Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \rightarrow l + X_t + X$

Conclusions

Top quark production through flavor violating neutral currents within the 2HDM type-III

WENDY CAROLINA GONZALEZ OLIVARES
Dr. M. Gómez Bock
Dr. A. Rosado Sánchez
Dr. M. Hentschinski
Dr. S. Navarro

Benemérita Universidad Autónoma de Puebla

November, 2024

Contents

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Motivations

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

In fact, Flavour Physics has shown a much more richer phenomenology than the one predicted by the Standard Model (SM). In order to know with certainty if we are in extended model domains, an excellent candidate to study is given by events which are associated with the production of the Higgs boson and the top quark, since its mass is the largest of the known elementary particles and easy to track down as it would not hadronize.

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

Objective

We explore the parameter space for processes with fermionic flavor violation within the 2HDM type III to determine possibilities to observe these events.

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

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.

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

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \rightarrow l + X_t + X$

Conclusions

The most general Yukawa Lagrangian is:

$$\mathcal{L}_Y = \sum_{a,i} Y_a^i \bar{F}_L^i \phi_a f_R^i + h.c \quad (1)$$

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 and Y_a^i are the 3×3 Yukawa matrices.

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

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Particularly for the type III:

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

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

where $\Phi_{1,2} = \left(\Phi_{1,2}^+, \Phi_{1,2}^0\right)^T$ *are the Higgs doublets,* $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$ *and* $Y_{12}^{u,d,l}$ *are the Yukawa matrices*. First equation is for quarks sector and second for the leptonic sector.

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

After EWSB one can derive the fermion mass matrices

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

In the physical basis, M_f is diagonal but not necessary are each of the two Yukawa matrices. In order to diagonalize analytically, we reduce the possible 3×3 flavor fermion mass matrices by a proposed *ansatz* with a hierarchical structure, which is based on a textures form (zero for some flavor mixing elements guided by experimental data)

$$M_f = \begin{pmatrix} 0 & C_l & 0 \\ C_l^* & \tilde{B}_l & B_l \\ 0 & B_l^* & A_l \end{pmatrix}; \quad Y_1 = \begin{pmatrix} 0 & C_1 & 0 \\ C_1^* & \tilde{B}_1 & B_1 \\ 0 & B_1^* & A_1 \end{pmatrix}; \; Y_2 = \begin{pmatrix} 0 & C_2 & 0 \\ C_2^* & \tilde{B}_2 & B_2 \\ 0 & B_2^* & A_2 \end{pmatrix}, \tag{5}$$

where the elements of the matrix should be taken with a hierarchy imposed by the measured fermion masses, $|A_l| \gg |\tilde{B}_l|, |B_l|, |C_l|$.

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

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

$$\begin{aligned} \bar{M}_u^{diag} &= V_L^u M_u V_R^{u\dagger}, \\ \bar{M}_d^{diag} &= V_L^d M_d V_R^{d\dagger}, \\ \bar{M}_l^{diag} &= O_L^l M_l O_R^{l\dagger}. \end{aligned} \tag{6}$$

Here, as usual, $V_{CKM} = V_L^u V_L^{d\dagger}$, and

$$\tilde{Y}_{1,2}^q = V_L^q Y_{1,2}^q V_R^{q\dagger} \quad \text{and} \qquad \tilde{Y}_{1,2}^l = O_L^l Y_{1,2}^l O_R^{l\dagger}, \tag{7}$$

yields the CKM matrix and $q = u, b$.

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \rightarrow l + X_t + X$

Conclusions

We further note the relation between the two Yukawa matrices:

$$\begin{aligned} \tilde{Y}_1^{d,l} &= \frac{\sqrt{2}}{v\cos\beta}\bar{M}_{d,l} - \tan\beta\,\tilde{Y}_2^{d,l} \\ \tilde{Y}_2^{u} &= \frac{\sqrt{2}}{v\sin\beta}\bar{M}_{u} - \cot\beta\,\tilde{Y}_1^{u} \end{aligned} \tag{8}$$

The equation (4) takes the form:

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

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 $l_3 = \tau$.[1]

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

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

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

$$\left(\tilde{Y}_2^{d,l}\right)_{i,j} = \frac{\sqrt{m_i^{d,l} m_j^{d,l}}}{v} \tilde{\chi}_{i,j}^{d,l}$$
$$\left(\tilde{Y}_1^{u}\right)_{i,j} = \frac{\sqrt{m_i^{u} m_j^{u}}}{v} \tilde{\chi}_{i,j}^{u} \tag{9}$$

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

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \rightarrow l + X_t + X$
Conclusions

Process

The process under analysis has next diagram

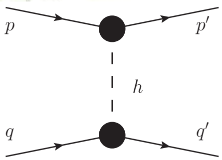

Figura: flavour violating process transmitted through a t-channel exchange of a neutral Higgs boson of an extended Higgs sector.

