Indirect $\mathcal{CP}$ probes of the Higgs–top-quark interaction: current LHC constraints and future opportunities

Henning Bahl

in collaboration with

P. Bechtle, S. Heinemeyer, J. Katzy, T. Klingl, K. Peters,

M. Saimpert, T. Stefaniak, G. Weiglein

DESY, Hamburg

DIS 2021

13.4.2021, online

Introduction

Global fit

Future sensitivity to tH production

Conclusions

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 $\rightarrow$ focus on Higgs–top-quark coupling,
- $\mathcal{CP}$ violation in the Higgs sector can be constrained by
  - demanding successful explanation of the baryon asymmetry,
  - electric dipole measurements,
  - collider constraints.

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 $\rightarrow$ focus on Higgs–top-quark coupling,
- $\mathcal{CP}$ violation in the Higgs sector can be constrained by
  - demanding successful explanation of the baryon asymmetry,
  - electric dipole measurements,
  - collider constraints.

Goal of present study

Assess LHC constraints on $\mathcal{CP}$-violating Higgs–top-quark interaction and discuss future opportunities.

Effective model

- Top-Yukawa Lagrangian (generated by $1/\Lambda^2(\Phi^\dagger\Phi)Q_L\tilde{\Phi}t_R$ operator),

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

- modified top-Yukawa coupling affects:
  - top-associated Higgs production ($t\bar{t}H$, tH, tWH)
  - Z-associated Higgs production,
  - gluon fusion,
  - $H \to \gamma\gamma$,
- additional free parameters
  - $c_V \to$ rescaling HVV couplings (tH and tWH production depend on c_V),
  - $\kappa_g \to$ rescaling $gg \to H$ ("removing" gluon fusion constraints),
  - $\kappa_\gamma \to$ rescaling $H \to \gamma\gamma$ ("removing" $H \to \gamma\gamma$ constraints),
- did not include $\mathcal{CP}$-odd HVV operators,
- SM: $c_t = 1$, $\tilde{c}_t = 0$, $c_V = \kappa_g = \kappa_\gamma = 1$.

$\to$ Assessed constraints on this model by performing a global fit.

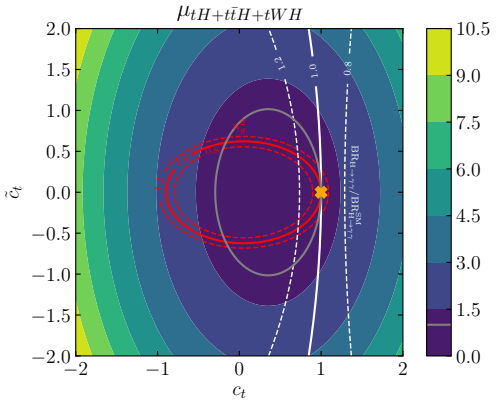
Fit setup

- Experimental input:
  - all relevant Higgs measurements:
    - Higgs signal-strength measurements,
    - ZH STXS measurements (p_T shape),
    - did not include dedicated experimental top-Yukawa $\mathcal{CP}$ analyses (difficult to reinterpret in other model),
  - if available, included all uncertainty correlations,
- theory input: derived fit formulas for all observables using `MadGraph`,
- considered four models:
  1. $(c_t, \tilde{c}_t)$ free (κ_g, κ_γ calculated as function of c_t and $\tilde{c}_t$)
  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,
- χ^2 fit performed using `HiggsSignals`.

Fit setup

- Experimental input:
  - all relevant Higgs measurements:
    - Higgs signal-strength measurements,
    - ZH STXS measurements (p_T shape),
    - did not include dedicated experimental top-Yukawa $\mathcal{CP}$ analyses (difficult to reinterpret in other model),
  - if available, included all uncertainty correlations,
- theory input: derived fit formulas for all observables using `MadGraph`,
- considered four models:
  1. $(c_t, \tilde{c}_t)$ free (κ_g, κ_γ calculated as function of c_t and $\tilde{c}_t$)
  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,
- χ^2 fit performed using `HiggsSignals`.

