CP-sensitive simplified template cross-sections for $t\bar{t}H$

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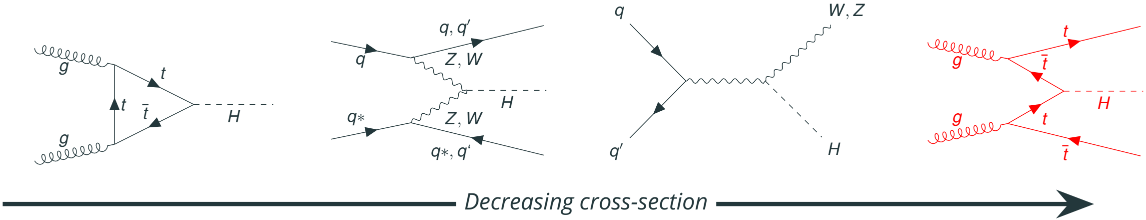
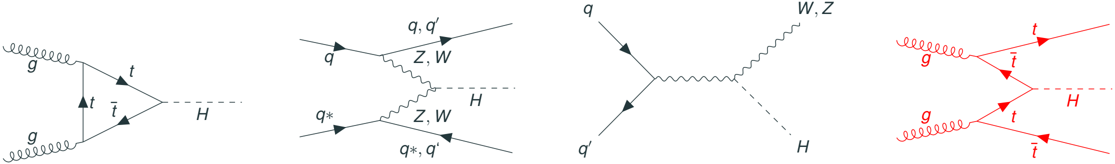
Summary

Introduction

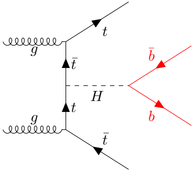
The $t\bar{t}H$ process



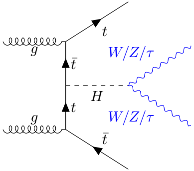


Decreasing cross-section

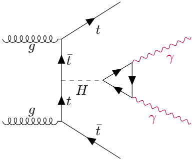
H→$b\bar{b}$



Multilepton



H→ $\gamma\gamma$



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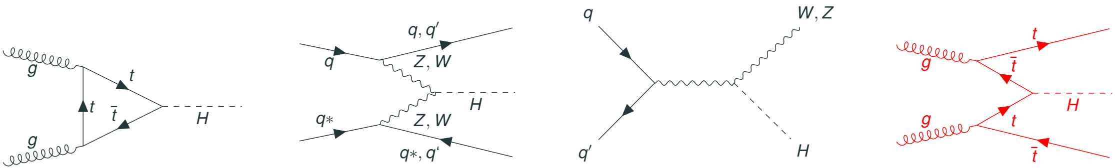

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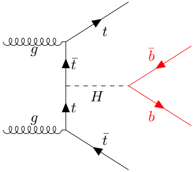
$H \to b\bar{b}$



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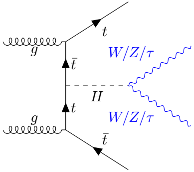
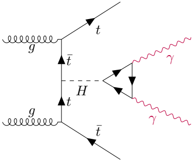


$H \to \gamma\gamma$



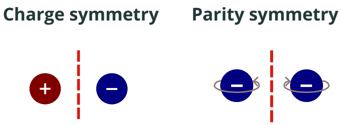
$t\bar{t}H$ published results:

- ATLAS 2018 (link), significance 6.3 σ using Run I plus partial Run II data using the three channels
- CMS 2018 (link), significance 5.2 σ using Run I plus partial Run II data using the three channels

Motivations to search for CP violation in the Higgs-Yukawa couplings

C and P symmetries

- **Charge and Parity** $\rightarrow$ important symmetries of the SM theory
- C,P and CP violated by weak interaction $\rightarrow$ allow matter, anti-matter asymmetry
- **There is not enough CP to match observed matter predominance**



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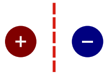
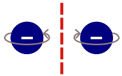
Charge symmetry



