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Z' Reservation at LEP2

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Abstract

We consider the possibility that one extra $Z \equiv Z'$ exists with arbitrary mass and fermion couplings that do not violate (charged) lepton universality. We show that, in such a situation, a functional relationship is generated between the deviations from the SM values of three leptonic observables of two-fermion production at future e^+e^- colliders that is completely independent of the values of the Z' mass and couplings. This selects a certain region in the 3-d space of the deviations that is characteristic of the model (Z' "reservation"). As a specific and relevant example, we show the picture that would emerge at LEP2 under realistic experimental conditions.

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The impressive amount of data collected in the last five years at LEP1 and SLC have led to the conclusion that all the theoretical predictions of the SM (with a possible still conceivably allowed exception for the Z partial width into $b\bar{b}$ [1]) are in spectacular agreement with the experimental results, to an accuracy that has reached for some observables the permille level. This has led to a first "filtering" of candidate models of new physics, whose effects have been really drastic only for a limited set of "classical" technicolour schemes [2], but rather mild for the majority of competitor proposals (supersymmetry, anomalous gauge couplings, extra U(1),...). Thus at the beginning of the second LEP2 phase, the hopes of either producing or detecting via virtual effects some evidence of new physics are still well alive for a number of respectable models, with some useful simplification possibly achieved by taking the LEP1, SLC results into account.

For the specific case of one $Z \equiv Z'$ of the most general theoretical origin, the relevant information that has been derived is that the $Z - Z'$ mixing is sufficiently small to be neglected in the theoretical analyses of two-fermion production at future e^+e^- colliders, which means that only the Z' exchange diagram must be retained. (This statement might be contradicted for the case of final WW states produced by longitudinally polarized leptons [3], that we shall not consider in this paper).

Let us discuss in some more detail this statement. As a matter of fact, numerical bounds for the mixing angle have been derived for a number of "canonical" cases of well defined group-theoretical (E_6, LR symmetry) origin [4] and, also, for a Z' of composite models origin [5]. The various results [6], [7] are in substantial agreement, and suggest a conservative bound of the order of (at most) one percent. For such a bound, it has already been shown [8], [9] that the mixing effects at future e^+e^- colliders (for fermion production) are completely irrelevant at the realistic expected experimental accuracies. In fact, it was shown in ref.[8] for the specific case of LEP2 that values of the mixing angle much larger than the final LEP1, SLC bounds (more precisely, values of a few percent or more) would not be experimentally visible, even for extremely low ($\simeq 250$ GeV) Z' mass, or, otherwise stated, that $Z - Z'$ mixing effects can be safely neglected. This conclusion can be reformulated in a more convenient way, that allows to extend it to the case of a Z' with arbitrary fermion couplings, just by noticing that, in fact, the LEP1, SLC bounds are obtained for several products of the type $\theta_M g'_{Vf}$, $\theta_M g'_{Af}$, [6] where $g'_{V,Af}$ are the vector and axial couplings of the Z' to a generic fermion. If the couplings are different from the "canonical" ones, the bound for the mixing angle will change, but those for the products $\theta_M g'_{V,Af}$ will remain invariant. Since these products are obviously the same that appear in the various $Z - Z'$ mixing effects at LEP2, the conclusions of ref.[8] remain consequently generally valid. This simplified argument allows us, in particular, to conclude that we shall be able to neglect the mixing effects in the purely leptonic processes that we shall consider, for general universal values of the Z' couplings to charged leptons.

This introductory discussion had a precise motivation. Actually, the aim of this short paper is that of showing that, from the combined analysis of leptonic processes at future e^+e^- colliders, it would be possible to identify the virtual signals of a Z' of the most general type i.e. with general (but universal) couplings with charged leptons (no universality assumption on the contrary on the couplings with the remaining fermions). To prove this statement requires the discarding of the mixing effects, that would otherwise introduce one extra unwanted parameter.

Considering a most general Z' of the type just illustrated can be explained, or justified, by two main simple reasons. The first one is the fact that some of the strong theoretical motivations that supported "canonical" schemes like e.g. the special group E_6 have become undeniably weak in the last few years. The second one is that a number of different models with one extra U(1) have meanwhile been proposed, or have resurrected [10]. These facts lead us to the conclusion that a totally general analysis might be more relevant than a few specific ones. Obviously, one will be able to recover the "canonical" results as special cases of our investigation.