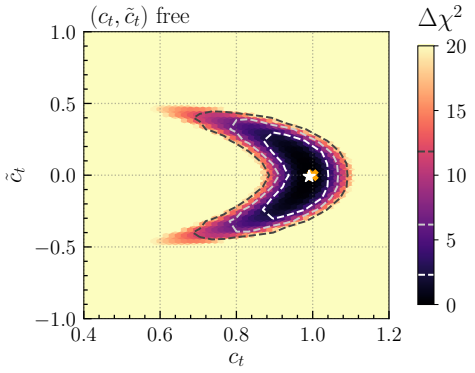
Theory input for top-associated Higgs production



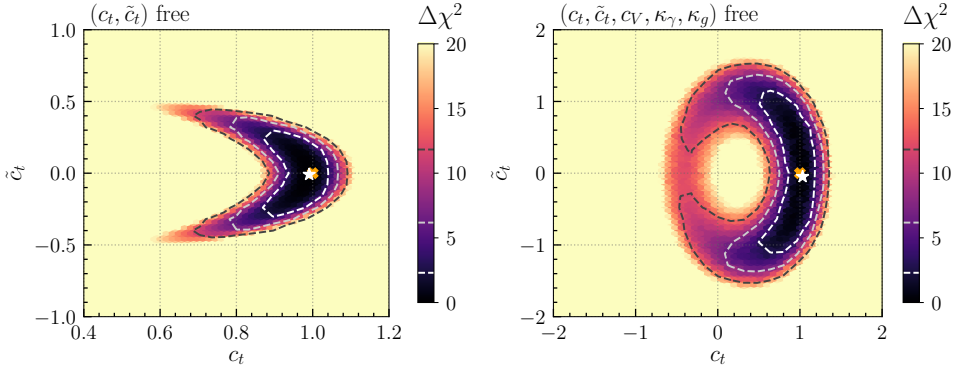
- red: κ_g^2,
- white: $\mathrm{BR}(H \to \gamma\gamma)/\mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma)$,
- $t\bar{t}H$ and tH difficult to disentangle,
- normally combination of both measured.

$\mu_{tH+t\bar{t}H+tWH} = \sigma(t\bar{t}H + tH + tWH)/\sigma_{\mathrm{SM}}(t\bar{t}H + tH + tWH)$,
$c_V = 1$

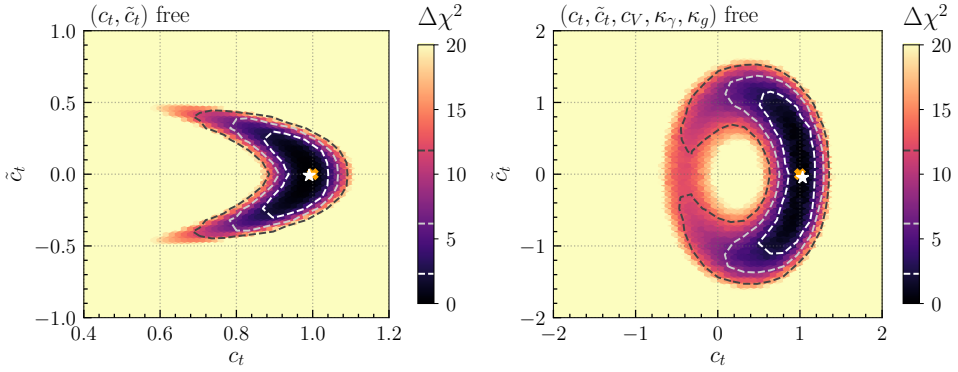
Fit results


$(c_t, \tilde{c}_t)$ free
$\Delta\chi^2$
20
15
10
5
0
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

Fit results


$(c_t, \tilde{c}_t)$ free
$\Delta\chi^2$
$\tilde{c}_t$
c_t
$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
$\Delta\chi^2$
$\tilde{c}_t$
c_t

Fit results



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

How to improve constraints in the future?

