IDENTIFICATION OF Z' BOSON MODELS AT THE ILC

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Abstract

The identification reaches of the new neutral gauge bosons at the International linear electron-positron collider (ILC) within the classes of E_6 and LR models were determined. In particular, it was shown that the polarized experiments at the ILC with the energy of 0.5 TeV and integrated luminosity of 100 fb^{-1} allow to identify the whole set of Z' models under consideration for $M_{Z'} < 6 \cdot \sqrt{s}$, and also, substantially improve the corresponding reaches obtained from unpolarized experiments.

1 Introduction

Searches for signals of new physics - that is, effects beyond Standard Model - represent an important part of experimental programs (both those that are being presently implemented and those that are planned) aimed at studying particle physics over the entire range of currently accessible energies. The principle reason for this is the following. Although the modern theory of electroweak and strong interactions is self-consistent and is capable of accurately describing available experimental data, some theoretical problems of a fundamental character remain unsolved [1]. Therefore, one would expect the existence of a more

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fundamental theory in which the SM is naturally embedded and which reduces to it at present energies.

Among the candidates for this more fundamental picture, grand unified theories are the most appealing ones. In particular, the exceptional group E_6, which contains the popular subgroups $SU(5)$ and $SO(10)$, has received most of the attention in recent years [2]-[7]. A general prediction of grand unified theories is the existence of additional gauge bosons Z'. This additional boson could then be light enough to generate observable effects at the next generation of electron-positron or hadron colliders.

Depending on the assumed luminosity of the machine, the nature of the Z' as well as its decay branching fractions, discovery limits range up to 4-5 TeV at the LHC. At e^+e^- ILC, since their presently planned energies do not exceed one TeV, the possibility of directly producing a new gauge boson is more limited than at LHC. However, even if a new Z' is too heavy to be produced as a resonance, it could give rise to virtual effects which are measurable. In this report, we shall discuss the possible effects of one extra neutral gauge boson at high energy e^+e^- colliders, concentrating on two general effective theories: $SU(2)_L \times U(l)_Y \times U(1)_{Y'}$ originating from the E_6 model and left-right models [2] based on an $SU(2)_L \times SU(2)_R \times U(1)$ symmetry.

2 Differential cross sections and Z' models

We consider the fermion pair production process

$$e^+ + e^- \to f + \bar{f}, \tag{1}$$

with $f \neq t$ at the ILC with c.m. energy $\sqrt{s} = 0.5\,\text{TeV}$ and polarized electron and positron beams. For the process Eq. (1), limiting ourselves to the cases $f \neq t$, we can neglect fermion masses with respect to $\sqrt{s}$, and express the amplitude in the Born approximation including the γ, Z and Z' s-channel exchanges. With P_e and $P_{\bar{e}}$ the longitudinal polarizations of the electron and positron beams, respectively, and θ the angle between the incoming electron and the outgoing fermion in the c.m. frame, the differential cross section can be expressed as [5]:

$$\frac{d\sigma(P^-,P^+)}{dz} = \frac{D}{4}\left[(1-P_{\text{eff}})\left(\frac{d\sigma_\text{L}}{dz}\right) + (1+P_{\text{eff}})\left(\frac{d\sigma_\text{R}}{dz}\right)\right], \tag{2}$$

where $z = \cos\theta$; L, R are the helicity indexes. Here,

$$P_{\text{eff}} = \frac{P_e - P_{\bar{e}}}{1 - P_e P_{\bar{e}}} \tag{3}$$

is the effective polarization, $|P_{\rm eff}| \le 1$, and $D = 1 - P_e P_{\bar e}$, and

$$\frac{d\sigma_{\rm L}}{dz} = \frac{d\sigma_{\rm LL}}{dz} + \frac{d\sigma_{\rm LR}}{dz}, \qquad \frac{d\sigma_{\rm R}}{dz} = \frac{d\sigma_{\rm RR}}{dz} + \frac{d\sigma_{\rm RL}}{dz}. \tag{4}$$

The formulas for helicity differential cross sections including the ones for Bhabha scattering can be found, for example, in [6, 7].

In the following analysis, cross sections will be evaluated including initial- and final-state radiation by means of the program ZFITTER [8], which has to be used along with ZEFIT, adapted to the present discussion, with $m_{\rm top} = 175$ GeV and $m_H = 120$ GeV. One-loop SM electroweak corrections are accounted for by improved Born amplitudes, such that the forms of the previous formulae remain the same. Concerning initial-state radiation, a cut on the energy of the emitted photon $\Delta = E_\gamma/E_{\rm beam} = 0.9$ is applied for $\sqrt{s} = 0.5$ TeV in order to avoid the radiative return to the Z peak, and increase the signal originating from the contact interaction contribution.

