Constraining the $\mathcal{CP}$ character of the Higgs–top-quark interaction

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Theory seminar

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Talk based on

- 2007.08542
  in collaboration with P. Bechtle, S. Heinemeyer, J. Katzy, T. Klingl, K. Peters, M. Saimpert, T. Stefaniak, G. Weiglein,
- 2110.10177
  in collaboration with S. Brass,
- work in progress
  in collaboration with P. Bechtle, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, G. Weiglein.

Introduction

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–fermion couplings
- $\mathcal{CP}$ 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 $\mathcal{CP}$ 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 $H \to \tau\tau$ [CMS-PAS-HIG-20-006] or jet angular correlations in VBF with $H \to \tau\tau$,
    - 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
    $\to$ 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),

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

- optional: additional free parameters
  - c_V → rescaling HVV couplings (tH and tWH production depend on c_V),
  - κ_g → rescaling $gg \to H$ ("removing" gluon fusion constraints),
  - κ_γ → rescaling $H \to \gamma\gamma$ ("removing" $H \to \gamma\gamma$ constraints),
- did not consider $\mathcal{CP}$-odd HVV operators,
- SM: $c_t = 1$, $\tilde{c}_t = 0$, $c_V = 1$.

Considered four models:

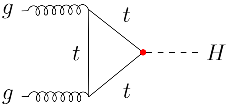
1. $(c_t, \tilde{c}_t)$ free,
2. $(c_t, \tilde{c}_t, c_V)$ free,
3. $(c_t, \tilde{c}_t, c_V, \kappa_\gamma)$ free,
4. $(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free.

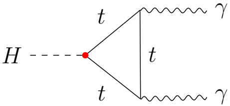
LHC constraints — setup

[based on HB et al., 2007.08542]

- Most relevant observables:
  - Higgs production (ggH, ZH, $t\bar{t}H$, tH, tWH)
  - Higgs decays ($H \to f\bar{f}, \gamma\gamma, gg$),
- 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,
- random scan with $\mathcal{O}(10^7 - 10^8)$ points,
- χ^2 fit performed using `HiggsSignals`.

Relevant processes: $gg \to H$ & $H \to \gamma\gamma$



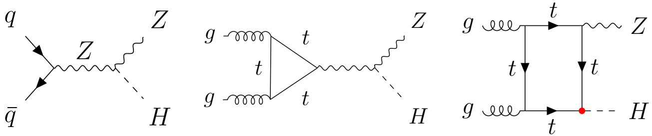


- top-Yukawa influences
  - $gg \to H$ signal strength

$$\kappa_g^2 \equiv \left.\frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\text{SM}}}\right|_{M_t\to\infty} \simeq c_t^2 + \frac{9}{4}\tilde{c}_t^2 + \ldots,$$

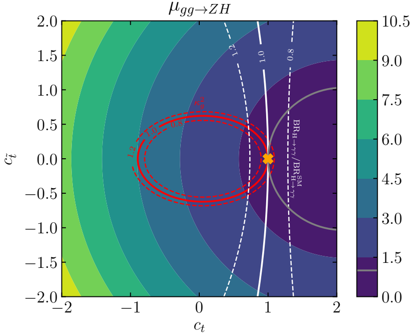
    calculate κ_g either in terms of c_t and $\tilde{c}_t$ or treat it as free parameter ($\to$ undiscovered colored BSM particles),
  - kinematic shapes could be sensitive ($\Delta\phi_{jj}$ in $gg \to H + 2j$, see [ATLAS-CONF-2020-055])
- similar for $H \to \gamma\gamma$: $\kappa_\gamma^2 \simeq 0.08c_t^2 + 0.18\tilde{c}_t^2 + 1.62c_V^2 - 0.71c_V c_t + \ldots$

Relevant processes: ZH production



Total rate:

- Experimental measurement: $pp \to ZH$,
- $\sigma^{\mathrm{SM}}_{q\bar{q}\to ZH} \approx 6\sigma^{\mathrm{SM}}_{gg\to ZH}$,
- but $\sigma_{gg\to ZH}$ can be significantly enhanced.



