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Flavor Changing Neutral Currents and a Z'

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Abstract We consider a non-universal Z' that affects primarily the third generation fermions with as an example of new physics associated with the top-quark. We first discuss constraints on the mass and coupling strength of such a Z'. We then turn our attention to the flavor changing neutral currents (FCNC) present in the model. We discuss the experimental constraints and their implications. We propose an ansatz to understand the smallness of the FCNC in terms of the CKM matrix.

Keywords Z-prime · FCNC · top-quark

1 Introduction

A Z' is the gauge boson associated with an additional $U(1)'$ gauge group and is present in many extensions of the standard model (SM) such as grand unified theories, left-right models, composite Higgs models, extra dimensions and others. A Z' produces one of the cleanest and easiest to find signals of new physics, and for this reason, it is typically one of the first new physics searches to be conducted by new experiments.

Many Z' models have been studied at length in the literature and we refer the reader to the recent review by Langacker for references and details [1]. There are: 'canonical' models which are universal and have a coupling constant of electroweak strength; models where the Z' does not couple to certain particles such as, 'fermiophobic' and 'leptophobic'; and non-universal models such as the one we consider here. Our version of non-universal Z' is one where the third generation fermions are preferred [2].

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Most of the experimental constraints one finds refer to the 'canonical' models. Typical constraints for these models from precision electroweak data require masses higher than about 0.5 TeV and very small $Z-Z'$ mixing; from LEP 2 and the Tevatron the mass constraints increase to (800-2000) GeV depending on the model; and it is expected that the LHC will rule out masses below 3 TeV with 10 fb^{-1} [1].

As we will discuss in this talk, for a non-universal Z' masses around 0.5 TeV are still possible and it will be much harder for the LHC to reach the 3 TeV exclusion. On the other hand the $Z-Z'$ mixing remains tightly constrained.

2 Non-universal Z' model

We use a left-right model based on the group $SU(3)\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ so that there is also a W'. To construct a model with enhanced couplings to the third generation we first choose the first two generations to have the same transformation properties as in the standard model with $U(1)_Y$ replaced by $U(1)_{B-L}$,

$$\begin{aligned}&Q_L=(3,2,1)(1/3),\quad U_R=(3,1,1)(4/3),\quad D_R=(3,1,1)(-2/3),\\&L_L=(1,2,1)(-1),\quad E_R=(1,1,1)(-2).\end{aligned}\tag{1}$$

The numbers in the first parenthesis are the $SU(3)$, $SU(2)_L$ and $SU(2)_R$ group representations respectively, and the number in the second parenthesis is the $U(1)$ charge. For the first two generations this is the same as the $U(1)_Y$ charge in the SM and for the third generation it is the usual $U(1)_{B-L}$ charge of LR models. The third generation is chosen to transform differently,

$$\begin{aligned}&Q_L(3)=(3,2,1)(1/3),\quad Q_R(3)=(3,1,2)(1/3),\\&L_L(3)=(1,2,1)(-1),\quad L_R=(1,1,2)(-1).\end{aligned}\tag{2}$$

The correct symmetry breaking and mass generation of particles can be induced by the vacuum expectation values of three Higgs representations: $H_R=(1,1,2)(-1)$, whose non-zero vacuum expectation value (vev) v_R breaks the group down to $SU(3)\times SU(2)\times U(1)$; and the two Higgs multiplets, $H_L=(1,2,1)(-1)$ and $\phi=(1,2,2)(0)$, which break the symmetry to $SU(3)\times U(1)_{\rm EM}$.

The relative strength of left- and right-handed interactions is determined by the parameter $\cot\theta_R$ which appears in the mixing of neutral bosons [2]. In the limit in which this parameter is large, the new right-handed interactions affect predominantly the third generation. We will assume that the $W-W'$ and $Z-Z'$ mixing angles are zero to conform with bounds from $b\to s\gamma$ [3] and $Z\to\tau^+\tau^-$ [2]. It is possible to relax the later constraint with models in which the third generation lepton couplings are not enhanced, but one then needs additional exotic fermions to make the models anomaly free.

