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# BOUNDS ON THE MASS AND MIXING OF $Z'$-BOSONS FROM LEP2 EXPERIMENTAL DATA

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Analysis of effects induced by $Z'$-bosons based on LEP2 experimental data (OPAL, DELPHI, ALEPH, L3) on differential cross sections of the $W^{\pm}$-pair production process was performed. Constraints on $Z'$-boson mass $M_{Z'}$ and $Z - Z'$ mixing angle $\phi$ were obtained for some specific extended gauge models.

## 1 Introduction

With the advent of the LHC, particle physics has entered a new exciting era. Within a few years of data accumulation, the LHC should be able to test and constrain many types of new physics beyond the standard model (SM). In particular, the discovery reach for extra neutral gauge bosons, the existence of which is predicted by extended gauge models, such as left-right (LR) models, $E_6$-models and others, is exceptional. Searches for a high invariant dilepton mass peak in about 100 $fb^{-1}$ of accumulated data will find or exclude $Z'$-bosons up to about 5 TeV, and a luminosity upgraded LHC (by roughly a factor of 10) can extend the reach by another TeV. However, the hadronic LHC environment will make it difficult to specify the $Z'$ properties completely or with satisfactory precision. Investigation of $Z'$ properties in other processes will therefore play an important complementary role in this context [1, 2, 3].

The process

$$e^+ + e^- \to W^+ + W^- \tag{1}$$

should be quite sensitive to indirect new physics effects, in particular, at high energies $\sqrt{s} \gg 2M_W$, which can destroy the SM gauge cancellation among the different contributions to the cross section, and hence cause deviations of the cross section from the SM prediction, which can increase with the CM energy [4]. In this regard, it is very interesting to analyze the data on $W^{\pm}$-pair boson production collected at OPAL, L3, DELPHI and ALEPH experiments at LEP2 [5, 6, 7, 8] in order to extract information on $Z'$-bosons. In particular, accumulated data on the angular distributions of charged gauge $W^{\pm}$-bosons allow to obtain constraints on the parameters of $Z'$-boson ($Z - Z'$ mixing angle $\phi$ and $Z'$-boson mass $M_{Z'}$).

## 2 Extended gauge models

The most popular models that predict the existence of $Z'$-bosons are the following:

**$\mathbf{E_6}$-models**. $E_6$-models are based on the ideas of Grand Unification. They comprise $SU(5)$ and $SO(10)$ subgroups and are free of anomalies.

$E_6$-models break into SM in the following way: $E_6 \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$. We consider the class of models, in which the linear combination

$$U(1)' = \cos\beta\, U(1)_\chi + \sin\beta\, U(1)_\psi$$

keeps safe up to the energies associated with electroweak processes.

The angle $\beta$ satisfies the condition $-1 \leq \cos\beta \leq 1$. Depending on the values of $\beta$ one can distinguish several $E_6$-based models:

$$\chi\text{-model: } \beta = 0^\circ \Longrightarrow U(1)' = U(1)_\chi \ ,$$

$$\psi\text{-model: } \beta = 90^\circ \Longrightarrow U(1)' = U(1)_\psi \ ,$$

$$\eta\text{-model: } \beta = -\arctan\sqrt{5/3} \simeq -52,2^\circ \Longrightarrow U(1)' = \sqrt{3/8}\, U(1)_\chi - \sqrt{5/8}\, U(1)_\psi \ ,$$

$$I\text{-model: } \beta = \arctan\sqrt{3/5} \simeq 37,8^\circ \Longrightarrow U(1)' = \sqrt{5/8}\, U(1)_\chi + \sqrt{3/8}\, U(1)_\psi \ .$$

