Minimal Flavour Violation in BGL Models

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Two Higgs Doublet Models

Despite several good motivations,
there is the need to suppress potentially dangerous FCNC:

Without HFCNC

- discrete symmetry leading to NFC

Weinberg, Glashow (1977); Paschos (1977)

- aligned two Higgs doublet model Pich, Tuzon (2009)

With HFCNC

- assume existence of suppression factors

Antaramian, Hall, Rasin (1992); Hall, Weinberg (1993); Joshipura, Rindani (1991)

- first models of this type with no ad-hoc assumptions

suppression by small elements of VCKM

Branco, Grimus, Lavoura (1996)

Minimal Flavour Violation

Notation

Yukawa Interactions

$$\mathcal{L}_Y = -\overline{Q_L^0}\ \Gamma_1 \Phi_1 d_R^0 - \overline{Q_L^0}\ \Gamma_2 \Phi_2 d_R^0 - \overline{Q_L^0}\ \Delta_1 \tilde{\Phi}_1 u_R^0 - \overline{Q_L^0}\ \Delta_2 \tilde{\Phi}_2 u_R^0 + \text{h.c.}$$

$$\tilde{\Phi}_i = -i\tau_2 \Phi_i^*$$

Quark mass matrices

$$M_d = \frac{1}{\sqrt{2}}(v_1 \Gamma_1 + v_2 e^{i\theta} \Gamma_2), \quad M_u = \frac{1}{\sqrt{2}}(v_1 \Delta_1 + v_2 e^{-i\theta} \Delta_2),$$

Diagonalised by:

$$U_{dL}^\dagger M_d U_{dR} = D_d \equiv \text{diag}\ (m_d, m_s, m_b)\,,$$
$$U_{uL}^\dagger M_u U_{uR} = D_u \equiv \text{diag}\ (m_u, m_c, m_t)\,.$$

Leptonic Sector

$$-\overline{L_L^0}\ \Pi_1\Phi_1\ell_R^0 - \overline{L_L^0}\ \Pi_2\Phi_2\ell_R^0\ + \mathrm{h.c.}$$

$$\Big(- \overline{L_L^0}\ \Sigma_1\tilde{\Phi}_1\nu_R^0 - \overline{L_L^0}\ \Sigma_2\tilde{\Phi}_2\nu_R^0 + \mathrm{h.c.} \Big)$$

$$\Big(\frac{1}{2}{\nu_R^0}^T C^{-1} M_R \nu_R^0 + \mathrm{h.c.} \Big)$$

Expansion around the vev's

$$\phi_j = \begin{pmatrix} \phi_j^+ \\ \frac{e^{i\alpha_j}}{\sqrt{2}}\left(v_j + \rho_j + i\eta_j\right) \end{pmatrix}, \quad j = 1,2$$

we perform the following transformation

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = U \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}; \quad \begin{pmatrix} G^0 \\ I \end{pmatrix} = U \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}; \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$U = \frac{1}{v}\begin{pmatrix} v_1 e^{-i\alpha_1} & v_2 e^{-i\alpha_2} \\ v_2 e^{-i\alpha_1} & -v_1 e^{-i\alpha_2} \end{pmatrix}; \; v = \sqrt{v_1^2 + v_2^2} = \left(\sqrt{2}\, G_F\right)^{-1/2} \simeq 246\,\mathrm{GeV}$$

U singles out

H^0 with couplings to quarks proportional to mass matrices

G^0 neutral pseudo-Goldstone boson

G^+ charged pseudo-Goldstone boson

Physical neutral Higgs fields are combinations of H^0, R and I

Neutral and charged Higgs Interactions for the quark sector

$$\begin{aligned}
\mathcal{L}_Y(\text{quark, Higgs}) = & -\overline{d_L^0}\frac{1}{v}\left[M_d H^0 + N_d^0 R + i N_d^0 I\right] d_R^0 \\
& -\overline{u_L^0}\frac{1}{v}\left[M_u H^0 + N_u^0 R + i N_u^0 I\right] u_R^0 \\
& -\frac{\sqrt{2}H^+}{v}\left(\overline{u_L^0} N_d^0\, d_R^0 - \overline{u_R^0} N_u^{0\dagger}\, d_L^0\right) + \text{h.c.}
\end{aligned}$$

$$N_d^0 = \frac{1}{\sqrt{2}}(v_2\Gamma_1 - v_1 e^{i\theta}\Gamma_2), \quad N_u^0 = \frac{1}{\sqrt{2}}(v_2\Delta_1 - v_1 e^{-i\theta}\Delta_2).$$

