Opportunities for Indirect Searches of Flavor Violation Higgs in Future DIS Experiments

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Contents

Motivations

The standard model has unanswered questions, in order to solve them, physicists have proposed new models beyond.

Higgs boson decays mediated by flavour changing neutral currents (FCNC) are very much suppressed in the Standard Model therefore, any experimental signal of them would immediately call for new physics.

Besides the top quark decay into the SM Higgs boson, is a very unusual decay, typically $BR(t \to cH^{SM}) \sim 10^{-14}$ [1]. However, when considering physics beyond the SM, there are possibilities that would allow to measure FCNC involving a Higgs boson and the top quark.[2]

[1] B. Mele, S. Petrarca, A. Soddu, Phys. Lett. B 435 (1998) 401, hep-ph/9805498; G. Eilam, J.L. Hewett, A. Soni, Phys. Rev. D 59 (1998) 039901, Erratum.

[2] J. Guasch, J. Sola, Nucl. Phys. B 562 (1999) 3, hep-ph/9906268.

- Why we chosen this process?

  - The top quark is the the most massive of all observed elementary particles, therefore gives important information of the scalar sector
  - Top quark processes, sets boundaries to The Standard Model and so beyond
  - The top quark decays before it hadronizes; Standard Model determines the mean lifetime to be roughly $5 \times 10^{-25} s$

Colliders

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

Figura: Baseline parameters of future electron-proton colliders configuration[3]

[3] Summary of the FCC-eh Parallel Sessions at the Annual FCC Workshop, Rome

Review of the 2HDM-III

The simplest extension is add another doublet, then we have the Two Higgs Doublet Model: "2HDM" In a model with only one doublet, quarks acquire their mass trough the same doublet, however in a model that contains two doublets, each one (or both) could give mass to the two types of quarks.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Extra\ Higgs\ doublet}$$

The most general Yukawa Lagrangian is:

$$\mathcal{L}_Y = \sum_{a,i} Y^i_a \bar{F}^i_L \phi_a f^i_R + h.c \qquad (1)$$

where F_L *stays for left fermionic doublet,* f_R *is right fermionic singlet and* ϕ_a*,* $(a = 1, 2)$ *are the Higgs doublets*; *i* is an flavour index

All models with two doublets have Flavour-Changing Neutral Currents (FCNC)

They keep under control

→ Discrete Symmetries

- 2HDM-I: When a single Higgs field gives masses to both types of quarks $Y_1^u = Y_1^d = 0$ or $Y_2^u = Y_2^d = 0$

- 2HDM-II: When each type of quark couples to a different Higgs doublet $Y_1^u = Y_2^d = 0$ or $Y_2^u = Y_1^d = 0$

→ Radiative Suppression: Here each fermion type couples to both Higgs doublets, FCNCs could be kept under control if there exists a hierarchy between $Y_1^{u,d}$ and $Y_2^{u,d}$ then, a given set of Yukawa matrices is present at the tree level, but the other ones arise only as a radiative effect

→ Flavour Symmetries : Suppression for FCNCs can also be achieved when a certain form of the Yukawa matrices that reproduce the observed fermion masses and mixing angles is implemented in the model, which is then named the 2HDM-III

Particularly for the type III:

$$\mathcal{L}_Y^q = Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R + Y_2^d \bar{Q}_L \Phi_2 d_R + h.c \quad (2)$$

$$\mathcal{L}_Y^l = Y_1^l \bar{L}_L \Phi_1 l_R + Y_2^l \bar{L}_L \Phi_2 l_R + h.c \quad (3)$$

where first equation is for quarks sector and second for the leptonic sector. Besides $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$ *and* $Y_{12}^{u,d,l}$ *are the Yukawa matrices*

After EWSB one can derive the fermion mass matrices

$$M_f = \frac{1}{\sqrt{2}} \left(v_1 Y_1^f + v_2 Y_2^f \right), \qquad f = u, d, l \tag{4}$$

The mass matrix is diagonalized through the biunitary matrices $V_{L,R}$ and is performed in the following way:

$$\bar{M}_f = V_{fL}^\dagger M_f V_{fR}$$

The mass eigenstates for the fermions take the form:

$$u = V_u^\dagger u' \qquad d = V_d^\dagger d' \qquad l = V_l^\dagger l'$$

The equation (4) takes the form:

$$\bar{M}_f = \frac{1}{\sqrt{2}} \left(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f \right)$$

where $\tilde{Y}_i^f = V_{fL}^\dagger Y_i^f V_{fR}$ and for the quark case we may write:

$$\begin{aligned} \tilde{Y}_1^d &= \frac{\sqrt{2}}{v \cos\beta} \bar{M}_d - \tan\beta \, \tilde{Y}_2^d \\ \tilde{Y}_2^u &= \frac{\sqrt{2}}{v \sin\beta} \bar{M}_u - \cot\beta \, \tilde{Y}_1^u \end{aligned} \tag{5}$$

