Constraints on $Z-Z'$ mixing from $W^-W^+$ production at the ILC

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Introduction

- Heavy neutral gauge $Z'$-bosons, are predicted by many theoretical schemes of physics beyond the SM, and their properties represent important tests of such extended models.
- Direct $Z'$ searches at the LHC place lower limits on $M_{Z'}$ of the order of 2.5–3.0 TeV depending on the $Z'$ models.
- For ILC with $E_{cm} \leq 1$ TeV only indirect signatures of $Z'$ exchanges or/and $Z-Z'$ mixing may occur at future colliders, through deviations of the measured observables (cross sections, asymmetries etc.) from the SM predictions.
Introduction

We discuss the potential 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.

- enhanced sensitivity to the Z′ parameters in \( e^+e^- \rightarrow W^+W^- \) (violation of the SM gauge cancellation mechanism).
- We consider a specific class of “conventional” Z′ models (E₆) called as “minimal-Higgs” models.
- Higgs vacuum expectation values (VEV) of extended models.
Z’ MODELS AND Z − Z’ MIXING

- **E6:**
  The most popular possible $U(1)' Z'$ scenarios originating from the spontaneous breaking of the exceptional group $E_6$. In this case, two extra, heavy neutral gauge bosons appear as consequence of the symmetry breaking and, generally, only the lightest is assumed to be within reach of the collider. It is defined, in terms of a new mixing angle $\beta$, by the linear combination.

\[
\chi\text{-model: } \beta = 0^\circ \implies U(1)' = U(1)_\chi
\]

\[
\psi\text{-model: } \beta = 90^\circ \implies U(1)' = U(1)_\psi
\]

\[
\eta\text{-model: } \beta = -\arctan \sqrt{5/3} \approx -52.2^\circ \implies U(1)' = \sqrt{3/8} U(1)_\chi - \sqrt{5/8} U(1)_\psi
\]
The mass eigenstates $Z_1$ and $Z_2$ are:

The mixing angle $\varphi$ 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. To a good approximation, for $M_1 \ll M_2$, in specific ‘minimal-Higgs models:

in the case of E6 superstring-inspired models $C$ can be expressed as:

Where $\sigma$ is the ratio of vacuum expectation values squared
\( \sigma^\pm \) are the cross sections for purely right-handed (\( \lambda = 1/2 \)) and left-handed (\( \lambda = -1/2 \)) electrons.

Feynman diagrams for the process \( e^-e^+ \rightarrow \gamma, Z_1, Z_2 \rightarrow W^-W^+ \) in the Born approximation.
As a criterion to derive the constraints on the coupling constants, the sensitivity of the polarized differential cross sections to \( \phi \) and \( M_2 \) is assessed numerically by dividing the angular range \( |\cos \theta| \leq 0.98 \) into 10 equal bins, and defining a \( \chi^2 \) function in terms of the expected number of events \( N(i) \) in each bin for a given combination of beam polarizations:

The 95% CL is obtained by choosing \( \chi_{CL}^2 = 5.99 \).
**EXPERIMENTAL INPUTS**

- $\sqrt{s} = 0.5 (1) \text{ TeV}$
- Integrated Luminosity: $L_{int} = 500 (1000) \text{ fb}^{-1}$
- Polarization:
- Efficiency: $\epsilon_w = 0.3$
- Systematics: $\delta\epsilon_w/\epsilon_w = 0.5\%$, $\delta P_L/P_L = 0.5\%$
Our results

Discovery reach for the χ model in the (φ, M_2) plane obtained from polarized initial e^+ and e^- beams with and unpolarized final W ± states.

Solid (dash-dotted) thick lines correspond to and L_{int} = 0.5 ab^{-1} (1 ab^{-1}). Also shown are the additional constraints in the minimal Higgs case (dashed line)
for $Z'_\Psi$. In the minimal Higgs case the constraints are for $\sigma = 0, 1, 5, \infty$.

for $Z'_\eta$. In the minimal Higgs case the constraints are for $\sigma = 0, 1, 5, \infty$. 
CONCLUSION

1) for minimal Higgs models the limits on $M_2$ are rather strong because $\phi$ and $M_2$ are correlated so that a small $M_2$ would require a large (excluded) $|\phi|$.

2) sensitivity of the ILC for probing the $Z-Z'$ mixing is substantially enhanced when the polarization of the initial beams (and also, possibly, the produced $W^\pm$ bosons) are considered.

