FCNC top decays in the A2HDM

Gauhar Abbas
Instituto de Física Corpuscular,
València, Spain

LHCPHENO 2015: Workshop on High-Energy Physics Phenomenology in the LHC era, November 27, 2015

Work done with
Celis, Li, Lu, Pich JHEP 1506 (2015) 005

Plan

- $t \to ch$ in the aligned two-Higgs-doublet model (A2HDM).
- $t \to cV(= \gamma, Z)$ in the aligned two-Higgs-doublet model (A2HDM).

The extended scalar sector

- Most extensions of the SM include an enlargement of the Higgs sector.
- Supersymmetry
- Spontaneous CP violation
- Strong CP problem
- Baryogenesis

The aligned two-Higgs-doublet model

- The 2HDM provides a minimal extension of the scalar sector with a second Higgs doublet, (ϕ_1, ϕ_2).

- A global SU(2) transformation in the scalar space (ϕ_1, ϕ_2) takes to the so-called Higgs basis (Φ_1, Φ_2)

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \frac{1}{v} \begin{bmatrix} v_1 & v_2 \\ v_2 & -v_1 \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta}\phi_2 \end{pmatrix} . \qquad (1)$$

The scalar potential

The scalar potential in Higgs basis

$$
\begin{aligned}
V &= \mu_1\Phi_1^\dagger\Phi_1 + \mu_2\Phi_2^\dagger\Phi_2 + [\mu_3\Phi_1^\dagger\Phi_2 + H.c] + \lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 \quad (2) \\
&+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
&+ \left[\left(\lambda_5\Phi_1^\dagger\Phi_2 + \lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + H.c.\right]
\end{aligned}
$$

The aligned two-Higgs-doublet model

- In this basis,

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + iG^0\right) \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + iS_3\right) \end{bmatrix}, \qquad (3)$$

  where $G^{\pm}$, G^0 are the Goldstone fields and $\langle H^+\rangle = \langle G^+\rangle = \langle G^0\rangle = \langle S_i\rangle = 0$.

- The five physical scalars are two charged fields $H^{\pm}(x)$ and three neutral ones $\varphi_i^0(x) = \{h(x), H(x), A(x)\}$.

- The neutral scalars are related to the S_i fields through an orthogonal transformation $\varphi_i^0(x) = \mathcal{R}_{ij} S_j(x)$.

- The form of $\mathcal{R}_{ij}$ depends on the scalar potential.

The aligned two-Higgs-doublet model

- In the CP-conserving limit

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}. \tag{4}$$

- The CP-odd field A corresponds to S_3.

- In the generic 2HDM, however, tree-level FCNC interactions generally exist, through non-diagonal couplings of neutral scalars to fermions.

The aligned two-Higgs-doublet model

- In the Higgs basis

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left[\bar{Q}'_L(M'_d\Phi_1+Y'_d\Phi_2)d'_R+\bar{Q}'_L(M'_u\tilde{\Phi}_1+Y'_u\tilde{\Phi}_2)u'_R+\bar{L}'_L(M'_\ell\Phi_1+Y'_\ell\Phi_2)\ell'_R\right]+\mathrm{h.c.}\,, \tag{5}$$

where $\tilde{\Phi}_i(x) = i\tau_2\Phi_i^*(x)$ are the charge-conjugated scalar doublets.

- In general, the Yukawa matrices M'_f and Y'_f cannot be simultaneously diagonalized in flavour space.

The aligned two-Higgs-doublet model

- An elegant solution is to use an appropriately chosen $\mathcal{Z}_2$ symmetries.
  Glashow and S. Weinberg 1977

- This guarantees the absence of FCNCs in the Yukawa sector.

The aligned two-Higgs-doublet model

- Flavour conservation in the neutral scalar couplings can be enforced in a rather trivial way requiring the Yukawa coupling matrices to be aligned in flavour space.

