Single top production via flavor violation 2HDM

MGB, MH, WO, AR, SRN Int.J.Mod.Phys.A 39 (2024) 30, 2450110

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Segundo taller:
Más Allá del Modelo Estándar y Astropartículas

septimbre 2025

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MGB,M. Hentschinsky, W. Olivares, A. Rosado, S. Rosado-Navarro, 1Int.J.Mod.Phys.A 39 (2024)

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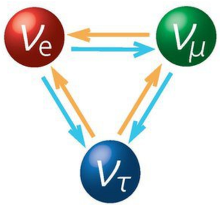
Motivation

Flavor Violation

Evidence for neutrino mixing, possibly non-universality for weak leptonic couplings.



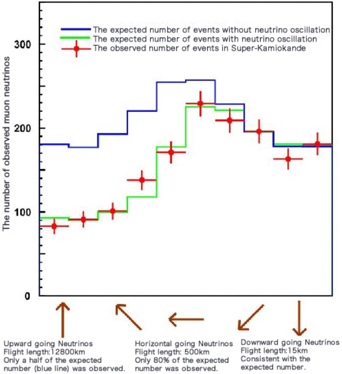


Figure: *neutrino mixing- flavor violation*

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Motivation

BSM - DM candidates

Dark Matter

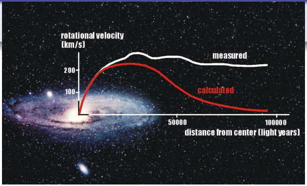

Figure: *DM evidence*

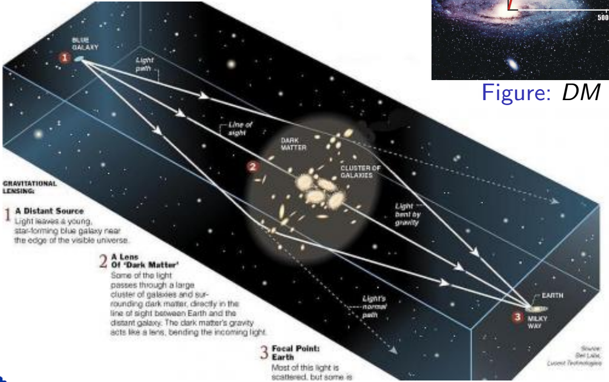

Figure: *Gravitational Lensing.*

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Motivation

BSM - scalar sector

Particle spectrum, possible more scalar particles

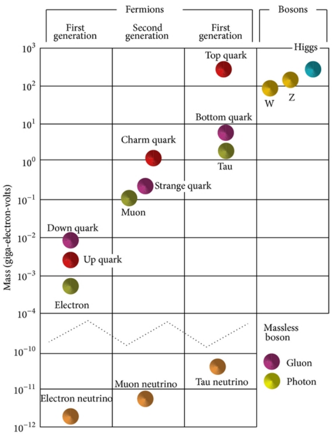

Figure: *Particle spectrum.*

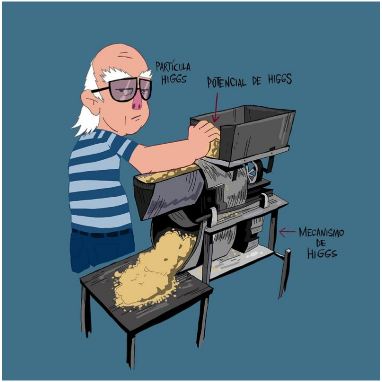

Figure: *Higgs mechanism (Mexican view)*

The SM scalar sector

SM Higgs doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Higgs Lagrangian

$$\mathcal{L}_H = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \tag{1}$$

Once a vev is chosen $\langle 0|\Phi|0\rangle = v \neq 0$ the EW symmetry is broken:

- ⋆ Gauge bosons acquire mass from the kinetic term.
- ⋆ Fermions acquire mass through the Yukawa couplings.
- ⋆ The Higgs mass is obtained from the Higgs potential after EW SSB.

