Constraints on the Mass and Mixing of Z'-Bosons from LEP2 Experimental Data

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Abstract

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 ϕ 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

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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, 4].

One of the most interesting processes for such investigations is the process of annihilation production of $W^{\pm}$-boson pairs

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

The main feature of the process (1) is its high sensitivity to "new physics", especially at high energies, when $\sqrt{s} \gg 2M_W$, because new interactions can violate gauge cancellation mechanism, which plays an important role in the SM and provides the proper behaviour of total cross sections with the increase of energy [5, 6, 7].

In this connection it is very interesting to analyse the data of OPAL, L3, DELPHI and ALEPH experiments at LEP2 [8, 9, 10, 11]. 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 ϕ and Z'-boson mass $M_{Z'}$).

2 Extended gauge models

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

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

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

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

η-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-model:

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

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 α_{LR} one can introduce a set of LR-models. In the general case parameter α_{LR} lies within the interval

$$\sqrt{2/3} \le \alpha_{LR} \le 1.53\,.$$

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. SSM is based on the gauge group

$$SU(2)_L \times U(1)_Y \times U(1)_{Y'}\,.$$

3 Cross section of process $e^+ + e^- \to W^+ + W^-$

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

Matrix element of process (1) can be presented as a sum of the following parts:

$$\mathcal{M} = \mathcal{M}(\nu) + \mathcal{M}(\gamma) + \mathcal{M}(Z_1) + \mathcal{M}(Z_2)\,. \tag{2}$$

Expression (2) can be rewritten as

$$\mathcal{M} = \mathcal{M}_{SM} + \Delta\mathcal{M} = \mathcal{M}(\nu) + \mathcal{M}(\gamma) + \mathcal{M}(Z) + \Delta\mathcal{M}\,, \tag{3}$$

$$\Delta\mathcal{M} = \mathcal{M}(Z_1) + \mathcal{M}(Z_2) - \mathcal{M}(Z)\,. \tag{4}$$

With the help of method of basis spinors [12] matrix element $\Delta\mathcal{M}$ can be written as:

$$\Delta\mathcal{M}^{\lambda,\lambda'}_{\tau,\tau'} = 4\pi\alpha\,\lambda\,\delta_{\lambda,-\lambda'}\beta_W \times g_1\,g_{WWZ}\,g_{-\lambda}\,\chi \times \mathcal{A}^{\lambda}_{\tau,\tau'}(Z) \times$$
$$\times \left[1 - \frac{g_{WWZ_1}\,g^{Z_1}_{-\lambda}\,\chi_1}{g_{WWZ}\,g_{-\lambda}\,\chi} - \frac{g_2\,g_{WWZ_2}\,g^{Z_2}_{-\lambda}\,\chi_2}{g_1\,g_{WWZ}\,g_{-\lambda}\,\chi}\right], \tag{5}$$

where $g_{WWZ_1} = \cos\phi \times g_{WWZ}$ and $g_{WWZ_2} = -\sin\phi \times g_{WWZ}$ – triple gauge couplings of Z_1 and Z_2 states, $g_1 = 1/(2\sin\theta_W\cos\theta_W)$, $\beta_W = \sqrt{1-4M_W^2/s}$ – the velocity of W-bosons, θ_W – weak mixing angle, g_2 depends on the type of extended gauge model used, $\mathcal{A}^{\lambda}_{\tau,\tau'}(Z)$ – functions that depend on the scattering angle θ.

$$\chi_{1,2} = s/(s-M^2_{1,2})\,, g_\lambda = v + \lambda a\,,\ g^{Z_1}_\lambda = v_1 + \lambda a_1\,,\ g^{Z_2}_\lambda = v_2 + \lambda a_2\,.$$

The last factor in expression (5) effectively contains "new physics" and covers the whole spectrum of extended gauge models. This factor is introduced as parameter $\xi_{-\lambda}$:

$$\xi_{-\lambda} = 1 - \frac{g_{WWZ_1}\,g^{Z_1}_{-\lambda}\,\chi_1}{g_{WWZ}\,g_{-\lambda}\,\chi} - \frac{g_2\,g_{WWZ_2}\,g^{Z_2}_{-\lambda}\,\chi_2}{g_1\,g_{WWZ}\,g_{-\lambda}\,\chi}\,. \tag{6}$$

This parametrization allows to perform model independent analysis of Z'-boson effects.

