$(g-2)_l$ IN THE GENERAL FLAVOUR CONSERVING 2HDM

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(with F. Cornet-Gómez and M. Nebot, PRD 98, 035046 (2018) and work in progress)

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Introduction I

- It is well-known that two Higgs doublet models (2HDM) can introduce new flavour structures in the couplings to the new scalars, including flavour changing neutral currents (FCNC).
- Therefore, 2HDM can introduce also diagonal lepton flavour structures **different from the charged lepton mass matrix** -lepton flavour universality violation (LFUV)-.
- We will revise 2HDM without FCNC (neither in the quark nor in the lepton sectors) but with **LFUV**
- We will study a simultaneous explanation of the electron and muon $(g-2)_l$ anomalies

The Flavour Sector of 2HDM I

$$L_Y = -\overline{Q}_L \left(\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2\right) d_R - \overline{Q}_L \left(\Delta_1 \widetilde{\Phi}_1 + \Delta_2 \widetilde{\Phi}_2\right) u_R$$
$$-\overline{L}_L \left(\Pi_1 \Phi_1 + \Pi_2 \Phi_2\right) l_R + .h.c.$$

$$\Phi_j = e^{i\theta_j} \begin{pmatrix} \varphi_j^+ \\ \left(v_j + \rho_j + i\eta_j\right) / \sqrt{2} \end{pmatrix}$$

The Yukawa sector in the Higgs basis $v^2 = v_1^2 + v_2^2$, $c_\beta = v_1/v$, $s_\beta = v_2/v$, $t_\beta = v_2/v_1$

$$\begin{pmatrix} e^{-i\theta_1}\Phi_1 \\ e^{-i\theta_2}\Phi_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

The Flavour Sector of 2HDM II

will be

$$
\begin{aligned}
L_Y &= -\overline{Q}_L \frac{\sqrt{2}}{v} \left(M_d^0 H_1 + \mathbf{N}_d^0 H_2 \right) d_R - \overline{Q}_L \frac{\sqrt{2}}{v} \left(M_u^0 \widetilde{H}_1 + \mathbf{N}_u^0 \widetilde{H}_2 \right) u_R \\
&\quad -\overline{L}_L \left(M_l^0 H_1 + \mathbf{N}_l^0 H_2 \right) l_R + h.c
\end{aligned}
$$

where by definition $\langle H_1 \rangle^T = \begin{pmatrix} 0 & v/\sqrt{2} \end{pmatrix}, \langle H_2 \rangle^T = \begin{pmatrix} 0 & 0 \end{pmatrix}$.
Once M_f^0 get diagonalized by rotating the fermion fields we get the diagonal mass matrices $M_{d,u,l}$ and the new coupling $N_{d,u,l}$ that are the "dangerous" matrices that in general can introduce FCNC. In general we cannot simultaneously diagonalize M_f^0 and N_f^0

General Flavour Conservation (gFC) I

The conditions to have simultaneous diagonalization of N_d^0, N_u^0, N_l^0 and the corresponding mass matrices M_d^0, M_u^0, M_l^0 were described long ago. In the most general 2HDM the necessary and sufficient conditions obeyed by the quark and lepton Yukawa coupling matrices $\Gamma_\alpha, \Delta_\alpha$ and Π_α in order to have gFC are that **each of the following sets are abelian.**

$$\begin{aligned}
\left\{\Gamma_\alpha \Gamma_\beta^\dagger\right\} \;;\; \left\{\Gamma_\alpha^\dagger \Gamma_\beta\right\} \;; \alpha, \beta &= 1,2 \\
\left\{\Delta_\alpha \Delta_\beta^\dagger\right\} \;;\; \left\{\Delta_\alpha^\dagger \Delta_\beta\right\} \;; \alpha, \beta &= 1,2 \\
\left\{\Pi_\alpha \Pi_\beta^\dagger\right\} \;;\; \left\{\Pi_\alpha^\dagger \Pi_\beta\right\} \;; \alpha, \beta &= 1,2
\end{aligned}$$

Therefore, to have a diagonal structure for the matrices N_d, N_u and N_l (to have gFC)

$$N_d = \begin{pmatrix} n_d & 0 & 0 \\ 0 & n_s & 0 \\ 0 & 0 & n_b \end{pmatrix}, N_u = \begin{pmatrix} n_u & 0 & 0 \\ 0 & n_c & 0 \\ 0 & 0 & n_t \end{pmatrix}, N_l = \begin{pmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{pmatrix}$$