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The Model 2HDM-III

A minimal extension of the SM which allows for flavor changing neutral currents at the level of the Lagrangian is provided by the 2HDM-III, with Flavour Violation (FV) at Leading Order (LO). Multi-Higgs models additional scalar spectrum. Extending the scalar sector more than one Higgs leads to increasing the scalar spectrum of particles:

- SM $\rightarrow h^0$
- 2HDM $\rightarrow h^0,\ H^0, A^0,\ H^\pm$

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The Model 2HDM-III

Two complex SU(2) Higgs doublets:

$$\Phi_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

physical Higgs particle spectrum 5:

ϕ_i , $CP = 1 \rightarrow$ two scalar fields: h^0, H^0,

χ_i , $CP = -1 \rightarrow$ one pseudo scalar fields: A^0.

and

$\phi^{\pm}$, $\rightarrow$ two charged fields: $H^{\pm}$

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The Model 2HDM-III

SSB: Assuming the scalar fields to develop nonzero vacuum expectation values that break $SU(2)_L$

$$\langle \Phi_1 \rangle = v_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = v_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{2}$$

Defining: $\tan\beta = \frac{v_2}{v_1}$ and $v = (v_1^2 + v_2^2)^{1/2} \approx 246\ GeV$.
The Lagrangian density describing the dynamics with two doubles would be:

$$\mathcal{L}_{\Phi_1,\Phi_2} = (D^\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (D^\mu \Phi_2)^\dagger (D_\mu \Phi_2) - V(\Phi_1, \Phi_2) \tag{3}$$

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The Model 2HDM-III

CP conserving Higgs potential

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {} & \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) \\
& +\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
& +\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\
& +[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + h.c.]
\end{aligned}
$$

The Model 2HDM-III

The interaction with Fermions is given through the Yukawa Lagrangian:

$$L_Y^q = Y_1^u \overline{Q}'_L \tilde{\Phi}_1 u'_R + Y_2^u \overline{Q}'_L \tilde{\Phi}_2 u'_R + Y_1^d \overline{Q}'_L \Phi_1 d'_R + Y_2^d \overline{Q}'_L \Phi_2 d'_R + h.c., \tag{4}$$

where $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$ and σ_2 is the Pauli matrix. The charged leptonic sector has a similar form to the one of the $d - type$ quark, and is obtained from the latter by replacing $d_i \to l_i$, including the masses. After spontaneous symmetry breaking, each of the two doublets acquire vacuum expectation values (vevs), $v_{1,2}$.

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The Model 2HDM-III

After SSB, the second derivative of the potential yields the following form of the mass matrices:

$$M_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 . Y_2^f), \qquad f = u, d, l. \qquad (5)$$

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).

$$Y_k = \begin{pmatrix} 0 & C_k & 0 \\ C_k^* & \tilde{B}_k & B_k \\ 0 & B_k^* & A_k \end{pmatrix} \qquad (6)$$

with $k = 1, 2$ then $|A_k| \gg |\tilde{B}_k|, |B_k|, |C_k|$

The Model 2HDM-III

The femions mass matrices can be diagonalized through a similarity transformation

$$\bar{M}_u^{diag} = V_L^u M_u V_R^{u\dagger},$$
$$\bar{M}_d^{diag} = V_L^d M_d V_R^{d\dagger},$$
$$\bar{M}_l^{diag} = O_L^l M_l O_R^{l\dagger}. \quad (7)$$

Yields the CKM matrix: $V_{CKM} = V_L^u V_L^{d\dagger}$, and

$$\tilde{Y}_{1,2}^q = V_L^q Y_{1,2}^q V_R^{q\dagger} \quad \text{and} \quad \tilde{Y}_{1,2}^l = O_L^l Y_{1,2}^l O_R^{l\dagger}, \quad (8)$$

Here $q = u, b$.

