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Width and flavor-changing decays of the Z as a test of exotic quarks and leptons

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With the advent of the SLAC Linear Collider and the CERN e^+e^- collider LEP, precision measurements of the width and the flavor-changing decays of the Z boson will soon be available. We evaluate the effect on these quantities of the mixing of heavy exotic quarks and leptons with the usual ones. The mixing angles are constrained from the forward-backward charge-asymmetry measurements. We find that the Z width is usually smaller than the standard-model value and the flavor-changing decays are large enough to be detectable.

I. INTRODUCTION

The SLAC Linear Collider (SLC) and the CERN e^+e^- collider LEP have already begun a careful analysis of the properties of the weak intermediate boson Z to check the predictions of the standard model (SM). For example, with $\sin^2\theta_W=0.233$ and $M_Z=91.1$ GeV, according to the SM the width of the Z boson $\Gamma_Z=2.41$ GeV, where it is assumed that $m_t > M_Z/2$. Further, in the SM flavor-changing (FC) decays of the Z are absent at the tree level and the one-loop contributions are on the verge of undetectability in the present round of experiments. The first published value[1] of Γ_Z from the Mark II group at SLC is $1.61^{+0.60}_{-0.43}$ GeV, which agrees with the standard model at the 1.5σ level. A preliminary analysis of the data from the LEP experiments yields[2] $\Gamma_Z=2.595\pm0.072$ GeV. Although the experimental value of Γ_Z agrees with the SM prediction fairly well, nonetheless it may not be unreasonable to examine models which lead to somewhat different values of the Z width. This is especially so since eventually it is expected that Γ_Z will be measured to a precision of 10 MeV. In this paper, a purely phenomenological viewpoint has been pursued to extend the SM by incorporating exotic heavy fermions (both leptons and quarks) which transform under the $SU(2)_L\times U(1)$ of the SM in a manner different from the usual fermions. Specifically, we consider the following three cases: (a) vector singlets, where both left- and right-handed members are $SU(2)_L$ singlets; (b) vector doublets, where both left- and right-handed states are members of $SU(2)_L$ doublets; and (c) mirror fermions, where left-handed members are singlets and right-handed members are doublets. We examine the effect of their mixing with the usual fermions on the properties of the Z boson. In the most general case, any exotic fermion may mix with all the usual fermions of the same charge which leads to effective off-diagonal couplings between the latter. Such mixing is strongly constrained in the hadronic sector from the suppression of flavor-changing neutral-current transitions, as in the neutral-kaon system. In the interest of simplicity and to minimize the number of free parameters, we assume that the mixing is restricted to one usual fermion only.[3] We constrain the mixing angles from the experimental data on the forward-backward charge asymmetry[4-6] (FBA). One novel feature we find is that the mixing of just one species of fermions can reduce Γ_Z by as much as 180 MeV and the branching ratio for the FC decays can be as high as 10^{-2}. In the following section we summarize the formalism necessary for our subsequent calculations. In the next section we discuss the experimental predictions following from the mixing of exotic fermions. We conclude with some discussions.

II. FORMALISM

Let (f_0,F_0) be the electroweak gauge eigenstates (where lower and upper cases correspond to the usual and exotic fermions, respectively) which are connected to the mass eigenstates (f,F) through

$$\begin{pmatrix} f \\ F \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} f_0 \\ F_0 \end{pmatrix} . \qquad (1)$$

Here we use the same mixing angle for both the left and right sectors. The results can easily be extended to the more general case. We set $m_f=0$ and assume m_F to be large and in particular $> M_Z/2$ (i.e., $Z\to F\bar F$ is kinematically forbidden).

On writing the neutral-current (NC) Lagrangian in the mass basis, apart from the usual $Zf\bar f$ terms, tree-level Glashow-Iliopoulos-Maiani-mechanism-violating off-diagonal $Zf\bar F, ZF\bar f$ couplings also appear. We obtain

$$\mathcal{L}_{NC}^{f\bar f} = \left(\frac{G_F M_Z^2}{2\sqrt2}\right)^{1/2}\left[\bar f\gamma_\mu\left(a_L\frac{1-\gamma_5}{2}+a_R\frac{1+\gamma_5}{2}\right)f\right]Z^\mu , \qquad (2)$$

$$\mathcal{L}_{NC}^{\bar fF+\bar Ff} = \left(\frac{G_F M_Z^2}{2\sqrt2}\right)^{1/2}\left[\bar f\gamma_\mu\left(b_L\frac{1-\gamma_5}{2}+b_R\frac{1+\gamma_5}{2}\right)F+\text{H.c.}\right]Z^\mu . \qquad (3)$$

