The many-parametric fit of the LEP2 data on $e^+ e^- \rightarrow e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-$ processes is performed to estimate signals of the Abelian $Z'$-boson beyond the standard model. The model-independent relations between the $Z'$ couplings to the standard model particles allow to describe the $Z'$ effects in lepton processes by 4 independent parameters. No signal is found by the complete LEP2 data set, and the 1.3σ signal is detected by the fit of the backward bins. The $Z'$ couplings to the vector and axial-vector lepton currents are constrained. The comparisons with the one-parameter fits and with the LEP1 experiments are performed.

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I. INTRODUCTION

The precision test of the standard model (SM) at LEP gave a possibility not only to determine all the parameters and particle masses at the level of radiative corrections but also afforded an opportunity for searching for signals of new heavy particles beyond the energy scale of it. On the base of the LEP2 experiments the low bounds on parameters of various models extending the SM have been estimated and the scale of new physics was obtained [1, 2, 3]. Although no new particles were discovered, a general believe is that the energy scale of new physics to be of order 1 TeV, that may serve as a guide for experiments at the LHC. In this situation, any information about new heavy particles obtained on the base of the present day data is desirable and important.

A lot of extended models includes a so-called $Z'$ gauge boson – a massive neutral vector particle associated with an extra $U(1)$ subgroup of the underlying group. Searching for this particle in either model-dependent or model-independent approaches is widely discussed in the literature [4]. In the papers of the present authors [5, 6, 7] the new method and the observables for the model-independent search for the $Z'$-boson were proposed and applied to analyze the LEP2 experiment data. In contrast to other model-independent searches, our approach gives a possibility to pick out uniquely this virtual state and determine its characteristics. It is based on two ingredients: 1) The relations between the low-energy parameters are derived from the renormalization group (RG) equation for the fermion scattering amplitude and therefore called the RG relations. Due to them the number of unknown $Z'$ parameters to be measured considerably decreases. 2) The kinematic properties of the $Z'$ signals in various scattering process exhibit themselves when these relations are accounted for. In these papers the one-parametric observables were introduced and the signals of the $Z'$ have been determined at the 1σ confidence level (CL) in the $e^+ e^- \rightarrow \mu^+ \mu^-$ process, and at the 2σ CL in the Bhabha process. The $Z'$ mass was estimated to be 1–1.2 TeV that gives a good chance to discover the particle at the LHC.

Recently the final data of the LEP collaborations DELPHI and OPAL [6, 8] were published and new more precise estimates could be obtained. In the present paper we update the results of the one-parameter fit and perform the complete many-parametric fit of the LEP2 data to estimate a possible signal of the $Z'$-boson. Usually, in a many-parametric fit the uncertainty of the result increases drastically because of extra parameters. On the contrary, in our approach due to the RG relations between the low-energy couplings there are only 2-3 independent parameters for the LEP scattering processes. Therefore, we believe that an inevitable increase of confidence areas (CA) in the many-parametric space could be compensated by accounting for all the accessible experimental information. As it will be shown, the uncertainty of the many-parametric fit can be comparable with the uncertainty of the previous one-parametric fits in Refs. [6, 8]. In this approach the combined data fit for all lepton processes is also possible.

II. THE ABELIAN $Z'$ BOSON AT LOW ENERGIES

Let us adduce a necessary information about the Abelian $Z'$-boson. This particle is predicted by a number of grand unification models. Among them the $E_6$ and $SO(10)$ based models [9] (for instance, LR, $\chi - \psi$ and so on) are often discussed in the literature. In all the models, the Abelian $Z'$-boson is described by a low-energy $U(1)$ gauge subgroup originated in some symmetry breaking pattern.

At low energies, the $Z'$-boson can manifest itself by means of the couplings to the SM fermions and scalars as a virtual intermediate state. Moreover, the $Z$-boson couplings are also modified due to a $Z-Z'$ mixing. In principle, arbitrary effective $Z'$ interactions to the SM fields could be considered at low energies. However, the couplings of non-renormalizable types have to be suppressed.

