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Flavourful global fit to LHCb data with the general two Higgs doublet model: An update

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We perform a global fit to the two Higgs doublet model (2HDM) with generic sources of flavour violation using GAMBIT. This is particularly interesting in light of significant deviations from the Standard Model predictions, such as the flavour anomalies $R(D^{(*)})$ and $b \to s\ell^+\ell^-$ and the indications for a charged Higgs with a mass of 130 GeV in top quark decays at ATLAS. We include all relevant constraints from precision, flavour and collider observables in the global fit, and in particular recent constraints from both quark flavour violating searches at ATLAS and CMS, and lepton flavour violation from Belle II. We also consider the impact of recent developments related to the W mass and muon $g-2$ observables. We find that it is possible to simultaneously explain both the charged and neutral flavour anomalies when excluding the values obtained by the CDF-II detector for the m_W mass and when using the BMW lattice results for muon $g-2$. In contrast if we either assume there is still a large deviation in muon $g-2$ requiring new physics, or that the CDF-II measurement of the W mass is correct, we find that a simultaneous explanation of all the anomalies is no longer possible. Finally we provide predictions that can probe or rule out the model in lepton flavour violating searches at Belle II and also in Higgs coupling strength measurements at the future HL-LHC.

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1. Introduction

The Standard Model (SM) is extremely successful in describing the interactions of matter at sub-atomic scales [1], *but* the data does contain a large number of anomalies and it has been argued that these collectively represent a growing challenge to the SM [2]. In particular, in semi-leptonic B meson decays significant deviations from the SM predictions, both in $b \to c\tau\nu$ [3] transitions (3.3σ) and in $b \to s\ell^+\ell^-$ observables [4–9] (6σ) persist. This hints at the presence of new physics (NP) contributions motivating the study of models capable of a combined explanation.

We investigate the plausibility of new physics explanations of these within the context of the two Higgs doublet model (2HDM) [10] – one of the simplest and most studied extensions of the SM scalar sector. The most general version[1] (G2HDM) with generic Yukawa couplings is able to explain $b \to c\tau\nu$ at the 1σ level [11–25] and address the anomalies in $b \to s\ell^+\ell^-$ [25–29].

Here we extend the works of Ref. [19, 25] to give the most complete picture possible regarding the capacity of the G2HDM to provide a simultaneous explanation of the interesting anomalies in the data. We include all of the observables considered in Ref. [25] and extend them by also including recent measurements of the charged lepton flavour violating (cLFV) search in $t \to \mu\tau q$ decays from ATLAS [30] and the latest universality test update from Belle II on $|g_\mu/g_e|$ [31] among other observables related to the charged anomalies. For more details on the model and observables used here the reader is refer to our complete work in [32].

In our main analysis we use muon $g-2$ and the W boson mass as *constraints* on new physics, using the BMW prediction [33, 34] for HVP contributions for the former and using oblique parameters from fits to electroweak precision observables [1] that exclude the CDF measurement [35] for the latter. However to show the impact of recent developments and these choices, we also perform additional global fits where we use the CDF measurement for the W mass and where we adopt the WP value [36] for the SM contributions to muon $g-2$. Finally, in addition to extending the set of observables and updating the data of [19, 25], we include three additional Yukawa couplings which were set to zero to understand correlations between the parameters and for simplicity. Indeed we find that those newly added Yukawas play an important role in evading flavour constraints.

