REVIEW OF CONSTRAINTS ON FERMION MIXING†

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ABSTRACT

The constraints on the mixing angles of the standard fermions with new heavy particles that can appear in many extensions of the electroweak theory are reviewed. Some emphasis is put in distinguishing the effects of a mixing with new states which transform in a non-canonical way with respect to $SU(2) \times U(1)$ (left-handed singlets or right-handed doublets), from the effects of a mixing with new states with standard quantum number assignments. Constraints from flavor changing neutral current processes, as well as from flavor diagonal and charged current experimental data are considered. New limits for lepton flavor violating mixings are presented. By using the most recent results on the $\tau$ mass, lifetime and branching ratios, updated limits on the mixing parameters of the $\tau$ neutrino are derived. These limits are improved up to a factor of 3, and no signals of deviation from the standard model predictions are found. Limits on the mass of a $Z_1$ gauge boson from $E_6$, from the absence of muon number violating processes are briefly discussed as well.

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1. Introduction

The Standard Model (SM) of the electroweak interactions has achieved a tremendous success in describing the experimental data within the range of energies available today, however too many questions are still left unanswered, and it is generally believed that the present theory cannot be the whole story. Several models which go beyond the SM and which do address some of these remaining questions predict the existence of new particles. In particular, in models based on gauge groups larger than the SM group $G_{SM} = SU(2)_L \times U(1)_Y \times SU(3)_C$ the new gauge interactions require the presence of new fermions to insure anomaly cancellation.

In the present analysis I will be only interested in fermions with conventional electric charges, implying that the new states must be singlets or doublets of weak–isospin. A rather heterodox exception is that of a gauge triplet of fermions, but this possibility will not be considered here. The possibilities for the new fermions are listed in Table 1. Vector singlet (doublet) fermions refer to particles whose $L$ and $R$ components both transform as singlets (doublets) under $SU(2)_L$. $SU(2)_L \times U(1)_Y$ singlet Weyl neutrinos can also be present. A typical example in which these new states appear is represented by E$_6$ models, that will be briefly discussed in Section 3. Mirror fermions are another type of new fermion, whose transformation properties under $SU(2)_L$ are opposite those of ordinary fermions, i.e. L-handed singlets and R-handed doublets. They appear, for instance, in grand unified theories which include family unification.

There are two ways to search for signals of new fermions: directly and indirectly. Model independent limits from direct production come from LEP and set a lower bound on the masses of such particles of $m_{new} \gtrsim 45$ GeV, although the mass limit on singlet neutrinos can be considerably weaker. As to indirect signals, one possibility is to look for loop-induced effects in high precision measurements or in rare processes. This are model-dependent analyses, depending on the number, masses and couplings of the new states, and will not be discussed here. The other possibility, which is the topic of this brief review, is to search for the new states by looking for signals of mixings of the new fermions with the known ones. This possibility relies on the fact that the most general gauge invariant Lagrangian involving the new particles usually leads to mass eigenstates which correspond to some superposition of the known and new gauge eigenstates. These mixings can be analysed in a model independent way.

In Section 2 I will briefly outline the formalism for dealing with mixing effects for the charged fermions in the neutral current (NC) sector. For a more
Table 1: Possible $SU(2)_L \times U(1)_Y$ assignments for new fermions. Pairs of particles enclosed in parentheses indicate $SU(2)_L$-doublets, otherwise they are $SU(2)_L$-singlets. $N$ and $E$ refer to leptons of charge 0 and $-1$, respectively. $U$ and $D$ are quarks of charge $2/3$ and $-1/3$.

