Model-independent determination of $Z'$ couplings at LEP 200

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ABSTRACT

All couplings of a new heavy gauge boson to ordinary fermions can be determined in a model-independent way at a large $e^+e^-$ collider for large enough statistics. No such determination is possible at LEP 200, however, because its design integrated luminosity is too low for existing and forthcoming limits on $Z'$ interactions. At any rate, it should be possible to distinguish between models for $Z'$ masses $< 1$ TeV, or to set limits of this order on $Z'$ masses for definite models. These are (preliminary) 1σ limits. We neglect systematic errors and assume an integrated luminosity of 0.5 $fb^{-1}$.

1. Introduction

There is no compulsory reason for expecting a new heavy $Z'$ boson, but there is neither a reason for excluding its existence. At present there are only bounds on its effects [1-6]. The question here is: Which information on an extra gauge boson can LEP 200 provide? At a large $e^+e^-$ collider if the $Z'$ effects are sizeable all $Z'$ couplings to ordinary fermions can be determined in a model-independent way [7,8]. However, the expected luminosity at LEP 200 is too low to allow for such a model-independent analysis. The typical value of the $Z'$ mass limit, or of the discovered $Z'$ mass, at TEVATRON when LEP 200 enters in operation is $\sim 500$ GeV [9]. For $Z'$ masses $< 1$ TeV it is possible to distinguish between definite models at LEP 200; for specific models it is also possible to set limits on $Z'$ masses $\sim 1$ TeV. Our analysis is preliminary. In what follows we review present and forthcoming $Z'$ limits (1.1) and the parametrization of $Z'$ effects in two-fermion final state observables at $e^+e^-$ (1.2). Our numerical estimates for $Z'$ physics at LEP 200 are given in Section 2.

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1.1 Present and forthcoming $Z'$ limits

Present limits on $Z'$ masses, $M_{Z'}$, come from the absence of an excess of $e^+e^-(\mu^+\mu^-)$ pairs with a large invariant mass at TEVATRON: direct limits [1,2]; and from the observation of no effect beyond the minimal standard model in precise electroweak data, mainly at LEP: indirect limits [3-6]. These limits for popular models, $\chi, \psi, \eta, LR$, are given in Table 1 [9,10]. TEVATRON can provide limits on $M_{Z'} \sim 500(600)\text{ GeV}$ for an integrated luminosity of $25(100)\text{ pb}^{-1}$. LEP allows for a precise measurement of the $Z$ current, providing a stringent limit on the $Z'Z_1$ mixing, $s_3 \equiv \sin \theta_3 < 0.01$ [3,6]. In models where this mixing is fixed by the $Z'$ mass, the limit on $s_3$ translates into stringent $M_{Z'}$ limits: constrained indirect limits. When $M_{Z'}$ and $s_3$ are independent the $Z'$ mass limits are modest: unconstrained indirect limits. The indirect limits on $M_{Z'}$ depend little on the top quark mass, $m_t$, except for top masses near the $m_t$ upper bound [5].

|      | direct (present) | direct ($\int Ldt = 25\text{ pb}^{-1}$) | direct ($\int Ldt = 100\text{ pb}^{-1}$) | indirect (constrained) | indirect (unconstrained) |
|------|-----------------|----------------------------------------|----------------------------------------|-------------------------|--------------------------|
| $\chi$ | 340             | 470                                    | 620                                    | 670                     | 380                       |
| $\psi$ | 320             | 450                                    | 600                                    | 200                     | 200                       |
| $\eta$ | 340             | 460                                    | 610                                    | 440                     | 210                       |
| $LR$   | 310             | 510                                    | 660                                    | 990                     | 430                       |

Table 1. $Z'$ mass limits (in GeV).

In conclusion we will assume for our estimates at LEP 200 that a new $Z'$ may exist with a mass $> 500\text{ GeV}$.