Parity symmetry



Yukawa interaction:

$$\mathcal{L}_{\text{Y.-fermion}} = -\left(\overline{\psi}^i_{\ell,L} y^\ell_{ij} \varphi \psi^j_{\ell,R} + \overline{\psi}^i_{q,L} y^u_{ij}\overline{\varphi}\psi^j_{u,R} + \overline{\psi}^i_{q,L} y^d_{ij}\varphi\psi^j_{d,R} + \dots\right)$$

- **Yukawa interactions account for fermion masses** in the SM
- Measurement of Yukawa couplings (y^k_{ij}) to fermions important probe for new physics $\rightarrow$ could behave different from SM expectations
- **Top quark** Yukawa coupling: largest coupling, order of unity

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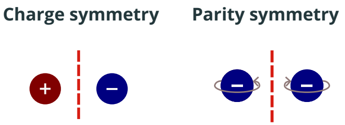

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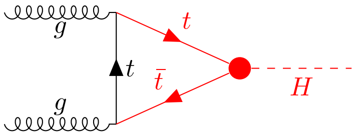

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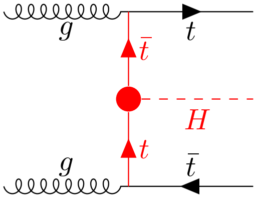
- **Top quark** Yukawa coupling: largest coupling, order of unity
- $t\bar{t}H$: **allow probe top-Higgs coupling at tree level**
- **Ideal to test possible CP violation in Yukawa interaction**



- CP parametrization in the top Yukawa coupling:

$$\mathcal{L}_{\text{Y.-top, CP}} = -\mathrm{y}_t \left\{ \bar{\psi}_t e^{i\,\alpha\gamma_5} \psi_t \right\} \varphi$$

$$\mathcal{L}_{\text{Y.-top, CP}} = -\mathrm{y}_t \left\{ \bar{\psi}_t \kappa'_t \left[\cos(\alpha) + i \sin(\alpha)\gamma_5\right] \psi_t \right\} \varphi$$

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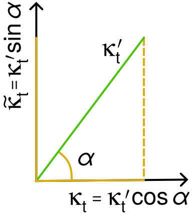

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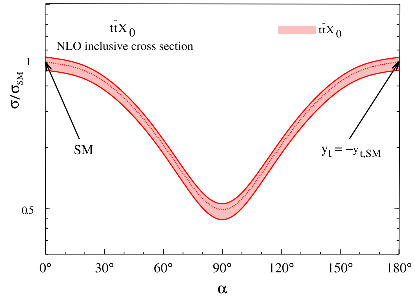

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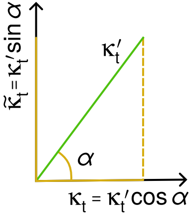
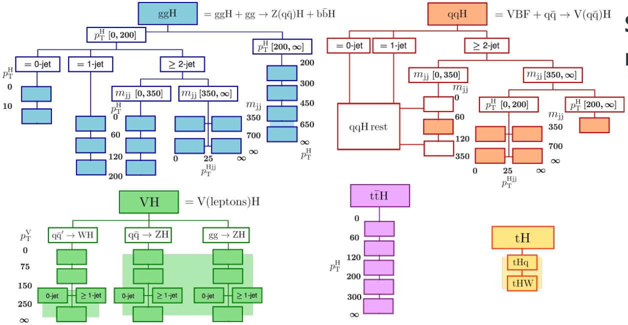
The plots set Higgs-top coupling to reproduce the SM gluon-fusion cross section for every value of α (link)



Model consequences:

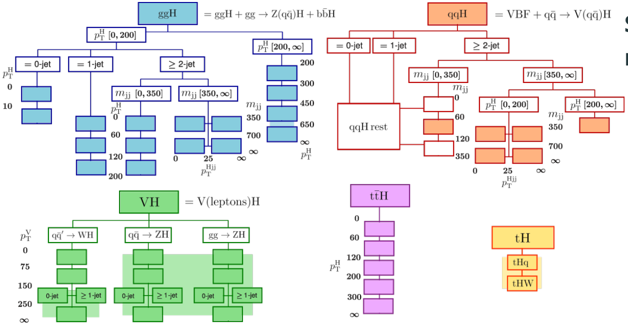
- Change in cross-section depending on CP hypothesis
- Lower angles have a behavior that is difficult to distinguish from the SM

