Comparative Analysis of the Model-Independent Constraints on Contact Interactions from LEP2 Data

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Comparative analysis of the nowdays model-independent searches for virtual states of new heavy particles at LEP2 experiment energies is presented. Three approaches developed are discussed and applied in order to find the signals of the heavy Z' gauge boson in the annihilation processes $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$. It is shown that the experimental data are in correspondence with existence of this particle.

Key words: four-fermion contact interaction, collider, polarization

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1 Introduction

Recently finished LEP2 experiment program has accumulated a huge amount of data on four-fermion scattering processes for the center of mass energies $\sqrt{s} = 130 - 207$ GeV [1] that gave a possibility to carry out the precision test of the standard model (SM) of elementary particle and fit all its parameters and particle masses. No deviations from the SM predictions were observed. This program has also included a part devoted to searching for the signals of new heavy particles beyond the SM. LEP collaborations applied either the model dependent or the model independent analysis of data. The former approach means that the comparison of experimental data with the predictions of some specific models which extend the SM at high energies is fulfilled. In this way a number of popular Grand Unified theories, the supersymmetry models were discussed and their parameters have been restricted. Model-dependent bounds are widely presented in the reports of LEP collaborations [1]. In the model-independent approach one fits some low-energy parameters such as four-fermion contact couplings. To find the expected signals the LEP collaborations have used a "helicity model fit". In this analysis an effective Lagrangian describing contact interactions of massless fermion states with a specific helicity (axial-axial (AA) model, vector-vector (VV) model, etc.) was introduced and the corresponding couplings have been restricted.

On the other hand, it would be desirable to perform a more general kind of analysis of the data that simultaneously includes all terms of the effective Lagrangian as free, potentially non-vanishing independent parameters and, at the same time, allows to disentangle their contributions to the basic observables in order to derive separate constraints within finite regions around the SM limit [2]. This consideration gives, in particular, possibility to derive a region in the parameter space comparable with the data in such a way that all other searches for new heavy particles (either model-dependent or model-independent) have to be in a correspondence with these restrictions. In Ref. [3] the model-independent search for manifestations of heavy virtual particles with the specific quantum numbers has been established. It is intended to pick up the signal of the heavy virtual particle without specifying a model beyond the SM. To realize this program some relations between the parameters of a theory beyond the SM following from the requirement of its renormalizability as well as the kinematics feature of the specific processes under consideration were taken into account.

The aim of the present report is to compare the results obtained in the mentioned model-independent fits of the experimental data for the processes $e^+e- \to \mu^+\mu^-, \tau^+\tau^-$ to search for the heavy Z' gauge boson.

2 Four - parametric model - independent analysis

The $SU(3) \times SU(2) \times U(1)$ symmetric $eeff$ contact-interaction Lagrangian with helicity-conserving and flavor-diagonal fermion currents can be expressed as [4]:

$$\mathcal{L} = \sum_{\alpha\beta} g^2_{\text{eff}}\, \epsilon_{\alpha\beta} \left(\bar{e}_\alpha \gamma_\mu e_\alpha\right) \left(\bar{f}_\beta \gamma^\mu f_\beta\right), \qquad (1)$$

where generation and color indices are not explicitly indicated, α, β = L, R denote left- or right-handed fermion helicities, and the parameters $\epsilon_{\alpha\beta} = \pm 1/\Lambda^2_{\alpha\beta}$ specify the chiral structure of the individual interactions, with $\Lambda_{\alpha\beta}$ some high energy scales that determine the size of the effects. Conventionally, the scales of Λ's are chosen by conventionally fixing $g^2_{\text{eff}}/4\pi = 1$ as a reminder that this new interaction, originally proposed for compositeness, would become strong at the reaction energy $\sqrt{s} \sim \Lambda_{\alpha\beta}$.