Single top production at an electron-proton collider would serve to constrain the coupling of a flavor violating Higgs to the leptonic sector, which is hard to control at an hadron hadron collide. We will therefore study for lepton-hadron reactions,

$$\begin{aligned} l(p) + c(q) &\rightarrow l'(p') + t(q'), \\ \bar{l}(p) + \bar{c}(q) &\rightarrow \bar{l}'(p') + \bar{t}(q'), \end{aligned} \tag{10}$$

where l is either an electron or a muon and and l' an electron, a muon, or a tau.

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

The scattering amplitude reads:

$$|\mathscr{M}|^2(ab \to a'b') = \frac{g^4}{64} C_{aa'}(\alpha,\beta) C_{bb'}(\alpha,\beta) \cdot \frac{m_a m_b m_{a'} m_{b'}}{m_W^4} \cdot \frac{\left[t-(m_a-m_{a'})^2\right]\left[t-(m_b-m_{b'})^2\right]}{(t-m_h^2)^2}. \tag{11}$$

We defined the flavour violation couplings as:

$$C_{aa'}(\alpha,\beta) = \frac{\cos^2(\alpha-\beta)}{\cos^2(\beta)}|\tilde{\chi}_{ll'}|^2, \qquad C_{bb'}(\alpha,\beta) = \frac{\cos^2(\alpha-\beta)}{\sin^2(\beta)}|\tilde{\chi}_{qq'}|^2. \tag{12}$$

For lepton-hadron process $C_{aa'}$ will come from the leptonic coupling, and $C_{bb'}$ from the t-type quark coupling.

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

Then, for the process $\mu c \to \mu t$, we have:

$$|\mathscr{M}|^2(\mu c \to \mu t) = \frac{g^4}{64} C_{\mu\mu}(\alpha,\beta) C_{32}(\alpha,\beta) \frac{m_\mu^2 m_c m_t}{m_W^4} \frac{t\left[t-(m_c-m_t)^2\right]}{(t-m_h^2)^2}, \qquad (13)$$

with

$$C_{\mu\mu}(\alpha,\beta) = \left| -\frac{\sqrt{2}\sin\alpha}{\cos\beta} + \frac{\cos(\alpha-\beta)}{\cos(\beta)} \tilde{\chi}_{22}^l \right|^2,$$

$$C_{32}(\alpha,\beta) = \left| \frac{\cos(\alpha-\beta)}{\sin\beta} \tilde{\chi}_{32}^u \right|^2, \qquad (14)$$

we must note that equation(13) could be zero for certain values of the parameters of the model, since $\tilde{\chi}_{22}^l$ is complex, which will imply that the whole process is not viable at LO for 2HDM-III.

$$-\frac{\sqrt{2}\sin\alpha}{\cos\beta} + \frac{\cos(\alpha-\beta)}{\cos\beta} \tilde{\chi}_{22}^l = 0; \qquad (15)$$

taking the extreme complex values for $\tilde{\chi}_{22}^l \sim \mathcal{O}(1)$, *i.e.* $\chi_{22}^l = \pm 1$, which will give the following restriction on α and β,

$$\sqrt{2}\sin\alpha = \pm\cos(\alpha-\beta) \Rightarrow \tan\alpha = \frac{\cos\beta}{\mp\sqrt{2}-\sin\beta}, \qquad (16)$$

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

Having discussed the structure of the couplings, we are able to construct now the analytical hadronic cross-sections, which read

$$\sum_{f=t,\bar{t}} \sigma(pl \to fl') = \frac{1}{16\pi} \int_{x_{min}}^{1} dx \int_{t^-}^{t^+} dt \left[\frac{|\mathscr{M}|^2 (lc \to l' t)}{(xs)^2} \cdot f_c(x, \mu_F) \right.$$
$$\left. \frac{|\mathscr{M}|^2 (l\bar{c} \to l' \bar{t})}{(xs)^2} \cdot f_{\bar{c}}(x, \mu_F) \right] \tag{17}$$

for the case of lepton-hadron scattering the center-of-mass energy squared as $\hat{s} = xs$, with $x_{min} = \frac{(m_{l'} + m_t)^2}{s} \approx \frac{m_t^2}{s}$.

FCNC single top production through $eq \to l + X_t + X$

The next process we analyze is given as $ep \to lX_tX$, where l is a charged lepton, X_t corresponds to a jet coming from top production and X could be anything.

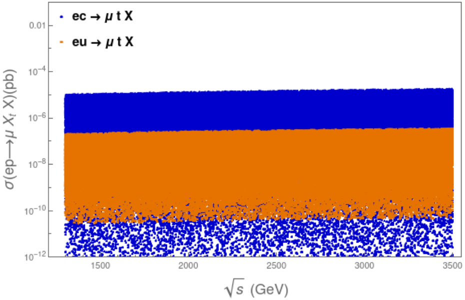

Figura: The contribution from each quark, u(orange), c(blue), to the total cross section of the process $eq \to \mu t$, where q stands for u, c. Considering the values of the parameters as $\tan\beta \in [1, 50]$, $\cos(\beta - \alpha) \in [0, 1]$ and $|\tilde{\chi}^l_{12}| = |\tilde{\chi}^u_{13}| = |\tilde{\chi}^u_{23}| = 1$.