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The Model 2HDM-III

We further note the following relation between the two Yukawa matrices for each fermion type:

$$\tilde{Y}_1^d = \frac{\sqrt{2}}{v\cos\beta}\bar{M}_d - \tan\beta\tilde{Y}_2^d, \tag{9}$$

$$\tilde{Y}_1^l = \frac{\sqrt{2}}{v\cos\beta}\bar{M}_l - \tan\beta\tilde{Y}_2^l, \tag{10}$$

$$\tilde{Y}_2^u = \frac{\sqrt{2}}{v\sin\beta}\bar{M}_u - \cot\beta\tilde{Y}_1^u. \tag{11}$$

Having an extra Higgs scalar doublet in the 2HDM, requires the use of α is the rotation angle for CP-even physical neutral Higgs bosons h^0 and H^0 states, and β is the angle associated with the Goldstone states basis, $\tan\beta = v_2/v_1$

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The Model 2HDM-III

In the physical basis, omitting Goldstone contributions, we have for the fermions couplings with neutral scalars:

$$
\begin{aligned}
\mathcal{L}_Y^q &= \frac{g}{2}\left\{\bar{u}_i\left[\left(\frac{m_{u_i}}{m_W}\right)\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]u_j h^0\right.\\
&+ \bar{d}_i\left[-\left(\frac{m_{d_i}}{m_W}\right)\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\cos\beta}(\tilde{Y}_2^d)_{ij}\right]d_j h^0\\
&\quad +\bar{u}_i\left[\left(\frac{m_{ui}}{m_W}\right)\frac{\sin\alpha}{\sin\beta}\delta_{ij} - \frac{\sqrt{2}\,\sin(\alpha-\beta)}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]u_j H^0\\
&+ \bar{d}_i\left[\left(\frac{m_{d_i}}{m_W}\right)\frac{\cos\alpha}{\cos\beta}\delta_{ij} + \frac{\sqrt{2}\,\sin(\alpha-\beta)}{g\,\cos\beta}(\tilde{Y}_2^d)_{ij}\right]d_j H^0\\
&\quad +i\bar{u}_i\left[-\left(\frac{m_{u_i}}{m_W}\right)\cot\beta\delta_{ij} + \frac{\sqrt{2}}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]\gamma^5 u_j A^0\\
&+ i\bar{d}_i\left[-\left(\frac{m_{d_i}}{m_W}\right)\tan\beta\delta_{ij} + \frac{\sqrt{2}}{g\,\cos\beta}(\tilde{Y}_2^d)_{ij}\right]\gamma^5 d_j A^0\left.\vphantom{\frac{1}{1}}\right\}. \qquad (12)
\end{aligned}
$$

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The Model 2HDM-III

From this Lagrangian density we observe the following:

- The leptonic part is obtained by replacing $d_i \to l_i$.
- We apply the Cheng-Sher ansatz to reproduce the mass hierarchy of the Fermions Then, the Yukawa matrix elements would be as

$$\begin{aligned} \left(\tilde{Y}_2^{d,l}\right)_{ij} &= \frac{\sqrt{m_i^{d,l} m_j^{d,l}}}{v} \tilde{\chi}_{ij}^{d,l}, \\ \left(\tilde{Y}_1^{u,\nu_l}\right)_{ij} &= \frac{\sqrt{m_i^{u,\nu_l} m_j^{u,\nu_l}}}{v} \tilde{\chi}_{ij}^{u,\nu_l}. \end{aligned} \qquad (13)$$

- The Yukawa couplings can be described in terms of dimensionless parameters $\tilde{\chi}_{ij}$ which could have a complex phase. In particular negative $\tilde{\chi}_{ij}$ are possible, as the matrices are Hermitian.
- The values for these parameters could be set experimentally.
- We see that for h^0 to be the SM-like Higgs (no flavor violation at LO), one needs to set $\alpha - \beta \sim \pi/2$ as the decoupling limit

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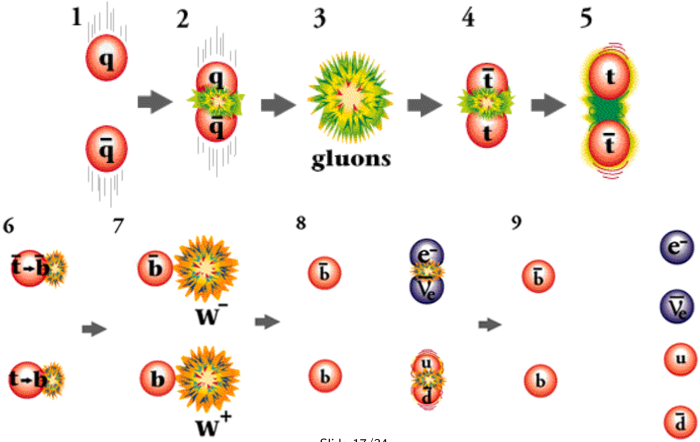
Top quark production

top production

The production of a pair of top or anti-top quarks at the LHC, as SM. BSM possible production from a potential transition of a charm quark into a top quark via a t-channel exchange of a flavor violating Higgs boson.



