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ESTIMATE OF THE ABELIAN Z' DECAY WIDTH

The Abelian Z' boson decay width is calculated in a model-independent approach. The analysis takes into consideration the special relations between Z' couplings to the Standard Model fields inherent in the renormalizable theories. The constraints on the Z' couplings to the Standard Model fermions corresponding to the narrow width approximation are derived. The results are compared with the benchmark Z' models, such as Z'_χ and LR. It is shown that the current experimental limits on the Standard model Z decay width impose no limits on the Z' width, so that the ratio $\Gamma_{Z'}/m_{Z'}$ is allowed to be up to 100%. This fact is connected with the smallness of $Z - Z'$ mixing. So, the finite-width Z' is admitted and cannot be excluded from consideration. Also, the new constraints on the $Z - Z'$ mixing angle are obtained which agree with the corresponding earlier results of the LEP data analysis.

Keywords: Abelian Z', new physics, decay width, LHC.

1. Introduction

The hypothetical heavy gauge Z' boson is one of the most expected new particles in the Large Hadron Collider (LHC) experiments. Hundreds of possible scenarios of the Standard Model (SM) extension are being discussed, and almost each of them contains a new neutral vector particle [1, 2]. Thus the Z' experimental discovery would open a great area for the new physics investigation.

The current experimental constraints on the Z' mass are about $m_{Z'} > 3.4$ TeV from the CMS and ATLAS data [3] with the 95% confidence level (C.L.). Let us notice that, on the one hand, the model identification reach for the Z' is about 5 TeV. This means that even if it is found above this threshold, it will be impossible to distinguish the specific basic model which it belongs to. On the other hand, the LHC statistics for the events having invariant mass above 5 TeV is rather poor itself (for example, [4, 5]). Such an effect origins from the behavior of the parton distribution functions (PDFs) describing the internal proton structure. Hence we may roughly state that if the Z' with the mass below 5 TeV is not discovered, it will not be discovered at the LHC at all. So, the current lower limit $m_{Z'} > 3.4$ TeV is a good point to discuss the general possible further strategies of the Z' searches.

The fact that no Z' signal has been detected yet can be interpreted in two ways. The first and simple one is to suppose that the Z' mass is really higher than 3.4 TeV and thus just has not been reached yet. Investigations of this case are not considered in the present paper. However, another possible explanation can be provided. It is usually assumed that the narrow width approximation (NWA) is applicable for the Z' state, so that the peak of the differential cross section of Z' production lies within the experimental resolution of the LHC detectors. Usually, the NWA condition is understood as $\Gamma_{Z'}/m_{Z'}$ is less than a few percent. This condition holds for the majority of existing Z' models, such as E_6, LR [6], LH [7], and others. Nevertheless, such an assumption is not obligatory. In the present paper, we show that in quite a general case, the finite-width Z' state is not forbidden. This investigation is the main purpose of our work. In what follows, we will obtain the limits of applicability of the NWA and show in a model-independent approach that the ratio

$\Gamma_{Z'}/m_{Z'}$ is allowed to be up to 100%.

2. The model-independent approach

We consider the Abelian Z' boson, so that the SM electroweak gauge sector is extended with additional $U(1)$ group. Often, the Z' searches are performed by using the specific models where different scenarios of breaking the Grand Unified Theory (GUT) symmetry group to the $U(1)$ are discussed. This approach leaves only the Z' mass as a free parameter that must be fitted from the experiments. On the contrary, we use the model-independent description [1, 8] that allows estimating not only the Z' mass but also Z' couplings with the SM fields.

It is assumed that $Z-Z'$ mixing takes place; thus we start from the effective Lagrangians

$$L_{Z\bar{f}f} = \bar{f}\,\gamma^{\mu}\left[\left(v_f^{SM} - a_f^{SM}\,\gamma^5\right)\cos\theta_0 + \left(v_f - a_f\,\gamma^5\right)\sin\theta_0\right] f\, Z_{\mu}\,, \tag{1}$$

$$L_{Z'\bar{f}f} = \bar{f}\,\gamma^{\mu}\left[\left(v_f - a_f\,\gamma^5\right)\cos\theta_0 - \left(v_f^{SM} - a_f^{SM}\,\gamma^5\right)\sin\theta_0\right] f\, Z'_{\mu} \tag{2}$$

where v_f and a_f are the vector and axial-vector couplings of Z and Z' with SM fermions, θ_0 is $Z-Z'$ mixing angle. So, the quantities $\{v_f, a_f, \theta_0, m_{Z'}\}$ are unknown Z' parameters that should be estimated.