Specifically, we consider here the electron-positron annihilation:

$$e^+ + e^- \to f + \bar{f}, \qquad (2)$$

with $f = \mu$ and τ, and the relevant precision data at LEP2 for $130 < \sqrt{s} < 207$ GeV, published in Ref. [1], where the results of the four experimental collaborations are combined. Such high precision data can be regarded as a powerful tool to severely test manifestations of non-standard interactions through deviations from the SM predictions and, clearly, the numerical comparison of such deviations to the experimental accuracies quantitatively determines the attainable reach in the free mass scales $\Lambda_{\alpha\beta}$ or, equivalently, the experimental sensitivity to the new coupling constants $\epsilon_{\alpha\beta}$.

In practice, the situation is complicated by the fact that, for a given flavor f, Eq. (1) defines eight individual, independent, models corresponding to the combinations of the four chiralities α, β with the $\pm$ signs of the ϵ's, and the general contact interaction could be any linear combination of these models. Accordingly, the aforementioned deviations from the SM predictions simultaneously depend on all four-fermion effective couplings and, for a fixed value of the energy $\sqrt{s}$, their straightforward comparison to the experimental uncertainties *a priori* could only produce numerical correlations among the possible values of different couplings, rather than separate, and restricted, allowed regions around the SM limit $\epsilon_{\alpha\beta} = 0$. This could be obtained only by a procedure based on suitable observables and/or the analysis of the appropriate samples of experimental data.

As it was mentioned above, the simplest and commonly adopted procedure consists in assuming non-zero values for just one of the $\epsilon_{\alpha\beta}$ at a time, and in constraining it to a finite interval by essentially the χ^2 fit analysis of the measured cross sections and forward-backward asymmetries, while all the other parameters are set equal to zero [5, 6]. In this way, only tests of specific models could be performed.

To present the analysis in Ref. [2] we restrict ourselves to the case of $f = \mu, \tau$. Neglecting all fermion masses with respect to $\sqrt{s}$, and taking into account the Born γ and Z exchanges in the s channel plus the contact-interaction term (1), the differential cross section of process (2) reads

[2]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{3}{8}\left[(1+\cos\theta)^2\sigma_+ + (1-\cos\theta)^2\sigma_-\right], \tag{3}$$

where θ is the angle between the incoming electron and the outgoing fermion in the c.m. frame. In terms of helicity cross sections, $\sigma_{\alpha\beta}$ with $\alpha, \beta =$ L, R:

$$\sigma_+ = \frac{1}{4}\left(\sigma_{\rm LL} + \sigma_{\rm RR}\right), \tag{4}$$

$$\sigma_- = \frac{1}{4}\left(\sigma_{\rm LR} + \sigma_{\rm RL}\right). \tag{5}$$

In Eqs. (4) and (5):

$$\sigma_{\alpha\beta} = \sigma_{\rm pt}|\mathcal{M}_{\alpha\beta}|^2, \tag{6}$$

where $\sigma_{\rm pt} \equiv \sigma(e^+e^- \to \gamma^* \to l^+l^-) = 4\pi\alpha_{\rm e.m.}^2/3s$ (for quark-antiquark production a color factor $N_C \simeq 3(1+\alpha_s/\pi)$ could be needed). The helicity amplitudes $\mathcal{M}_{\alpha\beta}$ can be written as

$$\mathcal{M}_{\alpha\beta} = Q_eQ_f + g_\alpha^e\, g_\beta^f\, \chi_Z + \frac{s}{\alpha_{\rm e.m.}}\epsilon_{\alpha\beta}, \tag{7}$$

where: $\chi_Z = s/(s - M_Z^2 + iM_Z\Gamma_Z)$ is the Z propagator; $g_{\rm L}^f = (I_{3L}^f - Q_f s_W^2)/s_W c_W$ and $g_{\rm R}^f = -Q_f s_W^2/s_W c_W$ are the SM left- and right-handed fermion couplings of the Z with $s_W^2 = 1 - c_W^2 \equiv \sin^2\theta_W$; $Q_e = Q_f = -1$ are the fermion electric charges.