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FV processes

Flavor violating process could have both leptonic and quark FCNC through a t-channel exchanging of an extended neutral Higgs boson.

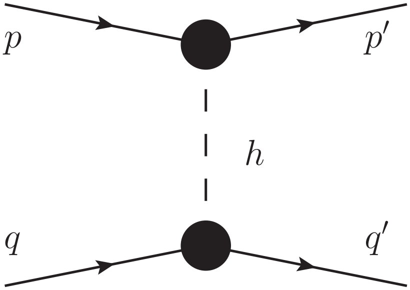

Figure: The t-channel top production.

The final state fermions are either two top quarks (hadron-hadron collisions) or a lepton in combination with a top quark or chatm-quark (lepton-hadron collisions).

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FV processes

- For the Large Hadron Collider, incoming fermions are both up and charm quarks and anti-quarks, where contributions due up (anti-) quarks are strongly suppressed in comparison to the charm contribution due to their masses, with the suppression factor of the order of 2.4×10^{-4}, even if the enhancement due to parton distribution functions is taken into account.
- We will therefore study for hadron-hadron colliders the processes

$$c(p) + c(k) \to t(p') + t(k'),$$

which allow to constrain the flavor violating coupling between charm and top quarks in the Higgs sector.

- For lepton-hadron reactions we will explore

$$l(p) + c(k) \to l'(p') + t(k'),$$
$$l(p) + c(k) \to l'(p') + c(k'). \quad (14)$$

where l could be either an electron or a muon (μIC) and l' a muon or a tau.

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FV processes

Color averaged scattering amplitude is identical for quark-quark and quark-lepton scattering and reads:

$$|\mathcal{M}|^2(ab \to a'b') = \frac{g^4}{64} C_{aa'}(\alpha,\beta) C_{bb'}(\alpha,\beta) \cdot \frac{m_a m_b m_{a'} m_{b'}}{m_W^4} \times \frac{\left[t-(m_a-m_{a'})^2\right]\left[t-(m_b-m_{b'})^2\right]}{(t-m_h^2)^2}, \qquad (15)$$

where quark and lepton masses are neglected against the top mass, whenever both are summed up.
We defined the flavor violation couplings for leptonic (or b-type quarks) and t-type quark, respectively as:

$$C_{aa'}(\alpha,\beta) = \frac{\cos^2(\alpha-\beta)}{\cos^2(\beta)} |\tilde{\chi}_{ll'}|^2, \quad C_{bb'}(\alpha,\beta) = \frac{\cos^2(\alpha-\beta)}{\sin^2(\beta)} |\tilde{\chi}_{qq'}|^2. \qquad (16)$$

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Cross section for t-channel

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

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

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

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The decoupling limit

- The couplings of the SM-like Higgs boson h with the gauge bosons are proportional to $\sin(\beta-\alpha)$, whereas for the heavier H the couplings are proportional to $\cos(\beta-\alpha)$.
- Considering now the additional Yukawa couplings, coming from $2HDM-III$ given in the next table

