NON-UNIVERSAL $Z'$ MODELS WITH PROTECTED FLAVOUR-CHANGING INTERACTIONS

MARTIN JUNG
Excellence Cluster Universe, Technische Universität München,
Boltzmannstr. 2, D-85748 Garching, Germany

We define a new class of $Z'$ models with neutral flavour-changing interactions at tree level in the down-quark sector. They are related in an exact way to elements of the quark mixing matrix due to an underlying flavoured $U(1)'$ gauge symmetry, rendering these models particularly predictive. The same symmetry implies lepton-flavour non-universal couplings, fully determined by the gauge structure of the model. Our models allow to address several presently observed deviations from the SM and specific correlations among the new physics contributions to the Wilson coefficients $C_{9,10}'$ can be tested in $b \rightarrow s \ell^+ \ell^-$ transitions. We furthermore predict lepton-universality violations in $Z'$ decays, testable at the LHC.

1 Introduction

The continuing success of the Standard Model (SM) has strong implications for new physics (NP) scenarios, which are consequently required to involve a very high mass scale, a highly non-trivial flavour structure, or both. Two recent measurements by the LHCb collaboration involving semileptonic $b \rightarrow s \ell^+ \ell^-$ transitions show deviations with respect to the SM expectations: The ratio $R_K = \text{Br}(B \rightarrow K \mu^+ \mu^-)/\text{Br}(B \rightarrow K e^+ e^-)$ has been measured with a central value indicating a violation of lepton universality at the 25% level\textsuperscript{1}, implying a 2.6σ deviation, and the angular analysis of $B \rightarrow K^* \mu^+ \mu^-$ decays, where specifically the observable $P_5'$ differs from the SM expectation with 2.9σ significance\textsuperscript{2}. Taking these measurements at face value, they require the NP to have (i) sizable contributions to $b \rightarrow s \ell^+ \ell^-$ transitions, and (ii) lepton non-universal couplings.

Extensions of the SM gauge group by an additional $U(1)'$ factor are among the possible NP scenarios that could explain these deviations. Such $U(1)'$ models have been popular extensions of the SM for many years\textsuperscript{3}, but are in their majority family universal, and therefore do not meet condition (ii). Models with departures from family universality can give rise to large flavour-changing $Z'$ interactions, which are strongly constrained by current flavour data, as will be discussed below. The conditions (i) and (ii) therefore limit considerably the viable $U(1)'$ gauge symmetries.

In order to avoid exotic vector-like quarks, the $U(1)'$ symmetry has to involve both quarks and leptons, and should be family-dependent in order to satisfy conditions (i) and (ii). However, such a non-trivial flavour symmetry in the quark sector requires the extension of the scalar sector in order to accommodate the quark masses and mixing angles\textsuperscript{4,5}. It has been shown in Ref.\textsuperscript{6} that this option can be realized by including an additional complex scalar doublet, yielding however up-quark FCNC which are not controlled by CKM elements or quark masses.

We would like our model to have all of its fermion couplings related exactly to elements of the CKM matrix. To that aim, we note that there is a class of two-Higgs-doublet models...
(2HDM) that achieves this, known as Branco–Grimus–Lavoura (BGL) models. These models have flavour-diagonal interactions in the up-quark and charged-lepton sectors, together with flavour-changing neutral currents (FCNCs) in the down-quark sector. The latter are suppressed by quark masses and/or off-diagonal CKM elements in an exact way, thereby providing an alternative solution to the flavour problem in 2HDMs which differs radically from the hypothesis of natural flavour conservation.

While in the original BGL model the flavour symmetry is global, in this work we promote it to a local one. This is achieved by charging also the leptons under the symmetry, thereby enabling anomaly cancellation. In this gauged BGL framework ($U(1)^\prime_{\text{BGL}}$), the properties of the BGL models are transferred to the gauge boson sector: we obtain FCNCs mediated at tree-level by the neutral scalar and massive gauge vector bosons of the theory, all of which are suppressed by off-diagonal CKM elements and/or fermion masses, and therefore naturally suppressed. This class of models necessarily exhibits deviations from lepton universality due to its gauge structure.

