A flavour physics scenario for the 750 GeV diphoton anomaly

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A simple variant of a realistic flavour symmetry scheme for fermion masses and mixings provides a possible interpretation of the diphoton anomaly as an electroweak singlet “flavon”. The existence of TeV scale vector-like T-quarks required to provide adequate values for CKM parameters can also naturally account for the diphoton anomaly. Correlations between \( V_{ub} \) and \( V_{cb} \) with the vector-like T-quark mass can be predicted. Should the diphoton anomaly survive in a future Run, our proposed interpretation can also be tested in upcoming B and LHC studies.

The ATLAS [1] and CMS [2] collaborations have presented first results obtained from proton collisions at the LHC with 13 TeV center-of-mass energy. The ATLAS collaboration sees a bump in the invariant mass distribution of diphoton events at 750 GeV, with a 3.9 sigma significance, while CMS sees a 2.6 sigma excess at roughly the same value. Taking these hints at face value, we suggest a possible theoretical framework to interpret these findings. We propose that the new particle is a \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) singlet scalar boson carrying a flavour quantum number. Our proposed framework accounts for three important aspects of the flavor puzzle:

- the observed value of the Cabbibo angle arises predicted by the flavour symmetry of the model.
- the observed pattern of neutrino oscillations [4] is well-described by the generalized b-tau unification formula [5–8],

\[
\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_\tau}{\sqrt{m_e m_\mu}}.
\]

(1)

predicted by the flavour symmetry of the model.

There are in principle several possible realizations of the 750 GeV anomaly as a flavon [9, 10]: a flavor–carrying \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) singlet scalar. Our main idea is to obtain a scheme where the CERN anomaly may be probed also in the flavor sector. For this purpose we consider a simple variant of that proposed in [5] in order to address the points above. Phenomenological consistency of the model requires the presence of vector–like fermions in order to account for the observations in the quark sector. Their presence can naturally account for a production cross section of the scalar anomaly through gluon–gluon fusion similar to that indicated by ATLAS and CMS [5] [7].

Here we investigate the allowed parameter space of our scheme which provides an adequate joint description of CKM physics describing the B sector and the recent CERN diphoton data, illustrating how the two aspects are inter-related in our scheme. For definiteness and simplicity, here we focus on a nonsupersymmetric version of the model discussed in [5]. The charge assignments for the fields is as shown in Table I.

| Fields       | \( L \) | \( E^c \) | \( Q \) | \( U^c \) | \( D^c \) | \( H^u \) | \( H^d \) | \( T \) | \( T^c \) | \( \sigma \) | \( \sigma^c \) | \( \xi \) |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| SU(2)_L     | 2      | 1      | 2      | 1      | 1      | 2      | 2      | 1      | 1      | 1      | 1      | 1      |
| \( A_4 \)   | 3      | 3      | 3      | 3      | 3      | 3      | 1      | 1      | 3      | 3      | 3      | 1      |
| \( Z_4 \)   | 1      | 1      | 1      | 1      | 1      | 1      | 1      | \( \omega \) | \( \omega^2 \) | \( \omega^3 \) | \( \omega^4 \) | \( \omega \) |

Table I. Matter content of the model, where \( \omega^4 = 1 \).

Here, \( T, T^c \) are a pair of vector like “quarks” transforming as \((3, 1, 4/3)\) and \((3, 1, -4/3)\) under the Standard Model gauge group \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \). The scalars \( \sigma, \sigma^c \) are singlets under \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) but transform as \( A_4 \) triplets and carry \( Z_4 \) charge. The scalar \( \xi \) is also a singlet under Standard Model as well as under the \( A_4 \) symmetry but transforms as \( \omega \) under the \( Z_4 \) symmetry. In addition to the above charges, the scalars and fermions also carry an additional \( Z_2 \) charge such that

\[1\] Indeed vector-like fermions have been suggested to account for the diphoton anomaly. For an extensive reference set see [11].
the scalar $H^u$ only couples to the up-type quarks, while $H^d$ only couples to the down-type quarks and charged leptons (this $Z_2$ symmetry would not be needed if supersymmetry were assumed). The invariant Yukawa Lagrangian of the model is given by,

$$\mathcal{L}_f = y_{ij}^u Q_i H^u_j U^c_k + y_{ij}^d Q_i H^d_j D^c_k + y_{ij}^l L_i H^q_j E^c_k + X'TU^c_i\sigma_i + \frac{Y}{\Lambda} Q_i(H^u\cdot\sigma')T^c + y_T T^c \xi$$

(2)

where we take all couplings $y_T$, $y_{ij}^a$, and $X, Y$ as real for simplicity; $a = u, d, l$ and $i, j, k = 1, 2, 3$.

