CP violation from Higgs-dependent Yukawa couplings

Oleg Lebedev

DESY

w/ G. Giudice

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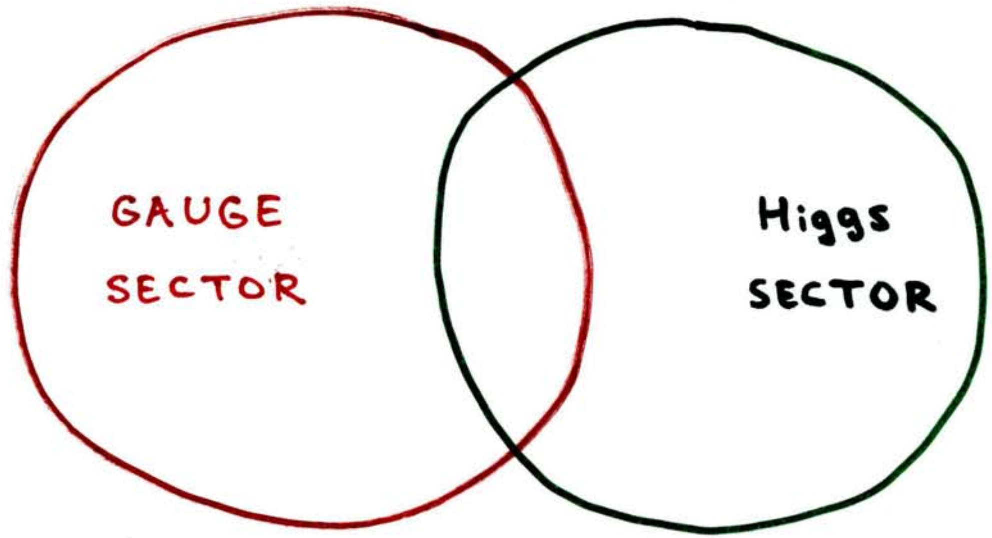
Basic idea

The SM is very successful but ...



measured/ understood

$A\bar{f}f$, ...

NOT measured/ understood

$h\bar{f}f$

In particular,

$$m_u \sim 10^{-5} \,, \quad m_d \sim 10^{-5} \,, \quad m_s \sim 10^{-3}$$

$$m_c \sim 10^{-2} \,, \quad m_b \sim 10^{-2} \,, \quad m_t \sim 1$$

Small Yukawa couplings : $10^{-5} \ldots 1$ → <u>**FLAVOR PUZZLE**</u>

Gauge couplings : $0.3, 0.6, 1$

Need BSM !

Most economical model

Uses ingredients of the SM : Higgs VEV

Effective Yukawa couplings :

$$Y = Y(H)$$

In general,

$$Y(H) = Y^{(0)} + Y^{(1)} \frac{H^{+}H}{M^{2}} + \dots$$

Here M = new physics scale .

Most interesting case:

Also Babu, Nandi

$$Y_{ij}(H) = c_{ij}\left(\frac{H^{+}H}{M^2}\right)^{n_{ij}}$$

$$\begin{cases} c_{ij} = O(1) \\ n_{ij} = \text{integer} \end{cases}$$

$$\mathcal{L} = \left(\frac{H^{+}H}{M^2}\right)^{n_{ij}} H\,\bar{q}_i d_j + \ldots \quad \longrightarrow \quad \left(\frac{v^2}{M^2}\right)^{n_{ij}} v\,\bar{q}_i d_j + \ldots$$

Small parameter $= \dfrac{v^2}{M^2}$

No small couplings !

Simplest possible "theory of flavor" (?)

What is M ?

$$\left.\begin{array}{l} m_t \rightarrow n=0 \\ m_b \rightarrow n=1 \end{array}\right\} \Rightarrow \frac{v^2}{M^2} \simeq \frac{m_b}{m_t} \simeq \frac{1}{60}$$

$$\boxed{M = \sqrt{\frac{m_t}{m_b}} \cdot v} = 1\text{-}2 \text{ TeV}$$

How to get $Y(H)$?