Process	SM	MSSM	THDM-III
$h^0 \to u_i \bar{u}_j$	$m_{u_i}\delta_{ij}$	$\frac{m_{u_i}\cos\alpha}{\sin\beta}\delta_{ij}$	$[m_{u_i}\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\sqrt{m_{u_i}m_{u_j}}\tilde{\chi}^u_{ij}]$
$h^0 \to d_i \bar{d}_j$	$m_{d_i}\delta_{ij}$	$\frac{m_{d_i}\sin\alpha}{\cos\beta}\delta_{ij}$	$[-m_{d_i}\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\sqrt{m_{d_i}m_{d_j}}\tilde{\chi}^d_{ij}]$
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$A^0 \to u_i \bar{u}_j$	-	$-m_{u_i}\cot\beta\delta_{ij}$	$[-m_{u_i}\cot\beta\delta_{ij} + \frac{\sqrt{m_{u_i}m_{u_j}}}{\sqrt{2}\sin\beta}\tilde{\chi}^u_{ij}]$
$A^0 \to d_i \bar{d}_j$	-	$-m_{d_i}\tan\beta\delta_{ij}$	$[-m_{d_i}\tan\beta\delta_{ij} + \frac{\sqrt{m_{d_i}m_{d_j}}}{\sqrt{2}\cos\beta}\tilde{\chi}^d_{ij}]$

- The latter means that the contributions from heavier Higgs boson H will be reduced in the limit of $\cos(\beta-\alpha)\to 0$.

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$h^0 \rightarrow u_i \bar{u}_j$	$m_{u_i}\delta_{ij}$	$\frac{m_{u_i}\cos\alpha}{\sin\beta}\delta_{ij}$	$[m_{u_i}\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\sqrt{m_{u_i}m_{u_j}}\tilde{\chi}^u_{ij}]$
$h^0 \rightarrow d_i \bar{d}_j$	$m_{d_i}\delta_{ij}$	$\frac{m_{d_i}\sin\alpha}{\cos\beta}\delta_{ij}$	$[-m_{d_i}\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\sqrt{m_{d_i}m_{d_j}}\tilde{\chi}^d_{ij}]$
$H^0 \rightarrow u_i \bar{u}_j$	-	$\frac{m_{u_i}\sin\alpha}{\sin\beta}\delta_{ij}$	$[m_{u_i}\frac{\sin\alpha}{\sin\beta}\delta_{ij} - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta}\sqrt{m_{u_i}m_{u_j}}\tilde{\chi}^u_{ij}]$
$H^0 \rightarrow d_i \bar{d}_j$	-	$\frac{m_{d_i}\cos\alpha}{\cos\beta}\delta_{ij}$	$[m_{d_i}\frac{\cos\alpha}{\cos\beta}\delta_{ij} + \frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta}\sqrt{m_{d_i}m_{d_j}}\tilde{\chi}^d_{ij}]$
$A^0 \rightarrow u_i \bar{u}_j$	-	$-m_{u_i}\cot\beta\delta_{ij}$	$[-m_{u_i}\cot\beta\delta_{ij} + \frac{\sqrt{m_{u_i}m_{u_j}}}{\sqrt{2}\sin\beta}\tilde{\chi}^u_{ij}]$
$A^0 \rightarrow d_i \bar{d}_j$	-	$-m_{d_i}\tan\beta\delta_{ij}$	$[-m_{d_i}\tan\beta\delta_{ij} + \frac{\sqrt{m_{d_i}m_{d_j}}}{\sqrt{2}\cos\beta}\tilde{\chi}^d_{ij}]$

- The latter means that the contributions from heavier Higgs boson H will be reduced in the limit of $\cos(\beta-\alpha) \rightarrow 0$.

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The decoupling limit

- The couplings of the SM-like Higgs boson h with the gauge bosons are proportional to $\sin(\beta - \alpha)$, whereas for the heavier H the couplings are proportional to $\cos(\beta - \alpha)$.
- Considering now the additional Yukawa couplings, coming from $2HDM - III$ given in the next table