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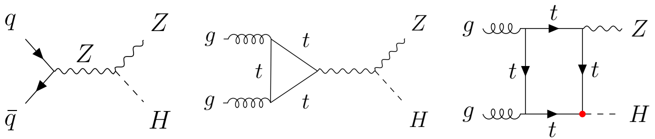

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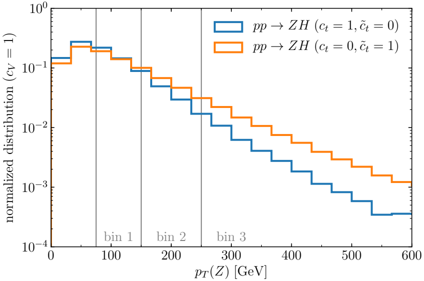
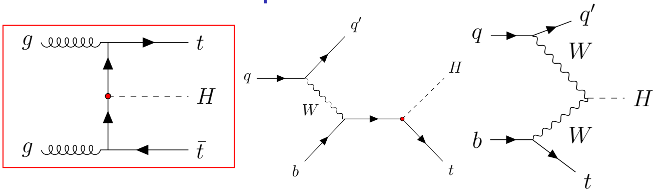
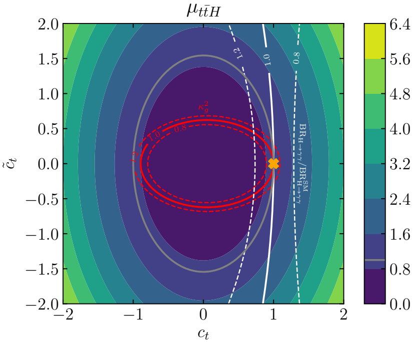
Kinematic shapes:

- Z p_T-shape sensitive to Higgs $\mathcal{CP}$-properties,
- use STXS bins as additional input.



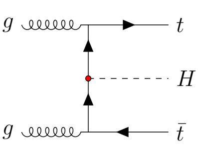
Relevant processes: *ttH* and *tH* production

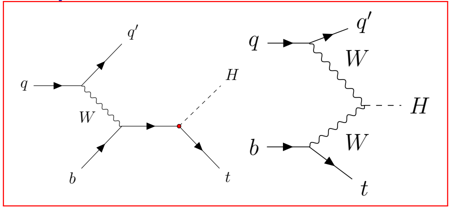




- $\sigma^{\mathrm{SM}}_{t\bar{t}H} \approx 7\sigma^{\mathrm{SM}}_{tH}$,
- but $\mathcal{CP}$-odd coupling can enhance σ_{tH}.

Relevant processes: *ttH* and *tH* production

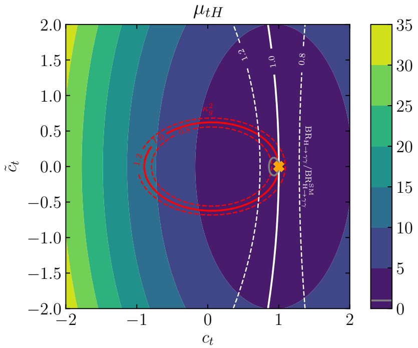




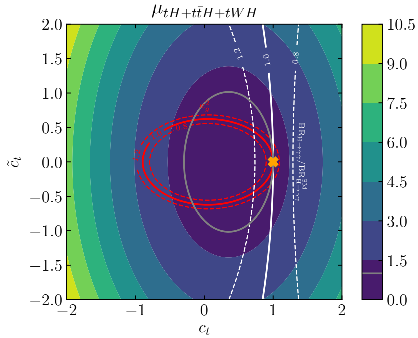
- $\sigma^{SM}_{t\bar{t}H} \approx 7\sigma^{SM}_{tH}$,
- but $\mathcal{CP}$-odd coupling can enhance σ_{tH}.

Kinematic shape:

- Higgs p_T shape measured in STXS framework, [ATLAS-CONF-2020-026]
- applicability questionable.