General Flavour Conservation (gFC) II

The conditions to be fulfilled are

$$\begin{aligned}
\left[\Gamma_\alpha\Gamma_\beta^\dagger, \Gamma_\gamma\Gamma_\delta^\dagger\right] &= 0\ ; \quad \left[\Gamma_\alpha^\dagger\Gamma_\beta, \Gamma_\gamma^\dagger\Gamma_\delta\right] = 0 \\
\left[\Delta_\alpha\Delta_\beta^\dagger, \Delta_\gamma\Delta_\delta^\dagger\right] &= 0\ ; \quad \left[\Delta_\alpha^\dagger\Delta_\beta, \Delta_\gamma^\dagger\Gamma_\delta\right] = 0 \\
\left[\Pi_\alpha\Pi_\beta^\dagger, \Pi_\gamma\Pi_\delta^\dagger\right] &= 0\ ; \quad \left[\Pi_\alpha^\dagger\Pi_\beta, \Pi_\gamma^\dagger\Pi_\delta\right] = 0
\end{aligned}$$

- There are solutions based on symmetries:
    1. The well known Z_2 symmetry leading to Natural Flavour Conservation (NFC) (Glashow, Weinberg, Paschos). That is the 2HDM types I,II,X and Y.
    2. Additional U(1) gauge symmetries (Ko et al., Campos et al.)
    3. R. Gatto, G. Morchio, G. Sartori, F. Strocchi, R. Barbieri, W. Grimus, G. Ecker, G. Segre, H. A. Weldonk, K. Kang, A.C. Rothman, M. Leurer, Y. Nir, N. Seiberg, etc.

General Flavour Conservation (gFC) III

- Suppression rather than forbiddance:
  1. By masses: Cheng-Sher ansatz. Also A. Antaramian, L.J. Hall, A. Rasin, S. Weinberg, Y.L. Wu, L. Wolfenstein, etc.
  2. Aligned model A2HDM (Pich, Tuzón)
  3. By CKM and masses: Branco, Grimus, Lavoura (BGL models) and its generalizations, also Joshipura and Rindani.

Stability of gFC under RGE I

The Yukawa couplings evolve under RGE as $\left(\mathcal{D} \equiv 16\pi^2 \mu \left(d/d\mu\right)\right)$

$$\mathcal{D}\Gamma_k = a_\Gamma \Gamma_k + \sum_{l=1}^{2} \left(T^d_{k,l}\Gamma_l - 2\Delta_l \Delta_k^\dagger \Gamma_l + \Gamma_k \Gamma_l^\dagger \Gamma_l + \frac{1}{2}\Delta_l \Delta_l^\dagger \Gamma_k + \frac{1}{2}\Gamma_l \Gamma_l^\dagger \Gamma_k \right)$$

$$\mathcal{D}\Delta_k = a_\Delta \Delta_k + \sum_{l=1}^{2} \left(T^u_{k,l}\Delta_l - 2\Gamma_l \Gamma_k^\dagger \Delta_l + \Delta_k \Delta_l^\dagger \Delta_l + \frac{1}{2}\Gamma_l \Gamma_l^\dagger \Delta_k + \frac{1}{2}\Delta_l \Delta_l^\dagger \Delta_k \right)$$

$$\mathcal{D}\Pi_k = a_\Pi \Pi_k + \sum_{l=1}^{2} \left(T^l_{k,l}\Pi_l + \Pi_k \Pi_l^\dagger \Pi_l + \frac{1}{2}\Pi_l \Pi_l^\dagger \Pi_k \right)$$

$$T^{u*}_{k,l} = 3\,Tr\left(\Gamma_k \Gamma_l^\dagger + \Delta_k^\dagger \Delta_l\right) + Tr\left(\Pi_k \Pi_l^\dagger\right) = T^d_{k,l} = T^l_{k,l}$$

