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Model identification of new heavy Z' bosons at ILC with polarized beams

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Abstract. Extra neutral gauge bosons, Z's, are predicted by many theoretical scenarios of physics beyond the Standard Model, and intensive searches for their signatures will be performed at present and future high energy colliders. It is quite possible that Z's are heavy enough to lie beyond the discovery reach expected at the CERN Large Hadron Collider LHC, in which case only indirect signatures of Z' exchanges may occur at future colliders, through deviations of the measured cross sections from the Standard Model predictions. We here discuss in this context the expected sensitivity to Z' parameters of fermion-pair production cross sections at the planned International Linear Collider (ILC), especially as regards the potential of distinguishing different Z' models once such deviations are observed. Specifically, we evaluate the discovery and identification reaches on Z' gauge bosons pertinent to the E_6, LR, ALR and SSM classes of models at the ILC.

1. Introduction

Electroweak theories beyond the Standard Model (SM) based on spontaneously broken extended gauge symmetries naturally envisage the existence of heavy, neutral, vector bosons Z'. The variety of the proposed Z' models is somewhat broad, and for definiteness in the sequel we shall focus on the so-called $Z'_{\rm SSM}$, Z'_{E_6}, $Z'_{\rm LR}$ and $Z'_{\rm ALR}$ models [1, 2]. Particular attention has recently been devoted to the phenomenological properties and the search reaches on such scenarios, and in some sense we may consider these Z' models as representative of this New Physics (NP) sector.

A typical manifestation of the production of such states is represented by (narrow) peaks observed in the cross sections for processes among SM particles at high energy accelerators, for example, in the dilepton invariant mass distributions for Drell-Yan (DY) process $pp \to Z' \to \ell^+\ell^- + X$ with $\ell = e, \mu$ at the CERN LHC hadronic colliders. Current experimental search limits on $M_{Z'}$ at 95% C.L., at the LHC with $\sqrt{s} = 13$ TeV using ≈ 36 fb^{-1} in DY, generally range in the interval 3.8–4.5 TeV, depending on the particular Z' model being tested [3, 4].

Clearly, the eventual discovery of a peak should be supplemented by the verification of the spin-1 of the assumed underlying Z', vs. the alternative spin-2 and spin-0 hypotheses corresponding, e.g., to exchanges of a Randall-Sundrum graviton resonance or a sneutrino. This kind of analysis relies on appropriate angular differential distributions and/or angular

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asymmetries. Finally, once the spin-1 has been established, the particular Z' scenario pertinent to the observed signal should be identified, see, e.g., Refs. [5, 6]. From studies of Drell-Yan processes at the LHC with a time-integrated luminosity of 100 fb^{-1}, it turns out that one can expect, at the 5-σ level, discovery limits on $M_{Z'}$ of the order of 4–4.5 TeV, spin-1 identification up to $M_{Z'} \simeq 2.5$–3.0 TeV and potential of distinction among the individual Z' models up to $M_{Z'} \simeq 2.1$ TeV (95% C.L.).

An alternative resource for the observation of virtual heavy gauge boson exchanges should be represented by the next generation e^+e^- ILC, with center of mass energy $\sqrt{s} = 0.5$–1 TeV and typical time-integrated luminosities $\mathcal{L}_{\rm int} \sim 0.5$–1 ab^{-1}, and the really high precision measurements that will be possible there. Indeed, the baseline configuration envisages a very high electron beam polarization (larger than 80%) and positron beam polarization of order 60% [7].

We will here focus on the fermion-antifermion production reactions at the polarized ILC [8]:

$$e^+ + e^- \to f + \bar{f}, \qquad f = e, \mu, \tau, c, b. \tag{1}$$

Particular emphasis will be given to the comparison between the cases of unpolarized and polarized initial beams, as regards the expected potential of ILC in identifying the Z' models of interest here, for $M_{Z'}$ values beyond the limits accessible at the LHC. Concerning the Z' mass, we will follow the scenario where the Z' mass range is above the LHC discovery limit and, here, with $M_{Z'}$ unknown, both discovery and identification reaches should be assessed for the ILC.

