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

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in collaboration with
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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.

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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 → 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 include $\mathcal{CP}$-odd HVV operators,
- SM: $c_t = 1$, $\tilde{c}_t = 0$, $c_V = \kappa_g = \kappa_\gamma = 1$.

→ 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`.

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  4. $(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free,
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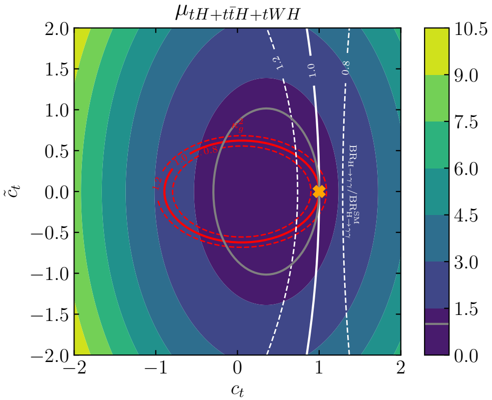
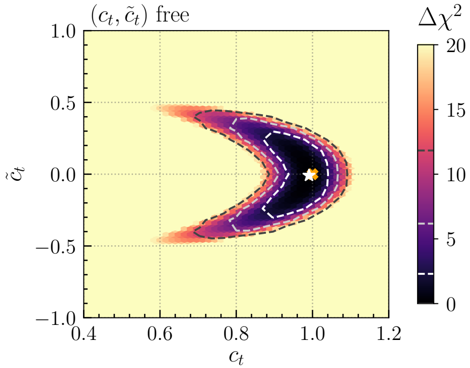
Theory input for top-associated Higgs production



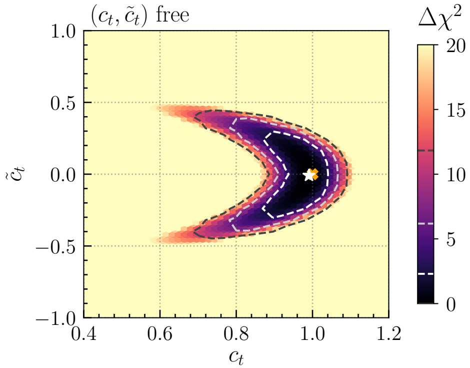
- red: κ_g^2,
- white: $\text{BR}(H \to \gamma\gamma)/\text{BR}_{\text{SM}}(H \to \gamma\gamma)$,
- $t\bar{t}H$ and tH difficult to disentangle,
- normally combination of both measured.

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

Fit results


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

Fit results



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c_t
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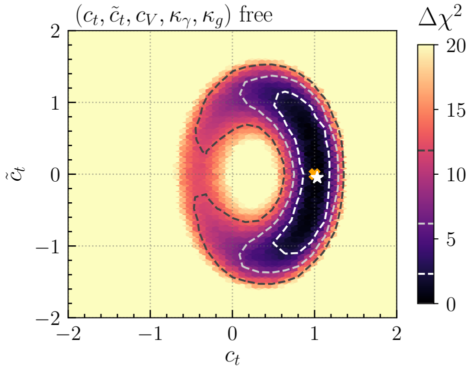
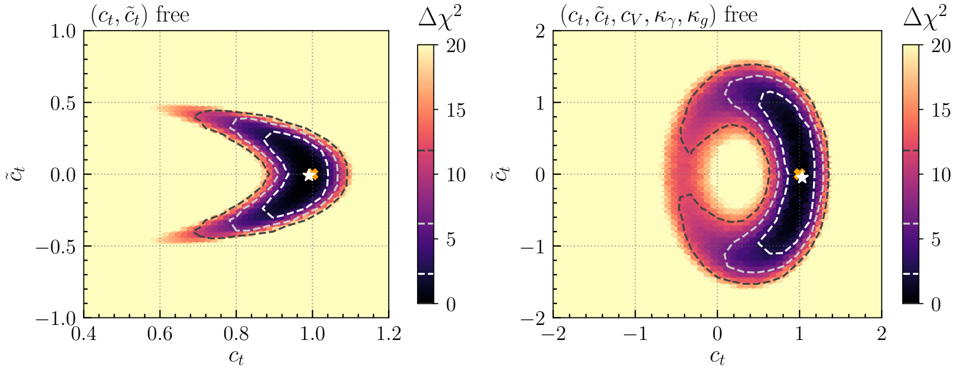


$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
$\Delta\chi^2$
c_t
$\tilde{c}_t$

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 all information but comparably high model dependence,
- 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.

