Polarization as a tool to study Z' vs. anomalous gauge coupling effects at the LC

A. A. Pankov

Gomel Polytechnical Institute, Gomel, 246746 Belarus

We show that the availability of longitudinally polarized electron beams at a $500\,GeV$ Linear Collider would allow, from an analysis of the reaction $e^+e^- \to W^+W^-$, to set stringent bounds on the couplings of a Z' of the most general type. In addition, to some extent, it would be possible to disentangle observable effects of the Z' from analogous ones due to competitor models with anomalous trilinear gauge couplings.

Introduction

It has been recently suggested [1] that theoretical models with one extra $Z \equiv Z'$ whose couplings to quarks and leptons are not of the 'conventional' type would be perfectly consistent with all the available experimental information from either LEP1 [2] and SLD [3] or CDF [4] data. Starting from this observation, a detailed analysis has been performed of the detectability in the final two-fermion channels at LEP2 of a Z' whose fermion couplings are arbitrary (but still family independent) [5]. Also, in [5] the problem of distinguishing this model from competitor ones (in particular, from a model with anomalous gauge couplings) has been studied.

The final two-fermion channel is not the only one where virtual effects generated by a Z' can manifest themselves. The usefulness of the final W^+W^- channel in e^+e^- annihilation to obtain improved information on some theoretical properties of such models, has already been stressed in previous papers in the specific case of longitudinally polarized beams for models of 'conventional' type (e.g., E_6, LR, *etc.*), showing that the role of polarization in these cases would be essential [6].

The aim of this note is that of considering whether the search for *indirect* effects of a 'unconventional' Z' in the W^+W^- channel would benefit from the availability of longitudinal polarization of initial beams, as it is the case for the 'conventional' situation. We shall show that in the parameter space the expected experimental sensitivity in the polarized processes is by far better than in the unpolarized case. For what concerns the differentiation from other sources of nonstandard effects, in particular those with anomalous gauge couplings, we shall also show that the characteristic feature of such a Z' would be the existence of certain peculiar properties of different observables, all pertaining to the final W^+W^- channel. All our discussions assume that longitudinal electron polarization will be available at the future $500\,GeV$ linear Collider (LC).

Constraints for general Z' parameters

The starting point will be the expression of the invariant amplitude for the process

$$e^+ + e^- \to W^+ + W^-. \tag{1}$$

In Born approximation, this can be written as a sum of a t-channel and of an s-channel component: $\mathcal{M}^{(\lambda)} = \mathcal{M}_t^{(\lambda)} + \mathcal{M}_s^{(\lambda)}$, where $\lambda = \pm 1/2$ is the electron helicity. Since we will concentrate on the sensitivity of process (1) to general features of Z'-exchange effects and their comparison to analogous effects in models with anomalous gauge couplings, we consider only the s-channel amplitudes. Accounting for one extra Z:

$$\mathcal{M}_s^{(\lambda)} = \left(-\frac{1}{s} + \frac{g_{WWZ_1}(v_1 - 2\lambda a_1)}{s - M_{Z_1}^2} + \frac{g_{WWZ_2}(v_2 - 2\lambda a_2)}{s - M_{Z_2}^2} \right) \times \mathcal{G}^{(\lambda)}(s,\theta). \tag{2}$$

$\mathcal{G}^{(\lambda)}(s,\theta)$ is a kinematical coefficient, depending also on the final W's helicities. For simplicity we omit its explicit form, which and can be found in the literature [7]. Eq. (2) shows two possible sources of effects from, respectively, the 'light' and the 'heavy' neutral gauge bosons Z_1 and Z_2.

The first one is the modification of the Z couplings, due to the presence of the extra Z', that can be induced, e.g., through the mechanism of $Z - Z'$ mixing. To account for this fact, the 'light' Z is now denoted as Z_1, and the same convention applies to its vector and axial-vector couplings to electrons v_1, a_1 and to the trilinear gauge coupling g_{WWZ_1}. The second effect is the actual heavy Z exchange denoted as Z_2, with analogous notations for its physical couplings.[1]