2. Observables and Z' models

The polarized differential cross section for the Bhabha process $e^+ + e^- \to e^+ + e^-$, where γ and Z can be exchanged also in the t-channel, can be written at leading order as [8]:

$$\begin{aligned}\frac{\mathrm{d}\sigma(P^-,P^+)}{\mathrm{d}z} &= \frac{(1+P^-)(1-P^+)}{4}\frac{\mathrm{d}\sigma_{\rm R}}{\mathrm{d}z} + \frac{(1-P^-)(1+P^+)}{4}\frac{\mathrm{d}\sigma_{\rm L}}{\mathrm{d}z} \\ &+ \frac{(1+P^-)(1+P^+)}{4}\frac{\mathrm{d}\sigma_{{\rm RL},t}}{\mathrm{d}z} + \frac{(1-P^-)(1-P^+)}{4}\frac{\mathrm{d}\sigma_{{\rm LR},t}}{\mathrm{d}z},\end{aligned} \tag{2}$$

with the decomposition

$$\frac{\mathrm{d}\sigma_{\rm L}}{\mathrm{d}z} = \frac{\mathrm{d}\sigma_{\rm LL}}{\mathrm{d}z} + \frac{\mathrm{d}\sigma_{{\rm LR},s}}{\mathrm{d}z}, \qquad \frac{\mathrm{d}\sigma_{\rm R}}{\mathrm{d}z} = \frac{\mathrm{d}\sigma_{\rm RR}}{\mathrm{d}z} + \frac{\mathrm{d}\sigma_{{\rm RL},s}}{\mathrm{d}z}. \tag{3}$$

In Eqs. (2) and (3), the subscripts t and s denote helicity cross sections with SM γ and Z exchanges in the corresponding channels, $z = \cos\theta$ and the subscripts L, R denote the respective helicities, P^- and P^+ denote the degrees of longitudinal polarization of the e^- and e^+ beams, respectively.[1] In terms of helicity amplitudes:

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\rm LL}}{\mathrm{d}z} &= \frac{2\pi\alpha^2_{\rm e.m.}}{s}\left|G^{ee}_{{\rm LL},s} + G^{ee}_{{\rm LL},t}\right|^2, \qquad \frac{\mathrm{d}\sigma_{\rm RR}}{\mathrm{d}z} = \frac{2\pi\alpha^2_{\rm e.m.}}{s}\left|G^{ee}_{{\rm RR},s} + G^{ee}_{{\rm RR},t}\right|^2, \\ \frac{\mathrm{d}\sigma_{{\rm LR},t}}{\mathrm{d}z} &= \frac{\mathrm{d}\sigma_{{\rm RL},t}}{\mathrm{d}z} = \frac{2\pi\alpha^2_{\rm e.m.}}{s}\left|G^{ee}_{{\rm LR},t}\right|^2, \qquad \frac{\mathrm{d}\sigma_{{\rm LR},s}}{\mathrm{d}z} = \frac{\mathrm{d}\sigma_{{\rm RL},s}}{\mathrm{d}z} = \frac{2\pi\alpha^2_{\rm e.m.}}{s}\left|G^{ee}_{{\rm LR},s}\right|^2.\end{aligned} \tag{4}$$

According to the previous considerations the amplitudes $G^{ee}_{\alpha\beta,i}$, with $\alpha, \beta = {\rm L,R}$ and $i = s, t$, are given by the sum of the SM γ, Z exchanges plus deviations representing the effect induced

[1] In the review [7], the opposite sign convention for positron polarization was adopted.

