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Flavour hierarchies and B-anomalies in a twin Pati-Salam theory of flavour

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In this proceedings, based on arXiv:2209.00276, I present a model which can simultaneously explain and connect the flavour hierarchies of the Standard Model with flavour anomalies in B-physics. I will briefly introduce the model and highlight the main features, including a common origin of Yukawa couplings and vector leptoquark U_1 couplings to Standard Model fermions. A GIM-like mechanism allows for large leptoquark couplings which can explain the B-anomalies, while protecting from the most dangerous FCNCs that could be mediated by a heavy coloron and Z'. Finally, I will highlight some of the most promising signals at low energy processes which can test the model in the upcoming future. The analysis has been updated with the late 2022 measurements of $R_{K^{(*)}}$ by LHCb.

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1. Introduction

Fundamental fermions in the Standard Model (SM) come in three copies, denoted as "flavours", which share universal gauge interactions but have different masses and mixings, also known as flavour parameters. The origin of flavour in the SM remains as a complete mystery, as it lacks of any dynamical explanation to the high number of flavour parameters and their hierarchical patterns. A further theory of flavour beyond the SM should provide a solution to the long-lasting "flavour puzzle".

Simultaneously, the non-universal structure of such a theory of flavour could leave its imprints in flavour physics observables, which are becoming accessible up to a high precision level in the current generation of colliders and meson factories. In this direction, a conspicuous series of anomalies in flavour observables emerged in the last years. Of particular interest were the anomalies in B-meson decays, namely the $R_{K^{(*)}}$ [1, 2] and $R_{D^{(*)}}$ [3] ratios hinting for the breaking of the SM lepton flavour universality (LFU), a feature which might well be a low energy signal of the theory addressing the origin of flavour hierarchies. The origin of flavour was connected to the B-anomalies in models featuring Z' bosons [4, 5] or scalar leptoquarks [6].

Interestingly, the vector leptoquark $U_1(\mathbf{3}, \mathbf{1}, 2/3)$ was the only leptoquark capable of addressing both "B-anomalies" simultaneously [7]. Moreover, hierarchical couplings of U_1 to SM fermions were required to simultaneously address both anomalies, which might well be related to the flavour hierarchies of the SM in the UV theory. The model presented here was built to address this 2021 picture of B-anomalies via U_1 exchange, and connect their origin to the origin of Yukawa couplings in the SM. However, in late 2022 the LHCb collaboration updated their measurements of $R_{K^{(*)}}$ [8], which are now in good agreement with the SM predictions. We consider these new measurements in this analysis, and show that the model is still compatible with the new data.

The massive U_1 leptoquark is well known to arise from spontaneous breaking of the traditional Pati-Salam gauge group (PS). However, this breaking happening at the TeV scale is at odds with current bounds from $K_L \to \mu e$ and other processes, unless further model building is performed. In this direction, a 4321 gauge symmetry,

$$G_{4321} \equiv SU(4) \times SU(3)_c^{'} \times SU(2)_L \times U(1)_{Y'}\,, \tag{1}$$

was proposed as a possible origin of U_1 at the TeV scale [9–12]. UV completions of the 4321 group had been proposed in recent years to connect the flavour hierarchies of the SM with the B-anomalies via U_1 [13, 14], however all of them consider that the third family of fermions transforms under the TeV scale $SU(4)$ (the others are singlets), which leads to strong constraints via high-p_T production of heavy gauge bosons arising after 4321 breaking [15, 16].

Instead, we proposed a twin Pati-Salam theory of flavour [17, 18] which features a TeV scale 4321 group under which all SM fermions are treated in the same way, they are singlets under the TeV scale $SU(4)$. Three families of vector-like fermions are charged under $SU(4)$ and couple to U_1, generating effective couplings to SM fermions via mixing. Simultaneously, the choice of the scalar sector and the twin PS symmetry forbid SM-like Yukawa couplings, which are generated via the same mixing that led to the leptoquark couplings. This provides a link between B-physics and the theory of flavour. In this manuscript, we will briefly introduce the model and summarise the main phenomenological consequences.