Flavour structure of quark sector of 2HDM characterised by:

$$\text{four matrices } M_d,\ M_u,\ N_d^0,\ N_u^0.$$

Likewise for Leptonic sector, Dirac neutrinos:

$$M_\ell,\ M_\nu,\ N_\ell^0,\ N_\nu^0.$$

Yukawa Couplings in terms of quark mass eigenstates

for H^+, H^0, R, I

$$\mathcal{L}_Y(\text{quark, Higgs}) =$$

$$-\frac{\sqrt{2}H^+}{v}\bar{u}\left(V N_d \gamma_R - N_u^\dagger\, V \gamma_L\right) d + \text{h.c.} - \frac{H^0}{v}\left(\bar{u} D_u u + \bar{d} D_d\, d\right) -$$

$$-\frac{R}{v}\left[\bar{u}(N_u\gamma_R + N_u^\dagger \gamma_L)u + \bar{d}(N_d\gamma_R + N_d^\dagger\gamma_L)\, d\right] +$$

$$+ i\frac{I}{v}\left[\bar{u}(N_u\gamma_R - N_u^\dagger\gamma_L)u - \bar{d}(N_d\gamma_R - N_d^\dagger\gamma_L)\, d\right]$$

$$V = V_{CKM}$$

$$\gamma_L = (1-\gamma_5)/2 \qquad \gamma_R = (1+\gamma_5)/2$$

Flavour changing neutral currents controlled by:

$$N_d = \frac{1}{\sqrt{2}} U_{d_L}^{\dagger} \left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2 \right) U_{d_R}$$

$$N_u = \frac{1}{\sqrt{2}} U_{u_L}^{\dagger} \left(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2 \right) U_{u_R}$$

For generic two Higgs doublet models

N_u, N_d non-diagonal arbitrary

For definiteness rewrite N_d :

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}$$

conserves flavour

leads to FCNC

Up till here everything is perfectly general for 2HDM

The flavour structure of Yukawa couplings is not constrained by gauge invariance

All flavour changing transitions in SM are mediated by charged weak currents with flavour mixing controlled by V_{CKM}

MFV essentially requires flavour and CP violation linked to known structures of Yukawa couplings

[all new flavour changing transitions are controlled by the CKM matrix]

About Minimal Flavour Violation

Buras, Gambino, Gorbahn, Jager, Silvestrini (2001)
D'Ambrosio, Giudice, Isidori, Strumia (2002)

leptonic sector

Cirigliano, Grinstein, Isidori, Wise (2005)

$G_F = U(3)^5$ largest symmetry of the gauge sector
flavour violation completely determined by Yukawa couplings

Our framework
- multi-Higgs models
- no Natural Flavour Conservation
- must obey above condition (one of the defining ingredients of MFV framework)

In order to obtain a structure for Γ_i, Δ_i such that FCNC at tree level strength completely controlled V_{CKM}

Branco, Grimus, Lavoura imposed symmetry

$$Q^0_{Lj} \to \exp(i\tau) Q^0_{Lj} \; ; \quad u^0_{Rj} \to \exp(2i\tau) u^0_{Rj} \; ; \quad \Phi_2 \to \exp(i\tau) \Phi_2 \; , \quad \tau \neq 0, \pi$$

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} ; \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix} ; \quad \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} ; \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$j = 3$

Both Higgs have non-zero Yukawa couplings in the up and down sector

Special WB chosen by the symmetry

FCNC in down sector

if instead of $u^0_{Rj} \to \exp(2i\tau) u^0_{Rj}$ impose $d^0_{Rj} \to \exp(2i\tau) d^0_{Rj}$

then FCNC in up sector

Six different BGL models

$$(N_d)_{rs} = \frac{v_2}{v_1}(D_d)_{rs} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)\underbrace{(V_{CKM}^{\dagger})_{r3}(V_{CKM})_{3s}}_{\text{MFV}}(D_d)_{sp}$$

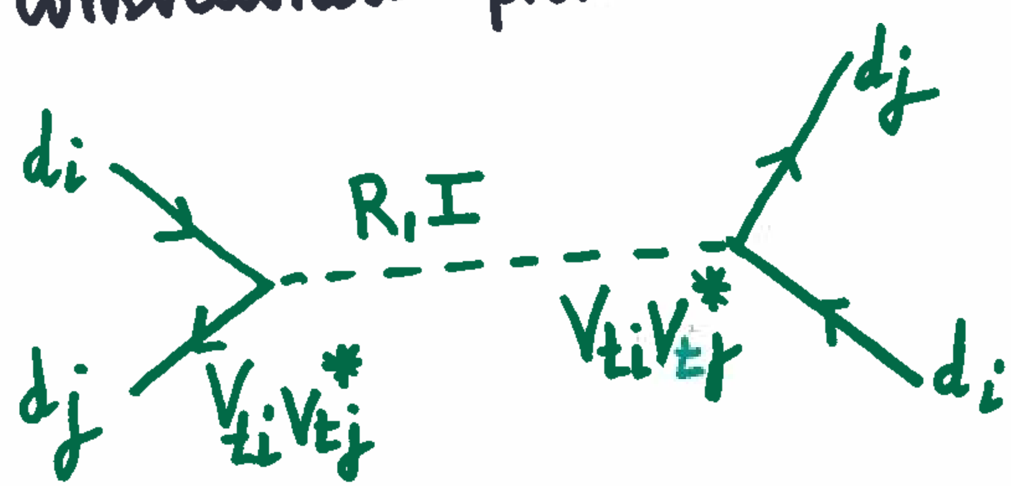
$$j = 3$$

$$N_u = -\frac{v_1}{v_2}\,\mathrm{diag}(0, 0, m_t) + \frac{v_2}{v_1}\,\mathrm{diag}(m_u, m_c, 0)$$

FCNC only in the down sector
suppression by the 3rd row of V_{CKM}
dependence on V_{CKM} and $\tan\beta$ only

Strong and Natural suppression of the most constrained processes

e.g. $|V_{td} V_{ts}^*|^2 \sim \lambda^{10}$



What is the necessary condition for N_d^0, N_u^0 to be of MFV type?

