Z' search in e^+e^- annihilation

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Abstract. Expectations for constraints on extra Z bosons are derived for LEP2 and future linear e^+e^- colliders. For typical GUTs, a Z' with \( M_{Z'} \leq 3 \) to 6\( \sqrt{s} \) may cause observable effects. The Z' discovery limits are dominated by statistical errors. However, if a Z' signal is observed, the discrimination between different models becomes much worse if systematic errors are taken into account. Discrimination between models is possible for \( M_{Z'} < 3 \sqrt{s} \). A determination of Z'ff couplings independently of models becomes attractive with future colliders. Anticipated bounds are determined.

1 Introduction

Extra neutral gauge bosons (Z') are predicted in many extensions of the Standard Model (SM). At future e^+e^- colliders, a Z' can be probed by its virtual effects on cross sections and asymmetries even if it is much heavier than the centre-of-mass energy. Presently, we have no experimental indications for extra neutral gauge bosons. Search results are usually reported as lower limits on the Z' mass, \( M_{Z'}^{min} \), or upper limits on the ZZ' mixing angle for various Z' models.

In this paper, we continue our study of these limits started in [1, 2]. In comparison to [3], expected systematic errors are included. Taking into account radiative and QCD corrections and applying cuts, we approach a more realistic description of future detectors and go beyond [3, 4, 5]. In addition to [4, 5], more observables are included.

We set the ZZ' mixing angle equal to zero in accordance with present experimental constraints [6, 7, 8]. CDF data indicate that LEP2 and LC500 will operate below a potential Z' peak [9]. Similarly, the LHC will be able to detect or exclude a Z', which could be produced at LC2000 on resonance. Here, we assume that LC2000 will operate below the Z' peak, too. Further, we presume universality of generations. Theories including extra neutral gauge bosons usually predict new fermions [10, 11]. Their effects are neglected here.

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We focus on a model-independent approach trying to constrain the mass and the couplings of Z' to fermions by different observables. For Z' couplings to leptons, this can be done without further assumptions. A measurement of Z' couplings to quarks demands non-zero couplings to leptons and is dependent on the latter. In addition to the model-independent analysis, we discuss limits on the Z' mass and couplings for some typical models given in the Particle Data Book [12].

Neutral currents due to the Z' are

\[
\begin{align*}
J_{E}^{\mu} &= J_{\chi}^{\mu} \cos \beta + J_{\psi}^{\mu} \sin \beta, \\
J_{E}^{\mu} &= \alpha_{LR} J_{3R}^{\mu} - \frac{1}{2\alpha_{LR}} J_{B-L}^{\mu}.
\end{align*}
\]

Some specified cases are the \( \chi, \psi, \) and \( \eta \) model with \( \beta = 0, \pi/2, -\arctan(\sqrt{5}/3) \) in the \( E_6 \) GUT [11, 13], while special cases discussed in the Left-Right model [13, 14] are obtained for \( \alpha_{LR} \) equal to \( \sqrt{2}/3 \) and \( 1/\sqrt{\cot^2 \theta_W - 1} \). The first value of \( \alpha_{LR} \) reproduces the \( \chi \) model while the second one gives the Left-Right Symmetric model (LR). We also consider the Sequential Standard Model (SSM), where the heavy Z' has exactly the same couplings to fermions as the Standard Z boson.

We compare the discovery potential of all relevant reactions in e^+e^- collisions in Sect. 2. In Sect. 3.1, we discuss model-independent constraints on the Z' couplings to leptons, which can be derived from the reaction e^+e^- \( \rightarrow \) ff. The model-independent Z' couplings to quarks are considered in Sect. 3.2. Section 4 summarizes expected limits for typical models. We conclude in Sect. 5.

2 Comparing the final states ff, W^+W^-, 4f

In this section, we compare the reactions e^+e^- \( \rightarrow \) ff, \( e^+e^- \rightarrow f_1f_2f_3f_4, \) and e^+e^- \( \rightarrow \) W^+W^- regarding their sensitivity to indirect Z' signals. We do not consider special effects from the t-channel of Bhabha scattering. For a Born analysis of e^+e^- \( \rightarrow e^-e^- \), we refer to [15].

A (virtual) Z' can be detected by an observable \( O \), if it induces a change \( \Delta^2 N \) in the event rate \( N_{SM} \), surpassing the experimental error \( \Delta O \), i.e.
\[\frac{\Delta^Z N}{N_{SM}} > \frac{\Delta O}{O}.\] (2)

For a crude estimate, one can approximate \(\Delta^Z N/N_{SM}\) by a ratio of propagators \(D_V = [s - M_Z^2 + i\Gamma_V M_V]^{-1}\) assuming that the \(Z'\), the photon and the SM Z boson couple with similar strengths to SM fermions\(^1\).

