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Flavor changing neutral currents in extended models

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ABSTRACT. We review the flavor changing neutral currents (FCNC) in the context of extended models. In particular, we examine the rare decays $\mu^- \to e^-\gamma$ and $\tau^- \to \mu^- e^+ e^-$. Using the experimental limits on these processes, we derive bounds on the Z–Z' mixing angle within the framework of the $SU(6)_L \otimes U(1)_Y$ model.

RESUMEN. Revisamos las corrientes neutras que cambian sabor (FCNC) en el contexto de modelos extendidos. En particular, examinamos los decaimientos raros $\mu^- \to e^-\gamma$ y $\tau^- \to \mu^- e^+ e^-$. Usando los límites experimentales sobre estos procesos, derivamos cotas sobre el ángulo de mezcla Z–Z' dentro del marco del modelo $SU(6)_L \otimes U(1)_Y$.

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1. INTRODUCTION

The standard model (SM) of particle physics provides a correct description of all experiments accessible to present day accelerators. However, there seems to be a consensus that it is not the final theory. It is thus important to search for physics beyond the standard model .

In this paper we analyze the lepton-flavor-violating-current (LFVC) interactions, strictly forbidden in the SM, but allowed in certain extended models. These processes, if they exist, could be signals of new physics.

The LFVC are generally present in extensions of the SM which predict one (or more) additional neutral gauge boson Z_1, new fermions, or which contain horizontal symmetries. In general, the Z_1 will be mixed with the standard Z_0 and the resulting mass eigenstates, which we denote as Z and Z', will have flavor-changing couplings to the known fermions. Also, mixing between ordinary and heavy fermions with non canonical SU(2)×U(1) assignments will usually induce FCNC between the ordinary fermions. In the context of extended models, the new interactions represent the main source of flavor-changing transition. A $Z_0 l_i l_j$ vertex can already appear at the tree level, where Z_0 is the standard neutral gauge boson and $l_i l_j$ are two different charged leptons mass eigenstates. However, we know that the Z_0 flavor-changing vertices are strongly suppressed. Morever, the flavor-changing Z_1 interactions stems from the fact that in some models no suppression factors are expected for the $Z_1 l_i l_j$ vertices. This last contribution can be safely neglected if Z_1 is sufficiently massive.

In Sect. 2 we review the formalism to describe the effects due to the presence of new neutral gauge bosons and new fermions that mix with the known ones. In order to impose some constraints on these mixings, in Sect. 3 we compute the leptonic flavor violation rare decays $\mu \to e\gamma$ and $\tau^- \to \mu^- e^+ e^-$.

2. FORMALISM FOR NEW NEUTRAL GAUGE BOSONS AND NEW FERMIONS

In this Section we follow the presentation given in Ref. 1 with special emphasis on flavor-changing parameters. We analyze the consequences of assuming the presence of a new neutral gauge boson at a relatively low energy and the effects induced on the currents coupled to the vector bosons due to the mixing between the known fermions and new heavy states.

2.1. EFFECTS FROM NEW NEUTRAL GAUGE BOSONS

In extended models, the neutral current (NC) Lagrangian has the form

$$\mathcal{L}_{NC} = eJ^{\mu}_{em}A_{\mu} + \sum_{m} g_m J^{\mu}_{m} Z_{m\mu}\,, \tag{1}$$

where the Z_m are the neutral massive vector bosons corresponding to the standard Z and to the Z's new ones. Different cases are studied in the literature in the context of grand unification and string theories [2].

Let us suppose that only one additional Z_1 mix with the standard Z_0. In the Z_0–Z_1 basis, the general form of the neutral gauge boson mass matrix is

$$M^2 = \begin{pmatrix} M^2_{Z_0} & \delta M^2 \\ \delta M^2 & M^2_{Z_1} \end{pmatrix}. \tag{2}$$

This matrix is diagonalized by an orthogonal transformation parametrized by one angle Θ, which relates the physical Z and Z' with the gauge eigenstates Z_0 and Z_1, *i.e.*,

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix} \begin{pmatrix} Z_0 \\ Z_1 \end{pmatrix}. \tag{3}$$

From Eq. (3) we see that the presence of the new gauge boson induce shifts in neutral currents amplitudes. Other indirect effects are the shifts induced by Z_0–Z_1 mixing on the value of the weak angle $\sin^2\theta_w$ and on the overall coupling strength g_0 when expressed as a function of the Z mass [1]. The new Z_1 correspond to additional symmetries in the extended model. For example, in the models of Refs. 3 and 4 it is a horizontal gauge boson. For the E_6 it corresponds to an additional U_1 factor [2].

