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Flavourful Z' models for $R_{K^{(*)}}$ from mixing with a fourth vector-like family

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In the talk we discussed how any flavour conserving Z' model can be made flavour violating and non-universal by introducing mass mixing of quarks and leptons with a fourth family of vector-like fermions with non-universal Z' couplings. We also explained the basic idea then gave two concrete examples, namely a fermiophobic model, and an $SO(10)$ GUT model, and discussed their prospects for accounting for the anomalous B decay ratios R_K and R_{K^*}. We also discuss here some recent work following the Corfu Workshop, concerning the experimental constraints on a version of the fermiophobic model.

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1. Introduction

Recently, the phenomenological motivation for considering non-universal Z' models has increased due to mounting evidence for semi-leptonic B decays which violate $\mu - e$ universality at rates which exceed those predicted by the SM [1, 2, 3]. In particular, the LHCb Collaboration and other experiments have reported a number of anomalies in $B \to K^{(*)} l^+ l^-$ decays such as the R_K [4] and R_{K^*} [5] ratios of $\mu^+\mu^-$ to e^+e^- final states, which are observed to be about 70% of their expected values with a 4σ deviation from the SM, and the P_5' angular variable, not to mention the $B \to \phi\mu^+\mu^-$ mass distribution in $m_{\mu^+\mu^-}$.

Following the measurement of R_{K^*} [5], a number of phenomenological analyses of these data, see e.g. [6, 7, 8, 9, 10, 11] favour a new physics operator of the $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ form [12, 13],

$$-\frac{1}{(31.5\text{ TeV})^2}\,\bar{b}_L\gamma^\mu s_L\,\bar{\mu}_L\gamma_\mu\mu_L. \tag{1.1}$$

or of the $C_{9\mu}^{NP}$ form,

$$-\frac{1}{(31.5\text{ TeV})^2}\,\bar{b}_L\gamma^\mu s_L\,\bar{\mu}\gamma_\mu\mu. \tag{1.2}$$

or some linear combination of these two operators. Other solutions different than $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ allowing for a successful explanation of the R_{K^*} anomalies are studied in detail in Ref. [14]. However the solution $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ can provide a simultaneous explanation of the R_{K^*} and R_{D^*} anomalies [15]. In a flavourful Z' model, the new physics operator in Eq.1.1 will arise from tree-level Z' exchange, where the Z' must dominantly couple to $\mu\mu$ over ee, and must also have the quark flavour changing coupling $b_L s_L$ which must dominate over $b_R s_R$.

In a recent paper, we showed how to obtain a flavourful Z' suitable for explaining R_{K^*} by adding a fourth vector-like family with non-universal $U(1)'$ charges [16]. The idea is that the Z' couples universally to the three chiral families, which then mix with the non-universal fourth family to induce effective non-universal couplings in the physical light mixed quarks and leptons. Two explicit examples were discussed in [16]: an $SO(10) \to SU(5) \times U(1)_X$ model, where we identified $U(1)' \equiv U(1)_X$, and a fermiophobic model where the $U(1)'$ charges are not carried by the three chiral families, only by fourth vector-like family.

The main progress since the Corfu Workshop, is summarised below:

1. Firstly, the mechanism has been discussed in the context of F-theory models with non-universal gauginos [17].

2. Secondly, the $SO(10) \to SU(5) \times U(1)_X$ case was recently explored in [18], where two open questions regarding such models were addressed: whether a consistent neutrino sector can be constructed for such models, and whether models of this type can provide a consistent explanation of the present R_{K^*} anomalies. It was shown that while the answer to the first question is positive (with linear and/or inverse low scale seesaw mechanism), the answer to the second question is negative [18].

3. Thirdly, a fermiophobic model, based on induced Z' couplings to third family left-handed quark doublets and second family left-handed lepton doublets, was shown to overcome all the

phenomenological flavour changing and collider constraints, while simultaneously providing an explanation for Dark Matter, via a flavourful Z' portal model with a coupling to a fourth-family singlet Dirac neutrino Dark Matter candidate [19].

4. Fourthly, the successful scheme, based on induced Z' couplings to third family left-handed quark doublets and second family left-handed lepton doublets, was discussed in [20] in the framework of an $SU(5)\times U(1)'$ model where it was shown to correct the Yukawa relation $Y_e \neq Y_d^T$ without the need for higher Higgs representations.

