Opportunities for Indirect Searches of Flavor Violation Higgs in Future DIS

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Abstract

Processes of Flavor Changing Neutral Currents are present at tree level in Beyond Standard Models which makes them an important source of new physics signals. To examine the scenarios that could exhibit such events, we have performed a search in the parameter space to determine the possible production of a single top quark in ep Deep Inelastic Scattering, in the context of a flavor violation extended model, the THDM type III, for energies given by current and future colliders. We show the order of magnitude for the model parameter $|\tilde{\chi}^f_{ij}|$ that would allow for the observation of flavor violation through the scalar sector.

1 Introduction

Within the Standard Model (SM) quarks acquire their mass through spontaneous symmetry breaking [1]. This mechanism can however not explain the mass spectrum or hierarchy. In particular, the coefficients directly related to the mass values, the Yukawa couplings, are only determined experimentally, for example in CMS [2]. The Higgs mechanism can be performed with more than one Higgs doublet [3]. The way to establish the precise model is by direct search of new scalars, but also through indirect searches such as rare processes. In order to arrive at a better understanding of possible new physics scenarios, we therefore need to consider new models beyond SM, where the requirement of non zero flavor mixing couplings are part of the model.

Adding another Higgs doublet to the Standard Model is the simplest extension possible. It leads to the the Two Higgs Doublets Models (THDM) in which masses of the quarks origin from two considered doublets and not only from one as in the SM. For type III models the two doublets are furthermore coupled to the two types of quarks (up and down) [4]. These features of the model would explain in a more natural way the mass hierarchy of the SM fermions.

Flavor Changing Neutral Currents (FCNC) are a promising process to search for physics beyond the Standard Model. This kind of processes are also present through radiative corrections in the SM, but at tree level in extended models. Their measurement would therefore yield an intermediate new physics signal. The experimental results for single top production as searched for within the CMS experiment [2], already reveals a first excess of events, although still within the statistical error and it remains to be seen whether this excess can be further established or not.

Flavor violating processes have been widely studied in literature, in particular for the so called exotic decays via neutral Higgs boson, for instance, with a top quark involved using an effective Lagrangian [5], through higher dimension operators in the context of THDM [6], and in the specific scenario of THDM-III [7, 8]. In order to know with certainty if we are in extended model domains, an excellent candidate to study such processes is given by events which come with a top quark: the top quark mass mass is the largest of the known elementary particles and its behavior sets experimental boundaries. Additionally, we have selected t-channel production since is the biggest cross section measured at the LHC. [9]

In the following we present cross sections of the top quark production processes in Deep Inelastic Scattering (DIS) in the context of the THDM-III for the current and future colliders energies.

2 Cross Section

To describe the cross-section of electron + proton → 2 fermions via neutral Higgs boson exchange, we make use of factorization of strong interaction matrix elements in the collinear limit, where the hard scales $M \gg \Lambda_{\rm QCD}$ is given by the mass of the produced top quark $M = m_t = 173.0$ GeV. We therefore find for cross-section the following factorized expression,

$$\sigma(ep \to l'q') = \sum_i \int_0^1 dx f_i(x, M^2)\, \hat{\sigma}^{eq}, \tag{2.1}$$

where $\hat{\sigma}^{eq}$ denotes the partonic electron-quark (eq) cross sections with i the quark flavor index and $f_i(x', M^2)$ the Parton Distribution Function of quark with flavor i. For the actual implementation we make use of of the pdf set MMHT2014 NLO 120 set [10]. The partonic cross-section $\hat{\sigma}^{eq}$ is given

$$\hat{\sigma}^{eq} = \frac{1}{16\pi(xs)^2} \int_{t^-}^{t^+} |\mathcal{M}(t)|^2 dt, \tag{2.2}$$

where $|\mathcal{M}(t)|^2$ is the squared matrix element of the process $ep \to l'q'$ and x denote the proton momentum fraction. It is important to keep in mind that we are looking for a single top production via neutral Higgs boson exchange (but with flavor exchange) at tree level. The reaction of interest process is therefore $ep \to \mu\, t$; for the relevant Feynman Diagram see Fig. 1

The quarks couplings with the neutral Higgs bosons [11] can be obtained from the the follow-

