SINGLE Z' PRODUCTION AT COMPACT LINEAR COLLIDER BASED ON e–γ COLLISIONS

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Submitted 10 October 2003

We analyze the potential of the compact linear collider (CLIC) based on e–γ collisions to search for the new Z' gauge boson. Single Z' production at e–γ colliders in two $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ models, the minimal model and the model with right-handed neutrinos is studied in detail. The results show that new Z' gauge bosons can be observed at the CLIC and that the cross sections in the model with right-handed neutrinos are bigger than those in the minimal one.

PACS: 12.10.-g, 12.60.-i, 13.10.+q, 14.80.-j

1. INTRODUCTION

Neutral gauge structures beyond the photon and the Z boson have long been considered as one of the best motivated extensions of the Standard Model of electroweak interactions. They are predicted in many models going beyond the Standard Model. These include the models based on the $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (3–3–1) gauge group [1–5]. These models have some interesting characteristics. First, they predict three families of quarks and leptons if the QCD asymptotic freedom is imposed. Second, the Peccei–Quinn symmetry naturally occurs in these models [6]. Finally, the characteristic of these models is that one generation of quarks is treated differently from the other two. This could lead to a natural explanation for the unbalancing heavy top quark.

The Z' gauge boson is a necessary element of the different models extending the Standard Model. In general, the extra Z' boson may not couple in a universal way. There are, however, strong constraints from flavor-changing neutral current processes specifically limiting the nonuniversality between the first two generations. Lower bounds on the mass of Z' following from the analysis of a variety of popular models are found to be in the energy range 500–2000 GeV [7, 8].

It was suggested recently that the 3–3–1 models arise naturally from the gauge theories in space–time with extra dimensions [9] where the scalar fields are the components in additional dimensions [10]. A few different versions of the 3–3–1 model have been proposed [11].

Recent investigations have indicated that signals of new gauge bosons in models may be observed at the CERN large hadron collider [12] or the next linear collider [13, 14]. In [15], two of us have considered single production of the bilepton and shown that several thousand events are expected at the integrated luminosity $L \approx 9 \cdot 10^4$ fb^{-1}. In this work, single production of the new Z' gauge boson in the 3–3–1 models is considered. The paper is organized as follows. In Sec. 2, we give a brief review of two models: relation among real physical bosons and constraints on their masses. Section 3 is devoted to single production of the Z' boson in the e–γ collisions. Discussions are given in Sec. 4.

2. A REVIEW OF THE 3–3–1 MODELS

To frame the context, it is appropriate to briefly recall some relevant features of the two types of 3–

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3–1 models: the minimal model proposed by Pisano, Pleitez, and Frampton [1, 2] and the model with right-handed neutrinos [4, 5].

2.1. The minimal 3–3–1 model

The model treats the leptons as the $SU(3)_L$ antitriplets [1, 2, 16][1)],

$$f_{aL} = \begin{pmatrix} e_{aL} \\ -\nu_{aL} \\ (e^c)_a \end{pmatrix} \approx (1, \bar{3}, 0), \tag{1}$$

where $a = 1, 2, 3$ is the generation index. Two of the three quark generations transform as triplets and the third generation is treated differently. It belongs to an antitriplet,

$$Q_{iL} = \begin{pmatrix} u_{iL} \\ d_{iL} \\ D_{iL} \end{pmatrix} \approx \left(3, 3, -\frac{1}{3}\right), \tag{2}$$

$$u_{iR} \approx (3, 1, 2/3), \quad d_{iR} \approx (3, 1, -1/3),$$
$$D_{iR} \approx (3, 1, -1/3), \quad i = 1, 2,$$

$$Q_{3L} = \begin{pmatrix} d_{3L} \\ -u_{3L} \\ T_L \end{pmatrix} \approx (3, \bar{3}, 2/3), \tag{3}$$

$$u_{3R} \approx (3, 1, 2/3), \quad d_{3R} \approx (3, 1, -1/3),$$
$$T_R \approx (3, 1, 2/3).$$

