Signal of FCNC and CPV in 2HDM

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STARS 2013
Havana, Cuba

05/05/2013

Outline

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Standard Model of the particle physics

- Gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Gauge invariance introduces interactions
- Higgs mechanism

Field Content:

$$q_L = \begin{pmatrix} u_{t,c,u} \\ d_{b,s,d} \end{pmatrix}_L, \; l_L = \begin{pmatrix} \nu_{t,c,u} \\ e_{\tau,\mu,e} \end{pmatrix}_L$$

$$u_{R(t,c,u)}, \quad d_{R(b,s,d)} \quad \text{and} \quad e_{R(\tau,\mu,e)}$$

where $\psi_{L,R} = \frac{I \mp \gamma_5}{2}\psi$.

Higgs mechanism

The basic idea was introduce a complex scalar doublet field with $Y = 1$

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi_0 \end{pmatrix}$$

and a potential,

$$V = -\mu^2 \left(\phi^\dagger \phi\right) + \frac{\lambda}{2} \left(\phi^\dagger \phi\right)^2$$

Then, SBB happens when vev is taken $\langle \phi \rangle^T = \begin{pmatrix} 0, & \frac{1}{\sqrt{2}} v \end{pmatrix}$ and

$$M_{W^\pm} = \frac{ev}{2 \sin \theta_W},$$

$$M_Z = \frac{M_{W^\pm}}{\cos \theta_W},$$

$$M_H = \lambda v.$$

Experimentally

- $\sin^2\theta_W = 0.23116(12)$,
- $M_W = 80.385(15)$ GeV,
- Observation of new boson like SM Higgs boson is given by ATLAS[1] and CMS[2] with a mass of the order of 126.0(0.4)GeV and 125.3(0.4)GeV,respectively.

[1] ATLAS collaboration, G. Aad et al., Phys. Lett. **B 716**, 1, (2012).

[2] CMS collaboration, S. Chatrchyan et al., Phys. Lett. **B 716**, 30, (2012).

Fermions-Higgs boson interaction

The interaction is introduced as

$$\mathcal{L}_{Yukawa} = \overline{q}^0_{Li} Y^u_{ij} \widetilde{\phi} u^0_{Rj} + \overline{d}^0_{Li} Y^d_{ij} \phi d^0_{Rj} + \overline{l}^0_{Li} Y^l_{ij} \phi e^0_{Rj} + h.c.,$$

with $\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ and $\widetilde{\phi} = i\sigma_2 \phi$.

After getting a correct SSB, $\langle \phi \rangle^T = \begin{pmatrix} 0, & \frac{1}{\sqrt{2}} v \end{pmatrix}$,

$$\mathcal{L}_{Yukawa} = \overline{u}_i M^u_{ij} u_j + \overline{d}_i M^d_{ij} d_j + \overline{e}_i M^e_{ij} e_j,$$

where $\psi^0_i = U^\psi_{ij} \psi_j$ for $\psi = u, d, e$.

CKM matrix

The quark and lepton kinetic terms are $\overline{\psi}\gamma^\mu D_\mu \psi$, with $D_\mu = \partial_\mu - ig_1 \frac{Y}{2} B_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu$.
Then, quarks are written in mass eigenstates

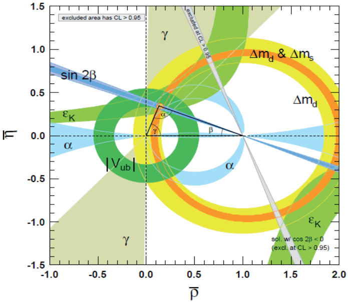
$$-\frac{e}{\sqrt{2}\sin\theta_W}\left[\overline{u}_{Li}\gamma^\mu W^+_\mu \left(V_{CKM}\right)_{ij} u_{Lj} + h.c.\right],$$

where $V_{CKM} = U^u_L \left(U^d_L\right)^\dagger$. The standard parametization is

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and δ is the CP-violating phase.

