

# 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  
→ 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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  - 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),

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

- ▶ modified top-Yukawa coupling affects:
  - top-associated Higgs production ( $t\bar{t}H$ ,  $tH$ ,  $tWH$ )
  - Z-associated Higgs production,
  - gluon fusion,
  - $H \rightarrow \gamma\gamma$ ,
- ▶ additional free parameters
  - $c_V \rightarrow$  rescaling  $HVV$  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 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.

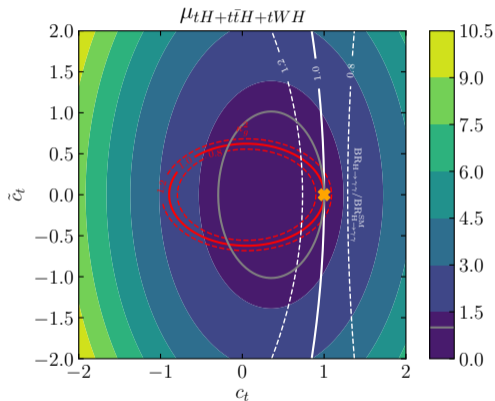
# Fit setup

- ▶ Experimental input:
  - all relevant Higgs measurements (pre ICHEP 2020):
    - ▶ Higgs signal-strength measurements,
    - ▶  $ZH$  STXS measurements ( $p_T$  shape),
  - 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
  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,
- ▶  $\chi^2$  fit performed using HiggsSignals.

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# Theory input for top-associated Higgs production



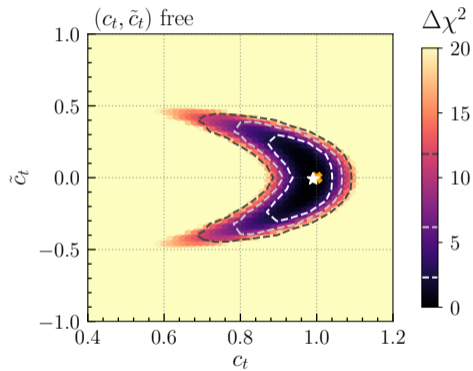
- ▶ red:  $\kappa_g^2$ ,
- ▶ white:  $\text{BR}(H \rightarrow \gamma\gamma)/\text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma)$ ,
- ▶  $t\bar{t}H$  and  $tH$  difficult to disentangle,
- ▶ normally combination of both measured.

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

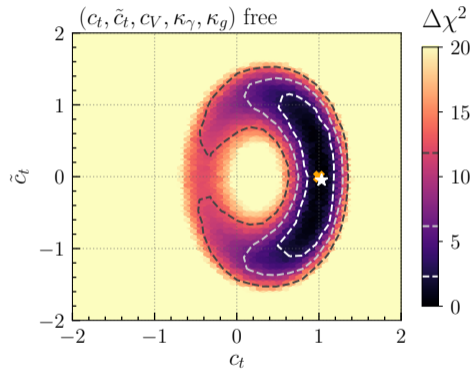
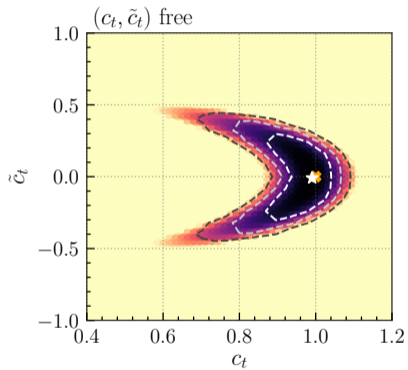
$$c_V = 1$$



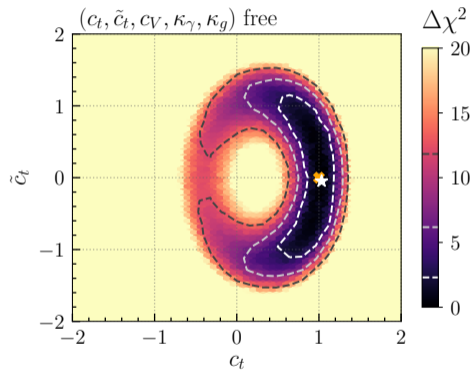
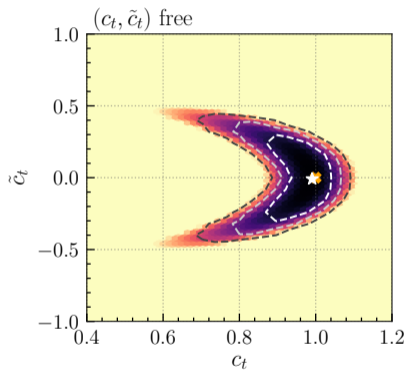
# Fit results



