Signals of Z' bosons in W-pair production at the ILC with polarized beams

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Abstract. We consider the sensitivity of the International Linear Collider (ILC) to probe $Z - Z'$ mixing and Z' mass by the reaction $e^+e^- \rightarrow W^+W^-$ with longitudinally polarized e^+e^- beams. We perform here a generic analysis of the deviations of the differential cross section from the Standard Model prediction, and apply it to a specific class of extended weak gauge models called as 'minimal-Higgs' models.

1 Introduction

The International Linear Collider (ILC) is a proposed high energy, high luminos- ity electron-positron collider with the mission of studying the standard model (SM) at high precision and to look for signals beyond the standard model. One of the best motivated extensions of the SM of the electroweak and strong interactions is a neutral gauge sector with an extra $U(1)$ symmetry in addition to the SM hypercharge $U(1)_Y$ and an associated Z' gauge boson, predicted in most Grand Unified Theories (GUTs) such as E_6[1–3]. Among these, models based on the E_6 GUT group and left-right symmetry groups have been extensively pursued in the literature and are particularly significant from the point of view of LHC phenomenology. Many of these GUTs, including superstring and left-right-symmetric models, predict the existence of new neutral gauge bosons, which might be light enough to be accessible at current and/or future colliders. Within a few years of data accumulation, the LHC should be able to test and constrain many types of new physics beyond the SM. In particular, the discovery reach for extra neutral gauge bosons is exceptional. Searches for a high invariant dilepton mass peak in about 100 fb^{-1} of accumulated data will find or exclude Z' bosons up to about 5 TeV. But, at present, direct Z' production searches at the LHC indicate a lower limit on $M_{Z'}$ of the order of 2.5–3.0 TeV depending on the Z' models [4, 5].

With the increased e^+e^- energy available at ILC, the reaction

$$e^+ + e^- \rightarrow W^+ + W^- \tag{1}$$

should represent a convenient tool to search for Z' effects [6]. Indeed, in this process, lack of gauge cancellation among the different amplitudes due to nonstandard physics should lead to deviations from the SM cross section rapidly increasing with energy and therefore, in principle, to enhanced sensitivity to the existence of the Z' if efficient W^+W^- reconstruction could be performed. Moreover, it turns out

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that the strongest sensitivity of process (1) to nonstandard effects would be obtained if initial beams were longitudinally polarized, that would lead to stringent restrictions on the $Z - Z'$ mixing angle.

In this note, we summarize the analysis done in [7] of the various Z' models, which include E_6 based Z'_χ, Z'_ψ, Z'_η and a sequential Z'_{SM} boson in (1) at future e^+e^- collider ILC, and present some its extension.

2 $Z - Z'$ mixing

The new gauge boson Z could mix with the SM gauge boson to give the physical eigenstates. Thus, the W-pair production in e^+e^- collisions has the advantage of directly probing the mixing unlike, for example, the fermion pair production process. The W does not interact directly with the Z.

Let us now turn to some general features of the scenario. The mass-squared matrix of the Z and Z' can have non-diagonal entries δM^2, which are related to the vacuum expectation values of the fields of an extended Higgs sector:

$$M^2_{ZZ'} = \begin{pmatrix} M^2_Z & \delta M^2 \\ \delta M^2 & M^2_{Z'} \end{pmatrix}. \tag{2}$$

Here, Z and Z' denote the weak gauge boson eigenstates of $SU(2)_L \times U(1)_Y$ and of the extra $U(1)'$, respectively. The mass eigenstates, Z_1 and Z_2, diagonalizing the matrix (2), are then obtained by the rotation of the fields Z and Z' by a mixing angle ϕ:

$$Z_1 = Z \cos\phi + Z' \sin\phi \,, Z_2 = -Z \sin\phi + Z' \cos\phi \,. \tag{3}$$

Here, the mixing angle ϕ is expressed in terms of masses as:

$$\tan^2\phi = \frac{M^2_Z - M^2_1}{M^2_2 - M^2_Z} \simeq \frac{2M_Z \Delta M}{M^2_2} \,, \tag{4}$$

where $\Delta M = M_Z - M_1 > 0$, M_Z is the mass of the Z_1-boson in the absence of mixing, i.e., for $\phi = 0$, and is given as

$$M_Z = \frac{M_W}{\sqrt{\rho_0} \cos\theta_W}. \tag{5}$$

Once we assume the mass M_1 to be determined experimentally, the mixing depends on two free parameters, which we identify as ϕ and M_2. We shall here consider the configuration $M_1 \ll \sqrt{s} \ll M_2$.