- Include more kinematic information, see ATLAS and CMS studies [2003.10866,2004.04545]
  $\rightarrow$ uses kinematic information but comparably high model dependence,
- construct $\mathcal{CP}$-odd observables
  $\rightarrow$ easy to interpret but experimentally difficult for top-associated Higgs production,
- inclusive measurements
  $\rightarrow$ comparably low model dep., but deviations could also be caused by other BSM physics.

$\Rightarrow$ Should pursue all approaches to exploit complementarity!

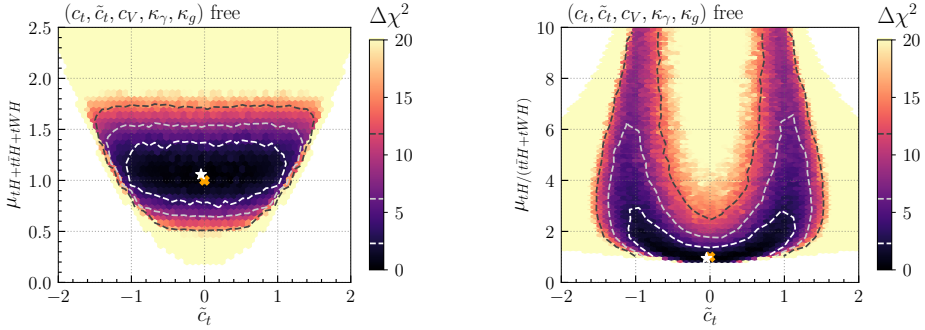
How to improve constraints in the future?

- Include more kinematic information, see ATLAS and CMS studies [2003.10866,2004.04545]
  $\rightarrow$ uses kinematic information but comparably high model dependence,
- construct $\mathcal{CP}$-odd observables
  $\rightarrow$ easy to interpret but experimentally difficult for top-associated Higgs production,
- inclusive measurements
  $\rightarrow$ comparably low model dep., but deviations could also be caused by other BSM physics.

$\Rightarrow$ Should pursue all approaches to exploit complementarity!

Future potential of inclusive measurements

- Most promising candidate: improved tH, $t\bar{t}H$ measurements.



$$[\mu_{tH/(t\bar{t}H+tWH)} = (\sigma(tH)/\sigma(t\bar{t}H + tWH))/(\sigma_{\mathrm{SM}}(tH)/\sigma_{\mathrm{SM}}(t\bar{t}H + tWH))]$$

- Measuring $tH + t\bar{t}H + tWH$ has low discrimination power regarding $\tilde{c}_t$.
- Need to disentangle tH and $t\bar{t}H + tWH$!

  However, still no sensitivity to sign of $\tilde{c}_t$...

Measuring tH production with $H \to \gamma\gamma$

Goal

Measure tH cross section in a model-independent way (i.e. without assumption on Higgs $\mathcal{CP}$ character).

- Present study: focus on $H \to \gamma\gamma$ but other decay channels could also be included.

