

Minimal Flavour Violation in

Two Higgs doublet Models

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on-going collaboration with

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Two Higgs doublet models (2HDM)

Several Motivations

- New sources of CP violation

SM cannot account for BHU

- Possibility of having spontaneous CP violation

EW sym breaking and \mathcal{CP} same footing

T. D. Lee 1973 ; Kobayashi and Maskawa 1973

- Strong CP problem, Peccei-Quinn

- Supersymmetry

LHC important role

Neutral currents have played an important role in the construction and experimental tests of unified gauge theories

EPS Prize in 2009 to Gargamelle, CERN

In the Standard Model Flavour Changing Neutral currents (FCNC) are forbidden at tree level

- in the gauge sector, ie m_Z FCNC
- in the scalar sector, ie m_H HFCNC

Models with two or more Higgs doublets potentially large HFCNC

Strict limits on FCNC processes!

Proposed solutions, case of Multi-Biggs models

without HFCNC

NFC

Wenberg, Glashow (1977)

Paschos (1977)

Aligned Two-Biggs - doublet model

Pek, Tugon (2009)

with HFCNC

existence of suppression factors in HFCNC

Antaramian, Hall, Rasin (1992)

Hall, Wenberg (1993)

Takahara, Rindani (1991)

first models of this type with no ad-hoc assumptions
suppression by small elements of VCKM: BGL models

Branco, Guinn, Lavoura (1996)

Minimal Flavour Violation

Notation

Yukawa interactions

$$\mathcal{L}_Y = -\bar{Q}_L^0 \Gamma_1 \tilde{\Phi}_1 d_R^0 - \bar{Q}_L^0 \Gamma_2 \Phi_2 d_R^0 - \bar{Q}_L^0 \Delta_1 \tilde{\Phi}_1 u_R^0 - \bar{Q}_L^0 \Delta_2 \Phi_2 \tilde{\Phi}_1 u_R^0 + h.c.$$
$$\tilde{\Phi}_L = -i\tau_2 \Phi_L^*$$

Quark mass matrices

$$M_D = \frac{1}{\sqrt{2}} (\nu_1 \Gamma_1 + \nu_2 e^{i\alpha} \Gamma_2); \quad M_U = \frac{1}{\sqrt{2}} (\nu_1 \Delta_1 + \nu_2 e^{-i\alpha} \Delta_2)$$

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

$$-\bar{L}_L^0 \Pi_1 \not{D}_R^0 - \bar{L}_L^0 \Pi_2 \not{D}_R^0 + h.c.$$

$$(-\bar{L}_L^0 \Sigma_1 \not{D}_R^0 - \bar{L}_L^0 \Sigma_2 \not{D}_R^0 + h.c.)$$

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

Expansion around the vev's

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

We perform the following transformation

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

$$U = \frac{1}{N} \begin{pmatrix} N_1 e^{-i\alpha_1} & N_2 e^{-i\alpha_2} \\ -N_2 e^{-i\alpha_1} & N_1 e^{-i\alpha_2} \end{pmatrix}; \quad N = \sqrt{N_1^2 + N_2^2} = (\sqrt{2} G_F)^{-\frac{1}{2}} \approx 246 \text{ GeV}$$

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

$$\begin{aligned}
 \mathcal{L}_Y(\text{quark, Higgs}) = & -\bar{d}_L^0 \frac{1}{\sqrt{2}} (M_d H^0 + N_d^0 R + i N_d^0 I) d_R^0 + \\
 & + \bar{u}_L^0 \frac{1}{\sqrt{2}} [M_u H^0 + N_u^0 R + i N_u^0 I] u_R^0 - \\
 & - \frac{\sqrt{2} H^+}{\sqrt{2}} (\bar{u}_L^0 N_d^0 d_R^0 - \bar{u}_R^0 N_u^0 d_L^0) + \text{h.c.}
 \end{aligned}$$

$$N_d^0 = \frac{1}{\sqrt{2}} (\sqrt{2} \Gamma_1 - \nu_1 e^{i\alpha} \Gamma_2), \quad N_u^0 = \frac{1}{\sqrt{2}} (\sqrt{2} \overset{\Delta_1}{\nu_2} - \nu_1 e^{-i\alpha} \Delta_2)$$