The nine gauge bosons $W^a (a = 1, 2, \ldots, 8)$ and B of $SU(3)_L$ and $U(1)_N$ are split into four light gauge bosons and five heavy gauge bosons after $SU(3)_L \otimes U(1)_N$ is broken to $U(1)_Q$. The light gauge bosons are those of the Standard Model: the photon (A), Z_1, and $W^\pm$. The remaining five correspond to new heavy gauge bosons Z_2, $Y^\pm$ and doubly charged bileptons $X^{\pm\pm}$. They are expressed in terms of W^a and B as [16]

$$\sqrt{2}\, W^+_\mu = W^1_\mu - iW^2_\mu, \quad \sqrt{2}\, Y^+_\mu = W^6_\mu - iW^7_\mu,$$
$$\sqrt{2}\, X^{++}_\mu = W^4_\mu - iW^5_\mu. \tag{4}$$

$$A_\mu = s_W W^3_\mu + c_W \left(\sqrt{3}\, t_W\; W^8_\mu + \sqrt{1-3\, t^2_W}\; B_\mu\right),$$
$$Z_\mu = c_W W^3_\mu - s_W \left(\sqrt{3}\, t_W\; W^8_\mu + \sqrt{1-3\, t^2_W}\; B_\mu\right), \tag{5}$$
$$Z'_\mu = -\sqrt{1-3\, t^2_W}\; W^8_\mu + \sqrt{3}\, t_W\; B_\mu,$$

where we use the notation

$$c_W \equiv \cos\theta_W, \quad s_W \equiv \sin\theta_W, \quad t_W \equiv \operatorname{tg}\theta_W.$$

The physical states are a mixture of Z and Z',

$$Z_1 = Z\cos\phi - Z'\sin\phi,$$
$$Z_2 = Z\sin\phi + Z'\cos\phi,$$

where ϕ is the mixing angle.

Symmetry breaking and fermion mass generation can be achieved by three scalar $SU(3)_L$ triplets Φ, Δ, Δ' and a sextet η,

$$\Phi = \begin{pmatrix} \phi^{++} \\ \phi^+ \\ \phi'^0 \end{pmatrix} \approx (1, 3, 1),$$

$$\Delta = \begin{pmatrix} \Delta^+_1 \\ \Delta^0 \\ \Delta^-_2 \end{pmatrix} \approx (1, 3, 0),$$

$$\Delta' = \begin{pmatrix} \Delta'^0 \\ \Delta'^- \\ \Delta'^{--} \end{pmatrix} \approx (1, 3, -1),$$

$$\eta = \begin{pmatrix} \eta^{++}_1 & \eta^+_1/\sqrt{2} & \eta^0/\sqrt{2} \\ \eta^+_1/\sqrt{2} & \eta'^0 & \eta^-_2/\sqrt{2} \\ \eta^0/\sqrt{2} & \eta^-_2/\sqrt{2} & \eta^{--}_2 \end{pmatrix} \approx (1, 6, 0).$$

The sextet η is necessary to give masses to charged leptons [3, 16]. The vacuum expectation value

$$\langle \Phi^T \rangle = (0, 0, u/\sqrt{2})$$

yields masses for the exotic quarks, the heavy neutral gauge boson Z', and two new charged gauge bosons X^{++}, Y^+. The masses of the standard gauge bosons and the ordinary fermions are related to the vacuum expectation values of the other scalar fields,

$$\langle \Delta^0 \rangle = v/\sqrt{2}, \quad \langle \Delta'^0 \rangle = v'/\sqrt{2},$$
$$\langle \eta^0 \rangle = \omega/\sqrt{2}, \quad \langle \eta'^0 \rangle = 0.$$

For consistency with the low-energy phenomenology, the mass scale of $SU(3)_L \otimes U(1)_N$ breaking must be much larger than that of the electroweak scale, i.e, $u \gg v, v', \omega$. The masses of gauge bosons are explicitly given by

$$m^2_W = \frac{1}{4} g^2 (v^2 + v'^2 + \omega^2),$$
$$M^2_Y = \frac{1}{4} g^2 (u^2 + v^2 + \omega^2), \tag{6}$$
$$M^2_X = \frac{1}{4} g^2 (u^2 + v'^2 + 4\omega^2),$$

1) The leptons may be assigned to a triplet as in [1]; the two models are mathematically identical, however.