Stability of gFC under RGE II

The Stability conditions for gFC under RGE are

$$\begin{aligned}
\mathcal{D}\left[\Gamma_\alpha \Gamma_\beta^\dagger, \Gamma_\gamma \Gamma_\delta^\dagger\right] &= 0\ ;\ \mathcal{D}\left[\Gamma_\alpha^\dagger \Gamma_\beta, \Gamma_\gamma^\dagger \Gamma_\delta\right] = 0 \\
\mathcal{D}\left[\Delta_\alpha \Delta_\beta^\dagger, \Delta_\gamma \Delta_\delta^\dagger\right] &= 0\ ;\ \mathcal{D}\left[\Delta_\alpha^\dagger \Delta_\beta, \Delta_\gamma^\dagger \Gamma_\delta\right] = 0 \\
\mathcal{D}\left[\Pi_\alpha \Pi_\beta^\dagger, \Pi_\gamma \Pi_\delta^\dagger\right] &= 0\ ;\ \mathcal{D}\left[\Pi_\alpha^\dagger \Pi_\beta, \Pi_\gamma^\dagger \Pi_\delta\right] = 0
\end{aligned}$$

The equations in the quark sector can be written in terms of a set of equations depending on V_{CKM}, on all the up and down quark masses and all the new complex parameters $n_u, n_{c,} n_t, n_d, n_s$ and n_b.
The equations in the lepton sector can be written in terms of the charged lepton masses and the new complex parameters n_e, n_μ and n_τ.

Stability of gFC under RGE (Solutions) I

In the context of the A2HDM $\Gamma_2 = d \cdot \Gamma_1$; $\Delta_2 = u \cdot \Delta_1$; $\Pi_2 = e \cdot \Pi_1$ one recovers two kinds of solutions:

1. $(u^* - d)\,(1 + ud) = 0$
   This result give rise to type I or type II 2HDM in the quark sector, without constraint in the lepton sector (including the inert 2HDM). By requiring in addition the non running of d, u and e one gets the 2HDM type I,II,X and Y (Ferreira, Lavoura and Silva).
2. $\Delta_1 \Delta_1^\dagger \Gamma_1 = \lambda_\Gamma \Gamma_1, \Gamma_1 \Gamma_1^\dagger \Delta_1 = \lambda_\Delta \Delta_1$
   If to this second solution we impose Yukawa structures which are, in leading order, in agreement with the observed pattern of quark masses and mixing we are lead to the democratic mass solution giving rise to an additional quark alignment among the up and the down sectors

$$\Delta_1 = c_u \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \text{ and } \Gamma_1 = c_d \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

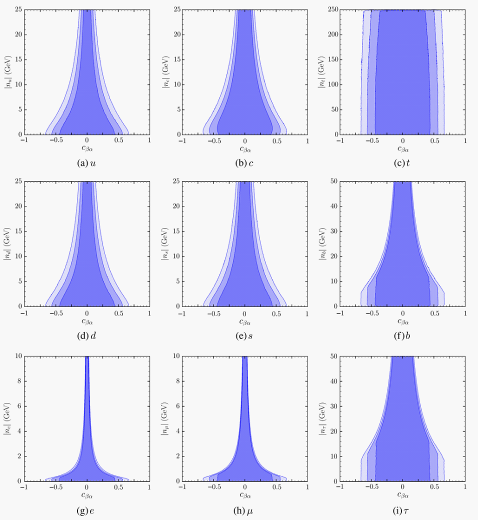
Stability of gFC under RGE (Solutions) II

3. Still looking at solution 1, a not so known result is the fact that in A2HDM $\Pi_2 = e \cdot \Pi_1$ is stable under RGE:
   Alignment in the charge leptonic sector is stable under RGE. The absence of right-handed neutrinos and the corresponding Yukawa coupling prevents any misalignment in the charged lepton sector. This results suggests to perform fits with 2HDM type I or II in the quark sector but aligned in the leptonic one.
4. **gFC in the leptonic sector is stable under RGE**. This suggests to perform fits with 2HDM type I or II but with a gFC leptonic sector. That means to use with type I or II in the quark sector, the following leptonic sector (stable under RGE)

$$N_l = \begin{pmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{pmatrix}$$

