Combined Explanation of the $Z \to b\bar{b}$ Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ Data

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In this article we propose a simple model which can provide a combined explanation of the $Z \to b\bar{b}$ forward-backward asymmetry, the Cabibbo Angle Anomaly (CAA), $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ data. This model is obtained by extending the Standard Model (SM) by two heavy vector-like quarks (an $SU(2)_L$ doublet (singlet) with hypercharge $-5/6$ (-1/3)), two new scalars (a neutral and a singly charged one) and a gauged $L_u - L_e$ symmetry. The mixing of the new quarks with the SM ones, after electroweak symmetry breaking, does not only explain $Z \to b\bar{b}$ data but also generates a lepton flavour universal contribution to $b \to s\ell^+\ell^-$ transitions. Together with the lepton flavour universality violating effect, generated by loop-induced $Z$ penguins involving the charged scalar and the heavy quarks, it gives an excellent fit to data ($6.1 \sigma$ better than the SM). Furthermore, the charged scalar (neutral vector) gives a necessarily constructive tree-level (loop) effect in $\tau$ decay which are very interesting, even though they are statistically less significant: i) $R(D^{(*)})$ [85–90] points towards $\tau - \mu$ LFU violation with a significance of $>3\sigma$ [91–95] ii) the anomalous magnetic moment of the muon $a_\mu$ [96] prefers NP coupling to mnuons by $3.7 \sigma$ [97] iii) $Br[\tau \to \mu\nu\nu]/Br[\tau \to e\nu\nu]$ and $Br[\tau \to \mu\nu\nu]/Br[\mu \to e\nu\nu]$ are indications for LUF violation with a significance of $\approx 2\sigma$ iv) the deficit in 1st row CKM unitarity, known as the Cabibbo Angle Anomaly (CAA), is at the $\approx 2 - 4\sigma$ level [98–100] and can possibly be interpreted as a sign of LUF violation [101–106].

Interestingly, it has been shown that NP models can provide combined explanations of these anomalies together with the $b \to s\ell^+\ell^-$ data. For example, common solutions of the $b \to s\ell^+\ell^-$ anomalies together with $a_\mu$ [107–112] and/or $b \to c\tau\nu$ data [113–115] were studied, mostly within leptoquark models and also the CAA was correlated to $b \to s\ell^+\ell^-$ data using a heavy vector boson in the adjoint representations of $SU(2)_L$. [112]

In addition to the anomalies i)-iv), related to $b \to s\ell^+\ell^-$ in the context of LUF violation, there is also the long-standing discrepancy between the SM predictions and the LEP measurement of the $Z \to b\bar{b}$ forward-
backward asymmetry \cite{125}. Here, the global fit to Zbb couplings reveals a tension of \( \approx 2\sigma \) both in the left-handed and in the right-handed coupling with a strong correlation \cite{126,127}. Interestingly, even though this observable could obviously be related to \( b \rightarrow s\ell^+\ell^- \) transitions via NP coupling to the bottom quark, models providing such a connection have received surprisingly little attention in the literature so far.

In this article, we want to fill this gap by presenting a model that cannot only provide a common explanation of \( b \rightarrow s\ell^+\ell^- \) data and the \( Z \rightarrow bb \) forward-backward asymmetry but also account for \( \tau \rightarrow \mu\nu\nu \) and the Cabibbo Angle Anomaly. Notice that a quite large effect in \( Z \rightarrow bb \) w.r.t the SM is necessary (in particular in the right-handed Zbb coupling), such that loop effects are in general too small to account for it. Therefore, two possibilities remain to construct a viable model: the mixing of the SM Z with a neutral \( Z' \) boson coupling to \( bb \), or vector-like quarks (VLQs) mixing with the SM ones after electroweak (EW) symmetry breaking. While the former case can in fact account for \( Z \rightarrow bb \), it is difficult to explain simultaneously \( b \rightarrow s\ell^+\ell^- \) data since the effect in \( Z\mu\mu \) would be too large \cite{128}. Concerning vector-like quarks, there is only one representation each that gives the appropriate effect in the left-handed or right-handed coupling\(^1\). Clearly, if these vector-like quarks mix with the strange quark as well, a modified Zsb coupling is generated. While such modified Z couplings can improve the fit in \( b \rightarrow s\ell^+\ell^- \), they cannot explain the hints for LFU violation in \( R(R(K^{(*)}) \) and additional ingredients are required to fully account for all data. Therefore, we will add two new scalar (one charged and one neutral) to our particle content and extend the gauge group by a \( L_\mu - L_\tau \) symmetry to obtain a LFU violating effect. Interestingly, the charged scalar turns out to have just the right quantum numbers to explain at the same time the Cabibbo Angle Anomaly via an effect in the determination of the Fermi constant from muon decay, while the \( Z' \) of the gauged \( L_\mu - L_\tau \) symmetry improves the agreement with data in Br[\( \tau \rightarrow \mu\nu\nu \)/Br[\( \tau \rightarrow e\nu\nu \)] and Br[\( \tau \rightarrow \mu\nu\)/Br[\( \mu \rightarrow e\nu \)].