STXS framework and current limits on CP violation in the top Yukawa coupling



Simplified template cross-section method (STXS, link):

- simplify combination between channels/measurements
- minimize the dependence on theory uncertainties
- maximize the experimental sensitivity
- isolate possible BSM effects



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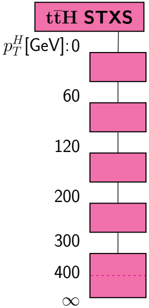
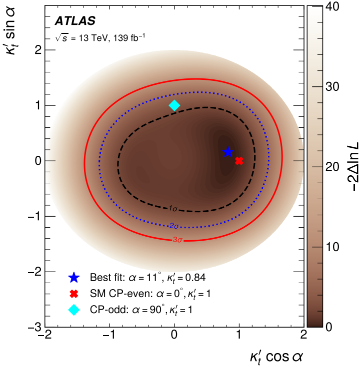
- **Goal:** developing an STXS extension targeting better tt̄H CP sensitivity
- CP-odd excluded by various studies at $4\sigma \rightarrow$ Obtained without the STXS framework
- $|\alpha| < 45^\circ \rightarrow$ decide to target 35°

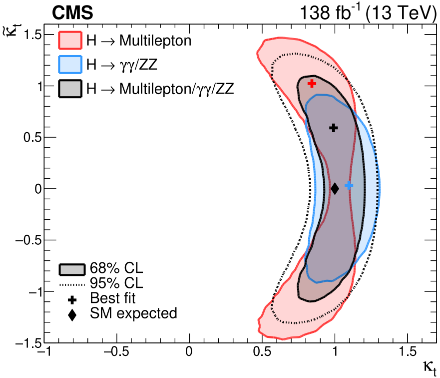


Published results for search of CP violation in $t\bar{t}H$

Methods currently in use relies on machine learning techniques, recent results started using directly CP-observables



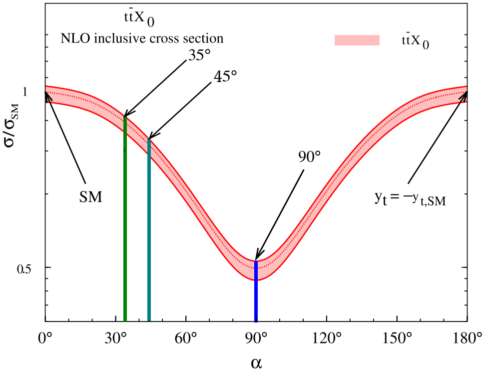
ATLAS $t\bar{t}H(H\to b\bar{b})$ (link) performed using CP-observables



CMS $t\bar{t}H$ (link), partial combination, BDT trained to separate CP-even/odd

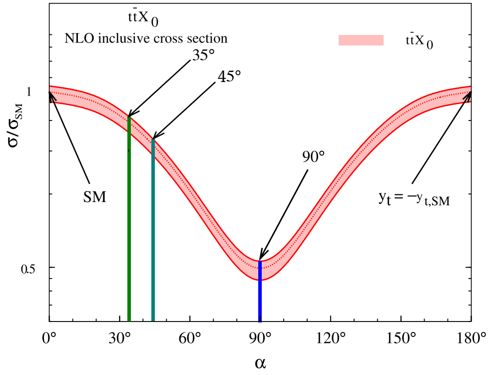
Study setup

Event generation and observables



- Generating $t\bar{t}H$ events with `MadGraph5_aMC@NLO`
- Scale factor to take into account for NLO effects
- Any CP hypothesis can be obtained as

$$N\left(\kappa_t', \alpha_t\right) = \kappa_t'^{,2}\left[N_{\mathrm{SM}} \cos^2\alpha_t + N_{\mathrm{odd}}\ \sin^2\alpha_t\right]$$