Process	SM	MSSM	THDM-III
$h^0 \to u_i \bar{u}_j$	$m_{u_i} \delta_{ij}$	$\frac{m_{u_i} \cos\alpha}{\sin\beta} \delta_{ij}$	$[m_{u_i} \frac{\cos\alpha}{\sin\beta} \delta_{ij} - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta} \sqrt{m_{u_i} m_{u_j}} \tilde{\chi}^u_{ij}]$
$h^0 \to d_i \bar{d}_j$	$m_{d_i} \delta_{ij}$	$\frac{m_{d_i} \sin\alpha}{\cos\beta} \delta_{ij}$	$[-m_{d_i} \frac{\sin\alpha}{\cos\beta} \delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta} \sqrt{m_{d_i} m_{d_j}} \tilde{\chi}^d_{ij}]$
$H^0 \to u_i \bar{u}_j$	-	$\frac{m_{u_i} \sin\alpha}{\sin\beta} \delta_{ij}$	$[m_{u_i} \frac{\sin\alpha}{\sin\beta} \delta_{ij} - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta} \sqrt{m_{u_i} m_{u_j}} \tilde{\chi}^u_{ij}]$
$H^0 \to d_i \bar{d}_j$	-	$\frac{m_{d_i} \cos\alpha}{\cos\beta} \delta_{ij}$	$[m_{d_i} \frac{\cos\alpha}{\cos\beta} \delta_{ij} + \frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta} \sqrt{m_{d_i} m_{d_j}} \tilde{\chi}^d_{ij}]$
$A^0 \to u_i \bar{u}_j$	-	$-m_{u_i} \cot\beta \delta_{ij}$	$[-m_{u_i} \cot\beta \delta_{ij} + \frac{\sqrt{m_{u_i} m_{u_j}}}{\sqrt{2}\sin\beta} \tilde{\chi}^u_{ij}]$
$A^0 \to d_i \bar{d}_j$	-	$-m_{d_i} \tan\beta \delta_{ij}$	$[-m_{d_i} \tan\beta \delta_{ij} + \frac{\sqrt{m_{d_i} m_{d_j}}}{\sqrt{2}\cos\beta} \tilde{\chi}^d_{ij}]$

- The latter means that the contributions from heavier Higgs boson H will be reduced in the limit of $\cos(\beta - \alpha) \to 0$.

Results FV in a pp collider

To estimate the impact of an evaluation of already collected 13 TeV data as well as the operation of the LHC in the high luminosity mode, we estimate a possible to be established lower limit as

$$\sigma_{max}(x\,\text{TeV}) = \sigma_{max}(7\,\text{TeV}) * \frac{\text{L}(7\,\text{TeV})}{\text{L}(x\,\text{TeV})}, \quad (18)$$

where $\text{L}(x\,\text{TeV})$ is the luminosity of the experiment at a given center of mass energy, x TeV, see [ATLAS:2022hro,Workman:2022ynf].

$\sqrt{s}$	luminosity	estimated bound
13 TeV	140.1 fb^{-1}	$\frac{\cos(\alpha-\beta)}{\sin\beta}\lvert\tilde{\chi}^q_{23}\rvert < 3.93$
14 TeV (HL)	3000 fb^{-1}	$\frac{\cos(\alpha-\beta)}{\sin\beta}\lvert\tilde{\chi}^q_{23}\rvert < 2.60$

Table: Bounds to be derived from an analysis of the so far collected 13 TeV data as well as data to be collected during the high luminosity mode of the LHC

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Results FV in a pp collider

Enhancement for the scattering cross section would be for low $\tan\beta \sim \mathcal{O}(10^{-2})$ and for $\cos(\alpha-\beta) \sim 1$, giving $\sigma(pp \to tt(\overline{tt})X)$ up to $\sim \mathcal{O}(10)pb$.

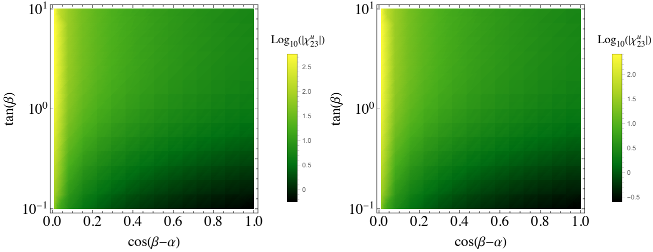

Figure: Projected excluded values for processes $\sigma(pp \to tt, \overline{tt}) < 1.7$ pb, with $|\chi^u_{23}|$ for a given value of $\tan\beta$ and $\cos(\beta-\alpha)$ for 13 TeV (with 140.1 fb^{-1}, [ATLAS:2022hro]) and for the high luminosity LHC at 14 TeV (with 3000 fb^{-1}, [ATLAS:2022hsp])