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Field	$SU(4)^{I}_{PS}$	$SU(2)^{I}_{L}$	$SU(2)^{I}_{R}$	$SU(4)^{II}_{PS}$	$SU(2)^{II}_{L}$	$SU(2)^{II}_{R}$	Z_4
$\psi_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	α, 1, 1
$\psi^c_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	α, α^2, 1
$\psi_{4,5,6}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	1, 1, α
$\overline{\psi}_{4,5,6}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	1, 1, α^3
$\psi^c_{4,5,6}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	1, 1, α
$\overline{\psi^c}_{4,5,6}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	1, 1, α^3
ϕ	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	1
$\overline{\phi}, \overline{\phi'}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	1, α^2
H	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	1
$\overline{H}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	1
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	1

Table 1: The field content under $G^{I}_{422} \times G^{II}_{422} \times Z_4$. The model consists of three left-handed chiral fermion families $\psi_{1,2,3}$, $\psi^c_{1,2,3}$ under the second PS group, plus three VL fermion families $\psi_{4,5,6}$, $\psi^c_{4,5,6}$ and their conjugates under the first PS group. Personal Higgs doublets are contained in H, $\bar{H}$, one for each second and third family charged fermion. The Higgs singlets in ϕ, $\bar{\phi}$ are called Yukons. In addition to the fields shown here, we require further high energy Higgs fields (not shown) whose VEVs will break the second PS group at a high scale, leaving the first unbroken (see [17, 18]). We also need further Higgs fields, which break the two left-right gauge groups into their diagonal subgroup.

2. The model

The theory is based on two copies of the traditional PS group,

$$G_{422} = SU(4) \times SU(2)_L \times SU(2)_R\,, \tag{2}$$

plus a shaping discrete symmetry Z_4, i.e.

$$G^{I}_{422} \times G^{II}_{422} \times Z_4\,. \tag{3}$$

The content of the model is depicted in Table 1. We assume that three chiral fermion families transform under the second PS group, G^{II}_{422}, which is broken at a high scale $M_{\mathrm{High}} \gtrsim 1$ PeV down to G_{4321}, the latter bound imposed by $K_L \to \mu e$. On the other hand, three vector-like (VL) fermion families transform under the first PS group, G^{I}_{422}, in such a way that they couple to the TeV scale leptoquark U_1 arising after the breaking of G_{4321} down to the SM. They further couple to a TeV scale coloron $g'(\mathbf{8},\mathbf{1},0)$ and $Z'(\mathbf{1},\mathbf{1},0)$ that also arise after the breaking of G_{4321}. The renormalizable mass Lagrangian is given by

$$\begin{aligned}\mathcal{L}^{ren}_{\mathrm{mass}} = {} & y^{\psi}_{ia}\overline{H}\psi_i\psi^c_a + y^{\psi}_{a3}H\psi_a\psi^c_3 + x^{\psi}_{ia}\phi\psi_i\overline{\psi}_a + x^{\psi^c}_{a2}\overline{\psi^c_a\phi'}\psi^c_2 + x^{\psi^c}_{a3}\overline{\psi^c_a\phi}\psi^c_3 + x^{\psi}_{16}\phi\psi_1\overline{\psi}_6 + x^{\psi^c}_{61}\overline{\psi^c_6\phi}\psi^c_1 \\ & + M^{\psi}_{ab}\psi_a\overline{\psi_b} + M^{\psi^c}_{ab}\psi^c_a\overline{\psi^c_b} + M^{\psi}_{66}\psi_6\overline{\psi_6} + M^{\psi^c}_{66}\psi^c_6\overline{\psi^c_6} \\ & + \lambda^{aa}_{15}\Omega_{15}\psi_a\overline{\psi_a} + \lambda^{66}_{15}\Omega_{15}\psi_6\overline{\psi_6} + \bar{\lambda}^{aa}_{15}\Omega_{15}\psi^c_a\overline{\psi^c_a} + \bar{\lambda}^{66}_{15}\Omega_{15}\psi^c_6\overline{\psi^c_6} + \mathrm{h.c.}\,,\end{aligned} \tag{4}$$

