-3-1 model the signatures for heavy fermions can be significant in both the NLC and in the CLIC colliders. Our study indicates the possibility of obtaining a clear signal of these new particles with a satisfactory number of events.

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[1] Muon $(g-2)$ Collaboration, H.N. Brown *et al.*, Phys. Rev. Lett. **86**, 2227 (2001).
[2] SAGE Collaboration, J.N. Abdurashitov *et al.*, Phys. Rev. C **60**, 055801 (1999); Phys. Rev. Lett. **77**, 4708 (1996); GALLEX Collaboration, W. Hampel *et al.*, Phys. Lett. B **477**, 127 (1999); Super Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2644 (1999); **81**, 1562 (1998); Homestake Collaboration, B.T. Cleveland *et al.*, Astrophys. J. **496**, 505 (1998); LNSD Collaboration, C. Athanassopoulos *et al.*, Phys. Rev. Lett. **81**, 1774 (1998); **77**, 3082 (1996); Kamiokande Collaboration, Y. Fukuda *et al.*, *ibid.* **77**, 1683 (1996).
[3] The LEP Collaborations, ALEPH, DELPHI, L3, and OPAL, Phys. Lett. B **B276**, 247 (1992).
[4] L. Abbot and E. Farhi, Phys. Lett. B **101**, 69 (1981); Nucl. Phys. **B189**, 547 (1981).
[5] For a review see W. Buchmüller, Acta Phys. Austriaca, Suppl. **XXVII**, 517 (1985).
[6] See, e.g., P. Langacker, Phys. Rep. **72**, 185 (1981).
[7] S. Dimopoulos, Nucl. Phys. **B168**, 69 (1981); E. Farhi and L. Susskind, Phys. Rev. D **20**, 3404 (1979); J. Ellis *et al.*, Nucl. Phys. **B182**, 529 (1981).
[8] J.L. Hewett and T.G. Rizzo, Phys. Rep. **183**, 193 (1989).
[9] J. Maalampi, K. Mursula, and M. Roos, Nucl. Phys. **B207**, 233 (1982).
[10] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).
[11] V. Pleitez and M.D. Tonasse, Phys. Rev. D **48**, 2353 (1993); M.D. Tonasse, Phys. Lett. B **381**, 191 (1996).
[12] P.H. Frampton, P.Q. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000); K. Cheung, R.J.N. Phillips, and A. Pilaftsis, Phys. Rev. D **51**, 4731 (1995).
[13] J.E. Cieza Montalvo, Phys. Rev. D **59**, 095007 (1999).
[14] F. Pisano and V. Pleitez, Phys. Rev. D **46**, 410 (1992); R. Foot, O.F. Hernandez, F. Pisano, and V. Pleitez, *ibid.* **47**, 4158 (1993).
[15] J.E. Cieza Montalvo and M.D. Tonasse, Nucl. Phys. **B623**, 325 (2002).
[16] B. Dion, T. Grégoire, D. London, L. Marleau, and H. Nadeau, Phys. Rev. D **59**, 075006 (1999); F. Cuypers and S. Davison, Eur. Phys. J. C **2**, 503 (1998), and references cited therein.
[17] Y. Okamoto and M. Yasué, Phys. Lett. B **466**, 267 (1999).
[18] P.H. Frampton, Phys. Rev. Lett. **69**, 2889 (1992).
[19] Y.A. Coutinho, P.P. Queiroz Filho, and M.D. Tonasse, Phys. Rev. D **60**, 115001 (1999); J.E. Cieza Montalvo and P.P. de Queiroz Filho, Int. J. Mod. Phys. A **17**, 4133 (2002).
[20] J.N. Bahcall *et al.*, Rev. Mod. Phys. **54**, 767 (1982).
[21] S.P. Mikheyev and A.Y. Smirnov, Yad. Fiz. **42**, 1441 (1985), [Sov. J. Nucl. Phys. **42**, 913 (1986)]; L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
[22] D.O. Caldwell and R.N. Mohapatra, Phys. Rev. D **48**, 3259 (1993).
[23] F.M.L. Almeida, Jr., Y.A. Coutinho, J.A.M. Simões, and P.P. Queiroz Filho, Phys. Lett. B **400**, 331 (1997); F.M.L. Almeida, Jr., Y.A. Coutinho, J.A.M. Simões, and M.A.B. do Vale, Phys. Rev. D **62**, 075004 (2000).