\section{The Model}

Our starting point is \( Z \rightarrow bb \) which, as outlined in the introduction, can only be explained by adding two new heavy quarks to the SM particle content, an \( SU(2)_L \) doublet with hypercharge \(-5/6\) (\( Q \)) and an \( SU(2)_L \) singlet with hypercharge \(-1/3\) (\( D \)). They couple to right-handed down-type quarks and left-handed quark doublets, respectively, via the SM Higgs doublet (\( H \)) and therefore can mix with \( b \) quarks after EW symmetry breaking. Due to the stringent LHC bounds on new quarks their mass must be larger than \( \approx 1 \text{TeV} \) \cite{130,131}. Therefore, the new quarks must be vector-like under the SM gauge group such that their masses are not confined to the EW scale. However, we assume them to be chiral under a new \( U(1)' \) gauge group (with coupling constant \( y' \)) such that they cannot be arbitrarily heavy but have masses of the order of the \( U(1)' \) breaking scale. In fact, we charge \( Q_R \) and \( D_R \) under \( U(1)' \) while \( Q_L \) and \( D_R \) are neutral. This does not only allow for the desired mixing with the SM down-type quarks but also turns out to be crucial for generating a \( Z'bs \) coupling later on. All SM particles are neutral under the gauged \( U(1)' \) except for leptons for which we assume a \( L_\mu - L_\tau \) symmetry \cite{132,133}. This symmetry cannot only naturally generate the observed pattern from the PMNS matrix \cite{135,137} but also avoids stringent LEP bounds on 4-lepton contact interactions \cite{138}. In addition, we introduce two \( SU(3)_c \times SU(2)_L \) singlet scalars with \( L_\mu - L_\tau \) charge of \(-1\): one electrically neutral (\( S \)) and the other with charge \(+1\) (\( \phi^+ \)). In summary, our particle content is given in Table I.

This allows for the following Yukawa-type interactions involving quarks

\[
-\mathcal{L}_Y^{\phi^+} = (Y_f^d \bar{q}_L f d_R + \lambda^D \bar{q}_L f D_R) + h_\phi \bar{q}_L f Q_R \phi^+ + (\lambda_{RL} Q_R D_L + \lambda_{LR} Q_L D_R + \lambda_{R\phi} \bar{q}_L D_R) H + (\eta_d \bar{D}_L D_R + \eta_q \bar{Q}_L Q_R) S^\dagger + Y_f^u \bar{q}_L f R_R \bar{H} + \text{h.c.},
\]

where \( \bar{H} = i\sigma_2 \bar{H}^* \) is the complex conjugate of the SM Higgs doublet and \( f \) and \( \bar{f} \) are flavour indices\(^2\). Here we choose to work in the down basis where \( Y^d \) is diagonal and the CKM matrix originates from the up-sector. In addition, there is only one possible coupling of the charged scalar to leptons allowed by our charge assignment

\[
-\mathcal{L}_Y^{L\phi^+} = \xi L_L^\phi \cdot L_1 \phi^+ + \text{h.c.} \quad \text{with} \quad \phi^+ \quad \text{stands for a}
\]