In this spirit, we have started by considering the theoretical expression of the scattering amplitude of the process $e^+e^- \to l^+l^-$ $(l = e, \mu, \tau)$ at squared c.m. energy q^2 in the presence of one Z'. At tree level, this can be written as :

$$A_{ll}^{(0)}(q^2) = A_{ll}^{(0)\gamma,Z}(q^2) + A_{ll}^{(0)Z'}(q^2) \tag{1}$$

where

$$A_{ll}^{(0)\gamma}(q^2) = \frac{ie_0^2}{q^2}\bar{v}_l\gamma_\mu u_l \bar{u}_l\gamma^\mu v_l \tag{2}$$

$$A_{ll}^{(0)Z}(q^2) = \frac{i}{q^2 - M_{0Z}^2}(\frac{g_0^2}{4c_0^2})\bar{v}_l\gamma_\mu(g_{Vl}^{(0)} - \gamma^5 g_{Al}^{(0)})u_l\bar{u}_l\gamma^\mu(g_{Vl}^{(0)} - \gamma^5 g_{Al}^{(0)})v_l \tag{3}$$

and (note the particular normalization)

$$A_{ll}^{(0)Z'}(q^2) = \frac{i}{q^2 - M_{0Z'}^2}(\frac{g_0^2}{4c_0^2})\bar{v}_l\gamma_\mu(g_{Vl}^{'(0)} - \gamma^5 g_{Al}^{'(0)})u_l\bar{u}_l\gamma^\mu(g_{Vl}^{'(0)} - \gamma^5 g_{Al}^{'(0)})v_l \tag{4}$$

$(e_0 \equiv g_0 s_0,\ c_0^2 \equiv 1 - s_0^2)$.

Following the usual approach, we shall treat the Z' effect at one loop in the SM sector and at "effective" tree level for the Z' exchange diagram, whose interference with the analogous photon and Z graphs will give the relevant virtual contributions. The Z' width will be considered "sufficiently" small with respect to $M_{Z'}$ to be safely neglected in the Z' propagator, and from what previously said the $Z - Z'$ mixing angle will be ignored. If we stick ourselves to final charged leptonic states, we must therefore deal with only two "effective" parameters, more precisely the ratios of the quantities $g'_{Vl}/\sqrt{M_{Z'}^2 - q^2}$ and $g'_{Al}/\sqrt{M_{Z'}^2 - q^2}$, that contain the (conventionally defined) "physical" Z' mass and two "physical" $Z'll$ couplings, whose meaningful definition would be related to a Z' discovery and to measurements of its various decays, that are obviously missing. This will not represent a problem in our case since in our approach these parameters, as well as any intrinsic overall (scale) ambiguity related to their actual definition, will disappear in practice, being replaced by model independent functional relationships between different leptonic observables.

For what concerns the treatment of the SM sector, a prescription has been very recently given [11] that corresponds to a "Z-peak subtracted" representation of two-fermion production, in which a modified Born approximation and "subtracted" one-loop corrections are used. These corrections, that are "generalized" self-energies, i.e. gauge-invariant combinations of self-energies, vertices and boxes, have been called in refs.[11], to whose notations and conventions we shall stick, $\tilde{\Delta}\alpha(q^2)$, $R(q^2)$ and $V(q^2)$ respectively. As it has been shown in ref.[11], they turn out to be particularly useful whenever effects of new physics must be calculated. In particular, the effect of a general Z' can be treated in this approach as a particular modification of purely "box" type to the SM values of $\tilde{\Delta}\alpha(q^2)$, $R(q^2)$ and $V(q^2)$ given by the following prescriptions:

$$\tilde{\Delta}^{(Z')}\alpha(q^2) = -\frac{q^2}{M^2_{Z'} - q^2}(\frac{1}{4s_1^2c_1^2})g^2_{Vl}(\xi_{Vl} - \xi_{Al})^2 \tag{5}$$

$$R^{(Z')}(q^2) = (\frac{q^2 - M^2_Z}{M^2_{Z'} - q^2})\xi^2_{Al} \tag{6}$$

$$V^{(Z')}(q^2) = -(\frac{q^2 - M^2_Z}{M^2_{Z'} - q^2})(\frac{g_{Vl}}{2s_1c_1})\xi_{Al}(\xi_{Vl} - \xi_{Al}) \tag{7}$$

where we have used the definitions :

$$\xi_{Vl} \equiv \frac{g'_{Vl}}{g_{Vl}} \tag{8}$$

$$\xi_{Al} \equiv \frac{g'_{Al}}{g_{Al}} \tag{9}$$

with $g_{Vl} = -\frac{1}{2}(1 - 4s_1^2)$; $g_{Al} = -\frac{1}{2}$ and $s_1^2 \equiv 1 - c_1^2$; $s_1^2c_1^2 = \pi\alpha(0)/\sqrt{2}G_\mu M_Z^2$.