As numerical inputs, we shall assume the commonly used reference values of the identification efficiencies: $\epsilon = 95\%$ for l^+l^-; $\epsilon = 60\%$ for $b\bar b$; $\epsilon = 35\%$ for $c\bar c$. In order to evaluate the statistical uncertainty we take $L = 100$ fb^{-1} (half for each polarization orientation) with uncertainty $\delta L/L = 0.5\%$, and a fiducial experimental angular range $|\cos\theta| \le 0.99$. Also, regarding electron and positron degrees of polarization, we shall consider the values: $|P_e| = 0.8$; $|P_{\bar e}| = 0.5$, with $\delta P_e/P_e = \delta P_{\bar e}/P_{\bar e} = 0.5$ %.

The list of Z' models that will be considered in our analysis is the following:

(i) The three possible $U(1)$ Z' scenarios originating from the exceptional group E_6 spontaneous breaking. They are defined in terms of a mixing angle β, and the couplings are as in Tab. 1. The specific values $\beta = 0$, $\beta = \pi/2$ and $\beta = \arctan(-\sqrt{5/3})$, correspond to different E_6 breaking patterns and define the popular scenarios Z'_χ, Z'_ψ and Z'_η, respectively.

(ii) The left-right models, originating from the breaking of an $SO(10)$ grand-unification symmetry, and where the corresponding $Z'_{\rm LR}$ couples to a combination of right-handed and $B-L$ neutral currents (B and L denote lepton and baryon currents), specified by a real parameter $\alpha_{\rm LR}$ bounded by $\sqrt{2/3} \le \alpha_{\rm LR} \le \sqrt{2}$. Corresponding Z' couplings are reported in Tab. 1. We fix $\alpha_{\rm LR} = \sqrt{2}$, which corresponds to a pure L-R symmetric model (LRS).

All numerical values of the Z' couplings needed for the amplitudes are collected in Table 1, where: $A = \cos\beta/2\sqrt{6}$ and $B = \sqrt{10}\sin\beta/12$ are used.

Table 1. Left- and right-handed couplings of the first generation of SM fermions to the Z' gauge bosons, in units of $1/c_W$ for the E_6 and LR models, where $c_W = \cos\theta_W$, $s_W = \sin\theta_W$.

E_6 model				
fermions (f)	ν	e	u	d
$g_L^{f'}$	$3A+B$	$3A+B$	$-A+B$	$-A+B$
$g_R^{f'}$	0	$A-B$	$A-B$	$-3A-B$
Left-Right model (LR)				
$g_L^{f'}$	$\frac{1}{2\alpha_{LR}}$	$\frac{1}{2\alpha_{LR}}$	$-\frac{1}{6\alpha_{LR}}$	$-\frac{1}{6\alpha_{LR}}$
$g_R^{f'}$	0	$\frac{1}{2\alpha_{LR}} - \frac{\alpha_{LR}}{2}$	$-\frac{1}{6\alpha_{LR}} + \frac{\alpha_{LR}}{2}$	$-\frac{1}{6\alpha_{LR}} - \frac{\alpha_{LR}}{2}$

3 Numerical analysis and constraints on Z' masses

Heavy resonances appearing in the clean Drell-Yan channel may be the first new physics to be observed at the LHC. In this section we assume that the Z' has been discovered in pp collisions as a mass peak or bump at the LHC and we want to discuss how to elucidate the origin of this new gauge boson at the ILC. In other words, we make the hypothesis that a Z' signal is effectively observed (so that the SM is excluded at a certain C.L.) and the data is consistent with one of the Z' models. We want to assess the level at which this Z' model, that we call "true" model, can be expected to be distinguishable from the other ones, that may compete with it as sources of the deviations from the SM and that we call "tested" models, for any values of their mass $M_{Z'}$. Quantitatively, this amounts to determine the foreseeable "identification reach" on the "true" model.

To illustrate the numerical procedure leading to the determination of an "identification reach", it should be useful to work out explicitly a definite example, and assume that the "true" non-standard model is a E_6 model with some value of $\cos\beta$ and $M_{Z'}$. Then, we may take as "tested" model anyone of the Z' models and, for definiteness, let us choose the LR model.

