Two Higgs Doublet Models

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IVICFA, EASTER WORKSHOP
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on-going collaboration
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Two Higgs doublet models (2HDM)

Several Motivations

- New Sources of CP violation

  SM cannot account for BAU

- Possibility of having spontaneous CP violation

  EW sym breaking and $\cancel{CP}$ same footing

  T. D. Lee 1973 ; Kobayashi and Maskawa 1973

- Strong CP problem , Peccei-Quinn
- Supersymmetry

LHC important rôle

Neutral currents have played an important rôle 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 no Z FCNC
- in the scalar sector, ie no HFCNC

Models with two or more Higgs doublets potentially large HFCNC

strict limits on FCNC processes!

Models with two or more Higgs doublets

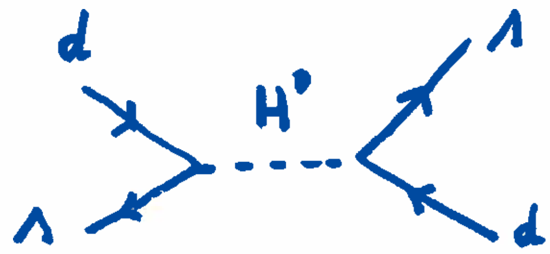
potentially large HFCNC

strict experimental limits on FCNC processes!

In the SM, FCNC are only generated at loop level

$\Rightarrow$ very suppressed

Processes that play a crucial role in testing the SM and putting limits on Physics BSM:



$K_L - K_S$ mass difference

$\Downarrow$

$m_H \gtrsim 1\,\text{TeV}$

CP violation ε_K

$m_H \gtrsim 30\,\text{TeV}$

$K^0 - \bar{K}^0$ mixing	rare Kaon decays
$D^0 - \bar{D}^0$ mixing	rare B-meson decays
$B_d^0 - \bar{B}_d^0$ mixing	CP violation
$B_s^0 - \bar{B}_s^0$ mixing	

Proposed solutions, case of Multi-Higgs models

without HFCNC

NFC — Weinberg, Glashow (1977)
Paschos (1977)

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

with HFCNC

existence of suppression factors in HFCNC
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 V_{CKM} : BGL models
Branco, Grimus, Lavoura (1996)

Minimal Flavour Violation

Notation

Yukawa interactions

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

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

Quark mass matrices

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

Diagonalized by

$$U_{d_L}^\dagger\, M_d\, U_{dR} = D_d \equiv \mathrm{diag}\,(m_d, m_s, m_b)$$

$$U_{u_L}^\dagger\, M_u\, U_{uR} = D_u \equiv \mathrm{diag}\,(m_u, m_c, m_t)$$

Leptonic Sector

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

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

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

Expansion around the vev's

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

we perform the following transformation

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

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

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

The case of the aligned 2HDM

Jung, Pich, Tuzon
Celis, Ilisie, Pich

Flavour structure

$$\Gamma_2 = \xi_d \, e^{-i\theta} \Gamma_1 \; ; \quad \Delta_2 = \xi_u^* \, e^{i\theta} \Delta_1 \; ; \quad \Pi_2 = \xi_\ell \, e^{-i\theta} \Pi_1$$

ξ_f arbitrary complex numbers

in WB characterised by M_d, M_u, M_ℓ and
three complex numbers $\rho_f(\xi_f, v_1, v_2)$

in fermion mass eigenstate basis, characterised by
$D_d, D_u, D_\ell, V_{CKM}, \rho_d, \rho_u, \rho_\ell$

ρ_f provide new sources of CP violation without tree level HFCNC

Higgs potential

general two Higgs doublet model

Yukawa interactions in mass eigenstate basis

- fermion mass terms
- neutral Yukawas diagonal in flavour

$$-\frac{\sqrt{2}}{v} H^+ \bar{u} \left[\rho_d V D_d P_R - \rho_u D_u V P_L \right] d -$$

$$- \frac{\sqrt{2}}{v} H^+ \rho_\ell \bar{\nu} D_\ell P_R \ell \qquad P_{RL} \equiv \frac{1}{2}(1 \pm \gamma_5)$$

all fermionic couplings to physical scalar $\propto D_f$

ρ_f are flavour blind, and observable

Important feature : presence of radiative FCNC's

"The alignment condition is broken by quantum corrections since it is not protected by any symmetry"