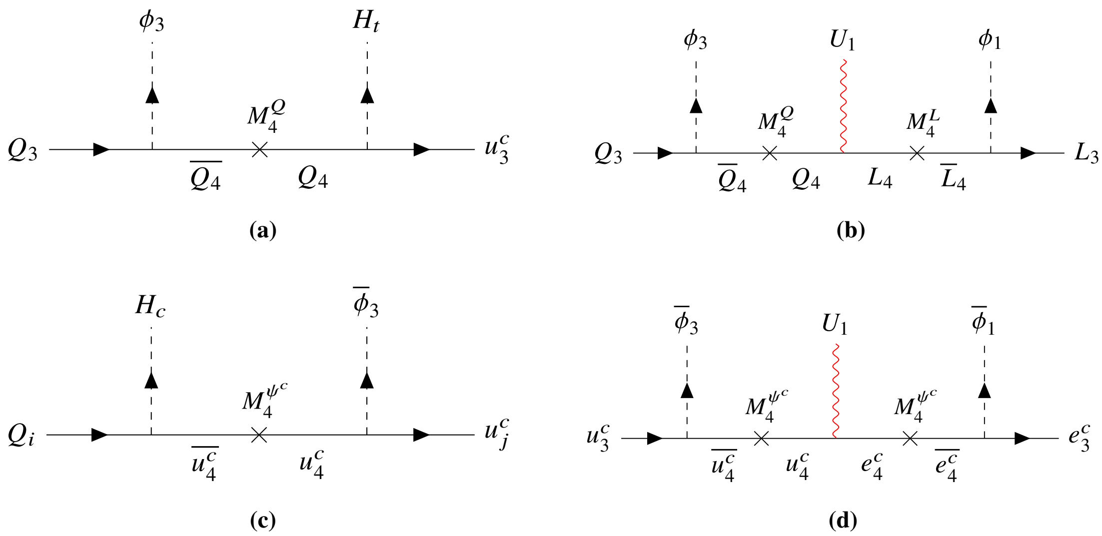


Figure 1: ***(Top)*** The diagram on the left leads to the mass of the top quark, and similar diagrams can be written for all third family charged fermions. The diagram on the right leads to effective couplings of the third family left-handed fermions to the U_1 vector leptoquark. ***(Bottom)*** The diagram on the left leads to the mass of second family charged fermions, $i, j = 2, 3$, and their mixing with the third family. The diagram on the right leads to effective couplings of the third family right-handed fermions to the U_1 vector leptoquark, which are suppressed as they are connected to the origin of second family fermion masses.

where $i, j = 2, 3$ and $a, b = 4, 5$. It can be seen that due to the choice of the scalar sector and the twin PS symmetry, SM-like Yukawa couplings are not present. The Lagrangian above can be written as a mass matrix, and its diagonalisation will lead to effective Yukawa couplings for SM fermions.

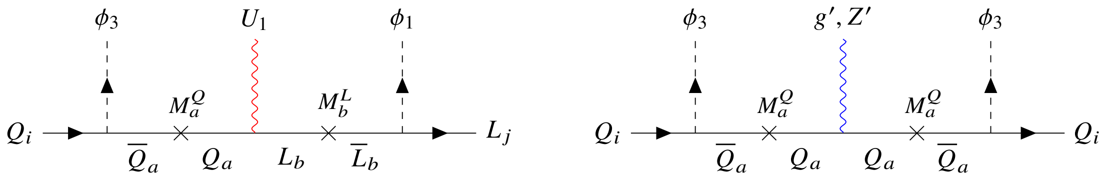
We shall refer to the Higgs doublets contained in $H, \bar{H}$ as personal Higgs doublets, since under the SM decomposition there will be a separate Higgs for each fermion mass as we shall see shortly. The Higgs singlet fields in ϕ , $\bar{\phi}$ are called Yukons, since they are necessary to generate the effective Yukawa couplings. They develop different VEVs in their quark and lepton components (ϕ_3 and ϕ_1), breaking G_{4321} at the TeV scale down to the SM.