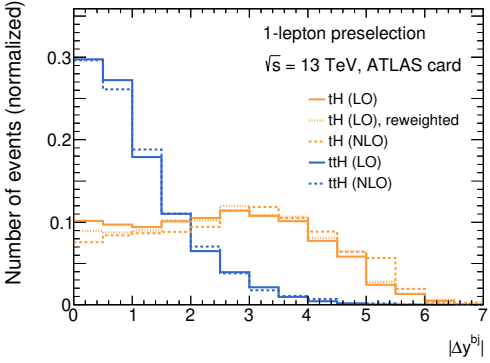
Strategy: Split events into

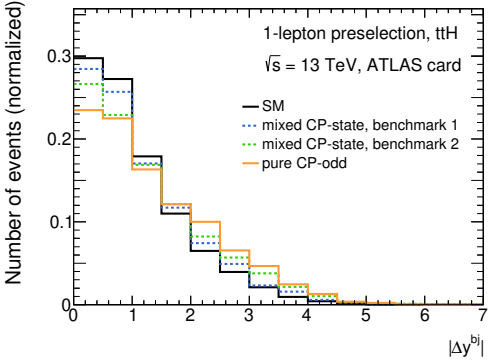
- 1-lepton category: $t\bar{t}H$, tH, tWH contribute
  $\to$ optimize for high tH fraction,
- 2-lepton category: $t\bar{t}H$, tWH contribute
  $\to$ independent measurement of $t\bar{t}H + tWH$ production.

Event simulation using `MadGraph + Pythia + Delphes` (LO + N_{jet}-reweighting).

Enhancing the tH fraction

- $N_{jet} = 2$, $N_{bjet} = 1$, $m_T^{top} < 200$ GeV

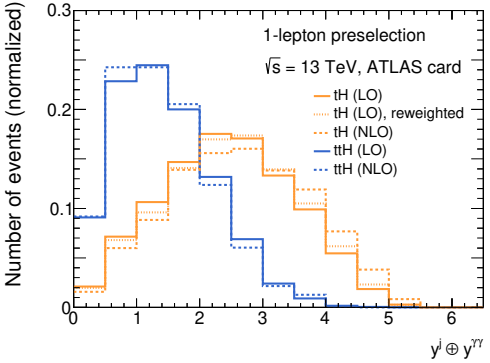


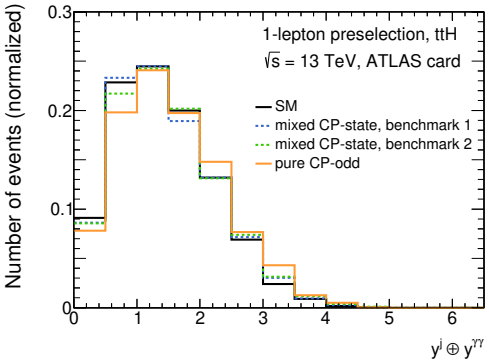


- jet-rapidity difference $|\Delta y^{bj}| > 2$
  $\rightarrow$ variation of $t\bar{t}H$ selection efficiency by $\sim 40\%$ in 1-lepton category for different $\mathcal{CP}$ hypotheses. ✗

Enhancing the tH fraction

- $N_{jet} = 2$, $N_{bjet} = 1$, $m_T^{top} < 200$ GeV





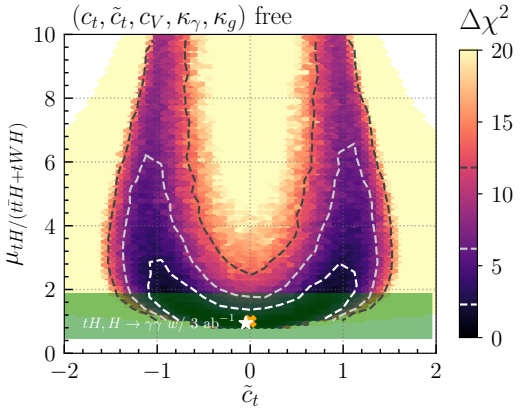
- new observable $y^j \oplus y^{\gamma\gamma} = \sqrt{(y^j)^2 + (y^{\gamma\gamma})^2} > 2$
  $\rightarrow$ variation of $t\bar{t}H$ selection efficiency by $\lesssim 2\%$ in 1-lepton category for different $\mathcal{CP}$ hypotheses. ✓

HL-LHC projection

Expected upper limit

With 3ab^{-1}, $\mu_{tH} < 2.21$ at 95% CL assuming SM data.

- 5x stronger than current strongest limit, [2004.04545]
- also stronger than most optimistic projected HL-LHC limit. [1902.00134,10.23731/CYRM-2019-007]



Conclusions

Initial question

How well can one constrain a $\mathcal{CP}$-odd component of the top-Yukawa coupling using current measurements?