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- Studied a group of possible discriminating observables
- Assume H, t and t̄ reconstructed

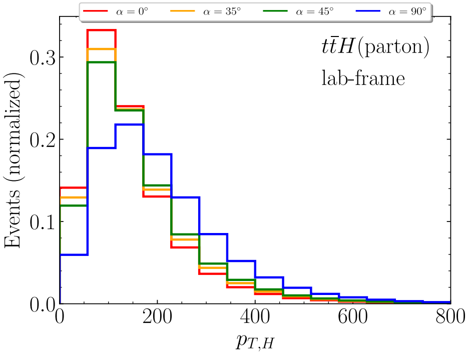
observable	definition	frame
p_T^H	-	lab, tt̄, tt̄H
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, tt̄H
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, tt̄H
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
$\cos(\theta^*)$	$\frac{\mathbf{p}_t \cdot \mathbf{n}}{\lvert\mathbf{p}_t\rvert \cdot \lvert\mathbf{n}\rvert}$	tt̄
b_1	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{p_T^t p_T^{\bar{t}}}$	all
b_2	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{\lvert\mathbf{p}_t\rvert \, \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
b_3	$\frac{p_t^x \; p_{\bar{t}}^x}{p_T^t p_T^{\bar{t}}}$	all
b_4	$\frac{p_t^z \; p_{\bar{t}}^z}{\lvert\mathbf{p}_t\rvert \, \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
ϕ_C	$\arccos\left(\frac{\lvert(\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}) \cdot (\mathbf{p}_t \times \mathbf{p}_{\bar{t}})\rvert}{\lvert\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}\rvert \, \lvert\mathbf{p}_t \times \mathbf{p}_{\bar{t}}\rvert}\right)$	H

Rest-frames considered:

- laboratory frame (**lab frame**),
- tt̄ rest frame, where $\mathbf{p}_t + \mathbf{p}_{\bar{t}} = \mathbf{0}$ (**tt̄ frame**),
- tt̄H rest frame, where $\mathbf{p}_t + \mathbf{p}_{\bar{t}} + \mathbf{p}_H = \mathbf{0}$ (**tt̄H frame**),
- H rest frame, where $\mathbf{p}_H = \mathbf{0}$ (**H frame**)

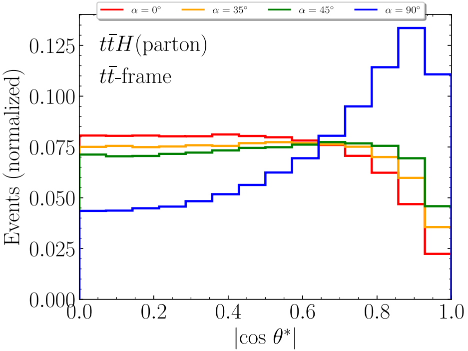
Examples of distributions at parton-level

$p_{T,H}$



Lab frame

$\cos(\theta^*) = \frac{\mathbf{p}_t \cdot \mathbf{n}}{|\mathbf{p}_t| \cdot |\mathbf{n}|}$



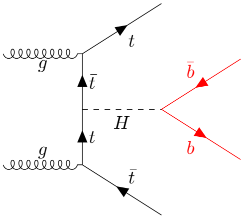
$t\bar{t}$ frame

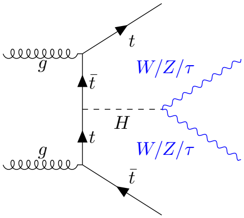
- Normalized distributions for some examples of observables
- Here the t and $\bar{t}$ kinematics is needed (no need to distinguish them)

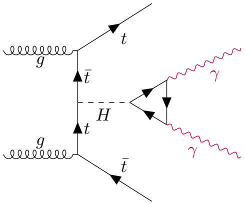
Analysis strategy

Detector effects and significance evaluation

- Channels considered: $t\bar{t}H(H\rightarrow \gamma\gamma)$, $t\bar{t}H(H\rightarrow b\bar{b})$ and $t\bar{t}H\rightarrow$ *multilepton final states*
- Took into account: acceptance / efficiency factors for event selection, smearing of the Higgs and top/antitop for reconstruction effects
- Yields validated from ATLAS/CMS results