Following Ref. [5] after electroweak symmetry breaking and requiring certain hierarchy in the flavon vs, $\langle H_u,d \rangle = (v_u, \varepsilon_1, \varepsilon_2)$ where $\varepsilon^u_{1,2} \ll v^u$ and $\varepsilon^d_{1,2} \ll v^d$, one gets the mass relation between the down-type quarks and charged leptons given by Eq. (1). The up-type quark sector gets modified due to the presence of vector like quarks so that the full up-type quark mass matrix is $4 \times 4$ and given by

$$M_u = \begin{pmatrix} 0 & a^u_{\alpha\alpha} & b^u & Y_1' \\ b^u_{\alpha\alpha} & 0 & a^u_{\alpha\beta} & Y_2' \\ a^u_{\beta\alpha} & b^u_{\beta\alpha} & 0 & Y_3' \\ X_1' & X_2' & X_3' & M_L^u \end{pmatrix}$$

(3)

where $a^u = y_{i1}^u \varepsilon_1$, $b^u = y_{i2}^u \varepsilon_2$, $\varepsilon_1, \varepsilon_2$ being the only two possible Yukawa couplings arising from the $A_4$-tensor in Eq. (2). Also, $r^u = v^u/\varepsilon_1$ and $s^u = \varepsilon_2/\varepsilon_1$. Moreover, $X_i' = X_i'(\sigma_i)$, $Y_i' = Y_i'(\langle H_u,d \rangle)/\Lambda$ and $M_T = y_T \langle \xi \rangle$.

The mass matrix in Eq. (3) is the same as that obtained in [5] where the detailed treatment of the Yukawa sector is given. Notice that the addition of vector quarks only changes the up sector mass matrix, the down sector mass matrix remaining unchanged and thus the relation in Eq. (1) remains unchanged, see [5] for further details.

The scalar sector of the model consists of SU(2)$_L$ doublet scalars $H^u$, $H^d$ both transforming as triplets under the $A_4$ symmetry. In addition it contains three types of SU(2)$_L$ singlet scalars with $\sigma, \sigma' \sim 3$ under $A_4$ while $\xi \sim 1$ under the $A_4$ symmetry. In order to illustrate how our candidate scalar can account for the $750$ GeV resonance, we consider a simplified scenario. Neglecting the mixing between the SU(2)$_L$ doublet and singlet scalars $\phi^0 = (\zeta^0, \sigma^0, \sigma'^0)$ we can phenomenologically express the various scalar mass eigenstates as follows

$$h_i = U_{ij} H^u_j, \quad (i, j = 1, \ldots, 6)$$

$$\chi_m = \mathcal{O}_{mn} s_n^0, \quad (m, n = 1, \ldots, 7)$$

(4)

Under this approximation the singlet scalars $\chi_i$ can be further decomposed as

$$\zeta = \chi_1 = \mathcal{O}_{11} \xi^0 + \mathcal{O}_{1m} \phi^0_n,$$

$$\chi_m = \mathcal{O}_{mn} s_n^0,$$

(5)

with $m, n = 2, \ldots, 7$ and we have identified the flavon field mass eigenstate $\zeta$ as our 750 GeV resonance candidate. Then, this flavon field is composed predominantly of SU(2)$_L$ singlet scalars. Note that the rotation matrix $\mathcal{O}$ determines the mixing amongst the singlet scalars that form the two $A_4$-triplets and the $A_4$-singlet $\xi$.

At the LHC $\zeta$ will be predominately produced through gluon-gluon fusion via a triangle loop involving the vector-like $T$-quarks. In the absence of mixing between the SU(2)$_L$ doublet and singlet scalars the tree level coupling of $\zeta$ to $W, Z$ bosons can be neglected. Similarly, the coupling of $\zeta$ to down-type fermions is also negligible. However the coupling of $\zeta$ to up-type quarks is determined by the off-diagonal elements of Eq. (3). Thus, $\zeta$ predominantly couples to the vector-like quarks $T, T^c$. As we show below, the flavour constraints require the vector-like quarks to be quite heavy so that, for a large range of parameters we have $m_T > m_\zeta/2$. Thus, the decay of $\zeta$ to $T, T^c$ is also kinematically forbidden.