However, without any additional conditions the number of the unknown parameters is too high, because we have vector and axial-vector couplings for each lepton and quark generation. So, two assumptions are made here. The first one is that the theory is renormalizable. Also we suppose that the axial-vector constant a_f is universal over all the fermions, that is

$$a \equiv a_e = -a_{\nu_e} = a_d = -a_u = \ldots \tag{3}$$

Under these assumptions, the following relations appear between the Z' couplings [8],

$$v_f - a_f = v_{f^*} - a_{f^*},\ \theta_0 = -2a\frac{\sin\theta_W\cos\theta_W}{\sqrt{4\pi\alpha_{em}}}\left(\frac{m_Z}{m_{Z'}}\right)^2 + O\left(\left(\frac{m_Z}{m_{Z'}}\right)^4\right) \tag{4}$$

where f and f^* are the partners of the $SU(2)_L$ fermion doublet, α_{em} is the fine structure constant, θ_W is the Weinberg angle. Using of these relations reduces the number of independent Z' parameters drastically. Actually we have to estimate only a, v_e, and v_u couplings at different values of $m_{Z'}$. In the following sections we will deal with these parameters only. Also we will use the "normalized" couplings

$$\bar{a} = \frac{1}{\sqrt{4\pi}}\frac{m_Z}{m_{Z'}}a\,,\ \ \bar{v}_{e,u} = \frac{1}{\sqrt{4\pi}}\frac{m_Z}{m_{Z'}}v_{e,u}\,. \tag{5}$$

The described model-independent approach covers many classes of existing Z' models. For example, in the popular Z'_χ and LR [6] models, the relations (4) hold. In Table 1 and 2, the couplings of Z' belonging to these models are put. The second, the third, and the fourth columns contain the Z' couplings to SM electron, up, and down quark respectively. All the values are normalized by the factor $e/\cos\theta_W$, so that

$$j_f^\mu = \frac{e}{\cos\theta_W}\gamma^\mu\left(\tilde{v}_f - \tilde{a}_f\gamma^5\right). \quad (6)$$

Table 1

The Z' couplings in the Z'_χ model

	e	*u*	*d*
$\tilde{a}_f$	$\frac{1}{2\sqrt{6}}$	$-\frac{1}{2\sqrt{6}}$	$\frac{1}{2\sqrt{6}}$
$\tilde{v}_f$	$\frac{1}{\sqrt{6}}$	0	$-\frac{1}{\sqrt{6}}$

Table 2

The Z' couplings in the LR model

	e	*u*	*d*
$\tilde{a}_f$	$\frac{\alpha_{LR}}{4}$	$-\frac{\alpha_{LR}}{4}$	$\frac{\alpha_{LR}}{4}$
$\tilde{v}_f$	$\frac{1}{2}\left(\frac{1}{\alpha_{LR}} - \frac{\alpha_{LR}}{2}\right)$	$\frac{1}{2}\left(\frac{\alpha_{LR}}{2} - \frac{1}{3\alpha_{LR}}\right)$	$-\frac{1}{2}\left(\frac{\alpha_{LR}}{2} + \frac{1}{3\alpha_{LR}}\right)$

3. The Z' decay width: the NWA applicability

As discussed in the introduction, we are going to investigate the total Z' decay width $\Gamma_{Z'}$. Using the Lagrangian (2) together with the relations (4), we calculate $\Gamma_{Z'}$ with the optical theorem,

$$\Gamma_{Z'} = -\frac{\mathrm{Im}\left(\Pi_{Z'}^{(2)}\left(m_{Z'}^2\right)\right)}{m_{Z'}} \quad (7)$$

where $\Pi_{Z'}^{(2)}\left(k^2\right)$ is a $g_{\mu\nu}$-proportional part of the Z' polarization operator in the second order in the electrical charge e. It is assumed that leptons and quarks of all the generations contribute to $\Pi_{Z'}^{(2)}\left(k^2\right)$. In the Figure 1, all the diagrams corresponding to $\Pi_{Z'}^{(2)}\left(k^2\right)$ are plotted with using FeynArts [9, 10].

