Constraining the $CP$ character of the Higgs–top-quark interaction

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Theory seminar

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Talk based on

- 2007.08542

- 2110.10177
  in collaboration with S. Brass,

- work in progress
Introduction

Current LHC constraints

Machine-learning-based inference

Complementarity with EDM and baryogenesis constraints

Conclusions
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Constraining the $C\mathcal{P}$ nature of the Higgs boson — motivation

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

Focus of this talk

How well can we constrain $C\mathcal{P}$ violation in the Higgs–top-quark interaction?
Establishing $\mathcal{CP}$ violation — different types of observables

Three different types of measurements: Measurements of

- pure $\mathcal{CP}$-odd observables:
  - unambiguous markers for $\mathcal{CP}$ violation:
    - LHC measurements:
      - e.g. decay angle in $H \rightarrow \tau\tau$ [CMS-PAS-HIG-20-006] or jet angular correlations in VBF with $H \rightarrow \tau\tau$,
    - EDM measurements.

- $\mathcal{CP}$-even observables:
  - many precision measurements are indirectly sensitive,
  - e.g. rate of Higgs production via gluon fusion,
  - deviations from SM need not be due to $\mathcal{CP}$ violation → potentially high model dependence.
Effective model

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

$$\mathcal{L}_{yuk} = -\frac{\gamma_{\tilde{t}}^{\text{SM}}}{\sqrt{2}} \bar{t} (c_t + i\gamma_5 \tilde{c}_t) t H.$$ 

- optional: additional free parameters
  - $c_V \rightarrow$ rescaling $HHV$ couplings
    ($tH$ and $tWH$ production depend on $c_V$),
  - $\kappa_g \rightarrow$ rescaling $gg \rightarrow H$ ("removing" gluon fusion constraints),
  - $\kappa_\gamma \rightarrow$ rescaling $H \rightarrow \gamma\gamma$ ("removing" $H \rightarrow \gamma\gamma$ constraints),

- did not consider $C\bar{P}$-odd $HHV$ operators,
- SM: $c_t = 1$, $\tilde{c}_t = 0$, $c_V = 1$.

Considered four models:

1. $(c_t, \tilde{c}_t)$ free,
2. $(c_t, \tilde{c}_t, c_V)$ free,
3. $(c_t, \tilde{c}_t, c_V, \kappa_\gamma)$ free,
4. $(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free.
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LHC constraints — setup
[based on HB et al., 2007.08542]

- Most relevant observables:
  - Higgs production ($ggH$, $ZH$, $t\bar{t}H$, $tH$, $tWH$)
  - Higgs decays ($H \rightarrow f\bar{f}$, $\gamma\gamma$, $gg$),

- experimental input:
  - all relevant Higgs measurements:
    - Higgs signal-strength measurements,
    - $ZH$ STXS measurements ($p_T$ shape),
    - CMS $H \rightarrow \tau\tau$ $CP$ analysis [2110.04836],
    - did not include dedicated experimental top-Yukawa $CP$ analyses (difficult to reinterpret in other model),
  - if available, included all uncertainty correlations,

- random scan with $O(10^7 - 10^8)$ points,
- $\chi^2$ fit performed using HiggsSignals.
Relevant processes: \( gg \rightarrow H \) & \( H \rightarrow \gamma \gamma \)

- top-Yukawa influences
  - \( gg \rightarrow H \) signal strength

\[
\kappa_g^2 \equiv \frac{\sigma_{gg\rightarrow H}}{\sigma_{gg\rightarrow H}^{SM}} \bigg|_{M_t \rightarrow \infty} \simeq c_t^2 + \frac{9}{4} \tilde{c}_t^2 + \ldots,
\]

calculate \( \kappa_g \) either in terms of \( c_t \) and \( \tilde{c}_t \) or treat it as free parameter (→ undiscovered colored BSM particles),

- kinematic shapes could be sensitive (\( \Delta \phi_{jj} \) in \( gg \rightarrow H + 2j \), see [ATLAS-CONF-2020-055])

- similar for \( H \rightarrow \gamma \gamma \): \( \kappa_{\gamma}^2 \simeq 0.08c_t^2 + 0.18\tilde{c}_t^2 + 1.62c_V^2 - 0.71c_V c_t + \ldots \)
Relevant processes: $ZH$ production