Flavour structure of quark sector of 2HDM characterized by

$$M_d, M_u, N_d^0, N_u^0$$

leptonic sector, Dirac neutrinos

$$M_e, M_\nu, N_e^0, N_\nu^0$$

Yukawa couplings in terms of quark mass eigenstates
for H^+ , H^0 , R , I

$$\begin{aligned} \mathcal{L}_Y = & \dots \frac{1}{\sqrt{2}} \frac{H^+}{\sqrt{2}} \bar{u} (-v N_d \gamma_R + N_u^+ v \gamma_L) d + \text{h.c.} - \\ & - \frac{H^0}{\sqrt{2}} (\bar{u} D_u u + \bar{d} D_d d) - \\ & - \frac{R}{\sqrt{2}} [\bar{u} (N_u \gamma_R + N_u^+ \gamma_L) u + \bar{d} (N_d \gamma_R + N_d^+ \gamma_L) d] + \\ & + i \frac{I}{\sqrt{2}} [\bar{u} (N_u \gamma_R - N_u^+ \gamma_L) u - \bar{d} (N_d \gamma_R - N_d^+ \gamma_L) d] \end{aligned}$$

$$\gamma_L = (1 - \gamma_5)/2; \quad \gamma_R = (1 + \gamma_5)/2 \quad V \equiv V_{CKM}$$

Flavour changing neutral currents unforbidden by:

$$N_d = \frac{1}{\sqrt{2}} U_{dL}^\dagger (\sqrt{2} \Gamma_1 - \sqrt{1} e^{i\alpha} \Gamma_2) U_{dR}$$

$$N_u = \frac{1}{\sqrt{2}} U_{uL}^\dagger (\sqrt{2} \Delta_1 - \sqrt{1} e^{-i\alpha} \Delta_2) U_{uR}$$

For generic two Higgs doublet models

N_u, N_d non-diagonal arbitrary

For definiteness rewrite N_d :

$$N_d = \frac{\sqrt{2}}{\sqrt{1}} D_d - \frac{\sqrt{2}}{\sqrt{2}} \left(\frac{\sqrt{2}}{\sqrt{1}} + \frac{\sqrt{1}}{\sqrt{2}} \right) U_{dL}^\dagger e^{i\alpha} \Gamma_2 U_{dR}$$

→ same flavour

→ leads to FCNC

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 Flavor Violation

Buras, Gambino, Gorbahn, Jager, Salvatori (2001)

D'Ambrosio, Giudice, Jagger, Strumia (2002)

Leptonic Vector

Giudice, Gurev, Jagger, Wise (2005)

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

Our framework

- multi-Higgs models
- No Natural Flavor 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 by CKM
 Branco, Gouvea, Lavoura imposed symmetry

$$Q_{Lj}^{\circ} \rightarrow \exp(iZ) Q_{Lj}^{\circ} ; U_{Rj}^{\circ} \rightarrow \exp(2iZ) U_{Rj}^{\circ} ; \Phi_2 \rightarrow \exp(iZ) \Phi_2, \tau \neq 0, \pi$$

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

$j=3$

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

Special WB shown by the symmetry

FCNC in down sector

$$\text{if instead of } U_{Rj}^{\circ} \rightarrow \exp(2iZ) U_{Rj}^{\circ} \text{ impose } d_{Rj}^{\circ} \rightarrow \exp(2iZ) d_{Rj}^{\circ}$$

then FCNC in up sector

See different BGL models

$$(N_d)_{\mu\nu} = \frac{\sqrt{2}}{\sqrt{1}} (D_d)_{\mu\nu} - \left(\frac{\sqrt{2}}{\sqrt{1}} + \frac{\sqrt{1}}{\sqrt{2}} \right) \underbrace{\left(V_{CKM}^\dagger \right)_{\mu 3} \left(V_{CKM} \right)_{3\nu}}_{MFV} (D_d)_{\mu\nu}$$