With all these ingredients one ends up with flavor diagonal couplings of the Z' that generically look like those in Figure. 1. It follows from this pattern

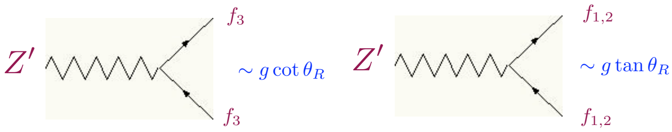

Fig. 1 Generic $Z'ff$ flavor diagonal couplings. For large $\cot\theta_R$, couplings to the first two generations are suppressed whereas couplings to the third generation are enhanced.

of couplings that processes involving fermions from the first two generations are very suppressed; processes involving one third generation fermion pair (such as $e^+e^- \to b\bar{b}$) receive corrections of electroweak strength; and processes involving only third generation fermions can be significantly enhanced.

In Ref. [2] we obtained constraints on these models from the process $e^+e^- \to b\bar{b}$ at LEP-II. Those results can be summarized approximately by the relation

$$\cot\theta_R \tan\theta_W \left(\frac{M_W}{M_{Z'}}\right) \lesssim 1. \tag{3}$$

In addition, $\cot\theta_R \lesssim 20$ is required by perturbative unitarity. For example, for an enhancement of third generation couplings by $\cot\theta_R = 10$ masses as low as $M_{Z'} \geq 450$ GeV are still possible. The LHC may be able to push this bound out to the 1.5 TeV mark but due to the large QCD background in the $pp \to b\bar{b}$ or $pp \to t\bar{t}$ modes, it depends on studying four-top channels that require some 300 fb^{-1} [4] (see Figure 2).

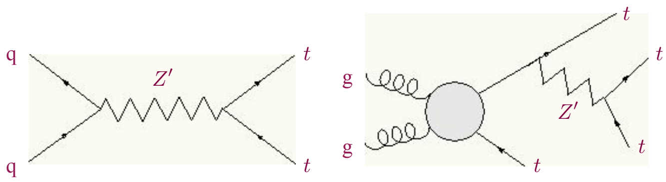

Fig. 2 The contribution of a Z' to $pp \to t\bar{t}$ at LHC is of electroweak strength and overwhelmed by QCD produced $t\bar{t}$ pairs. To constrain the Z' at LHC one needs to look at processes with two $t\bar{t}$ pairs as sketched in the figure.

3 Z' induced FCNC

It is well known that non-universal Z' models induce tree level FCNC [5] and the phenomenology of these FCNC has been studied at length in recent years [6–8]. We start with couplings of the Z' to quarks that are diagonal but non-universal in the weak basis,

$$\mathcal{L}_{Z'} = -\frac{g}{2\cos\theta_W}(\bar{U}_L\delta^U_L\gamma_\mu U_L + \bar{U}_R\delta^U_R\gamma_\mu U_R + \bar{D}_L\delta^D_L\gamma_\mu D_L + \bar{D}_R\delta^D_R\gamma_\mu D_R)Z'^\mu \tag{4}$$

For the models we are discussing we have

$$\delta_R^{U,D} = \kappa_R^{t,b}\; Z_\kappa, \;\; Z_\kappa = \begin{pmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & 1 \end{pmatrix}, \;\; r << 1. \tag{5}$$

Because these matrices are not proportional to the unit matrix, the rotation to the quark mass eigenstate basis (via the matrices $V_{L,R}^{U,D}$) introduces FCNC

$$\begin{aligned} \mathcal{L}_{FCNC} = & \frac{g}{2\cos\theta_W}\; \left(\bar{U}_i \gamma^\mu \left(\kappa_L^t a_{ij}^u P_L + \kappa_R^t b_{ij}^u P_R\right) U_j \right. \\ & \left. + \; \bar{D}_i \gamma^\mu \left(\kappa_L^b a_{ij}^d P_L + \kappa_R^b b_{ij}^d P_R\right) D_j\right) Z'^\mu \\ & a_{ij}^d = V_L^{D\dagger} Z_\kappa V_L^D \;, \;\; a_{ij}^u = V_L^{U\dagger} Z_\kappa V_L^U \\ & b_{ij}^d = V_R^{D\dagger} Z_\kappa V_R^D \;, \;\; b_{ij}^u = V_R^{U\dagger} Z_\kappa V_R^U . \end{aligned} \tag{6}$$

