Triple Gauge Boson Production and Dynamical Symmetry Breaking at the Next Linear Collider

Rogerio Rosenfeld\footnote{rosenfel@axp.ift.unesp.br} and Alfonso R. Zerwekh\footnote{zerwekh@axp.ift.unesp.br}

Instituto de Física Teórica - Universidade Estadual Paulista  
Rua Pamplona, 145 - 01405-900 São Paulo - SP, Brazil

Abstract

We study in a model independent way the role of a techniomega resonance in the process $e^+e^- \rightarrow W^+W^-Z$ at the Next Linear Collider.
The only sector of Standard Model that has not been directly tested so far is the electroweak symmetry breaking sector. The usual Higgs potential with an elementary Higgs boson is not satisfactory on the grounds of the triviality of a $\lambda \phi^4$ theory. There are two alternatives to describe the symmetry breaking sector that circumvent the triviality problem: supersymmetric models, with elementary Higgs bosons, and models with dynamical symmetry breaking, without elementary scalars. In this work we will deal with the latter models [1].

One of the places where the effects of dynamical symmetry breaking surely appear is in the production of longitudinally polarized electroweak gauge bosons, since they are directly related to the electroweak symmetry breaking of the Standard Model [2]. Therefore, multiple gauge boson production may provide an important signature for these types of models.

The signature for large multiplicity ($\geq 7$) gauge boson production in hadron colliders was studied in ref. [3] based on a scaling of pion multiplicity distribution at low energy electron-positron machines. The gauge boson pair production process as a test of alternative models of electroweak symmetry breaking has been analysed in detail recently in both hadron and electron-positron colliders [4].

The triple gauge boson production can occur through a techniomega resonance $\omega_T$, as first studied by Rosenfeld and Rosner [5] for $\omega_T$ production from both vector meson dominance and gauge boson fusion processes in hadron colliders. However, backgrounds at hadron colliders are very severe [6] and the rarer two body decay process $\omega_T \rightarrow \gamma(Z_T) + Z_L$, where $(Z, W)_{L, T}$ denotes longitudinally and transversally polarized gauge bosons may be preferred, as shown by Chivukula and Golden [7] in a minimal technicolor model.

Recently, techniomega production has been studied in the context of multiscale technicolor models [8] in hadron colliders. In multiscale walking technicolor models, where the $\omega_T$ can be as light as a few hundred GeV, there are pseudo-goldstone bosons ($\Pi_T$) that are not absorbed by the electroweak gauge bosons and therefore remain as physical particles. In these models, the decay mode $\omega_T \rightarrow \gamma \Pi_T \rightarrow \gamma b\bar{b}$ is the most promising one in hadron colliders [9].

In this Letter we study the contribution of a techniomega resonance to the production of three electroweak gauge bosons in the clean environment of an electron-positron collider. We employ a model independent approach, in the sense that we don’t work in any particular model but study discovery
regions in a general parameter space without any theoretical prejudice. We then discuss the implications of our results to different specific models.

The parameters that characterize the techniomega for our purposes are its mass $M_{\omega_T}$, its total width $\Gamma_{\omega_T}$ and its partial width into $W^+_L W^-_L Z_L, \Gamma_{WWZ}$. We make use of the equivalence theorem \[2\] to relate the unphysical pseudogoldstone bosons to the longitudinal components of the electroweak gauge bosons.

The coupling of the techniomega with a fermion-antifermion pair, which is relevant for its production in $e^+e^-$ colliders, can be estimated by a generalized vector meson dominance mechanism which describes its mixing with the $B$ gauge boson of $U(1)_Y$:

$$\mathcal{L}_{\omega_T B} = g_{\omega_T B} \omega^\mu B_\mu$$ (1)

where the mixing constant $g_{\omega_T B}$ is given by:

$$g_{\omega_T B} = 2\sqrt{2} \tan \theta_w m_w M_{\omega_T} (2A - 1)$$ (2)

where $m_w$ is the $W$-boson mass and $A$ is the electric charge of the technifermion with weak isospin $+1/2$. In our calculations we use $A = 2/3$. This coupling results in a partial width:

$$\Gamma(\omega_T \to e^+e^-) = \frac{5\alpha m_w^2 \sin^2 \theta_w}{3m_{\omega_T} \cos^4 \theta_w} (2A - 1)^2$$ (3)