In these proceedings, after reviewing the basic ingredients and mechanism in the next section, we then focus on the most promising fermiophobic scheme where, in the absence of mixing, the Z' is fermiophobic, having no couplings to the three chiral families, but with couplings to a fourth vector-like family. Then, due to mixing with the fourth family, the Z' gets induced couplings to second family left-handed lepton doublets and third family left-handed quark doublets, leading to the operator in Eq. 1.1. As we shall see, such a scheme raises interesting new flavour questions, and presents an experimental challenge to completely cover the allowed parameter space of the model.

2. The basic ingredients and mechanism [16]

A general problem with obtaining non-universal and flavour-dependent Z' couplings is that of anomaly cancellation. The proposal to overcome this is that the three chiral families couple to the Z' in a universal and flavour-independent way, as in usual Z' models. However, in addition, we propose a fourth vector-like family in which the gauged $U(1)'$ charges are different from the three chiral families, $q_i \neq q_4$, but where, due to the vector-like nature, anomalies are automatically cancelled, i.e. for every left-handed fourth family fermion multiplet with $U(1)'$ charge q_4 there is an identical right-handed multiplet with the same charge, so that anomalies cancel pairwise between left and right-handed fourth family fermions. The basic ingredients are shown in Table 1.

Non-universality arises due to mixing between the three chiral families and the fourth vector-like family, i.e. after mixing effects, the three chiral families contain admixtures of the fourth family fermions, and due to those admixtures, will have induced non-universal and favour-dependent couplings to Z' controlled by the amount of mixing. That is the basic idea, and the rest is model dependent details. Clearly there is much scope for model building, based on the ingredients of having a fourth vector-like family and a spontaneously broken $U(1)'$ but the basic ideas to keep in mind are firstly that anomaly cancellation is trivial and secondly that the flavourful Z' couplings completely arise from mixing between the three chiral families and the fourth vector-like family.

We assume that the $U(1)'$ charges allow for the fourth opposite chirality family $\tilde{\psi}_4$ to have interactions with the first three chiral families ψ_i via singlet fields ϕ which carry $U(1)'$ charge, in addition to explicit masses between opposite chirality fourth family fields $\tilde{\psi}_4$ and ψ_4 of the same charges,

$$\begin{aligned}\mathscr{L}^{mass} &= x_i^Q \phi_Q \overline{Q}_{Li}\tilde{Q}_{R4} + x_i^u \phi_u \overline{\tilde{u}}_{L4} u_{Ri} + x_i^d \phi_d \overline{\tilde{d}}_{L4} d_{Ri} + x_i^L \phi_L \overline{L}_{Li}\tilde{L}_{R4} + x_i^e \phi_e \overline{\tilde{e}}_{L4} e_{Ri} \\ &+ M_4^Q \overline{Q}_{L4}\tilde{Q}_{R4} + M_4^u \overline{\tilde{u}}_{L4} u_{R4} + M_4^d \overline{\tilde{d}}_{L4} d_{R4} + M_4^L \overline{L}_{L4}\tilde{L}_{R4} + M_4^e \overline{\tilde{e}}_{L4} e_{R4} + H.c. \end{aligned} \quad (2.1)$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_{Li}	**3**	**2**	$1/6$	q_{Q_i}
u_{Ri}	**3**	**1**	$2/3$	q_{u_i}
d_{Ri}	**3**	**1**	$-1/3$	q_{d_i}
L_{Li}	**1**	**2**	$-1/2$	q_{L_i}
e_{Ri}	**1**	**1**	-1	q_{e_i}
ν_{Ri}	**1**	**1**	0	q_{ν_i}
H	**1**	**2**	$-1/2$	q_H
$Q_{L4},\tilde{Q}_{R4}$	**3**	**2**	$1/6$	q_{Q_4}
$u_{R4},\tilde{u}_{L4}$	**3**	**1**	$2/3$	q_{u_4}
$d_{R4},\tilde{d}_{L4}$	**3**	**1**	$-1/3$	q_{d_4}
$L_{L4},\tilde{L}_{R4}$	**1**	**2**	$-1/2$	q_{L_4}
$e_{R4},\tilde{e}_{L4}$	**1**	**1**	-1	q_{e_4}
$\nu_{R4},\tilde{\nu}_{L4}$	**1**	**1**	0	q_{ν_4}
$\phi_{Q,u,d,L,e}$	**1**	**1**	0	$q_{\phi_{Q,u,d,L,e}}$

Table 1: The basic ingredients involve, in addition to the Standard Model (SM) with Higgs doublet H, a gauged $U(1)'$ and a fourth vector-like family. The three chiral families have universal $U(1)'$ charges q_i while the fourth vector-like family has non-universal $U(1)'$ charges $q_4 \neq q_i$. The gauged $U(1)'$ is broken by the VEVs of new Higgs singlets ϕ with suitable charges to allow mixing of and yield a massive Z'.