2.1 Effective Yukawa couplings and leptoquark couplings

The diagonalisation of the full mass matrix leads to mixing between VL and chiral fermions. Each VL family mixes with one chiral family, with mixing angles given by

$$s_{34}^{Q,L} = \frac{x_{34}^{\psi} \langle \phi_{3,1} \rangle}{\sqrt{\left(x_{34}^{\psi} \langle \phi_{3,1} \rangle\right)^2 + \left(M_4^{Q,L}\right)^2}} \,, \quad s_{25}^{Q,L} = \frac{x_{25}^{\psi} \langle \phi_{3,1} \rangle}{\sqrt{\left(x_{25}^{\psi} \langle \phi_{3,1} \rangle\right)^2 + \left(M_5^{Q,L}\right)^2}} \,, \quad s_{16}^{Q,L} = \frac{x_{16}^{\psi} \langle \phi_{3,1} \rangle}{\sqrt{\left(x_{16}^{\psi} \langle \phi_{3,1} \rangle\right)^2 + \left(M_6^{Q,L}\right)^2}} \,, \tag{5}$$

which further lead to effective Yukawa couplings and U_1 couplings for SM fermions, as depicted in the diagrams of Fig. 1. It can be seen that both the Yukawa couplings and U_1 couplings originate via the same physics, and are connected via the same mixing angles.



(a) **(b)**

Figure 2: ***(Left)*** Flavour off-diagonal effective couplings of the U_1 vector leptoquark to SM fermions. ***(Right)*** Flavour diagonal effective couplings of the heavy coloron and Z' to SM quarks. Similar diagrams are obtained for leptons with the Z' boson.

The large top mass requires $\langle \phi_3 \rangle / M_4^Q \sim 1$, hence the 3-4 mixing angle is expected to be very large. This is in good agreement with the expectation of $R_{D^{(*)}}$, which requires large couplings of U_1 to third family fermions, featuring a nice connection between the flavour puzzle and B-anomalies only present in our model. Moreover, the origin of second family masses requires heavy masses for EW singlets VL fermions, leading to the hierarchy of VL masses,

$$M_a^{\psi} \ll M_a^{\psi^c} \tag{6}$$

for $a = 4, 5, 6$. This way, leptoquark currents involving right-handed (EW singlets ψ^c) chiral fermions are suppressed by small mixing angles, connected to the origin of second family fermion masses, leading to a model which dominantly predicts left-handed leptoquark currents as preferred by the global fits of B-anomalies (see e.g. [7, 19, 20]). This way, we obtain another nice connection between the flavour puzzle and B-anomalies, see the bottom diagrams in Fig. 1.

2.2 GIM-like mechanism and FCNCs

The explanation of $R_{D^{(*)}}$ requires large flavour-violating U_1 couplings that compete with the tree-level SM charged current. Obtaining such large couplings while suppressing possible FCNCs mediated by the Z' and g' is a challenge for 4321 models, which is usually addressed via adopting an ad-hoc flavour structure, calling for an understanding in terms of a UV theory which the twin PS model can provide.

The scalar Ω_{15} transforming in the adjoint of $SU(4)^I$ splits the bare masses of VL quarks and leptons $M_{aa}^{Q,L}$, which otherwise would be identical due to the twin PS symmetry. The mass matrix of VL fermions is diagonalised via different transformations for quark and leptons, leading to large flavour-violating U_1 couplings,

$$\left.\begin{matrix} \begin{pmatrix} M_4^Q & 0 & 0 \\ 0 & M_5^Q & 0 \\ 0 & 0 & M_6^Q \end{pmatrix} = V_{45}^Q \begin{pmatrix} M_{44}^Q & M_{45}^{\psi} & 0 \\ M_{54}^{\psi} & M_{55}^Q & 0 \\ 0 & 0 & M_{66}^Q \end{pmatrix} V_{45}^{\bar{Q}\dagger} \\ \begin{pmatrix} M_4^L & 0 & 0 \\ 0 & M_5^L & 0 \\ 0 & 0 & M_6^L \end{pmatrix} = V_{45}^L \begin{pmatrix} M_{44}^L & M_{45}^{\psi} & 0 \\ M_{54}^{\psi} & M_{55}^L & 0 \\ 0 & 0 & M_{66}^L \end{pmatrix} V_{45}^{\bar{L}\dagger} \end{matrix}\right\} \Rightarrow \frac{g_4}{\sqrt{2}} Q_a^{\dagger} \gamma_\mu \begin{pmatrix} c_{\theta_{LQ}} & -s_{\theta_{LQ}} & 0 \\ s_{\theta_{LQ}} & c_{\theta_{LQ}} & 0 \\ 0 & 0 & 1 \end{pmatrix} L_b U_1^{\mu} + \text{h.c.} \tag{7}$$