The coupling constant describing the $\omega_T W^+_L W^-_L Z_L$ interaction can be estimated from the partial width $\Gamma_{WWZ}$ using the effective interaction proposed in the context of QCD \[10\]:

$$\mathcal{L}_{\omega_T 3\pi} = -i g_{\omega_T 3\pi} \epsilon^{\mu\lambda\sigma} \omega_\mu \partial_\lambda \pi^+ \partial_\sigma \pi^0$$ (4)

which, using the equivalence theorem, results in:

$$\Gamma_{WWZ} = \frac{g_{\omega_T 3\pi}^2 M_{\omega_T}}{144(2\pi)^3} \int_{m_V}^{(M_{\omega_T}^2 - 3m_V^2)} \frac{dE}{M_{\omega_T}} \left(\frac{(E^2 - m_V^2)^{3/2}(M_{\omega_T}^2 - 2M_{\omega_T}E - 3m_V^2)^{3/2}}{(M_{\omega_T}^2 - 2M_{\omega_T}E + m_V^2)^{1/2}}\right)$$ (5)

where we used a value of $M_V = 85$ GeV.

We incorporated these new interactions into a HELAS-like \[11\] subroutine and with the help of the package MADGRAPH \[12\], we computed the process
$e^+e^- \to W^+W^-Z$ in an extension of the Standard Model containing the techniomega contribution. In this way we automatically include the Standard Model irreducible background. Given the mass and the partial width, we compute the relevant coupling constants via equations 2 and 5.

We have checked our code by comparing its result for the partial widths $\Gamma(\omega_T \to e^+e^-)$ and $\Gamma_{WWZ}$ with the direct results from equations 3 and 5. Another check was made by comparing the result for $e^+e^- \to W^+_T W^-_L Z_L$ obtained from the code without the Standard Model with a Breit-Wigner approximation near the peak:

$$\sigma = \frac{12\pi(s/m_{\omega_T}^2)\Gamma(\omega_T \to e^+e^-)\Gamma(\omega_T \to W^+W^-Z^0)}{(s-m_{\omega_T}^2)^2 + m_{\omega_T}^2\Gamma_{tot}^2} \quad (6)$$

In Figure 1 we show three sets of curves representing the cross sections for the process $e^+e^- \to W^+W^-Z$ for the masses $M_{\omega_T} = 400, 500$ and $600$ GeV at $\sqrt{s} = 500$ GeV as a function of the branching ratio $BR(\omega_T \to W^+W^-Z)$. Each set has three curves, representing the different total widths $\Gamma_{\omega_T} = 20, 10$ and $5$ GeV. These are only representative values to illustrate our results. We also show as horizontal dot-dashed lines the Standard Model cross section as well as its $2\sigma$ deviation assuming a luminosity of $L = 10$ fb$^{-1}$ and an efficiency for the reconstruction of the three gauge bosons of $\epsilon = 12\%$.

For $M_{\omega_T}$ near the center-of-mass energy, there is a sensitivity up to branching ratios as small as $10^{-4}$ for a $2\sigma$ deviation in the total cross section. Branching ratios of the order of $10^{-2}$ can be reached for $M_{\omega_T} = 400$ GeV but for $M_{\omega_T} = 600$ GeV one is sensitive only to large branching ratios of order one.

The inversion of the order of the curves for the different sets of masses can be easily explained by inspection of the Breit-Wigner formula in equation 6. At the resonance, the cross section is proportional to $\Gamma_{\omega_T}^{-2}$, whereas for the cases studied here the off-resonance cross section is proportional to $\Gamma_{WWZ}$ which, for a fixed value of the branching ratio $BR(\omega_T \to W^+W^-Z)$ is proportional to $\Gamma_{\omega_T}$.

In Figure 2 we show curves for an $e^+e^-$ collider at $\sqrt{s} = 1000$ GeV, for a total width of $\Gamma_{\omega_T} = 20$ GeV and techniomega masses at $M_{\omega_T} = 950, 1000$ and $1050$ GeV. For masses at the center-of-mass energy, sensitivities up to $BR \approx 0.5\%$ can be achieved but the sensitivity rapidly deteriorates for masses outside this range.
Due to the fact that the signal is produced by an $s$-channel resonance, its angular distribution is more central than the Standard Model background, as can be seen in Figure 3, where the normalized gauge boson’s angular distribution is shown for the case of $\sqrt{s} = 500$ GeV for the Standard Model and for the Standard Model plus a techniomega with mass $M_{\omega_T} = 400$ GeV, total width $\Gamma_{\omega_T} = 20$ GeV and partial width $\Gamma_{WWZ} = 0.4$ GeV. However, we found that a cut in the angular distribution of the $W^+$ or $W^-$ does not improve the significance due to the reduced rates.