1.2 Parametrization of $Z'$ effects in two-fermion final state observables at $e^+e^-$

The effects of a new $Z'$ can be observed in the two-fermion channels at LEP 200. The relevant lagrangian reads:

$$-\mathcal{L}_{NC} = e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu + \frac{g}{2c_W} \sum_i \bar{\psi}_i \gamma^\mu (v^i - a^i \gamma_5) \psi_i Z_{1\mu} + \frac{g}{2c_W} \sum_i \bar{\psi}_i \gamma^\mu (v'^i - a'^i \gamma_5) \psi_i Z_{2\mu},$$

(1)

where the last piece describes the new $Z'$ interaction and the first two pieces define the standard model neutral lagrangian [1]. (We assume family universality and that the $SU(2)_L$ charges $T_i$ commute with the new charge $Q' : [Q', T_i] = 0$.) We neglect the $Z'Z_1$ mixing angle, for it is bounded, $s_3 < 0.01$, and its effects are unobservable at LEP 200. Hence, we identify $Z_1$ and $Z_2$ with the observed $Z$ and the new $Z'$ bosons, respectively. The three gauge bosons, $\gamma, Z, Z'$, are far off-shell for a center of mass energy of 200 GeV. The expected statistics allows for working at tree level. Radiative effects due to real $Z$ production are important but they can be taken away with a cut on the maximum photon energy [11]. We can neglect them in a first estimate of the $Z'$ potential of LEP 200. The main $Z'$ effects result from the interference of the $Z'$ amplitude,

$$\mathcal{A}'(Z') = \frac{1}{s - M^2_{Z'} + i\Gamma_{Z'} M_{Z'}} \left( \frac{g}{2c_W} \right)^2 \bar{u}_e \gamma^\mu (v'^e - a'^e \gamma_5) u_e \bar{u}_f \gamma^\mu (v'^f - a'^f \gamma_5) u_f,$$

(2)
with the $\gamma, Z$ amplitudes. Neglecting the $Z'$ width and for a fixed center of mass energy $\sqrt{s} (= 200 \, GeV)$, the $Z'$ amplitude and the corresponding $Z'$ effects in $e^+ e^- \rightarrow f \bar{f}$, with $f$ any ordinary fermion, depend on five couplings [7]:

$$\epsilon_A = \frac{a'^2}{c_W^2 s_W^2} \frac{s}{M^2_{Z'} - s}, \quad P^e_V = \frac{v'^e}{a'^e}, \quad P^q_L = \frac{v'^q + a'^q}{2a'^e}, \quad P^u_{R,d} = \frac{v'^u_{R,d} - a'^u_{R,d}}{v'^q + a'^q}. \quad (3)$$

At a large $e^+ e^-$ collider not only the pairs of charged leptons but the bottom and charm final states can be tagged. As a matter of fact, using the event shape, lepton tagging and/or vertex reconstruction LEP analyses have measured the total cross section and the forward-backward asymmetry of bottom and charm pairs [12]. Thus, the set of observables at LEP 200 includes the total cross section for charged leptons $\sigma^l$ and their forward-backward asymmetry $A^l_{FB}$ ($l$ stands for $e, \mu, \tau$), as well as for bottom and charm quarks $R^{b,c} = \frac{\sigma^{b,c}}{\sigma^l}$, $A^{b,c}_{FB}$, and the total cross section for hadrons $R^{had} = \frac{\sigma^{had}}{\sigma^l}$. (We assume only $s$-channel exchange for electrons, implying $\sigma^e \sim \sigma^\mu \sim \sigma^\tau$. We do not consider tau polarization asymmetries.) If beam polarization is available, the corresponding left-right asymmetries, $A^{b,c,\text{had}}_{LR}, A^{b,c}_{LR,FB}$, double the number of observables to be measured.