- leads to rich and viable phenomenology, interesting hierarchy of FCNC effects due to Yukawa couplings proportional to fermion masses

Alignment as an effective theory with NFC at UV scale

Serodio (2011)

exact alignment at all orders

- 2+N scalar doublets
- discrete symmetry leading to NFC
- 2 scalars couple to fermions, other are "hidden"
- two interacting Higgs very heavy
- effective Yukawa interaction connects fermions to both sectors with same Yukawa matrix for all of them

Charged Higgs phenomenology in the aligned two Higgs doublet model

- analysis of constraints on the three complex parameters ς_f with present data, leptonic, semileptonic, hadronic decays

Jung, Pich, Tuzón (2010)
Celis, Ilisie, Pich (2013)

Tree-level decays

- pure leptonic decays $\ell \to \ell' \bar{\nu}_{\ell'} \nu_\ell$ $\quad |\varsigma_\ell| / M_{H^\pm}$ (tau)
- leptonic decays of pseudoscalar mesons $\quad P^+ \to \ell^+ \nu_\ell \quad$ ς_u from ς_d
- semileptonic decays of pseudo scalar mesons : $B \to D \tau \nu$, $K \to \pi e \nu$

  $\varsigma_\ell^* \varsigma_u / M_{H^\pm}^2$, $\quad \varsigma_\ell^* \varsigma_d / M_{H^\pm}^2$

Loop induced processes

- $Z \to b\bar{b}$ $\quad$ stringent constraint on $|\varsigma_u|$ versus $M_{H^\pm}$
- $B^0 - \bar{B}^0$ mixing $\quad |\varsigma_u|$ versus $M_{H^\pm}$
- $K^0 - \bar{K}^0$ mixing : ε_K $\quad |\varsigma_u|$ versus $M_{H^\pm}$
- $\bar{B} \to X_s \gamma$ $\quad |\varsigma_u|^2$, $\varsigma_u^* \varsigma_d$

CP violation

From recent LHC results

$\underbrace{WW, ZZ}$, $\gamma\gamma$ decay channels
close to SM $\rightarrow$ rules out CP-odd new Higgs-like boson;

pure CP even or CP even-odd admixture possible

$H \rightarrow \gamma\gamma$

- sign flip top quark contribution to add constructively with dominant $W^{\pm}$ contribution possible in aligned 2HDM, requires $|\varsigma_u|$ large
  however $Z \rightarrow b\bar{b}$, $b \rightarrow s\gamma$, $B^0 - \bar{B}^0$ mixing require $|\varsigma_u| < 2$ - problematic without huge $M_{H^{\pm}}$
- charged scalar contribution promising

CP even and CP odd Higgs with quasi degenerate masses near 126 GeV - possible with $H \rightarrow \gamma\gamma$ enhancement

Complex Yukawa couplings and $H \rightarrow \gamma\gamma$ enhancement

Models with NFC

single scalar doublet coupling to each type of f_R

limits on ξ_f recover the different Z_2 type models and corresponding ρ_f values ($\xi_f \to 0$ or $\xi_f \to \infty$)

The softly broken Z_2 symmetric 2HDM potential

CP conserving type I and type II

recent work Barroso, Ferreira, Haber, Ivanov, Sher, Silva

2HDM type II Yukawa with CP violation

Basso, Lipniacka, Mahmoudi, Moretti, Pruna, Pourmohammadi (2012)