5. There are still other three solutions with $V_{Cabibbo}$ instead of V_{CKM}

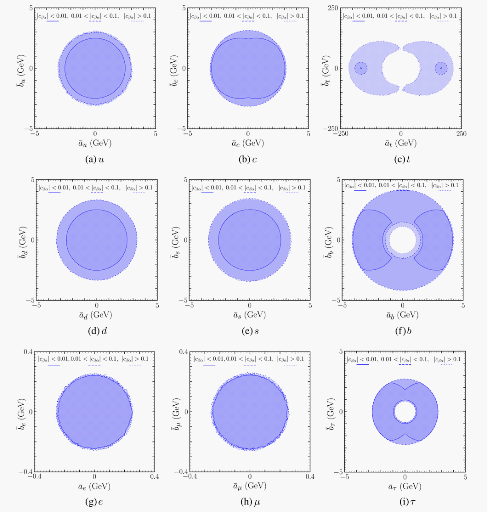
Phenomenology of gFC 2HDM I



Phenomenology of gFC 2HDM II

$$
\begin{aligned}
L_{hf\bar{f}} &= -h\bar{f}\left(a_f + ib_f\gamma_5\right) f \\
a_f &= \frac{m_f}{v} \Rightarrow a_f = \frac{1}{v}\left(s_{\beta\alpha} m_f + c_{\beta\alpha} n_f^R\right) \\
b_f &= 0 \Rightarrow b_f = c_{\beta\alpha}\frac{n_f^I}{v}
\end{aligned}
$$

Phenomenology of gFC 2HDM III



Two anomalies (work in progress) I

We are going to consider the two anomalies

$$\delta a_\mu^{\exp} \sim (2.7 \pm 0.9) \cdot 10^{-9} \quad ; \quad \delta a_e^{\exp} \sim -(8.7 \pm 3.6) \cdot 10^{-13}$$

$$\delta a_l = K_l \Delta_l \qquad K_l = \frac{1}{8\pi^2}\left(\frac{m_l}{v}\right)^2$$

$$\boldsymbol{\Delta_e \sim -16}$$

$$\boldsymbol{\Delta_\mu \sim 1}$$

In two general models:
2HDM type I (quark sector) and gFC in the lepton sector

$$N_d = \cot\beta M_d \quad ; \quad N_u = \cot\beta M_u \quad ; \quad N_l = \begin{pmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{pmatrix}$$

2HDM type II (quark sector) and gFC in the lepton sector

$$N_d = -\tan\beta M_d \quad ; \quad N_u = \cot\beta M_u \quad ; \quad N_l = \begin{pmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{pmatrix}$$

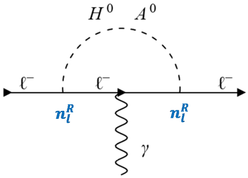
Two anomalies (work in progress) II

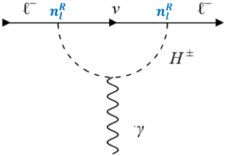
The complete model - in the quark type I or II framework- has a Z_2 symmetric Higgs potential with a soft breaking term.

$$
\begin{aligned}
V &= \mu_{11}^2 \Phi_1^\dagger \Phi_1 + \mu_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}\left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\
&\quad + \left[\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + h.c.\right] + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\
&\quad + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2
\end{aligned}
$$

1 and 2 loop contribution to (g-2) I

The 1 loop contribution is $(n_l = \mathrm{Re}\, n_l + i\, \mathrm{Im}\, n_l)$ with $\mathrm{Im}\, n_l = 0$ and $\mathrm{Re}\, n_l = n_l^R$



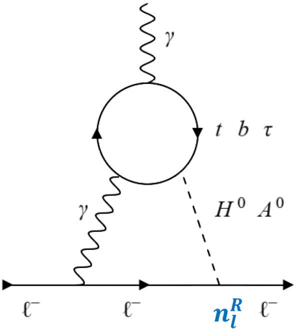


$$\delta a_l^1 \left(H + A + H^+\right) = K_l \left(n_l^R\right)^2 \left(\frac{h_{lH}}{M_H^2} - \frac{h_{lA} - \frac{2}{3}}{M_A^2} - \frac{2}{3 M_{H^+}^2}\right)$$

$$h_{fS} \approx -\frac{7}{6} - \ln\left(\frac{m_l}{M_S}\right)^2 ; \quad \begin{array}{l} h_{eS} \sim 24.6 - 29.2 \\ h_{\mu S} \sim 13.9 - 18.5 \end{array}$$

1 and 2 loop contribution to (g-2) II

The 2 loop contributions consider here are given by



1 and 2 loop contribution to (g-2) III

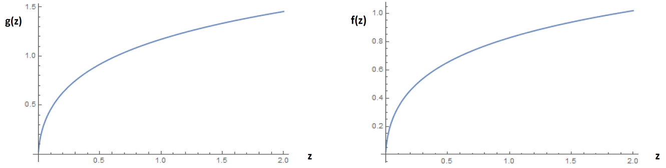
$$\delta a_l^2 = -K_l \left(\frac{2\alpha}{\pi}\right)\left(\frac{n_l^R}{m_l}\right) F_l\left(\beta, t, b, \tau, H, A\right) \;;\; F_l = F + \Delta F_l$$

