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VISIBLE AND CHARACTERISTIC NEW PHYSICS EFFECTS
ON THE TOTAL AND PARTIAL Z WIDTHS

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ABSTRACT

We show that a class of models predicting a new vector boson Z' of extended gauge E_6 origin has the rather characteristic property of being able to produce visible and negative shifts, with respect to the MSM predictions, both in the total width and in the leptonic width of the Z . This feature is not shared by other models of extended gauge symmetry. We also show that a certain combination of hadronic and leptonic widths is "blind" with respect to the considered Z - Z' mixing and could, therefore, be used to reveal in an unbiased way different signals of new physics.

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The total width of the Z and some of its fermionic components are no doubt among the first quantities that will be measured, immediately after the determination of the Z mass, during the first months of running on top of Z resonance at SLC and LEP 1. Since the theoretical predictions for the widths in the MSM are now rather well understood, to the level of accuracy of typically a relative 1% [1], an experimental determination of the same quality would allow to look for deviations from the MSM result as small as a relative 2% or less. This would be already sufficient to reveal a certain kind of spectacular manifestations of new physics. For example, a fourth generation of light neutrinos would increase the total Z width Γ_T by an amount of ~ 170 MeV, that would not be missed at a relative 2% (~ 50 MeV) overall accuracy. However, this would not be the only interesting possibility. In the case of light SUSY sparticles, for instance, the rising effect in Γ_T , although drastically dependent on the assumed values of the involved parameters, might be revealed as well. Thus, in a minimal supersymmetric model, possible Z decays into sleptons, charginos and/or neutralinos might be able to raise the width by non-negligible amounts for a substantial part of the allowed region in the parameter space [2]. Note that even particles or sparticles that are too heavy to be produced might add, via virtual one loop radiative corrections, sizeable effects. For instance, a heavy top (≈ 200 GeV) would increase the value of Γ_T evaluated for $m_Z \approx 60$ GeV by approximately 35 MeV [1], and similar effects would be produced by new families (or sfamilies) with mass $\gg M_Z$ and substantial mass splitting [3]. Thus, in conclusion, one can think of several appealing possibilities that would be able to combine and produce a visible ($\gtrsim 50$ MeV) increase of Γ_T related to the existence of still undiscovered particles and/or sparticles.

In the case of the partial fermionic widths, all the previous effects due to direct production of new objects on top of Z resonance would obviously disappear. The virtual effect from a heavy top or from new heavy families (sfamilies), on the other hand, would not be larger than approximately 1 MeV [1] in the leptonic width Γ_e and this would be rather hard to be identified at least in the first few months of running. Similar or worse conclusions obtain for the hadronic width $\Gamma_5 = \Gamma_{\text{udscb}}$ (we assume throughout this paper that the top is too heavy to be produced at $\sqrt{s} < 100$ GeV). Thus, no information on the existence of new fermions or sfermions would be derived from accurate measurements of these quantities. If a certain signal of dubious origin (e.g., an excess of approximately 50 MeV) were seen in the total width, there would be no extra checks from Γ_ℓ , Γ_5 in favour (or against) such possible exciting interpretations.

The aim of this paper is to show that, at least, one respectable source of new physics exists that would produce a clear signal, both in the total width and in the leptonic width of uniquely unambiguous signature. The theoretical origin of

this signal would be the existence of an extra gauge boson Z' of the most general E_6 origin [4], i.e., of the form [5]:

$$Z'_0 \equiv \cos \beta Z'_\chi + \sin \beta Z'_\psi \quad (1)$$

that would mix with the mathematical MSM Z_0 to produce a physical mass eigenstate Z :

$$Z = \cos \theta_M Z_0 + \sin \theta_M Z'_0 \quad (2)$$

This model shows the rather unique and interesting feature that, for a substantial fraction of the allowed $\cos \beta$ values, its effect on both the total and the leptonic Z widths might be large and negative. This would represent a clean and characteristic signal that would differentiate this source of new physics from the previously mentioned ones. Noticeably, other popular models of extended gauge groups, like $SU(2)_L \times SU(2)_R \times U(1)$ [6], would not be able to generate negative effects for the meaningful range of their parameters.