We can introduce a relative deviation of an observable $\mathcal{O}$ predictions arising from the chosen Z' model (Z'_{LR}):

$$\Delta\mathcal{O} = \frac{\mathcal{O}(Z'_{\mathrm{LR}}) - \mathcal{O}(Z'_{\mathrm{E_6}})}{\mathcal{O}(Z'_{\mathrm{E_6}})}. \tag{5}$$

As the observables $\mathcal{O}$ in (5) in this analysis we will use polarizing differential cross sections (2), $\mathcal{O} = \mathrm{d}\sigma(P^-, P^+)/\mathrm{d}z$.

According to the definition (5), one can introduce χ^2 function,

$$\chi^2 = \sum_f \chi_f^2, \tag{6}$$

where

$$\chi_f^2 = \sum_{\{P^-,\, P^+\}} \sum_{\text{bins}} \left(\frac{\Delta \mathcal{O}_f^{\text{bin}}}{\delta \mathcal{O}_f^{\text{bin}}} \right)^2 . \tag{7}$$

Here $\Delta\mathcal{O}_f$ is defined in Eq. (5), and the uncertainty $\delta\mathcal{O}_f$ is referred to the E_6 model prediction of the observable $\mathcal{O}_f$. $\delta\mathcal{O}_f$ combines both the statistical and systematic uncertainties. The inequality that defines the confusion region between the two Z' models, E_6 and LR, at the 95% C.L. can be determined from

$$\chi^2(\mathcal{O}_f) \leq 3.84. \tag{8}$$

Distinctive feature of linear e^+e^- colliders is possibility of carrying out of polarizing experiments. For studying of a role of beam polarization for identification classes of models with Z' - bosons in the experiments at ILC three types polarizing combinations, namely, not polarized electron and positron beams, ($P^- = 0$, $P^+ = 0$), the electron beam polarized only, ($P^- \neq 0$ $P^+ = 0$), and both polarized beams, ($P^- \neq 0$, $P^+ \neq 0$) have been investigated.

Fig. 1- 2 show the confusion region between between E_6 and left-right LR models in the model parameter plane $(\cos\beta, \alpha_{\text{LR}})$ for $M_{Z'} = 4.5$ TeV obtained with Eq. (8) from the processes with lepton and quark final states $e^+e^- \rightarrow e^+e^-$, l^+l^- ($l = \mu, \tau$) $c\bar{c}$, $b\bar{b}$ at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{int} = 500$ fb^{-1}. The role of polarization is also demonstrated by choosing different sets of polarized beams as explained above in the text. The exclusion range is indicated as white area, the shaded areas denote the regions of confusion.

4 Concluding remarks

In this report, we examined the potential of the e^+e^- ILC to search for and distinguish between new neutral gauge bosons signals predicted within various classes of models with extended gauge sector in fermion pair production processes. The presented analysis is based on the polarized differential observables

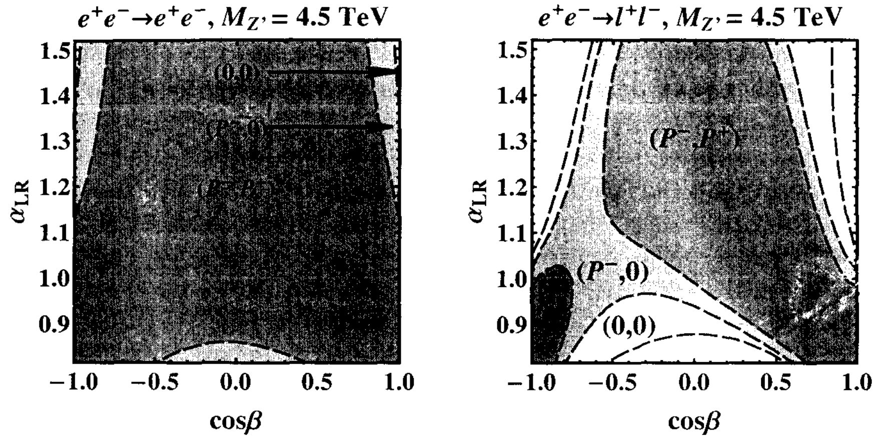

Figure 1. Regions of confusion between E_6 and left-right LR models in the model parameter plane $(\cos\beta, \alpha_{\rm LR})$ for $M_{Z'} = 4.5$ TeV obtained from the processes with lepton final states $e^+e^- \to e^+e^-$, l^+l^- $(l = \mu, \tau)$ at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{int} = 500$ fb^{-1}.

which provide higher sensitivity of the studied processes to Z' boson parameters with respect to the integrated observables. The identification reaches of the new neutral gauge bosons within the classes of E_6 and LR models were determined. In particular, it was shown that the polarized experiments at the electron-positron collider with the energy of 0.5 TeV and integrated luminosity of 100 fb^{-1} allow to identify the whole set of Z' models under consideration and substantially improve the corresponding reaches obtained from unpolarized experiments.