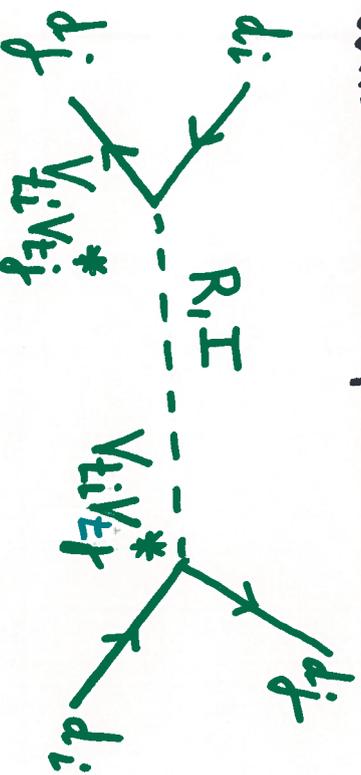
$j=3$

$$N_u = -\frac{\sqrt{1}}{\sqrt{2}} \text{diag}(0, 0, m_t) + \frac{\sqrt{2}}{\sqrt{1}} \text{diag}(m_u, m_c, 0)$$

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 not other flavour dependence
Furthermore, N_d^0, N_u^0 should transform appropriately under WB

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

$$M_d \rightarrow W_L^T M_d W_R^d, \quad M_u \rightarrow W_L^T M_u W_R^u$$

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

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

$$Y_d; (Y_d Y_d^T) Y_d; (Y_u Y_u^T) Y_d \quad \text{Yukawa}$$

see previous references

What is particular about BGL models in MFV context?

$$M_d M_d^\dagger \equiv H_d ; \quad U_{dL}^\dagger M_d U_{dR} = D_d ; \quad U_{dL}^\dagger H_d U_{dL} = D_d^2$$

$$D_d^2 = \text{diag}(m_d^2, m_s^2, m_b^2) = m_d^2 \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} + m_s^2 \begin{pmatrix} & & \\ & 1 & \\ & & 0 \end{pmatrix} + m_b^2 \begin{pmatrix} & & \\ & & \\ & & 0 \\ & & & 1 \end{pmatrix}$$

$$D_d^2 = \sum_i m_{d_i}^2 P_i \quad P_1 \quad P_2 \quad P_3$$

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

$U_{dL} P_i U_{dL}^\dagger$ 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

The Δ convenient to write H_d, H_u in terms of projection operators

Botella, Nebot, Vives 2004

$$H_d = \sum_i m_{d_i}^2 P_i^{dL} ; P_i^{dL} = U_{dL} P_i U_{dL}^\dagger ; (P_i)_{jk} = \delta_{ij} \delta_{ik} \quad \text{used}$$

MFV expansion for N_d^0 and N_u^0

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

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

\sum green terms that do not lead to FCNC

\sum red terms that lead to FCNC

\sum the quark eigenstate basis

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

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

At this stage λ and τ coefficients appear as free parameters, MFV
 Need for additional symmetries in order to constrain these coeff.