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by heavy mass scales because of decoupling. Therefore, significant signals beyond the SM can be inspired by the couplings of renormalizable types. Such couplings can be derived by adding the new $\hat{U}(1)$-terms to the electroweak covariant derivatives $D^{ew}$ in the Lagrangian $\mathcal{L}$

$$\mathcal{L} = \left| D^{ew}_{\mu} - \frac{i}{2} \tilde{\phi} \gamma_{\mu} \right|^{2} + i \sum_{f=1}^{4} F_{\gamma}^{\mu} \left( D^{ew}_{\mu} - \frac{i}{2} \tilde{\phi} \right) f, \quad (1)$$

where $\phi$ is the SM scalar doublet; $f_L, f_R$ are the SM left-handed fermion doublets and right-handed fermion singlets; $\tilde{Z}_{\mu}$ denotes the $\hat{U}(1)$ symmetry eigenstate; and $\tilde{y}_{f}, \tilde{y}_{fl}$ and $\tilde{y}_{fr}$ mean the unknown couplings characterizing the model beyond the SM. Instead of the couplings to the left-handed and right-handed fermion states it is convenient to introduce the couplings to the axial-vector and vector currents: $a_{f} \equiv (\tilde{y}_{f} - \tilde{y}_{fl})/2, v_{f} \equiv (\tilde{y}_{fl} + \tilde{y}_{fr})/2$.

The spontaneous breaking of the electroweak symmetry leads to the $Z-Z'$ mixing. In case of the Abelian $Z'$-boson, the $Z-Z'$ mixing angle $\theta_0$ is determined by the coupling $\tilde{y}_{f}$ as follows

$$\theta_0 = \frac{\sin \theta_{W} \cos \theta_{W}}{\sqrt{4\pi \alpha_{em}}} \frac{m_{Z'}^{2}}{m_{Z_0}^{2}} \tilde{y}_{f} + O \left( \frac{m_{f}^{4}}{m_{Z'}^{2}} \right), \quad (2)$$

where $\theta_{W}$ is the SM Weinberg angle, and $\alpha_{em}$ is the electromagnetic fine structure constant. Although the mixing angle is a small quantity of order $m_{Z'}^{2}$, it contributes to the $Z$-boson exchange amplitude and cannot be neglected at the LEP energies.

The Lagrangian (1) leads to the following interactions between the fermions and the $Z$ and $Z'$ mass eigenstates:

$$L_{Zf} = -\frac{1}{2} \frac{e}{\sin \theta_{W}} \cos \theta_{W} \frac{m_{Z}^{2}}{m_{Z_0}^{2}} \tilde{y}_{f}^{\mu} \left( i (v_{f}^{SM} + \gamma^{5} a_{f}^{SM}) \right) \cos \theta_0 + (v_{f} + \gamma^{5} a_{f}^{SM}) \sin \theta_0 f, \quad (3)$$

$$L_{Z'f} = -\frac{1}{2} \frac{e}{\sin \theta_{W}} \cos \theta_{W} \frac{m_{Z'}^{2}}{m_{Z_0}^{2}} \tilde{y}_{f}^{\mu} \left( v_{f} + \gamma^{5} a_{f}^{SM} \right) \cos \theta_0 - (v_{f}^{SM} + \gamma^{5} a_{f}^{SM}) \sin \theta_0 f,$$

where $f$ is an arbitrary SM fermion state; $v_{f}^{SM}, a_{f}^{SM}$ are the SM couplings of the $Z$-boson.

In a particular model the couplings $v_{f}$ and $a_{f}$ take some specific values. In case when the model is unknown, these parameters and the mixing angle remain potentially arbitrary numbers. However, this is not the case if one assumes that the underlying extended model is a renormalizable one. As it was shown in Ref. $\mathbb{F}$, some of them have to be correlated due to renormalizability. The corresponding relations are

$$v_{f} - a_{f} = v_{f}^{*} - a_{f}^{*}, \quad a_{f} = T_{3,f} \tilde{y}_{f}, \quad (4)$$

where $f^{*}$ is the SU(2) partner of a fermion $f$, and $T_{3,f}$ is the third component of the fermion isospin. They are motivated by the renormalization group equations at the $Z'$ decoupling energies and also connected with the $\hat{U}(1)$ gauge symmetry of the Lagrangian. These relations cover all the popular models of the Abelian $Z'$ boson allowing the model-independent searches for this particle.

The relations $\mathbb{I}$ incorporate the most common features of the Abelian $Z'$-boson. As it is seen, the axial-vector coupling is universal for all the fermion flavors. So, in what follows we will use the shorthand notation $a = a_{e} = a_{\mu} = a_{\tau}$. The axial-vector coupling determines also the coupling to the scalar doublet and, consequently, the mixing angle. As a result, the number of independent couplings is significantly reduced. Considering the leptonic processes $e^{+}e^{-} \rightarrow \ell^{+}\ell^{-} \quad (\ell = e, \mu, \tau)$, one has to keep 4 unknown couplings: $a, v_{e}, v_{\mu}, v_{\tau}$. Moreover, the RG relations serve to uniquely specify a kinematic domain of deviations from the SM predictions due to the virtual $Z'$ boson. Thereof a single definition of the $Z'$ signal can be done.