After the singlet fields ϕ develop vacuum expectation values (VEVs), we may define new mass parameters $M^Q_i = x^Q_i \langle \phi_Q \rangle$, and similarly for the other mass parameters, to give,

$$\mathscr{L}^{mass} = M^Q_\alpha \overline{Q}_{L\alpha} \tilde{Q}_{R4} + M^u_\alpha \overline{\tilde{u}}_{L4} u_{R\alpha} + M^d_\alpha \overline{\tilde{d}}_{L4} d_{R\alpha} + M^L_\alpha \overline{L}_{L\alpha} \tilde{L}_{R4} + M^e_\alpha \overline{\tilde{e}}_{L4} e_{R\alpha} + H.c. \tag{2.2}$$

where $\alpha = 1, \ldots, 4$.

Clearly only one linear combination of the four families (denoted by primes) couples to the "wrong-handed" fourth family states (denoted by tildes),

$$\mathscr{L}^{mass} = \tilde{M}^Q_4 \overline{Q'}_{L4} \tilde{Q}_{R4} + \tilde{M}^u_4 \overline{\tilde{u}}_{L4} u'_{R4} + \tilde{M}^d_4 \overline{\tilde{d}}_{L4} d'_{R4} + \tilde{M}^L_4 \overline{L'}_{L4} \tilde{L}_{R4} + \tilde{M}^e_4 \overline{\tilde{e}}_{L4} e'_{R4} + H.c. \tag{2.3}$$

The first three primed states of each fermion type such as $Q'_{L1}, Q'_{L2}, Q'_{L3}$ have zero mass, while the fourth primed component such as Q'_{L4} gets a heavy mass as in Eq.2.3. The mass eigenstate basis $Q'_L = (Q'_{L1}, Q'_{L2}, Q'_{L3}, Q'_{L4})^T$ is related by the original basis by 4×4 unitary mixing matrices,

$$Q'_L = V_{Q_L} Q_L, \; u'_R = V_{u_R} u_R, \; d'_R = V_{d_R} d_R, \; L'_L = V_{L_L} L_L, \; e'_R = V_{e_R} e_R. \tag{2.4}$$

The unitary mixing matrix which relates the column vector Q'_L of mass eigenstates (where the first three components are massless and the fourth component has a mass $\tilde{M}^Q_4$) to the original fields Q_L may be written as,

$$V_{Q_L} = V^{Q_L}_{34} V^{Q_L}_{24} V^{Q_L}_{14}, \tag{2.5}$$

where each of the unitary matrices $V^{Q_L}_{i4}$ are parameterised by a single angle θ_{i4} describing the mixing between the ith chiral family and the 4th vector-like family. Similarly for $V_{u_R}, V_{d_R}, V_{L_L}, V_{e_R}$.

The primed mass eigenstate basis is very useful for decoupling the heavy states, since in this basis only the fourth components get heavy masses, while the first three components remain massless (before electroweak symmetry breaking). However these first three massless components contain admixtures of the fourth vector-like family due to the mixing, and so will have modified Yukawa and gauge couplings, as compared to the original (unmixed) three chiral families, as follows.