Eq. (2) can be conveniently rewritten in the same form as the Standard Model (SM):

$$\mathcal{M}_s^{(\lambda)} = \left(-\frac{g_{WW\gamma}}{s} + \frac{g_{WWZ}(v - 2\lambda a)}{s - M_Z^2}\right) \times \mathcal{G}^{(\lambda)}(s,\theta), \tag{3}$$

where the 'effective' gauge boson couplings $g_{WW\gamma}$ and g_{WWZ} are defined as:

$$g_{WW\gamma} = 1 + \Delta_\gamma = 1 + \Delta_\gamma(Z_1) + \Delta_\gamma(Z_2), \tag{4}$$

$$g_{WWZ} = \cot\theta_W + \Delta_Z = 1 + \Delta_Z(Z_1) + \Delta_Z(Z_2), \tag{5}$$

with

$$\begin{aligned} \Delta_\gamma(Z_1) &= v \cot\theta_W \left(\frac{\Delta a}{a} - \frac{\Delta v}{v}\right)(1 + \Delta\chi)\,\chi; \\ \Delta_\gamma(Z_2) &= v\, g_{WWZ_2} \left(\frac{a_2}{a} - \frac{v_2}{v}\right)\chi_2, \end{aligned} \tag{6}$$

$$\Delta_Z(Z_1) = \Delta g_{WWZ} + \cot\theta_W \left(\frac{\Delta a}{a} + \Delta\chi\right); \qquad \Delta_Z(Z_2) = g_{WWZ_2}\frac{a_2}{a}\frac{\chi_2}{\chi}. \tag{7}$$

We have introduced electrons SM couplings normalized as: $v = (T_{3,e} - 2Q_e s_W^2)/2s_W c_W$; $a = T_{3,e}/2s_W c_W$ with $T_{3,e} = -1/2$; $s_W = \sin\theta_W$; $c_W = \cos\theta_W$. Moreover: $\Delta v = v_1 - v$, $\Delta a = a_1 - a$ and $\Delta g_{WWZ} = g_{WWZ_1} - \cot\theta_W$. Finally, neglecting gauge boson widths:

$$\chi(s) = \frac{s}{s - M_Z^2}; \qquad \chi_2(s) = \frac{s}{s - M_{Z_2}^2}; \qquad \Delta\chi(s) = -\frac{2M_Z \Delta M}{s - M_Z^2}, \tag{8}$$

[1] In Eq. (2), the couplings to W^+W^- of both Z_1 and Z_2 have been tacitly assumed of the usual Yang-Mills form.

where $\Delta M = M_Z - M_{Z_1}$ is the Z-Z_1 mass-shift, of the order of $150 - 200\,MeV$ according to most recent estimates [8, 9] (notice $\Delta M > 0$ if this is due to $Z - Z'$ mixing).

It should be stressed that, not referring to specific models, the parametrization (3)-(5) is both general and useful for phenomenological purposes, in particular to compare different sources of nonstandard effects contributing finite deviations (6) and (7) to the SM predictions.

We now focus on the effects of the heavy Z on polarized observables. The general expression for the cross section of process (1) with longitudinally polarized electron and positron beams can be expressed as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{4}\left[(1+P_L)\left(1-\bar{P}_L\right)\frac{d\sigma^+}{d\cos\theta} + (1-P_L)\left(1+\bar{P}_L\right)\frac{d\sigma^-}{d\cos\theta}\right], \quad (9)$$

where P_L and $\bar{P}_L$ are the actual degrees of electron and positron longitudinal polarization, respectively, and $\sigma^\pm$ are the cross sections for purely right-handed and left-handed electrons. We consider the cross section for polarized electrons and unpolarized positrons ($\bar{P}_L = 0$). Explicit expressions for the polarized cross can be found in [7, 10].

We reserve the notations σ^L and σ^R for the cross sections with $P_L = -0.9$ and $P_L = 0.9$, respectively, which seem to be realistically obtainable at the LC [11]. Our numerical analysis to assess the sensitivity of σ^L and σ^R to Δ_γ and Δ_Z follows the χ^2 procedure adopted in [10]. We represent the effect of non-standard couplings introduced above by the relative deviation of the cross section from the SM prediction:

$$\Delta \equiv \frac{\Delta\sigma}{\sigma_{SM}} = \frac{\sigma - \sigma_{SM}}{\sigma_{SM}}, \quad (10)$$

which is a function of Δ_γ and Δ_Z.