In our analysis, as the SM values of the cross-sections we use the quantities calculated by the LEP2 collaborations $\mathbb{G}$, $\mathbb{H}$, $\mathbb{J}$, $\mathbb{K}, \mathbb{L}$. They account for either the one-loop radiative corrections or initial and final state radiation effects (together with the event selection rules, which are specific for each experiment). The deviation from the SM is computed in the improved Born approximation. This accuracy is sufficient for our analysis, leading to the systematic error of fit results less than 5-10%.

The differential cross-section of the process $e^{+}e^{-} \rightarrow \ell^{+}\ell^{-}$ deviates from the SM value by various quadratic combinations of couplings $a, v_{e}, v_{\mu}, v_{\tau}$. For the Bhabha process it reads

$$\frac{d\sigma}{dz} \frac{d\sigma^{SM}}{dz} = f_{1}^{\gamma\gamma}(z) \frac{a^{2}}{m_{Z'}^{2}} + f_{2}^{\gamma\gamma}(z) \frac{v_{e}^{2}}{m_{Z'}^{2}} + f_{3}^{\gamma\gamma}(z) \frac{a^{2}v_{e}}{m_{Z'}^{2}}, \quad (5)$$

where the factors are known functions of the center-of-mass energy and the cosine of the electron scattering angle $z$. The deviation of the cross-section of $e^{+}e^{-} \rightarrow m^{+}m^{-} \quad (\tau^{+}\tau^{-})$ processes has the similar form

$$\frac{d\sigma}{dz} \frac{d\sigma^{SM}}{dz} = f_{1}^{\mu\mu}(z) \frac{a^{2}}{m_{Z'}^{2}} + f_{2}^{\mu\mu}(z) \frac{v_{e}v_{\mu}}{m_{Z'}^{2}} + f_{3}^{\mu\mu}(z) \frac{a^{2}v_{e}}{m_{Z'}^{2}} + f_{4}^{\mu\mu}(z) \frac{a^{2}v_{\mu}}{m_{Z'}^{2}}, \quad (6)$$

This is our definition of the $Z'$ signal.

Since the $Z'$ couplings enter the cross-section together with the inverse $Z'$ mass, it is convenient to introduce the dimensionless couplings

$$\tilde{a}_{f} = \frac{m_{Z}}{4\pi m_{Z'}} a_{f}, \quad \tilde{v}_{f} = \frac{m_{Z}}{4\pi m_{Z'}} v_{f}, \quad (7)$$

which can be constrained by experiments.

Note again, that the cross-sections in Eqs. $\mathbb{M}-\mathbb{O}$ account for the relations $\mathbb{I}$ through the functions $f_{1}(z), f_{3}(z), f_{4}(z)$, since the coupling $\tilde{y}_{f}$ (the mixing angle $\theta_{0}$) is substituted by the axial coupling constant $a$. Usually, this dependence on the scalar field coupling is neglected.
at all, when a four-fermion effective Lagrangian is applied to describe physics beyond the SM [8]. However, in our case, when we are interested in searching for signals of the \( Z' \)-boson on the base of the effective low-energy Lagrangian [10], these contributions to the cross-section are essential.

### III. MANY-PARAMETER FITS

As the basic observable to fit the LEP2 experiment data on the Bhabha process we propose the differential cross-section

\[
\frac{d\sigma_{\text{Bhabha}}}{dz} = \frac{d\sigma_{\text{Bhabha,SM}}}{dz} \bigg|_{z=z_i, \sqrt{s} = \sqrt{s_i}},
\]

where \( i \) runs over the bins at various center-of-mass energies \( \sqrt{s} \). The differential cross-sections measured by the ALEPH (130-183 GeV, [10]), DELPHI (189-207 GeV, [3]), L3 (183-189 GeV, [11]), and OPAL (130-207 GeV, [2]) collaborations are taken (299 bins).