We first consider the reaction \(e^+e^- \to f\bar{f}\). Only the ZZ' interference is important near but off the Z resonance,

\[\frac{\Delta^Z N}{N_{SM}} \approx \frac{|\Re D_Z D_{Z'}^*|}{|D_Z|^2} = \frac{(s - M_Z^2)\Gamma_Z^2 M_Z^2}{((s - M_Z^2)^2 + \Gamma_M^2 M_Z^2)(M_Z^2 - s)}.\] (3)

Choosing \(s = (M_Z + \Gamma_Z/2)^2\), we find from (2) and (3) that a \(Z'\) with a mass

\[M_{Z'} > M_Z \left(1 + \frac{O}{\Delta O} \frac{\Gamma_Z}{M_Z}\right)^{1/2}\] (4)

cannot be excluded. For \(e^+e^- \to f\bar{f}\) far off the resonance, we better consider the \(\gamma Z'\) interference. In this case, the deviation from the Standard Model event rate,

\[\frac{\Delta^Z N}{N_{SM}} \approx \frac{|\Re D_\gamma D_{Z'}^*|}{|D_\gamma|^2} = \frac{s}{M_{Z'}^2 - s}\] (5)

results to

\[M_{Z'} > \sqrt{s} \left(1 + \frac{O}{\Delta O} \frac{\Gamma_Z}{M_Z}\right)^{1/2}\] (6)

For \(\Delta O/O = 1\%), (6) leads to a lower bound on the \(Z'\) mass,

\[M_{Z'} > M_{Z'}^{\text{lim}} \approx \gamma s/\sqrt{s} (\text{two standard deviations}).\]

Comparing the two expressions (4) and (6) for \(Z'\) measurements near and far off the Z peak we see in (4) an additional suppression factor \(\Gamma_Z/M_Z\). With \(O/\Delta O \approx 1\) (6) is simplified to

\[M_{Z'} > \sqrt{s} \times \frac{\sqrt{O}}{\Delta O} \text{corresponding to the well known scaling law}\] [5, 16, 17]

\[M_{Z'} > (s L_{int})^{1/4}\] (7)

with an integrated luminosity \(L_{int}\).

Four fermion final states are created in higher order processes. Their cross sections are enhanced by resonating Z propagators near the two–Z–boson threshold. There, the \(Z'\) limits are also given by (4). As soon as we forbid resonating Z propagators by invariant mass cuts, formula (6) should be used. Unfortunately, we are left with no events in this case. As a result, four fermion final states will not add any useful information about a \(Z'\).

To get \(Z'\) signals in W pair production, one has to assume a non-zero \(Z'WW\) coupling, \(g_{Z'WW} = C g_{ZWW}\). Considering the \(\gamma Z'\) interference, we get

\[\frac{\Delta^Z N}{N_{SM}} \approx \frac{|\Re D_\gamma D_{Z'}^*|}{|D_\gamma|^2} = C \frac{s}{M_{Z'}^2 - s}\] (8)

and conclude that a \(Z'\) with a mass

\[M_{Z'} < \sqrt{s} \left(1 + C \frac{O}{\Delta O}\right)^{1/2}\] (9)

would give a signal in the observable \(O\).

\(^1\) This is not unreasonable in usual GUTs.

![Fig. 1. The normalized vector and axial couplings Z' for M_{Z'} = 3\sqrt{s} in typical GUTs. For illustration, M_{Z'} for the \(\chi\) model is varied in units of \(\sqrt{s}\).](image)

The magnitude of \(C\) defines the strength of the \(Z'WW\) coupling and is strongly limited by the decay width of the \(Z'\) to W pairs, \(\Gamma(Z' \to W^+W^-) \approx M_{Z'} C^2 M_Z^2/M_W^2\). In a usual GUT, a reasonable decay width \(\Gamma(Z' \to W^+W^-)\) results from \(C \approx \theta_M \approx M_Z^2/M_W^2\), where \(\theta_M\) is the \(Z'\) mixing angle. Taking into account present experimental limits on the \(Z'\) mixing and on the \(Z'\) mass, we conclude that \(C\) must be considerably smaller than one. Hence, the limit (9) is always worse than that from fermion pair production. The result of these simple estimations (9) is in accordance with the results of [18].

### 3 Model-independent Z' search

The reaction \(e^+e^- \to f\bar{f}\) being most sensitive to a \(Z'\) needs further consideration. We proceed from the following effective Lagrangian,

\[\mathcal{L} = e A_\beta J^\beta + g_1 Z_\beta J^\beta + g_2 Z'_{\beta J^\beta}\]

(10)

which contains a term describing the additional neutral current interactions of the \(Z'\) with SM fermions. The new interaction leads to an additional amplitude of fermion pair production,

\[\mathcal{M}(Z') = \frac{g_2}{s - m_{Z'}^2} \bar{u}_e \gamma_\beta (\gamma_5 a_1^e + v_1^e) u_\ell \bar{u}_\ell \gamma_\beta (\gamma_5 a_1^\ell + v_1^\ell) u_\ell\]

\[= -\frac{4\pi}{s} \left(\bar{u}_e \gamma_\beta (\gamma_5 a_1^e + v_1^e) u_\ell \bar{u}_\ell \gamma_\beta (\gamma_5 a_1^\ell + v_1^\ell) u_\ell\right)\]

(11)

with \(a_1^e = a_1^\ell = \sqrt{\frac{g_2^2}{4\pi}} \sqrt{\frac{s}{m_{Z'}^2 - s}}\)

(12)

and

\[m_{Z'}^2 = M_{Z'}^2 - i\Gamma_{Z'} M_{Z'}\]