- **Total rate:**
  - Experimental measurement: $pp \rightarrow ZH$,
  - $\sigma_{qq}^{SM} \rightarrow ZH \approx 6\sigma_{gg}^{SM} \rightarrow ZH$,
  - but $\sigma_{gg} \rightarrow ZH$ can be significantly enhanced.
Relevant processes: \( ZH \) production

Total rate:
- Experimental measurement: \( pp \rightarrow ZH \),
- \( \sigma_{q\bar{q}\rightarrow ZH}^{SM} \approx 6 \sigma_{gg\rightarrow ZH}^{SM} \),
- but \( \sigma_{gg\rightarrow ZH} \) can be significantly enhanced.

Kinematic shapes:
- \( Z p_T \)-shape sensitive to Higgs \( CP \)-properties,
- use STXS bins as additional input.
Relevant processes: $ttH$ and $tH$ production

$\sigma_{ttH}^{SM} \approx 7 \sigma_{tH}^{SM}$,

but $CP$-odd coupling can enhance $\sigma_{tH}$.
Relevant processes: $ttH$ and $tH$ production

$\sigma_{ttH}^{\text{SM}} \approx 7 \sigma_{tH}^{\text{SM}}$, but $C\bar{P}$-odd coupling can enhance $\sigma_{tH}$.

Kinematic shape:

- Higgs $p_T$ shape measured in STXS framework,
  
  [ATLAS-CONF-2020-026]

- applicability questionable.
Relevant processes: combined top-associated Higgs production

- $t\bar{t}H$ and $tH$ difficult to disentangle $\rightarrow$ normally combination of both measured,
- $\mu_{tH+t\bar{t}H+tWH} = \frac{\sigma(pp\rightarrow t\bar{t}H+tH+tWH)}{\sigma_{SM}(pp\rightarrow ttH+tH+tWH)}$,
- plots for $c_V = 1$. 
Fit results
Fit results

- (c_t, \tilde{c}_t) free
- (c_t, \tilde{c}_t, c_V) free
- (c_t, \tilde{c}_t, c_V, \kappa_\gamma) free

\Delta \chi^2

0.4 0.6 0.8 1.0 1.2
ct
□1.0
□0.5
0.0
0.5
1.0
\tilde{c}_t
(ct, \tilde{c}_t) free
\Delta \chi^2

0.4 0.6 0.8 1.0 1.2
ct
□1.0
□0.5
0.0
0.5
1.0
\tilde{c}_t
(ct, \tilde{c}_t, c_V) free
\Delta \chi^2

0.4 0.6 0.8 1.0 1.2
ct
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\Delta \chi^2

- Large model dependence, still significant
- CP-odd coupling allowed in 5D model.
Fit results

Large model dependence, still significant CP-odd coupling allowed in 5D model.
Fit results

- Large model dependence,
- still significant $CP$-odd coupling allowed in 5D model.
How to improve constraints in the future?

- Construct $CP$-odd observables
  → easy to interpret but experimentally difficult for top-associated Higgs production,
- indirect constraints
  → comparably low model dep., but deviations could also be caused by other BSM physics.
- include more kinematic information, [see e.g. ATLAS and CMS studies: 2003.10866,2004.04545]
  → model dependence (e.g. $HVV$ couplings)?

⇒ Should pursue all approaches to exploit complementarity!
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## Constructing the likelihood function — basics I

### Goal of LHC measurements

Derive likelihood function $p_{\text{full}}(\{x_i\}|\theta)$ giving probability of observing a set of events with observables $x_i$ for a given model with parameters $\theta$.

We can write

$$p_{\text{full}}(\{x_i\}|\theta) = \text{Pois}(n|L\sigma(\theta)) \prod_i p(x_i|\theta),$$

with the probability density of observing a single event

$$p(x|\theta) = \frac{1}{\sigma(x)} \frac{d^d\sigma(x|\theta)}{dx^d}$$

How can we obtain $p(x|\theta)$?
Constructing the likelihood function — basics II

MC simulators allow to sample $p(x|\theta)$ using the following steps:

1. generate parton-level events,
2. parton shower,
3. detector simulation.

$$
p(x|\theta) = \int dz_d \int dz_s \int dz_p p(x|z_d)p(z_d|z_s)p(z_s|z_p)p(z_p|\theta) = p(x,z|\theta) \tag{1}
$$

Large number of involved parameters $\rightarrow$ can not compute this integral directly!
Constructing the likelihood function — traditional approach

Summary statistics

Calculate most relevant observable(s) and bin events into histogram.