WB invariant definition for BGL models

$$N_d^0 = \frac{\sqrt{2}}{\sqrt{1}} M_d - \left(\frac{\sqrt{2}}{\sqrt{1}} + \frac{\sqrt{1}}{\sqrt{2}} \right) \mathcal{P}_f^d M_d$$

$$N_u^0 = \frac{\sqrt{2}}{\sqrt{1}} M_u - \left(\frac{\sqrt{2}}{\sqrt{1}} + \frac{\sqrt{1}}{\sqrt{2}} \right) \mathcal{P}_f^u M_u$$

together with

$$\mathcal{P}_f^u \Gamma_2 = \Gamma_2, \quad \mathcal{P}_f^u \Gamma_1 = 0$$

$$\mathcal{P}_f^d \Delta_2 = \Delta_2, \quad \mathcal{P}_f^d \Delta_1 = 0$$

\mathcal{P} stands for u (up) or d (down)

$\mathcal{P}_f^{\mathcal{P}}$ are projection operators

Bobala, Nubet, Yoon 2004

$$\mathcal{P}_f^u = U_{uL} P_f U_{uL}^\dagger$$

$$\mathcal{P}_f^d = U_{dL} P_f U_{dL}^\dagger$$

$$(P_f)_{jk} = \delta_{jk} \delta_{jk}$$

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

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 fixed on an

Abelian symmetry obeying the sufficient conditions of having M_u block diagonal together with the existence of a matrix P such that

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

Alternative MFV implementations in ZHD M

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

$$Y^U = \frac{\sqrt{2} M^U}{\nu}, \quad Y^D = \frac{\sqrt{2} M^D}{\nu}, \quad Y^E = \frac{\sqrt{2} M^E}{\nu}; \quad Y^S, \quad S = \kappa, H, A$$

e.g. leptonic vector $G_{\text{global}}^L = SU(3)_L \times SU(3)_E$

Definition leptonic MFV, only one spurion breaks G_{global}^L
 $\hat{Y} \sim (3, \bar{3})$

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

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

For each vector $F = U, D, E$ there are two Yukawa matrices $Y_{1,2}^F$

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

Flavour structure (quark sector)

M_d, M_u, N_d^0, N_u^0

Freedom of choice of WB

Zero textures are WB dependant

Symmetries are only apparent in particular WB

WB transformations do not change the physics

Symmetries have physical implications

Above four matrices encode breaking of Flavour

symmetry present in gauge sector

Large redundancy of parameters

WB invariants are very useful to study Flavour

see talk by G.C. Branco

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

Implies 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 EWs Higgs doublets with FCNC

- controlled by VCKM in the quark sector
- controlled by VPMNS in the leptonic sector

Case of Dirac neutrinos, straight forward

Same flavor structure

Six different BG-L-type models

Minimal Flavor Violation with Majorana neutrinos

Low energy effective theory and stability

$$\mathcal{L}_{\text{Majorana}} = \frac{1}{2} \nu_L^{0T} C^{-1} m_\nu \nu_L^0 + \text{h.c.}$$

generated from effective dimension five operator

$$\mathcal{O} = \sum_{i,j=1}^2 \sum_{\alpha,\beta=e,\mu,\tau} \sum_{a,b,c,d=1}^2 \left(L_{L\alpha a}^T \kappa_{\alpha\beta}^{(ij)} C^{-1} L_{L\beta c} \right) \left(\varepsilon^{ab} \phi_{iL} \right) \left(\varepsilon^{cd} \phi_{jL} \right)$$

$$\mathcal{L}_{\nu_e} = -\bar{L}_L^0 \pi_1 \phi_{1R}^0 - \bar{L}_L^0 \pi_2 \phi_{2R}^0 + \text{h.c.}$$

$$\pi_1, \pi_2, \kappa'', \kappa^{12}, \kappa^{21}, \kappa^{22} \quad \left(\kappa^{(ij)} \right)$$

$$L_{Lj}^0 \rightarrow \exp(i\alpha) L_{Lj}^0, \quad \phi_2^0 \rightarrow \exp(i\alpha) \phi_2^0$$

$$\alpha = \pi/2, \quad Z_4 \text{ symmetry}$$

Imposing Z_3 symmetry implies:

($j=3$)

$$K^{(12)} = K^{(21)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$K^{(11)} = \begin{pmatrix} X & X & 0 \\ X & X & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad K^{(22)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & X \end{pmatrix}$$

