Minimal Z' models for flavor anomalies

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By allowing gauge anomaly cancellation between fermions in different families we find a non-universal solution for a Z' family of models with the same content of fermions of the standard model plus three right-handed neutrinos. We also impose constraints from the Yukawa interaction terms in such a way that at the end we obtain a solution with six free parameters. Our solution contains as particular cases well-known models in the literature. As an application, we report a model which evades LHC constraints, flavor changing neutral currents and low energy constraints. Simultaneously, the model is able to explain the flavor anomalies in the Wilson coefficients $C_9(\mu)$ and $C_{10}(\mu)$ without modifying the corresponding Wilson coefficients for the first family. In our approach this procedure is always possible for Z' masses smaller than ~ 2.5 TeV.

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I. INTRODUCTION

In recent years, experimental anomalies in the LHCb and in low-energy experiments [1–4] have generated some theoretical speculation about the posibility that these results constitute a manifestation of physics beyond the standard model (SM). A number of anomalies in semileptonic B decays have been reported by the LHCb collaboration and other experiments [2, 5–10], finding various deviations from their predicted values in the SM. Even though the experimental results are not conclusive yet, the global fits improve for models where the new physics contributions to the Wilson coefficient C_9^{μ} decrease it by a quarter of the SM prediction [11]. Because the only lepton in the associated Wilson operator is the muon field, one of the preferred theoretical frameworks to explain these anomalies are the non-universal models [12–19], for which the electroweak (EW) parameters and quantum numbers are family dependent. In general, non-universal models are restricted severely by flavor changing neutral currents (FCNC); however, as it is well-known [20], we can get rid of these problems by guaranteeing that the gauge couplings of the new physics to the left-handed down-type quarks become identical (We do not know anything about the mixing of the right-handed quarks so that we can assume a diagonal matrix. That result quite useful to avoid further constraints on the Z' charges). That is particularly important for the first and second generation.

The best-known non-universal EW extensions of the SM correspond to the so-called 331 models; however, simpler solutions can be built by restricting the additional EW sector to an abelian $U(1)$ gauge symmetry with the same fermion content of the SM plus right-handed neutrinos. As we will show, these minimal solutions are able to explain these anomalies without increasing the number of new fields and parameters. These EW extensions are known as minimal models [21–32], and constitute the simplest EW extension of the SM. The best-known example is the left-right symmetric (LRS) model, which has universal EW charges for the three families and its content of fermions excess the SM one by a right-handed neutrino in every family. Earlier in the nineties, several works pointed out the non-fundamental character of the universality of the EW charges [33–44]. This was motivated by EW models based on string theory which, in most of the cases, result to be non-universal [25]. A general solution to the gauge anomalies involves a cubic Diophantine equation [45]; however, it is possible to find solutions with continuous parameters, which turn out quite useful to build benchmark models.

A lot of phenomenology has been based on the minimal models [13–16, 23, 26, 46–59], in spite of it, most of these analysis make use of some few well-known EW charge assignments leaving aside other possible solutions to the gauge anomaly equations with the same content of fermions. A first step to know the full set of solutions was given in

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Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
l_{Li}	1/2	1	2	-1/2	l_i
e_{Ri}	1/2	1	1	-1	e_i
ν_{Ri}	1/2	1	1	0	n_i
q_{Li}	1/2	3	2	1/6	q_i
u_{Ri}	1/2	3	1	2/3	u_i
d_{Ri}	1/2	3	1	-1/3	d_i
Φ_i	0	1	2	1/2	ϕ_i

TABLE I: Particle content. The subindex $i = 1, 2, 3$ stand for the family number in the interaction basis. In our solution $\phi_2 = \phi_3$ in such a way that only two Higgs doublets are needed. However, sometimes we keep the notation ϕ_i, which is quite convenient for notation purposes.

our previous work [60], where we assume two identical families and the non-universality show up only in the third generation. In the present manuscript, we allow non-universal charges for leptons and quarks in the three families, which result quite convenient in the study of the LHCb anomalies. Under some reasonable assumptions, many of these models are able to evade the FCNC constraints.

The paper is organized as follows: in Section II we derive the general expressions for the chiral charges of the models. In Section III we derive the 95% C.L. allowed limits on the model parameters by the most recent LHC data and the corresponding limits by the low energy EW data. Section IV summarizes our conclusions.