2. Model parameters

The most interesting flavour-violating anomalies appear in the decays and mixings of second and third generation quarks, e.g. the decays of B−mesons. Consequently, in our study we do not consider Yukawa textures involving mixing with the first family. In the case of leptons, we do also consider mixing between the first and third generation. The additional freedom makes it easier to evade strong constraints from lepton universality in τ decays while fitting the anomalies. Therefore, inspired by the textures in [25], we take in our recent work [] the Yukawa matrices to be

$$\rho_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}, \qquad \rho_d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \rho_d^{bb} \end{pmatrix}, \qquad \rho_l = \begin{pmatrix} 0 & 0 & \rho_l^{e\tau} \\ 0 & \rho_l^{\mu\mu} & \rho_l^{\mu\tau} \\ 0 & 0 & \rho_l^{\tau\tau} \end{pmatrix}, \tag{1}$$

[1] Sometimes this is also referred to as the type III 2HDM in the literature.

where we have expanded the choice in [25] with the second generation diagonal Yukawas for both the lepton and up-type matrices, $\rho_\ell^{\mu\mu}$ and ρ_u^{cc}, and the third generation down-type quark coupling ρ_d^{bb}. The diagonal down-type Yukawa coupling ρ_d^{ss} and the off-diagonal terms are, however, ignored because of strong constraints from LHC and $B_s - \bar{B}_s$ mixing. Moreover, the off-diagonal matrix elements ρ_u^{ct} and $\rho_\ell^{\tau\mu}$ are also set to zero from Kaon physics and $\mu \to e\gamma$ [25, 37] constraints.

To avoid the strong constraints on the SM Higgs signal strengths we work close to the alignment limit and thus $s_{\beta\alpha} \sim 1$. Therefore the ranges for the model parameters in this study are

$$\begin{aligned}
&m_{12} \in [-200,\ 200]\text{GeV}, \qquad m_{H^\pm} \in [120,\ 140]\text{GeV}, \qquad m_A,\, m_H \in [150,\ 350]\text{GeV}, \\
&s_{\beta\alpha} \in [0.98,\ 1.0], \qquad \tan\beta \in [0.01,\ 10], \qquad Y_u^{2,tt} \in [-1.0,\ 1.0], \qquad Y_u^{2,tc} \in [-0.6,\ 0.6], \\
&\text{Re},\ \text{Im}(Y_\ell^{2,\tau\tau}) \in [-0.1, 0.1], \qquad Y_\ell^{2,\mu\tau},\ Y_\ell^{2,e\tau} \in [-0.01, 0.01], \\
&Y_u^{2,cc} \in [-0.15,\ 0.15], \qquad Y_d^{2,bb} \in [-0.2,\ 0.2], \qquad Y_\ell^{2,\mu\mu} \in [-0.1,\ 0.1]. \qquad (2)
\end{aligned}$$

3. Observables

The flavour violating couplings of the G2HDM can provide large contributions to many observables for which the prediction of the SM vanishes or is small. Many of these observables are strongly constrained by experiments, and that reflects on tight constraints on the flavour violating couplings ρ_f^{ba} and the masses of the heavy Higgs bosons. Interestingly, a few of the experimental observations deviate from the predictions of the SM, typically by a small amount consistent with statistical fluctuations in the data. However, a selected few measurements show fairly strong deviations from the SM, from around 3σ for charged currents, to over 6σ for some combinations of the neutral ones. We present in Ref.[32] the details and equations of all the observables used in the scans.

4. Results

In order to confirm the results from [25], we first tested the native calculations of the relevant observables using GAMBIT, finding that the values match very well with those of [25]. The small differences in most of the values come from the use of different predictions for the SM, more precisely in [25] the HFLAV averages were used whereas in GAMBIT the values are computed from the form factors in SuperIso 4.1 instead.

In addition to the observables included in [25], we also include likelihoods from the LHCb of the neutral anomalies in all available $b \to s\mu^+\mu^-$ transitions, the ratio $R_{e/\mu} = \text{BR}(\overline{B} \to De\overline{\nu})/\text{BR}(\overline{B} \to D\mu\overline{\nu})$, the meson decays $\text{BR}(D_s \to \mu\nu)$ and $\text{BR}(D_s \to \tau\nu)$, the universality test g_μ/g_e, and the new ATLAS upper bound on the $t \to \mu^+\tau^- c$ decay. In addition, as advertised, this scan also includes the prediction for $(g_2)_\mu$, using the latest SM prediction obtained by the BMW group [34]. Since the latter is now consistent with the experimental measurement at 0.9σ, in this scan $g-2$ is used as a constraint on NP scenarios, rather than an anomaly to be fit.