The techniomega contributes only to the production of longitudinally polarized gauge bosons and therefore one could enhance the signal by selecting that particular polarization in the final state. We demonstrate this effect in Figure 4, where we show the cross section for $e^+e^- \rightarrow W^+W^-Z_L$, where the $Z$ boson is longitudinal, at $\sqrt{s} = 1000$ GeV, for $M_{\omega_T} = 950$ GeV and $\Gamma_{\omega_T} = 20$ GeV as a function of the branching ratio $BR(\omega_T \rightarrow W^+W^-Z)$. The Standard Model cross section and its $2\sigma$ deviation are shown as horizontal dot–dashed lines, assuming a luminosity of $L = 10$ fb$^{-1}$ and the same efficiency for the reconstruction of the three gauge bosons, $\epsilon = 12\%$. This is to be compared with the dotted line in Figure 2. We note an increase in the sensitivity of the cross section to the presence of a techniomega but due to the reduced statistics no major improvement seems to be achieved.

We conclude by commenting on some specific models. In usual technicolor models the techniomega mass and width are estimated by a simple scaling of QCD, resulting in typically $M_{\omega_T} \simeq 2$ TeV and $\Gamma_{\omega_T} \simeq 100$ GeV. However, these simple models run into problems with generating large fermion masses while keeping flavor changing neutral currents at acceptable levels.

Multiscale models [8], that appear naturally in walking technicolor [14] and topcolor-assisted technicolor [15] models, can ameliorate this problem at the same time predicting vector resonances with lower masses than the simple scaled up models. These models have many extra technipions $\Pi_T$’s that are not absorbed by the massless gauge bosons.

The techniomega would preferably decay into three $\Pi_T$’s:

$$\frac{\Gamma(\omega_T \rightarrow \Pi_T^+\Pi_T^-\Pi_T^0)}{\Gamma(\omega_T \rightarrow W^+_LW^-_LZ_L)} \propto \frac{1}{\sin^6\chi} \tag{7}$$

where $\chi$ is a mixing angle related to the ratio of the two different energy scales in a particular model.
It may be possible that the three $\Pi_T$'s channel is closed due to technipion mass enhancements in some of these models. In this case one would expect branching ratios of the order of:

$$BR(\omega_T \rightarrow W_L^+W_L^-Z_L) \simeq \sin^4\chi = \begin{cases} 
1.2\% & \text{for } \sin\chi = 1/3 \\
6.2\% & \text{for } \sin\chi = 1/2 
\end{cases} \tag{8}$$

which falls in the sensitive region for some of the cases studied here.

In summary, we have studied the role of a techniomega resonance in the production of three gauge bosons in $e^+e^-$ colliders. We considered the effects on the total cross section, the angular distribution, and in the total cross section for a longitudinally polarized $Z$ boson in the final state. Due to the narrow bandwidth of the machine, one is sensitive to techniomega masses close to the center-of-mass energy. In that case, one can be sensitive to rather small branching ratios. Initial state radiation may not be able to improve our results significantly. If the techniomega resonance is found at a hadron machine in the mode $\omega_T \rightarrow \gamma\pi_T \rightarrow \gamma bb$ [9], its properties can be further studied at an $e^+e^-$ collider running at its mass, which could also provide useful information about the underlying technicolor model.

This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP). We thank Gustavo Burdman and Jonathan Rosner for a critical reading of the paper. RR gratefully acknowledges the hospitality at the Fermilab Theory Group, where this work was completed.
Figure Caption

Figure 1:
Cross section for $e^+e^- \rightarrow W^+W^-Z$ at $\sqrt{s} = 500$ GeV as a function of the branching ratio $BR(\omega_T \rightarrow W^+W^-Z)$ without any cuts. The three sets of curves are the cross sections for the process $e^+e^- \rightarrow W^+W^-Z$ for the masses $M_{\omega_T} = 400$ GeV (middle set), 500 GeV (left set) and 600 GeV (right set). Each set has three curves, representing the different total widths $\Gamma_{\omega_T} = 20$ GeV (dotted line), 10 GeV (dashed line) and 5 GeV (solid line). The Standard Model cross section as well as its 2$\sigma$ deviation assuming a luminosity of $L = 10$ fb$^{-1}$ and an efficiency for the reconstruction of the three gauge bosons of $\epsilon = 12\%$ are shown as horizontal dot-dashed lines.