by a Z' boson:

$$
\begin{aligned}
G^{ee}_{\mathrm{LL},s} &= u\left(\frac{1}{s}+\frac{(g^e_{\mathrm{L}})^2}{s-M_Z^2}+\frac{(g^{e\prime}_{\mathrm{L}})^2}{s-M_{Z'}^2}\right), \qquad G^{ee}_{\mathrm{LL},t} = u\left(\frac{1}{t}+\frac{(g^e_{\mathrm{L}})^2}{t-M_Z^2}+\frac{(g^{e\prime}_{\mathrm{L}})^2}{t-M_{Z'}^2}\right),\\
G^{ee}_{\mathrm{RR},s} &= u\left(\frac{1}{s}+\frac{(g^e_{\mathrm{R}})^2}{s-M_Z^2}+\frac{(g^{e\prime}_{\mathrm{R}})^2}{s-M_{Z'}^2}\right), \qquad G^{ee}_{\mathrm{RR},t} = u\left(\frac{1}{t}+\frac{(g^e_{\mathrm{R}})^2}{t-M_Z^2}+\frac{(g^{e\prime}_{\mathrm{R}})^2}{t-M_{Z'}^2}\right),\\
G^{ee}_{\mathrm{LR},s} &= t\left(\frac{1}{s}+\frac{g^e_{\mathrm{R}}\,g^e_{\mathrm{L}}}{s-M_Z^2}+\frac{g^{e\prime}_{\mathrm{R}}\,g^{e\prime}_{\mathrm{L}}}{s-M_{Z'}^2}\right), \qquad G^{ee}_{\mathrm{LR},t} = s\left(\frac{1}{t}+\frac{g^e_{\mathrm{R}}\,g^e_{\mathrm{L}}}{t-M_Z^2}+\frac{g^{e\prime}_{\mathrm{R}}\,g^{e\prime}_{\mathrm{L}}}{t-M_{Z'}^2}\right). \qquad (5)
\end{aligned}
$$

Here, $u,t=-s(1\pm z)/2$ (we are neglecting fermion masses), $g_{\mathrm{L}}=-\cot 2\,\theta_W$ and $g_{\mathrm{R}}=\tan\theta_W$ with θ_W the electroweak mixing angle, whereas g'_{L} and g'_{R} are characteristic of the particular Z' model. In the annihilation channel, below the Z' mass, the Z' interference with the SM will be destructive in the LL and RR cross sections, whereas it can be of either sign in the LR and RL cross sections.

The polarized differential cross section for the leptonic channels $e^+e^-\to l^+l^-$ with $l=\mu,\tau$ can be obtained directly from Eq. (2), basically by dropping the t-channel contributions. The same is true, after some obvious substitutions, for the annihilations into $c\bar{c}$ and $b\bar{b}$ final states, in which case also the color (N_C) and QCD correction factors, $C_s\simeq N_C\,[1+\alpha_s/\pi+1.4\,(\alpha_s/\pi)^2]$, must be taken into account. The s-channel helicity amplitudes for the process (1) with $f\neq e,t$ can be written as:

$$
G^{ef}_{\alpha\alpha,s} = u\left(\frac{Q_e\,Q_f}{s}+\frac{g^e_\alpha g^f_\alpha}{s-M_Z^2}+\frac{g'^e_\alpha g'^f_\alpha}{s-M_{Z'}^2}\right), \qquad G^{ef}_{\alpha\beta,s} = t\left(\frac{Q_e\,Q_f}{s}+\frac{g^e_\alpha g^f_\beta}{s-M_Z^2}+\frac{g'^e_\alpha g'^f_\beta}{s-M_{Z'}^2}\right), \qquad (6)
$$

where in the latter expression $\alpha\neq\beta$.

We evaluate the discovery and identification reaches on Z' gauge bosons pertinent to the E_6, LR, ALR and SSM classes of models at the ILC.

3. Discovery reach on the Z' mass

In the absence of available data, the assessment of the expected 'discovery reaches' on the various Z's needs the definition of a 'distance' between the NP model predictions and those of the SM for the basic observables that will be measured. The former predictions parametrically depend on the Z' mass and its corresponding coupling constants, while the latter ones are calculated using the parameters known from the SM fits. Such a comparison can be performed by a standard χ^2-like procedure. We divide the full angular range into bins and identify the basic observables with the polarized differential angular distributions for processes (1), $\mathcal{O}=\mathrm{d}\sigma(P^-,P^+)/\mathrm{d}z$, in each bin. Correspondingly, the relevant χ^2 can symbolically be defined as:

$$
\chi^2(\mathcal{O})=\sum_f\sum_{\{P^-,\;P^+\}}\sum_{\mathrm{bins}}\frac{[\mathcal{O}(\mathrm{SM}+Z')-\mathcal{O}(\mathrm{SM})]^2_{\mathrm{bin}}}{(\delta\mathcal{O}_{\mathrm{bin}})^2}. \qquad (7)
$$