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
\( q_L \) & \( d_R \) & \( u_R \) & \( H \) & \( \ell_L \) & \( e_R \) & \( Q_L \) & \( Q_R \) & \( D_L \) & \( D_R \) & \( \phi^+ \) & \( S \) \\
\hline
\( SU(3)_c \) & & & & & & & & & & & & \\
\( SU(2)_L \) & & & & & & & & & & & & \\
\( U(1)_Y \) & & & & & & & & & & & & \\
\hline
\( \frac{1}{2} \) & \( \frac{1}{2} \) & \( 1 \) & \( 0 \) & \( 1 \) & \( 0 \) & \( 3 \) & \( 3 \) & \( 3 \) & \( 1 \) & \( 1 \) & \( 1 \) \\
\( \frac{1}{2} \) & \( \frac{1}{2} \) & \( 0 \) & \( 1 \) & \( 1 \) & \( 0 \) & \( 2 \) & \( 1 \) & \( 1 \) & \( 1 \) & \( 1 \) & \( 1 \) \\
\hline
\end{tabular}
\caption{SM particle content and the scalar and fermion fields added to it in our model together with their representations under the gauge group \( SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \). Here the bracket \((0,1,-1)\) in the columns for left and right-handed leptons means that we assume a \( L_\mu - L_\tau \) flavour symmetry.}
\end{table}

\footnotetext{1}{There is a second \( SU(2)_L \) doublet VLQ which contributes with opposite sign to the right-handed Zbb couplings. This VLQ could only account for the anomaly via an over-compensation in the fit which is in conflict with other EW data and \( b \rightarrow s\gamma \) \cite{129}.}

\footnotetext{2}{Note that in addition to the terms in Eq. \( \text{I} \), one could have a term \( \lambda^D_{L\phi} \bar{D}_L d_L S^\dagger \), which, however, without loss of generality, can be removed by rotations of \( d_L, D_R \) and an appropriate redefinition of the couplings.}
contraction in $SU(2)_L$ space via the anti-symmetry tensor.

The vacuum expectation value $(S = v_S/\sqrt{2})$ generates masses for the $Z'$ boson ($m_{Z'} = g' v_S/\sqrt{2} \eta_Q$) as well as the mass of the charged and neutral singlet ($m_\phi = \mathcal{O}(v_S)$, $m_S = \mathcal{O}(v_S)$). After EW symmetry breaking, the quark doublet is decomposed into its components and CKM rotations generate $V_{fJ} \delta_f + \alpha_f \delta^\tau Q_R$ couplings which will later be relevant for $D^0 - \bar{D}^0$ mixing.

### III. EXPLAINING THE ANOMALIES

Let us now discuss how our model can explain the anomalies and which observables are relevant in constraining it, starting with $Z^{bb}$.

#### A. $Z^{bb}$

The mixing of the heavy quarks with the SM ones leads to desired modifications of the $Z^{bb}$ couplings via diagram (A) shown in Fig. 1. Using the publicly available HEPfit code \[139\], we updated the fit of Refs. \[126, 127\], finding

$$\left|\lambda^g_{ij}\right|^2 = (1.12 \pm 0.46) \frac{M_Q}{\text{TeV}}, \quad \left|\lambda^\mu_{ij}\right|^2 = (0.18 \pm 0.09) \frac{M_Q}{\text{TeV}}.$$  \(2\)

Note that this combination of couplings is not significantly constrained from other observables so that we can fully account for the anomaly.

#### B. Cabibbo Angle Anomaly

The Cabibbo Angle Anomaly originates from a (apparent) deficit in 1st row CKM unitarity. Equivalently, it manifests itself in a disagreement between the determinations of $V_{us}$ from kaon and tau decays vs $V_{us}$ from super-allowed beta decays (assuming CKM unitarity). Following Ref. \[103\] we have

$$V_{us}^\beta = 0.2281(7), \quad V_{us}^\beta|_{\text{NNC}} = 0.2280(14),$$  \(3\)

where the latter value contains the “new nuclear corrections” (NNCs) proposed in Refs. \[140, 141\]. Since at the moment the issue of the NNCs is not settled, we will perform our fit for both determinations. The value of $V_{us}^\beta$ has to be compared to $V_{us}$ from kaon \[142\] and tau decays \[143\]

$$V_{us}^{K^0} = 0.22345(67), \quad V_{us}^{K^\pm} = 0.22320(61), \quad V_{us}^{\tau} = 0.22534(42), \quad V_{us} = 0.2195(19),$$  \(4\)

which are significantly lower.