2 Gauged BGL symmetry

The characteristic features of BGL models are a consequence of specific patterns of Yukawa couplings, generated by corresponding charge assignments under a horizontal, family-non-universal ($BGL^-$) symmetry. The quark Yukawa sector of the model reads ($i = 1, 2$) 

$$-\mathcal{L}_{\text{Yuk}}^{\text{quark}} = \sum_{i=1}^{3} \Gamma_i \Phi_i d_R^i + \overline{q_L^i} \Delta_i \Phi_i u_R^i + \text{h.c.},$$

where $\Gamma_i$ and $\Delta_i$ denote the Yukawa coupling matrices for the down- and up-quark sectors, respectively, and $\Phi_i \equiv i\sigma_2 \Phi_i^*$. The neutral components of the Higgs doublets acquire vacuum expectation values (vevs) $|\langle \Phi_i^0 \rangle| = v_i / \sqrt{2}$, with $\tan \beta = v_2 / v_1$ and $v \equiv (v_1^2 + v_2^2)^{1/2} \approx 246$ GeV.

Choosing an abelian symmetry under which a field $\psi$ transforms as $\psi \rightarrow e^{i\lambda \omega} \psi$, the most general quark-sector symmetry transformations yielding the required textures are of the form

$$\mathcal{A}^q = \frac{1}{2} [\text{diag} (X_{uR}, X_{uR}, X_{tR}) + X_{dR} \mathbb{1}], \quad \mathcal{A}^d = \text{diag} (X_{uR}, X_{uR}, X_{tR}), \quad X_{dR} = X_{dR} \mathbb{1},$$

with $X_{uR} \neq X_{tR}$. The Higgs doublets transform as $\mathcal{X}^\Phi = \frac{1}{2} \text{diag} (X_{uR} - X_{dR}, X_{tR} - X_{dR})$. There are several possible implementations of this symmetry, related by permutations in flavour space and exchanging up- and down-quark sectors; here, for definiteness, the top quark has been singled out, yielding the required patterns. These textures give rise to FCNCs in the down-quark sector, which are however suppressed by quark masses and off-diagonal elements of the third CKM row. This choice implies a particularly strong suppression of flavour-changing phenomena in light-quark systems. Present constraints from $\Delta F = 1$ and $\Delta F = 2$ quark flavour transitions are accommodated even when the scalars of the theory are light, with masses of $O(10^2)$ GeV.

When gauging a symmetry, special attention must be paid to whether it remains anomaly-free. BGL models are automatically free of QCD anomalies, i.e. $U(1)^{\prime} \left[ \text{SU}(3)_C \right]^2_{\text{SU(2)}_L, \text{U(1)}^\prime_{\text{U(1)}_Y}}$. However, the anomaly conditions for the following combinations need to be fulfilled as well: $U(1)^{\prime} \left[ \text{SU(2)}_L \right]^2_{\text{SU(2)}_L, \text{U(1)}^\prime_{\text{U(1)}_Y}}$. We find that there is no solution for this system within the quark sector alone with the charge assignments in Eq. (1). Satisfying these anomaly conditions is highly non-trivial and requires, in general, additional fermions. However, the implementation of the BGL symmetry as a local symmetry is possible by adding only the SM leptonic sector when allowing for lepton-flavour non-universal couplings. Gauging the BGL symmetry exhibits the following features, beyond removing the unwanted Goldstone boson, which is “eaten” by the $Z'$: (i) A massive $Z'$ with the SM fermion content, i.e. no vector-like quarks are necessary. (ii) Flavour-diagonal $Z'$ couplings in the up-quark and charged-lepton sector, FCNC’s in the down-quark sector, strongly suppressed by CKM matrix elements. (iii) The gauge structure yields lepton-universality violation without the introduction of lepton-flavour violation, thereby providing an explicit counter-example to the general arguments given in Refs. (iv) All flavour couplings but one are fixed due to the gauge symmetry when
including the anomaly conditions. The remaining one is fixed here via the condition $X_{\phi_2} = 0$ for definiteness. The only remaining freedom lies in discrete lepton-flavour permutations of the U(1)$'$ charges, yielding six model implementations with identical quark and scalar charges. In order to present the predictions for each of these models, we introduce generic lepton charges $X_{iL,R}$, such that each implementation is labeled by $(e, \mu, \tau) = (i, j, k)$. For numerical values and additional possibilities to implement the quark and neutrino sectors, see Ref. 10.