The E_6 Z' boson of Eqs. (1) and (2) also has the rather peculiar property that, to first order in θ_M (and in similar small parameters like $v \equiv 1-4s_w^2$), its effect on the leptonic width Γ_ℓ is exactly proportional to that on the full hadronic width $\Gamma_5 = \Gamma_{\text{udscb}}$ [7]. In fact, the effect on Γ_5 would be in percentage less important than that in Γ_ℓ . Thus, no extra information on the new Z' would be obtainable from the hadronic width. However, an obvious consequence of the previous property is that it will be possible to build a certain linear combination of Γ_5 and Γ_ℓ that will be completely free of possible mixing effects due to a Z' of E_6 origin. Remarkably and as a consequence of a known link between the E_6 model and left-right symmetry models [8], there will also be no effect due to a Z' of general $SU(2)_L \times SU(2)_R \times U(1)$ origin. In this linear combination, it will therefore be possible to look for deviations from the MSM that are not due to the mixing of Z_0 with a Z'_0 of gauge origin. In particular, it might be possible in this way to measure clean deviations from one of the ρ parameters [9], that would appear in the generalized V_ρ [10] quantity containing possible contributions from a heavy top or from new families (sfamilies) at one loop, or from Z_0 - Z mass mixing or from unconventional new Higgses [not in $SU(2)_L$ doublets or singlets] at tree level. Thus, measurements of Γ_T , Γ_ℓ and Γ_5 (or to be more precise of Γ_T , Γ_ℓ and of the ratio Γ_5/Γ_ℓ) at the percent accuracy might already reveal preliminary clear signals of some fascinating kind of new physics.

We begin our analysis with a quick list of the relevant formulae. We shall treat the various widths in their Born approximation since the Z' effect can be considered as a small perturbation to the latter one, and we shall only be interested in deviations from the MSM value that can be computed in this way,

i.e., ignoring the Z' effect on radiative corrections. To avoid possible consistency problems related to this assumption and arising for too small mixing angles [11], we shall also assume that α/θ_M is always sufficiently small, say $|\theta_M| \gtrsim 0.03$ which is on the other hand the natural limit at LEP 1 at the expected luminosity [7].

In Born approximation, we have:

$$\frac{\Gamma_{Z \rightarrow \nu\bar{\nu}}}{M_Z} \simeq \left[\frac{2\alpha}{48s^2c^2} \right] ; \quad s^2 = 1 - c^2 \simeq 0.23 \quad (3)$$

$$\frac{\Gamma_{Z \rightarrow e\bar{e}}}{M_Z} \equiv \frac{\Gamma_e}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \quad (4)$$

$$\frac{\Gamma_{Z \rightarrow u\bar{u}}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\frac{10 + 4v + 4v^2}{9} \right] \left[3 \left(1 + \frac{\alpha_s}{\pi} \right) \right] ; \quad v = 1 - 4s^2 \quad (5)$$

$$\frac{\Gamma_{Z \rightarrow d\bar{d}}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\frac{13 + 4v + v^2}{9} \right] \left[3 \left(1 + \frac{\alpha_s}{\pi} \right) \right] \quad (6)$$

The total fermionic width will thus be:

$$\frac{\Gamma_f}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\frac{86}{3} + \frac{20}{3}v + \frac{59}{3} \frac{\alpha_s}{\pi} \right] \quad (7)$$

Working to lowest order in the mixing angle θ_M and in other small parameters like $v = 1 - 4s^2$, one finds for the general E_6 generated Z' Eqs. (3), (4) the following mixing effect:

$$\frac{\delta \Gamma_{Z \rightarrow \nu\bar{\nu}}^{(E_6)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \left(\frac{6}{\sqrt{6}} \cos \beta + \frac{\sqrt{10}}{3} \sin \beta \right) \right] \quad (8)$$

$$\frac{\delta \Gamma_{Z \rightarrow e\bar{e}}^{(E_6)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \left(-\frac{2}{\sqrt{6}} \cos \beta - \frac{\sqrt{10}}{3} \sin \beta \right) \right] \quad (9)$$

