Invariants and Flavour in the General Two Higgs Doublet Model

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MORIOND QCD 2013
11 MARCH 2013

WORK IN COLLABORATION WITH

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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 ~~CP~~ same footing
  T. D. Lee 1973 ; Kobayashi and Maskawa 1973

- Peccei Quinn type solution to CP strong

- Supersymmetry

LHC important rôle

Notation

Yukawa interactions

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

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

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

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

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

Expansion around the vev's

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

We perform the following transformation

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

$$O = \frac{1}{v} \begin{pmatrix} v_1 & v_2 \\ v_2 & -v_1 \end{pmatrix} ; \quad v = \sqrt{v_1^2 + v_2^2} = \left(\sqrt{2}\, G_F\right)^{-1/2} \approx 246\ \text{GeV}$$

O singles out

H^0 with couplings to quarks proportional to mass matrices
G^0 the 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

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

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

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

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

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

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

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

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

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

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

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 :

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

conserves flavour

leads to FCNC

Models with two or more Higgs doublets

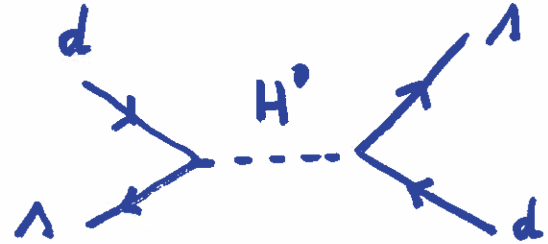
potentially large HFCNC

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

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

or

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)

More recently, we have generalized BGL models to larger class of models of "Minimal Flavour Violation" type

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 complitely 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

WB covariant definition

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

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

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

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

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

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

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

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

$U_{uL} \neq U_{dL}$ misalignment of the matrices H_d, H_u

analogously

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

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

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

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

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:

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

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

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

and again many more

The Minimal Flavour Violation case

Lowest invariant sensitive to CP violation

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

must contain flavour matrices from the up and down sector

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

BGL type models have richer flavour structure parametrized by four matrices

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

FCNC in down sector, P_3

$$\times (m_c^2 - m_u^2)\,\mathrm{Im}\left(V_{22}^* V_{32} V_{33}^* V_{23}\right)$$

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

Z_4 forbids $\phi_1^\dagger\phi_2$, $\phi_1^\dagger\phi_2\,\phi_i^\dagger\phi_i$, $\phi_1^\dagger\phi_2\,\phi_1^\dagger\phi_2$

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

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