2.2. Effects from new fermions

In extended models, besides the standard fermions denoted as the known fermions, appear new additional fermions to ensure anomaly cancellations.

It is convenient to classify the fermions in terms of their transformation properties under $\mathrm{SU(2)_L}$. We define as "ordinary" all left-handed particles ocurring in doublets and right-handed particles in singlets. All the remaining fermions, which have non canonical assignments, are refered as "exotic." Accordingly, we will denote the corresponding mass eigenstates as heavy, while the known mass eigenstates will be labelled as light. In the presence of additional fermions, the light mass eigenstates correspond to superpositions of the known and new gauge states. Different gauge eigenstates can mix only when they have the same electric and color charges, and hence the electromagnetic and color currents of the mass eigenstates are not modified by fermion mixings. However, the couplings of the mass eigenstates to the Z_0 and Z_1 bosons will in general be affected.

Since in the gauge currents chirality is conserved, it is convenient to group the fermions with the same electric charge and chirality $\alpha = \mathrm{L, R}$ in a column vector of the ordinary (O) and exotic (E) gauge eigenstates $\psi^o_\alpha = (\psi^o_{\mathrm{O}}, \psi^o_{\mathrm{E}})^T_\alpha$. They can mix via the mass matrix and their relation with the corresponding light and heavy mass eigenstates $\psi_\alpha = (\psi_l, \psi_h)^T_\alpha$ is given by a unitary transformation

$$\begin{pmatrix} \psi^o_{\mathrm{O}} \\ \psi^o_{\mathrm{E}} \end{pmatrix}_\alpha = U_\alpha \begin{pmatrix} \psi_l \\ \psi_h \end{pmatrix}_\alpha , \tag{4}$$

where

$$U_\alpha = \begin{pmatrix} A & E \\ F & G \end{pmatrix}_\alpha . \tag{5}$$

In Eq. (5), A_α is a matrix relating the ordinary states and the light-mass eigenstates, while G_α is a matrix relating the exotic and heavy states. E_α and F_α describe the mixing of the two sectors; these are the "light-heavy" mixing matrices. From the unitary of U_α we have,

$$A^+_\alpha A_\alpha + F^+_\alpha F_\alpha = A_\alpha A^+_\alpha + E_\alpha E^+_\alpha = I, \qquad \alpha = \mathrm{L, R}, \tag{6}$$

and so the matriz A_α deviates from unitary by small light-heavy mixing, which is associated with most of the physical effects of mixing with exotic fermions. The NC corresponding to a (broken) generator Q can be written in terms of the fermion mass eigenstates in the form

$$J^\mu_Q = \sum_{\alpha=\mathrm{L,R}} \overline{\psi}_\alpha \gamma^\mu U^+_\alpha Q_\alpha U_\alpha \psi_\alpha , \tag{7}$$

where Q_α represents a generic diagonal matrix of the charges for the chiral fermions. In one subspace of states with equal electric charge and chirality Q_α is proportional to the identity, implying the absence (at the tree level) of FCNC.

In models with exotic fermions, the diagonal matrices Q_α have the general form $Q_\alpha = \mathrm{diag}(Q_\alpha^o, Q_\alpha^E)$. Besides, if the gauge group is generation independent at the known and new states appearing in one vector, ψ_α^o have the same eigenvalues with respect to the generators of the gauge symmetry, $Q_\alpha^o = q_\alpha^o I$ and $Q_\alpha^E = q_\alpha^E I$.

Proyecting Eq. (7) on ψ_l, since we are only interested in the indired effects of fermions mixing in the coupling of the light mass eigenstates,

$$J_{lQ} = \sum_{\alpha=\mathrm{L,R}} \overline{\psi}_{l\alpha}\gamma^\mu\Big[q_\alpha^o + (q_\alpha^E - q_\alpha^o)F_\alpha^+ F_\alpha\Big]\psi_{l\alpha}\,. \tag{8}$$

Mixing between ordinary and exotic fermions modifies the isospin currents, and hence affects the couplings to the Z_0 (and $W^\pm$). The F^+F terms will be non diagonal, in general, and affects the strength of the flavor diagonal couplings of the mass eigenstates inducing FCNC's. In the case of charged fermions, ordinary-exotic mixing can induce FCNC in the interactions mediated by Z_0, through the off-diagonal terms $(F^+F)_{ij}$ $(i{\neq}j)$ in Eq. (8). However, stringent constrainst exist on μc,sd, bd, bs, τe, cu, $\tau\mu$ transitions [5]. Therefore, assuming the absence of FCNC, we can define the mixing angles $\theta_{\mathrm{L,R}}$ that describe the mixing between L or R ordinary and exotic partners in the form