| a) Vector Doublets | b) Vector Singlets | c) Weyl Neutrinos | d) Mirror Fermions |
|-------------------|------------------|------------------|-------------------|
| $(N^c)_L$         | $(N^c)_R$        | $N_L$            | $E^-_L$          |
| $(N^c)_L$         | $(U^c)_L$        |                  | $(N^c)_R$        |
| $(U^c)_L$         | $(U^c)_R$        | $U_L$ $D_L$      | $(U^c)_R$        |
| $(E^-)_L$         | $E^-_R$          | $U_R$ $D_R$      | $(E^-)_R$        |
| $(E^-)_R$         | $E^-_L$          | $D_L$            | $(E^-)_R$        |

complete treatment including the charged currents (CC) and the mixings of the neutral states I refer to the original works by Langacker and London$^4$, and Nardi, Roulet and Tommasini$^5,6$. In Section 3 I will review the constraints which current experimental data place upon the mixings between fermions with different $SU(2)_L$ transformation properties, and I will also describe the kind of constraints that, in the frame of $E_6$ models, can be set on the $Z_1$ parameters from an analysis of some unsuppressed flavor changing (FC) mixings of the known leptons.

2. Formalism

I will assume an effective low energy gauge group of the form $G_{SM} \times U(1)_1$ where, if the rank of the group is larger than 5, as in $E_6$, the additional abelian factor arises as a combination of different Cartan generators, and corresponds to the lightest additional neutral gauge boson. Then the neutral current Lagrangian in the gauge basis reads

$$-L_{NC} = e J_{em\mu} A_\mu + g_0 J_0^\mu Z_{0\mu} + g_1 J_1^\mu Z_{1\mu}. \quad (2.1)$$

The SM neutral gauge boson $Z_0$ couples with strength $g_0 = \sqrt{2}G_F M_{Z_0}^2$ to the usual combination of the neutral isospin and electromagnetic currents $J_0^\mu = J_3^\mu - \sin^2 \theta_W J_{em}^\mu$. Assuming that the new $U(1)_1$ originates from a GUT based on a simple group, and normalizing the new generator $Q_1$ to the hypercharge axis, the $Z_1$ couples to the new $J_1$ current with strength $g_1 \approx g_0 \sin \theta_W$. In general the standard $Z_0$ is expected to be mixed with the $Z_1$, however in this short presentation I will neglect these additional effects, since due to the tight limits implied for the $Z_0$-$Z_1$ mixing by low energy NC and LEP data ($\phi_{Z_0-Z_1} \lesssim 0.02$) they turn out to be less important than the effects due to direct $Z_1$ exchange$^8$. To ensure the absence of anomalies for the new gauge current $J_1$, new fermions must be present in addition to the standard 15 known fermions per generation. Here I will assume that some of the additional new fermions are electrically charged, and that they are mixed with the known
states. Each of the conventional light fermion mass eigenstate then corresponds to a superposition of the known states and the new states. Conservation of the electric and color charges forbids a mixing between gauge eigenstates with different $U(1)_{em}$ and $SU(3)_c$ quantum numbers, implying in turn that the corresponding currents are not modified by the presence of the new states. In contrast the neutral isospin generator $T_3$ and the new generator $Q_1$ are spontaneously broken, and a mixing between states with different $t_3$ and $q_1$ eigenvalues is allowed. This will affect the $J_3$ and $J_1$ currents and in turn the couplings of the light mass eigenstates to the $Z_0$ and $Z_1$. In the gauge currents chirality is conserved too, and it is then convenient to group the fermions with the same electric charge and chirality $\alpha = L, R$ in a vector of the known ($K$) and new ($N$) gauge eigenstates $\Psi^\alpha = (\Psi^K_\alpha, \Psi^N_\alpha)^T$. This vector is related to the corresponding vector of the light ($l$) and heavy ($h$) mass eigenstates $\Psi_\alpha = (\Psi^l_\alpha, \Psi^h_\alpha)^T$ through a unitary transformation

$$U_\alpha = \begin{pmatrix} A & G \\ F & H \end{pmatrix}, \quad \alpha = L, R. \quad (2.2)$$