The measured observables σ and $A_{\rm FB}$ are given by the relations:

$$\sigma = \int_{-1}^{1}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta = \\ = \frac{1}{4}\left[(\sigma_{\rm LL}+\sigma_{\rm RR}) + (\sigma_{\rm LR}+\sigma_{\rm RL})\right] \tag{8}$$

and

$$\sigma_{\rm FB} \equiv \sigma\, A_{\rm FB} = \left(\int_0^1 - \int_{-1}^0\right)\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta = \\ = \frac{3}{16}\left[(\sigma_{\rm LL}+\sigma_{\rm RR}) - (\sigma_{\rm LR}+\sigma_{\rm RL})\right]. \tag{9}$$

Finally, their relation to $\sigma_\pm$ is given by

$$\sigma_\pm = \frac{\sigma}{2}\left(1 \pm \frac{4}{3}A_{\rm FB}\right). \tag{10}$$

Taking Eq. (7) into account, Eqs. (8) and (9) show that σ and $\sigma_{\rm FB}$ (or $A_{\rm FB}$) simultaneously depend on *all* four contact interaction couplings, and therefore by themselves do not allow a model-independent analysis, but only the simplified one-parameter fit of individual models. However, σ and $\sigma_{\rm FB}$ depend on the two combinations of helicity cross sections, $(\sigma_{\rm LL}+\sigma_{\rm RR})$ and $(\sigma_{\rm LR}+\sigma_{\rm RL})$. Accordingly, a combined analysis of σ and $\sigma_{\rm FB}$ enables to separately constrain the pairs of parameters $(\epsilon_{\rm LL}, \epsilon_{\rm RR})$ and $(\epsilon_{\rm LR}, \epsilon_{\rm RL})$. Moreover, the combination of experimental data on σ and $\sigma_{\rm FB}$ at different values of the c.m. energy allows to further restrict such separate bounds in a model-independent way.

The detailed analysis of the LEP2 experiment data based on this consideration is given in Ref. [2] where the method of least squares is used. Its the main results are present in the Tables 1.

Table 1. Central value ϵ^0, global limits (allowed intervals) obtained as projections of the 95% CL four-dimensional region on the axes and 95% CL one-dimensional model-dependent constraints on the CI parameters.

Parameter [TeV^{-2}]	Model independent		Model dependent
	central value	global limits	
$\epsilon_{\rm LL}$	0.0085	(−0.175, 0.095)	$-0.0047^{+0.0071}_{-0.0071}$
$\epsilon_{\rm RR}$	−0.0195	(−0.187, 0.111)	$-0.0052^{+0.0078}_{-0.0078}$
$\epsilon_{\rm LR}$	0.0120	(−0.225, 0.060)	$-0.0012^{+0.0111}_{-0.0116}$
$\epsilon_{\rm RL}$	−0.0160	(−0.225, 0.060)	$-0.0012^{+0.0111}_{-0.0116}$

In Table 1 the components of the central value ϵ^0 (over-all minimum of χ^2) and the global limits (intervals $(\epsilon_{\rm min}, \epsilon_{\rm max})$)are shown for combining the μ and τ data which are obtained as projections of the confidence region on the corresponding axes. These intervals have to be considered as global, model-independent, constraints on the CI parameters $\epsilon_{\alpha\beta}$.

3 Model - independent search for Z' boson

To develop the model-independent searches for the manifestations of heavy particles with specific quantum numbers without specifying a model beyond the SM it is necessary to take into account some model-independent relations between the couplings of the heavy particle as well as the features of the kinematics of investigated scattering processes. We focus on the problem on model-independent searches for Z' boson [8] within the analysis of the LEP2 data on the lepton processes $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$. This particle is a necessary element of different models extending the SM. In what follows we assume that the Z' boson is heavy enough to be decoupled at the LEP2 energies.