ⓐ integrate out heavy states at $M \sim 1$ TeV

ⓑ SUSY / 2HDM case : Froggatt - Nielsen symmetry

$$Y_{ij} = c_{ij} \left(\frac{H_u H_d}{M^2} \right)^{n_{ij}}$$

$H_{u,d}$ carry $U(1)$ charge ; $n_{ij} = a_i + b_j = \sum$ charges

Higgs couplings

$$\mathcal{L} = c_{ij} \left(\frac{H^\dagger H}{M^2} \right)^{n_{ij}} H \bar{q}_i d_j + \ldots$$

$$(H^\dagger H)^n = (v + h)^{2n} = v^{2n} + \boxed{2n}\, h\, v^{2n-1} + \ldots$$

(h ← SM Higgs boson)

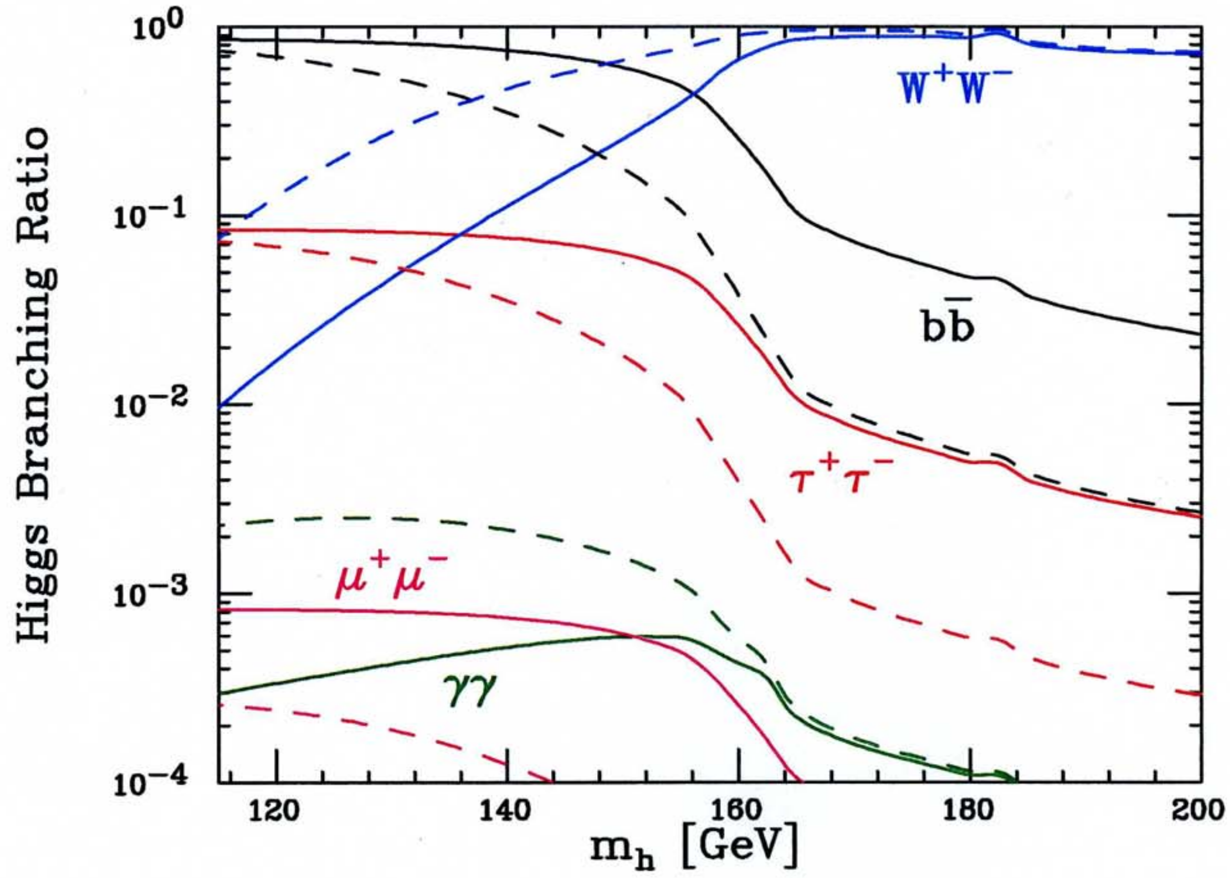
h - fermion coupling :

$$\mathcal{L}_h = -\frac{h}{\sqrt{2}}\, y_{ij}\, \bar{q}_i d_j + \ldots \quad , \text{ where}$$

$$\boxed{y_{ij} = (2n_{ij} + 1)\, y_{ij}\big|_{SM}}$$

$$\Gamma(h \to \bar{f} f) = \underline{\underline{(2n+1)^2}}\, \Gamma(h \to \bar{f} f)\big|_{SM}$$

Increase by a factor 9 - 49 !