To understand the philosophy of our approach it is convenient to write the expressions at one-loop of the <u>three</u> independent leptonic observables that will be measured at LEP2, i.e. the muon cross section and forward-backward asymmetry and the final τ polarization (the latter quantity being theoretically equivalent to the final lepton longitudinal polarization asymmetry, that might be measured at a future 500 GeV NLC). Leaving aside specific QED corrections, these expressions read:

$$\begin{aligned}\sigma_\mu(q^2) = \quad & \sigma_\mu^{Born}(q^2)\ \{\ 1 + \frac{2}{\kappa^2(q^2 - M_Z^2)^2 + q^4}[\kappa^2(q^2 - M_Z^2)^2\tilde{\Delta}\alpha(q^2) \\ & -q^4(R(q^2) + \frac{1}{2}V(q^2))]\ \}\end{aligned} \tag{10}$$

$$A_{FB,\mu}(q^2) = \quad A^{Born}_{FB,\mu}(q^2)\ \{\ 1+\frac{q^4-\kappa^2(q^2-M_Z^2)^2}{\kappa^2(q^2-M_Z^2)^2+q^4}[\tilde{\Delta}\alpha(q^2)+R(q^2)] + \frac{q^4}{\kappa^2(q^2-M_Z^2)^2+q^4}V(q^2)]\ \} \tag{11}$$

$$A_\tau(q^2) = \quad A^{Born}_\tau(q^2)\ \{\ 1+[\frac{\kappa(q^2-M_Z^2)}{\kappa(q^2-M_Z^2)+q^2}-\frac{2\kappa^2(q^2-M_Z^2)^2}{\kappa^2(q^2-M_Z^2)^2+q^4}][\tilde{\Delta}\alpha(q^2) + R(q^2)]-\frac{4c_1s_1}{v_1}V(q^2)\ \} \tag{12}$$

where κ^2 is a numerical constant ($\kappa^2 \equiv (\frac{\alpha}{3\Gamma_l M_Z})^2 \simeq 7$) and we defer to ref.[11] for a more detailed derivation of the previous formulae.

A comparison of eqs.(10)-(12) with eqs.(5)-(7) shows that, in the three leptonic observables, only two effective parameters, that could be taken for instance as $\xi_{Vl}M_Z/\sqrt{M^2_{Z'}-q^2}$, $(\xi_{Vl}-\xi_{Al})M_Z/\sqrt{M^2_{Z'}-q^2}$ (to have dimensionless quantities, other similar definitions would do equally well), enter. This leads to the conclusion that it must be possible to find a relationship between the relative Z' shifts $\frac{\delta\sigma_\mu^{Z'}}{\sigma_\mu}$, $\frac{\delta A_{FB,\mu}^{Z'}}{A_{FB,\mu}}$ and $\frac{\delta A_\tau^{Z'}}{A_\tau}$ (defining the shift, for each observable $\equiv \mathcal{O}$, through $\mathcal{O}\equiv\mathcal{O}^{SM}+\delta\mathcal{O}^{Z'}$) that is completely independent of the values of these effective parameters. This will correspond to a region in the 3-d space of the previous shifts that will be fully characteristic of a model with the most general type of Z' that we have considered. We shall call this region "Z' reservation"[1]