Experimentally



The angles of unitary triangle are

$$\beta = arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}), \quad \sin 2\beta = 0.679(20)$$

$$\alpha = arg(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}), \quad \alpha = (89.0^{+4.4}_{-4.2})^\circ$$

$$\gamma = arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}), \quad \gamma = (68^{+10}_{-11})^\circ$$

General 2HDM potential

- Two complex $SU(2)_L$ doublets: $\Phi_{1,2}$ $(Y = 1)$.

$$
\begin{aligned}
V \;=\; & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right] \\
& + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 \\
& + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\
& + \left[\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \mathrm{h.c.} \right] \\
& + \left[\lambda_7 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \lambda_8 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \mathrm{h.c.} \right]
\end{aligned}
$$

Explicit CP-Violation from m_{12}^2, $\lambda_{5,6,7}$.

Neutral Higgs mass-eigenstates

The most general $U(1)_{EM}$-conserving vacuum expectation value is: $\langle \Phi_a \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{v}_a \end{pmatrix}$, with $\hat{v}_a = e^{i\eta} \begin{pmatrix} \cos\beta \\ \sin\beta e^{i\xi} \end{pmatrix}$ for $a = 1, 2$.

The neutral Higgs mass-eigenstate are

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ a^0 \end{pmatrix}.$$

Flavor Changing Neutral Currents and CP-violation

The most general structure of the Yukawa interactions,

$$\mathcal{L}_{Yukawa} = \sum_{i,j=1}^{3}\sum_{a=1}^{2}\Big[\bar{q}^0_{Li}\,[Y^u_a]^0_{ij}\,\widetilde{\Phi}_a u^0_{Rj} + \bar{q}^0_{Li}\left[Y^d_a\right]^0_{ij}\Phi_a d^0_{Rj} + \bar{l}^0_{Li}\left[Y^l_a\right]^0_{ij}\Phi_a e^0_{Rj} + h.c.\Big],$$

Then,

$$M^{u,l} = \frac{v_1}{\sqrt{2}}Y_1^{u,l} + e^{-i\xi}\frac{v_2}{\sqrt{2}}Y_2^{u,l}$$

and

$$M^d = \frac{v_1}{\sqrt{2}}Y_1^d + e^{i\xi}\frac{v_2}{\sqrt{2}}Y_2^d$$

where $Y^f_a = V^f_L Y^{f,0}_a \left(V^f_R\right)^\dagger$ and $V^f_{L,R}$ are dimensionless 3×3 matrices such as $f^0_{(L,R)i} = \sum_j V^f_{(L,R)ij} f_{(L,R)j}$.

Flavor Changing Neutral Currents and CPV

We can write the Yukawa interactions between neutral Higgs bosons and up-quarks as

$$\begin{aligned}\mathcal{L}_{Yukawa} \quad = \quad & \sum_{i,j,k=1}^{3} \overline{u}_i \left[\frac{1}{v} \left(\frac{1}{\cos\beta} R_{k1} + i R_{k3} \tan\beta \gamma_5 \right) M_{ij}^u \right. \\ & - R_{k1} \tan\beta J_{+ij} + R_{k2} K_{+ij} - i R_{k3} \tan\beta \sin\beta J_{-ij} \\ & \left. - i R_{k3} \cos\beta K_{-ij} \right] h_k u_j ,\end{aligned}$$

where $J_\pm = e^{-i\xi} Y_2^u P_R \pm e^{i\xi} \left(Y_2^u \right)^\dagger P_L$ and
$K_\pm = Y_2^u P_R \pm \left(Y_2^u \right)^\dagger P_L$

Usual scalar mixing and Spontaneous CPV

Yukawa interactions for $\alpha_2 = \alpha_3 = 0$, $\alpha_1 = \alpha + \pi/2$, $h_1 = h^0$ and $h_2 = -H^0$, become as

$$\begin{aligned}\mathcal{L}^{up}_{Yukawa} \quad = \quad & \sum_{i,j=1}^{3} \overline{u}_i \left[-\frac{1}{v\cos\beta} \left(h_0 \sin\alpha + H_0 \cos\alpha \right) M^u_{ij} \right. \\ & + \tan\beta \left(h_0 \sin\alpha - H_0 \cos\alpha \right) J_{+ij} \\ & + \left(h_0 \cos\alpha + H_0 \sin\alpha \right) K_{+ij} \\ & \left. + i \left(\frac{\tan\beta}{v} \gamma_5 M^u_{ij} - \tan\beta \sin\beta J_{-ij} - \cos\beta K_{-ij} \right) A_0 \right].\end{aligned}$$

where $J_{\pm} = e^{-i\xi} Y^u_2 P_R \pm e^{i\xi} \left(Y^u_2 \right)^{\dagger} P_L$ and $K_{\pm} = Y^u_2 P_R \pm \left(Y^u_2 \right)^{\dagger} P_L$.