### 3 Phenomenology

The phenomenology of a scalar sector with a flavour structure identical to the one of our model has been analyzed in Ref. 11. Since we are assuming a decoupling scalar sector, we can naturally accommodate a SM-like Higgs at 125 GeV; the heavy scalars are not expected to yield sizable contributions to flavour observables in general. A potential exception are $B_{d,s} \rightarrow \mu^+\mu^-$ decays, as discussed in Ref. 10. We focus here on the phenomenological implications of the $Z'$ boson for this class of models.

Despite the large mass of several TeV, the $Z'$ boson yields potentially significant contributions to flavour observables, due to its flavour-violating couplings in the down-type quark sector. However, because of $M_{Z'}/M_Z^2 \lesssim 0.1\%$ and the CKM suppression of the flavour-changing $Z'$ couplings, these contributions can only be relevant when the corresponding SM amplitude has a strong suppression in addition to $G_F$. This is specifically the case for meson mixing amplitudes and electroweak penguin processes which we will discuss below. Further examples are differences of observables that are small in the SM, for example due to lepton universality or isospin symmetry. On the other hand, we observe that the global CKM fit remains essentially valid in our models 10. The particular flavour structure of the model implies a strong hierarchy for the size of different flavour transitions, similar to the situation in the SM.

Given the high experimental precision of $\Delta m_\mu$, the strength of the corresponding constraint depends completely on our capability to predict the SM value. Using the recently obtained values from Ref. 17 for the hadronic matrix elements, the obtained limit strengths to $M_{Z'}/g' \gtrsim 25$ TeV (95% CL) compared to Ref. 10, see also Fig. 1. In our models this bound is stronger than the ones from neutrino trident production and atomic parity violation 10; the fact that these constraints are directly comparable stems from the high predictivity of our model. Further potentially strong bounds stem from electric dipole moments (EDMs) and the anomalous magnetic moment of the muon. Both can be shown to receive small effects in our models 18,19,11,10.

The obvious way to search directly for a $Z'$ is via a resonance peak in the invariant-mass distribution of its decay products. At the LHC this experimental analysis is usually performed by the ATLAS 20 and CMS 21 collaborations for $Z'$ production in the s-channel in a rather model-independent way, but assuming validity of the narrow-width approximation (NWA), negligible contributions of interference with the SM 22, and flavour-universal $Z'$ couplings to quarks. While the assumptions for these expressions are not exactly fulfilled in our model, they are applicable when neglecting the small contributions proportional to the off-diagonal CKM matrix elements and taking into account that large couplings are typically excluded by flavour constraints 10.

Using these bounds together with the constraint from $R_K$, we find that a $Z'$ boson is excluded in our models for $M_{Z'} \lesssim 3-4$ TeV, depending on the lepton charge assignments, while $g'$ should be $O(10^{-1})$.

An important feature of our models are sizable contributions to $C_{NP}^{NP} \sim (g'/M_{Z'})^2$. The relative size of all these contributions is again fixed by the gauge symmetry. The neutral-current semileptonic $b \rightarrow s\ell^+\ell^-$ transitions allow for testing these coefficients in global fits. Furthermore, they provide precise tests of lepton universality when considering ratios of the type $R_M \equiv \frac{B(B \rightarrow M\mu^+\mu^-)}{B(B \rightarrow M\ell^+\ell^-)} \equiv 1 + \mathcal{O}(m_\mu^2/m_\tau^2)$, with $M \in \{K, K^*, X_{s}, K_0(1430), \ldots\}$ 23, where many

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*The same holds for $\Delta m_d, \epsilon_K$, which yield similar bounds.*
Table 1: Model-dependent bound on $C_9^{\text{NP}}$ from the $R_K$ measurement. The constraint from $B_s$ mixing is taken into account.

| Model   | $C_9^{\text{NP}}(1\sigma)$   | $C_9^{\text{NP}}(2\sigma)$   |
|---------|-------------------------------|-------------------------------|
| (1,2,3) | $-1.20, -0.61$                | $-1.20, -0.61$                |
| (3,1,2) | $-0.63, -0.43$                | $-0.63, -0.17$                |
| (3,2,1) | $-1.20, -0.53$                | $-1.20, -0.20$                |

Figure 1 – Model-dependent predictions for $R_K$ as a function of $g'/M_{Z'}$. The recent measurement of $R_K$ by the LHCb collaboration is shown at $1\sigma$ and $2\sigma$. Constraints from $B_s$ mixing are also shown at 95% CL.