The Z' signal in the noted processes $e^+e^- \to l^+l^-$ can be detected by using a sign-definite observable, which is ruled by the center-of-mass energy and an additional kinematic parameter. From the requirement that new unknown theory is renormalizable one has been derived the relations between the low-energy couplings of the Abelian Z'-boson to the SM fermions [3]:

$$v_f - a_f = v_{f^\star} - a_{f^\star}, \quad a_f = T_{3,f}\tilde{Y}_\phi, \\ \tilde{Y}_{\phi,1} = \tilde{Y}_{\phi,2} \equiv \tilde{Y}_\phi, \tag{11}$$

where a_f, v_f are the couplings to the axial-vector and vector fermion currents, T_f^3 is the third component of the fermion weak isospin, $\tilde{Y}_{\phi,1}, \tilde{Y}_{\phi,2}$ are the parameters describing the Z' interactions with the components of the scalar doublet and $f^\star$ means the isopartner of f (namely, $l^\star = \nu_l, \nu_l^\star = l, \ldots$).

As it follows from these relations, the couplings of the Abelian Z' to the axial-vector fermion currents have the universal absolute value proportional to the Z' coupling to the scalar doublet. So, we will use the short notation $a = a_l = -\tilde{Y}_\phi/2$. Note also that the Z–Z' mixing is expressed in terms of the axial-vector coupling a. An important benefit of the relations (3) is the possibility to reduce the number of independent parameters describing new physics.

In the lower order in $m_{Z'}^{-2}$ the Z' contributions to the differential cross-section of the process $e^+e^- \to l^+l^-$ are expressed in terms of four-fermion contact couplings, only. The incorporation of the next-to-leading terms in $m_{Z'}^{-2}$ allows to consider the Z' effects beyond the approximation of four-fermion contact interactions [9]. As a consequence, the four-fermion contact couplings and the Z' mass can be fitted. In the present analysis we keep the terms of order $O(m_{Z'}^{-4})$ to fit both of these parameters.

To take into consideration the correlations (3) one is able to introduce the observable $\sigma_l(z)$ defined as the difference of cross sections integrated in some ranges of the scattering angle θ [10]:

$$\sigma_l(z) \equiv \int_z^1 \frac{\mathrm{d}\sigma_l}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta - \int_{-1}^z \frac{\mathrm{d}\sigma_l}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta, \tag{12}$$

where z stands for the cosine of the boundary angle. The idea of introducing the z-dependent observable is to choose the value of z in such a way that to pick up the characteristic features of the Abelian Z' signals.

The deviation of the observable from its SM value can be derived by the angular integration of the differential cross-section and has the form:

$$\Delta\sigma_l(z) = \sigma_l(z) - \sigma_l^{\mathrm{SM}}(z) = \\ = \sum_{i=1}^{7}\sum_{j=1}^{i}\left[\tilde{A}_{ij}^l(s,z) + \tilde{B}_{ij}^l(s,z)\zeta\right]a_i a_j + \\ + \sum_{i=1}^{7}\sum_{j=1}^{i}\sum_{k=1}^{j}\sum_{n=1}^{k}\tilde{C}_{ijkn}^l(s,z)a_i a_j a_k a_n, \tag{13}$$

where the dimensionless quantities

$$\zeta = \frac{m_Z^2}{m_{Z'}^2}, \quad \epsilon = \frac{\tilde{g}^2 m_Z^2 a^2}{4\pi m_{Z'}^2}, \\ (a_k, k = \overline{1,7}) = \sqrt{\frac{\tilde{g}^2 m_Z^2}{4\pi m_{Z'}^2}}(a, v_e, v_\mu, v_\tau, v_d, v_s, v_b) \tag{14}$$

are introduced. In what follows the index $l = \mu, \tau$ denotes the final-state lepton.

The coefficients $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ are determined by the SM couplings and masses. Each factor may include the tree-level contribution, the one-loop correction and the term describing the soft-photon emission. The factors $\tilde{A}$ describe the leading-order contribution, whereas others correspond to the higher order corrections in $m_{Z'}^{-2}$.