Using Eq. 6, we calculate the effective $|\Delta F| = 1$ operators enhanced by $\cot\theta_R$ both at tree-level and at one-loop [6]. For down-type quarks they are illustrated in Figure 3, and for up-type quarks we find

$$b_{u_i u_j} = \sin\theta_W \cot\theta_R \cos\xi_Z V_{Rti}^{U\star} V_{Rtj}^U . \tag{7}$$

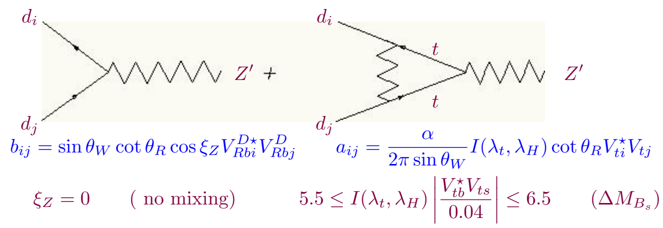

Fig. 3 $d_i d_j Z'$ FCNC couplings at tree and one-loop level that are enhanced by $\cot\theta_R$.

The constraints imposed by experiment (with certain assumptions for the comparisons) are summarized in Table 1 [6]. They can be summarized roughly

$$\left(\frac{M_Z}{M_{Z'}}\kappa_b\right) b_{ij}^d \lesssim \begin{pmatrix} - & 10^{-4} & 10^{-4} \\ 10^{-4} & - & 10^{-3} \\ 10^{-4} & 10^{-3} & - \end{pmatrix}, \;\; \left(\frac{M_Z}{M_{Z'}}\kappa_t\right) b_{ij}^u \lesssim \begin{pmatrix} - & 10^{-4} & ? \\ 10^{-4} & - & ? \\ ? & ? & - \end{pmatrix}.$$

Explicit numbers follow for an overall strength $M_Z\kappa/M_{Z'} \sim 1$ and get weaker for weaker couplings. Constraints on left-handed couplings (as they appear in other existing Z' models) are numerically similar.

Using the constraints in Table 1, we find that enhancements of up to two orders of magnitude over SM are still possible in other down-quark-sector modes, and even larger in up-quark sector modes. This is shown in Table 2.

Table 1 Summary of constraints for the right-handed mixing angles.

Process	Constraint (down-quark sector)	
$(\Delta M)_K$	$\mathrm{Re}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right)^2 < 2.4 \times 10^{-8}$	I
$(\Delta M)_{B_d}$	$\left\vert V^{D\star}_{Rbb}V^{D}_{Rbd}\right\vert < 1.8 \times 10^{-4}$	II
$(\Delta M)_{B_s}$	$\left\vert V^{D\star}_{Rbb}V^{D}_{Rbs}\right\vert < 3.5 \times 10^{-3}$	II$_s$
ϵ	$\mathrm{Re}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right)\mathrm{Im}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right) < 2 \times 10^{-11}$	III
ϵ'	$\left(\left\vert V^{D}_{Rbd}\right\vert^2 + \left\vert V^{u}_{Rtu}\right\vert^2\right)\mathrm{Im}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right) \leq 1.3 \times 10^{-5}$	IV
$B(K^+ \to \pi^+\nu\bar{\nu})$	$\left\vert V^{D\star}_{Rbs}V^{D}_{Rbd}\right\vert < 1.0 \times 10^{-5}$	V
	Constraint (up-quark sector)	
x (D-mixing)	$\left\vert V^{U\star}_{Rtc}V^{U}_{Rtu}\right\vert < 2.0 \times 10^{-4}$	I$_u$

Table 2 Summary of Predictions.