Should be functions of M_d, M_u no other flavour dependence

Furthermore, N_d^0, N_u^0 should transform appropriately under WB

$$Q_L^0 \to W_L Q_L^0 \,, \quad d_R^0 \to W_R^d \, d_R^0 \,, \quad u_R^0 \to W_R^u \, u_R^0$$

$$M_d \to W_L^\dagger M_d W_R^d \,, \qquad M_u \to W_L^\dagger M_u W_R^u$$

N_d^0, N_u^0 transform as M_d, M_u

$$N_d^0 \propto M_d \; ; \; (M_d M_d^\dagger) M_d \; ; \; (M_u M_u^\dagger) M_d$$

$$Y_d \; ; \; (Y_d Y_d^\dagger) Y_d \; ; \; (Y_u Y_u^\dagger) Y_d \qquad \text{Yukawa}$$

see previous references

What is particular about BGL models in MFV context?

$$M_d M_d^\dagger \equiv H_d \ ; \quad U_{d_L}^\dagger M_d U_{d_R} = D_d \ ; \quad U_{d_L}^\dagger H_d U_{d_L} = D_d^2$$

$$D_d^2 = \mathrm{diag}(m_d^2, m_s^2, m_b^2) = m_d^2 \underbrace{\begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}}_{P_1} + m_s^2 \underbrace{\begin{pmatrix} 0 & & \\ & 1 & \\ & & 0 \end{pmatrix}}_{P_2} + m_b^2 \underbrace{\begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}}_{P_3}$$

$$D_d^2 = \sum_i m_{d_i}^2 P_i$$

$$H_d = U_{d_L} D_d^2 U_{d_L}^\dagger = \sum_i m_{d_i}^2 U_{d_L} P_i U_{d_L}^\dagger = \sum_i m_{d_i}^2 P_i^{d_L}$$

$U_{d_L} P_i U_{d_L}^\dagger$ rather than $Y_d Y_d^\dagger$ are the minimal building blocks to be used in the expansion of N_d^0, N_u^0 conforming to the MFV requirement

Botella, Nebot, Vives 2004

WB covariant definition for BGL models

$$N_d^0 = \frac{v_2}{v_1} M_d - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) \mathcal{P}_j^\gamma M_d$$

$$N_u^0 = \frac{v_2}{v_1} M_u - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) \mathcal{P}_j^\gamma M_u$$

together with

$$\mathcal{P}_j^\gamma \Gamma_2 = \Gamma_2 \quad , \quad \mathcal{P}_j^\gamma \Gamma_1 = 0$$

$$\mathcal{P}_j^\gamma \Delta_2 = \Delta_2 \quad , \quad \mathcal{P}_j^\gamma \Delta_1 = 0$$

γ stands for u (up) or d (down)

$\mathcal{P}_j^\gamma$ are projection operators   Botella, Nebot, Vives 2004

$$\mathcal{P}_j^u = U_{uL} P_j U_{uL}^\dagger \qquad \mathcal{P}_j^d = U_{dL} P_j U_{dL}^\dagger$$

$$(P_j)_{\ell k} = \delta_{j\ell}\delta_{jk}$$

e.g. $P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

Possible generalisation of BGL models

MFV expansion for $N_d^0,\ N_u^0$

$$N_d^0 = \lambda_1\ M_d + \lambda_{2i}\ U_{dL} P_i U_{dL}^\dagger\ M_d + \lambda_{3i}\ U_{uL} P_i U_{uL}^\dagger\ M_d + \ldots$$

$$N_u^0 = \tau_1\ M_u + \tau_{2i}\ U_{uL} P_i U_{uL}^\dagger\ M_u + \tau_{3i}\ U_{dL} P_i U_{dL}^\dagger\ M_u + \ldots$$

In the quark mass eigenstate basis $N_d^0,\ N_u^0$ become:

$$N_d = \lambda_1\ D_d + \lambda_{2i}\ P_i\ D_d + \lambda_{3i}\ (V_{CKM})^\dagger\ P_i\ V_{CKM}\ D_d + \ldots$$

$$N_u = \tau_1\ D_u + \tau_{2i}\ P_i\ D_u + \tau_{3i}\ V_{CKM}\ P_i\ (V_{CKM})^\dagger\ D_u + \ldots$$