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

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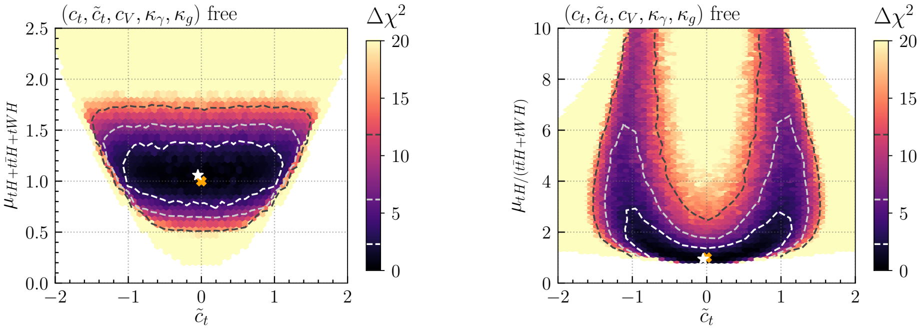
Future potential of inclusive measurements

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



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

- 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.

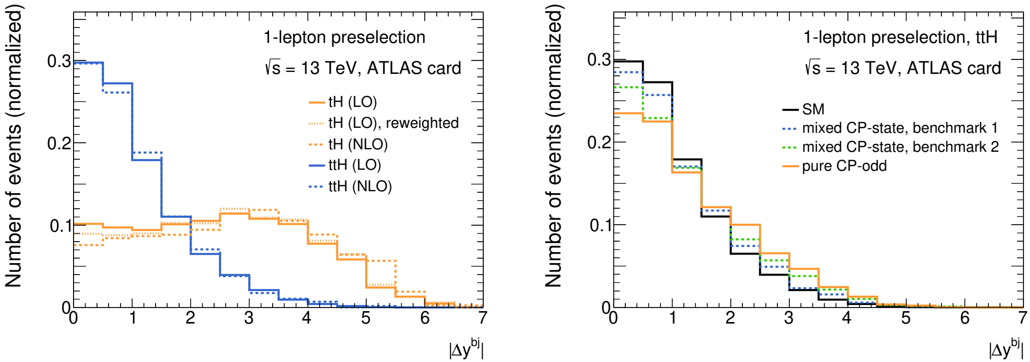
Strategy: Split events into

- 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. ✗

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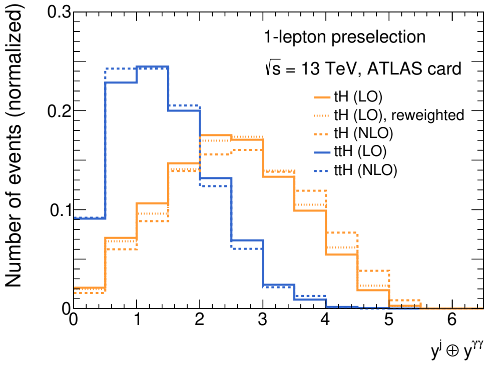
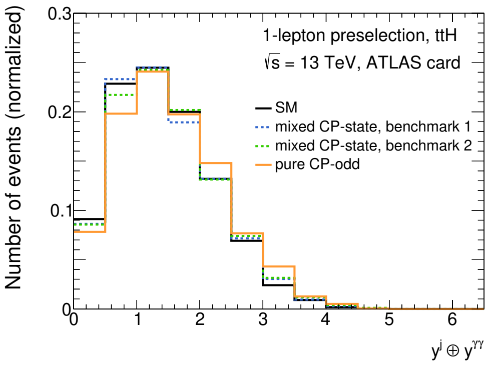




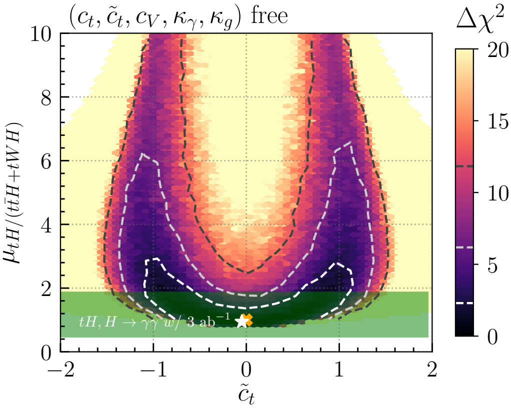
- new observable $y^j \oplus y^{\gamma\gamma} = \sqrt{(y^j)^2 + (y^{\gamma\gamma})^2} > 2$
  $\rightarrow$ variation of $t\bar{t}H$ selection efficiency by $\lesssim 2\%$ in 1-lepton category for different $\mathcal{CP}$ hypotheses. ✓

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.

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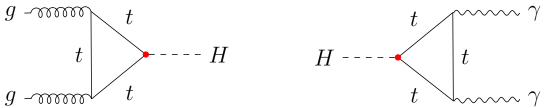
Thanks for your attention!