Therefore, $\zeta$ predominantly decays to photons and gluons through the triangle loop involving $T, T^c$, as shown in Fig. (1) and to up-type quarks through tree-level mixing.

![Decays of the 750 GeV scalar to gluons and photons.](image)

Apart from the above channels, $\zeta$ can also decay to $Z\gamma$ and $ZZ$ through analogous triangle loops involving $T, T^c$. Since $m_T^2 << m_\zeta^2$ the decay widths to $\gamma\gamma, Z\gamma$ and $ZZ$ are proportional to each other, so that,

$$\Gamma_{Z\gamma} \approx 2 \tan^2 \theta_W \quad \text{and} \quad \Gamma_{ZZ} \approx \tan^4 \theta_W$$

(6)

where $\theta_W$ is the weak mixing angle. In general $\zeta$ can also decay to two Higgs scalars as we discuss below.

Thus $\zeta$ seems, indeed, an ideal candidate to explain the 750 GeV di-photon excess recently observed at the LHC. Both $g$ and $\gamma$ couple to $T, T^c$ through gauge interactions with interaction strength proportional to $\alpha_s, \alpha$, the strong and electromagnetic coupling constants respectively. One can write down the effective Lagrangian for the coupling of $\zeta$ with gluons, $Z$ boson and photons which is

$$\mathcal{L}_{\text{eff}} = \frac{c_{\gamma}}{4} \zeta F_{\mu\nu} F^{\mu\nu} + \frac{c_{\gamma}}{4} \zeta G_{\mu\nu} G^{\mu\nu} + \frac{c_{ZZ}}{2} \zeta Z_{\mu\nu} Z^{\mu\nu} + \frac{c_{ZZ}}{4} \zeta Z_{\mu\nu} Z^{\mu\nu}$$

(7)

where $F_{\mu\nu}, G_{\mu\nu}$ are the usual electromagnetic and colour field strength tensors and $Z_{\mu\nu}$ is the field strength tensor for the $Z$ boson.

In Fig. [2] we show the allowed ranges for the effective couplings required to account for the 750 GeV di-photon
excess for both the CMS and ATLAS experiments within 95% confidence level. In the 8 TeV run neither ATLAS nor CMS have seen any statistically significant excess in any of the $\gamma \gamma$, $Z\gamma$ and $ZZ$ channels. The constraints from 8 TeV run on production times branching fraction $\sigma \times Br(\zeta \to ff)$; $f = g, Z, \gamma$ for these decay channels can be obtained from [12,13]. In Fig. 2 we have also included the constraints from the non-observation of any signal excess in the $\gamma \gamma$, $Z\gamma$ and $ZZ$ in the 8 TeV run. The upper colored region is consistent only with ATLAS data, while the lower one is consistent with only CMS data, while the middle region is consistent with both CMS and ATLAS. The solid and dashed lines delimit the regions disallowed by 8 TeV data for $\zeta \to \gamma \gamma$ decay and $\zeta \to Z\gamma$, decay, respectively. The constraints from $\zeta \to gg$ as well as $\zeta \to ZZ$ decays are rather weak and are not shown in the graph. The value of the effective couplings $c_g$ and $c_\gamma$ are determined by only two parameters, namely the mass $m_T$ of the vector quarks and the strength of the Yukawa coupling $\zeta TT$. The allowed parameter ranges for the mass $m_T$ and Yukawa coupling $y_T$ for both CMS and ATLAS experiments as well as the constraints from the 8 TeV run are shown in Fig. 3. In plotting Fig. 3 we have required that all the Yukawa couplings remain perturbative over the entire range of parameter space. The color scheme of Fig. 3 is the same as that of Fig. 2.

As shown in Fig. 3 the decay $\zeta \to \gamma \gamma$ in our model can explain the diphoton excess observed by both CMS and ATLAS experiments. Although the non-observation of similar diphoton excess in the 8 TeV run puts severe constraints on the allowed parameter range, our model still has enough freedom to reconcile these restrictions with the observed 13 TeV excess.