At this stage lambda and tau coefficients appear as free parameters

Need for symmetries in order to constrain these coefficients

BGL is the only implementation of models where Higgs FCNC are a function of V_{CKM} only (together with v_1, v_2) which are based on an Abelian symmetry obeying the sufficient conditions of having M_u block diagonal together with the existence of a matrix P such that

$$P\Gamma_2 = \Gamma_2 \quad ; \quad P\Gamma_1 = 0$$

Ferreira, Silva arXiv: 1012287

How to recognize a BGL model when written in arbitrary WB

Necessary and sufficient conditions for BGL

$$\Delta_1^\dagger \Delta_2 = 0 \; ; \quad \Delta_1 \Delta_2^\dagger = 0 \; ; \quad \Gamma_1^\dagger \Delta_2 = 0 \; ; \quad \Gamma_2^\dagger \Delta_1 = 0$$

Higgs mediated FCNC in the down sector

Imply existence of WB where these matrices can be cast in the form given before

The leptonic sector

Required for completeness

- study of experimental implications
- study of stability under RGE

Models with two Higgs doublets with FCNC

- controlled by V_{CKM} in the quark sector
- controlled by V_{PMNS} in the leptonic sector

Case of Dirac neutrinos, straightforward

Same flavour structure

Six different BGL-type models

Each of the thirty six models labelled by the pair (γ_j, β_k)

j, k refer to projectors $P_{j,k}$ in each sector γ, β

Example: $(up_3, \ell_2) = (t, \mu)$

will have no tree level NFC couplings (neutral flavour changing) in the up quark and charged lepton sectors, neutral HFC couplings in the down quark and neutrino sector controlled by

$V_{td_i} V^*_{td_j}$ and $U_{\mu\nu_a} U^*_{\mu\nu_b}$

Scalar Potential

The softly broken Z_2 symmetric 2HDM potential

$$V(\Phi_1,\Phi_2) = m_{11}^2 \phi_1^\dagger\phi_1 + m_{22}^2 \phi_2^\dagger\phi_2 - \left(m_{12}^2 \phi_1^\dagger\phi_2 + h.c.\right) + \frac{1}{2}\lambda_1 (\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2 (\phi_2^\dagger\phi_2)^2 + \lambda_3 (\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4 (\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5 (\phi_1^\dagger\phi_2)^2 + h.c.\right]$$

$$\phi_1 \to \phi_1 \;,\; \phi_2 \to -\phi_2$$

in our case $\phi_1 \to \phi_1$, $\phi_2 \to e^{iz}\phi_2$, $z \neq 0, \pi$ no λ_5 term

V does not violate CP neither explicitly nor spontaneously

7 free parameters : $m_h, m_H, m_A, m_{H^\pm}, v = \sqrt{v_1^2+v_2^2}, \tan\beta, \alpha \; (H^0, R)$

soft symmetry breaking prevents ungauged accidental continuous symmetry

In BǦL models the Higgs potential is constrained by the imposed symmetry to be of the form:

$$V_\Phi = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 - \left(m_{12} \Phi_1^\dagger \Phi_2 + \text{ h.c. } \right) + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right)$$
$$+ 2\lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 ,$$

Hermiticity would allow the coefficient
m_{12} to be complex, unlike the other coefficients of the scalar potential. However, freedom to rephase the scalar doublets allows to choose without loss of generality all coefficients real. As a result, V_Φ does not violate CP explicitly. It can also be easily shown that it cannot violate CP spontaneously. In the absence of CP violation the scalar field I does not mix with the fields R and H^0, therefore I is already a physical Higgs and the mixing of R and H^0 is parametrized by a single angle. There are two important rotations that define the two parameters, $\tan\beta$ and α, widely used in the literature:

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = \frac{1}{v} \begin{pmatrix} v_1 & v_2 \\ -v_2 & v_1 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

Our analysis: (arXiv:1401.6147)

Approximation of no mixing between R and H^0

We identify H^0 with the recently discovered Higgs field

This limit corresponds to $\beta - \alpha = \pi/2$

$v \equiv \sqrt{v_1^2 + v_2^2}$, $\tan\beta \equiv v_2/v_1$, **the quantity v is of course fixed by experiment**

Electroweak precision tests and in particular the T and S parameters lead to constraints relating the masses of the new Higgs fields among themselves

Grimus, Lavoura, Ogreid, Osland 2008

The bounds on T and S together with direct mass limits significantly restrict the masses of the new Higgs particles once the mass of charged Higgs is fixed