The softly broken Z_2 symmetric 2HDM potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \end{aligned}}$$

$$\boxed{\phi_1 \to \phi_1 \quad \phi_2 \to -\phi_2}$$

Build your favourite potential: CP conserving, explicit CP breaking, spontaneous CP breaking, by tuning m^2_{12} and λ_5 together with the possible vacuum configurations

- m^2_{12} and λ_5 real, vacuum configuration (CP-conserving)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \alpha,\ M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$

$\boxed{\tan\beta = \frac{v_2}{v_1}}$ ratio of vacuum expectation values

RUI SANTOS, MORIOND 2013

2HDM Lagrangian

- scalars-gauge bosons couplings

$$\boxed{g_{SM}\sin(\beta-\alpha)} \quad hW^+W^-$$

- Yukawa couplings

Extending the Z_2 symmetry to the fermions - 4 independent Yukawa Lagrangians

$$\boxed{g_{SM}\frac{f(\alpha)}{g(\beta)}} \quad h\bar{f}f$$

	I	II	III	IV
up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

III = I' = Y = Flipped

IV = II' = X = Leptonic

➡ we use as independent parameters

$$\boxed{\sin\alpha \quad \tan\beta}$$

	I	II	III	IV
leptons (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
down (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
up (h)	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
leptons (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
down (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$
up (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$

THE CONSTRAINTS

EXP

$B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ mixing

$R_b \equiv \Gamma(Z \to b\bar{b}) / \Gamma(Z \to \text{hadrons})$

Precision electroweak constraints

$B^+ \to \tau^+ \nu_\tau$

LEP from $e^+e^- \to H^+H^-$ $\qquad m_{H^\pm} \gtrsim 94$ GeV

B factories from $B \to X_s \gamma$ $\qquad m_{H^\pm} \gtrsim 360$ GeV (Type II)

ATLAS, CMS $\quad pp \to t\bar{t} \to \bar{b}b W^+ H^-$ $\qquad m_{H^+}$ versus $\tan\beta$

THEO

POTENTIAL BOUNDED FROM BELOW

UNITARITY LIMITS for QUARTIC Higgs couplings

NORMAL GLOBAL MINIMUM, unique

LHC data

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

$$90\ Gev \leqslant m_{H\pm}, m_A \leqslant 900\ GeV$$

$$m_h \leqslant m_H \leqslant 900\ GeV$$

$$1 \leqslant \tan\beta \leqslant 40$$

$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

$$-(900)^2\ Gev^2 \leqslant m_{12}^2 \leqslant 900^2\ GeV^2$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

- Impose averaged ATLAS and CMS results:

Arbey, Battaglia, Djouadi, Mahmoudi, 1211.4004.

$$\mu_{\gamma\gamma} = 1.66 \pm 0.33$$
$$\mu_{ZZ} = 0.93 \pm 0.28$$
$$\mu_{\tau\tau} = 0.71 \pm 0.42$$

$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

CP-conserving 2HDM with
lighest CP-even Higgs 125 GeV
is being severely cornered into
SM-like limit

2HDM notation 1

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

No FCNC:

$$\lambda_6 = 0; \quad \lambda_7 = 0$$

Allow CPV: $\lambda_5, \quad m_{12}^2$ **complex**

Constraints-theory

- Positivity
  - Explicit conditions
- Unitarity
  - Explicit conditions
- Perturbativity
- Global minimum
  - Three coupled cubic equations

Constraints-experiment

- $b \to s\gamma$
- $\Gamma(Z \to b\bar{b})$
- $B \to \tau\nu(X)$, $B \to D\tau\nu$, $D \to \tau\nu$
- $B_0 \leftrightarrow \bar{B}_0$
- $B_{d,s} \to \mu^+\mu^-$
- EW constraints: S, T
- Electron EDM
- LHC: $H_1 \to \gamma\gamma$
- LHC: $H_{2,3} \to W^+W^-$

Parameters

Input: $\boxed{\tan\beta,\ (M_1,\ M_2),\ (M_{H\pm},\ \mu^2),\ (\alpha_1,\ \alpha_2,\ \alpha_3)}$