The coupling constants in Eqs. (2) and (3) are given by

$$a_{L,R}=d_{L,R}\cos^2\phi+D_{L,R}\sin^2\phi\,,$$
$$b_{L,R}=(d_{L,R}-D_{L,R})\sin\phi\cos\phi\,, \tag{4}$$

$d_{L,R}=(4T_{3L,R}-4Q\sin^2\theta_W)$ being the usual weak couplings in the SM and $D_{L,R}$ those corresponding to the exotic fermions. In the three cases we examine, $D_{L,R}$ are given by

(i) vector singlet fermion: $D_L=D_R=d_R$,

(ii) vector doublet fermion: $D_L=D_R=d_L$, (5)

(iii) mirror fermion: $D_L=d_R,\ D_R=d_L$.

From Eqs. (2) and (3) one has

$$\Gamma(Z\to f\bar{f})=\frac{G_F M_Z^3}{48\sqrt{2}\pi}(a_L^2+a_R^2) \tag{6}$$

and

$$\Gamma(Z\to f^{\pm}F^{\mp})=\frac{2G_F M_Z^3}{48\sqrt{2}\pi}(b_L^2+b_R^2)f(m_F)\,, \tag{7}$$

where

$$f(m_F)=(1-m_F^2/M_Z^2)^2(1+m_F^2/2M_Z^2)\,. \tag{8}$$

For the case of quarks an additional factor of 3 has to be included in Eqs. (6) and (7) for the color degree of freedom. Notice that the FC Z decays [Eqs. (4) and (7)] proceed through only the left-handed sector for vector singlet fermions, the right-handed sector for vector doublet fermions, and through both sectors for mirror fermions. Moreover in all three cases, *the charge of the fermion drops out* and for identical mixing angle and exotic-fermion mass m_F, the rate is the same for charge $-\frac{1}{3}$ quarks and charge $+\frac{2}{3}$ quarks, which (due to color) is equal to thrice that for charge -1 leptons. Further, the FC decays appear with the same strength for exotic vector singlet and vector doublet fermions while for mirror fermions it is doubled.

The constraints on the mixing angles are imposed employing the experimental results of the forward-backward charge asymmetry in the process $e^+e^-\to f\bar{f}$. The expression for the FBA in the SM is well known. Its origin lies in the Z-mediated contribution to the $e^+e^-\to f\bar{f}$ amplitude and involve the coupling constants a_L and a_R. Using Eq. (4) and the experimental data on FBA, constraints can therefore be set on the mixing angle ϕ.

III. RESULTS

Using the formalism of Sec. II, it is possible to calculate the effect of mixing of the exotic fermions on flavor-violating decays and Γ_Z. In the interest of simplicity and for ease of presentation, we discuss the three cases corresponding to the mixing of (a) charge -1 leptons, (b) charge $-\frac{1}{3}$ quarks, and (c) charge $+\frac{2}{3}$ quarks separately. The case of mixing among neutral fermions is very similar. However, it is experimentally far more difficult to test. Therefore, we do not discuss it in the following.

Though in this work we are primarily concerned with the neutral-current sector, the mixing of exotic fermions with the standard ones will also affect the charge-current interactions. Because of the well-studied charge-current properties of the electron and the muon there is little freedom to entertain the possibilities of mixing with them. Thus in the leptonic sector, we consider the mixing of the exotic lepton with the τ only. For similar reasons in the charge $-\frac{1}{3}$ sector it is assumed that the exotic quark mixes with the b quark. Mixing of the charge $+\frac{2}{3}$ quark with the t quark is not of much relevance as far as the Z decay properties are concerned in view of the emerging consensus that $m_t>M_Z/2$. Therefore in this sector we discuss mixing with the c quark.

The strength of the FC Z decays, same for all quarks (modulo a color factor of 3) and leptons as a consequence of the weak couplings in Eqs. (4) and (5) as discussed in Sec. II, have been plotted in Fig. 1. It is interesting that *the corresponding branching ratio is quite high* ($\sim 10^{-2}$) and should be easily detectable at SLC and LEP from the characteristic signature of back-to-back fat and thin jets.