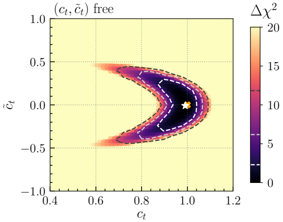


Relevant processes: combined top-associated Higgs production



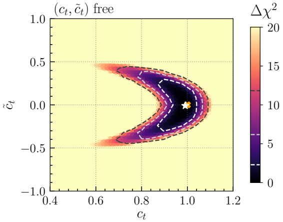
- $t\bar{t}H$ and tH difficult to disentangle $\to$ normally combination of both measured,
- $\mu_{tH+t\bar{t}H+tWH} = \frac{\sigma(pp \to t\bar{t}H+tH+tWH)}{\sigma_{\mathrm{SM}}(pp \to t\bar{t}H+tH+tWH)}$,
- plots for $c_V = 1$.

Fit results



$(c_t, \tilde{c}_t)$ free
$\Delta\chi^2$
1.0
0.5
0.0
−0.5
−1.0
$\tilde{c}_t$
0.4
0.6
0.8
1.0
1.2
c_t
20
15
10
5
0

Fit results



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10
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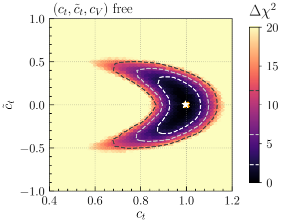
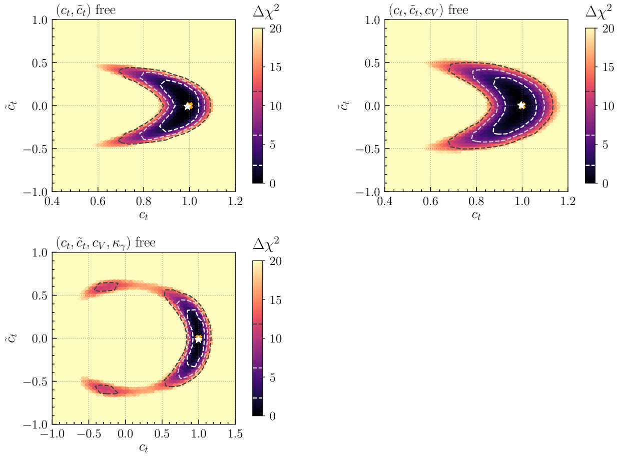


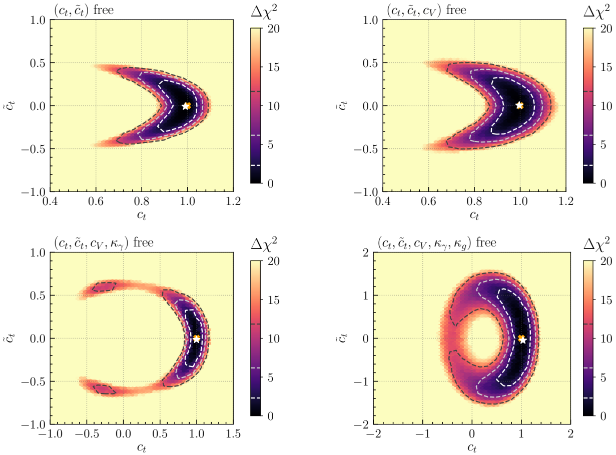
$(c_t, \tilde{c}_t, c_V)$ free
$\Delta\chi^2$
20
15
10
5
0
1.0
0.5
0.0
−0.5
−1.0
0.4
0.6
0.8
1.0
1.2
c_t
$\tilde{c}_t$

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
$\Delta\chi^2$
c_t
$\tilde{c}_t$