Typically: step ↑ fix ↑ step ↑ scan ↑

$$\mu^2 = \mathrm{Re}\, m_{12}^2 / 2\cos\beta\sin\beta$$

$$\sqrt{v_1^2 + v_2^2}$$

- 2HDM II parameter space is severely constrained by LHC data
- Parts of 2HDM II parameter space are still open
- SM would be excluded by charged Higgs discovery
- $pp \to \underbrace{jj}_{W} \underbrace{\ell^{\pm}\nu}_{W} \underbrace{b\bar{b}}_{H_1}$ channel allows detection in part of parameter space

$pp \to H^{\pm} W^{\mp} \to W^{+} W^{-} b\bar{b}$

PER OSLAND
CORFU 2012

MODELS WITH MINIMAL FLAVOUR VIOLATION

Neutral and charged Higgs interactions for the quark sector

$$\mathcal{L}_Y(\text{quark, Higgs}) = -\overline{d_L^0}\,\frac{1}{v}\left(M_d H^0 + N_d^0 R + i N_d^0 I\right) d_R^0 +$$

$$+\,\overline{u_L^0}\,\frac{1}{v}\left[M_u H^0 + N_u^0 R + i N_u^0 I\right) u_R^0 +$$

$$+\,\frac{\sqrt{2}H^+}{v}\left(\overline{u_L^0}\, N_d^0\, d_R^0 - \overline{u_R^0}\, N_u^{0\dagger}\, d_L^0\right) + \text{h.c.}$$

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

Flavour structure of quark sector of 2HDM characterized by

M_d, M_u, N_d^0, N_u^0

likewise leptonic sector, Dirac neutrinos

M_ℓ, M_ν, N_ℓ^0, N_ν^0

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

$$\mathcal{L}_Y = \ldots \sqrt{2}\,\frac{H^+}{v}\,\bar{u}\left(-V N_d \gamma_R + N_u^\dagger V \gamma_L\right) d \;+ h.c. \;-$$

$$- \frac{H^0}{v}\left(\bar{u} D_u u + \bar{d} D_d d\right) -$$

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

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

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

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 :

$$N_d = \underbrace{\frac{v_2}{v_1} D_d}_{\text{conserves flavour}} - \underbrace{\frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}}_{\text{leads to FCNC}}$$

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

All flavour changing transition 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
- obey above condition (one of the defining ingredients of MFV framework)

"Higgs-mediated FCNC's: Natural Flavour Conservation vs. Minimal Flavour Violation"

Buras, Carlucci, Gori, Isidori, arXiv:1005.5310 (JHEP)

Barbieri, Lodone, Straub, Jones-Perez ; Cervero, Gerard ; ....

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

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

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

$$j = 3$$

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 $u^0_{R_j} \to \exp(2i\tau) u^0_{R_j}$ impose $d^0_{R_j} \to \exp(2i\tau) d^0_{R_j}$

then FCNC in up sector

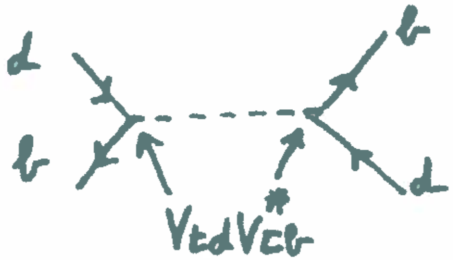
$$(N_d)_{ij} = \frac{v_2}{v_1}(D_d)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)\overbrace{(V^\dagger_{CKM})_{i3}(V_{CKM})_{3j}}^{\text{MFV}}(D_d)_{jj}$$

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

FCNC only in the down sector
suppression by the 3rd row of V_{CKM}

Strong and Natural suppression of the most constrained processes

$\Delta s = 2$ processes
$|V_{td}V^*_{ts}| \sim \lambda^5 \sim 10^{-4}$ (λ^{10} suppression)



may contribute significantly to $B_d - \bar{B}_d$ mixing

contribution to $B_s - \bar{B}_s$ mixing

How to find a general expansion of N_d^0, N_u^0 which conforms to the MFV requirements?