$$\frac{\delta \Gamma_{Z \rightarrow u\bar{u}}^{(E_6)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \left(-\frac{6}{\sqrt{6}} \cos \beta + \frac{3\sqrt{10}}{3} \sin \beta \right) \right] \quad (10)$$

$$\frac{\delta \Gamma_{Z \rightarrow d\bar{d}}^{(E_6)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \left(\frac{2}{\sqrt{6}} \cos \beta - 3 \frac{\sqrt{10}}{3} \sin \beta \right) \right] \quad (11)$$

so that

$$\frac{\delta \Gamma_f^{(E_6)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \left(\sqrt{6} \cos \beta - \sqrt{10} \sin \beta \right) \right] \quad (12)$$

Equation (12) is one of the major points of our paper, and we believe that it deserves some comments. First of all, the fact that the full fermionic width of the Z can (in principle) provide some information on the mixing angle stems from the (motivated) assumption that the top is too heavy to be produced either below or around the Z . Otherwise, the inclusion of the top contribution in Γ_f would automa-

tically kill the Z' effect to first order in θ_M , as it is well known from group theory arguments. Thus, in a sense, the disappointment for not being able to see a top at $\sqrt{s} < 100$ GeV might be partially compensated for by the consequent potential information obtainable on a new Z' . Secondly, the shifts in Eqs. (8)-(12) are those of pure mixing origin. To these, one should add the Z_0 - Z mass shift effects which act as effective redefinitions at tree level of the ρ parameter [10]. In the fermionic widths, such terms might, however, only add small positive shifts, as one can easily verify. Therefore, in the spirit of our paper, they would not be possibly confused with the negative signals that we are looking for, and we shall return to this point later on.

We have considered thus the possible effects of the Z_0 - Z mixing in Eq. (10) when $\cos\beta$ varies in the full range $-1 < \cos\beta < +1$ and θ_M lies, for each $\cos\beta$ value, in the experimentally allowed domain [5]. The result is a certain bound of variable size. According to our preliminary discussion, we shall define as "clean" potential Z' signal on Γ_T a negative shift of Γ_T of modulus bigger than 50 MeV. The shift should be computed starting from the lowest possible theoretical value of Γ_f in the MSM; the latter can be taken from Ref. [1] in correspondence to the most recent lower bound $m_t \approx 60$ GeV. [12]. In fact, we have allowed a 10% uncertainty on the quoted value of α_s . This would reduce the minimum of Ref. [1] to

$$\Gamma_T^{MSM}(MIN) \equiv \Gamma_f^{MSM}(MIN) = \Gamma_f^{MSM}(m_t \approx 60, m_H = 1000; \alpha_s = 0.11) \approx 2.550 \text{ GeV} \quad (13)$$

and different value of α_s can be easily introduced (the percentage α_s contribution in the width is $\sim [1 + 2/3(\alpha_s/\pi)]$). Note that we have assumed $M_Z = 92$ GeV in Eq. (13). For different M_Z values, the minimum can be easily modified.

Figure 1 contains the results of our analysis. As one sees, over a substantial fraction of the allowed $\cos\beta$ range, in particular for $-0.8 \lesssim \cos\beta \lesssim -0.3$, a large and negative signal might be produced whose modulus could be as large as ~ 70 MeV for a range of values that would include the superstring inspired η model [13] $\cos\beta = -\sqrt{3/8}$ (we are following the notations of Ref. [5]).

This spectacular signature would only characterize a new gauge boson of E_6 origin and not one of the left-right symmetry origin considered in Ref. [4]. To see this, one has to write the expressions of the various widths in the latter model. In the notation of Ref. [5], and to lowest order in θ_M , one finds:

$$\frac{\sigma \Gamma_{Z \rightarrow \nu\bar{\nu}}^{(LR)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M \frac{2}{\alpha_{LR}} \right] \quad (14)$$

$$\frac{\delta \Gamma_{Z \rightarrow e\bar{e}}^{(LR)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M(-\alpha_{LR}) \right] \quad (15)$$

$$\frac{\delta \Gamma_{Z \rightarrow u\bar{u}}^{(LR)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M\left(\frac{-2}{3\alpha_{LR}} - 2\alpha_{LR}\right) \right] \quad (16)$$