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
$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
$\Delta\chi^2$
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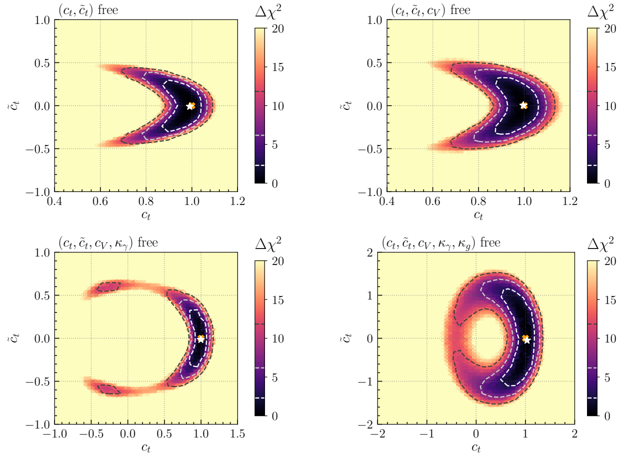
20
c_t
$\tilde{c}_t$
1.0
0.5
0.0
−0.5
−1.0
0.4
0.6
0.8
1.2
1.5
2
1
0
−1
−2

Fit results



- Large model dependence,
- still significant $\mathcal{CP}$-odd coupling allowed in 5D model.

How to improve constraints in the future?

- Construct $\mathcal{CP}$-odd observables
  $\rightarrow$ easy to interpret but experimentally difficult for top-associated Higgs production,
- indirect constraints
  $\rightarrow$ 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]
  $\rightarrow$ model dependence (e.g. HVV couplings)?

$\Rightarrow$ 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 θ.

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.

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

Large number of involved parameters → 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 $\to$ loose of information,
  - binning $\to$ loose of information.

$\to$ 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

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

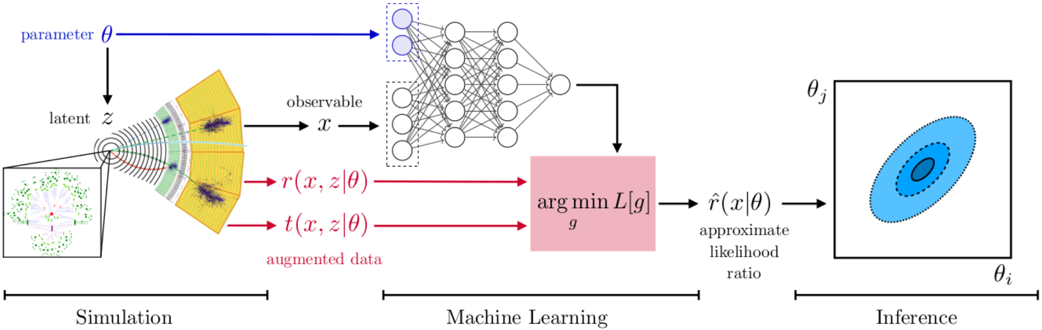
   [Note: evaluating $p(z_p|\theta)$ $\sim$ evaluating matrix element $\rightarrow$ relatively easy using morphing techniques,]

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



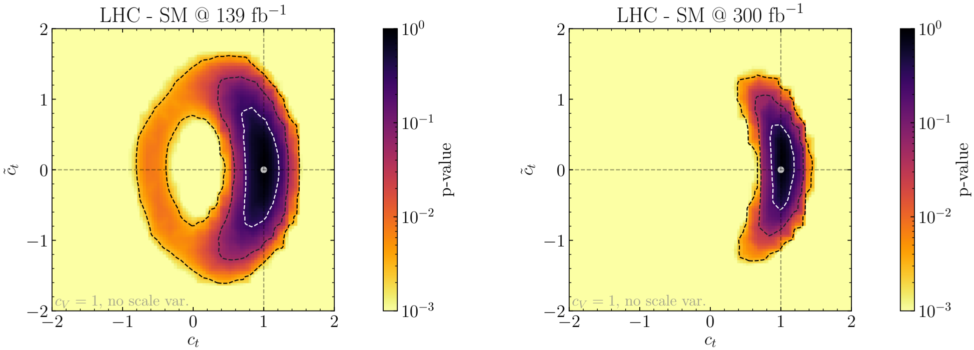
- We used implementation of publicly available code `MadMiner` designed to work with `MadGraph` + `Pythia` + `Delphes`.

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 μ_R),
- demand at least one lepton in final state $\to$ 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.