$$N_d^0 = U_{dL} N_d U_{dR}^\dagger = \frac{1}{\sqrt{2}}\left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2\right)$$

$$N_u^0 = U_{uL} N_u U_{uR}^\dagger = \frac{1}{\sqrt{2}}\left(v_2 \Delta_1 - v_1 e^{i\alpha} \Delta_2\right)$$

Necessary condition 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 under WB appropriate form

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

$$M_d \to W_L^\dagger M_d W_R^d \quad ; \quad M_u \to W_L^\dagger M_u W_R^u$$

$$U_{dL} \to W_L^\dagger U_{dL} \ ; \ U_{uL} \to W_L^\dagger U_{uL} \ ; \ U_{dR} \to W_R^{d\dagger} U_{dR} \ ; \ U_{uR} \to W_R^{u\dagger} U_{uR}$$

$$H_{d,u} \equiv (M_{d,u})(M_{d,u}^\dagger) \quad , \quad H_{d,u} \to W_L^\dagger H_{d,u} W_L$$

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

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

functions of M_d and M_u with correct transformation

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

$W_L \quad W_L^\dagger \qquad\qquad W_L \quad W_L^\dagger$

$Y_d \quad (Y_d Y_d^\dagger) Y_d \quad (Y_u Y_u^\dagger) Y_d$ Yukawa

see previous references

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

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

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

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

It is convenient to write H_d, H_u in terms of projection operators

Botella, Nebot, Vives 2004

$$H_d = \sum_i m_{d_i}^2 P_i^{dL} \; ; \quad P_i^{dL} = U_{dL} P_i U_{d_L}^\dagger \; ; \quad (P_i)_{jk} = \delta_{ij}\delta_{ik} \qquad u \leftrightarrow d$$

MFV expansion for N_d^0 and N_u^0

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

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

In green terms that do not lead to FCNC

In red terms that lead to FCNC

In 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 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

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

$$(P_j)_{\ell k} = \delta_{j\ell} \delta_{jk} \qquad \text{e.g. } P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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 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

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

Flavour structure

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

Freedom of choice of WB $\Rightarrow$ Work with WB invariants

Zero textures are WB dependent

Above four matrices encode breaking of flavour sym present in gauge sector

large redundancy of parameters

WB transformations do not change the physics

Examples of WB invariants : $\mathrm{tr}\,(H_u H_d)$, $\mathrm{tr}\,(H_u H_d^2)$

$\mathrm{tr}\,(H_u^2 H_d)$, $\mathrm{tr}\,(H_u^2 H_d^2)$ $\longrightarrow$ V_{CKM} ambiguity in sign

$\mathrm{Im}\, Q$, $Q_{\alpha i \beta j} = V_{\alpha i} V_{\beta j} V_{\alpha j}^* V_{\beta i}^*$ $(\alpha \neq \beta), (i \neq j)$

Branco, Lavoura, 1988

WB also very useful to study CP violation

$$I_1^{CP} \equiv \mathrm{tr}\,[H_u, H_d]^3 = 6i\,(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \times$$
$$\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\ \mathrm{Im}\ Q_{uscb}$$

Bernabeu, Branco, Gronau 1986

det $[H_u, H_d]$ Jarlskog, 1985 3 generations

One can check predictions of flavour model comparing invariant quantities with their corresponding experimental values

In 2HDM one can build new WB invariants which do not arise SM

Special WB's M_d diagonal, $N_d^0 \equiv N_d$

or M_u diagonal, $N_u^0 \equiv N_u$

Examples

$$V_{CKM} \equiv U_{u_L}^{\dagger} U_{d_L}$$

$I_1 \equiv \mathrm{tr}\left(M_d N_d^{0\dagger}\right) = m_d (N_d^*)_{11} + m_s (N_d^*)_{22} + m_b (N_d^*)_{33}$

not sensitive to HFCNC

$\mathrm{Im}\, I_1$ probes phases of $(N_d)_{jj}$ (electric dipole moment d quarks

