The $\mathcal{CP}$ character of the Higgs–fermion interactions: interplay of collider physics, EDMs and baryogenesis

Henning Bahl

in collaboration with

P. Bechtle, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen,

K. Peters, M. Saimpert, G. Weiglein

DESY, Hamburg

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Constraining the $\mathcal{CP}$ nature of the Higgs boson — motivation

- New sources of $\mathcal{CP}$ violation are necessary to explain the baryon asymmetry of the Universe,
- one possibility: $\mathcal{CP}$ violation in the Higgs sector with Higgs boson being $\mathcal{CP}$-admixed state,
- most BSM theories predict largest $\mathcal{CP}$ violation in Higgs–fermion couplings,
- $\mathcal{CP}$ violation in the Higgs sector can be constrained by
  - collider constraints,
  - electric dipole measurements (EDMs),
  - successful explanation of the baryon asymmetry of the Universe (BAU).

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Goal of present study

Assess LHC constraints on $\mathcal{CP}$-violating Higgs–fermion interactions and evaluate complementarity with EDM and BAU constraints.

Effective model

- Yukawa Lagrangian (generated e.g. by $1/\Lambda^2(\Phi^\dagger\Phi)Q_L\tilde{\Phi}f_R$ operator in SMEFT),

$$\mathcal{L}_{\rm yuk} = -\sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\rm SM}}{\sqrt{2}} \bar{f}\left(c_f + i\gamma_5 \tilde{c}_f\right) fH.$$

- optional: additional free parameter c_V $\rightarrow$ rescaling HVV couplings
- did not include $\mathcal{CP}$-odd HVV operators,
- SM: $c_f = 1$, $\tilde{c}_f = 0$, $c_V = 1$.

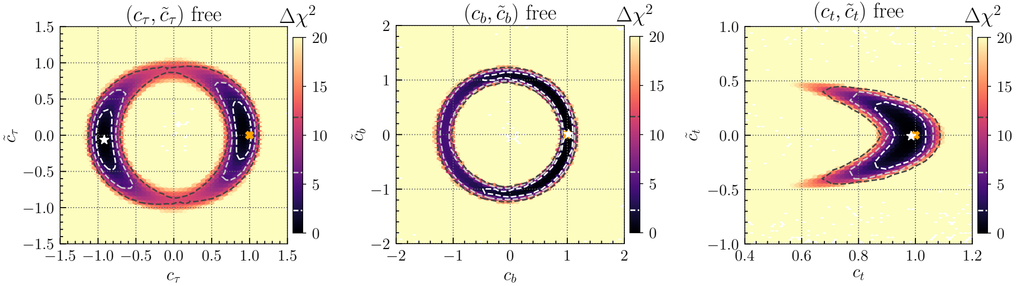
Study different simplified models:

- single flavour modification,
- common modification for 2nd and 3rd generation, $(c_{f_3} = c_\tau = c_t = c_b,\ \tilde{c}_{f_3} = \ldots,\ c_{f_2} = c_\mu = c_c = c_s,\ \tilde{c}_{f_2} = \ldots)$
- common modification of all Higgs–fermion coupling, $(c_f = c_e = \ldots = c_t = c_b,\ \tilde{c}_f = \ldots)$

LHC constraints — setup

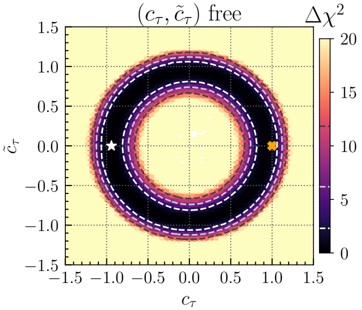
- Most relevant observables:
  - Higgs production (ggH, ZH, $t\bar{t}H$, tH, tWH)
  - Higgs decays ($H \to f\bar{f}, \gamma\gamma, gg$),
- experimental input:
  - all relevant Higgs measurements:
    - Higgs signal-strength measurements,
    - ZH STXS measurements (p_T shape),
    - CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis [2110.04836],
    - did not include dedicated experimental top-Yukawa $\mathcal{CP}$ analyses (difficult to reinterpret in other model),
  - if available, included all uncertainty correlations,
- χ^2 fit performed using `HiggsSignals`.

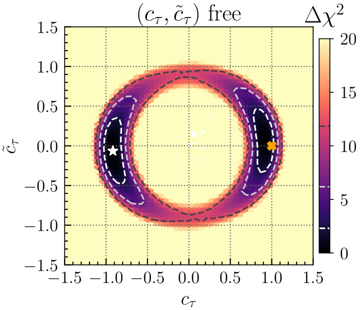
Single flavour modifications



- Strongest constraints on top-Yukawa coupling originating from ggH and $H \to \gamma\gamma$,
- $H \to \tau\tau$ are in contrast relatively model independent,
- difficult to disentangle c_b and $\tilde{c}_b$.

Impact of CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis



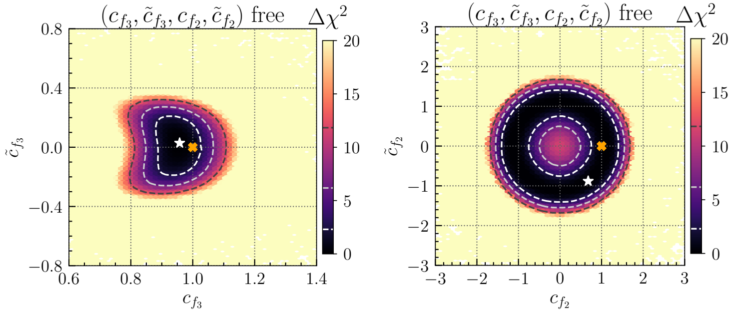


Left: fit result without CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis.