There is an interval of the boundary angle values at which the factors $\tilde{A}_{11}^l$, $\tilde{B}_{11}^l$, and $\tilde{C}_{1111}^l$ at the sign-definite parameters ϵ, $\epsilon\zeta$, and ϵ^2 contribute more than 95% of the observable value. It gives the possibility to construct the sign-definite observable $\Delta\sigma_l(z^*) < 0$ by specifying the proper value of z^* [11]. The boundary angle $z^* = 0.378$ at $\sqrt{s} = 200$ GeV and decreases with the growth of the center-of-mass energy.

To search for the model-independent signals of the Abelian Z'-boson we will analyze the introduced observable $\Delta\sigma_l(z^*)$ on the base of the LEP2 data set. In the lower order in $m_{Z'}^{-2}$ the observable (13) depends on one flavor-independent parameter ϵ,

$$\Delta\sigma_l^{\rm th}(z^*) = \tilde{A}_{11}^l(s,z^*)\epsilon + \tilde{C}_{1111}^l(s,z^*)\epsilon^2, \quad (15)$$

which can be fitted from the experimental values of $\Delta\sigma_\mu(z^*)$ and $\Delta\sigma_\tau(z^*)$. As we noted above, the sign of the fitted parameter ($\epsilon > 0$) is the characteristic feature of the Abelian Z' signal.

In what follows we will apply the usual fit method based on the likelihood function. The central value of ϵ is obtained by the minimization of the χ^2-function:

$$\chi^2(\epsilon) = \sum_n \frac{\left[\Delta\sigma_{\mu,n}^{\rm ex}(z^*) - \Delta\sigma_\mu^{\rm th}(z^*)\right]^2}{\delta\sigma_{\mu,n}^{\rm ex}(z^*)^2}, \quad (16)$$

where the sum runs over the experimental points entering a data set chosen.

We introduce the contact interaction scale $\Lambda^2 = 4m_Z^2\epsilon^{-1}$ and use again the likelihood method to determine a one-sided lower limit on the scale Λ at the 95% confidence level.

We also introduce the probability of the Abelian Z' signal as the integral of the likelihood function over the positive values of ϵ: $P = \int_0^\infty L(\epsilon')d\epsilon'$.

Table 2. The contact coupling ϵ with the 68% confidence-level uncertainty, the 95% confidence-level lower limit on the scale Λ, the probability of the Z' signal, P, and the value of $\zeta = m_Z^2/m_{Z'}^2$ as a result of the fit of the observable recalculated from the total cross-sections and the forward-backward asymmetries.

Data set	$\epsilon \times 10^5$	Λ, TeV	P	ζ
Winter 2002				
$\mu\mu$	$4.82^{+4.96}_{-4.93}$	15.7	0.83	0.007 $\pm$0.215
$\tau\tau$	$0.16^{+6.61}_{-6.56}$	16.0	0.51	−0.052 $\pm$8.463
$\mu\mu$ and $\tau\tau$	$3.13^{+3.96}_{-3.95}$	18.1	0.78	0.006 $\pm$0.264
Summer 2002				
$\mu\mu$	$3.66^{+4.89}_{-4.86}$	16.4	0.77	0.009 $\pm$0.278
$\tau\tau$	$-2.66^{+6.43}_{-6.39}$	17.4	0.34	−0.001 $\pm$0.501
$\mu\mu$ and $\tau\tau$	$1.33^{+3.89}_{-3.87}$	19.7	0.63	0.017 $\pm$0.609

The fitted value of the contact coupling ϵ comes mainly from the leading-order term in the inverse Z' mass in Eq. (13). The analysis of the higher-order terms then allows to estimate the constraints on the Z' mass alone. Substituting ϵ in the observable (13) by its fitted central value, $\bar{\epsilon}$, one obtains the expression

$$\Delta\sigma_l(z^*) = \left[\tilde{A}_{11}^l(s,z^*) + \zeta\tilde{B}_{11}^l(s,z^*)\right]\bar{\epsilon} + \\ + \tilde{C}_{1111}^l(s,z^*)\bar{\epsilon}^2, \quad (17)$$

which depends on the parameter $\zeta = m_Z^2/m_{Z'}^2$. Then, the central value of this parameter and the corresponding 1σ confidence level interval are derived in the same way as those for ϵ.