$$(F_\alpha^+ F_\alpha)_{ff'} = (S_\alpha^f)^2\delta_{ff'} \quad f_\alpha, f_\alpha' = e_\alpha, \mu_\alpha, \tau_\alpha, u_\alpha, c_\alpha, t_\alpha, d_\alpha, s_\alpha, b_\alpha\,, \tag{9}$$

where $\alpha =$ L, R and $(S_{\mathrm{L,R}}^f)^2{\equiv}1 - (C_{\mathrm{L,R}}^f)^2 \equiv \sin^2\theta_{\mathrm{L,R}}^f$. Obviously, the fermion mixing affects the charged current sector as well [5].

For the neutral fermions things are more complicated. This is, in first place, because there is not empirical evidence to justify the neglect the FCNC between the ordinary neutrinos. But, it is posible sum over the unobserved flavors of the final neutrinos in week processes, and hence one can still describe most mixing effects by one effective mixing angle ordinary neutrino. The other complication is that the neutral fields with three different week-isospin assignments can mix simultaneously in the presence of Majorana mass terms.

In analogy with the charged fermion case, we can write the weak and mass eigenstates as

$$n_{\mathrm{L}}^0 = \begin{pmatrix} n_{\mathrm{O}}^0 \\ n_{\mathrm{E}}^0 \end{pmatrix}\,, \tag{10}$$

which are related through $n_{\mathrm{L}}^0 = U_{\mathrm{L}} n_{\mathrm{L}}$. The unitary matrix U_{L} can be written as

$$U_{\mathrm{L}} = \begin{pmatrix} A & E \\ F & G \end{pmatrix}\,, \tag{11}$$

where A and F describe the overlap of the light neutrinos with n_{O}^0 and n_{E}^0.

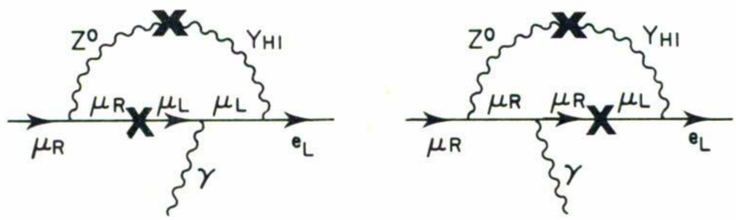

FIGURE 1. Leading diagrams contributing to the $\mu \to e\gamma$ process

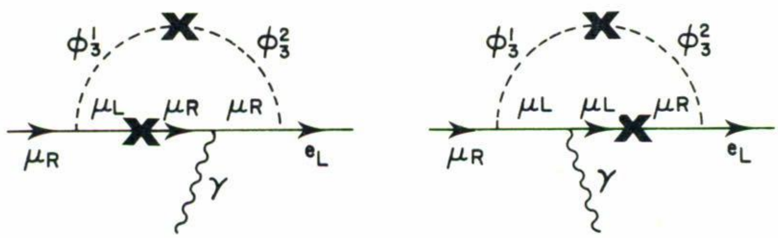

FIGURE 2. Diagrams forbidden by the Z_5 symmetry

3. Constraints on FCNC parameters from lepton flavor violation processes

In this Section we obtain bounds on the mixing angle between the neutral gauge boson of the SM and a horizontal gauge boson as well as on the mass of the heavy neutral Z' in the context of the SU(6)⊗U(1) model [4]. The fermions that appear in the processes are written in terms of their gauge eigenstates.

3.1. Constraints from $\mu^- \to e^-\gamma$

Working in the aproximation that charged leptons gauge eigenstates are mass eigenstates, the main contribution to the rare process $\mu \to e\gamma$ comes from the mixing of the gauge bosons eigenstates $Z_0 - Y_{H_1}$ throught the diagrams of Fig. 1.

Contributions from the would be Goldstone bosons to the process are forbidden in this model. To see why we arrive to this statement, let us remind that in the decay $f_1(p_1) \to f_2(p_2) + \gamma(q)$, where f_1 and f_2 are fermions and γ is the photon, the decay amplitude involve the operator $\overline{u}_2(p_2)\sigma^{\mu\nu}q_\nu\xi_\mu u_1(p_1)$, where $q = p_1 - p_2$ and ξ_μ is the vector polarization of the photon.

The presence of $\sigma^{\mu\nu}$ means that in this process participate both types of helicites, lefts and rights charged leptons. From this requeriment and after doing an analysis of the posible couplings of fermions with the Higgs multiplets used in the model, we obtain that the only possibility for the would be Goldstone bosons to contribute is from the diagrams of Fig. 2. However, the vertices of these diagrams are avoided by using a discrete Z_5 symmetry in order to maintain the Yukawa couplings of order unity.