The submatrices $A$ and $F$ describe the overlap of the light eigenstates with the known and the new states respectively, and the unitarity of $U_\alpha$ implies $A^\dagger A + F^\dagger F = A A^\dagger + G G^\dagger = I$. Note that there is no extra index to label the electric charge, nevertheless $\Psi^\alpha$ and $\Psi_\alpha$ will be treated as vectors corresponding to a definite value of $q_{em}$. In terms of the fermion mass eigenstates, the neutral current corresponding to a (broken) generator $Q = T_3, Q_1$ now reads

$$J^\mu_Q = \sum_{\alpha = L,R} \bar{\Psi}^\alpha \gamma^\mu U_\alpha^\dagger Q_\alpha U_\alpha \Psi_\alpha, \quad (2.3)$$

where $Q_\alpha$ represents a generic diagonal matrix of the charges $q_\alpha = t_3(f_\alpha), q_1(f_\alpha)$ for the chiral fermion $f_\alpha$. Since we are interested in the indirect effects of fermion mixings in the couplings of the light mass eigenstates, we have to project $J^\mu_Q$ onto the light components $\Psi^l$. In the particularly simple case when the mixing is with only one type of new fermions with the same $q^\alpha_N$ charges, by means of the unitarity relations for $U_\alpha$ we easily obtain

$$J^\mu_Q = \sum_{\alpha = L,R} \bar{\Psi}^{l\alpha} \gamma^\mu \left[ q^\alpha_K I + (q^\alpha_N - q^\alpha_K) F^\dagger_\alpha F_\alpha \right] \Psi^{l\alpha}. \quad (2.4)$$

In Eq. (2.4) $q^\alpha_K I$ represents the coupling of a particular light fermion in the absence of mixing effects, while the second term accounts for the modifications due to fermion mixings. The matrix $F^\dagger_\alpha F_\alpha$ is in general not diagonal, and clearly whenever the coefficient $(q^\alpha_N - q^\alpha_K)$ is nonvanishing, the off diagonal terms will induce FCNC, while the diagonal terms will affect the flavor-conserving couplings. It is useful to parametrize the FC mixing between the light particles $i$ and $j$ as

$$F^\alpha_{ij} = (F^\dagger_\alpha F_\alpha)_{ij}, \quad i \neq j, \quad \alpha = L, R. \quad (2.5)$$

From a phenomenological point of view we can now distinguish two cases. If the known states are mixed with new particles whose $L$ and/or $R$ components transform
in a noncanonical way under $SU(2)_L$ (and hence will be referred to as exotic) weak–isospin is violated: $t_3(f^e_i) \neq t_3(f^e_i)$. Then the $J_0$ current is affected and the $Z_0$ interactions will be FC. If the mixing is with new states which obey the same transformation properties than the known fermions (i.e. $L$-handed doublets and $R$-handed singlets, that will be referred to as ordinary) then $t_3(f^e_i) = t_3(f^e_i)$, and clearly the $J_0$ current is not affected and in particular it remains flavor-diagonal. However, in general we still have $q_1(f^e_0) \neq q_1(f^e_0)$. Then the isospin-conserving mixings can indeed affect the $J_1$ current, inducing sizeable FC couplings to the $Z_1$.

Now, to give an example of the possible form of the fermion mass matrices and to discuss the expected magnitude of the mixings between the known and the new fermions, let us introduce for each fermion family a vector gauge singlet of new fermions $O$ ($E =$ exotic, $O =$ ordinary, $i = 1, 2, 3$) with the same electric charge and color charges than the known fermions $f^0_i$. Then in the gauge eigenstate basis the mass term reads

$$\mathcal{L}_{\text{mass}} = (f^0_O, \bar{X}^0_e)_L \mathcal{M} \begin{pmatrix} f^0_O \\ \bar{X}^0_e \end{pmatrix}, \quad \mathcal{M} = \begin{pmatrix} D & D' \\ S' & S \end{pmatrix},$$