To derive the expected 'discovery' limits on Z' models at the ILC, for the 'annihilation' channels in Eq. (1), with $f\neq e,t$, we restrict ourselves to combining in Eq. (7) the $(P^-,P^+)=(|P^-|,-|P^+|)$ and $(-|P^-|,|P^+|)$ beam polarization configurations, that are the predominant ones. For the Bhabha process, $f=e$, we combine in (7) the cross sections with all four possible polarization configurations, i.e., $(P^-,P^+)=(|P^-|,-|P^+|)$, $(-|P^-|,|P^+|)$, $(|P^-|,|P^+|)$, $(-|P^-|,-|P^+|)$. Numerically, we take for the electron beam $|P^-|=0.8$ and for the positron beam $|P^+|=0.6$.

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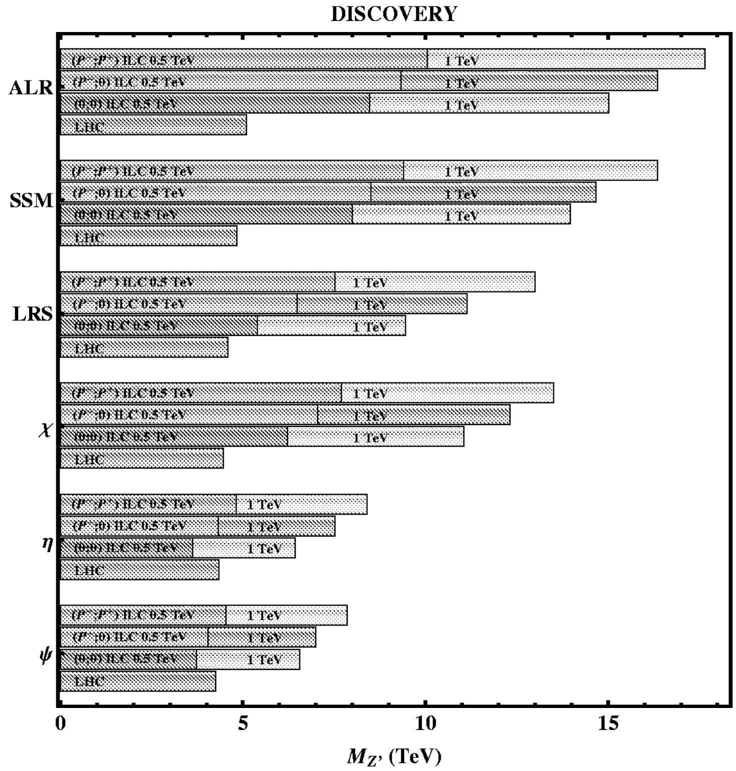

Figure 1. Discovery reaches on Z' models obtained from combined analysis of the unpolarized and polarized processes (1) (95% C.L.) at the ILC with $\sqrt{s} = 0.5$ TeV (1 TeV) and $\mathcal{L}_{\rm int} = 500$ fb^{-1} (1000 fb^{-1}), compared to the results expected from Drell-Yan processes at the LHC at the 5-σ level [6]. Three options of polarization are considered at the ILC: unpolarized beams, $P^- = P^+ = 0$; polarized electron beam, $|P^-| = 0.8$; both beams polarized, $|P^-| = 0.8$ and $|P^+| = 0.6$.

Regarding the ILC energy and the time-integrated luminosity (which, for simplicity, we assume to be equally distributed among the different polarization configurations defined above), we will give explicit numerical results for c.m. energy $\sqrt{s} = 0.5$ TeV with time-integrated luminosity $\mathcal{L}_{\rm int} = 500$ fb^{-1}, and for the 'ultimate' upgrade values $\sqrt{s} = 1.0$ TeV with $\mathcal{L}_{\rm int} = 1000$ fb^{-1}. The assumed final state identification efficiencies governing, together with the luminosity, the expected statistical uncertainties, are: 100% for e^+e^- pairs; 95% for l^+l^- events ($l = \mu, \tau$); 35% and 60% for $c\bar{c}$ and $b\bar{b}$.