  Pich and Tuzón 2009

- In the A2HDM, the interactions of scalar fields with fermions are described by

$$Y_{d,\ell} = \varsigma_{d,\ell} M_{d,\ell} , \qquad Y_u = \varsigma_u^* M_u . \qquad (6)$$

- In the A2HDM the mass-eigenstate Yukawa Lagrangian reads

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+(x) \left\{ \bar{u}(x) \left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L \right] d(x) \,+\, \varsigma_l\, \bar{\nu}(x) M_l \mathcal{P}_R l(x) \right\} - \\ -\frac{1}{v} \sum_{\varphi, f} y_f^{\varphi_i^0}\, \varphi_i^0(x)\, \bar{f}(x)\, M_f \mathcal{P}_R f(x) \,+\, \text{H.c.}\,, \quad (7)$$

  where V denotes the CKM matrix.

- The couplings of the neutral scalar fields are given by:

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\,\varsigma_{d,l}\,, \qquad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3})\,\varsigma_u^*\,. \quad (8)$$

The aligned two-Higgs-doublet model

- Quantum corrections induce some misalignment of the Yukawa coupling matrices, generating small FCNC effects suppressed by the corresponding loop factors.

- However, the special structure of the A2HDM strongly constrains the possible FCNC interactions.
  Pich and Tuzón 2009

The aligned two-Higgs-doublet model

- The one-loop gauge corrections preserve the alignment while the only FCNC structures induced by the scalar contributions take the form

$$\begin{aligned}\mathcal{L}_{\rm FCNC} &= \frac{C(\mu)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\;\times \\ &\times \sum_i \varphi_i^0(x)\,\Big\{(\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\,\Big[\bar{d}_L\, V^\dagger M_u M_u^\dagger\, V M_d\, d_R\Big] - \\ &\qquad - (\mathcal{R}_{i2}-i\,\mathcal{R}_{i3})\,(\varsigma_d^*-\varsigma_u^*)\,\Big[\bar{u}_L\, V M_d M_d^\dagger\, V^\dagger M_u\, u_R\Big]\Big\} \\ &+ \text{h.c.}\end{aligned}$$

Jung, Pich and Tuzón 2010

The aligned two-Higgs-doublet model

- The renormalization of the coupling constant $\mathcal{C}$ is determined, using dimensional regularization, to be

$$C = C_R(\mu) + \frac{1}{2}\left\{\frac{2\mu^{D-4}}{D-4} + \gamma_E - \ln(4\pi)\right\} , \tag{9}$$

Li, Lu and Pich 2014

- The renormalized coupling satisfies

$$C_R(\mu) = C_R(\mu_0) - \ln(\mu/\mu_0)\,. \tag{10}$$

- Assuming Yukawa alignment to be exact at a given energy scale Λ_A, so that $C_R(\Lambda_A) = 0$, implies that $C_R(\mu) = \ln(\Lambda_A/\mu)$.

The aligned two-Higgs-doublet model

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Table: *Two-Higgs-doublet models with natural flavour conservation.*

$t \to ch, cV$ decay

- The flavour-changing top decays $t \to ch, cV$ occur at the one-loop level in the SM.

- The decay rates is suppressed by the loop factor and also receives a strong CKM and GIM suppression.
  Eilam, Hewett and Soni 1991, Mele, Petrarca and Soddu 1998, Aguilar-Saavedr 2004

- Fixing the Higgs mass at $M_h \simeq 125$ GeV, one obtains the SM branching ratios: $\mathrm{Br}(t \to ch) \sim \mathcal{O}(10^{-15})$, $\mathrm{Br}(t \to c\gamma) \sim \mathcal{O}(10^{-14})$ and $\mathrm{Br}(t \to cZ) \sim \mathcal{O}(10^{-14})$.

- Within the A2HDM these decay rates can be enhanced due to additional charged Higgs contributions at the loop level.
  Celis, Li, Lu, Pich and GA 2015

$t \to ch, cV$ decays

- The ATLAS and CMS collaborations have searched for flavour-changing decays of the top quark.

