Parameterizing BSM effects in the top-Yukawa coupling: the Higgs characterization model

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Introduction

Comparison of SMEFT and Higgs Characterization models

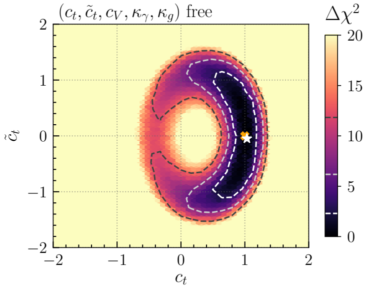
Making experimental results even more useful

Conclusions

My experience with the Higgs characterization (HC) model

Together with ATLAS members, I worked on [2007.08542]

- combining collider constraints on $\mathcal{CP}$-violation top-Yukawa coupling in a global fit,
- developing a $\mathcal{CP}$-independent measurement of tH production.



$\hookrightarrow$ Used HC model intensively for these studies.

Recap: the SM top-Yukawa coupling

$$\mathcal{L}^{\text{SM}}_{\text{top-Yuk}} = \frac{1}{\sqrt{2}} y_t H \bar{t}_L t_R + \text{h.c.} = \frac{1}{\sqrt{2}} H \bar{t}_L \left(\underbrace{\text{Re}(y_t)}_{\mathcal{CP}\text{ even}} + \underbrace{i\text{Im}(y_t)\gamma_5}_{\mathcal{CP}\text{ odd}} \right) t_R$$

- Real part of Yukawa coupling $\rightarrow$ $\mathcal{CP}$-even Yukawa coupling,
- imaginary part of Yukawa coupling $\rightarrow$ $\mathcal{CP}$-odd Yukawa coupling,
- in the SM, the Yukawa couplings are hermitian matrices,
- can be diagonalized by transforming quark fields $\rightarrow$ only one phase remains (CKM phase) $\hookrightarrow$ no $\mathcal{CP}$ violation in the SM top-Yukawa coupling.

BSM top-Yukawa coupling — concrete model example

Simplest example

THDM with CP violating Higgs potential → mixing between $\mathcal{CP}$-even h, H bosons and $\mathcal{CP}$-odd A boson at the tree level.

- mass eigenstates: $\mathcal{CP}$-mixed boson h_1, h_2, h_3 bosons

$$\begin{pmatrix} h \\ H \\ A \end{pmatrix} = R \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix},$$

- top-Yukawa coupling of h_1:

$$\mathcal{L}^{\text{THDM}}_{\text{top-Yuk}} = y_t^h h\bar{t}t + y_t^H H\bar{t}t + iy_t^A A\bar{t}t \xrightarrow{R} h_1 \bar{t}\left(R_{11}y_t^h + R_{21}y_t^H + iR_{31}y_t^A\gamma_5\right)t,$$

- in the limit $m_A \gg v$, mixing between h and A is suppressed by v^2/m_A^2

BSM top-Yukawa coupling — EFT perspective I

see e.g. [Dedes et al, 1304.03888]

- Assume that all new physics is heavy,
- deviations from the SM can be parameterized by higher-dimensional operators,
- at dimension 6, several operators modify the top-Yukawa coupling,

$$\mathcal{L}_{\text{dim-6}} = \frac{C_{t\varphi}}{\Lambda^2}(\varphi^\dagger\varphi)Q_L\tilde{\varphi}t_R + \frac{C_{\varphi\Box}}{2\Lambda^2}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \frac{C_{\varphi D}}{2\Lambda^2}(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi) + \text{h.c.},$$

where $\varphi^T = \left(G^+, 1/\sqrt{2}(v + H + iG^0)\right)$

BSM top-Yukawa coupling — EFT perspective II

$$\mathcal{L}_{\text{dim-6}} = \frac{c_{t\varphi}}{\Lambda^2}(\varphi^\dagger\varphi)Q_L\tilde{\varphi}t_R + \frac{c_{\varphi\Box}}{2\Lambda^2}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \frac{c_{\varphi D}}{2\Lambda^2}(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi) + \text{h.c.},$$

- $c_{\varphi\Box}$, $c_{\varphi D}$ can be assumed to be real (because of h.c.),
- $c_{t\Phi}$ can be complex $\rightarrow$ complex valued top-Yukawa coupling (phase can not be absorbed into quark fields),
- top-Yukawa coupling:

$$\Downarrow$$

$$\mathcal{L}^{\text{SMEFT}}_{\text{top-Yuk}} = \frac{1}{\sqrt{2}}H\bar{t}_L\left[\frac{y_t^{\text{SM}}}{\sqrt{2}}\left(1-\frac{1}{4}c_{\varphi D}\frac{v^2}{\Lambda^2}+c_{\varphi\Box}\frac{v^2}{\Lambda^2}\right)-\frac{v^2}{\sqrt{2}\Lambda^2}\text{Re}(c_{t\varphi})-i\gamma_5\frac{v^2}{\sqrt{2}\Lambda^2}\text{Im}(c_{t\varphi})\right]t_R$$

- in addition, also couplings like $HH\bar{t}t$ or $HHH\bar{t}t$ are induced.