- $r(x|\theta_0, \theta_1) \equiv \frac{p(x|\theta_0)}{p(x|\theta_1)} \leftrightarrow$ ratio of events predicted/measured per bin.

- Disadvantages:
  - low dimensionality $\rightarrow$ loose of information,
  - binning $\rightarrow$ loose of information.

$\rightarrow$ Can we use the whole available information?

Possible approaches: matrix element method or optimal observable approach.
[see e.g. Kraus,Martini,Peitzsch,Uwer,1908.09100]
Machine-learning-based inference

[Brehmer,Cranmer,Kling,...,1906.01578,1805.12244,1805.00013,1805.00020,1808.00973]

1. Calculate joint likelihood ratio

\[
r(x, z|\theta_0, \theta_1) \equiv \frac{p(x, z|\theta_0)}{p(x, z|\theta_1)} = \frac{p(x|z_d)p(z_d|z_s)p(z_s|z_p)p(z_p|\theta_0)}{p(x|z_d)p(z_d|z_s)p(z_s|z_p)p(z_p|\theta_1)} = \frac{p(z_p|\theta_0)}{p(z_p|\theta_1)} = \frac{d\sigma(z_p|\theta_0)}{d\sigma(z_p|\theta_1)} \sigma(\theta_1) \sigma(\theta_0),
\]

[Note: evaluating \(p(z_p|\theta)\) \(\sim\) evaluating matrix element \(\rightarrow\) relatively easy using morphing techniques.]

2. Define suitable loss function, e.g.

\[
L[\hat{r}(x|\theta_0, \theta_1)] = \frac{1}{N} \sum_{(x_i, z_i) \sim p(x, z|\theta_1)} |r(x_i, z_i|\theta_0, \theta_1) - \hat{r}(x_i|\theta_0, \theta_1)|^2,
\]

3. Express estimator \(\hat{r}(x_i|\theta_0, \theta_1)\) as neural network which is trained to minimize \(L\) \(\rightarrow\) \(\hat{r}\) converges to true \(r\)
Machine-learning-based inference — overview

We used implementation of publicly available code MadMiner designed to work with MadGraph + Pythia + Delphes.
Application to $\mathcal{CP}$ violation in the Higgs–top-quark interaction

- Concentrate on top-associated Higgs production ($t\bar{t}H$, $tH$, $tWH$) with $H \to \gamma\gamma$,
- free model parameters: $c_t$, $\tilde{c}_t$, $c_V$ (± renormalization scale $\mu_R$),
- demand at least one lepton in final state $\rightarrow$ backgrounds: $ZH$, $WH$,
  (non-Higgs backgrounds are assumed to be subtracted by fit to smoothly falling $m_{\gamma\gamma}$ distribution)
- used two different detector cards: ATLAS LHC card, HL-LHC card,
- defined 47 observables used by neural network,
- averaged over ensemble of six neural networks to minimize ML uncertainty.

$\rightarrow$ Evaluate likelihood for different luminosities.
Expected limits assuming SM data – LHC

Assumption: $c_V = 1$,

- no variation of renormalization scale.
Expected limits assuming SM data – HL-LHC + angle interpretation

- Can also interpret results in terms of $\mathcal{C}\mathcal{P}$-violating angle $\tan \alpha \equiv \tilde{c}_t/c_t$. 
Dependence on $c_V$ and renormalization scale

- Floating $c_V$ and $\mu_R$ only results in slightly looser constraints
  → only small dependence on our knowledge of the $HVV$ coupling and the theoretical uncertainty,
- additional uncertainty not considered: pdf uncertainty.
Expected limits assuming SM data – LHC

▶ Assumption: $c_t = 1$, $\tilde{c}_t = 0.5$ realized in Nature.
Most sensitive observables — Fisher information

What observables drive these constraints?