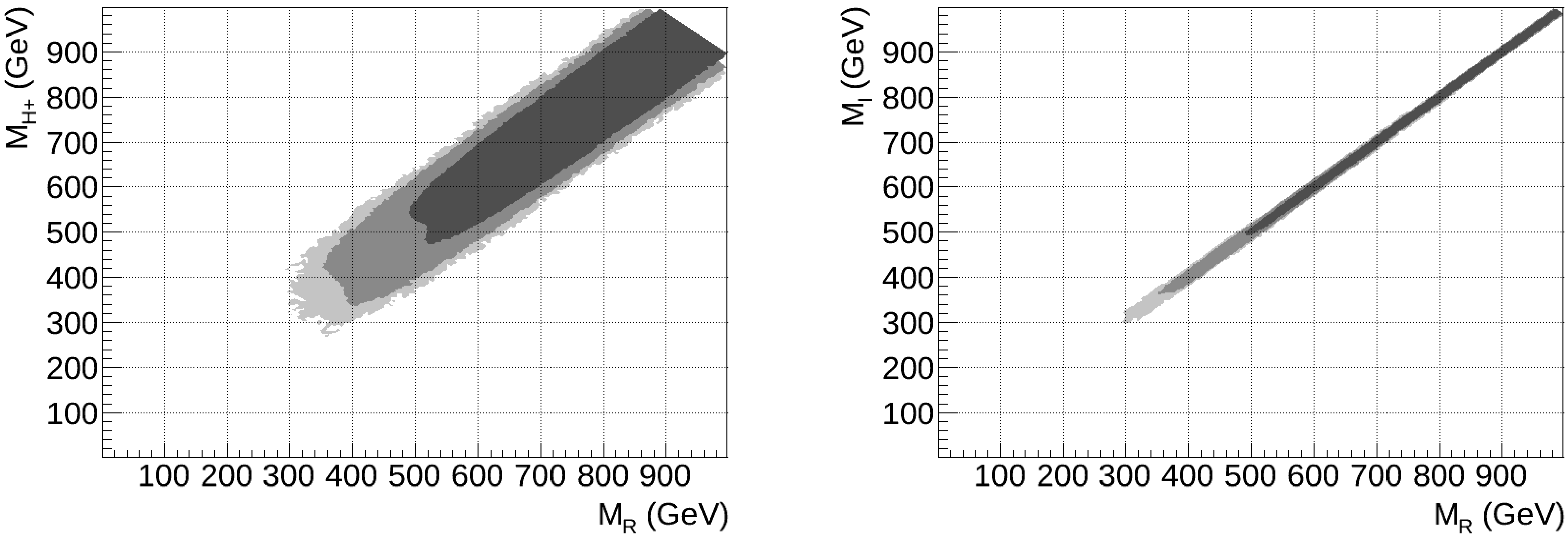
It is instructive to plot our results in terms of $m_{H^\pm}$ versus $\tan\beta$,

since in this context there is not much freedom left

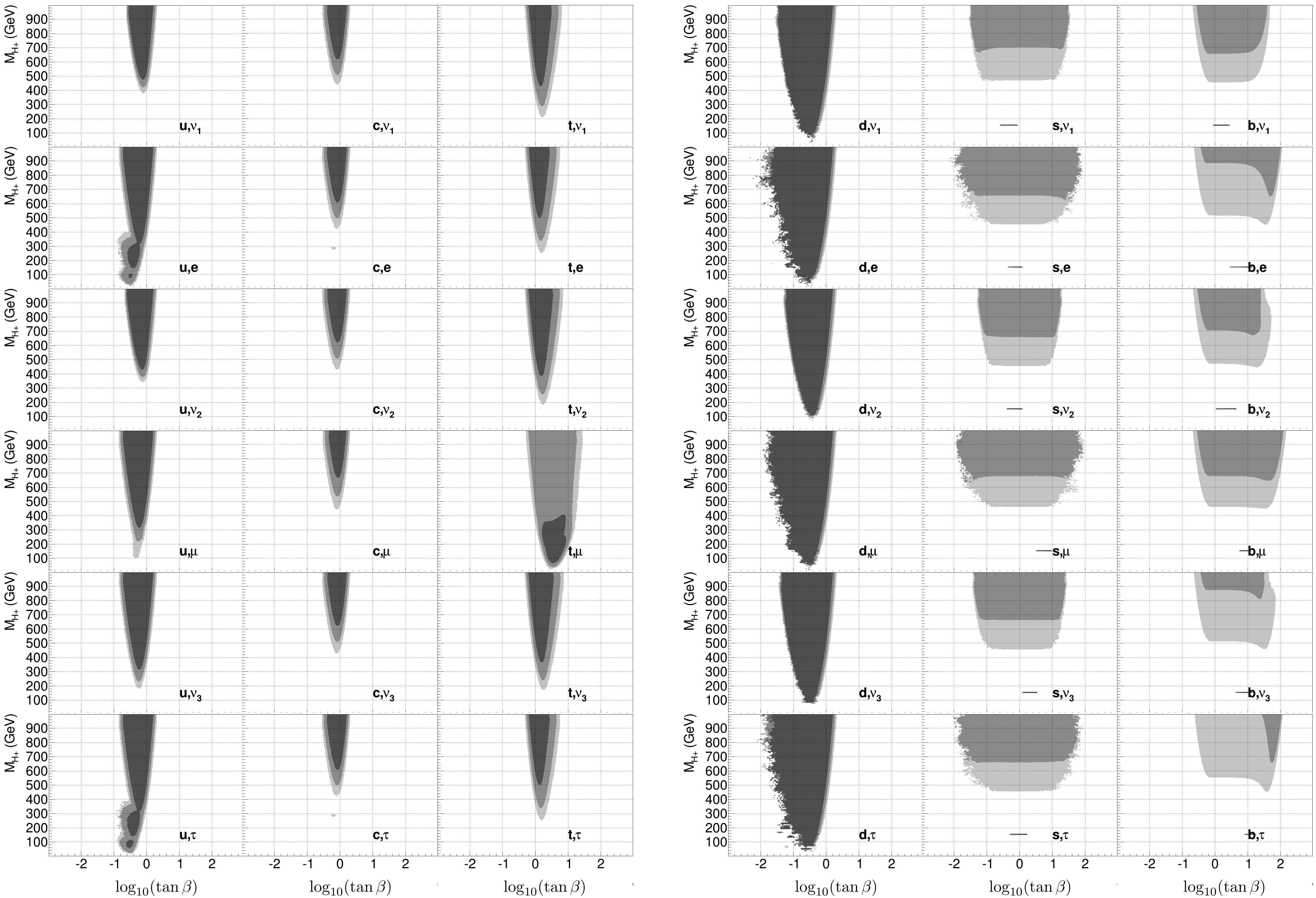
	BGL - 2HDM				SM	
	Charged $H^{\pm}$		Neutral R, I		Tree	Loop
	Tree	Loop	Tree	Loop		
$M \to \ell\bar{\nu}, M'\ell\bar{\nu}$	✓	✓		✓	✓	✓
Universality	✓	✓		✓	✓	✓
$M^0 \to \ell_1^+\ell_2^-$		✓	✓	✓		✓
$M^0 \rightleftarrows \bar{M}^0$		✓	✓	✓		✓
$\ell_1^- \to \ell_2^-\ell_3^+\ell_4^-$		✓	✓	✓		✓
$B \to X_s\gamma$		✓		✓		✓
$\ell_j \to \ell_i\gamma$		✓		✓		✓
EW Precision		✓		✓		✓