$\alpha = \pi/2$
 measures
 $K_{33}^{(22)} \neq 0$

$$\frac{1}{2} m_\nu = \frac{1}{2} \nu_1^2 K^{(11)} + \frac{1}{2} \nu_2^2 e^{2i\alpha} K^{(22)}$$

$$\Pi_1 = \begin{bmatrix} X & X & X \\ X & X & X \\ 0 & 0 & 0 \end{bmatrix}, \quad \Pi_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ X & X & X \end{bmatrix}$$

Higgs FCNC in the charged sector

Stability: $K^{(12)} = K^{(21)} = 0$

$$K^{(11)} \mathcal{P}_3^\nu = 0, \quad K^{(22)} \mathcal{P}_3^\nu = K^{(22)}$$

$$\mathcal{P}_3^\nu \Pi_1 = 0, \quad \mathcal{P}_3^\nu \Pi_2 = \Pi_2$$

stable under renormalization

Seesaw framework

$$\begin{aligned}
 \mathcal{L}_Y + m_{\text{mass}} = & -\bar{L}_L^0 \Pi_1 \phi_1 \mathcal{L}_R^0 - \bar{L}_L^0 \Pi_2 \phi_2 \mathcal{L}_R^0 - \\
 & -\bar{L}_L^0 \Sigma_1 \tilde{\phi}_1 \nu_R^0 - \bar{L}_L^0 \Sigma_2 \tilde{\phi}_2 \nu_R^0 + \\
 & + \frac{1}{2} \nu_R^{0T} C^{-1} M_R \nu_R^0 + \text{h.c.}
 \end{aligned}$$

$$m_\nu = \frac{1}{2} (\nu_1 \Pi_1 + \nu_2 e^{i\theta} \Pi_2), \quad m_D = \frac{1}{2} (\nu_1 \Sigma_1 + \nu_2 e^{-i\theta} \Sigma_2)$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} W_\mu^+ \bar{L}_L^0 \gamma^\mu \nu_L^0 + \text{h.c.}$$

$$\begin{aligned}
 \mathcal{L}_Y (\text{neutrals, leptons}) = & -\bar{L}_L^0 \frac{1}{\sqrt{2}} [m_\nu H^0 + N_L^0 R + i N_L^0 I] \mathcal{L}_R^0 - \\
 & -\bar{L}_L^0 \frac{1}{\sqrt{2}} [m_D H^0 + N_D^0 R + i N_D^0 I] \nu_R^0 + \text{h.c.}
 \end{aligned}$$

$$N_L^0 = \frac{\nu_2}{\sqrt{2}} \Pi_1 - \frac{\nu_1}{\sqrt{2}} e^{i\theta} \Pi_2$$

$$N_D^0 = \frac{\nu_2}{\sqrt{2}} \Sigma_1 - \frac{\nu_1}{\sqrt{2}} e^{-i\theta} \Sigma_2$$

$$f_{\text{max}} = -\bar{P}_L^0 m_P \bar{P}_R^0 + \frac{1}{2} (V_L^{0T}, (V_R^0)^{cT}) C^{-1} \mathcal{H}^* \begin{pmatrix} V_L^0 \\ (V_R^0)^c \end{pmatrix} + h_c$$

$$\mathcal{H} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \quad (V_L)^c \equiv C \gamma_0^T (V_L)^*$$

BGL type example, Z_4 symmetry

$L_{L3}^0 \rightarrow \exp(i\alpha) L_{L3}^0$, $V_{R3}^0 \rightarrow \exp(i2\alpha) V_{R3}^0$, $\phi_2 \rightarrow \exp(i\alpha) \phi_2$

$$\alpha = \frac{\pi}{2}$$

$$\Pi_1 = \begin{pmatrix} x & x & x \\ x & x & x \\ 0 & 0 & 0 \end{pmatrix}, \quad \Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{pmatrix}$$

$$\Sigma_1 = \begin{pmatrix} x & x & 0 \\ x & x & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Sigma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & x \end{pmatrix}, \quad M_R = \begin{pmatrix} x & x & 0 \\ x & x & 0 \\ 0 & 0 & x \end{pmatrix}$$