As for the major systematic uncertainties, they originate from errors on beam polarizations, on the time-integrated luminosity, and the final-state reconstruction and energy efficiencies. For the longitudinal polarizations, we adopt the values $\delta P^-/P^- = \delta P^+/P^+ = 0.25\%$, rather ambitious, especially as far as P^+ is concerned, but strictly needed for conducting the planned measurements at the permille level. As regards the other systematic uncertainties mentioned above, we assume for the combination the (perhaps conservative) lumpsum value of 0.5%. The systematic uncertainties are included using the covariance matrix approach.

The Fig. 1 includes a comparison with the discovery potential of the LHC with luminosity 100 fb^{-1}, from the Drell-Yan processes $pp \to l^+l^- + X$ ($l = e, \mu$) (at the 5-σ level). These values provide a representative overview of the sensitivities of the reach in $M_{Z'}$ on the planned energy and luminosity, as well as on beam polarization.

4. Distinction of Z' models

Basically, in the previous subsection we have assessed the extent to which Z' models can give values of e^+e^- differential cross sections that can *exclude* the SM hypothesis to a prescribed C.L. Such 'discovery reaches' are represented by upper limits on Z' masses, for which the observable deviations between the corresponding Z' models and SM predictions are sufficiently large compared to the foreseeable experimental uncertainties on the cross sections at the ILC).

However, since different models can give rise to similar deviations, we would like to determine the ILC potential of identifying, among the various competing possibilities, the source of a deviation, should it be effectively observed. These ID-limits should obviously be expected to lie below the corresponding ILC discovery reaches and, for an approximate but relatively simple assessment, we adapt the naive χ^2-like procedure applied in the previous subsection.

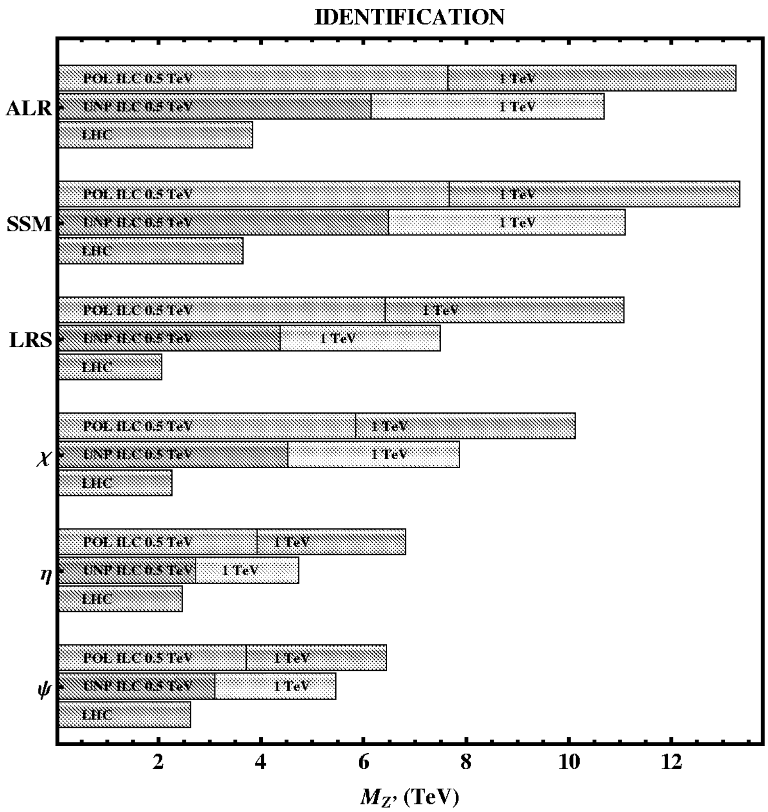

Figure 2. Comparison of the Z'-model distinction bounds on $M_{Z'}$ obtained from combined analysis of the unpolarized and polarized processes (1) at the ILC with $\sqrt{s} = 0.5$ TeV (1 TeV) and $\mathcal{L}_{\text{int}} = 500$ fb^{-1} (1000 fb^{-1}), compared to the results expected from Drell-Yan processes at the LHC at 95% C.L. [6] Two options of polarization are considered: unpolarized beams $P^- = P^+ = 0$ and both beams are polarized, $|P^-| = 0.8$ and $|P^+| = 0.6$.