Employing the constraints from the experimental data of FBA, the results for the charge $-\frac{1}{3}$ quark, charge $\frac{2}{3}$ quark, and charge -1 lepton are presented in Figs. 2(a)-2(c), respectively. It is seen that at the 1σ level the upper limits of the mixing angles are as follows: for charge $-\frac{1}{3}$ quarks (30°, 20°, 15°), for charge $\frac{2}{3}$ quarks (10°, 10°, 5°), and for charge -1 lepton (10°, 10°, 10°), where the first, second, and third angles in the parentheses correspond to vector singlet, vector doublet, and mirror fermions, respectively. It is noteworthy that in the case of the charge $\frac{2}{3}$ quark, mixing has been considered with a second-generation fermion and the limits are also tightest there.

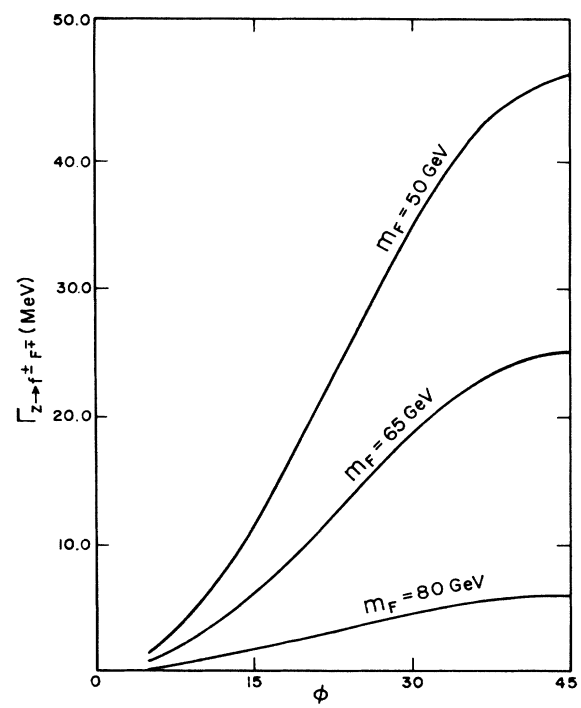

FIG. 1. $\Gamma(Z\to f^{\pm}F^{\mp})$ as a function of the mixing angle ϕ for 3 vector singlet (or doublet) lepton masses. For mirror leptons the results have to be doubled. For quarks there is a further color enhancement factor of 3.