For the purposes of this report we only compute the leading contribution from Fig. 1. We compute this diagram in the unitary gauge using the dimensional regularization

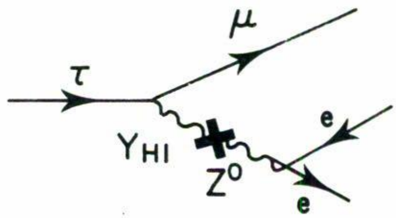

FIGURE 3. Diagrams forbidden by the Z_5 symmetry

method. Computing the decay amplitude and using the expression for the decay width for a process $f_1 \to f_1 + \gamma$, from Ref. 6, we obtain the result

$$\Gamma(\mu \to e\gamma) = k\frac{\alpha^3 {m_\mu}^5 \sin^2\Theta\cos^2\Theta}{\pi^2\cos^2\theta_w M_Z^4}\,, \tag{12}$$

where $k = 25/1152$. Using the experimental data given in Ref. 7 by Bolton, we get the bounds $|\Theta| < 5.27 \times 10^{-4}$ and $M_{Z'} > 5.20$ TeV.

3.2. CONSTRAINTS FROM $\tau^- \to \mu^- e^+ e^-$

In this decay the main contribution to the amplitude at tree level, is given by the diagram of the Fig. 3. The decay amplitude is

$$\mathcal{M} = \frac{g^2\cos\Theta\sin\Theta}{32\sqrt{3}\cos\theta_w}\overline{\mu}\,\gamma^\mu(1-\gamma_5)\tau\left[-\frac{g_{\mu\nu}+(p_\mu p_\nu)/(M_Z^2)}{P^2-M_Z^2}\right]\overline{e}\,\gamma^\nu(1+\gamma_5-4\sin^2\theta_w)e\,. \tag{13}$$

We achieve our calculation assuming that the momentum transfer $t = (q-p)^2$, where q is the the four-moment of τ^- and p is the four-moment of μ^- , is negligible compared with the square mass of the standard neutral gauge boson Z, that is, $t \ll M_Z^2$.

From the above amplitude we compute the partial decay rate

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32m_\tau^3}\sum_{\text{pol}}|\mathcal{M}|^2\,dt\,ds\,, \tag{14}$$

where $s = (q-r)^2$, and r is the four-momenta of e^-. The limits of integration are:

$$t^+ = (m_\tau - m_\mu)^2\,, \qquad t^- = 4m_e^2\,, \tag{15}$$

and

$$s^\pm = \left(m_\tau^2 + m_e^2\right) + t^{-1}\frac{1}{2}\left(t + m_\tau^2 - m_\mu^2\right)^2\left(t + m_e^2\right)$$
$$\pm\, t^{-1}m_\tau(t - m_e^2)\left[\left(\frac{m_\tau^2 + m_\mu^2 - t}{2m_\tau}\right)^2 - m_\mu^2\right]^{1/2}. \tag{16}$$

Integrating numerically we find that the width Γ is proportional to $\sin^4\Theta$, and using the experimental bound for this decay [7], we get

$$|\Theta| < 1.12 \times 10^{-5}\,. \tag{17}$$

In the $SU(6)_L \otimes U(1)_Y$ model the relation between the gauge boson mixing and $M_{Z'}$ has the form

$$\Theta \simeq \frac{2}{3} \cos\theta_W \frac{M_Z^2}{M_{Z'}^2} . \tag{18}$$

In this case the bound on Θ transmit also an indirect constraint on $M_{Z'}$. Assuming the Eq. (18) we obtain:

$$M_{Z'} > 27 \text{ TeV} . \tag{19}$$

Bounds on Θ have been derived in Ref. 8 for several models, which are less than 0.01. Theoretical relations between the mixing and the mass of the new gauge boson in most cases require $M_{Z'} > 1$ TeV.

4. Conclusions

We have analyzed some FCNC in the $SU(6)_L \otimes U(1)_Y$ model of unification of families with the standard electroweek interactions. To establish limits on the mixing angle between the standard Z_0 neutral gauge boson with a horizontal gauge boson of $SU(2)_H$, we compute the rare decays $\mu^- \to e^- \gamma$ and $\tau^- \to \mu^- e^+ e^-$.

The results can be summarized as follows:

1. The upper limit on Θ, the mixing angle between Z and Z' is of order 10^{-5}.
2. The mass of the horizontal gauge boson is limited to values highter than 27 TeV.

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