If a nonvanishing value of Δ was experimentally measured at some level of accuracy, the values of such parameters could be determined and possibly used to learn about the properties of the related nonstandard physics. Alternatively, in the case of no observation, one could derive numerical bounds on Δ_γ and Δ_Z, and therefore constrain the various extended models, at some confidence level. In this regard, assuming small deviations, Δ is expressed as a linear combination of Δ_γ and Δ_Z with coefficients which, generally, increase with s. Conversely, the SM cross section decreases as $1/s$ (at least) due to the gauge cancellation among the various amplitudes. Therefore, if we parametrize the sensitivity of process (1) to δ_γ and δ_Z by, e.g., the ratio $\mathcal{S} = \Delta/(\delta\sigma/\sigma)$ with $\delta\sigma/\sigma$ the attainable statistical uncertainty on the SM cross section, such sensitivity is expected to increase with energy, even at fixed integrated luminosity (basically, as $\mathcal{S} \propto \sqrt{L_{int} s}$).

By specifying λ, Eq. (3) directly shows that

$$\Delta\sigma^- \propto \Delta_\gamma - \Delta_Z \cdot g_e^L \chi; \qquad \Delta\sigma^+ \propto \Delta_\gamma - \Delta_Z \cdot g_e^R \chi, \tag{11}$$

where $g_e^R = v - a = \tan\theta_W \simeq 0.55$ and $g_e^L = v + a = g_e^R(1 - 1/2s_W^2) \simeq -0.64$. Thus, by themselves, σ^- (or σ^{unpol}) and σ^+ only provide correlations among Δ_γ and Δ_Z, rather than true limits. These correlations can be represented as bands in the $\Delta_\gamma - \Delta_Z$ plane with a width proportional to the corresponding sensitivities, and a relative angle of approximately 60 degrees. In contrast to the unpolarized case, finite allowed ranges for Δ_γ and Δ_Z are obtained from the intersection of the two bands.

Quantitatively, for the LC500 with an assumed $L_{int} = 50\,fb^{-1}$ and P_L as above, one can derive the following 95% CL allowed ranges [10]:

$$\begin{array}{c} -0.002 < \Delta_\gamma < 0.002 \\ -0.004 < \Delta_Z < 0.004. \end{array} \tag{12}$$

We now consider the application of the model-independent limits (12) to the case of an extra Z of extended gauge origin, generated by an E_6 symmetry. For such extended models one can write in Eqs. (4)-(7):

$$(v_1, a_1) \simeq (v + v'\phi, a + a'\phi) \Rightarrow (\Delta v, \Delta a) \simeq (v'\phi, a'\phi), \tag{13}$$

$$(v_2, a_2) \simeq (-v\phi + v', -a\phi + a'), \tag{14}$$

and

$$\Delta g_{WWZ} \simeq 0, \qquad g_{WWZ_2} \simeq -\cot\theta_W \phi. \tag{15}$$

Here, ϕ is the $Z - Z'$ mixing angle, and v', a' are the Z' vector and axial-vector couplings with electrons. The actual values of such couplings for the specific E_6 models (η, ψ and χ) can be found in the literature [12]. The above relations become equalities in linear approximation in the, expectedly small, angle ϕ, and give for Eqs. (6) and (7):

$$\Delta_\gamma = v \cot\theta_W \phi \left(\frac{a'}{a} - \frac{v'}{v}\right)\left(1 - \frac{\chi_2}{\chi} + \Delta\chi\right)\chi, \tag{16}$$

$$\Delta_Z = \cot\theta_W \left[\phi \frac{a'}{a}\left(1 - \frac{\chi_2}{\chi}\right) + \Delta\chi\right]. \tag{17}$$

Neglecting $\Delta\chi$ as being quadratic in ϕ, these relations show that every specific model is represented in linear approximation by a straight line in the $(\Delta_\gamma, \Delta_Z)$ plane, of equation:

$$\Delta_Z = \Delta_\gamma \frac{1}{v\chi} \frac{(a'/a)}{(a'/a) - (v'/v)}. \tag{18}$$

Such relation does not depend on either ϕ or M_{Z_2}, but only on ratios of the fermionic couplings.

The combination of (12) and (18) can be easily translated into limits on ϕ and M_{Z_2}. For the considered energy and luminosity of LC500, the typical bounds on ϕ are of the order of few $\times\, 10^{-3}$ for $M_{Z_2} \geq 1TeV$, and much more restrictive for smaller values of M_{Z_2} (up to one order of magnitude in the extreme case $M_{Z_2} \simeq \sqrt{s}$). The detailed analysis of different specific models is worked out in [10] and references there. At the LC1000, the numerical results can be obtained according to the scaling law $\sqrt{L_{int} s}$.