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## Fit results



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

## Influence of $ZH$ observables

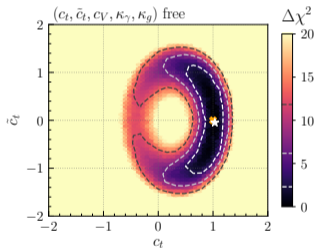
Assess influence of specific observables by successively excluding

- ▶  $ZH$  STXS measurements (“no shape mod.”),
- ▶  $ZH$  total rate measurements (“ $\kappa_{ggZH}$  free”).

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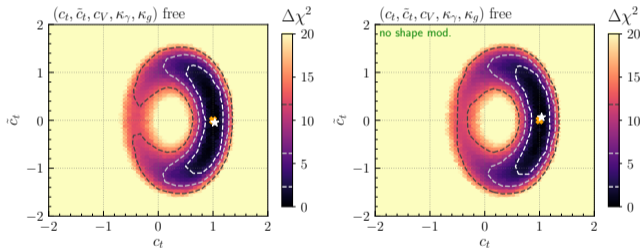
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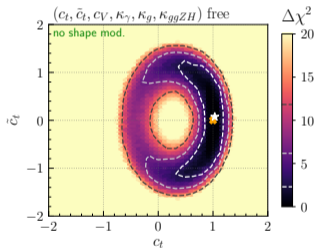
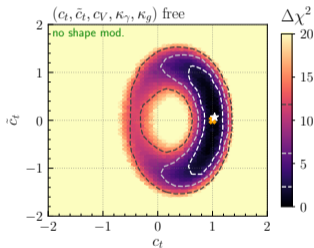
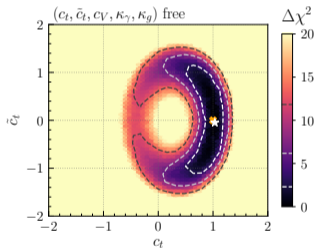
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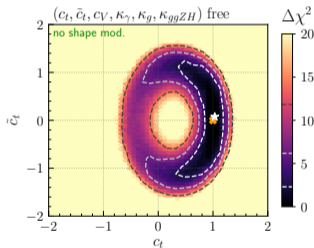
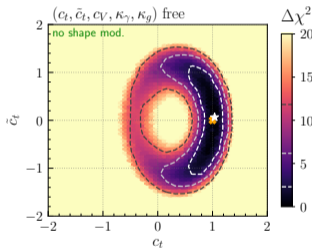
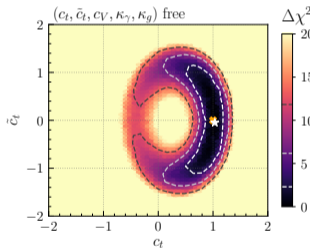
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- ▶ top-associated Higgs production most important,
- ▶ but also  $ZH$  production has a non-negligible impact.

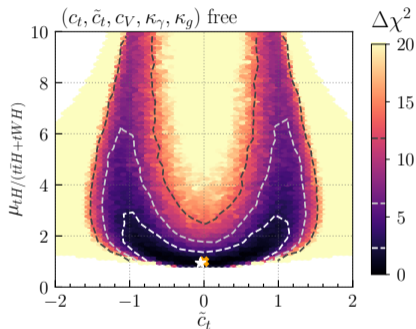
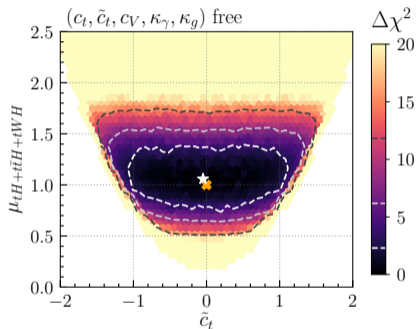