A key feature of our proposal is the identification of the 750 GeV anomaly as a flavon, i.e., a scalar state that carries flavour information. Indeed, our scalar $\zeta$ is directly coupled to the quarks, and hence to flavour, so we expect potential correlations between CKM physics and the properties of the observed anomaly. Therefore, in addition to the the quark and lepton masses, related by Eq. (1), the measured neutrino oscillation parameters [4], there are restrictions on the model parameters that come from the consistency of the quark sector, such as the measured quark mixing parameters [16]. In order to explore these implications of the model, one must check, as in Ref. [5] or other generic vector-like scenarios [17,18], that ours can indeed adequately reproduce CKM physics. To do this we include a selected set of additional observables sensitive to the new vector-like quark $T$ and to the deviations of the CKM matrix from the standard $3 \times 3$ unitary form. In particular, we include:

1. neutral meson mixing constraints: in $B^0_L - B^0_S$ and $B^0_s - B^0$ systems, mass differences and “golden” CP asymmetries in $B_d \to J/\Psi K_S$, $B_s \to J/\Psi \Phi$ decays, bounds on the short distance contribution to the mass difference in the $D^0 - \bar{D}^0$ system, and indirect and direct CP violation parameters $\epsilon_K$ and $\epsilon'/\epsilon_K$ for the $K^0 - \bar{K}^0$ system;

2. rare decays induced by different quark level transitions: $B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $B \to Xs\gamma$, $K_L \to \pi^0\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$, and short distance contributions to $D^0 \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$. Furthermore, to reflect LHC bounds on direct production of the new vector-like quark, we restrict our analysis to values of the mass $m_T > 1$ TeV [19]. Once compliance
with this set of constraints is ensured, we can address, in addition to the 750 GeV diphoton hint, other features of the model, in particular flavour related ones, like correlations among different observables. Due to the complexity of the problem in terms of the number of independent parameters, we focus on scenarios where the upper 3 × 3 block of the $M_u$ mass matrix and the remaining mass matrices are fixed, while the $X_i$, $Y_i$ and $M_{44}$ entries, related to the new vector-like quark, are free to vary. Furthermore, we consider separate variations of : (A) only the largest entries, namely \{$X_2, Y_3, M_{44}$\}, or (B) only (all) the $X_i$ entries.

To cover the available parameter space while maintaining agreement with all of the above constraints, we conduct a likelihood analysis based on Markov chain driven MonteCarlo simulations. Figures 4 and 5 illustrate the results of such analyses. In Fig. 4(a) the correlation among the values of $|V_{ub}|$ and the mass of the new quark $m_T$ is shown for scenario (A); in that case, accommodating larger $m_T$ values comes at the price of increasingly larger values of $|V_{ub}|$. To further illustrate the situation, Fig. 4(b) displays the correlation among $|V_{ub}|$ and $|V_{cb}|$ for separate ranges of $m_T$ values, $m_T \in [1.00; 1.02]$ TeV, $m_T \in [1.10; 1.12]$ TeV and $m_T \in [1.20; 1.22]$ TeV. In addition to the features seen in Fig. 4(a), Fig. 4(b) shows an additional (milder) correlation among $|V_{cb}|$ and $m_T$; larger masses prefer smaller $|V_{cb}|$ values. Figure 5 corresponds instead to scenario (B). In this case the corre-
lation trends are reversed with respect to scenario (A): while $|V_{cb}|$ is almost uncorrelated with $m_T$, $|V_{cb}|$ tends to be larger for increasing $T$-masses. It is also to be noticed that the range of $m_T$ values is much more limited than in scenario (A).

Finally, we briefly comment on the issue of width of the 750 GeV resonance. The first thing to notice is that with the current low statistics, the estimates for the decay width are very poor. This is reflected in the fact that, while the ATLAS experiment prefers a broad decay width of around 45 GeV, the CMS data suggest a decay width of few GeV. Such uncertain decay width estimates are likely to change significantly in the next run, if the anomaly survives.

In our model, since the $\zeta \to TT$ decay is not kinematically allowed, the decay width of $\zeta$ is a priori narrow. Even though $\zeta \to tt$ decay is mixing suppressed, it can contribute to the total width from a few hundred MeVs up to 10 GeVs. Partial widths to lighter fermions are smaller as well as that for the $\zeta \to hh$ decay (where $h$ is the Standard Model Higgs boson) which is constrained by the LHC Run1 data. If in future runs the ATLAS experiments confirm that a broad resonance persists this would imply that a significant novel decay of $\zeta$ is at work.