and

$$m_Z^2 = \frac{g^2}{4c_W^2}(v^2 + v'^2 + \omega^2) = \frac{m_W^2}{c_W^2},$$
$$M_{Z'}^2 = \frac{g^2}{3}\left[\frac{c_W^2}{1-4s_W^2}u^2 + \right. \qquad (7)$$
$$\left. + \frac{1-4s_W^2}{4c_W^2}(v^2+v'^2+\omega^2) + \frac{3s_W^2}{1-4s_W^2}v'^2\right].$$

Expressions in (6) yield a splitting between the bilepton masses [17],

$$|M_X^2 - M_Y^2| \le 3\, m_W^2. \qquad (8)$$

Combining the constraints from direct searches and neutral currents, we obtain the range for the mixing angle [16] as

$$-1.6 \cdot 10^{-2} \le \phi \le 7 \cdot 10^{-4}$$

and a lower bound on M_{Z_2},

$$M_{Z_2} \ge 1.3 \text{ TeV}.$$

Such a small mixing angle can safely be neglected. In that case, Z_1 and Z_2 are the Z boson in the Standard Model and the extra Z' gauge boson, respectively. With the new atomic parity violation in cesium, we obtain a lower bound for the Z_2 mass [18]:

$$M_{Z_2} > 1.2 \text{ TeV}.$$

2.2. The model with right-handed neutrinos

In this model, the leptons are in triplets and the third member is a right-handed neutrino [4, 5],

$$f_{aL} = \begin{pmatrix} \nu_{aL} \\ e_{aL} \\ (\nu_L^c)_a \end{pmatrix} \approx (1, 3, -1/3), \qquad (9)$$
$$e_{aR} \approx (1, 1, -1).$$

The first two generations of quarks are in antitriplets and the third one is in a triplet,

$$Q_{iL} = \begin{pmatrix} d_{iL} \\ -u_{iL} \\ D_{iL} \end{pmatrix} \approx (3, \bar{3}, 0), \qquad (10)$$

$$u_{iR} \approx (3, 1, 2/3), \quad d_{iR} \approx (3, 1, -1/3),$$
$$D_{iR} \approx (3, 1, -1/3), \quad i = 1, 2,$$

$$Q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \\ T_L \end{pmatrix} \approx (3, 3, 1/3), \qquad (11)$$

$$u_{3R} \approx (3, 1, 2/3), \quad d_{3R} \approx (3, 1, -1/3),$$
$$T_R \approx (3, 1, 2/3).$$

The doubly charged bileptons of the minimal model are here replaced by complex neutral ones as

$$\sqrt{2}\, W_\mu^+ = W_\mu^1 - iW_\mu^2, \quad \sqrt{2}\, Y_\mu^- = W_\mu^6 - iW_\mu^7,$$
$$\sqrt{2}\, X_\mu^0 = W_\mu^4 - iW_\mu^5. \qquad (12)$$

The physical neutral gauge bosons are again related to Z and Z' through the mixing angle ϕ. Together with the photon, they are defined as [5]

$$A_\mu = s_W W_\mu^3 + c_W\left(-\frac{t_W}{\sqrt{3}}\, W_\mu^8 + \sqrt{1 - \frac{t_W^2}{3}}\, B_\mu\right),$$
$$Z_\mu = c_W W_\mu^3 - s_W\left(-\frac{t_W}{\sqrt{3}}\, W_\mu^8 + \sqrt{1 - \frac{t_W^2}{3}}\, B_\mu\right), \qquad (13)$$
$$Z'_\mu = \sqrt{1 - \frac{t_W^2}{3}}\, W_\mu^8 + \frac{t_W}{\sqrt{3}}\, B_\mu.$$

Symmetry breaking can be achieved with just three $SU(3)_L$ triplets,

$$\chi = \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi'^0 \end{pmatrix} \approx (1, 3, -1/3), \qquad (14)$$

$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho'^+ \end{pmatrix} \approx (1, 3, 2/3), \qquad (15)$$

$$\eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta'^0 \end{pmatrix} \approx (1, 3, -1/3). \qquad (16)$$

The necessary vacuum expectation values are

$$\langle\chi\rangle^T = (0, 0, \omega/\sqrt{2}), \quad \langle\rho\rangle^T = (0, u/\sqrt{2}, 0),$$
$$\langle\eta\rangle^T = (v/\sqrt{2}, 0, 0). \qquad (17)$$