For the numerical calculation of the sub-processes $l_i q \to l_j t$ cross section, we consider first a range for $\cos(\beta - \alpha) \in [0, 1]$ and $\tan\beta \in [1, 50]$. In order to analyze the parameter dependence, we firts consider $|\tilde{\chi}^u_{23}| = 1$.

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

Considering experimental bounds for the FV parameter

- From ATLAS we have recent update result from $Br\,(t \to cH) < 0{,}094\,\%$
- Employing the ATLAS results to bound the free FV parameters $\tilde{\chi}^u_{23}$ of the model, we find

$$\left(\frac{\cos(\beta-\alpha)\chi^u_{23}}{\sin\beta}\right) < 0{,}06 \quad \text{for} \quad Br(t \to ch) < 9{,}4 \times 10^{-4} \qquad (18)$$

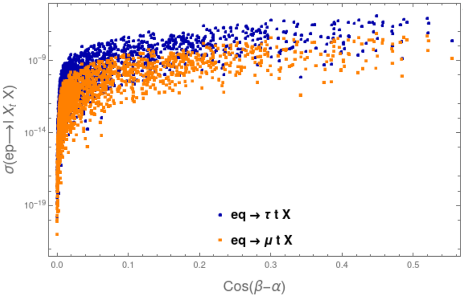

Figura: The total cross section for *ep* t-channel FCNC top production via DIS dependence with $\cos(\alpha - \beta)$. Comparing two leptonic processes: $ec \to \tau(\mu) + t$, *blue (orange)*. With a scan for the center of mass energy as $\sqrt{s} \in [1{,}3, 3{,}5]$ TeV and taking $|\tilde{\chi}^{l}_{ij}| = 1$ and $|\tilde{\chi}^{u}_{23}| = 0{,}2$, applying the ATLAS updated restriction on top FV neutral Higgs boson decay, (18).

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

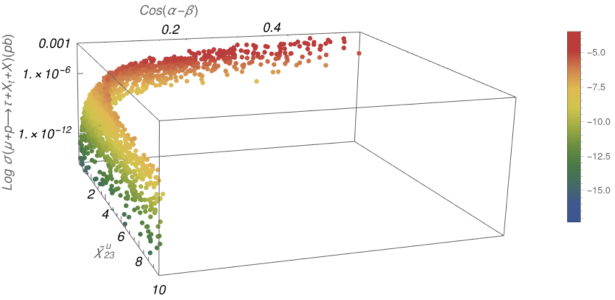

Figura: The total cross section to the process $\mu p \to \tau + X_t + X$, with center of mass energies $\sqrt{s} \in [1{,}3, 6{,}5]$ TeV. Is is shown its dependence on the wide range of free parameters $\tilde{\chi}^u_{ij} \in [0{,}1, 10]$, $\cos(\beta - \alpha) \in [0, 1]$, considering the $t \to ch$ restriction, (18).

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions

Conclusions

- Rare top processes could be a key analysis to establish the model structure of beyond the Standard Model physics in terms of the yukawa structure of the Higgs couplings and degrees of freedom which allow for flavor violating.
- The cross section is enhanced by two orders of magnitude when we consider muon-proton collider and tau involved.
- 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.

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \rightarrow l + X_t + X$

Conclusions

Top quark production

CAROLINA

Motivations

Objective

Two Higgs Doublet Model Type III

Process

FCNC single top production through $eq \to l + X_t + X$

Conclusions

♣ Thank you ♣

Bibliography I

[1] Georges Aad, B Abbott, Kira Abeling, Nils Julius Abicht, SH Abidi, Asmaa Aboulhorma, Halina Abramowicz, Henso Abreu, Yiming Abulaiti, AC Abusleme Hoffman, et al.
Search for heavy higgs bosons with flavour-violating couplings in multi-lepton plus b-jets final states in pp collisions at 13 tev with the atlas detector.
Journal of High Energy Physics, 2023(12):1–68, 2023.

[2] Georges Aad et al.
Search for flavour-changing neutral current interactions of the top quark and the Higgs boson in events with a pair of τ-leptons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
JHEP, 2306:155, 2023.

[3] L.A. Harland-Lang, A.D. Martin, P. Motylinski, and R.S. Thorne.
Parton distributions in the LHC era: MMHT 2014 PDFs.
Eur. Phys. J. C, 75(5):204, 2015.

Top quark production
CAROLINA
Motivations
Objective
Two Higgs Doublet Model Type III
Process
FCNC single top production through $eq \to l + X_t + X$
Conclusions