$\sigma^l$ and $A^l_{FB}$ have small linear terms in $P^e_V$, implying that unpolarized lepton probes only determine $\epsilon_A$ and $|P^e_V|$. Whereas the polarized probes $A^l_{LR}$ and $A^l_{LR,FB}$ are very sensitive to $P^e_V$, including its sign [7]. One combination of $P^q_L$, $P^u_{R,d}$ is fixed by $R^{had}$. A second combination is determined by $A^{had}_{LR}$ if polarization is available. In any case, flavour tagging is necessary for a complete determination of the $Z'$ couplings to quarks. $R^{b,c}$ and $A^{b,c}_{FB}$ allow for this determination even without electron beam polarization.

In Ref. [7] it is shown that a complete (model-independent) determination of the $Z'$ couplings to ordinary fermions is possible for a $Z'$ mass $\sim 1 \, TeV$ at NLC. As we show below such a determination is not possible at LEP 200.

2. LEP 200 results

In Table 2 we gather the expected values of two-fermion final state observables at LEP 200 for different models. We assume an integrated luminosity of 0.5 $fb^{-1}$. Errors are only statistical. The first four columns correspond to models $\chi, \psi, \eta, LR$ and a $Z'$ mass equal to 500 GeV. The fifth column gives the values of the same observables for the standard model.
Table 2. Values and statistical errors for two-fermion final state observables at LEP 200 (\(\sqrt{s} = 200\) GeV, \(\int L dt = 0.5\) fb\(^{-1}\)) for models \(\chi, \psi, \eta, LR\) (\(M_{Z'} = 500\) GeV) and for the standard model.

In order to decide on the \(Z'\) potential of LEP 200 we perform a \(\chi^2\) fit to the observables in Table 2 for models \(\chi, \psi, \eta, LR\). \(l\) stands for \(e, \mu, \tau\) and counts three times. The results are given in Table 3. The errors in parentheses are for unpolarized electron beams. In both cases the errors are so large that no model-independent determination of the \(Z'\) couplings to ordinary fermions is possible.

Table 3. Values of couplings in Eq. (3) and 1\(\sigma\) statistical errors at LEP 200 for popular models. Errors in parentheses correspond to unpolarized electron beams.

However, we can distinguish between specific models. Let us consider the class of \(E_6\) models parametrized by \(\beta\) in Table 4. Performing a \(\chi^2\) fit to the observables in Table 2 for models \(\chi, \psi, \eta\) with \(M_{Z'} = 500\) GeV, we obtain

\[
\beta = 0.0 \pm 0.10(0.27), 1.57 \pm 0.10(0.28), -0.91 \pm 0.11(0.13),
\]

respectively. Errors in parentheses correspond to unpolarized electron beams.
Table 4. Vector and axial $Z'$ couplings in Eq. (1) for a class of $E_6$ models. $\beta = 0, \frac{\pi}{2}, -\arctan \sqrt{\frac{5}{3}}$ for models $\chi, \psi, \eta$, respectively.

For definite models we can also determine the $Z'$ mass. A $\chi^2$ fit to the observables in Table 2 gives

$$M_{Z'} = 500 \pm 19(25), 83(102), 43(72), 14(50),$$

for models $\chi, \psi, \eta, LR$, respectively. In the Figure we show for the standard model observables in Table 2 the 1$\sigma$ $M_{Z'}$ limits for the $E_6$ models in Table 4 as a function of $\beta$. The solid curve corresponds to unpolarized beams.

3. Conclusions

For LEP 200 or for any center of mass energy of the same order and an integrated luminosity $\sim 0.5 \, fb^{-1}$ no model-independent determination of the $Z'$ couplings
to ordinary fermions is possible for $M_{Z^{'}} > 500$ GeV. However, we can distinguish between specific models for $M_{Z^{'}}$ fixed (and $< 1$ TeV). Limits on $M_{Z^{'}} \sim 1$ TeV can also be obtained for definite models. This analysis can be improved by including systematic errors and (initial) radiation.

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