The Feynman diagram (C) in Fig. 1 generates a necessarily constructive effect w.r.t the SM in $\mu \rightarrow e\nu\nu$ and modifies the determination of the Fermi constant ($G_F$) from muon decays. While the $V_{us}$ determination from kaon and tau decays is mostly independent of the Fermi constant, $V_{us}$ from super-allowed beta decays even has a sensitivity enhanced by $V_{ud}/V_{us}$ \[102\]. This means that the “real” Lagrangian value of $V_{us}$ of the unitary CKM matrix in terms of the one measured from beta decays is given by

$$V_{us} = V_{us}^\beta \left(1 - \frac{V_{ud}}{V_{us}} \frac{\xi^2 m_W^2}{m_\phi^2}\right).$$  \(5\)

As a modification of $G_F$ also affects the EW sector we included the determinations of $V_{us}$ in Eq. \(3\) and Eq. \(4\) into HEPfit and performed a global fit finding

$$V_{us}^\beta |_{\text{NNC}} : |\xi|^2 = (0.043 \pm 0.010) \frac{m_\phi^2}{\text{TeV}^2},$$  \(6\)

$$V_{us}^\beta |_{\text{NNC}} : |\xi|^2 = (0.021 \pm 0.013) \frac{m_\phi^2}{\text{TeV}^2}.$$  \(7\)

Note that this range for $\xi$ brings $V_{us}$ from beta decays into agreement with $V_{us}$ from $K \rightarrow \mu \nu$ to $\mu \nu$ and, therefore, also with respect to the CAA we improve by $\approx 2 \sigma$ w.r.t the SM, depending on the value of $V_{us}^\beta$ considered.

#### C. $\tau \rightarrow \mu \nu\nu$

Let us now study the effect of the $Z'$ in $\tau \rightarrow \mu \nu\nu$ which is modified by diagram (B) in Fig. 1, resulting in \[?\]

$$\frac{\text{BR} (\tau \rightarrow \mu \nu)}{\text{BR} (\tau \rightarrow e\nu\nu)}_{\text{SM}} = \frac{\text{BR} (\tau \rightarrow \mu \nu)}{\text{BR} (\mu \rightarrow e\nu\nu)}_{\text{SM}} \approx 1 + \Delta,$$  \(8\)

with

$$\Delta = \frac{3 (g')^2 \log (m_W^2/m_{Z'}^2)}{4 \pi^2} \left(1 - m_{Z'}/m_W\right) = (4.7 \pm 2.3) \times 10^{-3}.$$  \(9\)

The experimental value is obtained by averaging the measurements of both ratios, including the correlation of 0.48 \[143\]. In particular, for $m_{Z'} = 1$ TeV we find

$$(g')^2 = (1.9 \pm 0.9) \frac{m_{Z'}}{\text{TeV}},$$  \(10\)

neglecting logarithmic effects. Notice that the $Z'$ only affects the numerator of these ratios while $\mu \rightarrow e\nu\nu$ is affected by tree-level $\phi^+$ exchange as discussed above. However, the latter effect is stringently bounded by $V_{us}$ and the EW fit such that its impact on Eq. \(7\) is negligible.

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\[3\] There is a small correlations between the NP effect in $G_F$ and $Z \rightarrow bb$ such that for the central value of $\xi/m_\phi$ only a smaller NP effect in left-handed $Zbb$ coupling is needed.
The $Z'$ also contributes to neutrino trident production (NTP) and gives rise to the loop-corrections of $Z$ couplings to charged leptons and neutrinos. However, neither of these effects are NTP in any region of the preferred region from $\tau \to \mu \nu/\tau \to e\nu\nu$ and $\tau \to \mu \nu/\mu \to e\nu\nu$. Therefore, we can obtain the best fit point for $Br[\tau \to \mu \nu]/Br[\tau \to e\nu\nu]$ and $Br[\tau \to \mu \nu]/Br[\mu \to e\nu\nu]$ and thus improve on the SM by more than $2\sigma$.