$\rightarrow$ global fit to all relevant LHC data:

- Used effective Lagrangian with generalized top-Yukawa interaction,
- included total and differential cross-section measurements,
- fit results:
  - strong constraints from $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$,
  - sizable $\mathcal{CP}$-odd coupling allowed if κ_g and κ_γ are varied independently,
- future disentanglement of ttH and tH could further constrain a $\mathcal{CP}$-odd coupling,
- need to ensure that measurements do not rely on assumption on Higgs $\mathcal{CP}$ character.

Conclusions

Initial question

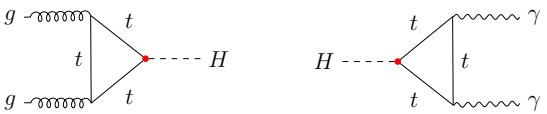
How well can one constrain a $\mathcal{CP}$-odd component of the top-Yukawa coupling using current measurements?

$\rightarrow$ global fit to all relevant LHC data:

- Used effective Lagrangian with generalized top-Yukawa interaction,
- included total and differential cross-section measurements,
- fit results:
  - strong constraints from $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$,
  - sizable $\mathcal{CP}$-odd coupling allowed if κ_g and κ_γ are varied independently,
- future disentanglement of ttH and tH could further constrain a $\mathcal{CP}$-odd coupling,
- need to ensure that measurements do not rely on assumption on Higgs $\mathcal{CP}$ character.

Thanks for your attention!

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

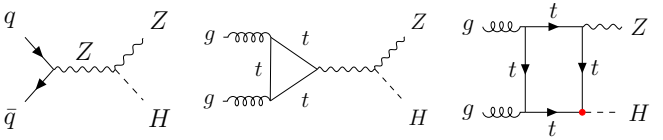


- top-Yukawa influences
  - $gg \to H$ signal strength

$$\kappa_g^2 \equiv \frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\mathrm{SM}}}\bigg|_{M_t\to\infty} = c_t^2 + \frac{9}{4}\tilde{c}_t^2 + \ldots,$$

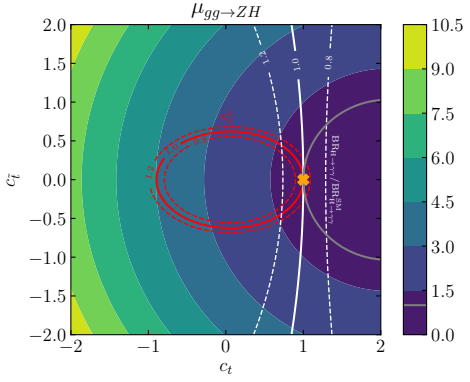
    calculate κ_g either in terms of c_t and $\tilde{c}_t$ or treat it as free parameter ($\to$ undiscovered colored BSM particles),
  - kinematic shapes not sensitive yet,
    (future potential: $\Delta\phi_{jj}$ in $gg \to H + 2j$)
- similarly $H \to \gamma\gamma$.

Relevant processes: ZH production

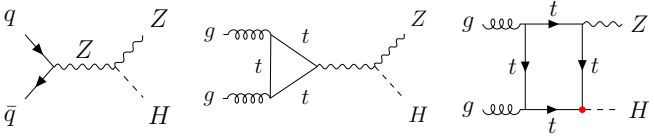


Total rate:

- 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.