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

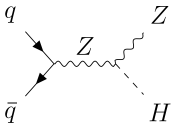


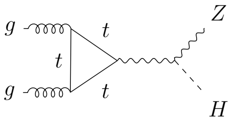
- top-Yukawa influences
  - $gg \to H$ signal strength

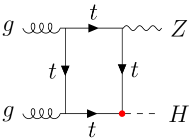
$$\kappa_g^2 \equiv \left.\frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\mathrm{SM}}}\right|_{M_t\to\infty} = c_t^2 + \frac{9}{4}\tilde{c}_t^2 + \ldots,$$

    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

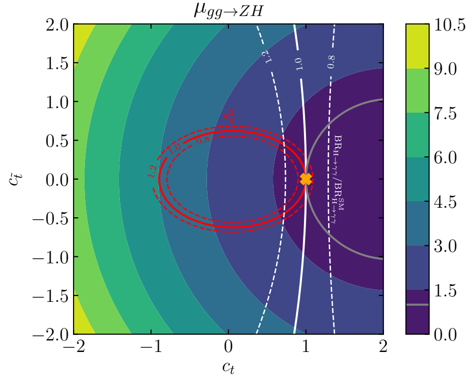




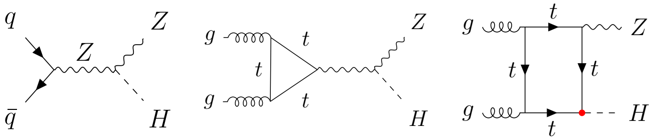


Total rate:

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



Relevant processes: *ZH* production



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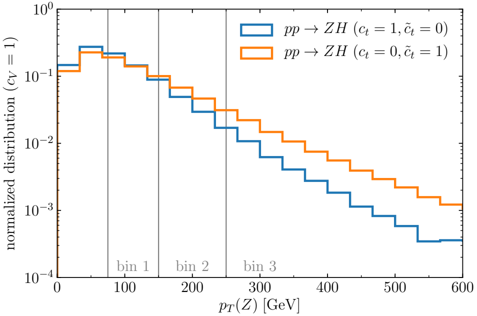
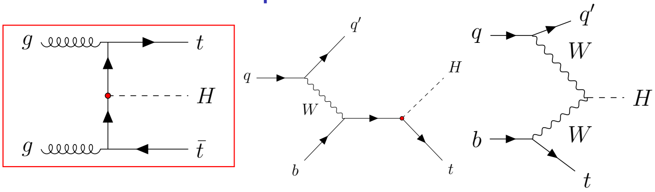
- but $\sigma_{gg\to ZH}$ can be significantly enhanced.

Kinematic shapes:

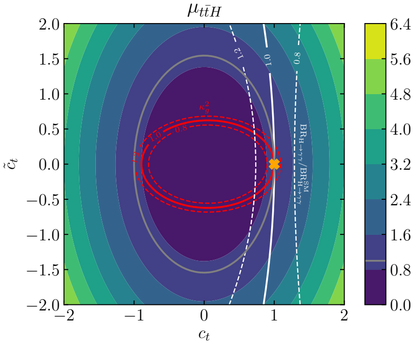
- Z p_T-shape sensitive to Higgs $\mathcal{CP}$-properties,
- use STXS bins as additional input.



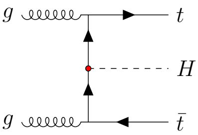
Relevant processes: ttH and tH production

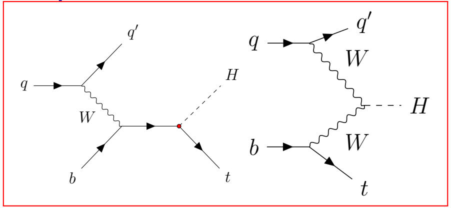


- $\sigma_{t\bar{t}H}^{\mathrm{SM}} \approx 7\sigma_{tH}^{\mathrm{SM}}$,
- but $\mathcal{CP}$-odd top-Yukawa coupling can enhance σ_{tH}.



Relevant processes: *ttH* and *tH* production

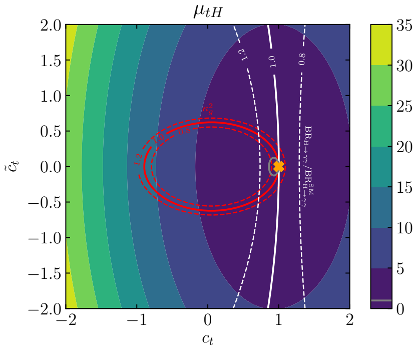




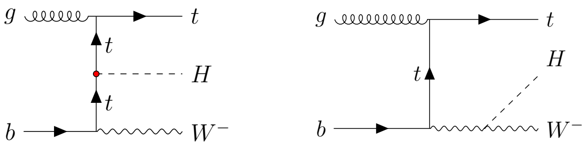
- $\sigma^{\text{SM}}_{t\bar{t}H} \approx 7\sigma^{\text{SM}}_{tH}$,
- but $\mathcal{CP}$-odd top-Yukawa coupling can enhance σ_{tH}.