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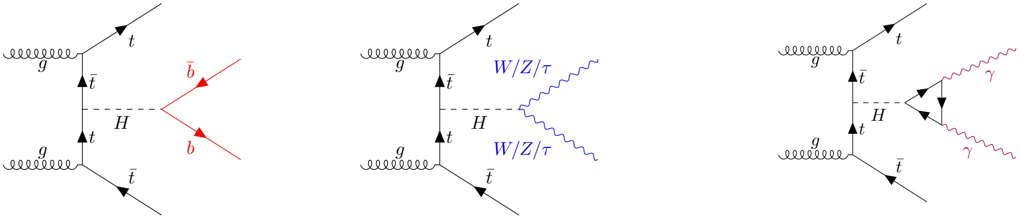

- Metric to judge the sensitivity of the various observables assuming acceptance, smearing, luminosity of 300 fb^{-1}
- Account for statistical and systematic uncertainty, in each bin σ_i is:

$$\sigma_i = \sqrt{\sigma_{sys}^2 + \sigma_{stat}^2}$$

- Define *significance* S according to link: taking n_i the SM- and m_i the BSM-$t\bar{t}H$ yield per bin

$$S = \sqrt{\sum_{i=1}^{N_{bins}} S_i} = \sqrt{2\sum_{i=1}^{N_{bins}} \left(n_i ln\left[\frac{m_i'(n_i+\sigma_i^2)}{n_i^2+m_i\sigma_i^2}\right] - \frac{n_i^2}{\sigma_i^2} ln\left[1+\frac{\sigma_i^2(m_i'-n_i)}{n_i(n_i+\sigma_i^2)}\right]\right)}$$

Initial results and optimization

Results and 2D combination

- Considered 31 different observables across four rest frames plus their two-dimensional combinations

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- The highest significance is obtained when combining $\Delta\phi_{t\bar{t}}$ and b_4 in the lab frame
- **Decided to use $p_{T,H}$ with a second observable** (to build on the existing STXS setup) $\rightarrow$ combined values similar to the best combination $\Delta\phi_{t\bar{t}}$ plus b_4

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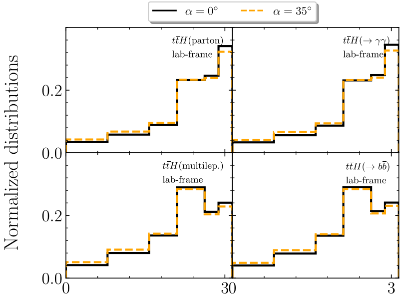
$\alpha_t = 35°$ $t\bar{t}H$ @ $\mathcal{L} = 300$ fb^{-1} 14 (6 × 6) bins for 1d (2d) dist. **comb. w/ $p_{T,H}^{lab}$**

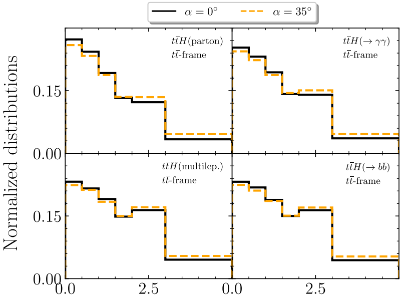
	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
$H \rightarrow \gamma\gamma$	1.51	1.56	1.54	1.56	1.55	1.52	1.55	1.48	1.5	1.51	1.58	1.59	1.5	1.58	1.51
Multilep.	0.53	0.69	0.9	0.89	0.87	0.73	0.69	0.54	0.52	0.45	0.77	0.8	0.48	0.82	0.56
$H \rightarrow b\bar{b}$	0.35	0.43	0.52	0.52	0.51	0.45	0.44	0.38	0.36	0.29	0.47	0.49	0.3	0.5	0.38
Combined	1.64	1.76	1.86	1.87	1.85	1.75	1.75	1.62	1.63	1.61	1.82	1.84	1.6	1.85	1.65