II. THE $SU(2)_L \otimes U(1) \otimes U(1)'$ GAUGE SYMMETRY

The aim of the present work is to build the most general parameterization for the minimal EW extension of the SM, limiting ourselves to the SM fermions plus right-handed neutrinos. In order to accomplish our purpose it is necessary to avoid the hypothesis of universality; with this in mind, let us consider the gauge group $SU(2) \otimes U(1) \otimes U(1)'$ as a non-universal anomaly-free extension of the EW sector of the SM.

In what follows T_{1L}, T_{2L} and T_{3L} denote the generators of $SU(2)_L$, while Y and $Q_{Z'}$ denote the generators of $U(1)$ and $U(1)'$, respectively. The covariant derivative for our model is given by [61]

$$D_\mu = \partial_\mu - ig\overrightarrow{T}_L \cdot \overrightarrow{A}_\mu - ig_Y Y B_{Y\mu} - ig_{Z'} Q_{Z'} Z'_\mu, \tag{1}$$

where g, g_Y and $g_{Z'}$ are the gauge couplings associated with the $SU(2)_L$, $U(1)$ and $U(1)'$ gauge groups, respectively, and $\overrightarrow{A}_\mu$, $B_{Y\mu}$ and Z'_μ stand for the corresponding gauge fields.

In order to find the most general solution to gauge anomaly cancellation, all families have different quantum numbers, because of this, at least two Higgs doublets are required in order to give masses to the three families, so:

$$\langle \Phi_i \rangle^T = (0, v_i/\sqrt{2}), \qquad i = 1, 2. \tag{2}$$

A. Gauge anomaly cancellation

For the $SU(2)_L \otimes U(1) \otimes U(1)'$ symmetry with the particle content shown in table I, the non-trivial gauge anomaly equations are:

$$\begin{aligned}
[SU(2)]^2U(1)' :&\ \ 0 = \Sigma q + \frac{1}{3}\Sigma l,\\
[SU(3)]^2U(1)' :&\ \ 0 = 2\Sigma q - \Sigma u - \Sigma d,\\
[\text{grav}]^2U(1)' :&\ \ 0 = 6\Sigma q - 3(\Sigma u + \Sigma d) + 2\Sigma l - \Sigma n - \Sigma e,\\
[U(1)]^2U(1)' :&\ \ 0 = \frac{1}{3}\Sigma q - \frac{8}{3}\Sigma u - \frac{2}{3}\Sigma d + \Sigma l - 2\Sigma e,\\
U(1)[U(1)']^2 :&\ \ 0 = \Sigma q^2 - 2\Sigma u^2 + \Sigma d^2 - \Sigma l^2 + \Sigma e^2,\\
[U(1)']^3 :&\ \ 0 = 6\Sigma q^3 - 3(\Sigma u^3 + \Sigma d^3) + 2\Sigma l^3 - \Sigma n^3 - \Sigma e^3,
\end{aligned} \tag{3}$$

where $\Sigma f = f_1 + f_2 + f_3$. We also take into account the constraints coming from the Yukawa couplings:

$$\begin{aligned}
\mathcal{L}_Y \supset\ & \bar{l}_{1_L}\tilde{\Phi}_1\nu_{1_R} + \bar{l}_{1L}\Phi_1 e_{1_R} + \bar{q}_{1_L}\tilde{\Phi}_1 u_{1_R} + \bar{q}_{1_L}\Phi_1 d_{1_R} +\\
& \bar{l}_{2_L}\tilde{\Phi}_2\nu_{2_R} + \bar{l}_{2L}\Phi_2 e_{2_R} + \bar{q}_{2_L}\tilde{\Phi}_2 u_{2_R} + \bar{q}_{2_L}\Phi_2 d_{2_R} +\\
& \bar{l}_{3_L}\tilde{\Phi}_2\nu_{3_R} + \bar{l}_{3_L}\Phi_2 e_{3_R} + \bar{q}_{3_L}\tilde{\Phi}_2 u_{3_R} + \bar{q}_{3_L}\Phi_2 d_{3_R} + \text{h.c.}
\end{aligned} \tag{4}$$