Now, with the Yukawas in this basis we rewrite the Lagrangian

$$
\begin{aligned}
\mathcal{L}_Y^q = & \frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{d}_i\left[\frac{\cos\alpha}{\cos\beta}\delta_{ij}+\frac{\sqrt{2}\sin(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]d_j H^0 \\
& \frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{d}_i\left[-\frac{\sin\alpha}{\cos\beta}\delta_{ij}+\frac{\sqrt{2}\cos(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]d_j h^0 \\
& i\frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{u}_i\left[-\tan\beta\,\delta_{ij}+\frac{\sqrt{2}}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]\gamma^5 d_j A^0 \\
& \frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[\frac{\sin\alpha}{\sin\beta}\delta_{ij}+\frac{\sqrt{2}\sin(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_1^u)_{ij}\right]u_j H^0 \\
& \frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[\frac{\cos\alpha}{\sin\beta}\delta_{ij}+\frac{\sqrt{2}\cos(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_1^u)_{ij}\right]u_j h^0 \\
& i\frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[-\cot\beta\,\delta_{ij}+\frac{\sqrt{2}}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_2^d)_{ij}\right]\gamma^5 u_j A^0
\end{aligned}
$$

Here $i = 1, 2, 3$, $d_1 = d$, $d_2 = s$, $d_3 = b$, $u_1 = u$, $u_2 = c$ and $u_3 = t$.
We get the leptonic current making $d_i \to l_i$ where $l_1 = e$, $l_2 = \mu$ and $l_3 = \tau$.[4]

[4] Flavor violating decays of the Higgs bosons in the THDM-III", M. Gómez-Bock, and R. Noriega-Papaqui

In this model, were proposed The Cheng-Sher anzats in order to keep under control FCNC processes

$$\left(\tilde{Y}_2^{d,l}\right)_{i,j} = \frac{\sqrt{m_i^{d,l} m_j^{d,l}}}{v} \tilde{\chi}_{i,j}^{d,l}$$
$$\left(\tilde{Y}_1^{u}\right)_{i,j} = \frac{\sqrt{m_i^{u} m_j^{u}}}{v} \tilde{\chi}_{i,j}^{u} \quad (6)$$

As we can note, the couplings are proportional to square root of masses product and the parameters $\tilde{\chi}_{i,j}^{f}$ must be determined by the experiment

Process

The process under analysis has next Feynman diagram

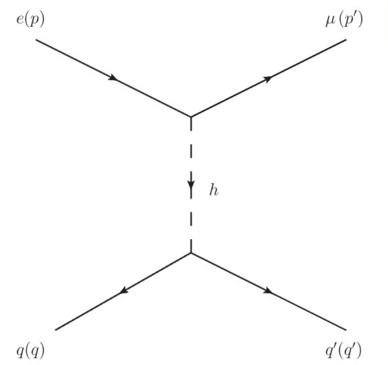


Figura: Feynman diagram for the inclusive process $e + u \to \; \mu + t$

The differential cross section is:

$$d\sigma^{eq} = \frac{|\mathcal{M}|^2}{16\pi\lambda(\hat{s}, m_e^2, m_q^2)} dt \qquad (7)$$

where:

$$\lambda(\hat{s}, m_e^2, m_q^2) = (\hat{s} - m_e^2 - m_q^2)^2 - 4m_e^2 m_q^2$$

$$\hat{s} = x's, \quad 0 < x' < 1$$

Then, total cross section will be

$$\sigma^{eq} = \int_{t^-}^{t^+} \frac{|\mathcal{M}|^2}{16\pi(x's)^2} dt \qquad (8)$$

For matrix element, we have:

$$|\mathcal{M}|^2 = \frac{4\cos^4(\alpha - \beta)}{\cos^2\beta\sin^2\beta}\frac{m_e m_{\mu/\tau} m_q m_t}{m_W^4}|\tilde{\chi}^l_{12}|^2|\tilde{\chi}^u_{13}|^2\frac{(p\cdot p' + m_e m_\mu)(q\cdot q' + m_q m_t)}{[(p-p')^2 - m_H^2]^2} \quad (9)$$

The scalar products are related to t as:

$$t = (p - p')^2$$
$$t = m^2_{\mu/\tau} + m_e^2 - 2p\cdot p'$$
$$\rightarrow p\cdot p' = -\frac{1}{2}(m^2_{\mu/\tau} + m_e^2 - t)$$

$$t = (q - q')^2$$
$$t = m_q^2 + m_t^2 - 2q\cdot q'$$
$$\rightarrow q\cdot q' = -\frac{1}{2}(m_q^2 + m_t^2 - t)$$