Process	Prediction	From	SM [11]
$B(K_L \to \pi^0\nu\bar{\nu})$	$< 1.4 \times 10^{-10}$	V	$(2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$
$B(B \to X_d\nu\bar{\nu})$	$< 2.5 \times 10^{-6}$	II	1.6×10^{-6}
$B(B \to X_s\nu\bar{\nu})$	$< 3.7 \times 10^{-4}$	II$_s$	4×10^{-5}
$B(B \to X_s\tau^+\tau^-)$	$< 4.4 \times 10^{-5}$	II$_s$	3.2×10^{-7} (short dis.)
$B(B_d \to \tau^+\tau^-)$	$< 1.8 \times 10^{-7}$	II	3.3×10^{-8}
$B(B_s \to \tau^+\tau^-)$	$< 6.3 \times 10^{-5}$	II$_s$	1.1×10^{-6}
			SM [9]
$B(D^0 \to X_u\nu\bar{\nu})$	$< 3 \times 10^{-10}$	I$_u$	5.0×10^{-16} (s.d.) 10^{-13} (l.d.)
$B(D^0 \to \mu^+\mu^-)$	$< 4 \times 10^{-15}$	I$_u$	3×10^{-13}
$B(t \to c\tau^+\tau^-)$	$< 4 \times 10^{-4}$	I$_u$	
$B(t \to cb\bar{b})$	$< 1 \times 10^{-3}$	I$_u$	

The rare D decays do not reach the level at which they can be observed [9, 10], but the rare top-quark decays are more promising.

The strength of $Z'tc$ coupling can also be tested in single top-production at LHC. The leading order process, $pp \to t\bar{c}$ is overwhelmed by background (single top production in the SM) [12]. Z' produced in association with single top is non-leading but can stand out above background. Integrated luminosities of a few hundred fb^{-1} are needed to study this process [13]. Other possibilities are discussed in Ref. [14].

4 Ansatz for small FCNC

In this section we present an ansatz to understand the smallness of the FCNC in the absence of a symmetry preventing them [15]. In general the quark mass matrices are diagonalized by a bi-unitary transformation

$$M_{D,U} = V_L^{D,U}\hat{M}_{D,U}V_R^{D,U\dagger}, \tag{8}$$

where the matrices $V^{D,U}_{L,R}$ are related to the CKM matrix, $V_{CKM} = V_L^{U\dagger}V_L^D$, but it is not possible to extract them completely from experiment. In certain models, however, the left and right-handed rotation matrices are related reducing the number of unknown parameters. For example, in LR models the mass matrices are Hermitian and can be diagonalized by a unitary transformation $M = V_L \hat{M} V_L^\dagger$ so that $V_R = V_L$ up to phases. Similarly, in certain GUT ($SO(10)$) the mass matrices are symmetric and can be diagonalized by an orthogonal transformation $M = V_L \hat{M} V_L^T$ so that $V_R = V_L^\star$. In these cases a simple ansatz can fix all the rotation matrices in terms of the CKM elements [16,17] and the Z' induced FCNC can be predicted.

One example that works for us is the Georgi-Jarlskog ansatz [16] in which a down-quark matrix of the form M_D is diagonalized by the matrix V_L^D given in terms of the Wolfenstein parameter λ by

$$M_D \sim \begin{pmatrix} 0 & B & 0 \\ B & A & 0 \\ 0 & 0 & C \end{pmatrix}, \quad V_L^D \sim \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{9}$$

resulting in the famous relation $\lambda \sim \sqrt{m_d/m_s}$. This ansatz predicts that the FCNC in the couplings of Z' occur only in the up-quark sector.

$$b^D \sim Z_\kappa, \;\; b^U \sim \begin{pmatrix} r & \mathcal{O}(\lambda^5) & (1-r)A\lambda^3(\rho - i\eta) \\ \mathcal{O}(\lambda^5) & r & (1-r)A\lambda^2 \\ (1-r)A\lambda^3(\rho + i\eta) & (1-r)A\lambda^2 & 1 \end{pmatrix}.$$

These results satisfy the constraints of Eq. 8, with the $c \to u$ entry at the upper-level allowed by D mixing. The ansatz predicts that the largest FCNC coupling occurs in $t \to c$ with a strength comparable to V_{ts} (and this was used for the numerical study of single top production at LHC). There are other simple ansatze that give comparable results [15].

5 Summary

We constructed explicit anomaly-free toy models for non-universal Z' bosons that prefer the third generation as examples of new physics for top and revisited the corresponding phenomenology. We constrained the mass and interaction strength from the non-observation of Z' at LEP II. We considered in detail the FCNC associated with a non-universal Z' including operators at tree-level and at one-loop that are enhanced by $\cot\theta_R$, constraining as many parameters as possible from experiment. We used these constraints to predict that large enhancements over SM are still possible in other rare processes. Finally, we constructed an ansatz to show how the smallness of FCNC can occur from the same physics behind the CKM matrix.

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