As the observables for \( e^+e^- \rightarrow \mu^+\mu^- , \tau^+\tau^- \) processes, we consider the total cross-section and the forward-backward asymmetry

\[
\sigma_{FB}^{\tau+\tau^-} - \sigma_{FB}^{\tau+\tau^-} \quad \text{and} \quad A_{FB}^{\tau+\tau^-} - A_{FB}^{\tau+\tau^-},
\]

where \( i \) runs over 12 center-of-mass energies \( \sqrt{s} \) from 130 to 207 GeV. We consider the combined LEP2 data [1] for these observables (24 data entries for each process). These data are more precise as corresponding differential cross-sections. Our analysis is based on the fact that the kinematics of the s-channel processes is rather simple and a differential cross-section is effectively the two-parametric function of the scattering angle. The total cross-section and the forward-backward asymmetry incorporate a complete information about the kinematics of the process and therefore are an adequate alternative for the differential cross-sections.

The data are analysed by means of the \( \chi^2 \) fit. Denoting the observables \( \sigma_i \) by \( \sigma_i \), one can construct the \( \chi^2 \)-function,

\[
\chi^2(\bar{a}, \bar{v}_e, \bar{v}_\mu, \bar{v}_\tau) = \sum_i \left[ \frac{\sigma_{\text{ex}} - \sigma_i^{\text{th}}(\bar{a}, \bar{v}_e, \bar{v}_\mu, \bar{v}_\tau)}{\delta\sigma_i} \right]^2,
\]

where \( \sigma_{\text{ex}} \) and \( \delta\sigma \) are the experimental values and uncertainties of the observables, and \( \sigma^{\text{th}} \) are their theoretical expressions presented in Eqs. [10] - [13]. The sum in Eq. [10] refers to either the data on one specific process or the combined data on several processes. By minimizing the \( \chi^2 \)-function, the maximal-likelihood estimate for the \( Z' \) couplings can be derived. The \( \chi^2 \)-function is also used to plot the CA in the space of \( \bar{a}, \bar{v}_e, \bar{v}_\mu \), and \( \bar{v}_\tau \).

For all the considered processes, the theoretic predictions \( \sigma_i^{\text{th}} \) are linear combinations of products of two \( Z' \) couplings

\[
\sigma_i^{\text{th}} = \sum_{j=1}^7 C_{ij} A_j,
\]

where \( C_{ij} \) are known numbers. In what follows we use the matrix notation \( \sigma^{\text{ex}} = \sigma_1^{\text{th}}, \sigma^{\text{ex}} = \sigma_2^{\text{ex}}, C = C_{ij}, A = A_j \).

Note that a number of terms in the observables for different processes are the same. Therefore, the number of \( \chi^2 \) d.o.f. in the combined fits is less than the sum of d.o.f. for separate processes. Hence, the predictive
power of the larger set of data is not drastically spoiled by increased number of d.o.f. In fact, combining the data of the Bhabha and $e^+e^- \rightarrow \mu^+\mu^-$ ($\tau^+\tau^-$) processes together we have to treat 5 linear-independent terms. The complete data set for all the lepton processes is ruled by 7 d.o.f. As a consequence, the combination of the data for all the lepton processes is possible.

The parametric space of couplings ($\bar{a}$, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) is four-dimensional. However, for the Bhabha process it is reduced to the plane ($\bar{a}$, $\bar{\nu}_e$), and to the three-dimensional volumes ($\bar{a}$, $\bar{\nu}_e$, $\bar{\nu}_\mu$), ($\bar{a}$, $\bar{\nu}_e$, $\bar{\nu}_\tau$) for the $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ processes, correspondingly. The predictive power of data is distributed not uniformly over the parameters. The parameters $\bar{a}$ and $\bar{\nu}_e$ are present in all the considered processes and appear to be significantly constrained. The couplings $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ enter when the processes $e^+e^- \rightarrow \mu^+\mu^-$ or $e^+e^- \rightarrow \tau^+\tau^-$ are accounted for. So, in these processes, we also study the projection of the CA onto the plane ($\bar{a}$, $\bar{\nu}_e$).

The beginning of the parametric space, $\bar{a} = \bar{\nu}_e = 0$, corresponds to the absence of the $Z'$ signal. This is the SM value of the observables. This point could occur inside or outside of the CA at a fixed CL. When it lays out of the CA, this means the distinct signal of the Abelian $Z'$. Then the signal probability can be defined as the probability that the data agree with the Abelian $Z'$ boson existence and exclude the SM value. This probability corresponds to the most stringent CL (the largest $\chi^2_{\text{CL}}$) at which the point $\bar{a} = \bar{\nu}_e = 0$ is excluded. If the SM value is inside the CA, the $Z'$ boson is indistinguishable from the SM. In this case, upper bounds on the $Z'$ couplings can be determined.