Yukawa couplings: In the primed basis in Eq.2.4, where only the fourth components of the fermions are very heavy, the Yukawa couplings are,

$$\mathscr{L}^{Yuk} = H_u \overline{Q'}_L \tilde{y}'^u u'_R + H_d \overline{Q'}_L \tilde{y}'^d d'_R + H_d \overline{L'}_L \tilde{y}'^e e'_R + H.c. \tag{2.6}$$

where

$$\tilde{y}'^u = V_{Q_L} \tilde{y}^u V^\dagger_{u_R}, \;\; \tilde{y}'^d = V_{Q_L} \tilde{y}^d V^\dagger_{d_R}, \;\; \tilde{y}'^e = V_{L_L} \tilde{y}^e V^\dagger_{e_R} \tag{2.7}$$

and $\tilde{y}^u, \tilde{y}^d, \tilde{y}^e$ are 4×4 matrices consisting of the original 3×3 matrices of the three chiral families, y^u, y^d, y^e, but augmented by a fourth row and column corresponding to the extra Yukawa couplings of the fourth vector-like family with the same handedness as the original three chiral families (i.e. not the "wrong-handed" fourth family fermions denoted by tildes). In the primed basis, the Yukawa matrices of the three massless families correspond to the upper 3×3 blocks of the matrices $\tilde{y}'^u, \tilde{y}'^d, \tilde{y}'^e$, i.e. we decouple the heavy fourth family in the primed mass eigenstate basis by simply striking out the fourth row and fourth column of these matrices.

Z' couplings: The Z' couplings to the four families of quarks and leptons in the primed mass eigenstate basis, where only the fourth components of the fermions are very heavy, are

$$\mathscr{L}^{gauge}_{Z'} = g' Z'_\mu \left(\overline{Q}'_L D'_Q \gamma^\mu Q'_L + \overline{u}'_R D'_u \gamma^\mu u'_R + \overline{d}'_R D'_d \gamma^\mu d'_R + \overline{L}'_L D'_L \gamma^\mu L'_L + \overline{e}'_R D'_e \gamma^\mu e'_R \right) \tag{2.8}$$

where

$$\begin{aligned} &D'_Q = V_{Q_L} D_Q V^\dagger_{Q_L}, \; D'_u = V_{u_R} D_u V^\dagger_{u_R}, \; D'_d = V_{d_R} D_d V^\dagger_{d_R}, \\ &D'_L = V_{L_L} D_L V^\dagger_{L_L}, \; D'_e = V_{e_R} D_e V^\dagger_{e_R}, \end{aligned} \tag{2.9}$$

and the diagonal $U(1)'$ charge matrices are

$$\begin{aligned} &D_Q = \mathrm{diag}(q_{Q1}, q_{Q2}, q_{Q3}, q_{Q4}), \; D_u = \mathrm{diag}(q_{u1}, q_{u2}, q_{u3}, q_{u4}), \; D_d = \mathrm{diag}(q_{d1}, q_{d2}, q_{d3}, q_{d4}), \\ &D_L = \mathrm{diag}(q_{L1}, q_{L2}, q_{L3}, q_{L4}), \; D_e = \mathrm{diag}(q_{e1}, q_{e2}, q_{e3}, q_{e4}). \end{aligned} \tag{2.10}$$

The 4×4 matrices D_Q, etc., are diagonal in flavour space, and the upper 3×3 blocks are proportional to the unit matrix (universal) for the first three families since we assume $q_{Q1} = q_{Q2} = q_{Q3}$. However the 4×4 matrices in the primed basis D'_Q, etc., become diagonal but not proportional to the unit matrix (non-universal) for the first three families in their upper 3×3 blocks after the heavy fourth components are decoupled, due to the mixing with the fourth family described by the matrices V_{Q_L}, etc.. After CKM-type mixing, the upper 3×3 blocks develop off-diagonal (flavour-violating) elements. All of the above is even true in the fermiophobic case where the three chiral families have no $U(1)'$ charges at all, $q_{Q1} = q_{Q2} = q_{Q3} = 0$, since non-zero diagonal elements of the upper 3×3 blocks of D'_Q will be generated by the mixing with the fourth family, as we now discuss.

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3. Fermiophobic model

In the fermiophobic example, the three chiral families of quarks and leptons (and the Higgs doublet) carry zero $U(1)'$ charges, i.e. $q_1 = q_2 = q_3 = 0$, but $q_4 \neq 0$. The diagonal charge matrices in Eq.2.10 are then:

$$D_Q = \mathrm{diag}(0,0,0,q_{Q4}),\; D_u = \mathrm{diag}(0,0,0,q_{u4}),\; D_d = \mathrm{diag}(0,0,0,q_{d4}),$$
$$D_L = \mathrm{diag}(0,0,0,q_{L4}),\; D_e = \mathrm{diag}(0,0,0,q_{e4}). \tag{3.1}$$