(2.6)

where e.g. $f^0 = (f^0_1, f^0_2, f^0_3)^T$ etc.. The entries $D$ and $D'$ in the non diagonal mass matrix $\mathcal{M}$, are $3 \times 3$ matrices generated by vacuum expectation values (vevs) of doublets multiplied by Yukawa couplings, while $S$ and $S'$ are generated by vevs of singlets. As a general rule, the mass terms which couple ordinary L-fermions to ordinary $R$-fermions (or exotic $L$-fermions to exotic $R$-fermions) arise from vevs of Higgs doublets, the entries which couple ordinary fermions to the exotic ones are generated by vevs of singlets. Higgs singlets are responsible for the large masses of the new heavy fermions in vector multiplets and, in most cases, also contribute to the mass of the new heavy gauge boson; hence it is natural to assume $S, S' \gg D, D'$. In the presence of such a hierarchy among the entries in $\mathcal{M}$ it is easy to see that for the matrix $U_\alpha$ in Eq. (2.2) describing the ordinary–exotic mixings between L-states it is natural to expect that the submatrices $F$ and $G$ would acquire an overall suppression factor $\sim S/D \ll 1$ of the order of the ratio of the light to heavy mass scale. In contrast such a suppression is not present for the ordinary-ordinary $F$ and $G$ mixing terms for the $R$-states. Now, since it is precisely $F^1 F$ in Eq. (2.4) which affects the flavor diagonal couplings and also induces FCNC, if the mass scale for the exotic fermions is large enough, the suppression of the ordinary–exotic mixings explains in a natural way the non–observations of these effects in the $Z_0$ interactions. On the other hand, for the ordinary–ordinary mixings there is no reason to expect the elements of $F^1 F$ to be particularly small, and accordingly FC processes can be expected to occur at a sizeable rate in $Z_1$ interactions. Then, in the cases in which the FC couplings to the $Z_1$ are not suppressed, the limits on FC processes point toward a rather heavy $Z_1$.

As can be seen from Table 2, for $t_3(f^e_i) \neq t_3(f^e_i)$ very stringent constraints can be derived for $F^j_{L,R} \neq 0$ which strongly limits the mixing of ordinary and exotic fermions. However, it is possible to evade these bounds by considering the fine-tuned cases in which the mixing matrices $F^j_{L,R}$ are diagonal. These correspond
to those directions in parameter space in which each known ordinary fermion mixes with its own exotic fermion. If the strong assumption \( F^{ij}_{L,R} = 0 \) for \( i \neq j \) is made, one can write
\[
(F^{\dagger}_i F^\alpha)_{ij} = (s^i_\alpha)^2 \delta_{ij}, \quad \alpha = L, R, \quad (2.7)
\]
in which \( (s^i_\alpha)^2 = \sin^2 \theta^i_\alpha \), where \( \theta^i_{L(R)} \) is the mixing angle of the \( i \)th \( L \)-handed (\( R \)-handed) light fermion. In this case the ordinary-exotic mixing is parametrized by one angle per each \( L \)- or \( R \)-handed charged fermion. The same angles enter also the expression for the CC measurables. We refer to Refs. [4,5] for the extension of the formalism to the CC sector. Even if the limits on FCNC processes are not effective to constrain these particular fine-tuned mixings, still all the \( (s^i_\alpha)^2 \) can be constrained by looking at the high precision data involving CC and flavor-diagonal NC. The corresponding limits are given in Table 3.

The formalism for the neutral sector is more complicated, both due to the possibility of Dirac and Majorana masses, and because there is no empirical evidence requiring the absence of FCNC between neutrino species. However, due to the fact that neutrinos are unobserved in experiments, it is possible to parametrize their mixing by one effective angle for neutrino flavor\(^4\), with the addition of an auxiliary effective parameter \( \Lambda \) that takes into account the type of new neutrinos involved in the mixing. If the mixing is purely with new ordinary, exotic singlet or exotic doublet neutrinos, we have respectively \( \Lambda = 0, 2, 4 \). Again we refer to Refs. [4,5] for a detailed discussion of the mixings in the neutral sector.