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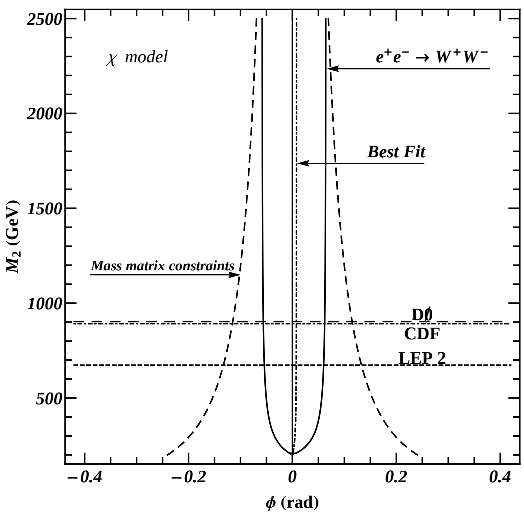


**Figure 1.** Constraints on $\phi$ and $M_2$ (95% *C.L.*) for $\chi$-model

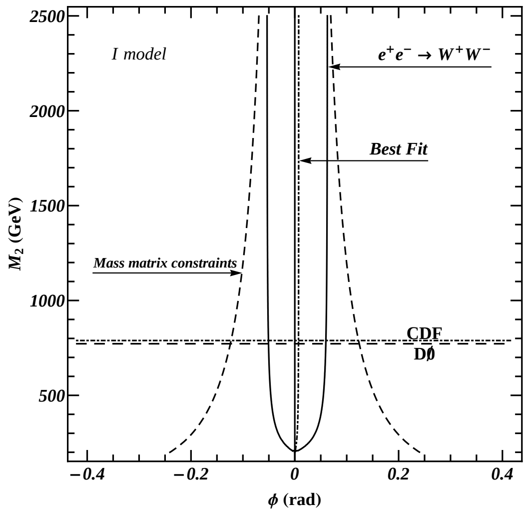


**Figure 2.** Constraints on $\phi$ and $M_2$ (95% *C.L.*) for $I$-model

**LR-models**. LR-models are based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Depending on the values of model parameter $\alpha_{LR}$ one can introduce a set of LR-models. In the general case parameter $\alpha_{LR}$ lies within the interval

$$1/\sqrt{2} \leq \alpha_{LR} \leq 1.53\ .$$

**Sequential Standard Model**. In addition to the above-mentioned models that are based on the extended gauge groups we will consider the so-called “sequential standard model” (SSM). The main feature of this model is that $Z'$-boson gauge couplings and standard $Z$-boson couplings are equal in this model. It’s a good benchmark model, therefore the analysis of $Z'$-boson effects in the framework of SSM is quite interesting.

## 3 Differential distribution of $W^{\pm}$-pair production

In the SM the process (1) in born approximation consists of two s-channel diagrams with $\gamma$ and $Z$-boson exchange and a t-channel diagram with neutrino $\nu$ exchange. Extended gauge models generate a different set of diagrams, that consists of the same t-channel diagram with neutrino $\nu$ and s-channel diagrams with $\gamma$, $Z_1$- and $Z_2$-bosons (mass eigenstates that correspond to $Z$- and $Z'$-bosons) exchange:

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix}, \tag{2}$$

where $Z,\ Z'$ are weak-eigenstates, $Z_1,\ Z_2$ are mass-eigenstates and $\phi$ is the $Z - Z'$ mixing angle. Taking Eq. (2) into account, the electron neutral current couplings to $Z_1$ and $Z_2$ are, respectively:

$$g^f_{1a} = g^f_a \cos\phi + g'^f_a \sin\phi\,; \qquad\qquad g^f_{2a} = -g^f_a \sin\phi + g'^f_a \cos\phi. \tag{3}$$

Finally, trilinear gauge boson couplings can be written as: $g_{WWZ_1} = \cot\theta_W \cos\phi$ and $g_{WWZ_2} = -\cot\theta_W \sin\phi$. Obviously, the SM case is reobtained when all (fermion and gauge boson) mixing angles are put equal to zero.