New feature m_{Vi} from $m_{eff} \equiv -m_D \frac{1}{M_R} m_D^T$ $M_{33} \neq 0$

Three light neutrinos ν_i , plus heavy neutrinos N_j

Right-Right, Right-heavy, heavy-heavy couplings

H^0, R, I couplings

$$U_{\text{eff}}^\dagger U^\dagger = d, \quad m_D \frac{1}{D} m_D^T = -U d U^T \quad (\text{WB HD diag})$$

$$m_D = i U \tilde{A} \sigma \sqrt{D} \quad \text{Gom and Shwarz, 2001}$$

$$(N_e)_{ij} = \frac{\sqrt{2}}{N_i} (D_e)_{ij} - \left(\frac{\sqrt{2}}{N_i} + \frac{\sqrt{I}}{\sqrt{2}} \right) (U_\nu^\dagger)_{is} (U_\nu)_{sj} (D_e)_{st}$$

Right-Right neutral couplings: diag, d

Right-heavy neutral couplings: sensitive to O^c, d, D

heavy-heavy neutral couplings: diag, sensitive to O^c, d, D

H^+ couplings

$$\frac{\sqrt{2} H^+}{\nu} (\bar{\nu}_L^0 N_e^0 e_R - \bar{\nu}_R^0 N_\nu^0 t_L^0) + \text{r.c.}$$

Scalar Potential

The softly broken Z_2 asymmetric 2HDM potential

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

$\phi_1 \rightarrow \phi_1, \phi_2 \rightarrow -\phi_2$

In our case $\phi_1 \rightarrow \phi_1, \phi_2 \rightarrow e^{i\tau} \phi_2, \tau \neq 0, \pi$ no λ_5 term

V does not violate CP neither explicitly nor spontaneously

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

Soft symmetry breaking prevents ungauged accidental continuous symmetry

Analysis of implications, 36 BGL models

Experimental constraints

- Neutral Meson Mixing $P^+ \rightarrow \ell^+ \nu_\ell$
 - Leptonic decays of pseudo scalar mesons
 - Charged Lepton Decays
 - $B \rightarrow \tau \nu$, $B \rightarrow D \tau \nu$, $B \rightarrow D^* \tau \nu$
 - Oblique parameters and Direct Searches for H^\pm
 - $Z \rightarrow \ell \bar{\ell}$
 - $\tau \rightarrow \nu \gamma$
 - $\ell_j \rightarrow \ell_i \gamma$: $Z \rightarrow \mu \gamma$, $\mu \rightarrow e \gamma$
- } $Z \rightarrow \ell \bar{\ell}$ stringent constraint

Best BGL implementation

HFCNC up quark $\nu_{\text{ster}} j=3$
HFCNC $\nu_{\text{ster}} j=3$

reasonable values tan β neutrino M_{H^\pm} Relaxing $Z \rightarrow \ell \bar{\ell}$

Relaxing T parameter, there are other BGL type models that become interesting

Models with NFC

Single scalar doublet coupling to each type of BR

The Affly broken Z_2 symmetric 2HDM potential

CP conserving type I and type II

Recent work Barros, Ferreira, Haber, Jivanov, Santos, Shu, Silva
Chern, Kang (2012); Gumbren, Utiyamat (2013); Eberhardt, Nierste, Wiebusch
(2013)

2HDM type II Yukawa with CP violation

Barros, Lipniacka, Mahmoudi, Moratti, Orlando, Perna, Pummhamadi (2012)
+ (2013)

Conclusions

LHC results may bring surprises for the

Higgs sector, e.g. discovery of charged Higgs

There are new mechanisms beyond NFC
to obtain strong suppression of FCNC
as required by experiment

BGL-type models are very interesting
candidates for New Physics