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 ..."]

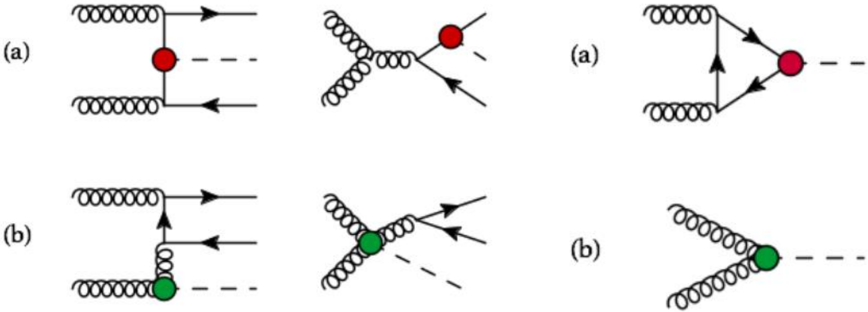
  - all Higgs production modes (apart from top-associated Higgs production) are constrained to their SM predictions $\rightarrow c_V = \kappa_g = \kappa_\gamma = 1$.
  - no two-dimensional likelihood given.

- ATLAS study:

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

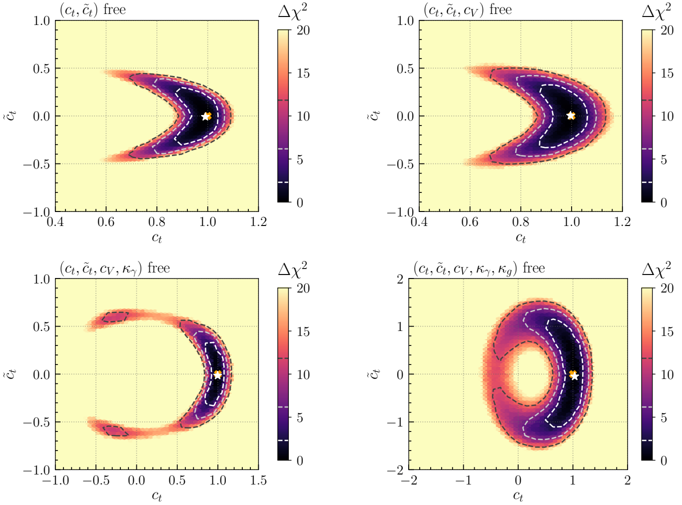
  - two setups:
    1. κ_g constrained by other measurements (ggH) excluding $t\bar{t}H$ and tH, but events generated at NLO
       $\rightarrow$ top-associated Higgs production and gluon fusion cannot be regarded as independent,
    2. κ_g and κ_γ calculated as function of c_t and $\tilde{c}_t$.
  - $c_V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

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



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

Fit results



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$\Delta\chi^2$
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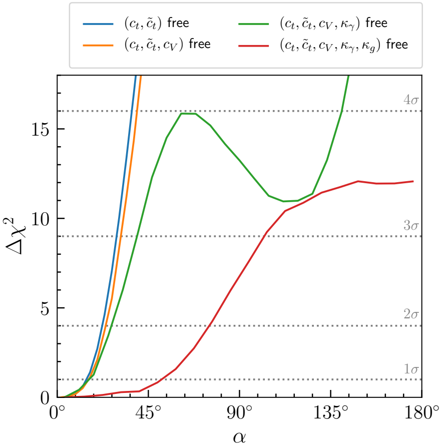
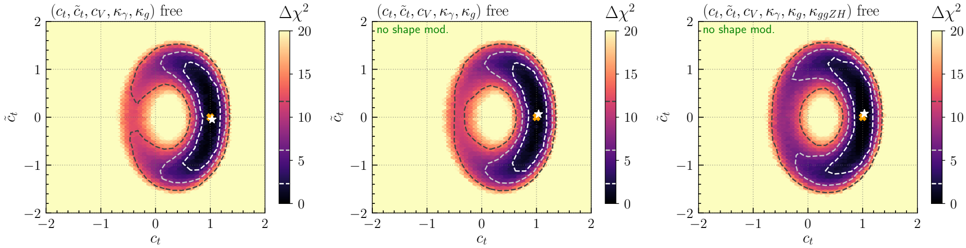
Interpretation in terms of mixing angle



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”).



- 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.