Comparison with a model with anomalous gauge couplings

The extra heavy neutral gauge boson Z' would produce virtual effects in the final W^+W^- channel that, in principle, could mimic those of a model with anomalous trilinear gauge boson couplings [13]. Therefore, the identification of such an effect, if observed at the LC, becomes a relevant problem. The relevant trilinear WWV interaction which conserves $U(1)_{e.m.}$, C and P, can be written as ($e = \sqrt{4\pi\alpha_{em}}$) [7]:

$$\begin{aligned}
\mathcal{L}_{eff} &= -ie(1+\delta_\gamma)\left[A_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + F_{\mu\nu}W^{+\mu}W^{-\nu}\right] \\
&- ie\left(\cot\theta_W + \delta_Z\right)\left[Z_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + Z_{\mu\nu}W^{+\mu}W^{-\nu}\right] \\
&- ie\,x_\gamma\,F_{\mu\nu}W^{+\mu}W^{-\nu} - ie\,x_Z\,Z_{\mu\nu}W^{+\mu}W^{-\nu} \\
&+ ie\,\frac{y_\gamma}{M_W^2}\,F^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \ \nu} + ie\,\frac{y_Z}{M_W^2}\,Z^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \ \nu}, \qquad (19)
\end{aligned}$$

where $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$ and $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$. In the SM at the tree-level, the anomalous couplings in (19) vanish: $\delta_\gamma = \delta_Z = x_\gamma = x_Z = y_\gamma = y_Z = 0$.

For the explicit form of helicity amplitudes for process (1) corresponding to (19) we refer to [7]. Here, for practical purposes, the Yang-Mills parts and their deviations proportional to δ_γ and $\delta_Z = g_{WWZ} - \cot\theta_W$ are reported separately from the anomalous 'magnetic' and 'quadrupole' terms.

While in the previous case of the Z' the deviations Δ_γ and Δ_Z have an explicit (although numerically not quite significant) s-dependence through Eqs. (6) and (7), the anomalous trilinear gauge boson couplings are considered as effective *constants*. As a consequence, we assume $\delta_\gamma \equiv 0$ to ensure $U(1)_{e.m.}$ gauge invariance. In the framework where anomalous gauge couplings arise from effective theories with $SU(2) \times U(1)$ gauge symmetry, representing low-energy expansions of the non-standard weak interaction [14], finite δ_γ (and in any case it must be $\delta_\gamma(0) = 0$) only occurs at next-to-leading dimension level [15]. Furthermore, it can be shown that the assumption of 'custodial' global $SU(2)$ symmetry of the New Physics, which naturally accounts for the smallness of the $\Delta\rho$ parameter, would require $\delta_\gamma = 0$ also at the higher, dim=8, level because the relevant operator would not respect this symmetry.

In most generality, Eq. (19) introduces five independent parameters into the analysis, and therefore the determination of suitable experimental observables, depending on subsets of anomalous gauge boson couplings, is a problem by itself (see, for example, refs. [16]).

Concerning the distinction between Z' and anomalous gauge boson coupling effects, one can try to define observables which are 'orthogonal' to the Z' mode. To this purpose, they should depend only on the x_V, y_V couplings that are specific of (19), but not on δ_Z which would represent an effect in common with the Z' model. Some attempts are presented in Ref. [10].

Concerning a possible discrimination between the Z' model of Sect. 2 and the model considered in this section, a strategy could be the following. If a signal is observed in either σ^L and/or σ^R and also in at least one of the 'orthogonal' observables defined above, we can conclude that it is due to the model with anomalous gauge couplings, and we can try to derive the values of some of them by properly analyzing the observed effects [16]. If, conversely, only σ^L and/or σ^R show an effect, we are left with the possibility that both models are responsible for such deviations. In this situation, we still have a simple tool to try to distinguish among the two models, which uses the observation that, under the assumption that only δ_V and Δ_V are effective, the expressions of the consequent deviations of the integrated cross sections σ^L and σ^R are, respectively:

$$\Delta\sigma^{R,L} \simeq \Delta\sigma^{\pm} \propto \delta_\gamma - \delta_Z g_e^{R,L}\chi, \tag{20}$$

and

$$\Delta\sigma^{R,L} \simeq \Delta\sigma^{\pm} \propto \Delta_\gamma - \Delta_Z g_e^{R,L}\chi. \tag{21}$$