3. Results

3.1. Limits on flavor changing ordinary-exotic fermion mixing

The limits on the FCNC parameters \( F^{ij} \) Eq. (2.5) which can be obtained assuming a mixing with new exotic fermions are listed in Table 2. The bounds on lepton flavor violating (LFV) NC from the leptonic decays \( \mu \not\rightarrow 3e, \tau \not\rightarrow 3e, 3\mu \) are taken or adapted from Ref. [8]. The bound on \( |F^{\mu e}| \) from the non-observation of \( \mu \not\rightarrow e \) conversion in nuclei is taken from Ref. [9]. The limits on \( |F^{\tau e}| \) and \( |F^{\tau \mu}| \) from \( Z_0 \not\rightarrow \tau e, \tau \mu \) are new, and have been derived from the experimental results given in the first paper in Ref. [10]. It is interesting to note that in all cases the best bounds are obtained from processes different from leptonic decays. The limits on hadronic FCNC have been presented in Ref. [11] and were taken, updated or adapted from Ref. [12]. There is no bound on \( |F^{bd}| \) from \( B^0_d - \bar{B}^0_d \) mixing because this mixing can in principle be explained by a non-zero \( F^{bd} \).

3.2. Limits on flavor diagonal ordinary-exotic fermion mixing

The limits on the flavor diagonal NC parameters \( (s^i_{L,R})^2 \) Eq. (2.7) are listed in Table 3, which is taken from Ref. 5. They correspond to those fine-tuned direction in parameter space for which the constraints from FCNC processes are evaded. The results of two different fits are shown. In the ‘individual fit’ only one mixing angle at a time is allowed to be non-zero, while in the ‘joint fit’ all mixing angles
Table 2: Limits on the FCNC parameters $F_{ij}$ for ordinary-exotic fermion mixing. The bounds on leptonic FCNC from leptonic decays are taken or adapted from Ref. [8], the one from $\mu N \not\to eN$ is taken from Ref. [9], and those from $Z_0 \not\to \tau e, \tau \mu$ are new. The limits on hadronic FCNC have been presented in Ref. [11] and were taken, updated or adapted from Ref. [12]. The experimental reference is given in the ‘Source’ column.

| Quantity | Upper Limit | Source |
|----------|-------------|--------|
| $|F_{\mu e}|$ | $2.4 \times 10^{-6}$ | $\mu \not\to 3e$ [3] |
|          | $1.0 \times 10^{-5}$ | $\mu N \not\to eN$ [13] |
|          | $1.4 \times 10^{-2}$ | $\tau \not\to 3e$ [3] |
|          | $8.0 \times 10^{-3}$ | $Z_0 \not\to \tau e$ [10] |
|          | $1.1 \times 10^{-2}$ | $\tau \not\to 3\mu$ [3] |
|          | $9.5 \times 10^{-3}$ | $Z_0 \not\to \tau \mu$ [10] |
| $|F_{\tau \mu}|$ | $6 \times 10^{-4}$ | $\Delta m_{K_L K_S}$ [3] |
|          | $1 \times 10^{-5}$ | $K_L \to \mu^+ \mu^-$ [3] |
|          | $9.5 \times 10^{-3}$ | $D^0-\bar{D}^0$ mixing [3] |
| $|F_{\tau \tau}|$, $|F_{bs}|$ | $2 \times 10^{-3}$ | $B \not\to \ell^+ \ell^- X$ [14] |