where the zeroes are enforced by the Z_4 symmetry. This way, we obtain a CKM-like matrix $W_{LQ} \equiv V_{45}^Q V_{45}^{L\dagger}$ in $SU(4)^I$ flavour space. Remarkably, this way we obtain large flavour-violating

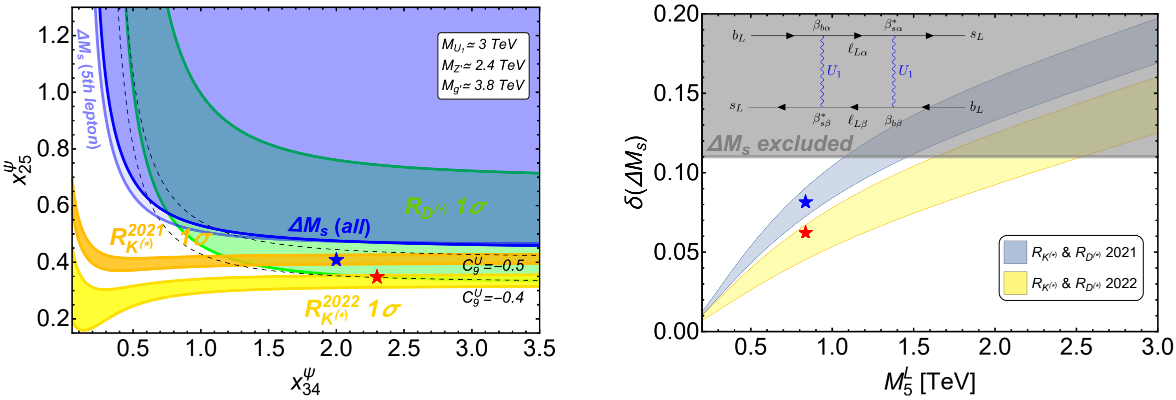


Figure 3: ***(Left)*** Parameter space in the plane $(x^\psi_{34}, x^\psi_{25})$ compatible with the LFU ratios. The rest of parameters are fixed as in the benchmark of [18] for both panels. The blue region is excluded by the ΔM_s bound, the region excluded only due to the contribution via the 5th lepton is also shown in lighter blue for comparison. The blue and red stars show benchmark points for 2021 and 2022 data. ***(Right)*** $\delta(\Delta M_s) = \Delta M_s^{\rm NP}/\Delta M_s^{\rm SM}$ as a function of the 5th family lepton vector-like mass term. x^ψ_{25} is varied in the range $x^\psi_{25} = [0.3, 0.35]$ ($[0.4, 0.45]$) preferred by $R^{2022}_{K^{(*)}}$ ($R^{2021}_{K^{(*)}}$), obtaining the yellow (blue) band. The gray region is excluded by the bound $\delta(\Delta M_s) < 0.11$ [18]. The stars denote benchmark points.

leptoquark currents in VL quark-lepton flavour space, while neutral currents mediated by g' and Z' remain flavour universal. Afterwards, 3-4, 2-5 and 1-6 mixing is performed (see Eq. (5)), inducing the required structure of U_1 couplings that contribute to LFU ratios. On the other hand, neutral currents become flavour diagonal, controlled by the mixing angles $s^{Q,L}_{34}$, $s^{Q,L}_{25}$ and $s^{Q,L}_{16}$, see Fig. 2.