- The ATLAS has set the bound $\mathrm{Br}(t \to qZ) < 0.73\%$ at the 95% confidence leve. Aad et al 2012

- The CMS has set a better limit, $\mathrm{Br}(t \to qZ) < 0.05\%$. Chatrchyan et al 2013

$t \to ch, cV$ decays

- The strongest current bound on $t \to c\gamma$ decay by the CMS is $\mathrm{Br}(t \to c\gamma) < 0.182\%$.
  CMS 2014

- The ATLAS collaboration sets the limit $\mathrm{Br}(t \to qh) < 0.79\%$.
  Aad et al 2014

- A slightly stronger limit, $\mathrm{Br}(t \to qh) < 0.56\%$, has been obtained by the CMS collaboration.
  CMS 2014

- One expects to improve the limits to $10^{-4} - 10^{-5}$ level for $\mathrm{Br}(t \to ch)$.

$t \to ch$ decays

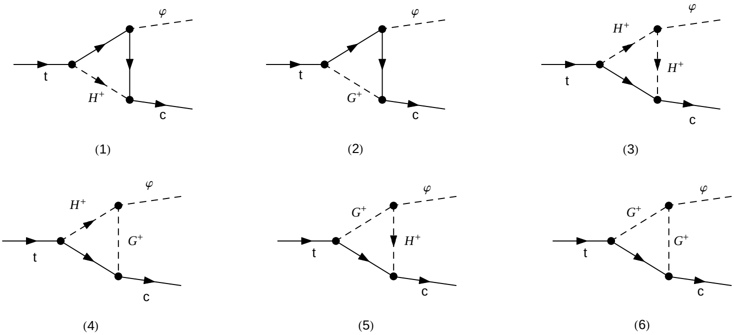


Figure: *Penguin diagrams contributing to* $t \to c\varphi_j^0$ *in the Feynman gauge.*

$t \to ch$ decays

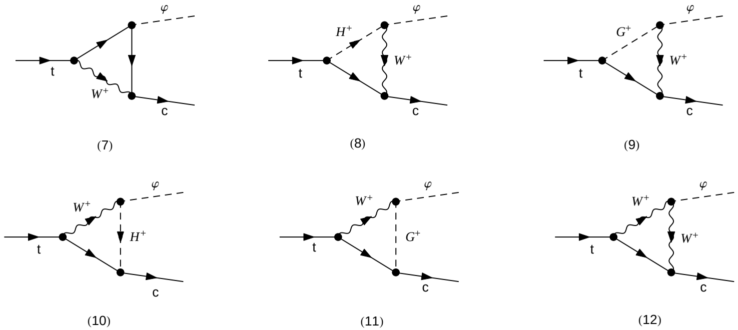


Figure: *Penguin diagrams contributing to $t \to c\varphi_j^0$ in the Feynman gauge.*

$t \to ch$ decays

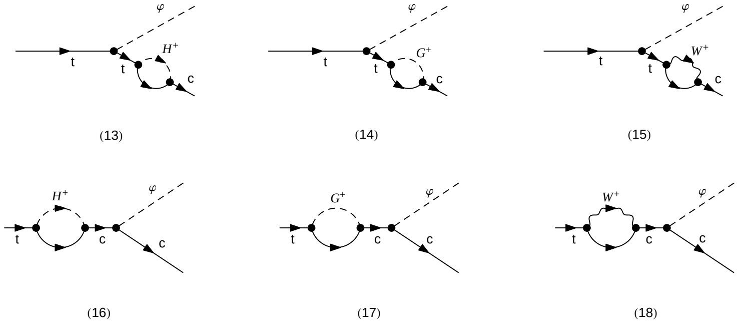


Figure: *Penguin diagrams contributing to $t \to c\varphi_j^0$ in the Feynman gauge.*

$t \to ch, cV$ decays

- The CP-conserving A2HDM contains 12 free real parameters: μ_2, λ_k ($k = 1, \ldots, 7$), the three alignment constants ς_f ($f = u, d, l$) and the counter-term coupling $\mathcal{C}_R(\mu)$.