If a $Z'$ boson is discovered during the next runs of the LHC, ratios of its decays to different leptons can be used to discriminate the models presented here.

Attributing the measurement of $R_K$ solely to NP already excludes some of our models, since it requires sizable non-universal contributions with a specific sign. The flavour structure in each of our models is fixed, so half of them cannot accommodate $R_K < 1$. This is illustrated in Fig. 1, where it is additionally seen that a large deviation from $R_K = 1$, as indicated by the present central value and $1\sigma$ interval, can actually only be explained in two of the remaining models. This strong impact shows the importance of further measurements of $R_M$ ratios.

In Fig. 2 we show the constraints from the $R_K$ measurement for the remaining models. The allowed regions are consistent with the constraint from $B_s^0$-meson mixing. LHC searches for a $Z'$ boson exclude values of $M_{Z'}$ below 3-4 TeV, as discussed above; the corresponding areas are shown in gray. We also show the theoretical perturbativity bounds obtained from the requirement that the Landau pole for the U(1)$'$ gauge coupling appears beyond the seesaw or the Grand Unification scales, i.e. $\Lambda_{\text{LP}} > 10^{14}$ GeV and $\Lambda_{\text{LP}} > 10^{16}$ GeV, respectively.

Regarding the angular analysis in $B \rightarrow K^*\mu^+\mu^-$, we find that when translating the $R_K$ measurement into a bound on $C_9^{\text{NP}}$ in our models, see Table 1, the ranges are perfectly compatible with the values obtained from $P_5'$, as also observed for other $Z'$ models. This is highly non-trivial given the strong correlations in our models and will allow for decisive tests with additional data.

4 Conclusions

The class of family-non-universal $Z'$ models presented in this article exhibits FCNCs at tree level that are in accordance with available flavour constraints while still inducing potentially sizable effects in various processes, testable at existing and future colliders. This is achieved by gauging the specific (BGL)-symmetry structure, introduced in Ref. for the first time, which renders the
resulting models highly predictive. Additional phenomenological features are (i) non-universal lepton couplings determined by the charges under the additional $U(1)'$ symmetry, (ii) absence of FCNCs in the charged-lepton or up-quark sectors, and (iii) complete determination of the $U(1)'$ sector up to two real parameters, $M_{Z'}$ and $g'$, where all observables at the electroweak scale and below depend only on the combination $g'/M_{Z'}$.

Present data already strongly restrict the possible parameter ranges in our models: direct searches exclude $Z'$ masses below $3 - 4$ TeV and the constraint from $B$ mixing implies $M_{Z'}/g' \geq 25$ TeV (95% CL). Three of our models can explain the deviations from SM expectations in $\nu \rightarrow \nu$ transitions seen in LHCb measurements$^{2,1}$, while the other three are excluded (at 95% CL) by $R_K < 1$. These findings are illustrated in Figs. 1 and 2.

We predict in our models $R_M = 1$, as well as universal ratios $R^\nu_M$ in $B \rightarrow M\bar{\nu}\nu$ decays, as well as specific ratios for potential measurements of $\sigma(pp \rightarrow Z' \rightarrow \bar{\ell}_i \ell_i)/\sigma(pp \rightarrow Z' \rightarrow \bar{\ell}_j \ell_j)$ at the LHC. In the near future we will therefore be able to differentiate our new class of models from other $Z'$ models as well as its different realizations from each other. This will be possible due to a combination of direct searches/measurements at the LHC and high-precision measurements at low energies, e.g. from Belle II and LHCb. Further progress can come directly from theory, e.g. by more precise predictions for $\Delta m_{d,s}$ or $\epsilon_K$.

Acknowledgments

I would like to thank the organizers for a fruitful workshop, and Alejandro Celis, Javier Fuentes-Martín as well as Hugo Serêdio for an enjoyable collaboration. This research was supported by the DFG cluster of excellence “Origin and Structure of the Universe”.

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