The mixing angle ϕ will play an important role in our analysis. In general, such mixing effects reflect the underlying gauge symmetry and/or the Higgs sector of the model. We set $\rho_0 = 1$ here, which corresponds to a Higgs sector with only $SU(2)$ doublets and singlets. Furthermore, if the $U(1)'$ charge assignments of the Higgs fields, Q'_i, are known in a specific model, then there exists an additional constraint [3]. To a good approximation, for $M_1 \ll M_2$, in specific 'minimal-Higgs models' [8],

$$\phi \simeq -s^2_W \frac{\sum_i \langle \Phi_i \rangle^2 I^i_{3L} Q'_i}{\sum_i \langle \Phi_i \rangle^2 (I^i_{3L})^2} = C \frac{g_2}{g_1} \frac{M^2_Z}{M^2_{Z'}}. \tag{6}$$

Here, $\langle \Phi_i \rangle$ are the Higgs vacuum expectation values spontaneously breaking the symmetry, and Q'_i are their charges with respect to the additional $U(1)'$, $g_1 = g_L / \cos\theta_W$ and where $g_2 = \sqrt{5/3}\, g_1 \sin\theta_W \sqrt{\lambda}$ is the $U(1)'$ gauge coupling. In addition, in these models the same Higgs multiplets are responsible for both generation of mass M_1 and for the strength of the Z-Z' mixing [3]. Thus C is a model-dependent constant.

For the E_6 based models one may restrict oneself to the case where the Higgs fields arise from a **27** representation. The $U(1)'$ quantum numbers are then predicted and C receives contributions from the VEVs of three Higgs doublets, $x \equiv \langle\phi_\nu\rangle$, $v \equiv \langle\phi_N\rangle$ and $\bar{v} \equiv \langle\phi_{\bar{N}}\rangle$, respectively, in correspondence with the standard lepton doublet, as well as the two doublets contained in the $\bar{\mathbf{5}}$ and $\mathbf{5}$ of $SU(5) \subset E_6$. They satisfy the sum rule, $|v|^2 + |\bar{v}|^2 + |x|^2 = (\sqrt{2}\,G_F)^{-1} = (246.22\text{ GeV})^2$, and we introduce the ratios,

$$\tau = \frac{|\bar{v}|^2}{|v|^2 + |\bar{v}|^2 + |x|^2} \qquad (0 \leq \tau \leq 1), \qquad (7)$$

$$\omega = \frac{|x|^2}{|v|^2 + |\bar{v}|^2 + |x|^2} \qquad (0 \leq \omega \leq 1), \qquad (8)$$

resulting in different expressions and ranges for C in different models [9].

The mixing angle is rather highly constrained, to an upper limit of a few $\times\,10^{-3}$, mainly from LEP measurements at the Z [9]. The high statistics on W-pair production expected at the ILC might in principle allow to probe such small mixing angles effectively.

3 Analyses of $e^+ + e^- \rightarrow W^+ + W$

The general expression for the cross section of process (1) with longitudinally polarized electron and positron beams can be expressed as

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

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 ($\lambda = 1/2$) and left-handed ($\lambda = -1/2$) electrons. From Eq. (9), the cross section for polarized (unpolarized) electrons and unpolarized positrons corresponds to $P_L \neq 0$ and $\bar{P}_L = 0$ ($P_L = \bar{P}_L = 0$).

The sensitivity of the polarized differential cross sections to ϕ and M_2 is assessed numerically by dividing the angular range $|\cos\theta| \leq 0.98$ into 10 equal bins, and defining a χ^2 function in terms of the expected number of events $N(i)$ in each bin for a given combination of beam polarizations:

$$\chi^2 = \sum_{\{P_L, \bar{P}_L\}} \sum_i^{\text{bins}} \left[\frac{N_{\text{SM}+Z'}(i) - N_{\text{SM}}(i)}{\delta N_{\text{SM}}(i)}\right]^2, \qquad (9)$$

where $N(i) = \sigma_i\,\varepsilon_W$ with the time-integrated luminosity. Furthermore,

$$\sigma_i = \sigma(z_i, z_{i+1}) = \int_{z_i}^{z_{i+1}} \left(\frac{d\sigma}{dz}\right) dz, \qquad (10)$$