In one version of the fermiophobic model, the relevant non-trivial mixing matrices are assumed to be [19, 20]:

$$V_{Q_L} = V_{34}^{Q_L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34}^{Q_L} & s_{34}^{Q_L} \\ 0 & 0 & -s_{34}^{Q_L} & c_{34}^{Q_L} \end{pmatrix}, \quad V_{L_L} = V_{24}^{L_L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24}^{L_L} & 0 & s_{24}^{L_L} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24}^{L_L} & 0 & c_{24}^{L_L} \end{pmatrix}. \tag{3.2}$$

After mixing with the fourth family, the only modified charge matrices from Eq. 2.9 become:

$$D'_Q = q_{Q_4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & (s_{34}^Q)^2 & c_{34}^Q s_{34}^Q \\ 0 & 0 & c_{34}^Q s_{34}^Q & (c_{34}^Q)^2 \end{pmatrix}, \quad D'_L = q_{L_4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & (s_{24}^L)^2 & 0 & c_{24}^L s_{24}^L \\ 0 & 0 & 0 & 0 \\ 0 & c_{24}^L s_{24}^L & 0 & (c_{24}^L)^2 \end{pmatrix}. \tag{3.3}$$

In the low energy effective theory, after integrating out the fourth heavy family, the Z' couplings to the three massless families of quarks and leptons from Eqs. 2.8,3.3 are [1]

$$\mathcal{L}_{Z'}^{\mathrm{gauge}} = g' Z'_\mu \left(q_{Q_4} (s_{34}^Q)^2 \bar{Q}'_{L_3} \gamma^\mu Q'_{L_3} + q_{L_4} (s_{24}^L)^2 \bar{L}'_{L_2} \gamma^\mu L'_{L_2} \right), \tag{3.4}$$

where $Q'_{L3} = (t'_L, b'_L)$ and $L'_{L2} = (\nu'_{\mu L}, \mu'_L)$.

After CKM-type quark mixing effects (i.e. unitary transformations required to diagonalise the 3×3 Yukawa matrices) are taken into account,

$$\begin{aligned} b'_L &= (V'^{\dagger}_{dL})_{31} d_L + (V'^{\dagger}_{dL})_{32} s_L + (V'^{\dagger}_{dL})_{33} b_L \\ t'_L &= (V'^{\dagger}_{uL})_{31} u_L + (V'^{\dagger}_{uL})_{32} c_L + (V'^{\dagger}_{uL})_{33} t_L \end{aligned} \tag{3.5}$$

assuming

$$|(V'_{(d,u)L})_{31}|^2 \ll |(V'_{(d,u)L})_{32}|^2 \ll |(V'_{(d,u)L})_{33}|^2 \approx 1 \tag{3.6}$$

the terms in Eq. 3.4 give rise to the phenomenological couplings,

$$\mathcal{L} \supset Z'_\mu \left(g_{bb} \bar{q}_L \gamma^\mu q_L + g_{bs} \bar{b}_L \gamma^\mu s_L + g_{\mu\mu} \bar{\ell}_L \gamma^\mu \ell_L \right), \tag{3.7}$$

in the notation where the mass eigenstate fields do not have primes, $q_L = (t_L, b_L)^T$, $\ell_L = (\nu_{\mu L}, \mu_L)^T$, assuming that the charged lepton mass matrix is diagonal so that we may drop the primes on

[1] A similar model but with s_{24}^L replaced by s_{34}^L as originally proposed [16] does not work due to a constraint from $\tau \to \mu\mu\mu$ arising from the coupling $g' Z'_\mu q_{L_4} (s_{34}^L)^2 \bar{L}'_{L_3} \gamma^\mu L'_{L_3}$ leading to $g' Z'_\mu q_{L_4} (s_{34}^L)^2 (V'^{\dagger}_{eL})_{32} \bar{\tau}_L \gamma^\mu \mu_L$.

the muon field so that $\mu'_L = \mu_L$, and we have written $g_{bb} = g' q_{Q4} (s^Q_{34})^2$, $g_{bs} = g_{bb} (V'^{\dagger}_{dL})_{32}$, $g_{\mu\mu} = g' q_{L_4} (s^L_{24})^2$. We expect the quark mixing element $(V'^{\dagger}_{dL})_{32}$ to satisfy $|(V'^{\dagger}_{dL})_{32}| \lesssim |V_{ts}|$, where $|V_{ts}| \approx 0.04$ is the 3-2 entry of the CKM matrix, as otherwise unnatural cancellations would be required. It follows that $|g_{bs}| \lesssim |V_{ts} g_{bb}|$. We will assume for simplicity that $g_{bs} = V_{ts} g_{bb}$.