$I_2 \equiv \mathrm{tr}\left[M_d N_d^0, M_d M_d^\dagger\right]^2$ sensitive to off-diag elements N_d

$I_1^{CP} \propto \mathrm{Im}\, Q_{uscb}$, $V_{CKM} = U_{u_L}^\dagger U_{d_L}$

$U_{u_L} \neq U_{d_L}$ misalignment of the matrices H_d, H_u

analogously

$I_3^{CP} \equiv \mathrm{tr}\left[H_d, H_{N_d^0}\right]^3 = 6i\, \Delta_d\, \Delta_{N_d}\, \mathrm{Im}\, Q_3$, $V_3 \equiv U_{d_L}^\dagger U_{N_d^0 L}$

$H_{N_d^0} = N_d^0 N_d^{0\dagger}$

$I_2^{CP} \equiv \mathrm{tr}\left[H_u, H_{N_d^0}\right]^3 = 6i\, \Delta_u\, \Delta_{N_d}\, \mathrm{Im}\, Q_2$, $V_2 = U_{u_L}^\dagger U_{N_d^0 L}$

$I_6^{CP} \equiv \mathrm{tr}\left[H_{N_d^0}, H_{N_u^0}\right]^3$

and many more

V_{CKM}, V_2, V_3 signal misalignment in flavour space of Hermitian matrices constructed in the framework of 2HDM

So far, we have only written invariants which are sensitive to left-handed mixings

One can construct analogous invariants which are sensitive to right-handed mixings, like:

$$I_7^{CP} \equiv \mathrm{Tr}\,[H'_d, H'_{N_d^0}]^3 = 6i\,\Delta_d\,\Delta_{N_d}\,\mathrm{Im}\,Q_7$$

$$H'_d = M_d^\dagger M_d \quad , \quad H'_{N_d^0} = N_d^{0\dagger} N_d^0$$

Q_7 rephasing invariant quartet of $U_{dR}\, U_{N_d^0 R}^\dagger$

and again many more

The Minimal Flavour Violation Case

Lowest invariant sensitive to CP violation

$$I_q^{CP} \equiv \operatorname{Im} \operatorname{tr} \left[M_d N_d^{0\dagger} M_d M_d^\dagger M_u M_u^\dagger M_d M_d^\dagger \right]$$

must contain flavour matrices from the up and down sector

lower order in powers of mass than SM case ($\operatorname{Tr} [H_u, H_d]^3 \propto 12$)

BGL type models have richer flavour structure parametrized by four matrices

$$I_q^{CP} (\gamma = u, i=3) = - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) (m_\beta^2 - m_\lambda^2)(m_\beta^2 - m_d^2)(m_\lambda^2 - m_d^2) \times$$

FCNC in down sector, P_3

$$\times (m_c^2 - m_u^2) \operatorname{Im} (V_{22}^* V_{32} V_{33}^* V_{23})$$

I_q^{CP} controlled by V_{CKM} (BGL)

$I_q^{CP} \neq 0$ even if $m_t = m_c$ or $m_t = m_u$ since discrete symmetry singles out top quark

I_q^{CP} can be related to baryon asymmetry generated at EW phase transition

Scalar Potential

Sym. forbids $\phi_1^\dagger \phi_2$, $\phi_1^\dagger \phi_2 \phi_2^\dagger \phi_2$, $\phi_1^\dagger \phi_2 \phi_1^\dagger \phi_2$

ungauged accidental continuous symmetry
not a symmetry of full Lagrangean

after spontaneous gauge symmetry breaking →
→ pseudo Goldstone boson

solution : soft symmetry breaking $m_{12} \phi_1^\dagger \phi_2 + h.c.$

Work in progress

Phenomenological implications of BGL models

36 different models $\quad$ 6 quark × 6 lepton

i) making use of exp results in agreement with the SM plus World average on $B \to \tau\nu$

ii) all the above plus $B \to D\tau\nu$ from BABAR

Taking into account the T parameter constraint and all experimental constraints

Conclusions

Multi-Higgs models are very interesting candidates for NP

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

LHC results may bring surprises for the Higgs sector

WB invariant conditions are a powerful tool to analyse the flavour structure of these models