D. $b \to s\ell^+\ell^-$

Here we want to explain $b \to s\ell^+\ell^-$ data with a combination of a LFV effect from modified $Zsb$ coupling (diagram (D)) and a LFV violating one originating from the $Z'$ (diagram (A)). The former one is generated at tree-level via the mixing of the vector-like quark with SM quarks and is given by

$$
C^{U}_{10^{(i)}} = C^{U}_{10^{(i)}} = \frac{2\pi^2}{c^2 M_Q^2} \sqrt{2} G_F V_{tb} V_{ts}^* \phi_{b},
$$

in the conventions of Ref. [34]. For the latter one, the $Z' sb$ coupling is generated at the loop level through diagrams like the one shown in Fig. 1. We parameterize the effective $Z'$ coupling to down-quarks generically as

$$
\mathcal{L} = \bar{d}_f \gamma^\mu \left( \Delta_{dL}^{uL} P_L + \Delta_{dR}^{uR} P_R \right) \phi_b Z'_\mu d_i,
$$

and obtain

$$
\Delta_{dL}^{uL} = g' \frac{\kappa^\text{u}_b \phi^*_b}{16\pi^2} \left( x + x \log(x) + 1 \right) \left( x - 1 \right)^3,
$$

with $x = m_{\phi}/M_Q$. This results in the purely LFU violating effects

$$
C^{U}_{9\mu} = -16\pi^2 \frac{\Delta_{dL}^{uL} (\Delta_{dL}^{uL} + \Delta_{dL}^{uL})}{\epsilon^2 4\sqrt{2} G_F M_Q^2 V_{tb} V_{ts}^*},
$$

Performing a global fit within this scenario we find a pull of 6.1 $\sigma$ w.r.t the SM and a p-value of 47.5%. The best fit points and 1 $\sigma$ CL intervals for the Wilson coefficients are

$$
C^{U}_{9\mu} = -1.06 \pm 0.16 ,
$$

$$
C^{U}_{10^i} = -0.24 \pm 0.17 ,
$$

$$
C^{U}_{10^e} = 0.18 \pm 0.19.
$$

However, $b \to s\ell^+\ell^-$ cannot be explained without affecting $\Delta F = 2$ processes. While tree-level $Z$ and $Z'$ effects turn out to be negligible (due to the tiny $sb$ couplings) $\phi^+$ box contributions generate

$$
C^{\phi^+}_{1} = \frac{(\kappa_b \phi^* b)^2 m_b^4 - 2 m_b^2 m_{\phi}^2 \log \frac{m_b^2}{m_{\phi}^2}}{128\pi^2 (m_{\phi}^2 - m_b^2)^3},
$$

following the conventions in Ref. [142]. Including the 2-loop RGE of Ref. [150, 151] and the bag factor of Ref. [152] we find at the $B_s$ meson scale

$$
\frac{\Delta m_{B_s}}{\Delta m_{B_{D^0}}} = 1 + 1.1 C^{\phi^+}_{1} \times 10^{10} \text{GeV}^2 = 1.11 \pm 0.09
$$

for real NP contributions according to the global fit of Ref. [152]. Similarly, we get a bound from CP violation in the $D^0 - \bar{D}^0$ system [153, 154] with $C^{D^0 - \bar{D}^0}_{1} \sim 3 \times 10^{12} \text{GeV}^2 < 0.033 \text{ GeV}$,

Note that in the simpler case with only the VLQ $Q$ (but not $D$) we would obtain to a good approximation scenario 11 of Ref. [9] with a pull of 6.3 $\sigma$. 

![FIG. 1: Diagrammatic representation of how the Feynman diagrams (A)-(D) within our model contribute to $Z \to bb(\tilde{s}s)$, muon decay, $\tau \to \mu \nu\nu$ and $b \to s\ell\ell$ and explain the associated anomalies.](image-url)
we assumed that the SM contribution to CP violation in $D^0 - \bar{D}^0$ mixing is negligible.