Having assumed for simplicity that $g_{bs} = V_{ts} g_{bb}$, and that g_{bb} and $g_{\mu\mu}$ have the same sign, then the relevant parameters are: $(g_{bb}, g_{\mu\mu})$ and $(M_{Z'})$. From the theory point of view these are three essentially free parameters which may be chosen to explain R_K and R_{K^*}. These three parameters are further constrained by flavour physics, multiple low-energy precision measurements and colliders as follows (with original references and more discussion in [19]).

3.1 R_K and R_{K^*}

As discussed in the Introduction, one possible explanation of the R_K and R_{K^*} measurements in LHCb is that the low-energy Lagrangian below the weak scale contains an additional contribution to the effective 4-fermion operator with left-handed muon, b-quark, and s-quark fields:

$$\Delta \mathscr{L}_{\text{eff}} \supset G_{bs\mu} (\bar{b}_L \gamma^\mu s_L)(\bar{\mu}_L \gamma_\mu \mu_L) + \text{h.c.}, \qquad G_{bs\mu} \approx \frac{1}{(31.5 \text{ TeV})^2}. \tag{3.8}$$

We can express the coefficient $G_{bs\mu}$ as function of the couplings in Eq. 3.7,

$$G_{bs\mu} = -\frac{g_{bs} g_{\mu\mu}}{M^2_{Z'}} = -\frac{V_{ts} g_{bb} g_{\mu\mu}}{M^2_{Z'}}. \tag{3.9}$$

Together, Eqs. (3.8) and (3.9) imply the constraint on the parameters g_{bb}, $g_{\mu\mu}$ and $M_{Z'}$:

$$\frac{g_{bb} g_{\mu\mu}}{M^2_{Z'}} \approx \frac{1}{(6.4 \text{ TeV})^2}. \tag{3.10}$$

3.2 $B_s - \bar{B}_s$ mixing

The Z' coupling to bs leads to an additional tree-level contribution to $B_s - \bar{B}_s$ mixing due to the effective operator arising from integrating out the Z' at tree level:

$$\Delta \mathscr{L}_{\text{eff}} \supset -\frac{G_{bs}}{2} (\bar{s}_L \gamma^\mu b_L)^2 + \text{h.c}, \qquad G_{bs} = \frac{g^2_{bs}}{M^2_{Z'}} = \frac{g^2_{bb} V^2_{ts}}{M^2_{Z'}}. \tag{3.11}$$

Such a new contribution is highly constrained by the measurements of the mass difference ΔM_s of neutral B_s mesons leading to a 2017 bound from updated lattice results of $(G_{bs})^{-1/2} \sim 500$ TeV as compared to the 2015 bound of $(G_{bs})^{-1/2} \sim 150$ TeV.

3.3 Neutrino trident

The production of a muon pair from the scattering of a muon-neutrino off the Coulomb field of a nucleus, known as neutrino trident production, is a rare process that has been observed in a few experiments. In our case the trident production $\nu_\mu N \to \nu_\mu \mu^+ \mu^- N$ is mediated by the Z' coupling to left-handed muons which leads to a new tree-level contribution to the effective 4-lepton interaction

$$\Delta \mathscr{L}_{\text{eff}} \supset -\frac{G_\mu}{2} (\bar{\ell}_L \gamma^\mu \ell_L)^2, \qquad G_\mu = \frac{g^2_{\mu\mu}}{M^2_{Z'}}. \tag{3.12}$$

Such an operator is bounded by $(G_\mu)^{-1/2} \sim 400$ GeV.

3.4 LHC searches

The LHC measurements of the SM gauge boson Z decaying to four muons, $Z \to 4\mu$, with the second muon pair produced in the SM via a virtual photon, sets relevant constraints in the low mass region of Z' models, $5 \lesssim M_{Z'} \lesssim 70$ GeV, where the virtual photon may be replaced by a Z' coupling to four muons. For heavier Z' masses, the subprocess $b\bar{b} \to Z' \to \mu^+\mu^-$ can be probed by dimuon resonance searches at the LHC, leading to further collider limits on the Z' mass and couplings. The strongest limits exist from ATLAS for Z' masses between about 150 GeV and 5 TeV.