Rare top decay

The decay width for rare top decay is given by

$$\begin{aligned}
\Gamma_{t\to c l^+ l^-} \quad = \quad & \frac{m_t^5 m_l^2 \left|Y_{23}^u\right|^2}{512\pi^3 m_{h_1}^4 v^2} \left| \frac{\sqrt{2} v \cos(\alpha-\beta)}{2 m_l} Y_{33}^l - \frac{\sin\alpha}{\cos\beta} \right|^2 \\
& \left[\frac{R_{13}^2}{\cos^2\beta} \left(\cos^4\beta + \sin^4\beta + 2\cos^2\beta \sin^2\beta \cos\xi\right) \right. \\
& -2 R_{11} R_{12} \tan\beta \cos\xi - 2 R_{11} R_{13} \sin\beta \cos\xi \\
& +2 R_{12} R_{13} \frac{\sin\xi}{\cos\beta} \left(\cos^2\beta \cos\xi + \sin^2\beta\right) \\
& \left. + R_{12}^2 + R_{11}^2 \tan^2\beta \right] F(\mu_1, \mu_2),
\end{aligned}$$

where

$$\begin{aligned}
F(\mu_1,\mu_2) \quad = \quad & 2\left(1+\mu_1-4\mu_2\right)\sqrt{\mu_1} I_1 \\
& + \left(1+\mu_1-4\mu_2-2\sqrt{\mu_1}\right) I_2 - I_3
\end{aligned}$$

with $\mu_1 = \frac{m_c^2}{m_t^2}$, $\mu_2 = \frac{m_l^2}{m_t^2}$. NN

SCP-violation phase and usual cases

In particular,

$$\Gamma_{t\to cl^+l^-} = \frac{m_t^5 \left|Y_{23}^u\right|^2}{256\pi^3 m_{h^0}^4} \left| \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta} Y_{33}^l - \frac{m_l}{v} \frac{\sin\alpha}{\cos\beta} \right|^2$$
$$\left(\tan^2\beta \sin^2\alpha + 2\tan\beta\cos\alpha\sin\alpha\cos\xi + \cos^2\alpha\right) F\,($$

Then, branching ratio is $Br\left(t\to cl^+l^-\right) \approx \frac{\Gamma_{t\to cl^+l^-}}{\Gamma_{top}}$, where $\Gamma_{top} = 1.2$ GeV,

$$Br\left(t\to cl^+l^-\right) \approx \frac{m_t^5 \left(I_2 - I_3\right)}{512\pi^3 m_{h^0}^4} \left|Y_{23}^u\right|^2 \left|Y_{33}^l\right|^2 \left(\frac{\cos(\alpha-\beta)}{\cos\beta}\right)^4, \quad (2)$$

The mixing angle β has been bounded as $1 \le \tan\beta \le 50$ and $-\pi/2 \le \alpha \le \pi/2$

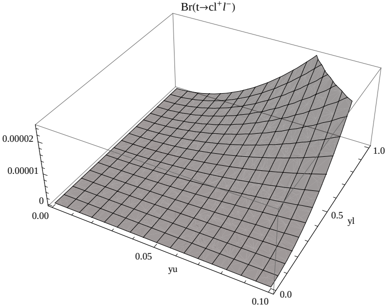


Figure: $Br(t \to c\tau^+\tau^-)$ for values $\alpha = 0.1$, $\tan\beta = 1$ and $\xi = 0$.

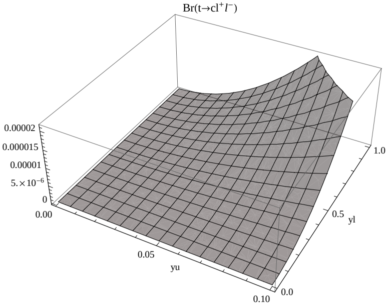


Figure: $Br(t \to c\tau^+\tau^-)$ for values $\alpha = 0.1$, $\tan\beta = 1$ and $\xi = 0.1$.

Final remarks

- 2HDM is a source for FCNC and CPV
- Top factories
- SM has been probed successfully

Thank you