The corresponding constraints coming from the terms in the above Lagrangian are (where $\phi_2 = \phi_3$):

$$\begin{aligned}
0 &= e_i - l_i + \phi_i,\\
0 &= n_i - l_i - \phi_i,\\
0 &= d_i - q_i + \phi_i,\\
0 &= u_i - q_i - \phi_i.
\end{aligned} \tag{5}$$

The solution to the gauge anomaly equations (3) and the constraints from the Yukawa interaction terms (5) corresponds to the charges shown in table II (there are six solutions corresponding to the permutations between the indices ijk). In general, every one of these solutions depends on six parameters, (q_i, n_i), with $i = 1, 2, 3$, corresponding to the Z' charges for the quark doublet and the right-handed neutrino in every generation, respectively. By removing the constraint $\phi_j = \phi_k$ there are two additional solutions which will be reported elsewhere since they do not fit well the flavor anomalies.

f	$\epsilon^{Z'}(f)$
l_i	$-3q_i$
e_i	$-n_i - 6q_i$
u_i	$+n_i + 4q_i$
d_i	$-n_i - 2q_i$
l_j	$+\frac{1}{2}[n_j - n_k - 3(q_j + q_k)]$
e_j	$-n_k - 3(q_j + q_k)$
u_j	$+\frac{1}{2}(n_j + n_k + 5q_j + 3q_k)$
d_j	$-\frac{1}{2}(n_j + n_k + q_j + 3q_k)$
l_k	$+\frac{1}{2}[-n_j + n_k - 3(q_j + q_k)]$
e_k	$-n_j - 3(q_j + q_k)$
u_k	$+\frac{1}{2}(n_j + n_k + 3q_j + 5q_k)$
d_k	$-\frac{1}{2}(n_j + n_k + 3q_j + q_k)$

TABLE II: The Z' couplings for the Higgs doublets Φ_i are $\phi_i = n_i + 3q_i$ and $\phi_j = \phi_k = \frac{1}{2}[n_j + n_k + 3(q_j + q_k)]$, respectively. The higgs field ϕ_i couples to fermions in the i-th family. The integers ijk are a permutation of 123.

By setting $(n_j - n_k)/2 = L_i = -L_k = 1$, $n_k = -1$ and $q_i = q_j = q_k = n_i = 0$, from this solution we can obtain the model $L_j - L_k$ where L_i is 1 for the leptons in the i-th family and zero otherwise. From these solutions, the most known model is the $L_\mu - L_\tau$ model, which has been widely used to explain the $g - 2$ anomaly [50].

$\mathcal{O}$	Value [62, 69]	SM prediction $\mathcal{O}_{\rm SM}$ [62]	$\Delta\mathcal{O} = \mathcal{O} - \mathcal{O}_{\rm SM}$
$Q_W(p)$	0.064 ± 0.012	0.0708 ± 0.0003	$4\left(\frac{M_Z}{g_1 M_{Z'}}\right)^2 \Delta_A^{ee}\left(2\Delta_V^{uu} + \Delta_V^{dd}\right)$
$Q_W(\mathrm{Cs})$	-72.62 ± 0.43	-73.25 ± 0.02	$Z\Delta Q_W(p) + N\Delta Q_W(n)$
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0003	$4\left(\frac{M_Z}{g_1 M_{Z'}}\right)^2 \Delta_A^{ee}\Delta_V^{ee}$
$1 - \sum_{q=d,s,b} \lvert V_{uq}\rvert^2$	$1 - 0.9999(6)$	0	$\frac{3}{4\pi^2}\frac{M_W^2}{M_{Z'}^2}\left(\ln\frac{M_{Z'}^2}{M_W^2}\right)\Delta_L^{\mu\mu}\left(\Delta_L^{\mu\mu} - \Delta_L^{dd}\right)$
$C_9^{\rm NP}(\mu)$	$-1.29^{+0.21}_{-0.20}$	0	$-\frac{1}{g_1^2 M_{Z'}^2}\frac{\Delta_L^{sb}\Delta_V^{\mu\bar{\mu}}}{V_{ts}^* V_{tb}\sin^2\theta_W}$
$C_{10}^{\rm NP}(\mu)$	$+0.79^{+0.26}_{-0.24}$	0	$-\frac{1}{g_1^2 M_{Z'}^2}\frac{\Delta_L^{sb}\Delta_A^{\mu\bar{\mu}}}{V_{ts}^* V_{tb}\sin^2\theta_W}$
$\frac{\sigma^{{\rm SM}+Z'}}{\sigma_{SM}}$	0.83 ± 0.18	1	$\frac{1+\left(1+4s_W^2+\Delta_V^{\mu\mu}\Delta_L^{\nu\nu}v^2/M_{Z'}^2\right)^2}{1+(1+4s_W^2)^2} - 1$