muon proton collider

We could have $l = l'$ in the case of the muon-proton collider. In such case we should also consider the SM coupling as is given in Eq. (12). Then, for the process $\mu c \to \mu t$, we have:

$$|\mathscr{M}|^2(\mu c \to \mu t) = \frac{g^4}{64} C_{\mu\mu}(\alpha, \beta) C_{32}(\alpha, \beta) \frac{m_\mu^2 m_c m_t}{m_W^4} \frac{t\left[t - (m_c - m_t)^2\right]}{(t - m_h^2)^2}, \tag{19}$$

with

$$C_{\mu\mu}(\alpha, \beta) = \left| -\frac{\sqrt{2}\sin\alpha}{\cos\beta} + \frac{\cos(\alpha - \beta)}{\cos(\beta)} \tilde{\chi}_{22}^{l} \right|^2,$$
$$C_{32}(\alpha, \beta) = \left| \frac{\cos(\alpha - \beta)}{\sin\beta} \tilde{\chi}_{32}^{u} \right|^2. \tag{20}$$

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Restriction on FV quarks coupling

Considering experimental bounds for the FV parameter.

- The searches for *top* FCNC at the LHC, from CMS have searched a limit on the flavor violating branching fraction $Br(t \to ch) < 0.56\%$
- From ATLAS we have a recent updated result from $Br(t \to ch) < 0.094\%$
- Using the ATLAS results to bound the free FV parameter $\tilde{\chi}^u_{23}$ of the model we find

$$\left(\frac{\cos(\beta-\alpha)\chi^u_{23}}{\sin\beta}\right) < 0.06 \quad \text{for} \quad Br(t \to ch) < 9.4 \times 10^{-4}$$

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CLFV single top quark production at LHeC

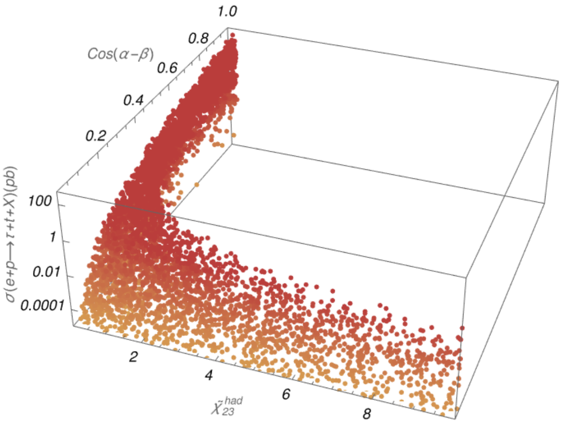

Figure: The total cross section for ep t-channel FCNC top production via DIS, the process $ep \to \tau + X_t + X$.

FV single tau production at EIC

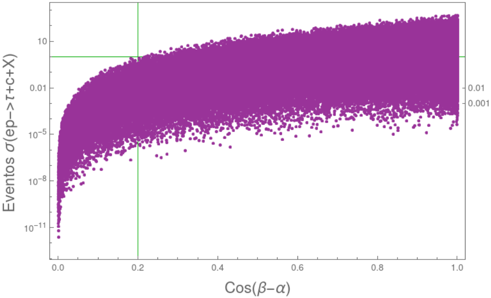

Figure: The number of events for ep t-channel FCNC tau production via DIS, with $\cos(\alpha - \beta)$ dependence. With a scan for the center of mass energy as $\sqrt{s} \in [1.3, 3.5]$ TeV , applying the ATLAS updated restriction on top FV decay to the neutral Higgs boson. The decoupling limit further restricts the possible observation of the process.

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Flavor Violation restrictions from experimental data.