Differential cross section for initial $e^+_{\lambda'}e^-_{\lambda}$ and final $W^+_{\tau'}W^-_{\tau}$ states can be written as:

$$\frac{d\sigma^{\lambda\lambda'}_{\tau\tau'}}{d\cos\theta} = \frac{\beta_W}{32\pi s}|\mathcal{M}^{\lambda\lambda'}_{\tau\tau'}|^2\,. \tag{7}$$

Index $\lambda, (\lambda') = \pm1$ denotes electron (positron) helicity and $\tau\,(\tau') = \pm1, 0$ - W^- (W^+) boson spin states.

4 Numerical results and conclusions

In order to obtain constraints on parameters ξ_+ and ξ_- a χ^2 method was used [13]. We construct the function

$$\chi^2(\Omega) = \sum_j^{energy} \sum_{i=1}^{bins} \left[\frac{d\sigma_i(exp) - d\sigma_i(theory)}{\Delta\sigma_i^2}\right]^2, \tag{8}$$

where $\mathbf{\Omega} = \{\xi_+, \xi_-\}$, $d\sigma_i(exp)$ – experimental values of differential cross sections of the process (1) in i-th bin, $d\sigma_i\,(theory)$ – theoretical values of differential cross sections in i-th bin.

We have taken into account both theoretical and experimental errors, as well as radiative corrections to the process.

$$\Delta\sigma_i^2 = \Delta\sigma_i^2(exp) + \Delta\sigma_i^2(theory)\ .$$

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

$$\chi^2\left(\mathbf{\Omega}\right) \leq \chi^2_{min} + \Delta\chi^2_{C.L.}\ , \qquad (9)$$

Using inequality (9) one can obtain constraints on parameters ξ_+ and ξ_- for different values of confidence level. The results are presented on Figs. 1, 2.

On the basis of "allowed" areas for parameters ξ_+ and ξ_- one can derive interval estimations for them.

For 1σ intervals (68% $C.L.$):

$$\begin{aligned} \Delta\xi_+ &= \pm\, 0,0455\ , \\ \Delta\xi_- &= \pm\, 0,2879\ . \end{aligned} \qquad (10)$$

For 2σ intervals (95% $C.L.$):

$$\begin{aligned} \Delta\xi_+ &= \pm\, 0,0734\ , \\ \Delta\xi_- &= \pm\, 0,4650\ . \end{aligned} \qquad (11)$$

Finally, one can change the parametrization, i.e. replace ξ_+ and ξ_- with M_2 (Z_2-boson mass) and ϕ ($Z - Z'$ mixing angle). In order to do this it is necessary to specify the model, i.e. fix the fermion gauge couplings of Z'-boson and g_2 coupling.

The corresponding constraints on $Z - Z'$ mixing angle ϕ and Z_2-boson mass M_2 for some E_6-models can be found on Figs. 3,4. Horizontal lines on these figures correspond to lower bounds on Z'-boson mass obtained from D0 [14] and CDF [15] experiments, which were devoted to the search of resonance effects at TEVATRON, and from LEP2 experiments [16] that measured Z' propagator effects in four-fermion processes. The figures also contain mass matrix constraints that were obtained using the properties of mass matrix.

For large values of M_2 the contribution of diagram with Z_2-boson exchange is negligible. The contribution of diagram with Z_1-boson exchange and effects of $Z - Z'$-mixing are dominating here. That's why the constraints on $Z - Z'$-mixing angle ϕ slightly depend on M_2 in this region. The typical scale of constraints in this mass region is $\phi \geq 5 \times 10^{-2}$.

When $M_2 \to \sqrt{s}$, the contribution of diagram with Z_2-boson exchange start to dominate. Besides, the signs of contributions resulting from $Z-Z'$-mixing and direct exchange of Z_2-boson become equal and two effects enhance each other. This enhancement leads to more stringent constraints on ϕ that can reach or even exceed present-day values $\phi \sim 10^{-3}$, which were obtained mainly from precision measurements ($\sqrt{s} \approx M_Z$) of boson mixing effects at LEP1 and SLC. All above-mentioned features can be seen on Figs. 3,4.