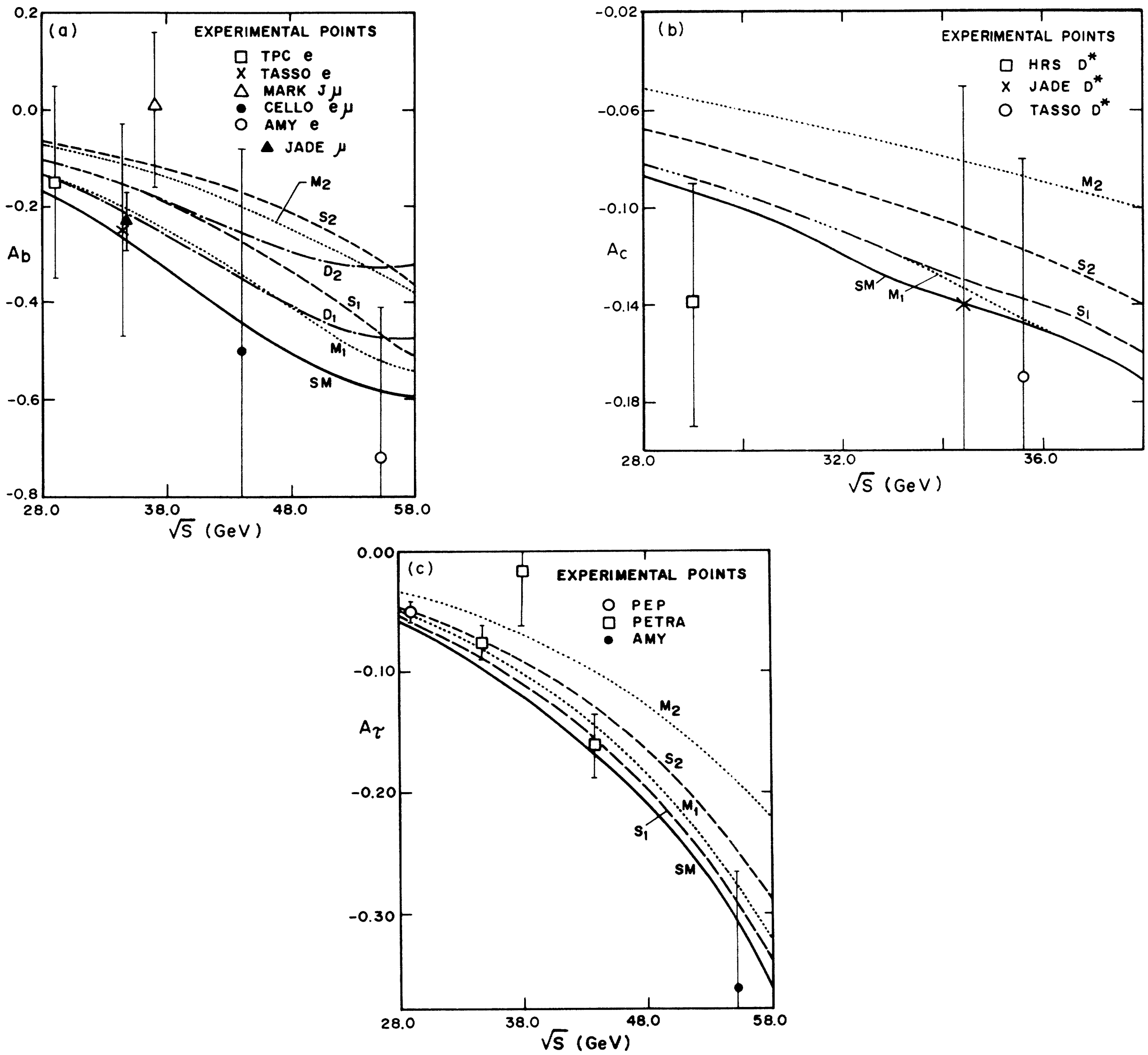

FIG. 2. FBA for the usual fermions as a function of $\sqrt{s}$: (a) the b quark, (b) the c quark, and (c) the τ lepton. The solid line corresponds to the standard model while the dashed, dash-dotted, and dotted lines correspond to mixing with vector singlet, vector doublet, and mirror fermions, respectively. The mixing angles are as follows: (a) $S_{1,2} \equiv (30°, 40°)$, $D_{1,2} \equiv (20°, 30°)$, and $M_{1,2} \equiv (15°, 25°)$; (b) $S_{1,2} \equiv (10°, 20°)$ and $M_{1,2} \equiv (5°, 20°)$; (c) $S_{1,2} \equiv (10°, 20°)$ and $M_{1,2} \equiv (10°, 20°)$. In (b) and (c) the vector singlet and vector doublet exotic fermions cannot be distinguished in the scale of the figure. The experimental data are from Refs. 4–6.

TABLE I. The forward-backward charge asymmetry on the Z pole for different mixing angles allowed by Figs. 2(a)–2(c). VS, VD, and M correspond to vector singlet, vector doublet, and mirror exotic fermions, respectively.

Mixing angle ϕ (deg)	A_τ VS	A_τ VD	A_τ M	A_b VS	A_b VD	A_b M	A_c VS	A_c VD	A_c M
0	0.014	0.014	0.014	0.095	0.095	0.095	0.067	0.067	0.067
5	0.011	0.017	0.014	0.085	0.110	0.097	0.060	0.077	0.069
10	0.004	0.030	0.015	0.054	0.140	0.100	0.037	0.110	···
15	···	···	···	0.002	0.210	0.110	···	···	···
20	···	···	···	−0.076	0.300	···	···	···	···
25	···	···	···	−0.018	···	···	···	···	···
30	···	···	···	−0.030	···	···	···	···	···

TABLE II. $\Gamma(Z\rightarrow f\bar{f})$ for quarks and leptons for mixing angles within the allowed range. VS, VD, and M correspond to vector singlet, vector doublet, and mirror fermions, respectively. Note that a factor of 3 for color has been included for quarks.