To draw this reservation would be rather easy if one relied on a calculation in which the Z' effects are treated in first approximation, i.e. only retaining the leading effects, and not taking into account the QED (initial-state) radiation. After a rather straightforward calculation one would then be led to the following approximate expressions that we only give for indicative purposes:

$$[\frac{\delta A_\tau^{(Z')}}{A_\tau}]^2 \simeq f_1 f_3(\frac{8c_1^2s_1^2}{v_1^2})\frac{\delta\sigma_\mu^{(Z')}}{\sigma_\mu}\ [\ \frac{\delta A_{FB,\mu}^{(Z')}}{A_{FB,\mu}}+\frac{1}{2}f_2\frac{\delta\sigma_\mu^{(Z')}}{\sigma_\mu}\ ] \tag{13}$$

where

$$f_1 = \frac{\kappa^2(q^2-M_Z^2)^2+q^4}{\kappa^2(q^2-M_Z^2)^2} \tag{14}$$

$$f_2 = \frac{\kappa^2(q^2-M_Z^2)^2-q^4}{\kappa^2(q^2-M_Z^2)^2} \tag{15}$$

[1]Reservation : "Tract of land reserved for exclusive occupation by native tribe", Oxford Dictionary, 1950.

$$f_3 = \frac{\kappa^2(q^2 - M_Z^2)^2 + q^4}{\kappa^2(q^2 - M_Z^2)^2 - q^4} \tag{16}$$

Eq.(13) is only an approximate one. A more realistic description can only be obtained if the potentially dangerous QED effects are fully accounted for. In order to accomplish this task, the QED structure function formalism [12] has been employed as a reliable tool for the treatment of large undetected initial-state photonic radiation. Using the structure function method amounts to writing, in analogy with QCD factorization, the QED corrected cross section [13] as a convolution of the form [2]

$$\sigma(q^2) = \int dx_1\, dx_2\, D(x_1, q^2) D(x_2, q^2) \sigma_0\left((1 - x_1 x_2) q^2\right) \{1 + \delta_{fs}\}\, \Theta(\text{cuts}), \tag{17}$$

where σ_0 is the lowest-order kernel cross section, taken at the energy scale reduced by photon emission, and $D(x, q^2)$ is the electron (positron) structure function. Its expression, as obtained by solving the Lipatov–Altarelli–Parisi evolution equation in the non-singlet approximation, is given by [12]:

$$\begin{aligned} D(x, q^2) \;&=\; \Delta' \frac{\beta}{2}(1 - x)^{\frac{\beta}{2} - 1} - \frac{\beta}{4}(1 + x) \\ &+\; \frac{1}{32}\beta^2 \left[-4(1 + x)\ln(1 - x) + 3(1 + x)\ln x - 4\frac{\ln x}{1 - x} - 5 - x\right], \end{aligned} \tag{18}$$

with

$$\beta = 2\frac{\alpha}{\pi}(L - 1) \tag{19}$$

where $L = \ln(q^2/m^2)$ is the collinear logarithm. The first exponentiated term is associated to soft multiphoton emission, the second and third ones describe single and double hard bremsstrahlung in the collinear approximation. The K-factor Δ' is of the form

$$\Delta' = 1 + \left(\frac{\alpha}{\pi}\right)\Delta_1 + \left(\frac{\alpha}{\pi}\right)^2 \Delta_2 \tag{20}$$

where Δ_1 and Δ_2 contain respectively $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha^{\in})$ non-leading QED corrections known from explicit perturbative calculations. The actual expression used for these non-leading corrections is the one valid in the soft-photon approximation, which is justified by the fact that, in order to avoid the Z radiative return, a cut on the hard-photon tail is imposed. In eq. (17) Θ(cuts) represents the rejection algorithm to implement possible experimental cuts, δ_{fs} is the correction factor to account for QED final-state radiation. Since only a cut on the invariant mass $s' = x_1 x_2 q^2$ of the event after initial-state radiation is imposed in our numerical analysis (see below), the simple formula $\delta_{fs} = 3\pi/4\alpha$

[2]The actual implementation of QED corrections is performed, in the Monte Carlo code, at the level of the differential cross section, taking into account all the relevant kinematical effects according to [13]; in the present paper only a simplified formula is described, for the sake of simplicity.