The constraints for other extended gauge models have also been obtained. The results are shown in Tab. 1.

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Table 1. The constraints on $Z - Z'$ mixing angle ϕ for different extanded gauge models and $M_{Z'} = 1$ TeV.

Model	ϕ_{min}	ϕ_{max}	ϕ_{best}
χ-model	-0.0545	0.0590	0.0076
ψ-model	-0.1499	0.1302	0.0167
η-model	-0.5056	0.1514	0.0257
I-model	-0.0484	0.0590	0.0060
LR-model	-0.0893	0.1135	0.0136
SSM	-0.0711	0.0515	-0.0090

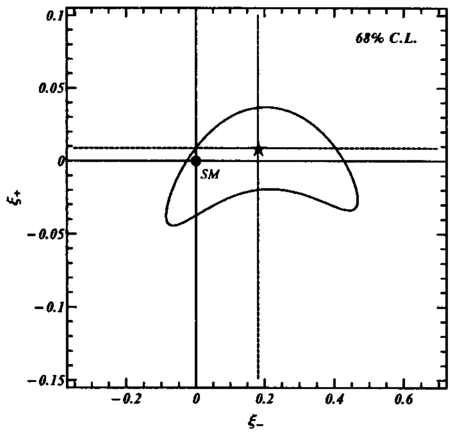

Figure 1. Constraints on ξ_+ and ξ_- parameters for 68% $C.L.$ The star symbol corresponds to the minimum of χ^2 function

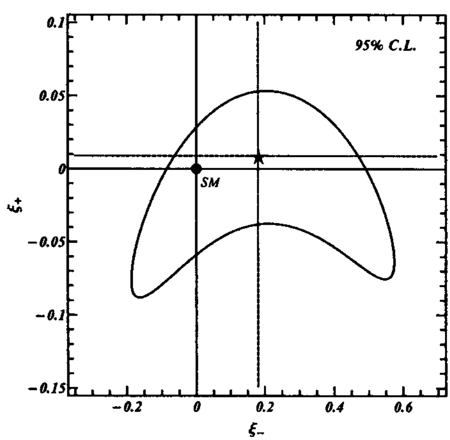

Figure 2. Constraints on ξ_+ and ξ_- parameters for 95% $C.L.$ The star symbol corresponds to the minimum of χ^2 function

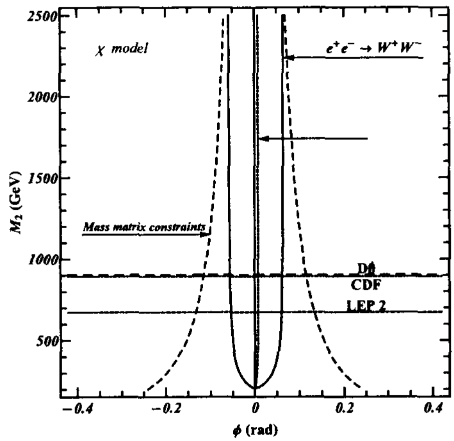

Figure 3. Constraints on ϕ and M_2 parameters (95% $C.L.$) for χ-model

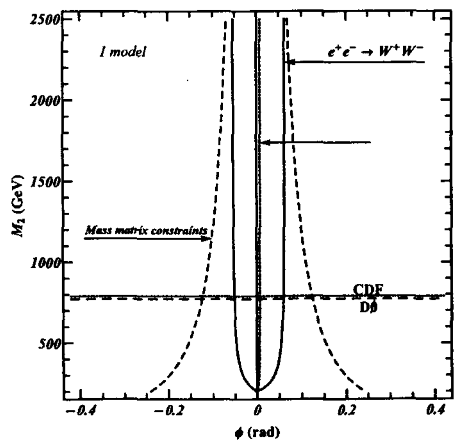

Figure 4. Constraints on ϕ and M_2 parameters (95% $C.L.$) for I-model

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