The vacuum expectation value $\langle\chi\rangle$ generates masses for the exotic 2/3 and –1/3 quarks, while the values $\langle\rho\rangle$ and $\langle\eta\rangle$ generate masses for all ordinary leptons and quarks. After symmetry breaking, the gauge bosons gain masses as

$$m_W^2 = \frac{1}{4}g^2(u^2 + v^2), \quad M_Y^2 = \frac{1}{4}g^2(v^2 + \omega^2),$$
$$M_X^2 = \frac{1}{4}g^2(u^2 + \omega^2), \qquad (18)$$

and

$$m_Z^2 = \frac{g^2}{4c_W^2}(u^2+v^2) = \frac{m_W^2}{c_W^2}, \qquad (19)$$

$$M_{Z'}^2 = \frac{g^2}{4(3-4s_W^2)}\left[4\omega^2 + \frac{u^2}{c_W^2} + \frac{v^2(1-2s_W^2)^2}{c_W^2}\right]. \qquad (20)$$

To be consistent with the low-energy phenomenology, we have to assume that $\langle\chi\rangle \gg \langle\rho\rangle, \langle\eta\rangle$, such that $m_W \ll M_X, M_Y$.

The symmetry-breaking hierarchy gives us a splitting between the bilepton masses [19]

$$|M_X^2 - M_Y^2| \le m_W^2. \qquad (21)$$

It is therefore acceptable to put $M_X \approx M_Y$.

The constraint on the $Z - Z'$ mixing based on the Z decay is given in [5],

$$-2.8\cdot10^{-3} \le \phi \le 1.8\cdot10^{-4};$$

in this model, we do not have a limit for $\sin^2\theta_W$. With this small mixing angle, Z_1 and Z_2 are the Z boson in the Standard Model and the extra Z' gauge boson, respectively. From the data on parity violation in the cesium atom, we obtain a lower bound on the Z_2 mass in the range between 1.4 TeV and 2.6 TeV [18]. Data on the kaon mass difference Δm_K gives the bound $M_{Z_2} \le 1.02$ TeV [8].

3. Z' PRODUCTION IN e–γ COLLISIONS

Now we are interested in the single production of new neutral gauge bosons Z' in e–γ collisions,

$$e^-(p_1,\lambda) + \gamma(p_2,\lambda') \to e^-(k_1,\tau) + Z'(k_2,\tau'), \qquad (22)$$

where p_i and k_i are the momenta and λ, λ', τ, and τ' are the helicities of the particles. At the tree level, there are two Feynman diagrams contributing to reaction (22), depicted in Fig. 1 The s-channel amplitude is given by

$$M_s^{Z'} = \frac{ieg}{2c_W q_s^2}\epsilon_\mu(p_2)\epsilon_\nu(k_2)\overline{u}(k_1)\times \\ \times\gamma^\nu[g_{2V}(e) - g_{2A}(e)\gamma_5]\not{q}_s\gamma^\mu u(p_1), \qquad (23)$$

where $q_s = p_1 + p_2$. The u-channel amplitude is

$$M_u^{Z'} = \frac{ieg}{2c_W q_u^2}\epsilon_\mu(k_2)\epsilon_\nu(p_2)\overline{u}(k_1)\gamma^\nu\not{q}_u\times \\ \times\gamma^\mu[g_{2V}(e) - g_{2A}(e)\gamma_5]u(p_1), \qquad (24)$$

where $q_u = p_1 - k_2$; $\epsilon_\mu(p_2)$, $\epsilon_\nu(p_2)$ and $\epsilon_\nu(k_2)$, $\epsilon_\mu(k_2)$ are the respective polarization vectors of the photon γ and the Z' boson, and $g_{2V}(e)$, $g_{2A}(e)$ are the coupling constants of Z' to the electron e. In the minimal model, they are given by [16]

$$g_{2V}(e) = \frac{\sqrt{3}}{2}\sqrt{1-4s_W^2}, \\ g_{2A}(e) = -\frac{1}{2\sqrt{3}}\sqrt{1-4s_W^2}, \qquad (25)$$

and in the model with right-handed neutrinos [5],

$$g_{2V}(e) = \left(-\frac{1}{2}+2s_W^2\right)\frac{1}{\sqrt{3-4s_W^2}}, \\ g_{2A}(e) = \frac{1}{2\sqrt{3-4s_W^2}}. \qquad (26)$$

From Eqs. (25) and (26), we see that because of the factor

$$\sqrt{1-4s_W^2} \ll 1,$$

the cross sections in the minimal model are smaller than those in the model with right-handed neutrinos. We work in the center-of-mass frame and let θ denote the scattering angle (the angle between the momenta of the initial electron and the final one). We have evaluated the θ dependence of the differential cross section $d\sigma/d\cos\theta$, the energy, and the Z' boson mass dependence of the total cross section σ.