Summary of relevant constraints

This table indicates possible new contributions but for each specific model type some of them will be absent



Effect of the oblique parameters constraints in model (t, τ)

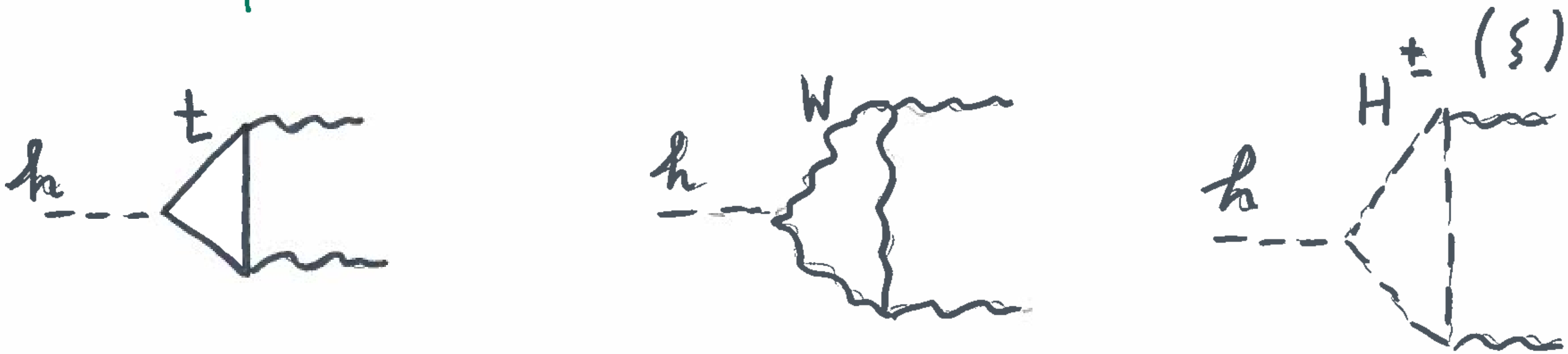


M_{H+} (GeV)
$\log_{10}(\tan\beta)$
u,ν_1
c,ν_1
t,ν_1
d,ν_1
s,ν_1
b,ν_1
u,e
c,e
t,e
d,e
s,e
b,e
u,ν_2
c,ν_2
t,ν_2
d,ν_2
s,ν_2
b,ν_2
u,μ
c,μ
t,μ
d,μ
s,μ
b,μ
u,ν_3
c,ν_3
t,ν_3
d,ν_3
s,ν_3
b,ν_3
u,τ
c,τ
t,τ
d,τ
s,τ
b,τ

Study of charged Higgs contribution to $h \to \gamma\gamma$, $h \to Z\gamma$

$\beta - \alpha = \frac{\pi}{2}$ $\qquad m_h = 125$ GeV $\qquad m_\xi > 100$ GeV

unitarity of scattering amplitudes
global stability of the potential
oblique electroweak T parameter



$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma^{SM}(h \to \gamma\gamma)} \qquad \mu_{Z\gamma} = \frac{\Gamma(h \to Z\gamma)}{\Gamma^{SM}(h \to Z\gamma)}$$

$m_\xi - \mu_{\gamma\gamma}$ plane $\qquad \mu_{\gamma\gamma}$ versus $\mu_{Z\gamma}$