Figure 2:
Same as in Figure 1 but for $\sqrt{s} = 1000$ GeV and a fixed total width $\Gamma_{\omega_T} = 20$ GeV. The different techniomega masses are $M_{\omega_T} = 950$ GeV (dotted line), 1000 GeV (solid line) and 1050 GeV (dashed line).

Figure 3:
Normalized angular distribution for the three final state gauge bosons for $e^+e^- \rightarrow W^+W^-Z$ at $\sqrt{s} = 500$ GeV. Solid line is the Standard Model result and dashed line is the Standard Model plus a techniomega with $M_{\omega_T} = 400$ GeV, $\Gamma_{\omega_T} = 20$ GeV and $\Gamma_{WWZ} = 0.4$ GeV.

Figure 4:
Same as the dotted line in Figure 2 but requiring a longitudinally polarized $Z$ boson in the final state. The Standard Model cross section as well as its 2$\sigma$ deviation assuming a luminosity of $L = 10$ fb$^{-1}$ and an efficiency for the reconstruction of the three gauge bosons of $\epsilon = 12\%$ are shown as horizontal dot-dashed lines.
References

[1] For a collection of reprints, see Dynamical Gauge Symmetry Breaking, edited by E. Farhi and R. Jackiw (World Scientific, 1982). More recent developments can be found in K. Lane, in Proceedings of the 28th International Conference on High Energy Physics, edited by Z. Ajduk and A. K. Wroblewski (World Scientific 1997) - hep-ph/9610463.

[2] J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. D10 (1974) 1145; D11 (1975), 972(E); M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B261 (1985) 379.

[3] D. A. Morris, R. D. Peccei and R. Rosenfeld, Phys. Rev. D47 (1993) 3839.

[4] For recent reviews see:
   R. S. Chivukula, R. Rosenfeld, E. H. Simmons and J. Terning, in Electroweak Symmetry Breaking and New Physics at the TeV Scale, edited by T. L. Barklow, S. Dawson, H. E. Haber and J. L. Siegrist (World Scientific, 1996);
   M. Golden, T. Han and G. Valencia, ibid.;
   T. L. Barklow et al., Summary of the Snowmass Working Group on Strong Coupling Electroweak Symmetry Breaking, to appear in the Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High Energy Physics, Snowmass, CO, June 25 – July 12, 1996, hep-ph/9704217.

[5] R. Rosenfeld and J. L. Rosner, Phys. Rev. D38 (1988) 1530.

[6] M. Golden and S. Sharpe, Nucl. Phys. B261 (1985) 217.

[7] R. S. Chivukula and M. Golden, Phys. Rev. D41 (1990) 2795.

[8] K. Lane and E. Eichten, Phys. Lett. B222 (1989) 274.

[9] E. Eichten and K. Lane, Phys. Lett. B388 (1996) 803; E. Eichten and K. Lane and J. Womersley, hep-ph/9704455.

[10] S. Rudaz, Phys. Lett. 145B (1984) 381.

7
[11] H. Murayama, I. Watanabe and K. Hagiwara, KEK report No. 91-11 (unpublished).

[12] T. Stelzer and W. F. Long, *Comput. Phys. Commun.* **81** (1994) 357.

[13] A. Miyamoto, preprint KEK-95-185, presented at the Third Workshop on Physics and Experiments with e+ e- Linear Colliders (LCWS95), Iwate, Japan, 8-12 September 1995.

[14] B. Holdom, *Phys. Rev.* **D24** (1981) 1441; *Phys. Lett.* **150B** (1985) 301; T. Appelquist, D. Karabali and L. C. Wijewardhana, *Phys. Rev. Lett.* **57** (1986) 957; T. Appelquist and L. C. Wijewardhana, *Phys. Rev.* **D36** (1987) 568; K. Yamawaki, M. Bando and K. Matsumoto, *Phys. Rev. Lett.* **56** (1986) 1335; T. Akiba and T. Yanagida, *Phys. Lett.* **169B** (1986) 432.

[15] C. T. Hill, *Phys. Lett.* **B345** (1995) 483.
Fig. 3

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_Z} \quad \cos \theta_Z
\]

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_{W^-}} \quad \cos \theta_{W^-}
\]

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_{W^+}} \quad \cos \theta_{W^+}
\]