## Future potential of inclusive measurements

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

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

- ▶ 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 $H \rightarrow \gamma\gamma$

## Goal

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

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

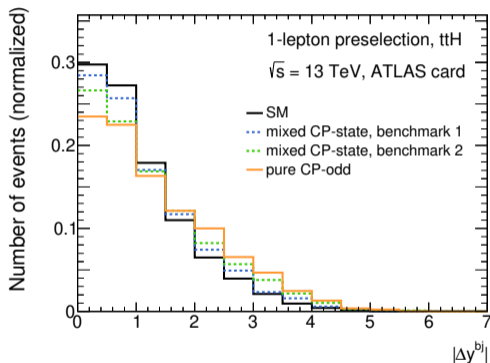
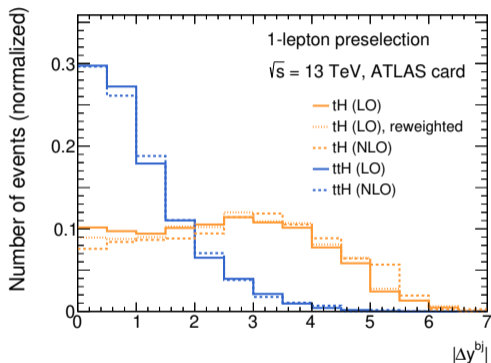
Strategy: Split events into

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

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

## Enhancing the $tH$ fraction

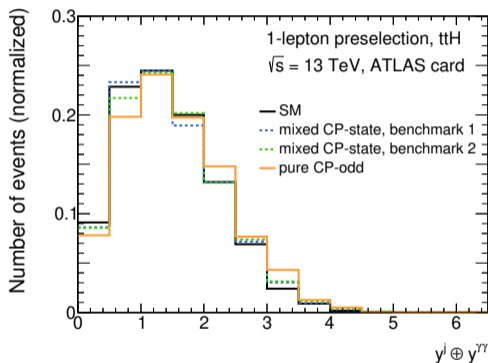
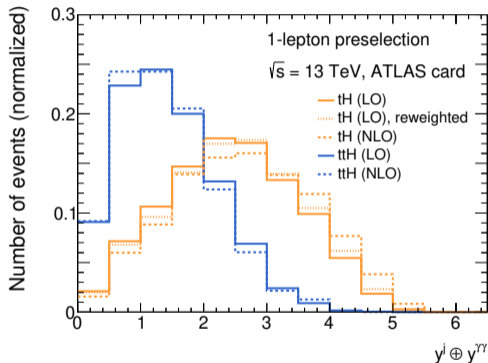
- ▶  $N_{jet} = 2$ ,  $N_{bjet} = 1$ ,  $m_T^{top} < 200$  GeV



- ▶ jet-rapidity difference  $|\Delta y^{bj}| > 2$   
→ 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  $y^j \oplus y^{\gamma\gamma} = \sqrt{(y^j)^2 + (y^{\gamma\gamma})^2} > 2$   
 → variation of  $t\bar{t}H$  selection efficiency by  $\lesssim 2\%$  in  
 1-lepton category for different  $\mathcal{CP}$  hypotheses. ✓

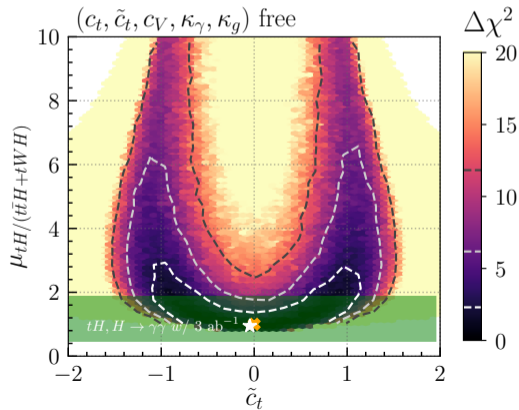
# HL-LHC projection

## Expected upper limit

With  $3\text{ab}^{-1}$ ,  $\mu_{tH} < 2.21$  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?