We show in Figure 1 the results from this, more thorough scan. We observe from the top-left that $\Delta C_9 \simeq -1.0$ at the best fit point simultaneously explaining the $R(D^{(*)})$ charged anomalies at $1\,\sigma$ (top middle). The masses of the CP-even and CP-odd heavy Higgses prefer a lighter m_A whereas

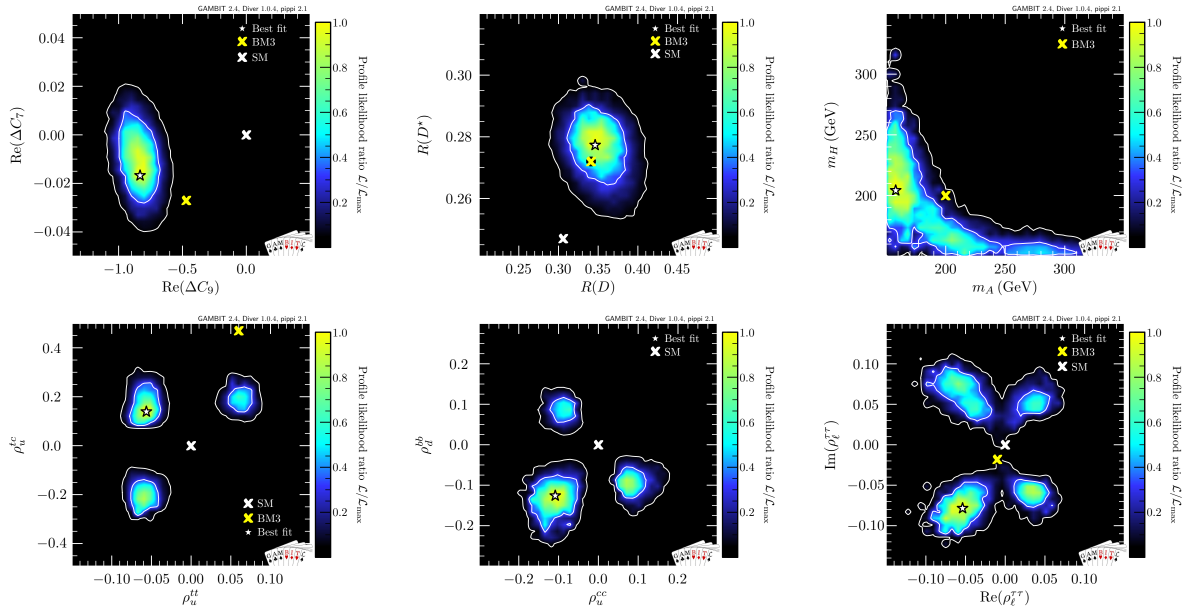

Figure 1: *Profile likelihood ratios for different combinations of model parameters and observables using the PDG 2024 values for the S, T and U parameters. The white star denotes the best fit point, the white cross the SM prediction, and the yellow cross corresponds to BM3 from [25]. White contours around the best fit point are the 1σ and 2σ confidence intervals.*

m_H is slightly heavier at around 200 GeV although degenerated masses or inverted hierarchies are also possible (top right panel in 1). On the other hand, the degenerated regions of solutions in the $\rho_u^{tc} - \rho_u^{tt}$, $\rho_d^{bb} - \rho_u^{cc}$ and $\mathrm{Im}\left(\rho_\ell^{\tau\tau}\right) - \mathrm{Re}\left(\rho_\ell^{\tau\tau}\right)$ planes (bottom panels) can be understood as the overlap of the ΔC_7, ΔC_9 and $R(D^{(*)})$ functions. Regarding the neutral anomalies, we can see that rather large $|\rho_d^{bb}|$, $|\rho_u^{cc}| \simeq 0.1$ are needed in order to get the required values for the ΔC_7 and ΔC_9 Wilson coefficients respectively, shifting on one hand ΔC_7 towards slightly more negative values and on the other, generating constructive interference with the ρ_u^{cc} terms in ΔC_9.