Relevant processes: ZH production

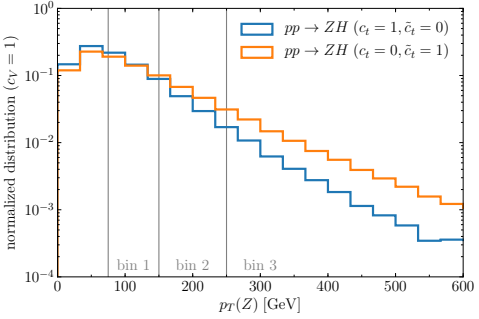


Total rate:

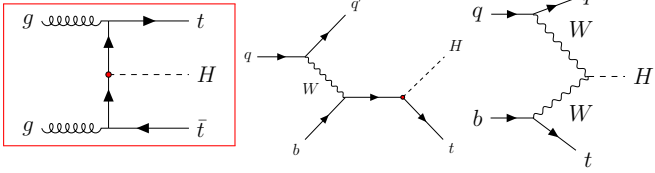
- Experimental measurement: $pp \to ZH$,
- $\sigma^{\mathrm{SM}}_{q\bar{q}\to ZH} \approx 6\sigma^{\mathrm{SM}}_{gg\to ZH}$,
- but $\sigma_{gg\to ZH}$ can be significantly enhanced.

Kinematic shapes:

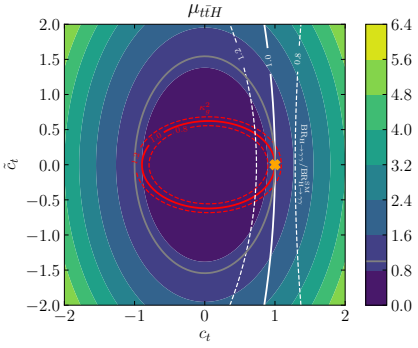
- Z p_T-shape sensitive to Higgs $\mathcal{CP}$-properties,
- use STXS bins as additional input.



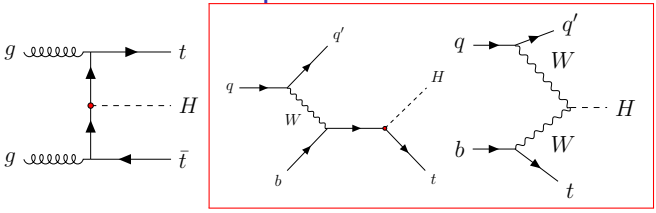
Relevant processes: *ttH* and *tH* production



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



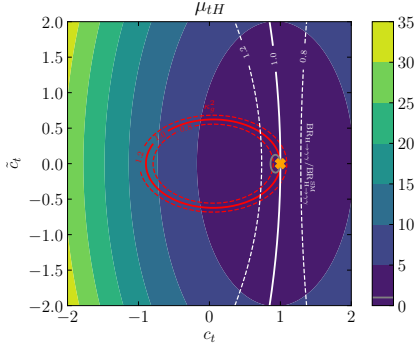
Relevant processes: ttH and tH production



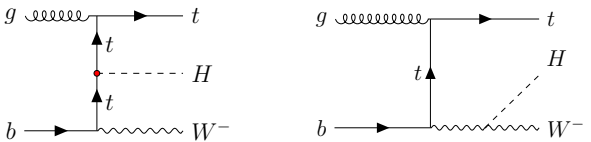
- $\sigma^{\mathrm{SM}}_{t\bar{t}H} \approx 7\sigma^{\mathrm{SM}}_{tH}$,
- but $\mathcal{CP}$-odd top-Yukawa coupling can enhance σ_{tH}.

Kinematic shape:

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



tWH production



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

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

Reasons for not including ATLAS and CMS studies

Disclaimer

Sorry if we misunderstood anything!

- CMS study:

  [2003.10866, "Measurements of $t\bar{t}H$ Production and the CP Structure of the Yukawa Interaction ..."]