- If $s^{Q,L}_{25} \approx s^{Q,L}_{16}$ then there is no 1-2 tree-level FCNCs, featuring a GIM-like mechanism which allows for large flavour-violating leptoquark couplings to explain the anomalies but protects from the most dangerous FCNCs. A down-aligned flavour structure is achieved in the 2-3 sector (see [18]), protecting from tree-level contributions to $B_s - \bar{B}_s$ meson mixing.
- $s^Q_{34} \approx 1$ is motivated by the top mass and $R_{D^{(*)}}$, as anticipated before. $s^Q_{16} \approx 0.2$ is compatible with bounds from coloron production at LHC.
- We choose a suitable benchmark $\langle \phi_{3,1} \rangle \approx 0.6\,$TeV, $0.3\,$TeV and $M^{Q,L}_{44} < M^{Q,L}_{55}, M^{Q,L}_{66} \approx 1.2\,\text{TeV} - 0.8\,\text{TeV}$ and we explore the parameter space of x^ψ_{34} and x^ψ_{25} (see [18] for further details about the benchmark).

3. Phenomenology

Fig. 3a shows that the model is compatible with both LFU ratios at 1σ, although the good parameter space is narrow with 2022 data on $R_{K^{(*)}}$. A large contribution to $B_s - \bar{B}_s$ meson mixing, namely to ΔM_s, arises at 1-loop mediated by U_1 and constrains part of the parameter space. This loop is dominated by the 5th VL charged lepton, which is required to be light in order to pass the stringent test of ΔM_s, see Fig. 3b. This way, a light vector-like lepton is predicted with a mass around 1 TeV, accessible to direct searches at LHC.