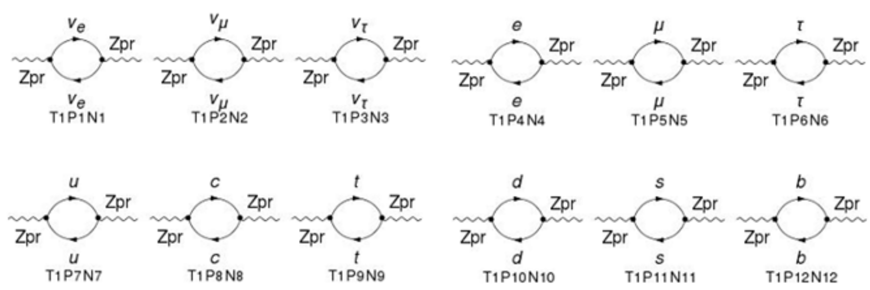
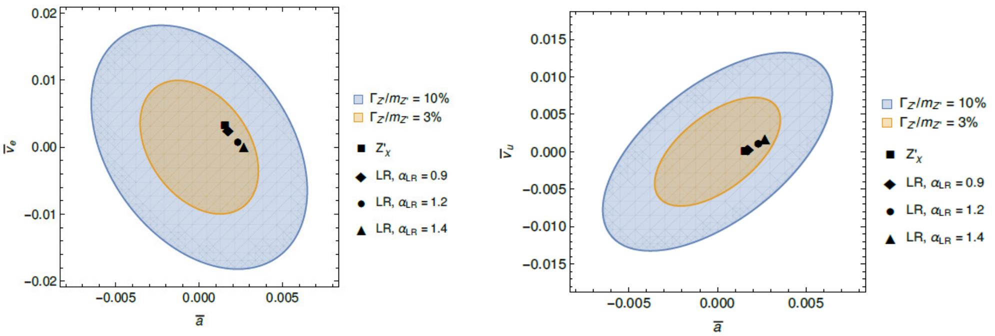


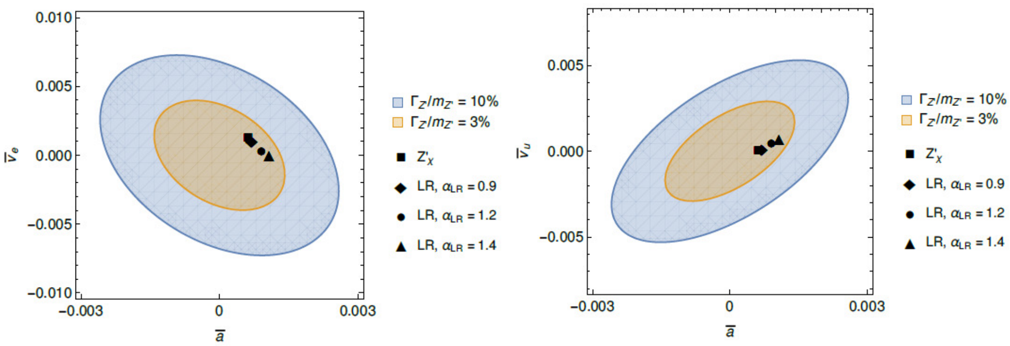
Fig. 1. The Z' self-energy diagrams contributing to the Z' decay width.

Using (2) and (7), we obtain the explicit expression for $\Gamma_{Z'}$. This allows us to establish the constraints on the Z' couplings that correspond to the NWA. In the Figures 2 – 5 below, we show some of the obtained coupling regions for $\Gamma_{Z'}/m_{Z'} < 3\%$ and $\Gamma_{Z'}/m_{Z'} < 10\%$ at different Z' masses.