$$\frac{\delta \Gamma_{Z \rightarrow d\bar{d}}^{(LR)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M\left(\frac{4}{3\alpha_{LR}} - \alpha_{LR}\right) \right] \quad (17)$$

leading to

$$\frac{\delta \Gamma_f^{(LR)}}{M_Z} \simeq \left[\frac{\alpha}{48s^2c^2} \right] \left[\theta_M\left(\frac{26}{3\alpha_{LR}} - 10\alpha_{LR}\right) \right] \quad (18)$$

where

$$\alpha_{LR} = \sqrt{\left(\frac{g_R}{g_L}\right)^2 \left(\frac{1-s^2}{s^2}\right) - 1} \quad (19)$$

In the realistic range [4]

$$\sqrt{\frac{2}{3}} \lesssim \alpha_{LR} \lesssim \sqrt{2} \quad \left(\frac{1}{2} g_L^2 \lesssim g_R^2 \lesssim g_L^2 \right) \quad (20)$$

one sees that the allowed effect of this mixing would be either positive or, when negative, too small to be revealed. Thus, the only clean signal of a Z' of extended gauge origin in the fermionic width would correspond to the E_6 band surrounding the superstring inspired η model.

If a negative signal were seen in the fermionic width, it would become obviously important to look for independent manifestations of the possible involved theoretical source. Two immediate candidates in this sense would be the leptonic width Γ_λ and the hadronic one $\Gamma_5 = \Gamma_{(uds\bar{c}b)}$. However, these would not provide independent information in the relevant E_6 model, since [7]

$$\frac{\delta \Gamma_5^{(E_6)}}{\Gamma_5} \simeq \left[\frac{g}{59} \theta_M\left(-\frac{2}{\sqrt{6}} \cos\beta - \frac{\sqrt{10}}{3} \sin\beta\right) \right] \simeq \frac{g}{59} \frac{\delta \Gamma_{Z \rightarrow e\bar{e}}^{(E_6)}}{\Gamma_{Z \rightarrow e\bar{e}}} \quad (21)$$

Note that the percentage Z' effect would be larger in Γ_λ , that remains therefore the most useful width to be compared with Γ_T for this purpose.

Figure 2 shows the results of our investigation (identical to that performed for the full fermionic width) of the possible θ_M effect of an E_6 generated Z' on Γ_λ . This time, we have considered as a "clean" Z' signal one that produces a negative shift of modulus bigger than 2 MeV. Note that in this case, positive shifts might also be interesting since no new particle production can affect Γ_λ .

However, an extra possible positive effect of $\nabla\rho$ -kind, e.g., due to a heavy top or to Z_0 - Z mass mixing, should be taken into account, whose size might be of, say, 1 MeV or (a little) more. For the negative shift the problem would disappear, since the smallest value of Γ_λ in the MSM would be fixed and equal to [1]:

$$\Gamma_{Z \rightarrow \ell\bar{\ell}}^{\text{MSM}}(\text{MIN}) = \Gamma_{Z \rightarrow \ell\bar{\ell}}^{\text{MSM}}(m_t \approx 60, m_H = 1000) \approx 85.5 \text{ MeV} \quad (22)$$

($M_Z = 92$)

As one sees from Fig. 2, the remarkable property exists that the same range of $\cos\beta$ values that could produce a visible negative shift in Γ_T would automatically produce a visible negative shift in Γ_λ . (In fact, the range would be enlarged up to $\cos\beta \approx 0$ in the leptonic width.) Note that the effect could be, in the neighbourhood of the η model, as large as ~ 7 -8 MeV!

Again the considered left-right symmetric models would be unable to produce this signature, since one sees from Eq. (15) and Ref. [5] that the shift would be systematically positive in this case.

Thus, we conclude that the simultaneous observation, both in Γ_T and in Γ_λ , of a negative shift with respect to the minimum MSM values Eqs. (13) and (22), would be a rather impressive signature of a new gauge boson of E_6 , possibly superstring motivated, origin.