Right: fit result with CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis.

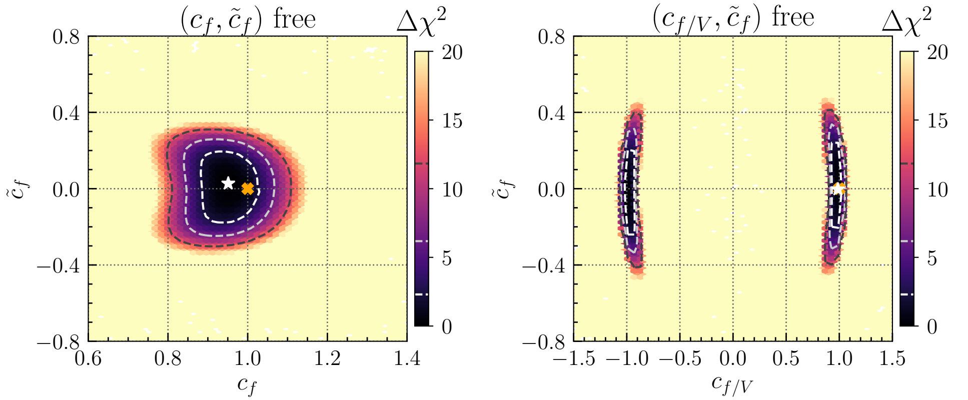
- Decay width $\Gamma_{H\to\tau\tau} \propto c_\tau^2 + \tilde{c}_\tau^2$,
- CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis disentangles c_τ and $\tilde{c}_\tau$.

Modification of 2nd and 3rd generation Yukawas



- 3rd generation constraints dominated by top-Yukawa constraints,
- 2nd generation constraints dominated by $H \to \mu\mu$ constraints.

Global modification



- Constraints dominated by 3rd generation constraints,
- setting $c_V = c_f = c_{f,V}$ (mixing with pseudoscalar) yields second region at negative $c_{V,f}$.

EDM and BAU constraints

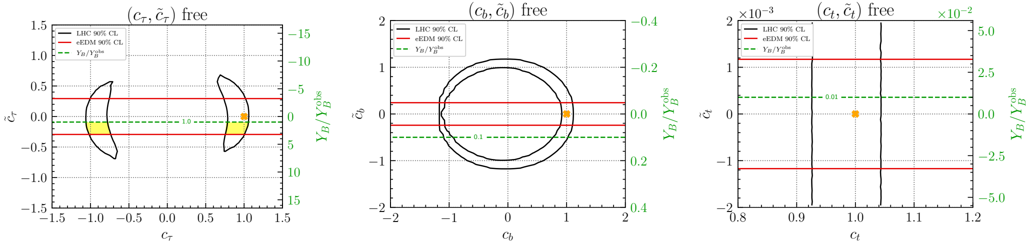
EDM:

- Several EDMs are sensitive to $\mathcal{CP}$ violation in the Higgs sector,
- we consider only constraints from theoretically cleanest EDM — the electron EDM (eEDM),
- eEDM evaluated using results from [Brod et al.,1310.1385,1503.04830].

BAU:

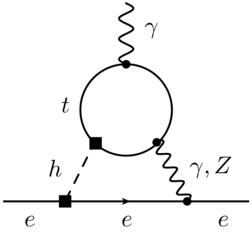
- different techniques used in the literature to calculate baryon asymmetry Y_B $\rightarrow$ large theoretical uncertainty,
- we use benchmark model for bubble wall properties maximising Y_B $\rightarrow$ values should be regarded as an upper bound,
- evaluation based on simple fit formula. [Shapira,2106.05338]

Single flavour modifications

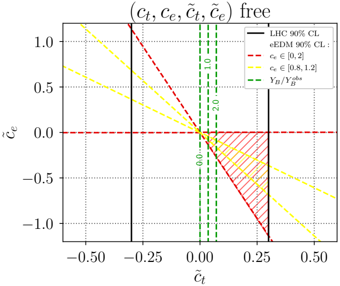


- Only $\mathcal{CP}$ violation in tau-Yukawa coupling able to explain substantial amount of BAU while still satisfying eEDM and LHC constraints,
- sizeable $\mathcal{CP}$ violation in bottom-Yukawa coupling still possible but very small contribution to BAU,
- eEDM places very strong constraints on $\mathcal{CP}$-violating top-Yukawa coupling; very similar for global modification (floating c_f and $\tilde{c}_f$).

Dependence on electron-Yukawa coupling



[taken from 1310.1385]



- eEDM $d_e/d_e^{\text{exp}} \approx 854 c_e \tilde{c}_t + 1082 \tilde{c}_e c_V - 610 \tilde{c}_e c_t + \ldots$,
- hardly any collider constraints on c_e and $\tilde{c}_e$,
- cancellation between electron and top contributions to eEDM possible,
- allows for substantial contribution of $\mathcal{CP}$-violating top-Yukawa coupling to BAU.

Conclusions

Initial question

How well can one constrain $\mathcal{CP}$ violating Higgs–fermion–fermion interactions using collider, EDM and BAU constraints?

- Used effective Lagrangian with generalized Yukawa interactions,
- global fit to all relevant LHC data:
  - included total and differential XS measurements as well as dedicated $H \to \tau\tau$ $\mathcal{CP}$ analysis,
  - first and second generation couplings only weakly constrained,
  - strongest constraints on top- and tau-Yukawa couplings.
- complementarity with EDM and BAU constraints:
  - eEDM puts stringent constraints on $\mathcal{CP}$ violation in the Higgs sector,
  - eEDM constraints, however, strongly depend on the electron-Yukawa coupling,
  - $\mathcal{CP}$ violation in the tau-Yukawa coupling most promising for explaining BAU.

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Thanks for your attention!