→ 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  $\kappa_g$  and  $\kappa_\gamma$  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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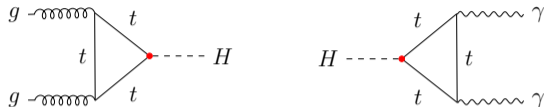
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**Thanks for your attention!**



## Relevant processes: $gg \rightarrow H$ & $H \rightarrow \gamma\gamma$



- ▶ top-Yukawa influences
  - $gg \rightarrow H$  signal strength

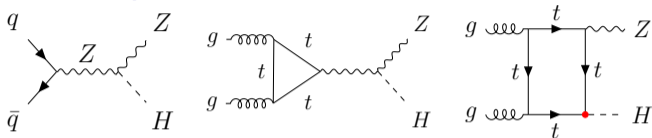
$$\kappa_g^2 \equiv \left. \frac{\sigma_{gg \rightarrow H}}{\sigma_{gg \rightarrow H}^{\text{SM}}} \right|_{M_t \rightarrow \infty} = c_t^2 + \frac{9}{4} \tilde{c}_t^2 + \dots,$$

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

- kinematic shapes not sensitive yet,  
 (future potential:  $\Delta\phi_{jj}$  in  $gg \rightarrow H + 2j$ )

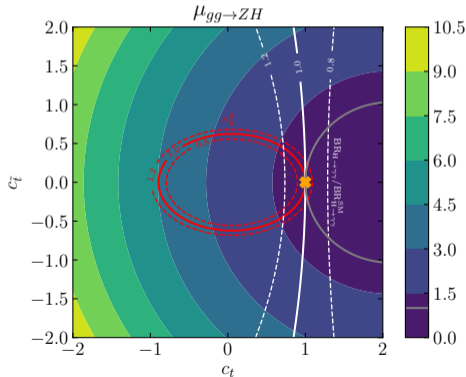
- ▶ similarly  $H \rightarrow \gamma\gamma$ .

## Relevant processes: $ZH$ production

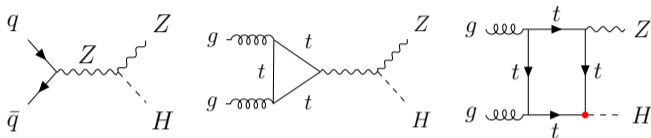


Total rate:

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



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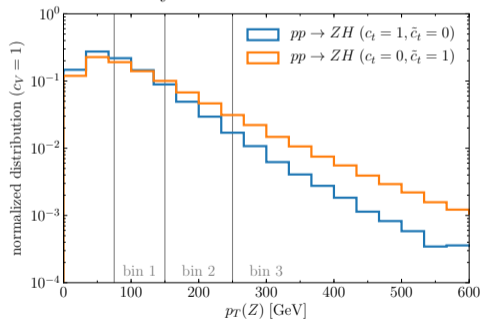


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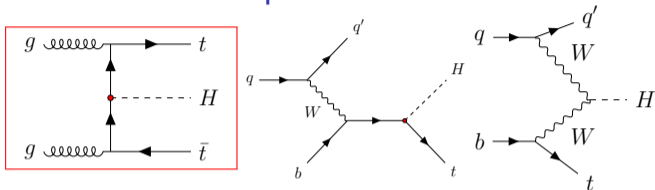
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Kinematic shapes:

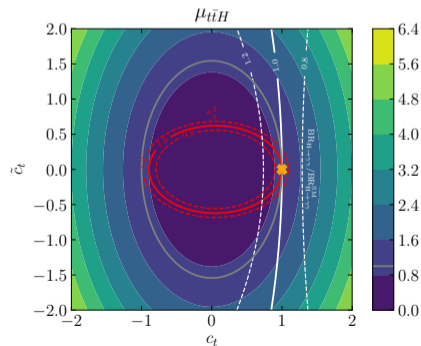
- ▶  $Z$   $p_T$ -shape sensitive to Higgs  $\mathcal{CP}$ -properties,
- ▶ use STXS bins as additional input.