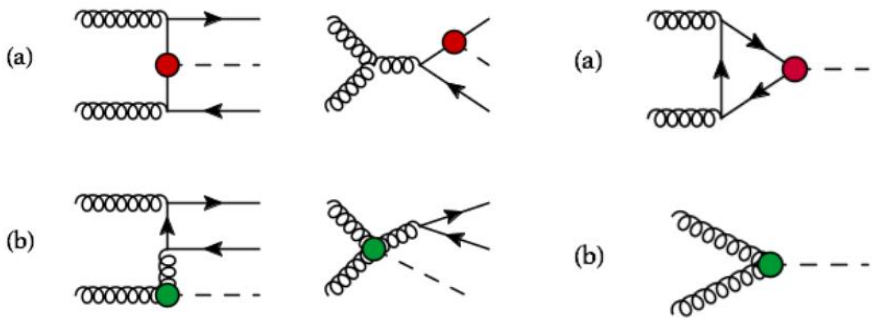
  - all Higgs production modes (apart from top-associated Higgs production) are constrained to their SM predictions $\rightarrow c_V = \kappa_g = \kappa_\gamma = 1$.
  - no two-dimensional likelihood given.

- ATLAS study:

  [2004.04545, "*CP* Properties of Higgs Boson Interactions with Top Quarks ..."]

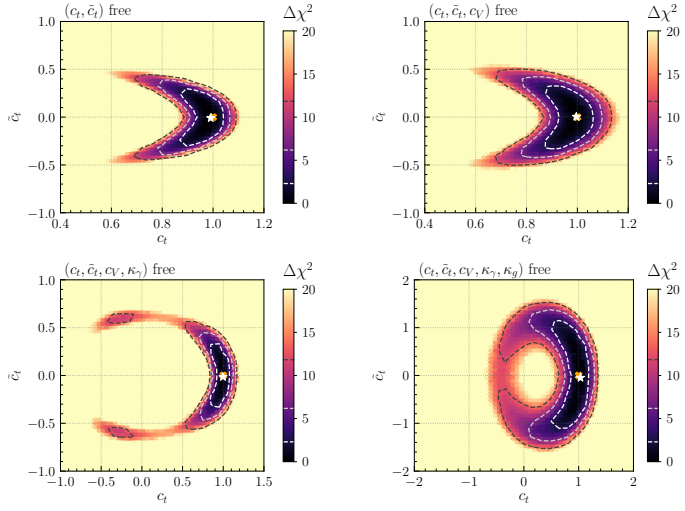
  - two setups:
    1. κ_g constrained by other measurements (ggH) excluding $t\bar{t}H$ and tH, but events generated at NLO
       $\rightarrow$ top-associated Higgs production and gluon fusion cannot be regarded as independent,
    2. κ_g and κ_γ calculated as function of c_t and $\tilde{c}_t$.
  - $c_V = 1$.

Correlation between ggH and $t\bar{t}H$ at NLO e.g. [1607.05330]

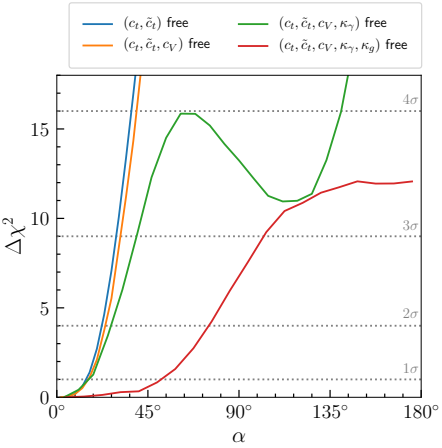


- SMEFT operators: $O_{t\varphi}$, $O_{\varphi G}$

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

Interpretation in terms of mixing angle



Influence of ZH observables

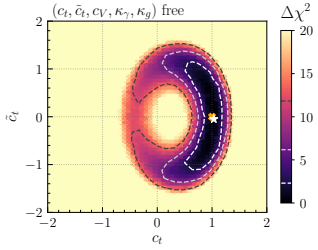
Assess influence of specific observables by successively excluding

- ZH STXS measurements ("no shape mod."),
- ZH total rate measurements ("κ_{ggZH} free").