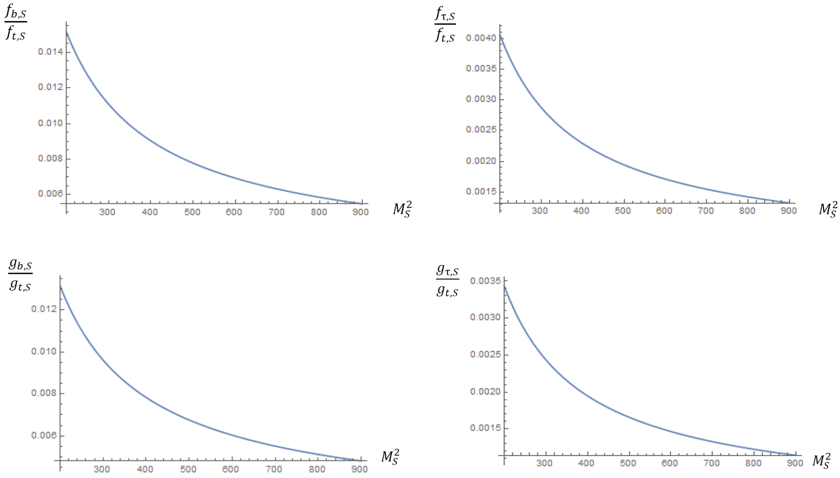
$$F^I = \frac{\cot\beta}{3}\left[4\left(f_{tH} + g_{tA}\right) + \left(f_{bH} - g_{bA}\right)\right] + \left(\frac{n_\tau^R}{m_\tau}\right)\left(f_{\tau H} - g_{\tau A}\right)$$

$$F^{II} = \frac{\cot\beta}{3}\left[4\left(f_{tH} + g_{tA}\right) - \tan^2\beta\left(f_{bH} - g_{bA}\right)\right] + \left(\frac{n_\tau^R}{m_\tau}\right)\left(f_{\tau H} - g_{\tau A}\right)$$

$$\Delta F_l = \left(\frac{n_l^I}{n_l^R}\right)\left(\frac{n_\tau^I}{m_\tau}\right)\left(f_{\tau A} - g_{\tau H}\right)$$

$$f_{fS} = f\left(\frac{m_f^2}{M_S^2}\right)$$
$$g_{fS} = g\left(\frac{m_f^2}{M_S^2}\right)$$





Our approach to understand both δa_e and δa_μ will be the following (in the limit of $n_l = n_l^R$, that is $n_l^I = 0$)

1 and 2 loop contribution to (g-2) V

- δa_e will be explained by the 2 loop contribution with $n_e^R \sim$ few GeV
- δa_μ will be explained, mainly, by the 2 loop contribution, in fact it is trivial to see the scaling of the 2 loop formula .

$$\frac{\delta a_e}{\delta a_\mu} = \frac{m_e n_e^R}{m_\mu n_\mu^R}$$

what gives rise to the following constraint

$$n_\mu^R = -\left(15.11^{+15.11}_{-7.56}\right) n_e^R$$

For the muon we will have some contribution from 1 loop in regions of the parameter space with large $\tan\beta$, n_e^R large and light M_H.

General Constraints I

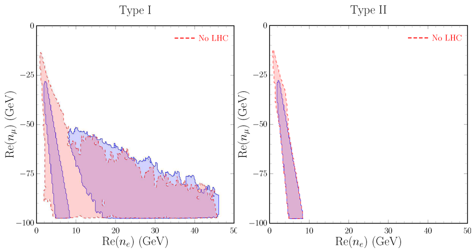
- Scalar sector: boundness, perturbative unitarity and oblique parameters.
- Production×decay signal strengths of the 125 GeV Higgs-like scalar h and other properties. Because we need $n_e^R >> m_e$ and $n_\mu^R >> m_\mu$, we get important constraint on the mixing among h and the other scalars (in fact we are near to the alignment limit).
- We impose the constraints related to Lepton Flavour Universality (LFU): $l \to l' \nu_l \overline{\nu}_{l'}$ (including right-handed currents) $, \pi^- \to \mu^- \overline{\nu}_\mu, \pi^- \to e^- \overline{\nu}_e, K^- \to \mu^- \overline{\nu}_\mu, K^- \to e^- \overline{\nu}_e, \tau^- \to \pi^- \nu_\tau, \tau^- \to K^- \nu_\tau$
- Flavour constraints: the charged Higgs contribution to meson mixing and to $b \to s\gamma$.
- Constraints on $e^+ e^- \to l^+ l^-$ from LEP up to 200 GeV