Higgs Branching Ratio
10^0
10^-1
10^-2
10^-3
10^-4
120
140
160
180
200
m_h [GeV]
W+W-
bb̄
τ+τ-
μ+μ-
γγ

- - - - = SM

——— = our model

FCNC

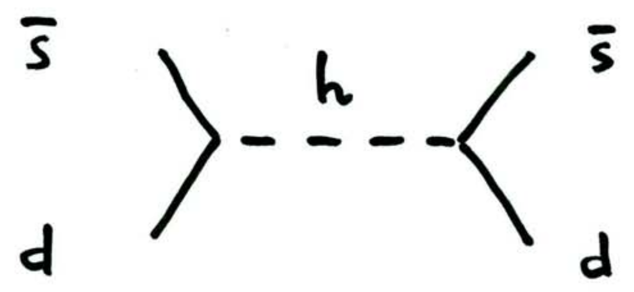
fermion masses : $m_{ij} \sim Y_{ij}$

h - couplings : $y_{ij} \sim (2n_{ij}+1)\, Y_{ij}$

m_{ij} and y_{ij} are <u>not</u> diagonal in the same basis !

mass eigenstate basis :

$$\mathcal{L} \sim h\, y_{ij}\, \bar{q}_i d_j + \dots \Rightarrow$$



$$\sim \frac{m_q^2}{v^2} \frac{1}{m_h^2} (\sin\alpha)^2$$

$$\Rightarrow \sin\alpha \lesssim 0.06$$

Define

$$\epsilon \equiv \frac{v^2}{M^2} \qquad \simeq \frac{1}{60}$$

Take

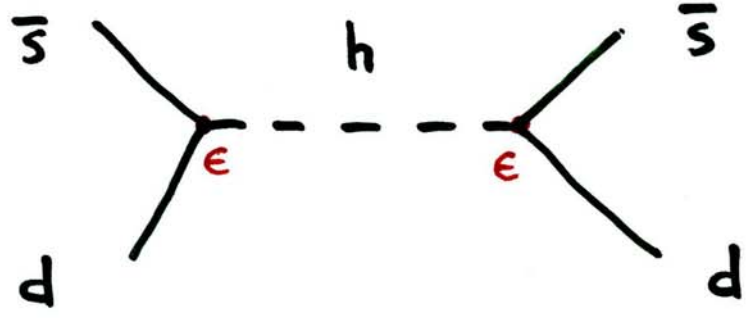
$$\begin{cases} m_t \sim \epsilon^0 \;, & m_{b,c} \sim \epsilon \;, \quad m_s \sim \epsilon^2 \;, \quad m_{u,d} \sim \epsilon^3 \\ V_{us} \sim \epsilon^0 \;, & V_{cb,ub} \sim \epsilon \end{cases}$$

Solve for $n_{ij} = a_i + b_j$:

$$a = (1,1,0) \;, \quad b^d = (2,1,1) \;, \quad b^u = (2,0,0)$$

$$\Rightarrow \qquad Y^d \sim \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon & \epsilon \end{pmatrix} \;, \qquad Y^u \sim \begin{pmatrix} \epsilon^3 & \epsilon & \epsilon \\ \epsilon^3 & \epsilon & \epsilon \\ \epsilon^2 & 1 & 1 \end{pmatrix}$$

$\Rightarrow$



All FCNC constraints = OK !

($\epsilon_K \rightarrow$ mild constraint on the phase)

$\not{CP}$

Physics is invariant under basis transforms :

$$q_L \to V_L\, q_L \quad , \quad d_R \to V_R^d\, d_R \quad , \quad u_R \to V_R^u\, u_R$$

Then

$$\begin{cases} Y^u \to V_L^\dagger\, Y^u\, V_R^u \\ Y^d \to V_L^\dagger\, Y^d\, V_R^d \end{cases}$$

$$Y \xrightarrow{CP} Y^*$$

Jarlskog invariant :

$$J = \mathrm{Tr}\left[Y^u Y^{u\dagger}, Y^d Y^{d\dagger} \right]^3$$

$\to$ need 3 generations of u <u>and</u> d !

$$J \sim (m_s^2 - m_d^2)(m_b^2 - m_d^2) \ldots \quad \sin\theta_{13} \ldots$$

$J < 10^{-20}$ (in EW units) $\Rightarrow$ no baryogenesis !

Our model :

$\not{C}\!P$ exists with 2 generations of u's !