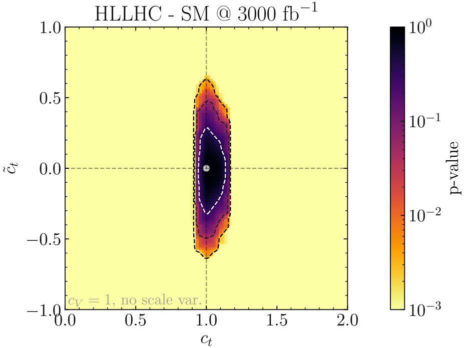
$\to$ Evaluate likelihood for different luminosities.

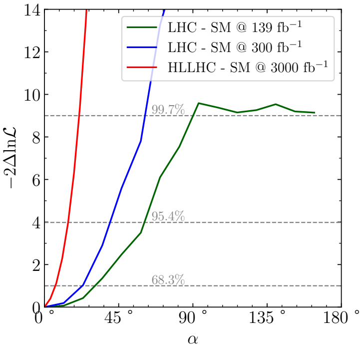
Expected limits assuming SM data – LHC



- Assumption: $c_V = 1$,
- no variation of renormalization scale.

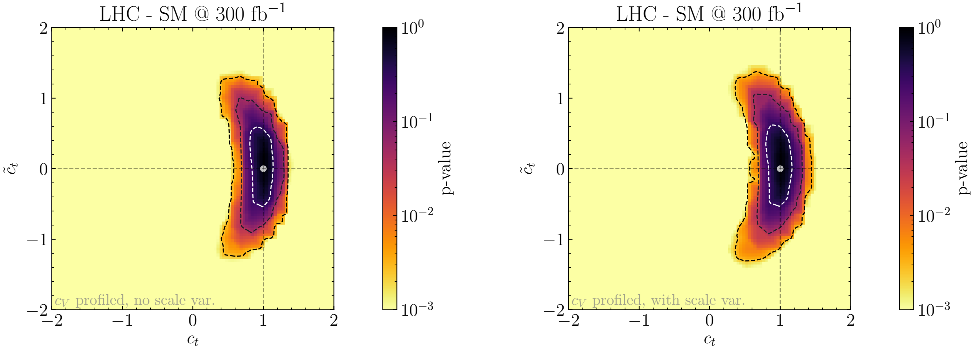
Expected limits assuming SM data – HL-LHC + angle interpretation





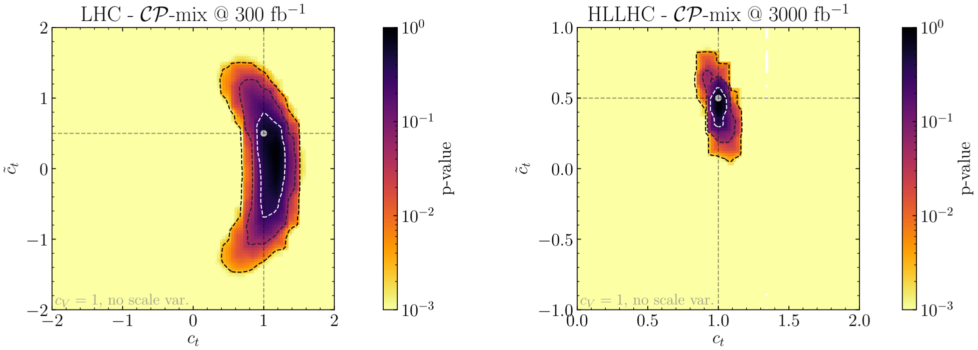
- Can also interprete results in terms of $\mathcal{CP}$-violating angle $\tan\alpha \equiv \tilde{c}_t/c_t$.