Fig. 1. Feynman diagrams for the reaction $e^-\gamma \to Z'e^-$

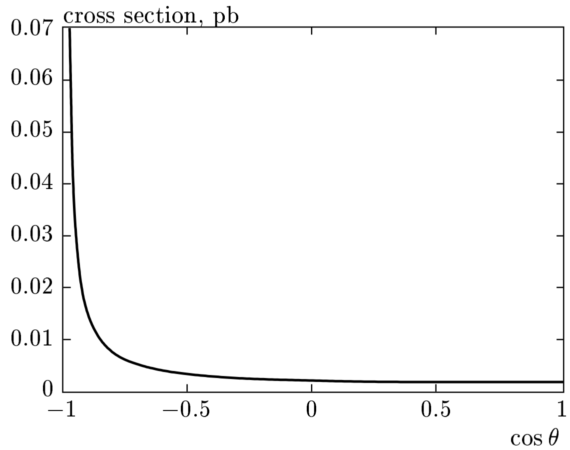

Fig. 2. Differential cross section of the minimal model, $\sqrt{s}$=2733 GeV, $m_{Z'} = 800$ GeV

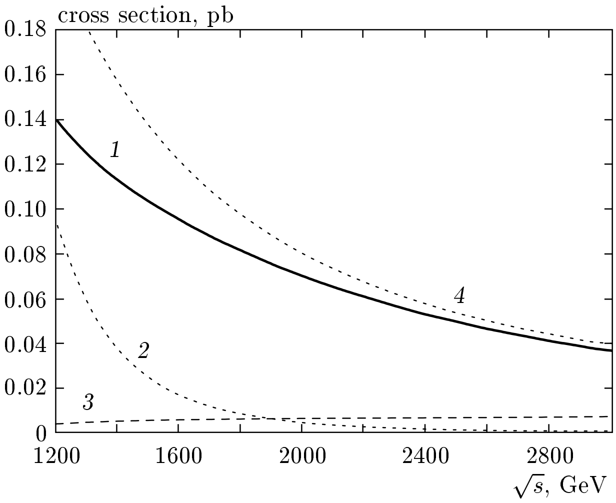

Fig. 3. Cross section $\sigma(e^-\gamma \to Z'e^-)$ of the minimal model as a function of $\sqrt{s}$: *1* — total cross section, *2* — cross section in u-channel, *3* — cross section in s-channel, *4* — cross section in Standard Model; $m_{Z'} = 800$ GeV

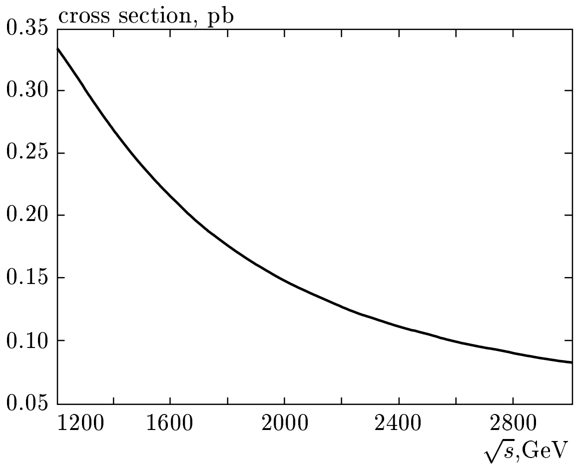

Fig. 4. Cross section $\sigma(e^-\gamma \to Z'e^-)$ of the model with right-handed neutrinos as a function of $\sqrt{s}$; $m_{Z'} = 800$ GeV

1) In Fig. 2, we plot $d\sigma/d\cos\theta$ for the minimal model as a function of $\cos\theta$ for the collision energy at CLIC $\sqrt{s} = 2733$ GeV [20] and the relatively low value of mass $m_{Z'} = 800$ GeV. From Fig. 2, we see that $d\sigma/d\cos\theta$ is peaked in the backward direction (this is due to the e^- pole term in the u-channel) but is flat in the forward direction. We note that the behavior of $d\sigma/d\cos\theta$ for the model with right-handed neutrinos is similar at other values of $\sqrt{s}$.