Influence of *ZH* observables

Assess influence of specific observables by successively excluding

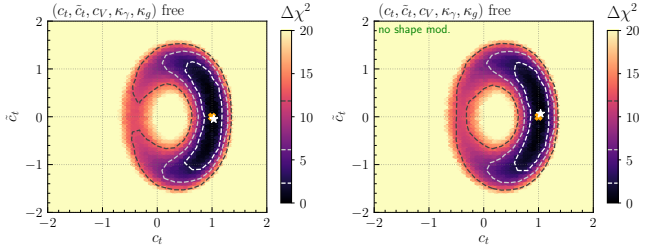
- *ZH* STXS measurements ("no shape mod."),
- *ZH* total rate measurements ("κ_{ggZH} free").



Influence of *ZH* observables

Assess influence of specific observables by successively excluding

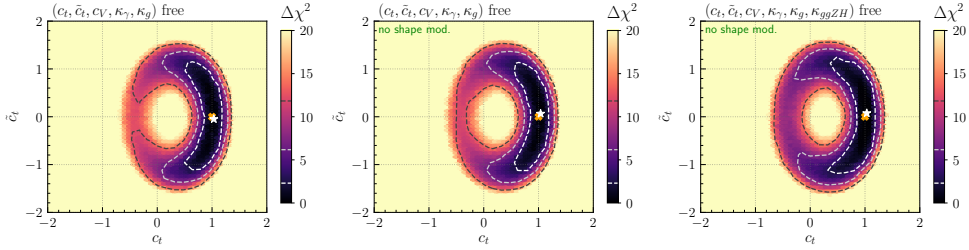
- *ZH* STXS measurements ("no shape mod."),
- *ZH* total rate measurements ("κ_{ggZH} free").



Influence of *ZH* observables

Assess influence of specific observables by successively excluding

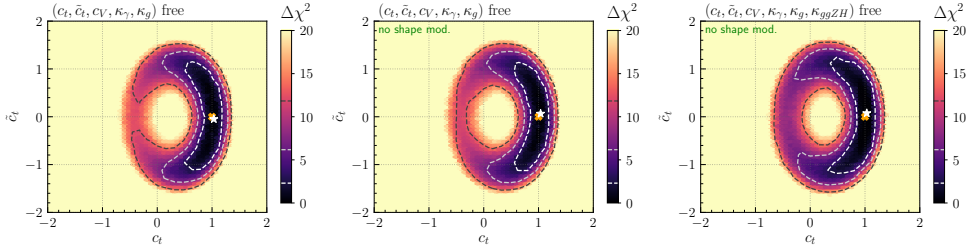
- *ZH* STXS measurements ("no shape mod."),
- *ZH* total rate measurements ("κ_{ggZH} free").



Influence of *ZH* observables

Assess influence of specific observables by successively excluding

- *ZH* STXS measurements ("no shape mod."),
- *ZH* total rate measurements ("κ_{ggZH} free").



- top-associated Higgs production most important,
- but also *ZH* production has a non-negligible impact.

Cutflow

Observable / Selection	1-lepton selection	2-lepton selection
N_γ	≥ 2	
$m_{\gamma\gamma}$	$[105 - 160]$ GeV	
$(p_{T,1}^\gamma, p_{T,2}^\gamma)$	$\geq (35, 25)$ GeV	
$(p_{T,1}^\gamma / m_{\gamma\gamma}, p_{T,2}^\gamma / m_{\gamma\gamma})$	$\geq (0.35, 0.25)$	
N_{bjet}	≥ 1	
p_T^{miss}	≥ 25 GeV	
N_ℓ	exactly 1	exactly 2 with opposite sign
$m_{\ell\ell}$	–	$[80, 100]$ GeV vetoed if same flavour
N_{jet}	exactly 2	–
N_{bjet}	exactly 1	–
m_T^{top}	< 200 GeV	–
$y^j \oplus y^{\gamma\gamma}$	> 2	–

Motivation for $y^j \oplus y^{\gamma\gamma}$

$y^j \oplus y^{\gamma\gamma} \simeq$ distance from origin in $(y^j, y^{\gamma\gamma})$ plane.