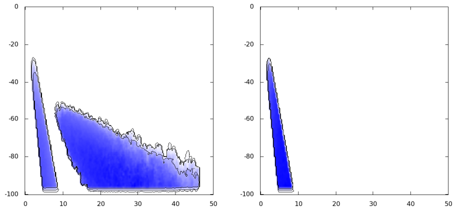
General Constraints II

- The $(g-2)$ for the electron and muon and when we allowed, in full generality, $n_l = n_l^R + i n_l^I$ (with $n_l^I \neq 0$) we also impose the leptons edm. In general we use $|n_l| < 100 GeV$.
- Searches of dilepton resonances.

Results II

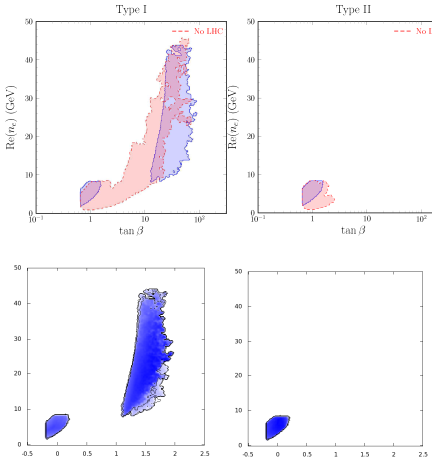
- In the context of type I and type II in the quarks sector **with SB** in the Higgs potential we get



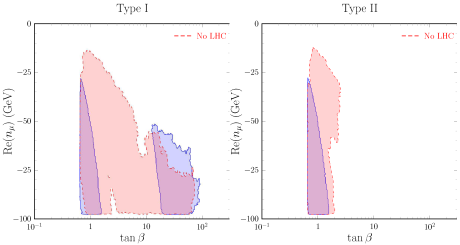


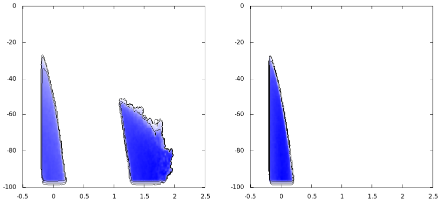
Results III

- The previous correlation plots in $\mathrm{Re}\,(n_\mu) - \mathrm{Re}\,(n_e)$ correspond to the following $\mathrm{Re}\,(n_e) - \tan\beta$ regions



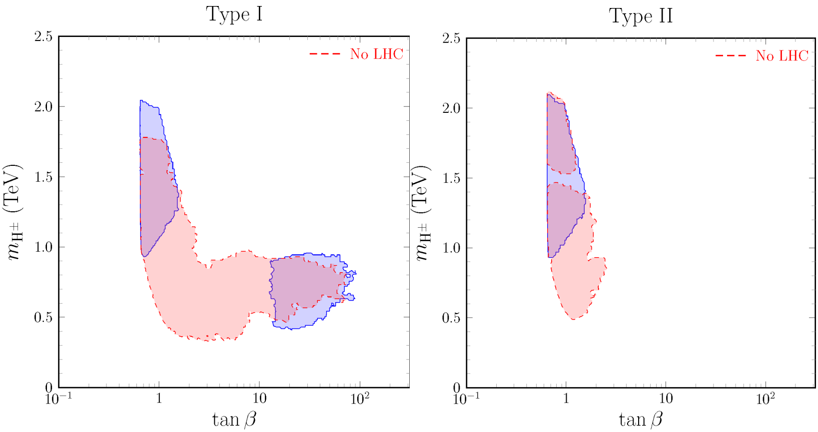
- And to the following $\mathrm{Re}\left(n_\mu\right) - \tan\beta$ regions