In Figure 2 we can see that Δa_μ (top left) is perfectly compatible with the SM and with the BMW lattice results at the $0.91\,\sigma$ level. On the other hand, we can also see in the right panel that ΔM_{B_s} gets a worse fit than the SM, but is still compatible with it within the large theoretical uncertainty of the SM (dashed orange lines). A solution to this could be the inclusion of the tree level effects proportional to a small ρ_d^{bs} to fit the experimental value. Lastly, we show our predictions for the lepton flavour violating decays $\tau \to \mu\gamma$ and $\tau \to 3\mu$ in the bottom right panel of Figure 2, which are within 2σ of the future sensitivity limit from Belle II [38].

Additionally, with respect to the Higgs coupling strengths, we also show the predictions for the tau lepton and the charm and bottom quarks $\kappa_{b,\tau,c}$ in Figure 3. We see that the deviation at $1\,\sigma$ level in κ_b and κ_τ could be about 10% while as large as 30% for κ_c. Given that the current uncertainty of κ_b and κ_τ is about 10% as well the fit perfectly agrees with the data. However, HL-LHC will shrink those uncertainties to 4% and 2% respectively and hence they could see a possible deviation from their current central values [39]. On the other hand, we would need future lepton colliders to probe κ_c at less than 10% [39, 40] in ordet to test our prediction for it.

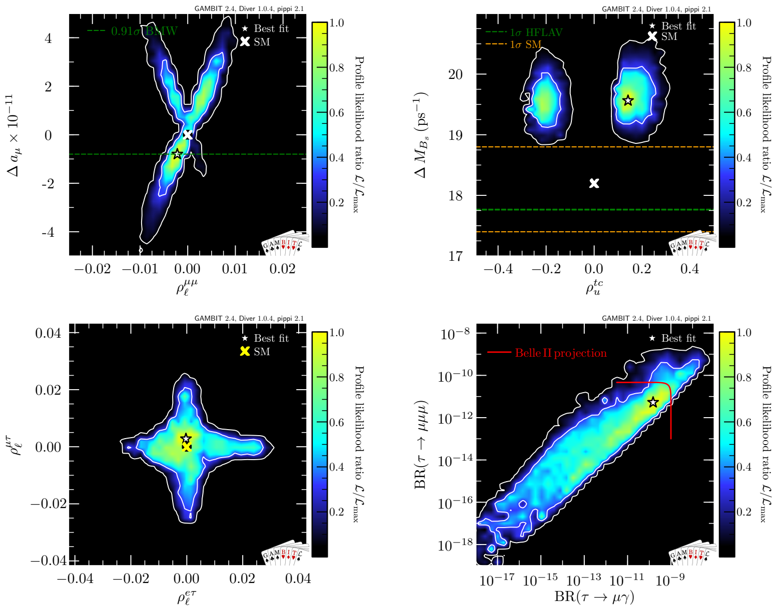

Figure 2: *Profile likelihood ratios $\mathcal{L}/\mathcal{L}_{max}$ for different 2D plots of the parameter space.*