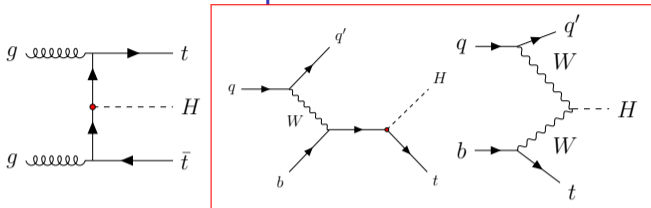
# Relevant processes: $t\bar{t}H$ and $tH$ production



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



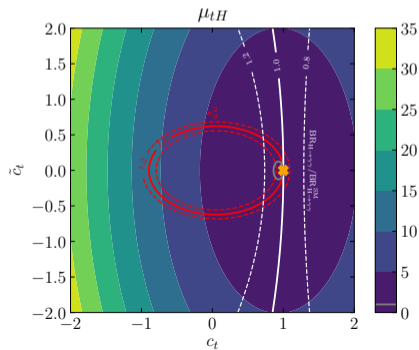
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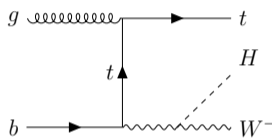
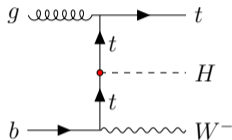
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Kinematic shape:

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



## $tWH$ production



- ▶ interferes with  $t\bar{t}H$  production,
  - ▶  $\sigma_{t\bar{t}H}^{\text{SM}} \approx 34\sigma_{tWH}^{\text{SM}}$ ,
  - ▶ 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.

# 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 ..."]

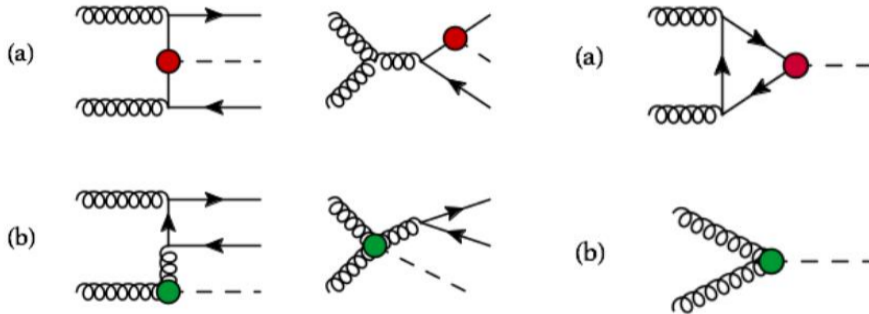
- all Higgs production modes (apart from top-associated Higgs production) are constrained to their SM predictions  $\rightarrow c_V = \kappa_g = \kappa_\gamma = 1$ .
- no two-dimensional likelihood given.

### ▶ ATLAS study:

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

- two setups:
  1.  $\kappa_g$  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.  $\kappa_g$  and  $\kappa_\gamma$  calculated as function of  $c_t$  and  $\tilde{c}_t$ .
- $c_V = 1$ .

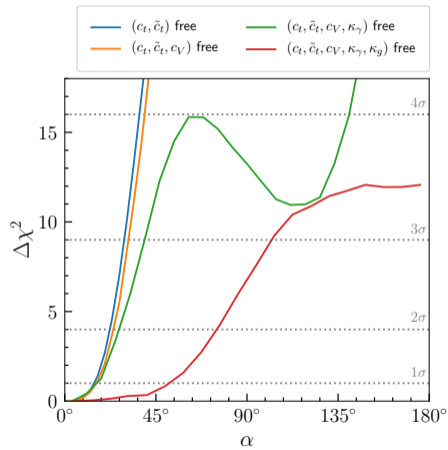
# Correlation between $ggH$ and $t\bar{t}H$ at NLO e.g. [1607.05330]



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



## Interpretation in terms of mixing angle



## Cutflow

Observable / Selection	1-lepton selection	2-lepton selection
$N_\gamma$		$\geq 2$
$m_{\gamma\gamma}$		$[105 - 160]$ GeV
$(p_{T,1}^\gamma, p_{T,2}^\gamma)$		$\geq (35, 25)$ GeV
$(p_{T,1}^\gamma/m_{\gamma\gamma}, p_{T,2}^\gamma/m_{\gamma\gamma})$		$\geq (0.35, 0.25)$
$N_{bjet}$		$\geq 1$
$p_T^{miss}$		$\geq 25$ GeV
$N_\ell$	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.