Results V

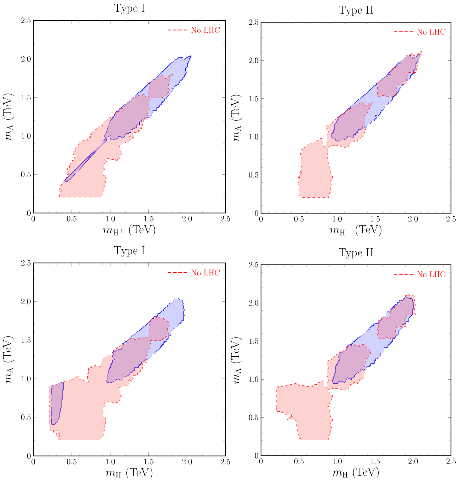
- Looking at the $M_{H^\pm} - \tan\beta$ correlations it is clear that the region with large $\tan\beta$ has light charged Higgs



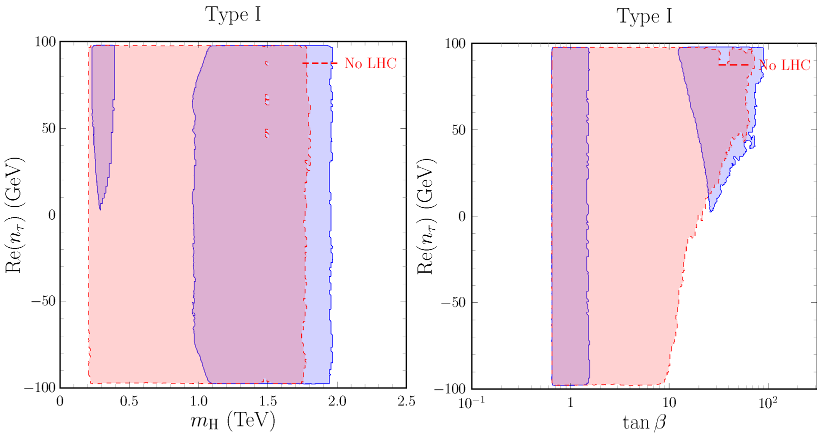
Results VI

- And looking at the scalar masses regions we see that the large $\tan\beta$ region corresponds to light scalars with the allowed channels $A \longrightarrow HZ$ and $H^{\pm} \longrightarrow HW^{\pm}$

Results VII


Type I
No LHC
m_A (TeV)
$m_{H^\pm}$ (TeV)
Type II
No LHC
m_A (TeV)
$m_{H^\pm}$ (TeV)
Type I
No LHC
m_A (TeV)
m_H (TeV)
Type II
No LHC
m_A (TeV)
m_H (TeV)

- $\mathrm{Re}\,(n_\tau)$ has its role also in the light Higgs-large $\tan\beta$ region.



Results IX

- **Once we include dilepton resonance searches there are no solutions in the Z_2 symmetric case**. The absence of m_{12} does not allow neither large $\tan\beta$ neither heavy $(\geq 1\,TeV)$ scalars. And this fact diminishes the possibilities of evading the dilepton resonance searches.

Conclusions I

- In the context of the gFC 2HDM in the simplified version of having type I or II for the quark sector we can explain simultaneously both the electron and muon $g-2$ anomalies.
- This explanation is possible provided one introduces a soft breaking term in the Z_2 invariant Higgs potential.
- In the type II the solution comes from the 2 loop diagrams. Heavy Higgs bosons 1 TeV $\lesssim M_S \lesssim$ 2 TeV, $\tan\beta \sim 1$ and $n_\mu^R \sim -15 n_e^R$ with $n_e^R \in (2,8)$ GeV.
- In type I there is a solution similar to the previous one. But there is an additional solution with light scalars - and having also 1 loop contribution to the muon $g-2$- verifying: $M_A \sim M_{H^\pm} \in (400, 950)$ GeV, $M_A > M_H$, $10 \lesssim \tan\beta \lesssim 100$ and 230 GeV $\lesssim M_H \lesssim$ 390 GeV. Having $A \to HZ$ and $H^\pm \to HW^\pm$ as dominant channels

GUIFEST2019

15 October 2019
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HIGGS AND FLAVOUR TODAY

A Scientific Symposium Celebrating Gui Rebelo's 60th Birthday

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Luis Lavoura
Takuya Morozumi (*)
Miguel Nebot
Per Osland
Sergio Palomares
Pedro Pereira
Morimitsu Tanimoto
Jose W. F. Valle
George Zoupanos

(*) to be confirmed

Our friend Gui has been a long term collaborator of several groups at IFIC in Valencia, with many joint publications in hot topics such as CP violation, neutrinos, multi-Higgs models or models with vector-like quarks

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