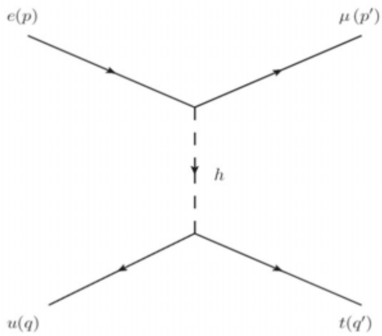

Figure 1: Process $eu \to \mu t$

ing Lagrangian:

$$\begin{aligned}
\mathcal{L}_Y^q =& \frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{d}_i\left[\frac{\cos\alpha}{\cos\beta}\delta_{ij}+\frac{\sqrt{2}\sin(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]d_jH^0\\
&+\frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{d}_i\left[-\frac{\sin\alpha}{\cos\beta}\delta_{ij}+\frac{\sqrt{2}\cos(\alpha-\beta)}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]d_jh^0\\
&+i\frac{g}{2}\left(\frac{m_{d_i}}{M_W}\right)\bar{u}_i\left[-\tan\beta\delta_{ij}+\frac{\sqrt{2}}{g\cos\beta}\left(\frac{m_W}{m_{d_i}}\right)(\tilde{Y}_2^d)_{ij}\right]\gamma^5d_jA^0\\
&+\frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[\frac{\sin\alpha}{\sin\beta}\delta_{ij}+\frac{\sqrt{2}\sin(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_1^u)_{ij}\right]u_jH^0\\
&+\frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[\frac{\cos\alpha}{\sin\beta}\delta_{ij}+\frac{\sqrt{2}\cos(\alpha-\beta)}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_1^u)_{ij}\right]u_jh^0\\
&+i\frac{g}{2}\left(\frac{m_{u_i}}{M_W}\right)\bar{u}_i\left[-\cot\beta\delta_{ij}+\frac{\sqrt{2}}{g\sin\beta}\left(\frac{m_W}{m_{u_i}}\right)(\tilde{Y}_2^d)_{ij}\right]\gamma^5u_jA^0
\end{aligned} \tag{2.3}$$

The leptonic part is obtained by replacing $d_i \to l_i$. By using the Cheng-Sher ansatz to reproduce the mass hierarchy, the Yukawa couplings from the previous Lagrangian can be described in terms of dimensionless experimental parameters $\tilde{\chi}_{i,j}$.,

$$\begin{aligned}
\left(\tilde{Y}_2^{d,l}\right)_{i,j} &= \frac{\sqrt{m_i^{d,l}m_j^{d,l}}}{v}\tilde{\chi}_{i,j}^{d,l}\\
\left(\tilde{Y}_1^{u,l}\right)_{i,j} &= \frac{\sqrt{m_i^{u}m_j^{u}}}{v}\tilde{\chi}_{i,j}^{u}.
\end{aligned} \tag{2.4}$$

Similar to Eq. (2.4), a large number of proposals to a achieve specific fermion mass matrices are possible, see for instance reference [12]. The four zero texture matrix fits however quite well with the quark mixing data. It is worth to point out that, as a consequence of regarding $\tilde{\chi}_{i,j}^f$ as experimental parameters, we will be able to define a range where it would be feasible to measure this FCNC processes. According to Eqs. (2.3) and (2.4), the vertex factor at the leptonic line reads:

$$\frac{g}{2}\bar{l}_i\left[-\left(\frac{m_{l_i}}{m_W}\right)\frac{\sin\alpha}{\cos\beta}\delta_{ij}+\frac{\cos(\alpha+\beta)}{\sqrt{2}\cos\beta}\left(\frac{\sqrt{m_{l_i}m_{l_j}}}{m_W}\tilde{\chi}_{ij}^l\right)l_j\right]h^0, \tag{2.5}$$

while one has for up type quarks:

$$\frac{g}{2}\bar{u}_i\left[\left(\frac{m_{u_i}}{m_W}\right)\frac{\cos\alpha}{\sin\beta}\delta_{ij}-\frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\left(\frac{\sqrt{m_{u_i}m_{u_j}}}{m_W}\tilde{\chi}_{ij}^u\right)u_j\right]h^0. \tag{2.6}$$