Best pairs & Optimized binning

- Best results from combining p_T^H with $\Delta\phi_{t\bar{t}}^{\mathrm{lab}}$, b_1^{lab}, $\Delta\eta_{t\bar{t}}^{t\bar{t}}$, $\theta^{*,t\bar{t}}$, b_2^{lab}.
- For these pairs: binning optimization performed targeting six bins to determine best pair, distributions presented below (comparing SM scenario with $\alpha = 35°$)



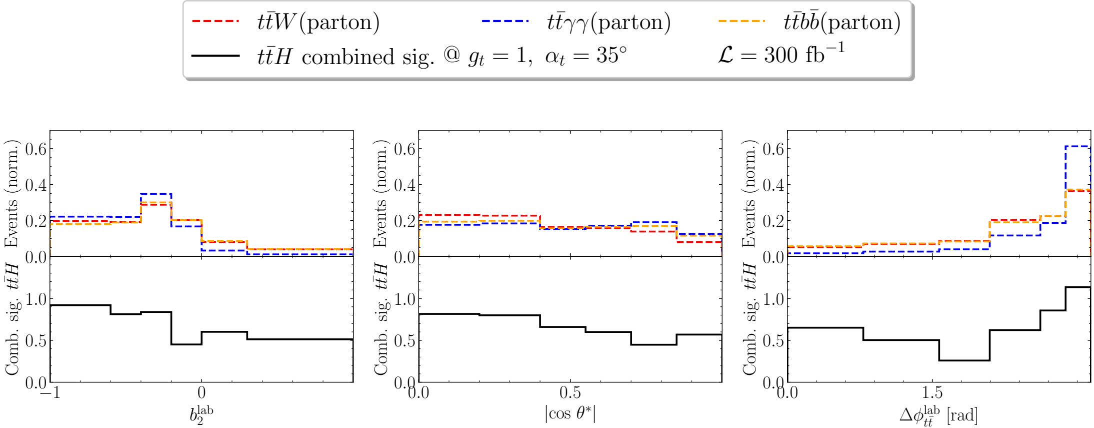
$\Delta\phi_{t\bar{t}}^{\mathrm{lab}}$: [0, $\pi/4$, $\pi/2$, $2\pi/3$, $5\pi/6$, $11\pi/12$, π]



$\Delta\eta_{t\bar{t}}^{t\bar{t}}$: [0, 0.5, 1, 1.5, 2, 3, 5]

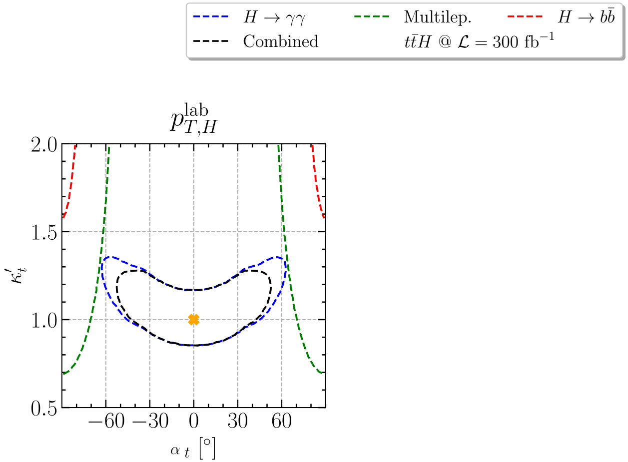
background distribution study

- Sensitivity of the observables in the various bins compared to the background distributions for the most sensitive observables
- Observables where the significance could have been over-estimated due to low signal over background ratio are excluded
- Example on three observables of background shapes