TABLE III: Experimental value and the new physics prediction for the shift in the weak charge of the proton $Q_W(p)$, Cesium $Q_W(\mathrm{Cs})$ and the electron $Q_W(e)$, owed to the interaction with the Z'. The fourth observable is the constraint on the violation of the first-row CKM unitarity [62, 68]. Constraints on neutrino trident production and the limits on the Wilson coefficients C_9 and C_{10} are also included. For the rotation from the weak basis to the mass eigenstates we adopt the convention [70]: $\Delta_{L,R}^{ff} = g_{Z'}\epsilon_{L,R}^{Z'}(f)$ for up-type quarks, *i.e.*, u, c, t, right-handed down-type quarks, *i.e.*, d_R, s_R, b_R (to avoid FCNC) and charged leptons. For left-handed down-type quarks, *i.e.*, d, s and b we use $\Delta_L^{fg} = g_{Z'}\sum_{f',f''} V_{CKM}^{\dagger ff'}\epsilon_L^{Z'}(f')\delta_{f',f''}V_{CKM}^{f''g}$, and a similar expression for neutrinos but using the PMNS matrix. It is useful to define the vector and axial expressions $\Delta_{V,A}^{ff} = \Delta_R^{ff} \pm \Delta_L^{ff}$ [71]. The neutron weak charge $Q_W(n)$ is similar to that of the proton by interchanging $u \leftrightarrow d$.

III. LHC AND LOW ENERGY CONSTRAINTS

Part of the aim of this work is to show that it is possible to explain the flavor anomalies by minimal Z' models. In order to demonstrate this statement, we carry out a χ^2 analysis including the most relevant constraints on the Z' parameter space. For models with axial couplings to the electron different from zero *i.e.*, $\epsilon_L^{Z'} - \epsilon_R^{Z'} \neq 0$, important constraints come from atomic parity violation which result from the measurements of the weak charges of the cesium [62–64], the electron [62, 65] and the proton [62, 66]. Another constraint that only involves left-handed chiral charges derives from the CKM unitarity [67, 68]. This constraint is important since it applies even for models with zero couplings to the quarks.

The C_9 and C_{10} observables, which are involved in the recent discussions about the LHCb anomalies [2, 5–10], have a value different from zero in the SM; our purpose is to include in the analysis the corresponding corrections to these coefficients due to the interaction of the SM fermions with a Z' gauge boson. These shifts are denoted by $C_9^{\rm NP}$ and $C_{10}^{\rm NP}$ and are expect to be zero in the SM as indicated in table III.

We also include constraints coming from neutrino trident production in the scattering of muon neutrino with nuclei. The effective Lagrangian for the new physics involved in this process is $\mathcal{L}_{\nu_\mu\to\nu_\mu\mu\bar{\mu}} = -C_W\bar{\mu}\gamma^\alpha\mu\bar{\nu}\gamma_\alpha P_L\nu$, where $C_W = \Delta_V^{\mu\mu}\Delta_L^{\nu\nu}/(2M_{Z'}^2)$ is the Wilson coefficient at tree level. From this result we obtain a contribution to the neutrino-nucleon scattering like the one shown in the last row in table III [16, 72].

By choosing $(i,j,k) = (1,2,3)$ in table II and identifying these labels with the charges of the first, second and third family, respectively, it is possible to obtain a solution with zero couplings to the first family, *i.e.*, $q_1 = n_1 = 0$. This choice has a double purpose, first of all, to avoid the strongest constraints from colliders, which are weakened for a Z' with zero couplings to the up and down quarks, and second, avoid contributions of the Z' boson to the $C_9(e)$ and $C_{10}(e)$ coefficients. In order to avoid FCNC, we also impose that the Z' couplings to the left-handed down and left-handed strange be identical. Under these restrictions and some other on the absolute value of the charges (see the caption in table IV), we found good fits for Z' masses below 2.5 TeV (see table V).