- Some of the parameters of the scalar potential can be traded by the physical scalar masses and the mixing angle $\tilde{\alpha}$.

- The decays $t \to c\,\varphi_j^0, cZ$ are only sensitive to $\{M_{\varphi_j^0}$, $M_{H^\pm}$, $\cos\tilde{\alpha}$, λ_3, λ_7, ς_u, ς_d, $\mathcal{C}_R(M_W)\}$.

- We assume that the 125 GeV Higgs boson corresponds to the lightest CP-even state h; *i.e.*, we fix $M_h \simeq 125$ GeV.

- The LHC data imply that it couples to the massive gauge vector bosons with a SM-like strength so that $\cos\tilde{\alpha} \simeq 1$.

$t \to ch, cV$ decays

We analyze the parameter space of the A2HDM, subject to the following assumptions and constraints:

- The LHC and Tevatron Higgs data imply that $\cos\tilde{\alpha} > 0.9$ (68% CL) and $|y_f^h| \sim 1$ $(f = u, d, l)$.

- We work in the limit $\cos\tilde{\alpha} = 1$ so that no constraints on the alignment parameters are obtained from the 125 GeV Higgs data.
  Celis, Ilisie and Pich 2013

- We take into account constraints in the $\varsigma_u - \varsigma_d$ plane derived from the measurement of $\mathrm{Br}(\bar{B} \to X_s\gamma)$.
  Jung, Pich and Tuzón 2010, Jung, Li and Pich 2012

$t \to ch, cV$ decays

- We restrict the alignment parameter $|\varsigma_u| \leq 2$, in order to satisfy the constraints from $Z \to \bar{b}b$ decay and $B^0_{s,d} - \bar{B}^0_{s,d}$ mixings.

- The parameters $\varsigma_{d,l}$ are much less constrained phenomenologically; we take $|\varsigma_{d,\ell}| \leq 50$.
  Jung, Pich and Tuzón 2010, Jung, Li and Pich 2012

- The LEP has searched for charged Higgs bosons in the framework of 2HDMs, excluding $M_{H^\pm} \lesssim 80$ GeV (95% CL).
  G. Abbiendi et al. 2013

$t \to ch, cV$ decays

- Searches for a light charged Higgs via the decay $t \to H^+ b$ performed by the ATLAS and CMS, together with the limits on a charged Higgs from the Tevatron are taken into account.
  Aad et. al 2013, 2014, CMS 2014, Gutierrez et. al 2010

- These direct searches give an upper bound on the Yukawa combination $|\varsigma_u \varsigma_d|$, which, although being weaker than the one from $\mathrm{Br}(\bar{B} \to X_s \gamma)$, basically exclude one of the two possible strips allowed by the latter.
  Celis, Ilisie and Pich 2013

$t \to ch, cV$ decays

- We consider the perturbativity bound on the quartic scalar couplings $|\lambda_{3,7}| \leq 4\pi$.

- Additionally, the loop-induced decay $h \to \gamma\gamma$ is sensitive to λ_3 and λ_7 through the charged Higgs contribution to this process.
  Celis, Ilisie and Pich 2013

- We take into account the latest measurements of the Higgs signal strengths in the $h \to \gamma\gamma$ channel by ATLAS and CMS.
  ATLAS, CMS 2015

$t \to ch, cV$ decays

- In the limit $\cos\tilde{\alpha} = 1$, the decay rate for $t \to ch$ does not depend on $\mathcal{C}_R(M_W)$ and λ_7.

- In particular, for $\cos\tilde{\alpha} = 1$ we have $\lambda^h_{H^+H^-} = \lambda_3$.

- The measured Higgs signal strengths by ATLAS and CMS in the di-photon channel are then only sensitive to λ_3 and $M_{H^\pm}$.