Turning to the phenomenological analysis, notice that we can generate $C^U_{10,10}$ from the modified $Zb\ell$ couplings without generating a relevant effect in $B_s - \bar{B}_s$ mixing. Therefore, we can account for the full range of values for $C^U_{10,10}$ preferred by the fit to $b \to s\ell^+\ell^-$ data. Similarly, note that generating $C^V_{g'}$ from the $Z'$ penguins also gives rise to an effect in $D^0 - \bar{D}^0$ mixing due to CKM rotations. However, the resulting constraint is sub-leading for $\kappa_b > \kappa_s$. Therefore, we find the results shown in Fig. 2 from which it is clear that we can reach the best fit point for $b \to s\ell^+\ell^-$ without being in conflict with $B_s - \bar{B}_s$ mixing while choosing $g'/m_{Z'}$ as preferred by $\text{Br}[\tau \to \mu\nu\nu]/\text{Br}[\tau \to e\nu\nu]$ and $\text{Br}[\tau \to \mu\nu\nu]/\text{Br}[\mu \to e\nu\nu]$. Note that LHC bounds are not important here due to the small couplings to quarks. Therefore, we can improve the fit compared to the SM by 6.1σ in the $b \to s\ell^+\ell^-$ channel.

\section{Conclusions and Outlook}

In this article we proposed a simple model obtained from the SM by adding:

\begin{itemize}
  \item Two heavy quarks which are vector-like ($Q$ and $D$) under the SM gauge group.
\end{itemize}

$\kappa_s, \kappa_b^* = -0.3$ and $m_Q = m_D$. Note that for $m_Qm_b > 1.5\text{TeV}^2$ one can account for $b \to s\ell^+\ell^-$ data while being in agreement with $B_s - \bar{B}_s$ mixing at the $\sigma$ level.

This model can explain:

\begin{itemize}
  \item The $Z \to bb$ forward-backward asymmetry via the mixing of the vector-like quarks with the SM bottom quark.
  \item The Cabibbo Angle Anomaly via a positive definite shift in $G_F$ induced by the singly charged scalar.
  \item $\tau \to \mu\nu\nu/\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu/\mu \to e\nu\nu$ via the box contributions involving the $Z'$.
  \item Accounts for $b \to s\ell^+\ell^-$ data through a modified $Z'$ coupling and a loop induced $Z'$ effect without being in conflict with $B_s - \bar{B}_s$ mixing.
\end{itemize}

This is illustrated in Fig. 1.

Therefore, our model describes data significantly better than the SM and constitutes the first unified explanation of all four anomalies. With new particles at the TeV scale, it provides interesting discovery potential for the (HE-) LHC \cite{156} and the FCC-hh \cite{157} but could also be indirectly verified through $Z$ pole observables by FCC-ee \cite{158}, ILC \cite{159}, CEPC \cite{160} or CLIC \cite{161}. Also BELLE II is sensitive to the $Z \to bb$ asymmetry through electron beams \cite{162}. Furthermore, precision measurements of $\tau$ decays at BELLE II \cite{163} and of course the pattern predicted in $b \to s\ell^+\ell^-$ at the HL-LHC \cite{164} and BELLE II \cite{165} could test our model.

In this work we presented the minimal model capable of providing an explanation of the hints for NP. As it possesses gauge anomalies, it is interesting to look for extensions which are free of this obstacle (see e.g. Refs. \cite{165,166} for accounts in the context of $b \to s\ell^-$). For example, by adding two more heavy quarks $Q_{L,R}'$ and $D_{L,R}'$ with the same representation under $SU(3)_c \times SU(2)_L$ as $Q_{L,R}$ and $D_{L,R}$ but with opposite $U(1)_Y$ and $U(1)'$ charge this can be easily achieved without any significant effect on the phenomenology. In general, embedding our model into a more unified framework would be very interesting and opens up novel avenues for model building.

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\footnote{Note that recasting the ATLAS analysis \cite{155} for our $Z'$ we find that bounds are not constraining since the couplings to quarks are not only loop-induced and therefore small but also the production cross section is reduced by the small bottom PDF.}