3) Only 1 TeV of CM energy allows us to improve constraints on $Z-Z'$

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<table>
<thead>
<tr>
<th>$Z'$ model</th>
<th>$Z'_{\chi}$</th>
<th>$Z'_{\psi}$</th>
<th>$Z'_{\eta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma = 0$</td>
<td>2.3 (3.7)</td>
<td>1.5 (2.5)</td>
<td>1.0 (1.7)</td>
</tr>
<tr>
<td>$\sigma = 1$</td>
<td>2.2 (3.7)</td>
<td>–</td>
<td>1.1 (1.9)</td>
</tr>
<tr>
<td>$\sigma = 5$</td>
<td>2.2 (3.7)</td>
<td>1.3 (2.2)</td>
<td>1.6 (2.6)</td>
</tr>
<tr>
<td>$\sigma = \infty$</td>
<td>2.2 (3.7)</td>
<td>1.5 (2.5)</td>
<td>1.7 (2.9)</td>
</tr>
</tbody>
</table>

Discovery reach on the mass $M_2$ (in TeV) for extra $Z'_{\chi}$, $Z'_{\psi}$, $Z'_{\eta}$ bosons within minimal Higgs models.

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Table 5: Combined mass limits at 95% C.L. on the $E_6$-motivated $Z'$ models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$Z'_{\chi}$</th>
<th>$Z'_{\psi}$</th>
<th>$Z'_{\eta}$</th>
<th>$Z'_{\chi}$</th>
<th>$Z'_{\psi}$</th>
<th>$Z'_{\eta}$</th>
<th>$Z'_{\chi}$</th>
<th>$Z'_{\psi}$</th>
<th>$Z'_{\eta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed mass limit [TeV]</td>
<td>2.38</td>
<td>2.39</td>
<td>2.44</td>
<td>2.42</td>
<td>2.47</td>
<td>2.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected mass limit [TeV]</td>
<td>2.37</td>
<td>2.38</td>
<td>2.43</td>
<td>2.40</td>
<td>2.46</td>
<td>2.53</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Thank you for attention
Table 6 Helicity amplitudes for $e^+e^- \rightarrow \gamma, Z_1, Z_2 \rightarrow W^+W^-$

\[ e^+_L e^-_L \rightarrow W^+_L W^-_L \]
\[ e^+_L e^-_L \rightarrow W^+_T W^-_T \]
\[ e^+_L e^-_L \rightarrow W^+_T W^-_L \]

\[ \tau = \tau' = 0 \]
\[ - \frac{C_{W}^2}{4s} \sin \theta \]

\[ \tau = \tau' = \pm 1 \]
\[ - \frac{C_{W}^2}{4s} \sin \theta \]

\[ \cos \theta - \beta_W \]
\[ - \beta_W \]

\[ \tau = 0, \tau' = \pm 1 \]
\[ - \frac{C_{W}^2}{4s} \left( \tau' \cos \theta - 2 \lambda \right) \]

\[ \tau = \pm 1, \tau' = 0 \]
\[ - \frac{C_{W}^2}{4s} \left( \tau \cos \theta + 2 \lambda \right) \]

\[ \frac{\sqrt{2} C_{W}}{2M_W} \left[ \cos \theta(1 + \beta_W^2) - 2 \beta_W \right] \]
\[ - \frac{2M_W}{\sqrt{2}} \left( \tau \sin^2 \theta / r - \beta_W \right) \]

\[ \frac{\sqrt{2} C_{W}}{2M_W} \left[ \cos \theta(1 + \beta_W^2) - 2 \beta_W \right] \]
\[ - \frac{2M_W}{\sqrt{2}} \left( \tau \sin^2 \theta / r - \beta_W \right) \]

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Fig. 3  Top panel: Unpolarized total cross section for the process $e^+e^- \rightarrow W^+W^-$ for $Z'$ from $E_6$. Bottom panel: Polarized total cross section. Solid lines correspond to the SM case. Dashed (dash-dotted) lines correspond to a $Z'$ model with $\phi = 1.6 \cdot 10^{-3}$ ($\phi = -1.6 \cdot 10^{-3}$), $I_2 = 0.025 \times M_2$ and $M_2 = 2$ TeV.

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$Z_{\chi}$: $\beta = 0^\circ \implies Z' = Z_{\chi}$, which is also the unique solution to the conditions of (i) family universality, (ii) no extra matter other than right handed neutrino, (iii) absence of gauge and mixed gauge/gravitational anomalies and (iv) orthogonality to the hypercharge generator.

$Z_{\psi}$: $\beta = 90^\circ \implies Z' = Z_{\psi}$, possessing only axial vector couplings to ordinary fermions. As discussed in Section 4, it is among the least constrained by the precision data.

$Z_\eta$: $\beta = -\arctan \sqrt{5/3} \approx -52.2^\circ \implies Z' = \sqrt{3/8} Z_{\chi} - \sqrt{5/8} Z_{\psi} \equiv Z_\eta$, occurring in Calabi-Yau compactifications [19] of the heterotic string [20] if $E_6$ breaks directly to a rank 5 subgroup [21] via the Hosotani mechanism [22].

As an illustration, 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 Eq. (2.5) receives contributions from the VEVs of three Higgs doublets, $x \equiv \langle \phi_\nu \rangle$, $v \equiv \langle \phi_N \rangle$ and $\bar{v} \equiv \langle \phi_N \rangle$, respectively, in correspondence with the standard lepton doublet, as well as the two doublets contained in the 5 and 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,