To obtain the corresponding terms for down quarks, we perform the substitution $l \to d$ in Eq. (2.5). Hence for the case shown in the Fig. 1 we obtain:

$$|\mathscr{M}|^2 = \frac{1}{[(p-p')^2 - m_H^2]^2} \sum_{s,s'} \mathscr{M}_{leptonic} \mathscr{M}^{quark}, \tag{2.7}$$

with

$$\mathscr{M}_{leptonic} = \bar{\mu}(p') \left[\frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta} \frac{\sqrt{m_e m_\mu}}{m_W} \tilde{\chi}^l_{ij} \right] e(p)\bar{e}(p) \left[\frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta} \frac{\sqrt{m_e m_\mu}}{m_W} \left(\tilde{\chi}^l_{ij}\right)^* \right] \mu(p'), \tag{2.8}$$

$$\mathscr{M}^{quark} = \bar{t}(q') \left[\frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta} \frac{\sqrt{m_u m_t}}{m_W} \tilde{\chi}^u_{ij} \right] u(q)\bar{u}(q) \left[\frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta} \frac{\sqrt{m_u m_t}}{m_W} \left(\tilde{\chi}^u_{ij}\right)^* \right] t(q'), \tag{2.9}$$

and

$$|\mathscr{M}|^2 = CW|\tilde{\chi}^l_{12}|^2|\tilde{\chi}^u_{13}|^2 \frac{\left[t-(m_\mu - m_e)^2\right]\left[t-(m_q-m_t)^2\right]}{(t-m_H^2)^2}, \tag{2.10}$$

where

$$C = \frac{\cos^4(\alpha-\beta)}{\cos^2\beta \sin^2\beta} \quad \text{and} \quad W = \frac{m_e m_\mu m_u m_t}{m_W^4}.$$

Combining Eqs. (2.1) and (2.2) we find

$$\sigma^{ep}(ep \to \mu t) = CW|\tilde{\chi}^l_{12}|^2|\tilde{\chi}^u_{13}|^2 \sum_i \int_0^1 dx' \frac{f_i(x',\tilde{Q}^2)}{x' s} \cdot \int_{-t}^{+t} dt \frac{\left[t-(m_\mu-m_e)^2\right]\left[t-(m_q-m_t)^2\right]}{(t-m_H^2)^2}. \tag{2.11}$$

For the following analysis we further define

$$k = CW|\tilde{\chi}^l_{12}|^2|\tilde{\chi}^u_{13}|^2, \tag{2.12}$$

which collects the model dependent coupling constants. In the next section, we will discuss the consequences of the k value on the total cross section given by Eq. (2.11), particularly the effects on the $|\tilde{\chi}^{u,d,l}_{i,j}|^2$ parameters.

3 Results

Once we have obtained Eq. (2.11) we are in a position to make an important assignment: for the case where $k \neq 1$, the parameters $|\tilde{\chi}^{u,d,l}_{i,j}|$ are of the order of magnitude of about $\sim 10^1$ as proposed in [11]. Using this approximations, the cross section gets reduced in a notable way due to the value of W which has an order of magnitude of about 10^{-13}, making the observation of a flavor violating process highly unlikely. On the other hand if we had an scenario with $k = 1$ then the cross section σ^{ep} would be experimentally observable. In such case the order of magnitude of the parameters must be of order $|\tilde{\chi}^{u,d,l}_{ij}|^2 \sim 10^3$.

Our results are shown in Fig. 2 and Fig. 3. Fig. 2 shows electron and up quark (eu) at the initial state and Fig. 3 electron and charm quark (ec); note that convolutions with the corresponding parton distribution functions have been taken. Each figure display two cases, $k = 1$ where $|\tilde{\chi}^{u,d,lf}_{i,j}|^2 \sim 10^3$ and $k \neq 1$ where $|\tilde{\chi}^f_{12}|^2 \sim 10^1$. The center of mass energies used for calculation are: HERA $\sqrt{s} = 0.310$ TeV, LHeC $\sqrt{s} = 1.3$ TeV, LHeC-he $\sqrt{s} = 1.9$ TeV, and FCC-he $\sqrt{s} = 3.5$ TeV (see also [13])