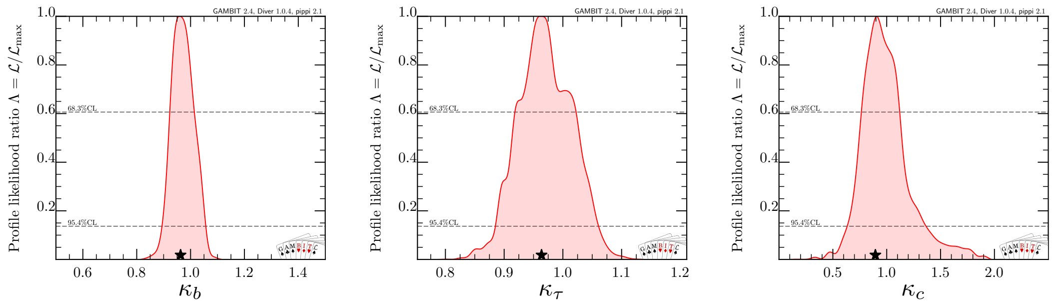

Figure 3: *One-dimensional profile likelihood ratios $\mathcal{L}/\mathcal{L}_{max}$ for the Higgs coupling strength of the bottom quarks, tau lepton, and charm quarks from left to right.*

Finally, in Table 1 we make a comparison between the best fit values obtained using the S, T and U parameters related to the PDG 2024 and the CDF-II data. We see that both the neutral and charged anomalies get slightly worse values at the best fit point when using CDF-II data compared to the PDG 2024 and more importantly, the CDF-II data can be explained only at the 2σ level, whereas the PDG 2024 data can be fitted at the 1σ level. Regarding $(g_2)_\mu$, CDF-II data actually drives the fit towards a positive value for Δa_μ in comparison to PDG 2024, which prefers a negative value for it, nevertheless in agreement at the 0.9σ level with the latest BMW lattice group results and also allows for positive values within the 1σ level. Notably, the CDF-II fit, although less favoured than the PDG 2024 one, predicts a much smaller branching ratio for the $B_c \to \tau\nu$ decay.

5. Conclusions

We show that it is possible to fit at the $1\,\sigma$ level both the charged and the neutral anomalies in the G2HDM constrained by both top and meson decays among lepton flavour violation and lepton

STU	PDG 2024	CDF-II
m_{H^+}	131 GeV	133 GeV
$m_{H,A}$	205, 158 GeV	227, 201 GeV
$c_{\beta\alpha}$	0.007	0.03
ρ_u^{tt}	−0.06	−0.06
ρ_u^{tc}	0.14	−0.15
ρ_u^{cc}	−0.1	0.1
ρ_d^{bb}	−0.07	0.1
$\rho_\ell^{\tau\tau}$	$-0.05(1 \pm 1.6\,i)$	$-0.002(1 \pm 25\,i)$
$\rho_\ell^{\mu\mu}$	−0.0015	0.002
$\rho_\ell^{\mu\tau}$	0.003	−0.001
$\rho_\ell^{e\tau}$	3×10^{-4}	0.007
$\mathrm{BR}(t \to b\bar{b}c)$	0.16%	0.16%
$R(D)$	0.346	0.371
$R(D^*)$	0.277	0.258
$\mathrm{BR}(B_c \to \tau\bar{\nu})$	39 %	8 %
ΔC_9^U	−0.83	−0.76
ΔC_7	−0.016	−0.011
$\Delta a_\mu^{BMW} \times 10^{-11}$	−0.8	1.2
STU $(\Delta\chi^2)$	0.06	−11.5

Table 1: The values of the parameters at the best fit point and predictions from the scan using the BMW group value for $g-2$ for the S, T and U parameters related to the m_W mass from the PDG 2024 value (left) and the CDF-II detector (right). Here we define $\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm G2HDM}$.

universality tests, while simultaneously satisfying *constraints* from $(g_2)_\mu$ and electroweak precision observables from PDG 2024 within 1 σ. When using the CDF II detector value for m_W we find that the model can fit the data for the S, T and U parameters only at the 2σ level, giving a worse fit to the flavour anomalies and at the same time improving(worsening) the fit to Δa_μ when using the BMW(WP) value. We also found that the model can be tested at Belle II in LFV searches for $\tau \to 3\mu$ and $\tau \to \mu\gamma$. Finally, we show that the model can also be probed in the measurements of κ_b and κ_τ in the future HL-LHC.

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