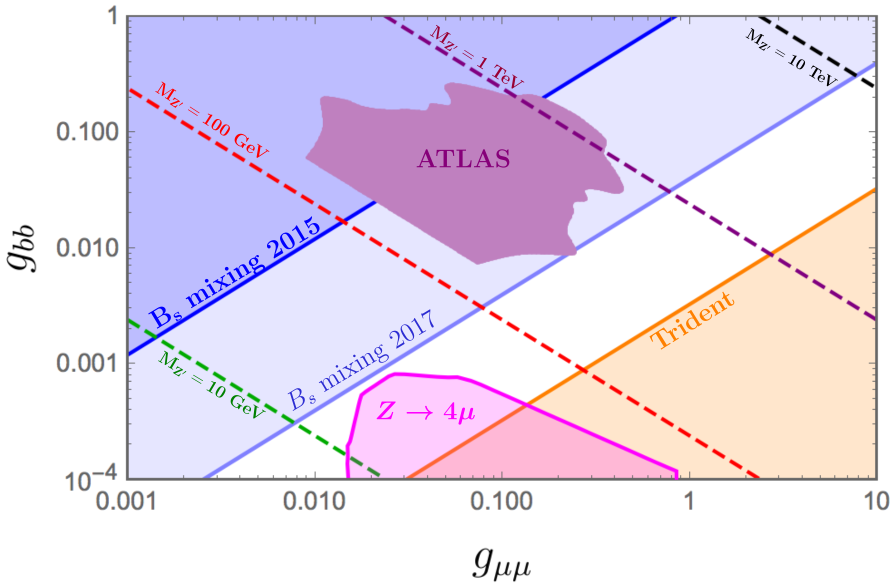

Figure 1: The parameter space in the $(g_{\mu\mu}, g_{bb})$ plane compatible with $R_{K^{(*)}}$ anomalies and flavour constraints (white). The Z' mass varies over the plane, with a unique Z' mass for each point in the plane as determined by Eq. 3.10. We show the recent B_s mixing constraints (light blue), and the trident bounds (orange); for reference we also display the previous weaker B_s mixing bounds (dark blue). The green, red, purple and black lines correspond to $M_{Z'} = 10, 100, 1000, 10000$ GeV respectively. Figure taken from [19].

3.5 Results and Summary

The allowed region of parameter space in the $(g_{\mu\mu}, g_{bb})$ plane compatible with $R_{K^{(*)}}$ anomalies and the above constraints is shown as the white regions in Fig. 1, taken from [19], where the original references from which the constraints are extracted are given. The main point is that there are allowed regions of parameter space which satisfy all constraints, for example in the region $M_{Z'} \sim 100 - 1000$ GeV with $g_{bb} \sim 0.001 - 0.01$ and $g_{\mu\mu} \sim 0.1 - 1$. If we recall that $g_{bb} = g' q_{Q4} (s^Q_{34})^2$ and $g_{\mu\mu} = g' q_{L_4} (s^L_{24})^2$, then assuming that gauge coupling and charges expected to be of order unity, such a region of parameter space would correspond to $(s^Q_{34})^2 \sim 0.001 - 0.01$ and $(s^L_{24})^2 \sim 0.1 - 1$. This implies $s^Q_{34} \sim 1/30 - 1/10$ and $s^L_{24} \sim 1/3 - 1$, where the latter corresponds to a rather large mixing angle $\theta^L_{24} \sim 20^\circ - 90^\circ$ as compared to the other mixing angles such as θ^L_{34} which is assumed to be much smaller.

Although the fermiophobic model can successfully account for R_K and R_{K^*}, clearly it raises new and interesting theoretical flavour puzzles such as why θ^L_{24} is larger than θ^L_{34}. On the experimental side, the challenge is to close the allowed parameter space of the model by improving limits by making better precision measurements of the trident $\nu_\mu N \to \mu^+\mu^-\nu_\mu N$ process, by improving the theoretical precision of the SM prediction for the B_s meson mass difference, as well as by improved LHC sensitivity to $b\bar{b} \to Z' \to \mu^+\mu^-$.

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