are simultaneously present. In the ‘Source’ column in Table 3 are listed those observables which are most important for constraining the mixing angles in the individual fits. The $\Gamma$’s denote partial widths of the $Z_0$, the $A$’s are asymmetries, $\nu e$ and $\nu q$ refer to low energy NC scattering experiments, $eq$ refers to measurements of parity violation in atoms, $g_\ell$ ($\ell = e, \mu, \tau$) are derived from lepton universality in CC processes, $V_{ui}^2$ refers to the unitarity of the CKM matrix, while $s_{\ell \ell}^{LC}$ and $s_{\ell \ell}^{NC}$ refer to the weak mixing angle as extracted in NC measurements at the $Z_0$ peak and at low energy, respectively. In the joint fit it is possible to evade the bounds from these observables through fine-tuned cancellations between different mixings, so that the constraints in the joint fit are somewhat weaker than those in the individual fit. In this case other observables, which depend on different combinations of the mixings and which are denoted by a * in Table 3, become important. It should be stressed that the data used to obtain these constraints are already a bit out of date. For example, only the 1990 LEP data was used. The inclusion of the 1991-92 LEP data would surely strengthen most of the bounds somewhat. The most important new development is in $\tau$-decays. The value of $(g_\tau/g_e)^2$ that was used in Ref. [5] was about 1.5 standard deviations away from its SM value, pointing towards a non-zero mixing for $\nu_\tau$. In the present analysis the new values for the tau mass $m_\tau = 1776.9 \pm 0.5$ MeV, for the $\tau$ lifetime $T_\tau = 295.7 \pm 3.2$ fs, and for the $\tau$ leptonic branching fractions $B(\tau \to e\bar{\nu}e) = (17.75 \pm 0.15)\%$ and $B(\tau \to \mu\bar{\nu}\mu) = (17.39 \pm 0.15)\%$ have been used. As a result any hint for a non-zero mixing of the $\tau$ neutrino has disappeared, while the limits on $(s_{\tau\tau}^{\nu})^2$ have been improved up to a factor of 3.

3.3. Limits on a $Z_1$ from $E_6$ from ordinary-ordinary fermion mixing
Table 3: 90% C.L. upper limits on the ordinary-exotic flavor diagonal mixing angles for individual fits (one angle at a time is allowed to vary) and joint fits (all angles allowed to vary simultaneously)\textsuperscript{5}. Observables which are most important for the constraints are shown in the ‘Source’ column. The different values of the parameter \( \Lambda \) correspond to mixings with different kinds of new neutrinos, as explained in the text. For the limits on \((s^e_L)^2\) the most recent results on the \(\tau\) mass\textsuperscript{15}, lifetime\textsuperscript{16} and branching ratios\textsuperscript{17} have been used.