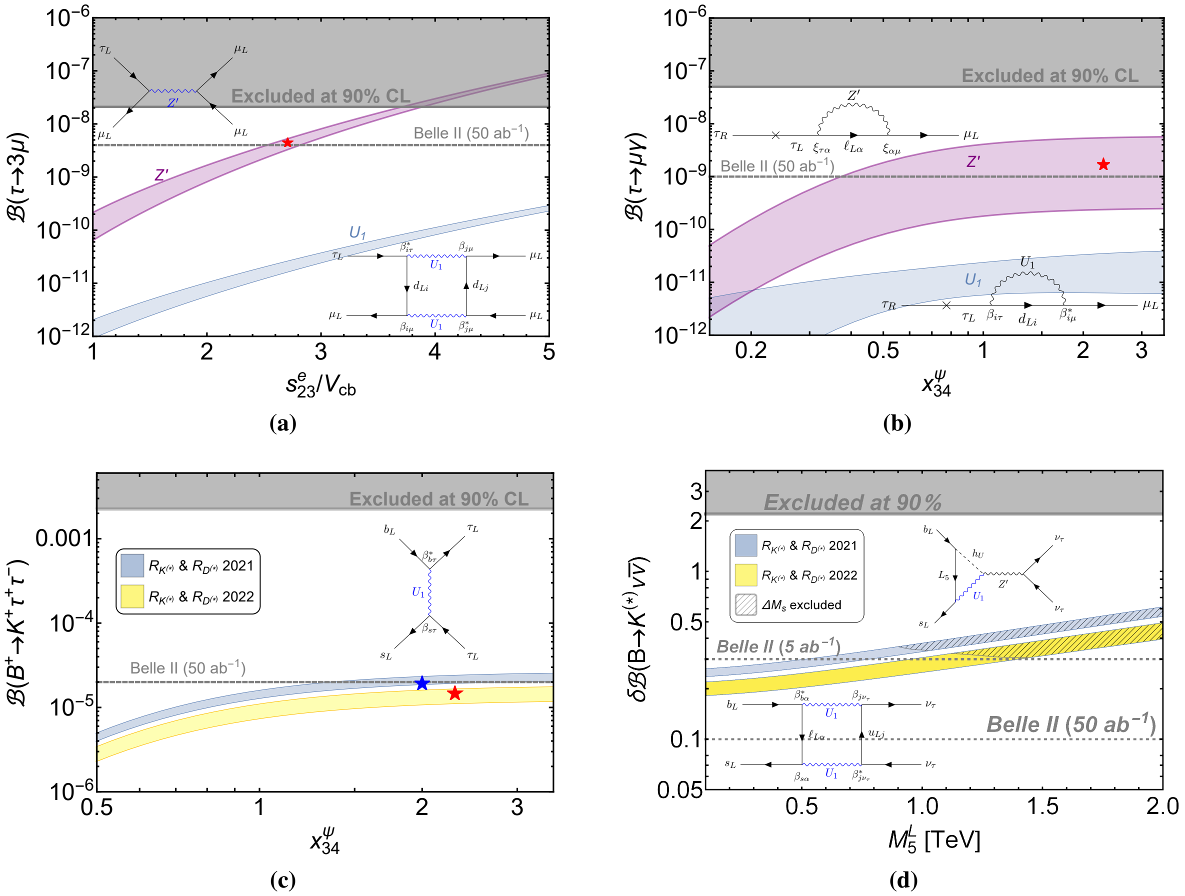


Figure 4: ***(Top)*** Branching fractions of LFV τ decays as a function of the 2-3 charged lepton mixing sine s^e_{23} (for $\tau\to3\mu$) and x^ψ_{34} (for $\tau\to\mu\gamma$). The purple region denotes the Z' contribution while the blue region denotes the U_1 contribution. For $\tau\to3\mu$ we have varied $x^\psi_{25}=[0.3,0.35]$ which is compatible with the 2022 LFU ratios, for $\tau\to\mu\gamma$ we have varied $s^e_{23}=[V_{cb},5V_{cb}]$. ***(Bottom)*** On the left panel, the branching fraction of $B\to K\tau\tau$ as a function of x^ψ_{34}. On the right, $\delta(B\to K\nu\nu)=\mathcal{B}(B\to K\nu\nu)/\mathcal{B}(B\to K\nu\nu)_{\text{SM}}-1$ as a function of the 5th family lepton vector-like mass term. In both panels, x^ψ_{25} is varied in the range $x^\psi_{25}=[0.3,\,0.35]$ ($[0.4,\,0.45]$) preferred by $R^{2022}_{K^{(*)}}$ ($R^{2021}_{K^{(*)}}$), obtaining the yellow (blue) band. The hatched region is excluded by the ΔM_s bound, and the stars denote benchmark points.

Signals in τ LFV decays, as per Figs. 4a and 4b, are directly related to the nature of the model as a theory of flavour. The model allows for large leptonic 2-3 FCNCs mediated by the Z' boson, and proportional to $\tau-\mu$ mixing arising through a diagram similar to that of Fig. 1c but for charged leptons. This Z' contribution is intrinsic to the twin PS model, and dominates over a further 1-loop contribution mediated by U_1 which is common to all 4321 models, hence allowing to disentangle the twin PS theory from other proposals. A wide range of the parameter space will be tested in the future by Belle II.

On the other hand, the model predicts large contributions to $b\to s\tau\tau$ and $b\to s\nu_\tau\nu_\tau$ connected to the explanation of $R_{D^{(*)}}$, as depicted in Figs. 4c and 4d . In particular, the full parameter space of the model will be tested by Belle II via $B\to K^{(*)}\nu\nu$.

4. Conclusions

We have presented a model where the flavour hierarchies are related to flavour anomalies in B-physics. The model features two Pati-Salam gauge groups broken at different scales, leading to a TeV scale 4321 gauge group. SM-like fermions are all singlets under the TeV scale $SU(4)$, and hence originally do not couple to the U_1 vector leptoquark arising after the breaking of the 4321 symmetry. SM-like Yukawa couplings are forbidden due to the choice of the scalar sector along with the twin PS symmetry. Both the effective Yukawa couplings and the U_1 couplings for SM fermions arise through mixing with vector-like fermions transforming under the TeV scale $SU(4)$. This way, flavour hierarchies and contributions to LFU ratios via U_1 find a common origin, and are connected via the same physics.

The model predicts a rich phenomenology at low energies, and will be tested by Belle II via signals in LFV τ decays and $B \to K^{(*)}\nu\nu$. A plethora of new states are predicted at the TeV scale, which could be directly detected at the LHC, including the heavy U_1, coloron and Z'. Remarkably, a vector-like lepton is preferred to be around 1 TeV to pass the stringent bounds of $B_s - \bar{B}_s$ meson mixing. The model is still compatible with 2022 data on $R_{K^{(*)}}$, although the window to explain $R_{D^{(*)}}$ at 1σ is now very narrow.

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