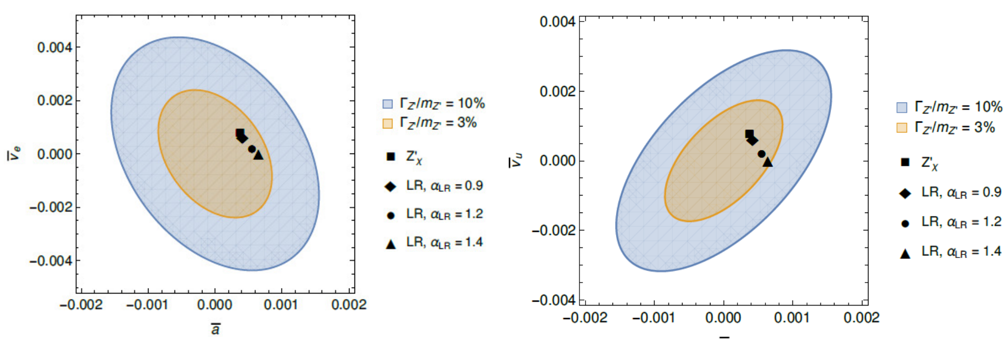
a) b)

Fig. 2. The regions $\Gamma_{Z'}/m_{Z'} < 3\%$ and $\Gamma_{Z'}/m_{Z'} < 10\%$ at $m_{Z'} = 1.2$ TeV in $(\bar{a}, \bar{v}_e)$ plane (a) and $(\bar{a}, \bar{v}_u)$ plane (b). The Z'_χ and LR models for different α_{LR} are marked.



a) b)

Fig. 3. The regions $\Gamma_{Z'}/m_{Z'} < 3\%$ and $\Gamma_{Z'}/m_{Z'} < 10\%$ at $m_{Z'} = 3$ TeV in $(\bar{a}, \bar{v}_e)$ plane (a) and $(\bar{a}, \bar{v}_u)$ plane (b). The Z'_χ and LR models for different α_{LR} are marked.



a) b)

Fig. 4. The regions $\Gamma_{Z'}/m_{Z'} < 3\%$ and $\Gamma_{Z'}/m_{Z'} < 10\%$ at $m_{Z'} = 5$ TeV in $(\bar{a}, \bar{v}_e)$ plane (a) and $(\bar{a}, \bar{v}_u)$ plane (b). The Z'_χ and LR models for different α_{LR} are marked.

Thus we have established the Z' coupling regions where the NWA is applicable.

4. Analysis of the Z' width from the Standard Model Z width constraints

An important assumption being used for our model-independent approach is that the Z' state is mixed with the Z one. Hence the Z' parameters can modify the Standard Model Z observables. At the same time, the latter were measured with the high precision at the LEP. So, when putting any constraints on the Z' couplings, we must check whether the Z observables stay within their experimental uncertainty.

One of the well-measured Z parameters is its decay width [11],

$$\Gamma_Z = \overline{\Gamma}_Z \pm \Delta\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}. \tag{8}$$

In an extended theory,

$$\overline{\Gamma}_Z = \overline{\Gamma}_Z\left(a, v_e, v_u; m_{Z'}\right). \tag{9}$$

To leave (8) correct, we can vary the Z' couplings only in such limits that Γ_Z is kept within the $\Delta\Gamma_Z$ interval.

Thus we establish the following estimation,

$$\left|\overline{\Gamma}_Z\left(a, v_e, v_u; m_{Z'}\right) - \overline{\Gamma}_Z\left(0,0,0; m_{Z'}\right)\right| \le \Delta\Gamma_Z \tag{10}$$

where $\overline{\Gamma}_Z\left(0,0,0; m_{Z'}\right)$ must obviously coincide with the SM value 2.4952 GeV. In the Figure 5, the plot of the region (10) is shown in the $\left(\overline{a}, \overline{v}_e\right)$ plane.