$t \to ch, cV$ decays

- One can write the Higgs signal strength in the di-photon channel as

$$\mu^h_{\gamma\gamma} \;=\; \frac{\sigma(pp \to h) \times \mathrm{Br}(h \to 2\gamma)}{\sigma(pp \to h)_{\mathrm{SM}} \times \mathrm{Br}(h \to 2\gamma)_{\mathrm{SM}}} \;\simeq\; \left(1 - 0.15\, C^h_{H^\pm}\right)^2 , \qquad (11)$$

where $C^h_{H^\pm}$ encodes the charged Higgs contribution to $h \to 2\gamma$ and is given by

$$C^h_{H^\pm} \;=\; \frac{v^2}{2M^2_{H^\pm}}\, \lambda^h_{H^+H^-}\, \mathcal{A}(x_{H^\pm})\,. \qquad (12)$$

Celis, Ilisie and Pich 2013

- Here

$$\mathcal{A}(x) \;=\; -x - \frac{x^2}{4}\, f(x)\,, \qquad\qquad f(x) \;=\; -4\arcsin^2(1/\sqrt{x})\,, \qquad (13)$$

with $x_{H^\pm} = 4M^2_{H^\pm}/M^2_h$.

$t \to ch, cV$ decays

- We require that the Higgs signal strength lies within the 2σ range of the experimental measurements.

- The latest results by ATLAS $\mu^h_{\gamma\gamma} = 1.17^{+0.28}_{-0.26}$, and by CMS $\mu^h_{\gamma\gamma} = 1.12 \pm 0.24$, are consistent with the SM.
  ATLAS, CMS 2015

- A scan is performed over $\{\varsigma_u, \varsigma_d, \lambda_3\}$ with the restrictions specified earlier.
- We fix the charged Higgs mass to benchmark values to obtain the upper bounds on $\mathrm{Br}(t \to ch)$ and $\mathrm{Br}(t \to cV)$.
  Celis, Li, Lu, Pich and GA 2015

$t \to ch, cV$ decays

- In the window 90 GeV $< M_{H^\pm} <$ 150 GeV the alignment parameter ς_d is constrained to be small by the direct charged Higgs searches at the LHC via top decays which gives $|\varsigma_d| \lesssim 10$.
  Celis, Ilisie and Pich 2013

- For $M_{H^\pm} <$ 90 GeV a weaker bound on $|\varsigma_d|$ is obtained by a combination of LHC and Tevatron limits, $|\varsigma_d| \lesssim 25$.
  Celis, Ilisie and Pich 2013

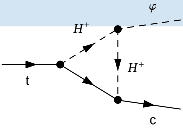
$t \to ch, cV$ decays

- For $M_{H^\pm} > 150$ GeV the largest decay rates for $t \to ch, cV$ are obtained for $|\varsigma_u| < 1$ and $|\varsigma_d| \simeq 50$.

- The decay rate for $t \to ch$ can receive much larger enhancements, due to the intermediate charged Higgs contribution involving the cubic Higgs coupling $\lambda^h_{H^+H^-}$.

- The maximum values for $\mathrm{Br}(t \to ch)$ are obtained when the cubic scalar coupling $\lambda^h_{H^+H^-}$ saturates either the $h \to 2\gamma$ limits or the perturbativity bound.

$t \to ch, cV$ decays



(3)

- Diagram 3 dominates the corresponding decay amplitude in this case.
- The contribution from this diagram to the decay amplitude is proportional to $\varsigma_u\varsigma_d\lambda^h_{H^+H^-}$ and $\varsigma_d^2\lambda^h_{H^+H^-}$.
- While the product $\varsigma_u\varsigma_d$ is constrained to be small in magnitude by $\mathrm{Br}(\bar{B} \to X_s\gamma)$, the term proportional to ς_d^2 becomes greatly enhanced for large $|\varsigma_d|$ values.
- Such large values of $|\varsigma_d|$ can be obtained outside the window 90 GeV $< M_{H^\pm} <$ 160 GeV.

$t \to ch, cV$ decays

- Analyses of decay $t \to ch$ within the type II 2HDM, prior to the Higgs discovery, have found that a light charged Higgs can enhance considerably the associated decay rate for large cubic coupling.