The unpolarized cross section of process (1) can be expressed in general as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{4}\left[\frac{d\sigma^{RL}}{d\cos\theta} + \frac{d\sigma^{LR}}{d\cos\theta} + \frac{d\sigma^{RR}}{d\cos\theta} + \frac{d\sigma^{LL}}{d\cos\theta}\right]. \tag{4}$$

The relevant polarized differential cross sections for $e^-_a e^+_b \to W^-_\alpha W^+_\beta$ can be written as

$$\frac{d\sigma^{ab}_{\alpha\beta}}{d\cos\theta} = C \cdot \sum_{k=0}^{k=2} F^{ab}_k\, \mathcal{O}_{k\,\alpha\beta}. \tag{5}$$

Here $C = \pi\alpha^2_{e.m.}\beta_W/2s$, with $\beta_W = (1 - 4M^2_W/s)^{1/2}$ to be the $W$ velocity in the CM frame, the helicities of the initial $e^+e^-$ and final $W^+W^-$ states are labeled as $ab = (RL,\ LR,\ LL,\ RR)$ and $\alpha\beta = (LL,\ TT,\ TL)$, respectively. The $\mathcal{O}_k$ are functions of the kinematical variables, which characterize the various possibilities for the final $W^+W^-$ polarizations ($TT$, $LL$, $TL$+$LT$ or the sum over all $W^+W^-$ polarization states for unpolarized W’s). The $F_k$ are combinations of coupling constants including the two kinds of mixings [4].

**Table 1.** Constraints on $Z - Z'$ mixing angle $\phi$ for different extended gauge models at $M_2$= 1 TeV obtained from LEP2 data for $W^{\pm}$-pair production.

| Model | $\phi_{min}$ | $\phi_{max}$ | $\phi_{best}$ |
|---|---|---|---|
| $\chi$-model | -0.05 | 0.06 | 0.01 |
| $\psi$-model | -0.15 | 0.13 | 0.02 |
| $\eta$-model | -0.50 | 0.15 | 0.03 |
| $I$-model | -0.05 | 0.06 | 0.01 |
| LR-model | -0.09 | 0.11 | 0.01 |
| SSM | -0.07 | 0.05 | -0.01 |

## 4 Numerical results

In order to obtain constraints on parameters $\phi$ ($Z - Z'$ mixing angle) and $M_2$ ($Z_2$-boson mass) a $\chi^2$ method was used [9]. We construct the function

$$\chi^2(\mathbf{\Omega}) = \sum_{j}^{energy} \sum_{i=1}^{bins} \left[ \frac{\Delta\sigma_i(exp) - \Delta\sigma_i\,(theory)}{\delta\sigma_i^2} \right]^2 , \tag{6}$$

where $\mathbf{\Omega} = \{\phi, M_2\}$, $\Delta\sigma_i(exp)$ – experimental values of differential cross sections of the process (1) in $i$-th bin, $\Delta\sigma_i\,(theory)$ – theoretical values of differential cross sections in $i$-th bin defined as $\Delta\sigma_i = \int_{bin}(d\sigma_i/\cos\theta)\,d\cos\theta$. Here we take into account both theoretical and experimental uncertainties as

$$\delta\sigma_i = \sqrt{\delta\sigma_i^2(exp) + \delta\sigma_i^2(theory)}\,.$$

Constraints on parameters that appear in $\mathbf{\Omega}$ can be obtained on the basis of the following inequality:

$$\chi^2(\mathbf{\Omega}) \le \chi^2_{min} + \Delta\chi^2_{C.L.}\,. \tag{7}$$

Using inequality (7) one can obtain constraints on parameters $\phi$ and $M_2$ shown for some specific extended models in Fig. 1 and Fig. 2. Horizontal lines correspond to the lower bounds on $Z'$-boson mass obtained from D0 [10] and CDF [11] experiments at Tevatron. Also, constrains on $Z'$-boson mass obtained from LEP2 experiments [12] with four-fermion processes above $Z$ peak are displayed in the figures. Finally, figures also contain the mass matrix constraints obtained by using the properties of mass matrix (2). As can be seen from the Fig. 1 and Fig. 2, the typical scale of constraints on the mixing angle for the mass of $M_2 \sim$1 TeV is as large as $\phi \sim 5 \cdot 10^{-2}$. The constraints for other extended gauge models are summarized in Tab. 1.

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