2) The energy dependence of the cross section for the minimal model is shown in Fig. 3. The same value of the mass as in the first case, $m_{Z'} = 800$ GeV, is chosen. The energy range is

$$1200 \text{ GeV} \le \sqrt{s} \le 3000 \text{ GeV}.$$

Curve *1* is the total cross section for the minimal model, curves *2* and *3* represent the respective cross sections of the u- and s-channels. Curve *4* is the cross section for the Standard Model, reduced three times. The u-channel, curve *2*, rapidly decreases with $\sqrt{s}$, while the s-channel has a zero point at $\sqrt{s} = m_{Z'}$ and then slowly increases. In the high-energy limit, the s-channel gives the main contribution to the total cross section. In Fig. 3, the cross section of the Standard Model reaches 0.18 pb and then slowly decreases to 0.05 pb, while the cross section of the minimal model is only 0.14 pb at $\sqrt{s} = 800$ GeV and 0.05 pb at $\sqrt{s} = 2733$ GeV. The same situation occurs in the model with right-handed neutrinos. In this model, we fix $m_{Z'} = 800$ GeV and illustrate the energy dependence of the cross section in Fig. 4. The energy range is the same as in Fig. 3, $1200 \text{ GeV} \le \sqrt{s} \le 3000$ GeV. We see from Fig. 4 that the cross section σ decreases with $\sqrt{s}$, from $\sigma = 0.35$ pb to $\sigma = 0.08$ pb.

3) We have plotted the boson mass dependence of the number of events in the three models in Fig. 5. The energy is fixed as $\sqrt{s} = 2733$ GeV and the mass range is $800 \text{ GeV} \le m_{Z'} \le 2000$ GeV. As we mentioned above, due to the coupling constant, the order of the lines of number of events, from bottom to top, is the following: the minimal model, the Standard Model, and the model with right-handed neutrinos. The smallest number of events is for the minimal model. With the integrated

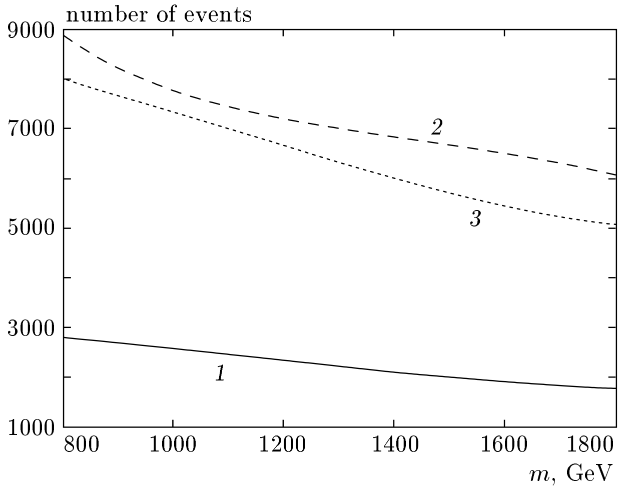

Fig. 5. Number of events of three models: *1* — minimal model, *2* — right-handed neutrinos model, *3* — Standard Model

luminosity $L \approx 100$ fb^{-1}, the number of events can be several thousand.

In the final state, Z' decays into leptons and quarks. Its partial decay width is equal to [21]

$$\Gamma(Z' \to f\bar{f}) = \\ = \frac{G_F m_{Z'}^2}{6\sqrt{2}\pi} N_c^F \left[(g_{2A}^f)^2 R_A^f + (g_{2V}^f)^2 R_V^f\right] = \\ = \begin{cases} 6.4 & \text{GeV for minimal model,} \\ 11.8 & \text{GeV for right-handed neutrinos model.} \end{cases}$$

Because of the coupling constants, the lifetime of Z' in the minimal model is longer than that in the model with right-handed neutrinos.