- The measurement of the Higgs signal strengths in the di-photon channel restrict the allowed size of the cubic Higgs coupling $\lambda^h_{H^+H^-}$ for a light charged Higgs.

- The charged Higgs gives the following finite correction to the hH^+H^- vertex, at the one-loop level:

$$(\lambda^h_{H^+H^-})_{\text{eff}} \;=\; \lambda^h_{H^+H^-}\;\left[1+\frac{v^2(\lambda^h_{H^+H^-})^2}{16\pi^2 M^2_{H^\pm}}\,\mathcal{Z}\left(\frac{M_h^2}{M^2_{H^\pm}}\right)\right]\;\equiv\;\lambda^h_{H^+H^-}\;(1+\Delta)\;, \tag{14}$$

where

$$\mathcal{Z}(X)\;=\;\int_0^1 dy\;\int_0^{1-y} dz\;\left[(y+z)^2+X\,(1-y-z-yz)\right]^{-1}\,. \tag{15}$$

- We allow this correction to be at most 50% ($\Delta \leqslant 0.5$).

$t \to ch$ decay

Impact of perturbative bound

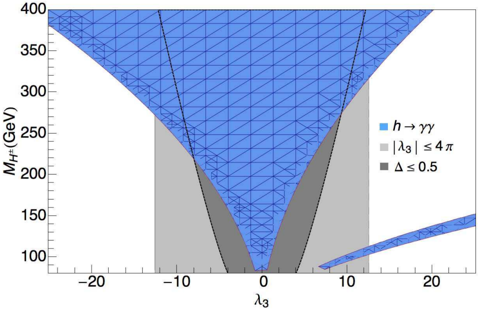


Figure: *Allowed region by measurements of the Higgs signal strengths in the di-photon channel (blue-meshed) together with the perturbativity limits $|\lambda_3| \leqslant 4\pi$ (light gray) or $\Delta \leqslant 0.5$ (dark gray). See text for details.*

- In figure we show the region allowed at 2σ by the measurement of the Higgs signal strengths in the di-photon channel, together with the bounds extracted with the perturbativity limits $|\lambda_3| \leqslant 4\pi$ and $\Delta \leqslant 0.5$.

- The constraints from $h \to \gamma\gamma$ give rise to a large allowed region, centered around $\lambda_3 = 0$, whose width increases for higher values of $M_{H^\pm}$.

- In this area the $h \to \gamma\gamma$ decay amplitude is dominated by the W-boson and top-quark loop contributions, as in the SM; the charged Higgs contribution remains subdominant.

$t \to ch$ decay

Impact of perturbative bound

- For light charged Higgs masses a small disjoint allowed region appears with $\lambda_3 \gtrsim 6$.
- The perturbativity limit $\Delta \leqslant 0.5$, being more stringent for light charged Higgs masses, excludes this small region.
- For a light charged Higgs the maximum values of $\mathrm{Br}(t \to ch)$ are obtained precisely in this separate region, where the value for $|\lambda^h_{H^+H^-}|$ reaches its maximum allowed value.

$t \to ch, cV$ decays

- Taking into account the measurements of the 125 GeV Higgs properties, all constraints specified earlier, we find that the decay rate for $t \to ch, cV$ lie beyond the reach of the high luminosity LHC in 2HDMs without tree-level FCNCs.

- Under the constraints considered the largest decay rate is obtained for $M_{H^\pm}$ being slightly below 90 GeV, $\mathrm{Br}(t \to ch) \lesssim 2 \times 10^{-7}$.