Consider $\{t, c\}$:

$$Y = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix}, \qquad y = \begin{pmatrix} n_{11} Y_{11} & n_{12} Y_{12} \\ n_{21} Y_{21} & n_{22} Y_{22} \end{pmatrix}$$

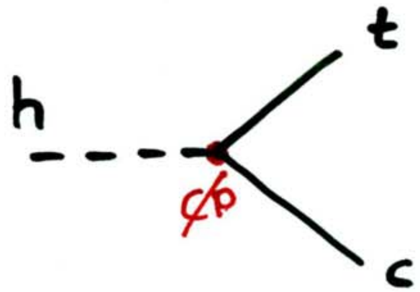
$$Y, y \rightarrow U_L^{+} \, Y, y \, U_R$$

$$\tilde{J} = \mathrm{Tr}\left[(Y y^{+})^2 - h.c. \right]$$

$$\tilde{J} \sim \mathrm{Im}\left(Y_{11} Y_{22} Y_{12}^{*} Y_{21}^{*}\right) \cdot \left(h_{11} h_{22} - h_{21} h_{12}\right)$$

$$\tilde{J} \sim m_t m_c \left(m_t^2 - m_c^2\right)$$

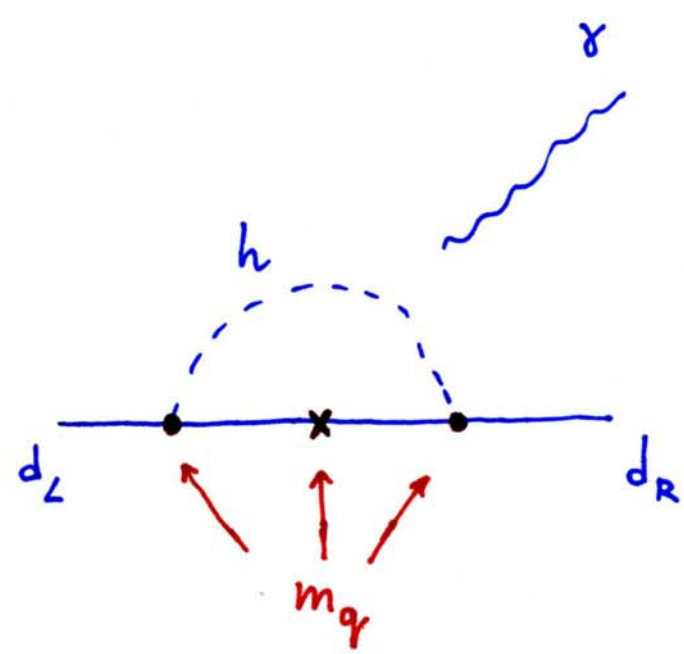
In EW units : $\underline{\tilde{J} \sim 10^{-4}}$ $\Rightarrow$ baryogenesis ?



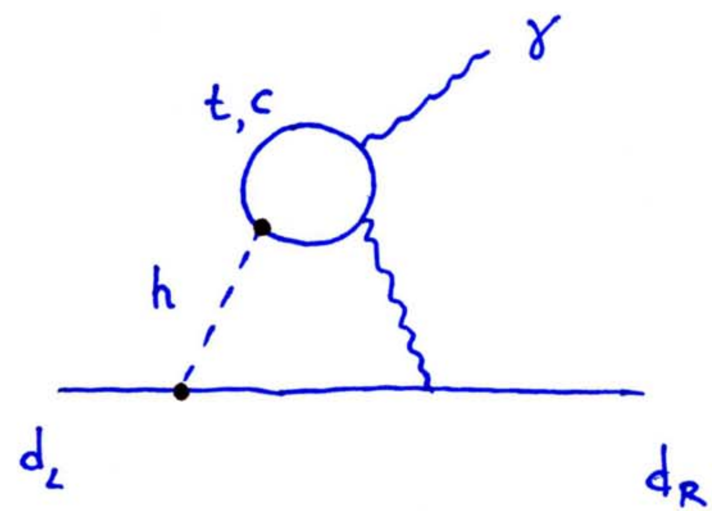
$\sim$ $BR\left(h \to t\bar{c}\right) \sim 10^{-3}$

LHC ?

EDMs :



$\sim m_q^3$



$\lesssim 10^{-27}$ e·cm

observable !

Conclusions

- no small Yukawas
- $BR(h \to f\bar{f})$ change drastically
- $\not{CP}$ increases by $10^{15} - 10^{20}$ (baryogenesis ?)
- EDMs