Dependence on c_V and renormalization scale



- Floating c_V and μ_R only results in slightly looser constraints
  $\rightarrow$ 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

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

- related to the minimal covariance of an estimator $\hat{\theta}$ via

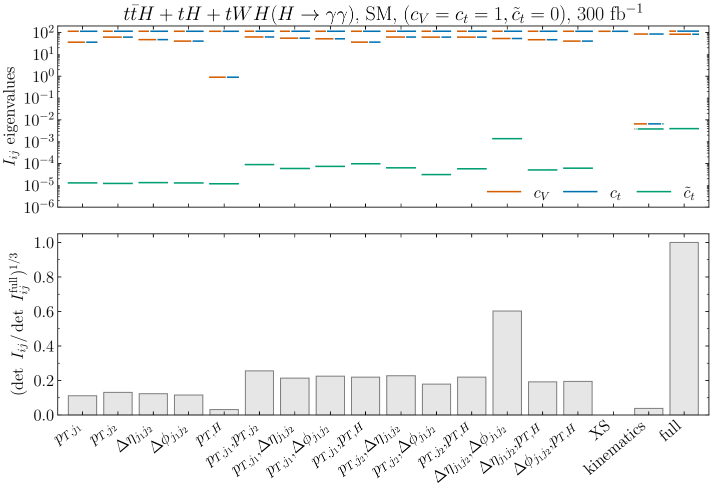
$$\mathrm{cov}(\hat{\theta}|\theta)_{ij} \geq I_{ij}^{-1}(\theta),$$

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

$$\Downarrow$$

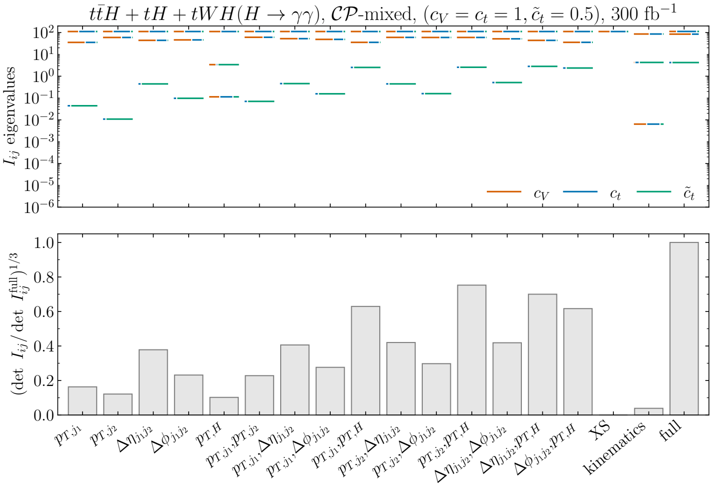
Higher information $\longrightarrow$ higher precision

Most sensitive observables — SM



- $\tilde{c}_t$ hard to constraint close to SM point without full kinematic information.

Most sensitive observables — $\mathcal{CP}$-mixed benchmark point



- Higgs p_T shape 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

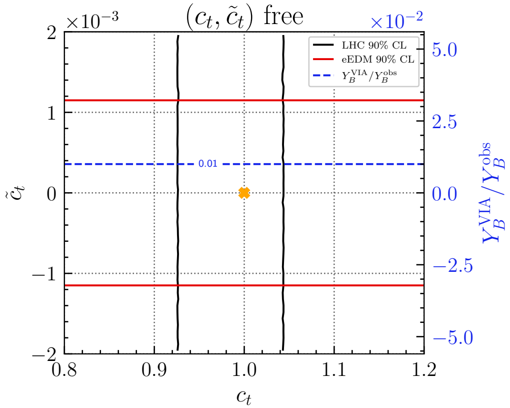
EDM:

- Several EDMs are sensitive to $\mathcal{CP}$ 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:

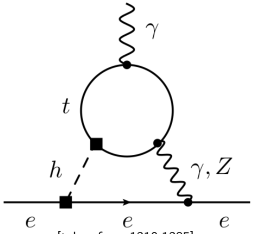
- different techniques used in the literature to calculate baryon asymmetry Y_B $\rightarrow$ large theoretical uncertainty,
- we employ vev-insertion approximation (VIA) with benchmark model for bubble wall properties maximising Y_B $\rightarrow$ values should be regarded as an upper bound,
- evaluation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

Single flavour modifications

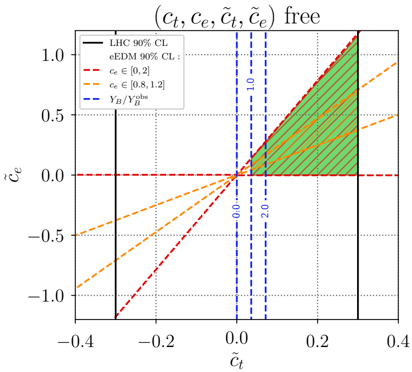


- eEDM places very strong constraints on $\mathcal{CP}$-violating top-Yukawa coupling; very similar for global modification.