Minimal Flavour Violation with Majorana neutrinos

Low energy effective theory and stability

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

generated from effective dimension five operator

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

$$\mathcal{L}_{Y_\ell} = - \overline{L^0_L}\, \Pi_1 \phi_1 \ell^0_R - \overline{L^0_L}\, \Pi_2 \phi_2 \ell^0_R + h.c.$$

$$\Pi_1 , \Pi_2 , \quad \kappa^{11} , \kappa^{12} , \kappa^{21} , \kappa^{22} \qquad (\kappa^{(ij)})$$

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

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

Imposing this Z_4 symmetry implies: $(j=3)$

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

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

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

$$\frac{1}{2} m_\nu = \frac{1}{2} v_1^2 \, k^{(11)} + \frac{1}{2} v_2^2 e^{2i\theta} \, k^{(22)}$$

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

Higgs FCNC in the charged sector

Stability: $k^{(12)} = k^{(21)} = 0$ $\quad k^{(11)} P_3^\nu = 0$ $\quad k^{(22)} P_3^\nu = k^{(22)}$

$P_3^\nu \Pi_1 = 0$ $\quad P_3^\nu \Pi_2 = \Pi_2$

stable under renormalization

W. Grimus, L. Lavoura 2005

Seesaw framework

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

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

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

$$\mathcal{L}_Y (\text{neutral, lepton}) = -\bar{\ell}_L^0 \frac{1}{v} [m_\ell H^0 + N_\ell^0 R + i N_\ell^0 I] \ell_R^0 - \bar{\nu}_L^0 \frac{1}{v} [m_D H^0 + N_\nu^0 R + i N_\nu^0 I] \nu_R^0 + h.c.$$

$$N_\ell^0 = \frac{v_2}{\sqrt{2}} \Pi_1 - \frac{v_1}{\sqrt{2}} e^{i\theta} \Pi_2$$

$$N_\nu^0 = \frac{v_2}{\sqrt{2}} \Sigma_1 - \frac{v_1}{\sqrt{2}} e^{-i\theta} \Sigma_2$$

$$\mathcal{L}_{mass} = -\bar{\ell}_L^0 m_\ell \ell_R^0 + \frac{1}{2}\left(\nu_L^{0T}, (\nu_R^0)^{cT}\right) C^{-1} \mathcal{M}^* \begin{pmatrix} \nu_L^0 \\ (\nu_R^0)^c \end{pmatrix} + hc$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad (\Psi_L)^c \equiv C \gamma_0^T (\Psi_L)^*$$

BGL type example , Z_4 symmetry

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

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

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

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

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

Three light neutrinos ν_i, plus heavy neutrinos N_j

light - light, light - heavy, heavy - heavy couplings

H^0, R, I couplings

$U^\dagger m_{eff} U^* = d$, $\quad m_D \frac{1}{D} m_D^T = -U d U^T$ (WB M_D diag)

$m_D = i\, U \sqrt{d}\, O^c \sqrt{D}$ Casas and Ibarra, 2001

$$(N_\ell)_{ij} = \frac{v_2}{v_1} (D_\ell)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) (U_\nu^\dagger)_{i3} (U_\nu)_{3j'} (D_\ell)_{j'j}$$

light - light neutral couplings : diag, d

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

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

H^+ couplings

$$\frac{\sqrt{2}\, H^+}{v} \left(\bar{\nu}_L^0 N_\ell^0 \ell_R - \bar{\nu}_R^0 N_\nu^{0\dagger} \ell_L^0 \right) + h.c.$$