|                | Individual | Joint | Source                                      |
|----------------|------------|-------|---------------------------------------------|
|                | \( \Lambda = 2 \) | \( \Lambda = 0 \) | \( \Lambda = 4 \) |
| \((s^e_L)^2\)  | 0.0047     | 0.015 | 0.0090 | 0.015 | \( \Gamma_e, M_{W^e}, A_{\mu}^{F B^e}, e q^e, g_e^e \) |
| \((s^\nu_L)^2\) | 0.0062     | 0.010 | 0.0082 | 0.010 | \( \Gamma_e, A_{\mu}^{F B}, A_{\mu}^{F B^e}, \nu e^* \) |
| \((s^\nu_R)^2\) | 0.0017     | 0.0094| 0.0090 | 0.011 | \( V_{ui}^2, \nu q, g_{\mu}, \Gamma_{\mu, s}^{LEP} \) |
| \((s^\tau_L)^2\) | 0.0086     | 0.014 | 0.014 | 0.013 | \( \Gamma_{\mu}, A_{\mu}^{F B} \) |
| \((s^\tau_R)^2\) | 0.011     | 0.017 | 0.015 | 0.017 | \( \Gamma_{\tau}, A_{\mu}^{F B}, A_{\mu}^{F B^e}, \nu_\tau^e \) |
| \((s^\nu_R)^2\) | 0.011     | 0.012 | 0.014 | 0.012 | \( \Gamma_{\tau}, A_{\mu}^{F B}, A_{\mu}^{F B^e}, g_{\mu}^e \) |
| \((s^\nu_L)^2\) | 0.0045     | 0.019 | 0.015 | 0.019 | \( V_{ui}^2, \Gamma_{h, Z}, e q, \nu q \) |
| \((s^e_L)^2\)  | 0.018     | 0.024 | 0.025 | 0.024 | \( e q, \Gamma_{h, Z}, \nu q \) |
| \((s^\nu_R)^2\) | 0.0046     | 0.019 | 0.016 | 0.019 | \( V_{ui}^2, \Gamma_{h, Z}, \nu q \) |
| \((s^\nu_L)^2\) | 0.020     | 0.030 | 0.028 | 0.029 | \( e q, \Gamma_{h, Z}, \nu q \) |
| \((s^\nu_R)^2\) | 0.36      | 0.67  | 0.63  | 0.74 | \( \Gamma_{h, Z} \) |
| \((s^\nu_L)^2\) | 0.013     | 0.040 | 0.042 | 0.042 | \( \Gamma_{h, Z}, \Gamma_{\nu, Z}, A_{\nu, Z}^Z \) |
| \((s^\nu_R)^2\) | 0.029     | 0.097 | 0.10  | 0.099 | \( \Gamma_{h, Z}, A_{\tau, Z}^Z, \Gamma_{e, Z}, A_{\nu, Z}^Z \) |
| \((s^\nu_L)^2\) | 0.011     | 0.070 | 0.072 | 0.069 | \( \Gamma_{h, Z}, \Gamma_{h, Z}, A_{\nu, Z}^Z \) |
| \((s^\nu_R)^2\) | 0.33      | 0.39  | 0.40  | 0.39 | \( \Gamma_{b, Z}, \Gamma_{b, Z}, A_{b, Z}^{F B^e} \) |
| \((s^\nu_L)^2\) | 0.0097    | 0.015 | 0.016 | 0.014 | \( s_{\nu, f f}^{L E P} \cdot \nu e, s_{\nu, f f}^{L E P}, M_W^{\nu e} \) |
| \((s^\nu_R)^2\) | 0.0019    | 0.015 | 0.0087 | 0.011 | \( V_{ui}^2, \nu q, \nu q, s_{\nu, f f}^{L E P} \cdot M_W^{\nu e} \) |
| \((s^\nu_R)^2\) | 0.023     | 0.033 | 0.034 | 0.026 | \( \Gamma_{Z, \nu q} \) |

E\textsubscript{6} GUTs are well known examples of theories where additional fermions and new neutral gauge bosons are simultaneously present. For a general breaking of E\textsubscript{6} (rank 6) to the SM (rank 4) it is possible to define a whole class of Z\textsubscript{1} bosons corresponding to a linear combination of the two additional Cartan generators. I will parametrize this combination in terms of an angle \( \beta \). Fermions are assigned to the fundamental representation of the group which contains 12 additional states for each generation, among which we have a vector doublet of new leptons \((N E^-)\textsuperscript{e} L, (E^+ N^c)\textsuperscript{e} L\). Non-diagonal mass terms with the standard \((\nu e^-)\textsuperscript{L} L\) and \(e^e_L\) leptons will give rise respectively to ordinary-ordinary and ordinary-exotic mixings, and in particular will induce LFV \(L\) and \(R\) chiral couplings between the first and second
Figure 1: Limits on the $Z_1$ LFV parameter $M_{Z_1} \cdot (F_L^{\mu})^{-1/2}$ from the limits on the $\mu$-e conversion process\textsuperscript{13}, for a general $E_6$ gauge boson, as a function of $\sin \beta$. The mixing term $F_L^{\mu}$ is in units of $10^{-2}$, vertical units are TeV. Limits on the $Z_1$ mass for different values of $F_L^{\mu}$ can be easily read off the figure by properly rescaling the vertical units.

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