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1. Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Technical Report ATLAS-CONF-2015-081, CERN, Geneva (2015), URL \url{http://cds.cern.ch/record/2114853}
2. C. Collaboration, Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV (2015) CMS-PAS-EXO-15-004, URL \url{https://cds.cern.ch/record/2114808}
3. R. Gatto, G. Sartori and M. Tonin, Weak Selfmasses, Cabibbo Angle, and Broken SU(2) x SU(2), Phys. Lett. B28 (1968) 128–130.
4. D. Forero, M. Tortola and J. Valle, Neutrino oscillations refitted, Phys.Rev. D90 (2014) 093006, \url{arXiv:1405.7540 [hep-ph]}
5. S. Morisi et al., Quark-Lepton Mass Relation and CKM mixing in an A4 Extension of the Minimal Supersymmetric Standard Model, Phys.Rev. D88 (2013) 036001, \url{arXiv:1303.4394 [hep-ph]}
6. S. Morisi, E. Peinado, Y. Shimizu and J. W. F. Valle, Relating quarks and leptons without grand-unification, Phys.Rev. D84 (2011) 036003, \url{arXiv:1104.1633 [hep-ph]}
7. S. King, S. Morisi, E. Peinado and J. W. F. Valle, Quark-Lepton Mass Relation in a Realistic A4 Extension of the Standard Model, Phys. Lett. B 724 (2013) 68–72, \url{arXiv:1301.7065 [hep-ph]}
8. C. Bonilla, S. Morisi, E. Peinado and J. W. F. Valle, Relating quarks and leptons with the $T_f$ flavour group, Phys.Lett. B742 (2015) 99–106, \url{arXiv:1411.4883 [hep-ph]}
9. S. Morisi and J. W. F. Valle, Neutrino masses and mixing: a flavour symmetry roadmap, Fortsch.Phys. 61 (2013) 466–492, \url{arXiv:1206.6673 [hep-ph]}
10. S. F. King et al., Neutrino Mass and Mixing: from Theory to Experiment, New J.Phys. 16 (2014) 045018, \url{arXiv:1402.4271 [hep-ph]}
11. F. Staub et al., Precision tools and models to narrow in on the 750 GeV diphoton resonance (2016), \url{arXiv:1602.05581 [hep-ph]}
12. G. Aad et al. (ATLAS), Search for new resonances in $W\gamma$ and $Z\gamma$ final states in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B738 (2014) 428–447, \url{arXiv:1407.8150 [hep-ex]}
13. G. Aad et al. (ATLAS), Search for an additional, heavy Higgs boson in the $H \to ZZ$ decay channel at $\sqrt{s} = 8$ TeV in $pp$ collision data with the ATLAS detector, Eur. Phys. J. C76 (2016) 1–45, \url{arXiv:1507.05930 [hep-ex]}
14. G. Aad et al. (ATLAS), Search for high-mass diphoton resonances in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Rev. D92 (2015) 3 032004, \url{arXiv:1504.05511 [hep-ex]}
15. Search for new resonances in the diphoton final state in the range between 150 and 850 GeV in $pp$ collisions at $\sqrt{s} = 8$ TeV, Technical Report CMS-PAS-HIG-14-006, CERN, Geneva (2014), URL \url{http://cds.cern.ch/record/1714076}
16. K. Olive et al. (Particle Data Group), Review of Particle Physics, Chin. Phys. C38 (2014) 090001.
17. F. J. Botella, G. C. Branco and M. Nebot, Small violations of unitarity, the phase in $B^0_s \to B^0$ and visible $t \to cZ$ decays at the LHC, Phys.Rev. D79 (2009) 096009, \url{arXiv:0805.3995 [hep-ph]}
18. F. J. Botella, G. C. Branco and M. Nebot, The Hunt for New Physics in the Flavour Sector with up vector-like quarks, JHEP 12 (2012) 040, \url{arXiv:1207.4440 [hep-ph]}
19. G. Aad et al. (ATLAS), Search for single production of vector-like quarks decaying into $Wb$ in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector (2016), \url{arXiv:1602.05606 [hep-ex]}
20. J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07 (2014) 079, \url{arXiv:1405.0301 [hep-ph]}
21. R. D. Ball et al. (NNPDF), Parton distributions with
QED corrections, Nucl. Phys. B877 (2013) 290–320, arXiv:1308.0598 [hep-ph]