Mixing angle ϕ (deg)	$\Gamma(Z\rightarrow \tau\bar{\tau})$ (MeV) VS	VD	M	$\Gamma(Z\rightarrow b\bar{b})$ (MeV) VS	VD	M	$\Gamma(Z\rightarrow c\bar{c})$ (MeV) VS	VD	M
0	83.1	83.1	83.1	365.9	365.9	365.9	283.6	283.6	283.6
5	81.7	81.9	80.6	359.6	364.8	358.5	278.5	281.3	276.1
10	77.9	78.6	73.4	341.1	364.7	336.9	263.5	274.8	· · ·
15	· · ·	· · ·	· · ·	312.0	357.8	303.9	· · ·	· · ·	· · ·
20	· · ·	· · ·	· · ·	274.7	354.7	· · ·	· · ·	· · ·	· · ·
25	· · ·	· · ·	· · ·	232.1	· · ·	· · ·	· · ·	· · ·	· · ·
30	· · ·	· · ·	· · ·	187.4	· · ·	· · ·	· · ·	· · ·	· · ·

A measurement at SLC and LEP of A_f on the Z pole will be a straightforward check of this model. Our results are summarized in Table I from where it can be seen that the effect is completely different depending on the type of exotic fermion and the deviation from the SM can be large enough to be observable.

We now turn to the effect of these exotic fermions on the Z width. It is clear from Eqs. (4) and (6) that $\Gamma(Z\rightarrow f\bar{f})$ will be a function of the mixing angle ϕ. Concentrating for the moment on the vector singlet (vector doublet) exotic fermion, using Eq. (5) it is seen that $a_R=d_R$ ($a_L=d_L$) irrespective of the mixing angle ϕ. The change in Γ_Z due to the mixing arises entirely from the altered values of a_L (a_R). In fact, $a_L=0$ ($a_R=0$) when $\phi=\phi_m$ where $\tan^2\phi_m=r_f$ ($\cot^2\phi_m=r_f$) with

$$r_f=(T_3-Q\sin^2\theta_W)/Q\sin^2\theta_W\,. \qquad (9)$$

However, this angle ϕ_m may fall outside the range allowed by the FBA measurements. For mirror fermions, both a_L and a_R are functions of the angle ϕ. In Table II we present our results on Γ_Z for different values of ϕ. Note that within the allowed range of ϕ it is possible to reduce Γ_Z by as much as 180 MeV from the mixing of just one species of fermion (in this case the b quark). The effective total reduction in the width is likely to be larger if all the species of fermions are mixed with their exotic partners. Of course, the existence of a fourth generation will add its own contribution to Γ_Z and the total may well mimic the SM value.[7]

IV. DISCUSSIONS

Here we summarize the salient features of our work. Motivated by the upcoming experiments at SLC and LEP, we have examined with a purely phenomenological viewpoint the mixing of the usual quarks and leptons with exotic fermions. We include exotic fermions of three different varieties: vector singlet, vector doublet, and mirror. (Such fermions arise in currently fashionable E_6 models, in some Kaluza-Klein-type models, and also in left-right-symmetric theories.) Measurements of the forward-backward charge asymmetry on the Z pole will enable a distinction between these different possibilities. The mixing angle is restricted by the experimental data on the forward-backward charge asymmetry. Within the allowed range, the width of the Z boson can be reduced from its SM value quite significantly due to this mixing. This allows a precision test of the ideas of this paper in the upcoming experiments at LEP and SLC. We have not included the effect of radiative corrections in our calculations. For the decay of the Z boson, the QCD corrections dominate and increase Γ_Z (Ref. 8) by about 69 MeV for $M_Z=91.1$ GeV.[9] The electroweak corrections are negligibly small. Since the exotic fermions differ from their ordinary partners only in their electroweak properties, the effect of the radiative corrections here will be just as in the standard model and the change in Γ_Z due to mixing is unaffected. Needless to say, a value of Γ_Z near the SM prediction can, in this scenario, be a consequence of the mixing of the kind discussed above *and* the existence of a fourth generation of fermions. Another testable effect of the mixing is the prediction of off-diagonal Glashow-Ilioupoulos-Maiani-mechanism-violating couplings and flavor-changing Z decays in the detectable range.

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