The pulls of the observables in table III are shown in table IV. In order to avoid a best-fit point in the non-perturbative region in the minimization of the χ^2, we restrict the absolute value of the parameters to be less than 1 for the second generation and 3 for l_3 which corresponds to the Z' left-chiral coupling to the τ. By changing these conditions other solutions are possible; however, our aim is to show that it is possible to build a model satisfying all the constraints. It is important to emphasize that because the Z' couplings to the first family are zero, there is no contribution to the weak charge of the cesium, proton, and the electron, hence the corresponding pulls for these observables are the same as those of SM.

In figure 1 the 95% CL allowed regions for several observables are shown. It is important to stress that a similar

	$\text{Pull}^i=\frac{\mathcal{O}^i_{\text{exp}}-\mathcal{O}^i_{\text{th}}}{\sqrt{\sigma^{i2}_{\text{exp}}+\sigma^{i2}_{\text{th}}}}$							
$\mathcal{O}^i$	$Q_W(p)$	$Q_W(\text{Cs})$	$Q_W(e)$	CKM	C_9	C_{10}	ν-Trident	χ^2_{min}
	-0.566	1.46	1.38	-0.733	-0.789	0.967	-0.985	7.4

TABLE IV: Pulls for low energy experiments in the χ^2 minimization for a $M_{Z'} = 2.5$ TeV. In this analysis we identify $i = 1, 2, 3$ with the first, second and third generation of fermions, respectively. The minimization was carried out by imposing the constraints $q_1 = q_2$, and $q_1 = u_1 = d_1 = 0$, in order to avoid FCNC and LHC constraints, respectively. This choice has a double purpose since it forbids any contribution of the Z' to $C_9(e)$ and $C_{10}(e)$ which involve fermions of the first family. To evade too large lepton couplings (in order to avoid non-perturbative charges) in the second and third family we restrict the Z' couplings of the SM fermions of the second and third families to have an absolute value smaller than 1 and 3, respectively (for the third family the constraints are weaker). We did not impose any constraint on the right-handed neutrino couplings n_i due to the absence of constraints on these parameters. For the minimization of the χ^2 we restrict the absolute value of the parameters to be less than 1 for the second generation, and 3 for l_3 which corresponds to the Z' left-chiral coupling to the τ. Another sets of charges are also possible by changing these constraints.

$M_{Z'} = 2.5$ TeV	$i = 1$	$i = 2$	$i = 3$
$g_{Z'} l_i$	0	1	-3
$g_{Z'} e_i$	0	0.3523	-3.648
$g_{Z'} n_i$	0	1.648	-2.352
$g_{Z'} q_i$	0	0	2/3
$g_{Z'} u_i$	0	0.6477	1.314
$g_{Z'} d_i$	0	-0.6477	0.01897
$g_{Z'} \phi_i$	0	0.03975	

TABLE V: Best fit values for the Z' chiral charges of SM fermions, right-handed neutrinos and the Higgs doublets. $i = 1, 2, 3$ correspond to the first, second and third generation of fermions.

plot exists between any couple of parameters of the model. For this reason it is difficult to obtain general conclusions from this figure; however, the plot serves to get some idea about how each observable put constraints on the parameter space. These parameters, n_2 and q_1, are important owing that they are related to the observables of our analysis. n_2 appears in all the charges of the second family except in the Z' coupling of the right-handed muon. q_1 corresponds to the Z' coupling of the left-handed up and down quark and the Z' coupling of the left-handed electron is also proportional to this parameter. The latter is important for the collider constraints [60, 74–77].

For the time being, the strongest constraints come from the proton-proton collisions data collected by the ATLAS experiment at the LHC with an integrated luminosity of 36.1 fb^{-1} at a center of mass energy of 13 TeV [78]. In particular, we used the upper limits at 95% C.L. on the total cross-section of the Z' decaying into dileptons (*i*.e., e^+e^- and $\mu^+\mu^-$). Figure 1 shows the contours in the parameter space of the minimal models at 95% C.L. for $M_{Z'} = 2.5$TeV. We obtain these limits from the intersection of $\sigma^{\text{NLO}}(pp \to Z' \to l^- l^+)$ with the ATLAS 95% C.L. upper limits on the cross-section (for additional details see reference [79]). As a cross-check we calculated these limits for the sequential SM and some E_6 models finding the same value than that reported by the collaboration [77].