Higgs characterization (HC) model

[Atroisenet et al, 1306.6464]

Main goal

EFT framework to characterize Higgs properties/couplings.

- Higgs is called X_0,
- X_0 can be spin-0, spin-1, or spin-2 resonance,
- HC model implements all interactions involving up to one X_0 in a general form.

Spin-0 case

HC model corresponds to taking all interactions involving one Higgs from SMEFT $\rightarrow$ and rewriting them in an easily interpretable way.

Higgs characterization (HC) model — Yukawa sector

$$\mathcal{L}_{\text{Yuk}}^{\text{HC}} = -\sum_{f=t,b,\tau} \bar{f}_L \left(c_\alpha \kappa_{Hff} g_{Hff} + i\gamma_5 s_\alpha \tilde{\kappa}_{Aff} g_{Aff} \right) f_R X_0,$$

- κ_f, $\tilde{\kappa}_f$ are κ modifiers for the $\mathcal{CP}$-even and $\mathcal{CP}$-odd part of the Yukawa coupling,
- α can be seen as a mixing angle between the $\mathcal{CP}$-even and the $\mathcal{CP}$-odd components of X_0,
- g_X are the respective SM couplings ($g_{Hff} = g_{Aff} = m_f/v$),
- parameterization is redundant, could also write

$$\mathcal{L}_{\text{top-Yuk}}^{\text{HCmod}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t}_L \left(c_t + i\gamma_5 \tilde{c}_t \right) t_R X_0,$$

- $\mathcal{CP}$ violation if $\alpha \neq 0, \pi/2$.

Higgs characterization (HC) model — gauge sector

- HC model also includes modifications of other Higgs couplings,

$$
\begin{aligned}
\mathcal{L}_V = \Big\{ & \frac{1}{2} c_\alpha \kappa_{\rm SM} g_{HZZ} Z_\mu Z^\mu + c_\alpha \kappa_{\rm SM} g_{HWW} W^+_\mu W^{-\mu} \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} \left[c_\alpha \kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + c_\alpha \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \left(c_\alpha \kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + \text{h.c.} \right) \right] \Big\} X_0,
\end{aligned}
$$

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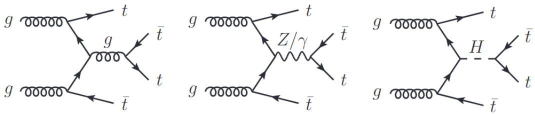
\end{aligned}
$$

- relevant for top-associated Higgs production.

Comparison of SMEFT and HC models

- Underlying assumptions between SMEFT and HC models are the same.
- SMEFT is more complete (includes all dim-6 operators and not only a subset),



- Assuming that new physics only affects Higgs couplings
  ⇒ SMEFT and HC models are equivalent,
- can rewrite constraints on $c_{\varphi t}$ into constraints on κ_t and $\tilde{\kappa}_t$ (and vice versa),
- personal view: constraints on κ_t and $\tilde{\kappa}_t$ are more intuitive.

Comparison of SMEFT and HC models — technical aspects I

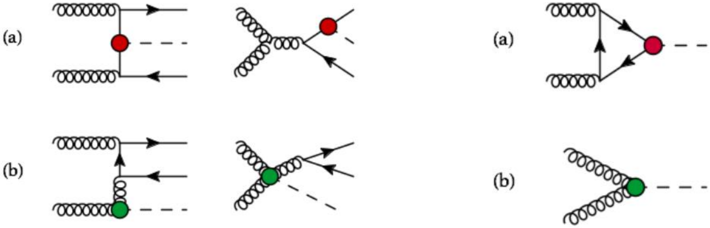
- UFO models exists for both models,
- both models allow to include NLO QCD effects.

Warning

At NLO QCD, top-associated Higgs production can not be regarded as being independent from other processes like gluon fusion.

- Modified top-Yukawa couplings strongly constrained by gluon fusion (and $H \to \gamma\gamma$),
- want to assess constraints on top-Yukawa coupling independently of gluon fusion,
  $\to$ need to use additional Hgg operator to tune back gluon fusion cross section

Comparison of SMEFT and HC models — technical aspects II



Red: *Htt* operators, green: *Hgg* operators, figure from [1607.05330]

⇒ gluon fusion and top-associated Higgs production entangled at $\mathcal{O}(\alpha_s)$.