The results are presented in Table 3. As is seen, the more precise $\mu\mu$ data demonstrate the signal of about 1σ level. It corresponds to the Abelian Z'-boson with the mass of order 1.2–1.5TeV if one assumes the value of $\tilde{\alpha} = \tilde{g}^2/4\pi$ to be in the interval 0.01–0.02. No signal is found by the analysis of the $\tau\tau$ cross-sections. The combined fit of the $\mu\mu$ and $\tau\tau$ data leads to the signal below the 1σ confidence level.

4 Confronting analysis of the Z' boson searches

Now, let us turn to comparison of the four-parametric fit and the model-independent searching for Z' gauge boson. The key point in this analysis is the fact noted in Ref. [11] that AA "helicity model" of the one-parametric fit carried out by LEP collaborations is responsible mainly for the signal of Z' gauge boson. Hence, one should derive in the parametric space determined in section 2 the domain which corresponds to the AA-model. As we shown in section 3, due to the relations (3) the signal of the Z' is correlated with the sign at the a^2 parameter. So, we have to construct from the variables $\sigma_{\rm LL}, \sigma_{\rm LR}, \sigma_{\rm LR}$ and $\sigma_{\rm RR}$ the observable corresponding to the a^2. It is easy to check that this variable is

$$\epsilon_{a^2} = \sigma_{\rm LL} + \sigma_{\rm RR} - \sigma_{\rm LR} - \sigma_{\rm RL} = = -\frac{a^2}{m_Z^2}(1 + \frac{2m_Z^2}{s - m_Z^2}), \quad (18)$$

where the explicit values of the scattering amplitude parameters are substituted. As one can see, this expression is proportional to the a^2 and negative. So, the direct comparison of both methods is possible.

The region in the parametric space corresponding to ϵ_{a^2} lays in the interval

$$-0.1 \text{ TeV}^{-2} \le \epsilon_{a^2} \le 0.24 \text{ TeV}^{-2}. \quad (19)$$

To compare this with the results of the model-independent method in section 3 we estimate ϵ_{a^2} (in TeV^{-2}) for the energies $\sqrt{s} = 136, 173, 207$ GeV, corresponding to the lower, middle and maximal values of the LEP2 experiment. We find correspondingly,

$$\begin{aligned} -0.027 \le \epsilon_{a^2} \le 0.004, &\quad \sqrt{s} = 136 \text{ GeV}, \\ -0.018 \le \epsilon_{a^2} \le 0.003, &\quad \sqrt{s} = 173 \text{ GeV}, \\ -0.015 \le \epsilon_{a^2} \le 0.002, &\quad \sqrt{s} = 207 \text{ GeV}. \quad (20) \end{aligned}$$

As it is seen, the all values in Eq. (20) lay the interval Eq. (19) as it should be in a consistent description. It is important that this property holds for all energies investigated. Hence we conclude that the model-independent search for Z' gauge boson is in correspondence with general analysis which does not assume any specific kinematics or relations taken into consideration.

As a conclusion on the carried out analysis we would like to note that both model-independent methods do not exclude the Z' boson existence.

The present analysis shows that the 1σ deviation from the SM prediction is found by treatment of the LEP2 data. This deviation is in accordance with the existence of the Abelian Z' boson. One would believe that the deviation is inspired by the Abelian Z' boson, but the LEP2 experiment accuracy is insufficient to detect the signal at more than 1σ confidence level. Evidently, the signal could be picked up more clearly by increasing the experimental statistics. In this regard, it is of interest to estimate the parameters of future electron-positron colliders required to verify the Z' signal. In order to pick up the signal at 2σ confidence level at a collider with the center-of-mass energy $\sqrt{s} = 500$ GeV the luminosity of 168 pb^{-1} is required. This luminosity has to be reached at the first run of such a collider. Therefore, we hope that the Z' boson has a good chance to be discovered soon.

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