In our analysis of Z' effects we have not been able to derive any extra information from the hadronic width Γ_5 because of the proportionality relationship Eq. (21). This negative feature is, however, compensated by a positive one. Consider the two quantities

$$\mathcal{J} \equiv \frac{9}{\alpha(M_Z)} \frac{\Gamma_{Z \rightarrow \ell\bar{\ell}}}{M_Z} \quad (23)$$

(the multiplicative factors are conventionally introduced [10] to fix the normalization to approximately one) and

$$\mathcal{R}' \equiv \frac{3}{59} \frac{\Gamma_5}{\Gamma_{Z \rightarrow \ell\bar{\ell}}} \quad (24)$$

(again we work with a quantity normalized to one). The ratio $\mathcal{R}'$ has several virtues from both a theoretical and experimental point of view, as it has been shown very recently [7,14]. As a consequence of Eq. (19), it is then rather simple to find that:

$$\mathcal{J}^{(E_6)} \left[\mathcal{R}' + \frac{50}{59} \mathcal{J} \right] = 0 \quad (25)$$

i.e., the combination in square brackets is "E₆ blind" with respect to the mixing, to the lowest meaningful θ_M order. Moreover, it is easy to verify that:

$$\delta^{(LR)} \left[R' + \frac{50}{59} \gamma \right] \simeq \frac{8}{59} \left[\theta_M \left(\frac{1}{\alpha_{LR}} - \frac{3}{2} \alpha_{LR} \right) \right] \quad (26)$$

and this shift is always smaller than 1% in the considered range of α_{LR} Eq. (20) (actually, it vanishes exactly, as it should, for $\alpha_{LR} = \sqrt{2/3}$). Thus, the combination of widths:

$$B \equiv R' + \frac{50}{59} \gamma = \frac{3}{59} \frac{\Gamma_S}{\Gamma_{Z \rightarrow \ell \bar{\ell}}} + \frac{450}{59 \alpha(M_Z)} \frac{\Gamma_{Z \rightarrow \ell \bar{\ell}}}{M_Z} \quad (27)$$

is "blind" with respect to any new Z' mixing of either E₆ or left-right symmetry origin considered in this paper. It would, therefore, appear as an ideal quantity to look for other (unknown) effects of different origin. To make this statement more quantitative, we show the expression that Eq. (27) would assume for the models considered in this paper:

$$\left[R' + \frac{50}{59} \gamma \right] \simeq \left[R' + \frac{50}{59} \gamma \right]^{(0)} + \frac{80}{59} \nabla_p + \frac{\alpha_s}{\pi} \quad (28)$$

where the first bracket contains the "known" MSM expression:

$$\left[R' + \frac{50}{59} \gamma \right]^{(0)} \simeq \frac{109}{59} + \frac{53}{59} (1 - 4s^2) \quad (29)$$

$$s^2 = \frac{1}{2} - \frac{1}{2} \sqrt{1 - \frac{4(37.28 \text{ GeV})^2}{M_Z^2}}$$

(extra-direct-radiative corrections are rather small, the electric charge renormalization is already included in the definition of γ). The second term in the right-hand side of Eq. (28) contains the fascinating and obscure block ∇_p [10] with possible effects from heavy families, new Higgses, Z₀-Z mass shifts; finally, in the third term the strong coupling constant α_s appears. If the latter were known from other sources to an accuracy of, say, $\delta \alpha_s / \pi < 0.01$, Eq. (28) might be used to measure the obscure block ∇_p to about 1%. Although this would not be comparable with the accuracy provided by a future measurement of the W-Z mass ratio [10], it

might still contain preliminary, simple and unbiased information on this hidden and fascinating sector of possible new physics.

In conclusion, we have shown that the potential information contained in the full and in the partial widths of the Z is remarkable, for a wide class of respectable models of new physics beyond the MSM. The measurements at SLC-LEP 1 might thus give us rather interesting news very soon.

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FIGURE CAPTIONS

Fig. 1 : Allowed region for the shifts in Γ_T due to Z-Z' mixing at variable $\cos\beta$.

Fig. 2 : Same as in Fig. 1, with Γ_ℓ replacing Γ_T .

FIGURE 1

FIGURE 2