To this purpose, we start by defining a 'distance' between pairs of Z' models, i and j with i, j denoting any of the SSM, SM, ALR, LRS, ψ, η, χ, but $i \neq j$. We assume for example model i to be the 'true' model, namely, we consider 'data' sets obtained from the dynamics i, with corresponding 'experimental' uncertainties, compatible with the expected 'true' experimental data. The assessment of its distinguishability from a j model, that we call 'tested' model, can be performed by a χ^2 comparison analogous to (7), with the χ^2 defined as:

$$\chi^2(\mathcal{O})_{i,j} = \sum_f \sum_{\{P^-,\ P^+\}} \sum_{\text{bins}} \frac{\left[\mathcal{O}(Z'_i) - \mathcal{O}(Z'_j)\right]^2_{\text{bin}}}{\left(\delta_i \mathcal{O}_{\text{bin}}\right)^2}. \tag{8}$$

Here, we study a scenario where the Z' mass cannot be known *a priori*, e.g., the Z' is too heavy to be discovered at the LHC (say, $M_{Z'}$ >4–5 TeV), but deviations from the SM predictions can still be observed at the ILC. Actually, models with different Z' masses and coupling constants can in principle be the source of a deviation from the SM predictions observed at the ILC. With the coupling constants held fixed numerically at the theoretical values pertinent to the Z'_i and Z'_j models under consideration, the χ^2_{ij} of Eq. (8) becomes a function of the two masses, $M_{Z'_i}$ and $M_{Z'_j}$, both assumed to lie in the respective ILC discovery ranges.

Finally, Fig. 2 shows the comparison of identification reaches or distinction bounds on the Z'-models considered in Fig. 1, together with the corresponding bounds on $M_{Z'}$ obtained from the process $pp \to l^+l^- + X$ at the LHC with c.m. energy 14 TeV and time-integrated luminosity 100 fb^{-1}. We assume, for the ILC, the same c.m. energy, luminosty and beam polarization as in Fig. 1. The figure speaks for itself, and in particular clearly exhibits the roles of the ILC parameters.

In summary, one might be able to distinguish among the considered Z' models at 95% C.L. up to $M_{Z'} \simeq 3.1$ TeV (4.0 TeV) for unpolarized (polarized) beams at the ILC (0.5 TeV) and 5.3 TeV (7.0 TeV) at the ILC (1 TeV), respectively. In particular, the figure explicitly manifests the substantial role of electron beam polarization in sharpening the identification reaches. Positron polarization can also give a considerable enhancement in this regard (if measurable with the same high accuracy as for electron polarization), although to a more limited extent in some cases.

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References
[1] Langacker P. 2009 *Rev. Mod. Phys.* **81** 1199
[2] Erler J., Langacker P., Munir S. and E.Rojas E. 2009 *JHEP* **0908** 017
[3] Aaboud M. *et al.* [ATLAS Collaboration], arXiv:1707.02424 [hep-ex]
[4] The CMS Collaboration [CMS Collaboration], CMS-PAS-EXO-15-005
[5] Osland P., Pankov A. A., Paver N. and Tsytrinov A. V. 2008 *Phys. Rev.* D **78** 035008
[6] Osland P., Pankov A. A., Tsytrinov A. V. and Paver N. 2009 *Phys. Rev.* D **79** 115021
[7] Moortgat-Pick G. A. *et al.* 2008 *Phys. Rept.* **460** 131
[8] For details of the analysis and original references, see Osland P., Pankov A. A. and Tsytrinov A. V. 2010 *Eur. Phys. J.* C **67** 191; 2017 *Phys. Rev.* D **96** 055040