4. CONCLUSION

In this paper, we have considered the production of a single Z' boson in the e–γ reaction in the framework of the 3–3–1 models. We see that with this process, the reaction mainly occurs at small scattering angles. The results show that if the mass of the boson is in a range of 800 GeV, then single boson production in e–γ collisions may give observable values at moderately high energies. At CLIC based on e–γ colliders, with the integrated luminosity $L \approx 100$ fb^{-1}, we expect observable experiments in future colliders. Because of the values of the coupling constants, cross sections in the model with right-handed neutrinos are bigger than in the minimal model.

In conclusion, we have pointed out the usefulness of electron–photon colliders in testing the 3–3–1 models at high energies, through the reaction

$$e^-\gamma \to e^- Z'.$$

If the Z' boson is not very heavy, this reaction offers a much better discovery reach for Z' than the pair production in e^+–e^- or e^-–e^- collisions.

One of the authors (H. N. L) would like to thank Members of Physics Division, National Center for Theoretical Sciences (NCTS), Hsinchu, Taiwan, where this work was completed, for warm hospitality during his visit. His work is supported by the NCTS under grant from National Science Council of Taiwan R. O. C. This work was supported in part by the National Council for Natural Sciences of Vietnam.

REFERENCES

1. F. Pisano and V. Pleitez, Phys. Rev. D **46**, 140 (1992).

2. P. H. Frampton, Phys. Rev. Lett. **69**, 2889 (1992).

3. R. Foot et al., Phys. Rev. D **47**, 4158 (1993).

4. R. Foot, H. N. Long, and Tuan A. Tran, Phys. Rev. D **50**, R34 (1994).

5. H. N. Long, Phys. Rev. D **53**, 437 (1996); Phys. Rev. D **54**, 4691 (1996).

6. P. B. Pal, Phys. Rev. D **52**, 1659 (1995).

7. LEPEWWG $f\bar{f}$ Subgroup, C. Geweriger et al., Preprint LEP2FF/00-03.

8. H. N. Long and V. T. Van, J. Phys. G **25**, 2319 (1999).

9. I. Antoniadis et al., Preprints ETH-TH/01-10, CERN-TH/2001-202, New J. Phys. **3**, 20 (2002); T. Li and L. Wei, Phys. Lett. B **545**, 147 (2002); S. Dimopoulos et al., Phys. Lett. B **534**, 124 (2002); I. Gogoladze et al., Phys. Lett. B **554**, 81 (2003).

10. H. Hatanaka et al., Mod. Phys. Lett. A **13**, 2601 (1998); H. Hatanaka, Prog. Theor. Phys. **102**, 407 (1999); G. Dvali et al., Phys. Rev. D **65**, 064021 (2002); N. Arkani-Hamed et al., Phys. Lett. B **513**, 232 (2001).

11. T. Kitabayshi and M. Yasue, Phys. Rev. D **63**, 095002 (2001); Phys. Lett. B **508**, 85 (2001); Nucl. Phys. B **609**, 61 (2001); Phys. Lett. B **524**, 308 (2002); L. A. Sanchez et al., Phys. Rev. D **64**, 075013 (2001); W. A. Ponce et al., Phys. Rev. D **67**, 075001 (2003).

12. B. Dion et al., Phys. Rev. D **59**, 075006 (1999).

13. P. Frampton and A. Rasin, Phys. Lett. B **482**, 129 (2000).

14. H. N. Long and D. V. Soa, Nucl. Phys. B **601**, 361 (2001).

15. D. V. Soa, T. Inami, and H. N. Long, E-print archives hep-ph/0304300.

16. D. Ng, Phys. Rev. D **49**, 4805 (1994).

17. J. T. Liu and D. Ng, Z. Phys. C **62**, 693 (1994); N. A. Ky, H. N. Long, and D. V. Soa, Phys. Lett. B **486**, 140 (2000).

18. H. N. Long and L. P. Trung, Phys. Lett. B **502**, 63 (2001).

19. H. N. Long and T. Inami, Phys. Rev. D **61**, 075002 (2000).

20. Z. Z. Aydin et al., E-print archives hep-ph/0208041; R. W. Assman et al., E-print archives CERN 2000-008 (2000), p. 6; J. Ellis et al., E-print archives CERN-EP/98-03, CERN-SL/98-004 (AP), CERN-TH/98-33.

21. Particle Data Group, Phys. Rev. D **66**, 010001 (2002).