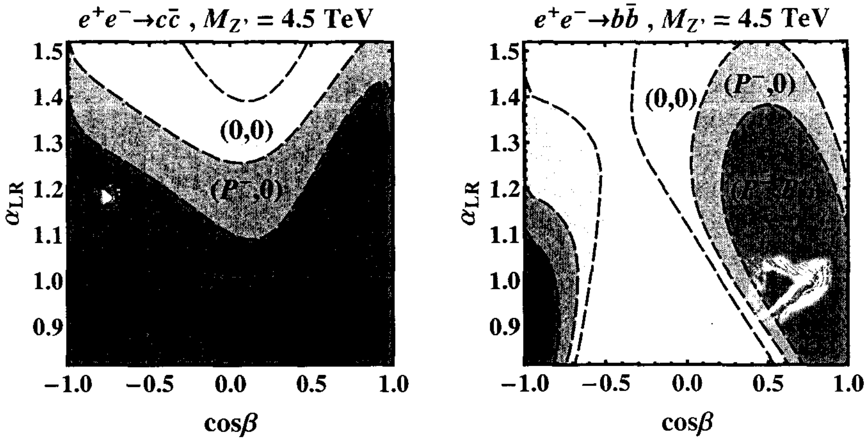

Figure 2. Regions of confusion between E_6 and left-right LR models in the model parameter plane $(\cos\beta, \alpha_{\rm LR})$ for $M_{Z'} = 4.5$TeV obtained from the processes with quark final states $e^+e^- \to c\bar{c}$, $b\bar{b}$ at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{int} = 500$ fb^{-1}.

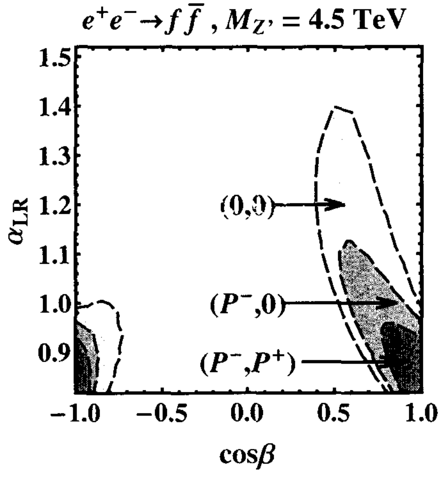

Figure 3. Regions of confusion between E_6 and left-right LR models in the model parameter plane $(\cos\beta, \alpha_{\rm LR})$ for $M_{Z'} = 4.5$ TeV derived from the combined all the processes $e^+e^- \to f\bar{f}$, at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{int} = 500$ fb^{-1}.

References

[1] P. Langacker, arXiv:0901.0241 [hep-ph].

[2] J. L. Hewett and T. G. Rizzo, Phys. Rept. **183** (1989) 193.

[3] A. Leike, Phys. Rept. **317** (1999) 143.

[4] J. Erler, P. Langacker, S. Munir and E. R. Pena, JHEP **0908** (2009) 017 [arXiv:0906.2435 [hep-ph]].

[5] A. A. Pankov and N. Paver, Phys. Rev. D **72**, 035012 (2005).

[6] A. A. Pankov and N. Paver, Eur. Phys. J. C **29**, 313 (2003).

[7] A. A. Pankov, N. Paver and A. V. Tsytrinov, Phys. Rev. D **73**, 115005 (2006).

[8] D. Y. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann and T. Riemann, Comput. Phys. Commun. **133**, 229 (2001).

[9] For reviews see, e.g., O. Nicrosini and L. Trentadue, in *Radiative Corrections for e^+e^- Collisions*, ed. J. H. Kühn 25 (Springer, Berlin, 1989), p. 25; in *QED Structure Functions, Ann Arbor, MI, 1989*, ed. G. Bonvicini, AIP Conf. Proc. No. 201 (AIP, New York, 1990), p. 12.