Exp. Bound	**Parameter Restriction**
$\mathcal{B}r(t \to ch) < 9.4 \times 10^{-4}$	$\left\lvert \frac{\cos(\beta-\alpha)\chi^u_{23}}{\sin\beta} \right\rvert < 0.06$
$\mathcal{B}r(h \to e\mu) < 4.4 \times 10^{-5}$	$\left\lvert \frac{\cos(\beta-\alpha)\chi^l_{12}}{\cos\beta} \right\rvert < 3.75$
$\mathcal{B}r(h \to e\tau) < 2 \times 10^{-3}$	$\left\lvert \frac{\cos(\beta-\alpha)\chi^l_{13}}{\cos\beta} \right\rvert < 6.17$
$\mathcal{B}r(h \to \mu\tau) < 1.5 \times 10^{-3}$	$\left\lvert \frac{\cos(\beta-\alpha)\chi^l_{23}}{\cos\beta} \right\rvert < 0.14$
$\mathcal{B}r(h \to \mu\mu) = (2.6 \pm 1.5) \times 10^{-4}$	$4.21 \leq \left\lvert \frac{-\sqrt{2}\sin\alpha+\cos(\beta-\alpha)\chi^l_{22}}{\cos\beta} \right\rvert \leq 7.30$

Table: Restrictions from the experimental bounds on the values of model parameters.

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FV top production at LHeC with experimental bounds

The number of events drops drastically when we consider the FV experimental bounds for ep t-channel top production via DIS.

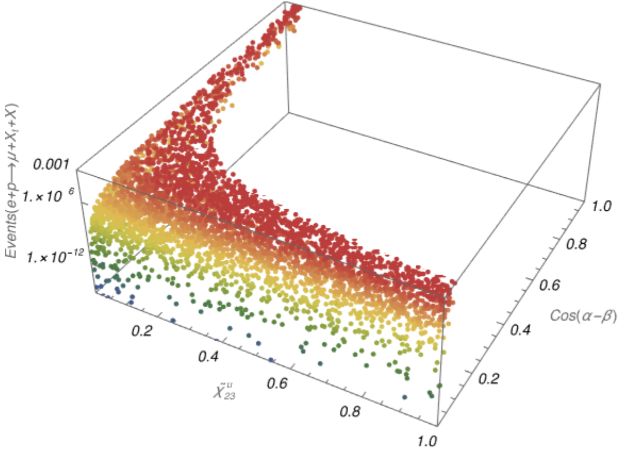

Figure: Number of events $ep \to \mu + X_t + X$. We show $|\tilde{\chi}^u_{23}|$ and $\cos(\beta - \alpha)$ allowed.

Summary

- The cross section $\sigma(pp \to tt(\overline{tt})X)$ enhancement, up to $\sim \mathcal{O}(10)pb$, would be for low $\tan\beta \sim \mathcal{O}(10^{-2})$ and for high $\cos(\alpha-\beta) \sim 1$.
- The *decoupling limit* conditions for 2HDM-III will imply reduced values for $\cos(\alpha-\beta) \sim 0$ and also for the flavor violation parameter $\tilde{\chi}^u_{23} \sim 0$. While the former value reduces the cross section in general, the last condition gives higher possible values for the top quark production cross section, under these conditions.
- We find that cross-sections for $\sigma(ep \to ltX)$ are small, and its observation would be challenging, while muon collider cross section, $\sigma(\mu p \to \tau tX)$, is enhanced by two orders of magnitude when we consider a CLFV, tau involved.
- Considering the CLFV experimental data restrictions, would further reduce the chances for an exotic FV process observation in current colliders; nevertheless is worth noting that the model would survive in a reduced parameter space.

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Once Again...

Really appreciate your comments

THANK YOU!

Results FV in a ep collider

graphics/Gra-epmut-ucX02.png

For the LHeC, single top quark production via charged-current DIS is dominant in all the top quark production channels. Only for SM processes we can implement them in CalcHEP to calculate the possible top production within the SM as background, see table 3.

process	$\sigma(pb)$	uncertainty $(\%)$
$ep \to e + 1jet$	42.6	0.00846
$ep \to e + 2jet$	8.876	0.0566
$ep \to e + 2jet + t$	0.1702	0.8305
$ep \to \nu_e + W^- + 1jet \to \nu_e + \mu + \bar{\nu}_\mu + 1jet$	2.87	0.03053

Table: Total cross section at LHeC ($\sqrt{s} = 1.296TeV$) for SM background processes regarding the tree level single top production through t-channel. The jets include the top quarks.

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