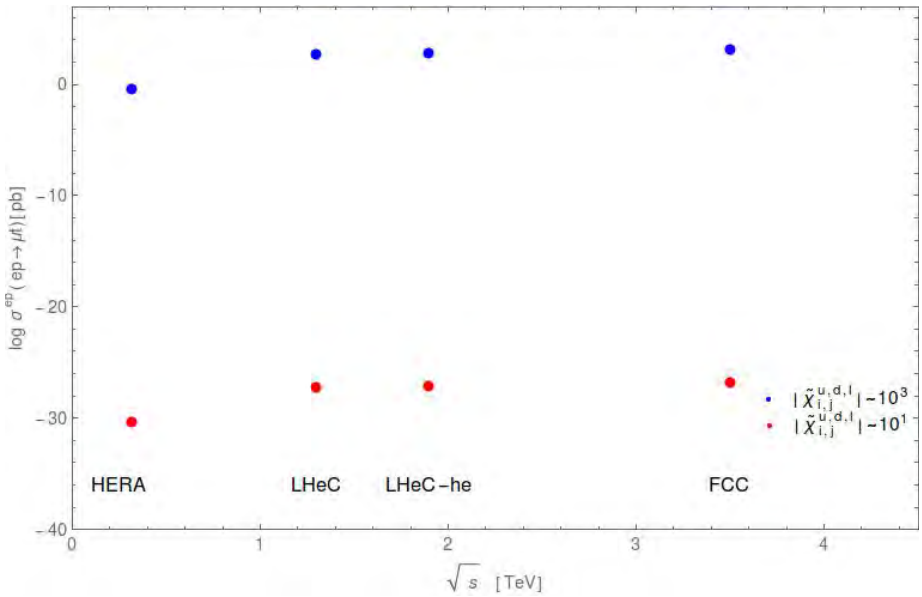

Figure 2: eu as initial state

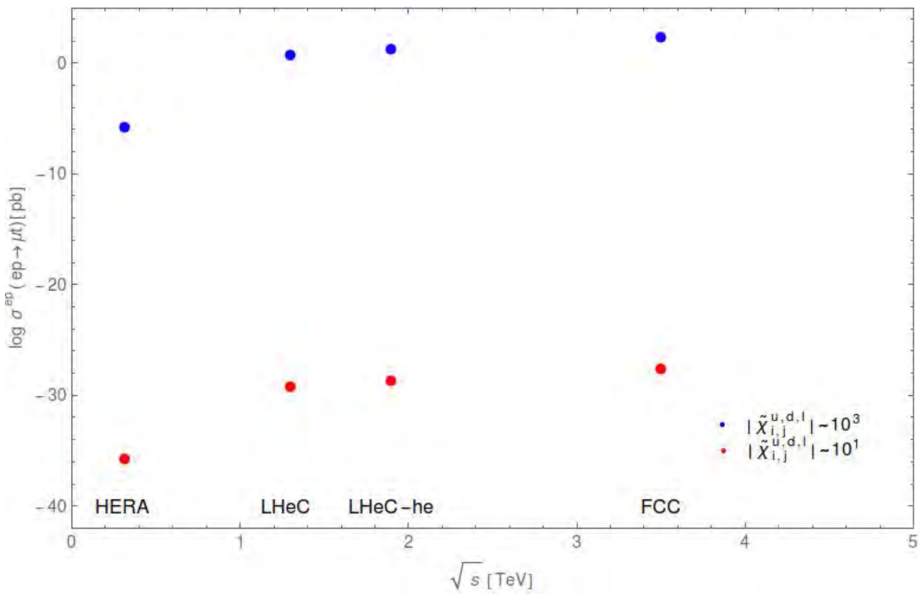

Figure 3: ec as initial state

4 Conclusions

In this contribution we discussed the possiblity to observe effects of a flavor violating Higgs boson in Deep Inelastic Scattering processes at current and future colliders. While cross-sections are small and their observation would be challenging, it can be seen that in the case of $k = 1$ experimental detection might be possible, especially as the highest center of mass energies.

In general, Flavour Changing Neutral Currents interactions where Higgs Boson and top quark are involved, are an excellent source to seek beyond Standard Model signals. In addition, according to [14] those kind of processes have not been reviewed so far, so we continue investigating what will be observed in different scenarios. In fact it is the goal of our work to know which conditions would lead us to a $k = 1$ scenario. For $|\tilde{\chi}^f_{12}|^2 \sim 10^1$ the cross section is on the other hand too small and an experimental observation appears hardly possible. It seems therefore not possible to exclude this kind of scenarios through Deep Inelastic Scattering processes.

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