- not taken into account in ATLAS ttH, tH ($H \to \gamma\gamma$) study [2004.04545],
- HC UFO model does not allow to take into account ggH operators and other $\mathcal{O}(\alpha_s)$ contributions simultaneously [Demartin et al, 1407.5089],
- SMEFT UFO model should fully support NLO QCD.

Thoughts on presentation of experimental results

Disclaimer

I am looking at this from a phenomenologist's perspective. Sorry if I misunderstood something!

- Experimental results are often interpreted using only simplified models,
- most concrete BSM are, however, more complex,
- recasting of experimental interpretations often very difficult or even impossible.

Possible ways to improve situation

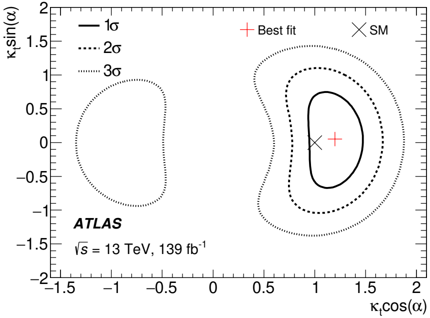
- Give as much information as possible to maximize impact on phenomenological studies,
  - e.g. higher-dimensional likelihoods, efficiency maps, cut flows, ...
- use more general models for interpretation.

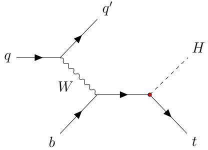
Example I — ATLAS ttH, $H \to \gamma\gamma$ $\mathcal{CP}$ study [2004.04545]

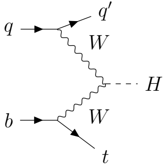
- Results presented as 2D likelihood for the parameters $\kappa_t \cos(\alpha)$ and $\kappa_t \sin(\alpha)$,
- no information about dependence on HWW coupling given,
- most BSM models will, however, not only change $H\bar{t}t$ coupling.

↪ Would need likelihood encoding dependence on all relevant Higgs couplings.

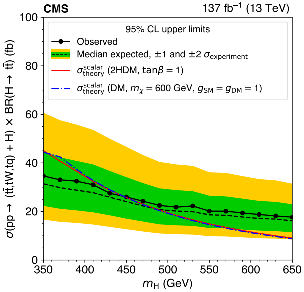
Note: also $\bar{t}t$ background depends on Higgs couplings [Martini et al, 2104.04277]

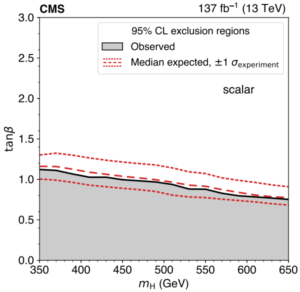






Example II — CMS search for $t\bar{t}t\bar{t}$ production [1908.06463]





- Interpretation in $\mathcal{CP}$-conserving THDM,
- assumes coupling of H to W bosons to be zero (exact alignment limit),
- no information about relative contribution of different production channels given,
- hardly applicable to any model apart from the $\mathcal{CP}$-conserving THDM in the exact alignment limit...

$\hookrightarrow$ would need likelihood depending on the mass as well as the different production modes and/or the $H\bar{t}t$ and HWW couplings.

Conclusions

Comparison of SMEFT and Higgs Characterization model:

- equivalent if
  - BSM physics is assumed to only affect Higgs couplings,
  - only interactions involving up to one Higgs are considered,
- personal view: HC model more intuitive,
- be cautious at NLO QCD.

Presentation of experimental results:

- maximize impact on phenomenological studies by as much information as possible,
- more general models makes reinterpretation easier.

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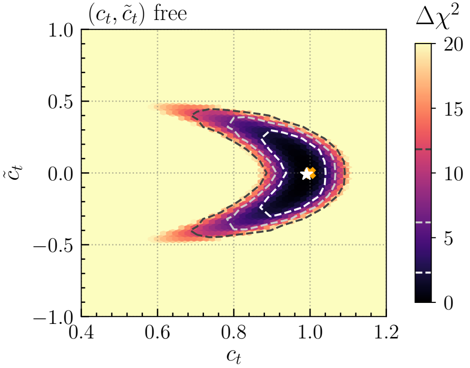
Thanks for your attention!

$$\frac{\sigma(gg \to H)}{\sigma_{\text{SM}}(gg \to H)} = (c_g + c_t)^2 + \frac{9}{4}(\tilde{c}_g + \tilde{c}_t)^2$$



from [2005.14536].