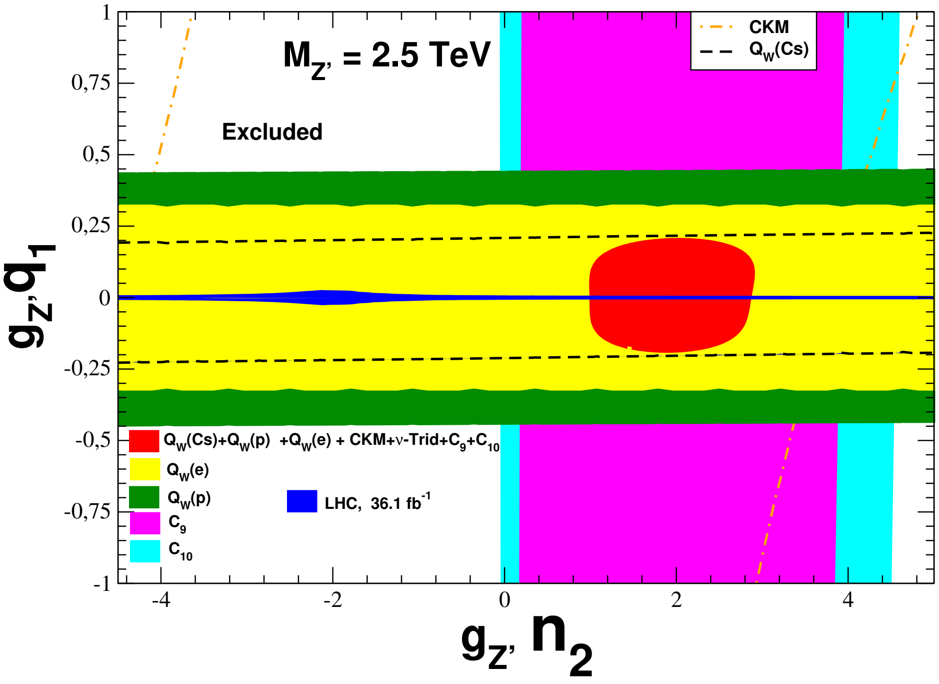

FIG. 1: Colored regions correspond to the allowed parameter space at the 95% C.L for a $M_{Z'} = 2.5$TeV. The region enclosed between the black-dashed lines corresponds to the 95% C.L. allowed parameter space by the cesium weak charge measurements [62–64, 73]. The yellow region corresponds to the 95% C.L. allowed parameter space by the electron weak charge measurements in Moller scattering [62, 65]. The green region corresponds to the 95% C.L. allowed parameter space by the proton weak charge measurements [62, 66]. The region enclosed between the orange-dot-dashed lines corresponds to the 95% C.L. allowed parameter space by the constraints on the violation of the first-row CKM unitarity [67, 68]. By combining all the low energy data considered in our analysis the 95% C.L. allowed parameter space corresponds to the red region. The cyan and magenta regions correspond to the 95% C.L. parameter spaces consistent with the best fit values for the C_9 and C_{10}, respectively. The blue region corresponds to the 95% C.L. parameter space allowed by data from proton-proton collisions decaying to μ pairs in the ATLAS detector for an integrated luminosity of 36.1 fb^{-1} at a center of mass energy of 13TeV.

IV. CONCLUSIONS

In this work we presented an anomaly-free non-universal Z' family of models, which only includes SM fermions plus right-handed neutrinos and two Higgs doublets. Our solutions have three families with different charges for every family, *i.*e., the model is non-universal; however, a priori it is not possible to identify one of them with a particular family in the SM; hence, it is necessary a study of the phenomenology of all the possibilities.

By means of an explicit example, we show that it is possible to build a model with zero couplings to the up and down quarks and in general to the fermions of the first family, in such a way that the model evades collider constraints and does not contribute to the corresponding the Wilson coefficients $C_9(e)$ and $C_{10}(e)$. Simultaneously, our solution is flexible enough to accommodate the flavor anomalies in the Wilson coefficients $C_9(\mu)$ and $C_{10}(\mu)$. By requiring that the left-handed couplings of the down and strange couplings be identical it is possible to avoid FCNC.

What follows is to analyze the constraints for a Z' with strong couplings to the μ and τ leptons but zero couplings to the up and down quarks [17].

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