where $z = \cos\theta$ and polarization indices have been suppressed. Also, ε_W is the efficiency for W^+W^- reconstruction, for which we take the channel of lepton pairs ($e\nu + \mu\nu$) plus two hadronic jets, giving $\varepsilon_W \simeq 0.3$ basically from the relevant branching ratios. The procedure outlined above is followed to evaluate both $N_{\text{SM}}(i)$ and $N_{\text{SM}+Z'}(i)$.
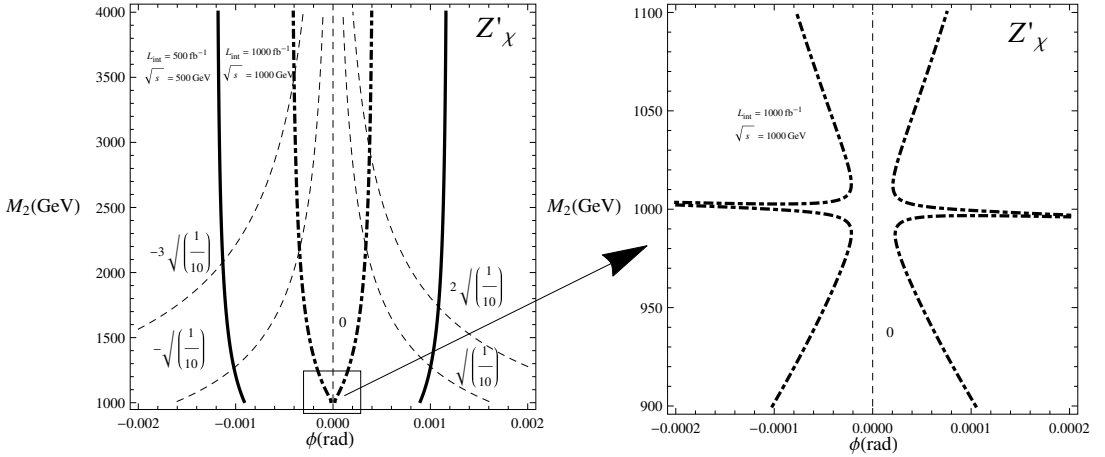
Figure 1. Discovery reach on Z'_χ parameters in the (ϕ, M_2) plane obtained from polarized initial e^+ and e^- beams with $(P_L = \pm 0.8,\ \bar{P}_L = \mp 0.5)$. Solid (dash-dotted) lines correspond to $\sqrt{s} = 0.5$ TeV (1 TeV) and = 0.5 ab^{-1} (1 ab^{-1}). Also shown are the additional constraints in the minimal Higgs model (dashed line). The numbers attached to the curves correspond to different choice of parameter C.
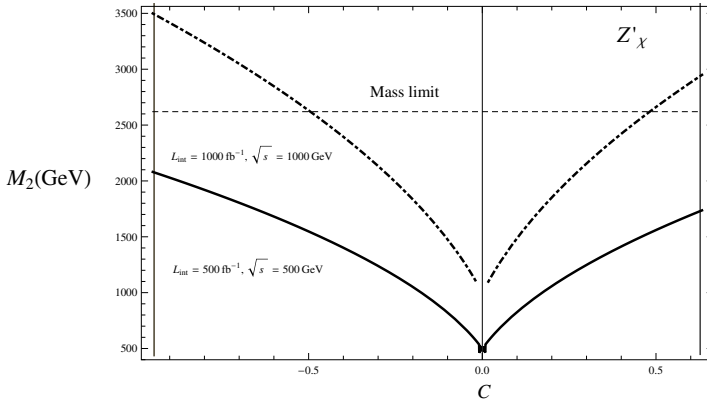

Figure 2. Constraints on the constant C for the Z'_χ model in the (C, M_2) plane. Also the mass limit form the ATLAS experiment is shown(dashed line).

4 Concluding remarks

We have discussed the foreseeable sensitivity to Z's in $W^\pm$-pair production cross sections at the ILC. Our numerical results for our models are summarized in Fig. 1-2 and Table 1. Fig. 1 shows the 95% C.L. allowed contours in $\phi - M_2$ plane for the χ model. Taking in attention modern mass limits for Z' we have calculated regions for constant C allowed for observation at the ILC (Fig. 2 and Table 1).

Table 1. Regions of parameter C where discovery reach on M_2 obtained from process (1) at the ILC(1 TeV) exceeds the current limits on Z' masses derived from dilepton process at the LHC.

Z' model	Z'_χ	Z'_ψ	Z'_η
C	(-0.95,-0.49)(0.48,0.63)	(-0.82,-0.61)(063, 0.82)	(0.40,1.03)
LHC reach on M_2 (TeV)	2.62	2.51	2.44
Z' model	Z'_I	Z'_S	Z'_N
C	(-1,-0.53)(0.50,1)	(-1,-0.53)(0.50,1)	(-0.63,-0.60) (0.59,0.95)
LHC reach on M_2 (TeV)	2.42	2.47	2.39

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