The 95% CL areas in the ($\bar{a}$, $\bar{\nu}_e$) plane for the separate processes are plotted in Fig. 1. As it is seen, the Bhabha process constrains both the axial-vector and vector couplings. As for the $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ processes, the axial-vector coupling is significantly constrained, only. The CAs include the SM point at the meaningful CLs, so the experiment could not pick out clearly the Abelian $Z'$ signal from the SM. An important conclusion from these plots is that the experiment significantly constrains only the couplings entering sign-definite terms in the cross-sections.

The combination of all the lepton processes is presented in Fig. 2. There is no visible signal beyond the SM. The couplings to the vector and axial-vector electron currents are constrained by the many-parameter fit as $|\bar{\nu}_e| < 0.012$, $|\bar{a}| < 0.018$ at the 95% CL. If the charge corresponding to the $Z'$ interactions is assumed to be of order of the electromagnetic one, then the $Z'$ mass should be greater than 0.67 TeV. For the charge of order of the SM SU(2)$_L$ coupling constant $m_{Z'} \geq 1.4$ TeV. One can see that the constraint is not too severe to exclude the $Z'$ searches at the LHC.

Let us compare the obtained results with the one-parameter fits in Ref. 7. Fitting the current data with the one-parameter observable, we find the updated values of the $Z'$ coupling to the electron vector current together with their 1σ uncertainties:

- **ALEPH**: $\bar{\nu}_e^2 = -0.11 \pm 6.53 \times 10^{-4}$
- **DELPHI**: $\bar{\nu}_e^2 = 1.60 \pm 1.46 \times 10^{-4}$
- **L3**: $\bar{\nu}_e^2 = 5.42 \pm 3.72 \times 10^{-4}$
- **OPAL**: $\bar{\nu}_e^2 = 2.42 \pm 1.27 \times 10^{-4}$
- **Combined**: $\bar{\nu}_e^2 = 2.24 \pm 0.92 \times 10^{-4}$.

As it is seen, the most precise data of DELPHI and OPAL collaborations are resulted in the Abelian $Z'$ signals at one and two standard deviation level, correspondingly. The combined value shows the 2σ signal, which corresponds to $0.006 \leq |\bar{\nu}_e| \leq 0.020$.

On the other hand, our many-parameter fit constrains the $Z'$ coupling to the electron vector current as $|\bar{\nu}_e| \leq 0.012$ with no evident signal. Why does the one-parameter fit of the Bhabha process show the 2σ CL signal whereas there is no signal in the two-parameter one? Our one-parameter observable accounts mainly for the backward bins. This is in accordance with the kinematic features of the process. Therefore, the difference of the results can be inspired by the data sets.
used. To check this, we perform the many-parameter fit with the 113 backward bins \((z \leq 0)\), only. The \(\chi^2\) minimum, \(\chi^2_{\text{min}} = 103.0\), is found in the non-zero point \(|\bar{a}| = 0.00017\), \(\bar{v}_e = 0.015\). This value of the \(Z'\) coupling \(\bar{v}_e\) is in an excellent agreement with the mean value obtained in the one-parameter fit. The 68% CA in the \((\bar{a}, \bar{v}_e)\) plane is plotted in Fig. 3. There is a visible signal of the Abelian \(Z'\) boson. The zero point \(\bar{a} = \bar{v}_e = 0\) (the absence of the \(Z'\) boson) corresponds to \(\chi^2 = 107.9\). It is covered by the CA with 1.33\(\sigma\) CL. Thus, the backward bins show the 1.33\(\sigma\) signal of the Abelian \(Z'\) boson in the many-parameter fit. So, the many-parameter fit is less precise than the analysis of the one-parameter observables.

At LEP1 experiments [13] the \(Z\)-boson coupling constants to the vector and axial-vector lepton currents \((g_V, g_A)\) were precisely measured. The Bhabha process shows the 1\(\sigma\) deviation from the SM values for Higgs boson masses \(m_H \geq 114\) GeV (see Fig. 7.3 of Ref. [13]). This deviation could be considered as the effect of the \(Z-Z'\) mixing. It is interesting to estimate the bounds on the \(Z'\) couplings following from these experiments.

Due to the RG relations, the \(Z-Z'\) mixing angle is completely determined by the axial-vector coupling \(\bar{a}\). So, the deviations of \(g_V, g_A\) from their SM values are governed by the couplings \(\bar{a}\) and \(\bar{v}_e\),

\[
g_V - g_V^{\text{SM}} = -49.06\bar{a}\bar{v}_e, \quad g_A - g_A^{\text{SM}} = 49.06\bar{a}^2. \tag{16}
\]

Let us assume that a total deviation of theory from experiments follows due to the \(Z-Z'\) mixing. This gives an upper bound on the \(Z'\) couplings. In this way one can estimate is the \(Z'\) boson excluded by the experiments or not.