$t \to ch, cV$ decays

$M_{H^\pm}$ [GeV]	$\mathrm{Br}(t \to c\gamma)$	$\mathrm{Br}(t \to cZ)$	$\mathrm{Br}(t \to ch)$
100	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-13}$	$\lesssim 6 \times 10^{-9}$
200	$\lesssim 10^{-10}$	$\lesssim 3 \times 10^{-11}$	$\lesssim 3 \times 10^{-8}$
300	$\lesssim 10^{-11}$	$\lesssim 5 \times 10^{-12}$	$\lesssim 2 \times 10^{-8}$
400	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-12}$	$\lesssim 5 \times 10^{-9}$
500	$\lesssim 10^{-12}$	$\lesssim 10^{-12}$	$\lesssim 2 \times 10^{-9}$
Exp. limit	$< 1.8 \times 10^{-3}$ CMS, 2014	$< 5 \times 10^{-4}$ Chatrchyan et al 2013	$< 5.6 \times 10^{-3}$ CMS, 2014

Table: *Upper bounds for $\mathrm{Br}(t \to ch, cV)$ in the CP-conserving A2HDM.*

Summary

- We perform a complete one-loop computation of the two-body flavour-changing top decays $t \to ch$ and $t \to cV$ $(V = \gamma, Z)$, within the aligned two-Higgs-doublet model.

- We evaluate the impact of the model parameters on the associated branching ratios, taking into account constraints from flavour data and measurements of the Higgs properties.

- Assuming that the 125 GeV Higgs corresponds to the lightest CP-even scalar of the CP-conserving aligned two-Higgs-doublet model, we find that the rates for such flavour-changing top decays lie below the expected sensitivity of the future high-luminosity phase of the LHC.

- Measurements of the Higgs signal strength in the di-photon channel are found to play an important role in limiting the size of the $t \to ch$ decay rate when the charged scalar of the model is light.

- If small deviations from the limit $\cos\tilde{\alpha} = 1$ are considered, the LHC Higgs data gives rise to strong bounds on the magnitude of the alignment parameters.
- Since $|y_f^h| = |\cos\tilde{\alpha} + \varsigma_f \sin\tilde{\alpha}|$ $(f = u, d, l)$ is constrained to be close to one, one obtains $|\varsigma_f| \lesssim \mathcal{O}(1)$ when $\cos\tilde{\alpha} < 1$.
  Celis, Ilisie and Pich 2013
- This implies in particular that $|\varsigma_d|$ should be small and large enhancements of $\mathrm{Br}(t \to ch)$ are not possible.
- Allowing for CP violation would not led to any significant enhancement either, given the strong constraints on CP-violating couplings derived from electric dipole moment experiments.
  Jung, Pich and Tuzón 2010

- The direct counter-term contribution to $t \to ch$ decay is not present in 2HDMs with NFC.
- The flavour structure of the A2HDM counter-term implies a strong suppression of its effects, due to the explicit powers of quark masses and the unitarity of the quark mixing matrix.
- Neglecting the loop contribution (at $\mu = M_W$),

$$\begin{aligned} \mathrm{Br}(t \to ch)_{\mathrm{tree}} &\approx \frac{\alpha^2\,\pi^2\,|V_{cb}|^2\,m_b^4}{2\,\sin^4\theta_W\,M_W^4}\,\frac{(1-M_h^2/m_t^2)^2}{(1-M_W^2/m_t^2)^2\,(1+2M_W^2/m_t^2)}\,\sin^2\tilde{\alpha}\,|E_d|^2 \\ &\approx 2\times 10^{-11}\,\sin^2\tilde{\alpha}\,|E_d|^2\,, \end{aligned} \quad (16)$$

where

$$E_d \;=\; \frac{1}{4\pi^2}\,\mathcal{C}_R(M_W)\,(1+\varsigma_u\varsigma_d)\,(\varsigma_d-\varsigma_u)\;. \quad (17)$$

$t \to ch$ decay

The direct counter term contribution

- The size of E_d is constrained by the mixing between the neutral B_s^0 meson and its antiparticle, which receives also contributions from the three neutral scalars $\varphi_i^0 = \{h, H, A\}$.
- This process allows for $|E_d| \sim \mathcal{O}(1)$, even when the masses of the neutral scalars are of $\mathcal{O}(100\text{ GeV})$, but this is far too small to generate any observable signal in $t \to ch$.
  Braeuninger, Ibarra and Simonett 2010