Here, both Δ_V and δ_V have been taken nonvanishing, and $g_e^{L,R} = v \pm a$ are the left- and right-handed electron couplings, respectively. However, recalling that $\delta_\gamma = 0$ in the case of anomalous trilinear gauge boson couplings, using the experimental value of $s_W^2 \simeq 0.23$, one has for such a model the very characteristic feature

$$\Delta\sigma^L \simeq \left(1 - \frac{1}{2s_W^2}\right) \Delta\sigma^R = -1.17\Delta\sigma^R, \tag{22}$$

where the explicit expressions of g_e^L and g_e^R have been used. If, on the contrary, the effect is due to a model with a Z', no *a priori* relationship exists between $\Delta\sigma^L$ and $\Delta\sigma^R$. Accordingly, from inspection of these two quantities, if they are found not to be related by Eq. (22) to a given confidence level, one would conclude that the observed effect should be due to the general extra Z discussed in Sect. 2. Then, depending on the actual values of the experimental deviations, a determination of the two parameters Δ_γ and Δ_Z might be carried on.

Actually, if the deviations of $\sigma^{L,R}$ satisfy the correlation Eq. (22), a small residual ambiguity would remain. Although the possibility that in a model with both Δ_γ and Δ_Z nonvanishing the correlation Eq. (22) is satisfied just by chance seems rather unlikely, one cannot exclude it *a priori*. Should this be the real situation, further analysis, e.g., in the different final fermion-antifermion channel would be required. The discussion of this essentially unlikely case can be performed, but is beyond the purpose of this note.

Concluding remarks

We have shown in this paper that the availability of longitudinal electron beam polarization at the LC would be very useful for the study of the most general model with one extra Z from an analysis of the final W^+W^- channel. In principle, it would also be possible to discriminate this model from a rather 'natural' competitor one where anomalous gauge boson couplings are present. This could be done by analyzing suitable experimental variables, all defined in the same W^+W^- final channel. All these facts allow us to conclude that polarization at the LC would be, least to say, a highly desirable opportunity.

References

[1] P. Chiappetta, J. Layssac, F. M. Renard and C. Verzegnassi, Phys. Rev. D **54** (1996) 789; G. Altarelli, N. Di Bartolomeo, F. Feruglio, R. Gatto and M. Mangano, Phys. Lett. **B375** (1996) 292.

[2] For an updated review see, e.g., A. Blondel, talk at the *28th International Conference on High Energy Physics*, 25-31 July 1996, Warsaw, Poland.

[3] For an updated review see, e.g., M. W. Grünewald, talk at the *28th International Conference on High Energy Physics*, 25-31 July 1996, Warsaw, Poland.

[4] E. Buckley-Geer, FERMILAB-Conf-95/316-E (1995), Proceedings of the *EPS Conference on High Energy Physics*, Brussels, Belgium (1995).

[5] G. Montagna, F. Piccinini, J. Layssac, F. M. Renard and C. Verzegnassi, Z. Phys. C **75** (1997) 641. Montpellier Report PM 96-25 (1996).

[6] A. A. Pankov and N. Paver, Phys. Rev. D **48** (1993) 63.

[7] G. Gounaris, J. Layssac, G. Moultaka and F. M. Renard, Int. J. Mod. Phys. A **8** (1993) 3285.

[8] G. Altarelli, CERN report CERN-TH-96-265, presented at the *NATO Advanced Study Institute on Techniques and Concepts of High-Energy*

Physics, St. Croix, U.S. Virgin Islands (1996); CERN report CERN-TH.7464/94, Proceedings of the Workshop on *Radiative Corrections: Status and Outlook*, (Gatlinburg, Tenn., USA, 1994), ed. B. L. Ward, World Scientific 1995.

[9] K. S. Babu, C. Kolda and J. March-Russell, Phys. Rev. D **54** (1996) 4635.

[10] A.A. Pankov, N. Paver and C. Verzegnassi, hep-ph/9701359, to appear in Int. J. Mod. Phys. **A**.

[11] C. Y. Prescott, Proceedings of the Workshop *Physics and Experiments with Linear e^+e^- Colliders*, (Waikoloa, Hawaii, 1993), eds. F. A. Harris, S. L. Ȯlsen, S. Pakvasa and X. Tata, (World Scientific, Singapore 1993), p. 379.

[12] For a review see, e.g.: J. L. Hewett, T. G. Rizzo, Physics Reports **183** (1989) 193.

[13] A. A. Pankov and N. Paver, Phys. Lett. **B393** (1997) 437.

[14] See, e.g., K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Lett. B **283** (1992) 353; Phys. Rev. D **48** (1993) 2182; and references there.

[15] G. Gounaris and F. M. Renard, Z. Phys. C **59** (1993) 133.

[16] V. V. Andreev, A. A. Pankov and N. Paver, Phys. Rev. D **53** (1996) 2390.