- Evaluate sensitivity using Fisher matrix

\[ I_{ij}(\theta) = \mathbb{E} \left[ \frac{\partial \log p_{\text{full}}(\{x\} | \theta)}{\partial \theta_i} \frac{\partial \log p_{\text{full}}(\{x\} | \theta)}{\partial \theta_j} \right] \]

- Related to the minimal covariance of an estimator \( \hat{\theta} \) via

\[ \text{cov}(\hat{\theta}|\theta)_{ij} \geq I_{ij}^{-1}(\theta), \]

- 1D case: \( \Delta \theta = \text{var}(\hat{\theta}|\theta) \geq \frac{1}{\sqrt{I(\theta)}}. \)

\[ \downarrow \]

Higher information \( \longrightarrow \) higher precision
Most sensitive observables — SM

\[ t\bar{t}H + tH + tWH (H \rightarrow \gamma\gamma), \text{ SM, } (c_V = c_t = 1, \tilde{c}_t = 0), \text{ 300 fb}^{-1} \]

\[ I_{ij} \text{ eigenvalues} \]

\[ (\det I_{ij} / \det I_{\text{full}ij})^{1/3} \]

\[ \tilde{c}_t \text{ hard to constraint close to SM point without full kinematic information.} \]
Most sensitive observables — $\mathcal{CP}$-mixed benchmark point

$\tilde{c}_t$ seems to be well suited to constrain $\tilde{c}_t$ in case of a deviation from the SM.
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EDM and BAU constraints

EDM:
▶ Several EDMs are sensitive to $CP$ 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 $Y_B$
  → large theoretical uncertainty,
▶ we employ vev-insertion approximation (VIA) with benchmark model for bubble wall properties maximising $Y_B$
  → values should be regarded as an upper bound,
▶ evaluation based on simple fit formula. [Shapira,2106.05338]
Single flavour modifications

- eEDM places very strong constraints on $C\bar{P}$-violating top-Yukawa coupling; very similar for global modification.
Dependence on electron-Yukawa coupling

- $e_{\text{EDM}} \approx 870 c_e \tilde{c}_t - 1082 \tilde{c}_e c_V + 610 \tilde{c}_e c_t + \ldots$,
- hardly any collider constraints on $c_e$ and $\tilde{c}_e$,
- fine-tuned cancellation between electron and top contributions to $e_{\text{EDM}}$ possible,
- allows for substantial contribution of $\mathcal{C}\mathcal{P}$-violating top-Yukawa coupling to BAU.
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Initial question

How can we constrain a $CP$-odd component of the top-Yukawa coupling?

- Current LHC rate measurements:
  - strong constraints from $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$,
  - sizable $CP$-odd coupling allowed if $\kappa_g$ and $\kappa_\gamma$ are varied independently,

- Kinematic constraints using top-associated Higgs production:
  - ML-based inference promises strong constraints at HL-LHC,
  - Higgs $p_T$-shape appears to be a promising observable,

- EDM and BAU constraints:
  - strong complementary constraints,
  - have to be careful with interpretation due to strong dependence on first-generation Yukawa couplings.
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Thanks for your attention!
Appendix
Relevant processes: \( tWH \) production

- interferes with \( t\bar{t}H \) production,
- \( \sigma_{t\bar{t}H}^{\text{SM}} \approx 34 \sigma_{tWH}^{\text{SM}} \),
- but non-negligible contribution in \( \mathcal{CP} \)-odd case: \( \sigma_{t\bar{t}H}^{\mathcal{CP}\text{-odd}} \approx 3.5 \sigma_{tWH}^{\mathcal{CP}\text{-odd}} \),
→ fully taken into account in numerical analysis.
Impact of CMS $H \rightarrow \tau\tau$ $\mathcal{C}\mathcal{P}$ analysis

Left: fit result without CMS $H \rightarrow \tau\tau$ $\mathcal{C}\mathcal{P}$ analysis.

- Decay width $\Gamma_{H \rightarrow \tau\tau} \propto c_\tau^2 + \tilde{c}_\tau^2$.
- CMS $H \rightarrow \tau\tau$ $\mathcal{C}\mathcal{P}$ analysis disentangles $c_\tau$ and $\tilde{c}_\tau$.

Right: fit result with CMS $H \rightarrow \tau\tau$ $\mathcal{C}\mathcal{P}$ analysis.
Single flavour modifications

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