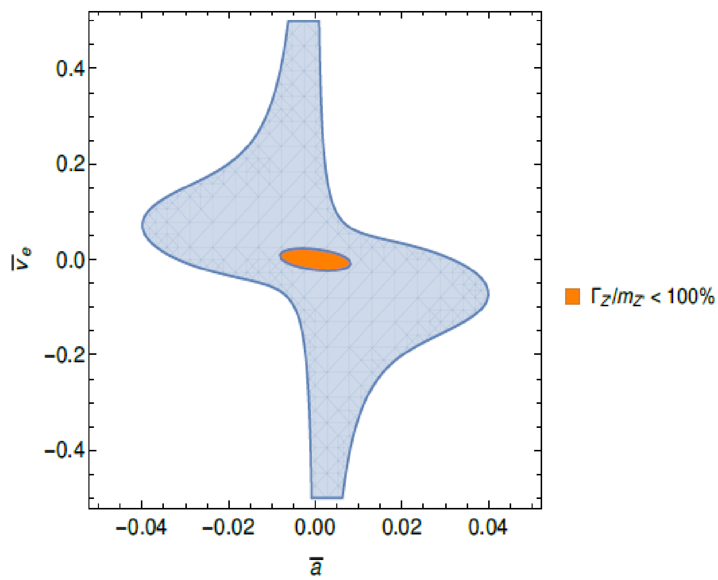


Fig. 5. The plot of (10). The ellipse inside corresponds to the region $\Gamma_{Z'}/m_{Z'} < 100\%$.

The obtained results have several consequences. It can be seen from the figure that the axial-vector coupling $\overline{a}$ turns out to be constrained. So, we come to the new independent estimation on $\overline{a}$

$$\left|\overline{a}\right| < 0.04 . \tag{11}$$

Using (4), we can also obtain the corresponding estimation on θ_0

$$|\theta_0| < 10^{-3} - 10^{-4} \qquad (12)$$

which agrees with the standard LEP constraints on the $Z - Z'$ mixing and some other known estimates [12].

An important conclusion is that the region (10) admits any Z' width,

$$\Gamma_{Z'}/m_{Z'} < 100\% . \qquad (13)$$

This hereby means that the NWA is not a strictly necessary condition for the Z' searches. This statement can be considered as a main result of our work.

5. Summary and discussion

The Abelian Z' decay width has been analyzed in a model-independent approach which allows to estimate not only the Z' mass but also the Z' couplings to the SM fields. The investigation was performed by using the effective Lagrangians (1), (2). The relations (4) were used in order to decrease the number of independent Z' parameters. As a result, the Z' coupling regions corresponding to the NWA have been derived. By investigating the Z' influence on the Z width, it has been shown that Z' having any width up to $\Gamma_{Z'}/m_{Z'} < 100\%$ is admitted. The fact that actually the Z width measurements do not impose any additional restrictions on the Z' width is nontrivial. It follows from our consideration that it is closely connected with the smallness of the $Z - Z'$ mixing angle.

The obtained results mean that despite the fact that the NWA is a widely used and convenient assumption for the Z' search, it should not hold obligatory. It follows from here that the standard direct search methods may occur irrelevant for Z'.
For example, let us consider the Z' with $m_{Z'} = 4$ TeV and the couplings corresponding to the Z'_χ model. Let us believe that it has a narrow peak $\Gamma_{Z'}/m_{Z'} = 1\%$, so that $\Gamma_{Z'} = 40$ GeV (at this point we forget that the width is defined by the couplings just to illustrate the inconsistency of direct Z' searches for a finite-width Z' state). Finally, imagine that we are searching for Z' in the Drell-Yan production at $\sqrt{s} = 13$ TeV. Using the Lagrangian (1), (2), we obtain that the Z' production cross section integrated over the invariant mass bin $4000 - 40 < M < 4000 + 40$ GeV is about 0.05 fb. Taking the present CMS total integrated luminosity $L_{total} = \int L dt \approx 50\,\mathrm{fb}^{-1}$, we conclude that it is possible to detect about $N_{Z'} = \sigma L_{total} \approx 2 - 3$ Z' events (the acceptance effects are neglected).

Now let us turn to the finite-width case $\Gamma_{Z'}/m_{Z'} = 30\%$, so that $\Gamma_{Z'} = 1200$ GeV. If we still believe that the Z' has a narrow peak and search for it in the same invariant mass bin $4000 - 40 < M < 4000 + 40$ GeV, we obtain that the Z' production cross section is about 10^{-4} fb. In this case $N_{Z'} << 1$, thus no Z' signal will be detected at the LHC.

It follows from the above that indirect off-peak approaches should be used. For example, such methods have been used successfully in [13] to estimate the Z' couplings from the forward-backward asymmetry of the Drell-Yan process at low energies. The necessity of the finite-width Z' investigations is also emphasized in some recent papers (for example, see [14]). Our future works will be devoted to the further development of the indirect Z' detection.

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