The 1\(\sigma\) CL area for the Bhabha process from Ref. [13] is converted to the \((\bar{a}, \bar{v}_e)\) plane in Fig. 3. The SM values of the couplings correspond to the top quark mass \(m_t = 178\) GeV and the Higgs scalar mass \(m_H = 114\) GeV. As it is seen, the LEP1 data on the Bhabha process is compatible with the Abelian \(Z'\) existence at the 1\(\sigma\) CL.

The axial-vector coupling is constrained as \(|\bar{a}| \leq 0.005\). This bound corresponds to \(\bar{a}^2 \leq 2.5 \times 10^{-5}\), which agrees with our previous one-parameter fits of the LEP2 data for \(e^+e^- \rightarrow \mu^+\mu^-\), \(\tau^+\tau^-\) processes \(\mathbb{K}\) \(\bar{a}^2 = 1.3 \pm 3.89 \times 10^{-5}\) at 68% CL). On the other hand, the vector coupling constant \(\bar{v}_e\) is practically unconstrained by the LEP1 experiments.

IV. DISCUSSION

LEP collaborations have reported about a good agreement between the experimental data and the predictions of the SM \([\mathbb{1}, \mathbb{2}, \mathbb{10}, \mathbb{11}]\). Our analysis of the leptonic processes based on the same data set and the same SM values of cross-sections showed that the existence of \(Z'\) boson with the mass of order 1-1.2 TeV is not excluded at the 1-2\(\sigma\) CL. We observed this in one-parameter fits \(\mathbb{K}\) and in the many-parameter fits in the present paper. The estimated \(Z'\) parameters derived in different methods are in good agreement with each other. So, we are faced with a necessity to find a possible explanations of this discrepancy. We believe that the reason is in the RG relations, which play a crucial role in treating experimental data. As we showed, the RG relations served to reduce the number of unknown parameters and extract a maximal information about the signal of the particle of interest from the experimental data set. If the RG relations are not taken into account, no signals of \(Z'\) will be found.

LEP collaborations performed also model-dependent fits concerning popular \(Z'\) models. Since these models are included in the ones suiting the RG relations \(\mathbb{1}\), it is interesting to compare their analysis with our results. In experiments \([\mathbb{1}, \mathbb{2}, \mathbb{3}, \mathbb{10}, \mathbb{11}]\) the low bound on the \(Z'\) mass was obtained. It varies from 400 to 800 GeV at the 95\% CL dependently on the \(Z'\) model. These bounds allow the \(Z'\) boson with the mass of order 1 TeV, being compatible with our results. A possibility to select \(Z'\) signals in specific scattering processes was not discussed in these papers. This is the reason why no signals were observed.

In our analysis we treat the data for leptonic processes only. LEP2 collaborations measured also the total cross-sections of the electron-positron annihilation into quark-antiquark pairs. The Abelian \(Z'\) signal in \(e^+e^- \rightarrow q\bar{q}\) process is characterized by 5 independent parameters (for example, two \(Z'\) couplings to electron, \(\bar{a}\) and \(\bar{v}_e\), and three \(Z'\) couplings to \(d, s\) and \(b\) quarks). There are 8 linear independent terms in the cross-section. As one can check, the experimental statistics of 12 cross-sections for different center-of-mass energies is completely insufficient to constrain significantly the parameters of the \(Z'\) boson.

As we have shown in Ref. [\mathbb{2}], there is the 2\(\sigma\) signal of the Abelian \(Z'\) boson in the one-parameter fit of LEP2 data for the Bhabha process. This result is reproduced in the present paper by fitting the updated experimental data. In the present analysis we applied many-parameter...
fits for leptonic processes for different sets of bins included. In particular, for the backward bins (responsible for the signal due to the kinematics of the process) the $1.3\sigma$ signal of the particle is found. The fit of the complete set of bins constrains the $Z'$ couplings to vector and axial-vector electron currents allowing the $Z'$ boson with the mass of order 1 TeV. Thus, we have to conclude that the LEP2 data allow the existence of quite light $Z'$-boson, which has a chance to be discovered in the nearest future, at the LHC. We believe that the RG relations used in the present analysis will be also important in searches for the $Z'$ boson at the LHC.

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