Bhattacharyya, Das, Pal, MNR (2013)

h mediated FCNC (arXiv:1508.05101)

Flavour changing decays of top quarks

$$Y^U_{qt}(d_\rho) = -V_{q\rho} V^*_{t\rho} \, \frac{m_t}{v} \, c_{\beta\alpha}(t_\beta + t_\beta^{-1}) \, , \quad q = u, c \, .$$

Model	$t \to hu$	$t \to hc$
d	$\|V_{ud}V_{td}\|^2 \, (\sim \lambda^6) = 7.51 \cdot 10^{-5}$	$\|V_{cd}V_{td}\|^2 \, (\sim \lambda^8) = 4.01 \cdot 10^{-6}$
s	$\|V_{us}V_{ts}\|^2 \, (\sim \lambda^6) = 8.20 \cdot 10^{-5}$	$\|V_{cs}V_{ts}\|^2 \, (\sim \lambda^4) = 1.53 \cdot 10^{-3}$
b	$\|V_{ub}V_{tb}\|^2 \, (\sim \lambda^6) = 1.40 \cdot 10^{-5}$	$\|V_{cb}V_{tb}\|^2 \, (\sim \lambda^4) = 1.68 \cdot 10^{-3}$

$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| \lesssim 4.9$ for b and s type models

Flavour changing Higgs decays

The decays $h \to \ell\tau$ ($\ell = \mu, e$)

$$Y^\ell_{\mu\tau}(\nu_\rho) = \frac{1}{v} \, c_{\beta\alpha} \left(N_\ell^{(\nu_\sigma)}\right)_{\mu\tau} = -c_{\beta\alpha}(t_\beta + t_\beta^{-1}) \, U_{\mu\sigma} U^*_{\tau\sigma} \, \frac{m_\tau}{v}$$

Model	$h \to e\mu$	$h \to e\tau$	$h \to \mu\tau$
ν_1	$\|U_{e1}U_{\mu 1}\|^2(\sim \frac{1}{9}) = 0.105$	$\|U_{e1}U_{\tau 1}\|^2(\sim \frac{1}{9}) = 0.118$	$\|U_{\mu 1}U_{\tau 1}\|^2(\sim \frac{1}{36}) = 0.028$
ν_2	$\|U_{e2}U_{\mu 2}\|^2(\sim \frac{1}{9}) = 0.089$	$\|U_{e2}U_{\tau 2}\|^2(\sim \frac{1}{9}) = 0.126$	$\|U_{\mu 2}U_{\tau 2}\|^2(\sim \frac{1}{9}) = 0.115$
ν_3	$\|U_{e3}U_{\mu 3}\|^2 = 0.0128$	$\|U_{e3}U_{\tau 3}\|^2 = 0.0097$	$\|U_{\mu 3}U_{\tau 3}\|^2(\sim \frac{1}{4}) = 0.234$

$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| \sim 1$ to produce $\mathrm{Br}(h \to \mu\bar{\tau} + \tau\bar{\mu})$ of order 10^{-2}

Flavour changing Higgs decays

The flavour changing decays $h \to bq$ $(q = s, d)$

$$Y^D_{qb}(u_k) = -c_{\beta\alpha}(t_\beta + t_\beta^{-1})\, V^*_{kq} V_{kb}\, \frac{m_b}{v}\,,\ \ q \neq b,\ \text{no sum in } k$$

Model	$h \to bd$	$h \to bs$
u	$\lvert V_{ud}V_{ub}\rvert^2\,(\sim \lambda^6) = 1.33 \cdot 10^{-5}$	$\lvert V_{us}V_{ub}\rvert^2\,(\sim \lambda^8) = 7.14 \cdot 10^{-7}$
c	$\lvert V_{cd}V_{cb}\rvert^2\,(\sim \lambda^6) = 8.52 \cdot 10^{-5}$	$\lvert V_{cs}V_{cb}\rvert^2\,(\sim \lambda^4) = 1.59 \cdot 10^{-3}$
t	$\lvert V_{td}V_{tb}\rvert^2\,(\sim \lambda^6) = 7.90 \cdot 10^{-5}$	$\lvert V_{ts}V_{tb}\rvert^2\,(\sim \lambda^4) = 1.61 \cdot 10^{-3}$

- in models c and t,

$$\mathrm{Br}(h \to \bar{b}s + b\bar{s}) \sim c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,\lambda^4\ \sim 10^{-3}\,c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,,$$

- in model u,

$$\mathrm{Br}(h \to \bar{b}s + b\bar{s}) \sim c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,\lambda^8\ \sim 10^{-7}\,c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,,$$

- in all u, c and t models,

$$\mathrm{Br}(h \to \bar{b}d + b\bar{d}) \sim c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,\lambda^6\ \sim 10^{-5}\,c^2_{\beta\alpha}(t_\beta + t_\beta^{-1})^2\,.$$