Hence

$$|\mathcal{M}|^2 = CW|\tilde{\chi}^l_{12}|^2|\tilde{\chi}^u_{13}|^2 \frac{\left[t-(m_{\mu/\tau}-m_e)^2\right]\left[t-(m_q-m_t)^2\right]}{(t-m_H^2)^2} \quad (10)$$

with

$$C = \frac{\cos^4(\alpha - \beta)}{\cos^2\beta \sin^2\beta}$$

$$W = \frac{m_e m_\mu m_u m_t}{m_W^4}$$

The sub-process cross section

$$\sigma^{eq} = \frac{1}{16\pi(x's)^2}\int_{t^-}^{t^+} |\mathcal{M}|^2 dt \quad (11)$$

We have to integrate

$$I = \int_{t^-}^{t^+} \frac{(t-a)(t-b)}{(t-c)^2} dt = \frac{(a-c)(b-c)}{c-x} - (a+b-2c)\log(c-t) + t \quad (12)$$

Now, making use of the energies values from table 1:

$a = (m_\mu - m_e)^2 = 0{,}011(GeV)^2$
$b = (m_u - m_t)^2 = 29583,42(GeV)^2$
$c = m_H^2 = 15625(GeV)^2$

Due to the kinematics of the process, limits of integration are giving by

$$t^{\pm} = m_u^2 + m_t^2 + 2E_u^* E_t^* (-1 \pm 1) \qquad (13)$$

Physical considerations taken into account

- $m_u^2 + m_t^2 \ll E_u^* E_t^*$
- $E_u^* \sim 7\ TeV$
- $E_t^* \sim 173\ GeV$

So we obtain:

$t^{+} = 0$

$t^{-} = -4E_u^* E_t^* = -4(7000)(173{,}3) = -4,852,400$

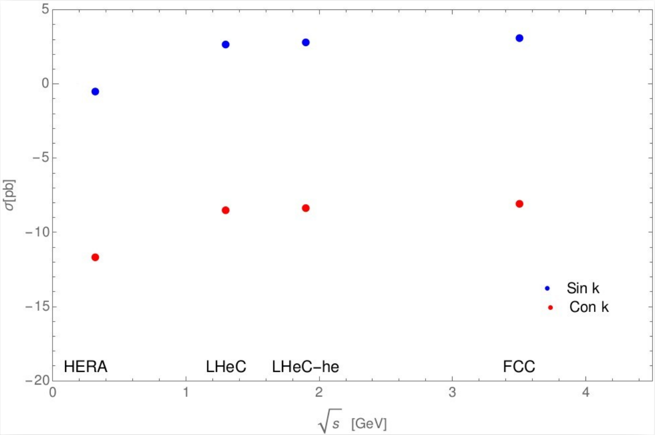
And finally we obtain

$$\sigma^{eq} = \frac{|\tilde{\chi}^{l}_{12}|^2 |\tilde{\chi}^{u}_{13}|^2}{16\pi(x's)^2} \frac{\cos^4(\alpha - \beta)}{\cos^2\beta \sin^2\beta} (3{,}67 \times 10^{-13})(4{,}83 \times 10^{6}) \tag{14}$$

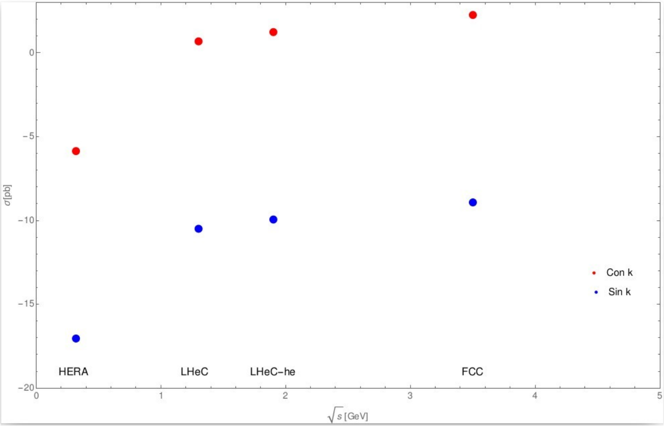
if

$$k = \frac{|\tilde{\chi}^{l}_{12}|^2 |\tilde{\chi}^{u}_{13}|^2}{16\pi(x's)^2} \frac{\cos^4(\alpha - \beta)}{\cos^2\beta \sin^2\beta}$$

Process $eu \to \mu t$



Process $ec \to \mu\, t$



Conclusions

Hence, if we can obtain the scenario where $k = 1$, the order of magnitude of the parameters $|\tilde{\chi}^f_{i,j}|$ have to be about $\sim 10^2$. This is a good approximation, due in the literature the order is taken to be $\sim 10^1$, so we are close to those scenarios which have given good phenomenological results.

To summarize, the FCNC interaction of the Higgs bosons and the top quark can be a helpful complementary strategy to search for signals of physics beyond the SM. According *Higgs Boson Flavor-Changing Neutral Decays into Top Quark in a General Two-Higgs-Doublet Model, arXiv:hep-ph/0307144* those kind of process have not been studied anywhere in the literature, then we are still investigating what would be obtained in different scenarios.

♣ Thank you ♣