holds. In order to proceed with the numerical simulation of the $Z^{'}$ effects under realistic experimental conditions, the master formula (17) has been implemented in a Monte Carlo event generator which has been first checked against currently used LEP1 software [14], found to be in very good agreement and then used to produce our numerical results. The $Z^{'}$ contribution has been included in the kernel cross section σ_0 computing the $s-$channel Feynman diagrams associated to the production of a $l\bar{l}$ pair in a e^+e^- annihilation mediated by the exchange of a photon, a standard model Z and an additional $Z^{'}$ boson. In the calculation, which has been carried out within the helicity amplitude formalism for massless fermions and with the help of the program for the algebraic manipulations `SCHOONSCHIP` [15], the coupling of the $Z^{'}$ boson to the leptons has been parametrized, as already pointed out, as:

$$\gamma^{\mu}\left(g_{Vl}^{'(0)} - g_{Al}^{'(0)}\gamma_5\right) \tag{21}$$

and the $Z^{'}$ propagator has been included in the zero-width approximation (see above). Moreover, the bulk of non-QED corrections has been included in the form of Improved Born Approximation, choosing $\bar{\alpha}(q^2), M_Z, G_F$, together with Γ_Z, as input parameters. The values used for the numerical simulation are [16]: $M_Z = 91.1887$ GeV, $\Gamma_Z = 2.4979$ GeV; the center of mass energy has been fixed at a typical LEP2 value $\sqrt{q^2} = 175$ GeV and the cut $s^{'}/q^2 > 0.35$ has been imposed in order to remove the events due to Z radiative return and hence disentangle the interesting virtual $Z^{'}$ effects. These have been investigated allowing the previously defined ratios ξ_V and ξ_A to vary within the ranges $-2 \leq \xi_A \leq 2$ and $-10 \leq \xi_V \leq 10$. Higher values might be also taken into account; the reason why we chose the previous ranges was that, to our knowledge, they already include all the most popular existing models.

The results of our calculation are shown in Fig. 1. The central box corresponds to the "dead" area where a signal would not be distinguishable corresponds to an assumed (relative) experimental error of 1.5% for σ_μ and to 1% (absolute) errors on the two asymmetries. The region that remains outside the dead area represents the Z' reservation at LEP2, to which the effect of the most general Z' must belong.

One might be interested in knowing how different the realistic Fig. 1 is from the approximate "Born" one, corresponding in particular to the simplest version given by eq. (13). This can be seen in Fig. 2, where we showed the two surfaces (the points correspond to the realistic situation, Fig. 1). One sees that the simplest Born calculation is, qualitatively, a good approximation to a realistic estimate, which could be very useful if one first wanted to look for sizeable effects.

The next relevant question that should be now answered is whether the correspondence between Z' and reservation is of the one to one type, which would lead to a unique identification of the effect. We have tried to answer this question for one specific and relevant case, that of virtual effects produced by anomalous gauge couplings (AGC). In particular, we have considered the case of the most general, dimension six, $SU(2)\otimes U(1)$ invariant effective Lagrangian recently proposed [17]. This has been fully discussed in a separate paper [18], where the previously mentioned "Z-peak subtracted" approach has been used. The resulting AGC reservation in the (σ_μ, $A_{FB,\mu}$, A_τ) plane is a certain region, drawn, for simplicity, in Born approximation as suggested by the previous remarks. In Fig. 3 we have plotted this region and it can be compared to the general Z' one plotted in Fig.2. As one sees, the two reservations do not overlap in the meaningful region. Although we cannot prove this property in general, we can at least conclude that, should a clear virtual effect show up at LEP2, it would be possible to decide unambiguously to which among two very popular proposed models it does belong.

If the signal belonged to the Z' reservation, the immediate request would be to identify its origin. Clearly, this would imply a knowledge of the Z' mass, that could only be achieved by future direct production, but this discussion is clearly beyond the purposes of this paper. The point that we wanted to raise here is that LEP2 might already provide convincing indications of the existence of a Z' before it is actually discovered. This would generalize to the New Physics sector the previous remarkable prediction of LEP1 for the top quark.

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Figure Captions

Fig. 1 $\frac{\delta A^\tau}{A^\tau}$ versus $\frac{\delta\sigma^\mu}{\sigma^\mu}$ and $\frac{\delta A^\mu_{FB}}{A^\mu_{FB}}$. The central "dead" area where a signal would not be distinguishable corresponds to an assumed (relative) experimental error of 1.5% for σ_μ and to 1% (absolute) errors on the two asymmetries. The region that remains outside the dead area represents the Z' reservation at LEP2, to which the effect of the most general Z' must belong.

Fig. 2 The same as Fig. 1, comparing the realistic results obtained via Monte Carlo simulation with the approximate ones according to eq. (13).

Fig. 3 The same as Fig. 2, showing the region corresponding to AGC.