Important correlations among Observables

BGL and the Cheng and Sher ansatz

$$|Y_{\mu\tau}| \leq \sqrt{m_\mu m_\tau}/v$$

neutrino type k model in BGL:

$$\begin{aligned} Y_{\mu\tau} &= -c_{\alpha\beta}\left(t + t^{-1}\right) U_{\mu k} U^*_{\tau k} \frac{m_\tau}{v} \\ Y_{\tau\mu} &= -c_{\alpha\beta}\left(t + t^{-1}\right) U_{\tau k} U^*_{\mu k} \frac{m_\mu}{v} \end{aligned}$$

$$|Y_{\tau\mu} Y_{\mu\tau}| = \left|c_{\alpha\beta}\left(t + t^{-1}\right)\right|^2 \left|U_{\mu k} U^*_{\tau k}\right| \left|U_{\tau k} U^*_{\mu k}\right| \frac{m_\mu m_\tau}{v^2}$$

BGL meets CS criterium provided:

$$\left|c_{\alpha\beta}\left(t + t^{-1}\right)\right|^2 \left|U_{\mu k} U^*_{\tau k}\right| \left|U_{\tau k} U^*_{\mu k}\right| \leq 1$$

$$\left|c_{\alpha\beta}\left(t + t^{-1}\right)\right| \lesssim 3$$

Conclusions

HFCNC at tree level are not ruled out even allowing for scalar masses of the order of a few hundred GeV

There are several promising scenarios within the 36 models that were presented.

Bhattacharyya, Das, Kundu 2014

The LHC may bring us interesting surprises!

Alternative MFV implementations in 2HDM

Dery, Efrati, Hiller, Hochberg, Nir (2013)

$$Y^U = \frac{\sqrt{2}\, M^U}{v}, \quad Y^D = \frac{\sqrt{2}\, M^D}{v}, \quad Y^E = \frac{\sqrt{2}\, M^E}{v}; \quad Y_S^F, \quad S = h, H, A$$

e.g. leptonic sector $G^{\ell}_{global} = SU(3)_L \times SU(3)_E$

Definition leptonic MFV, only one spurion breaks G^{ℓ}_{global}

$$\hat{Y} \sim (3, \bar{3})$$

In the most general case, each Yukawa matrix Y_1, Y_2 is a power series in this spurion

$$Y_i = [a_i + b_i \hat{Y}\hat{Y}^\dagger + c_i (\hat{Y}\hat{Y}^\dagger)^2 + \dots]\hat{Y} \qquad i = 1, 2$$

For each sector $F = U, D, E$ there are two Yukawa matrices $Y^F_{1,2}$

- Is there a loss of generality when we choose as basic spurion one over the other?
- Can we choose the mass matrices $(\sqrt{2}/v) M^F$ to play the role of spurions?

Similarly, for the leptonic sector,

In the leptonic sector, with Dirac type neutrinos, there is perfect analogy with the quark sector. The requirement that FCNC at tree level have strength completely controlled by the Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix, U is enforced by one of the following symmetries. Either

$$L^0_{Lk} \to \exp(i\tau)\ L^0_{Lk}\ , \qquad \nu^0_{Rk} \to \exp(i2\tau)\nu^0_{Rk}\ , \qquad \Phi_2 \to \exp(i\tau)\Phi_2\ ,$$

or

$$\tau \neq 0, \pi$$

$$L^0_{Lk} \to \exp(i\tau)\ L^0_{Lk}\ , \qquad \ell^0_{Rk} \to \exp(i2\tau)\ell^0_{Rk}\ , \qquad \Phi_2 \to \exp(-i\tau)\Phi_2\ ,$$

which imply

$$\begin{aligned} \mathcal{P}^\beta_k \Pi_2 &= \Pi_2\ , \qquad \mathcal{P}^\beta_k \Pi_1 = 0\ , \\ \mathcal{P}^\beta_k \Sigma_2 &= \Sigma_2\ , \qquad \mathcal{P}^\beta_k \Sigma_1 = 0\ , \end{aligned}$$

where β stands for neutrino (ν) or for charged lepton (ℓ) respectively. In this case

$$\mathcal{P}^\ell_k = U_{\ell L} P_k U^\dagger_{\ell L}\ , \qquad \mathcal{P}^\nu_k = U_{\nu L} P_k U^\dagger_{\nu L}\ ,$$

where $U_{\nu L}$ and $U_{\ell L}$ are the unitary matrices that diagonalize the corresponding square mass matrices

$$\begin{aligned} U^\dagger_{\ell L} M_\ell M^\dagger_\ell U_{\ell L} &= \mathrm{diag}\left(m^2_e, m^2_\mu, m^2_\tau\right)\ , \\ U^\dagger_{\nu L} M_\nu M^\dagger_\nu U_{\nu L} &= \mathrm{diag}\left(m^2_{\nu_1}, m^2_{\nu 2}, m^2_{\nu 3}\right)\ , \end{aligned}$$

$$M_\ell = \frac{1}{\sqrt{2}}(v_1 \Pi_1 + v_2 e^{i\theta}\Pi_2)\ , \quad M_\nu = \frac{1}{\sqrt{2}}(v_1 \Sigma_1 + v_2 e^{-i\theta}\Sigma_2)\ .$$