Dependence on electron-Yukawa coupling



[taken from 1310.1385]



- eEDM $d_e/d_e^{\text{exp}} \approx 870 c_e \tilde{c}_t - 1082 \tilde{c}_e c_V + 610 \tilde{c}_e c_t + \ldots$,
- hardly any collider constraints on c_e and $\tilde{c}_e$,
- fine-tuned cancellation between electron and top contributions to eEDM possible,
- allows for substantial contribution of $\mathcal{CP}$-violating top-Yukawa coupling to BAU.

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Initial question

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

- Current LHC rate measurements:
  - strong constraints from $gg \to H$ and $H \to \gamma\gamma$,
  - sizable $\mathcal{CP}$-odd coupling allowed if κ_g and κ_γ 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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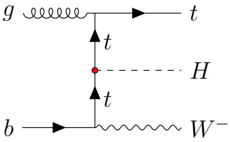
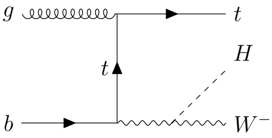
Thanks for your attention!

Appendix

Relevant processes: tWH production

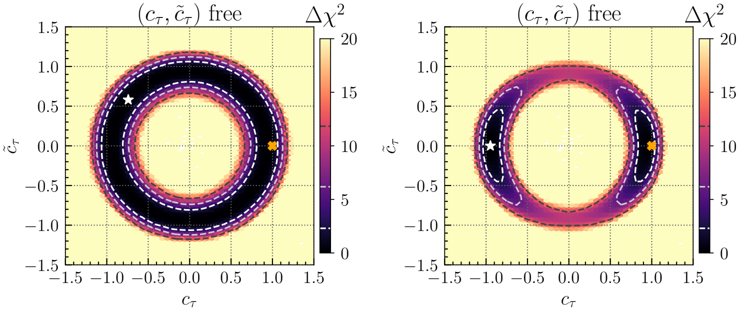




- interferes with $t\bar{t}H$ production,
- $\sigma_{t\bar{t}H}^{\text{SM}} \approx 34\sigma_{tWH}^{\text{SM}}$,
- but non-negligible contribution in $\mathcal{CP}$-odd case: $\sigma_{t\bar{t}H}^{\mathcal{CP}\text{-odd}} \approx 3.5\sigma_{tWH}^{\mathcal{CP}\text{-odd}}$,

$\rightarrow$ fully taken into account in numerical analysis.

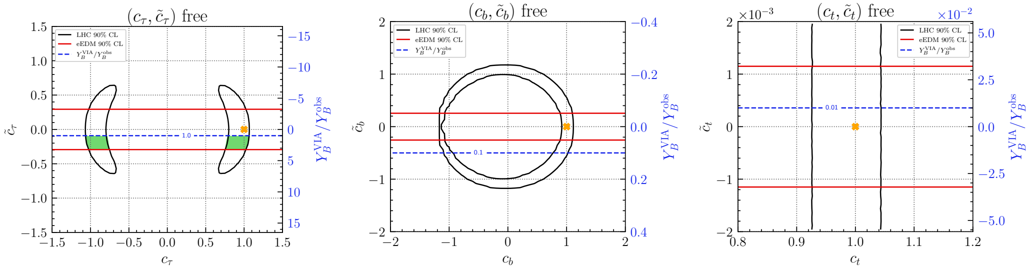
Impact of CMS $H \to \tau\tau$ $\mathcal{CP}$ analysis



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 $\tilde{c}_\tau$.

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 $\tilde{c}_f$).