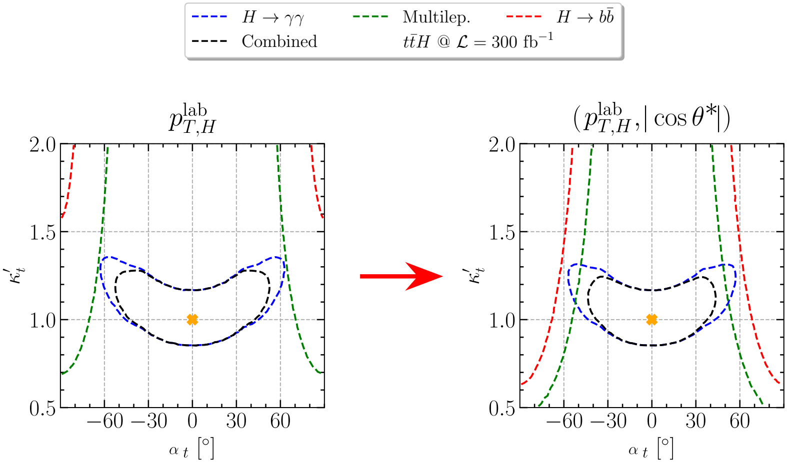
Final result and proposed STXS extension

Expected sensitivity to CP: STXS extension with $|\cos\theta^*|$



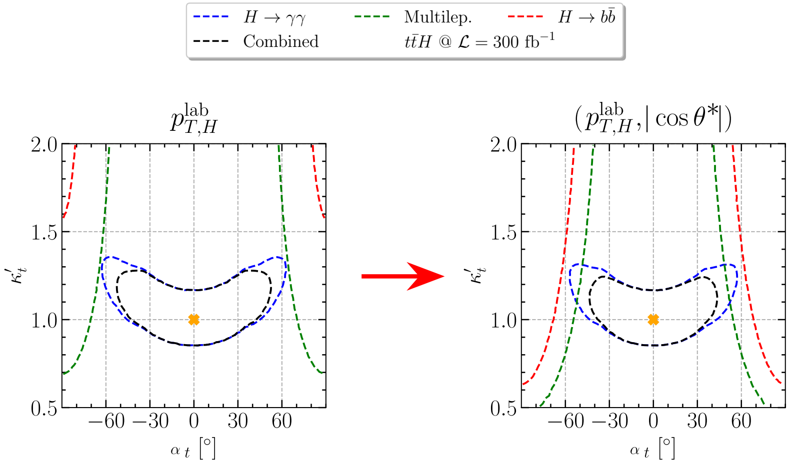
- Expected exclusion limits considering our model use 300 fb^{-1}

Expected sensitivity to CP: STXS extension with $|\cos\theta^*|$



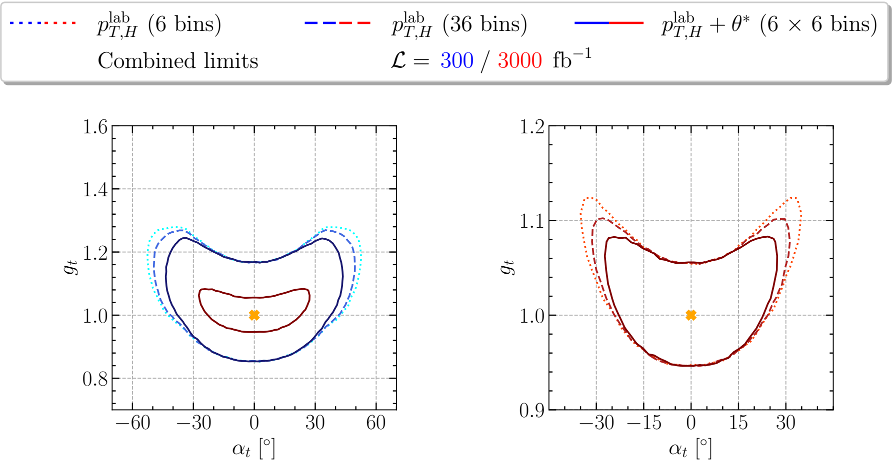
- Expected exclusion limits considering our model use 300 fb^{-1}
- Final limit at $\kappa_t' = 1$, $|\alpha| \lesssim 36°$ at 68% CL $\to$ **12% better with respect to not using** $|\cos\theta^*|$

Expected sensitivity to CP: STXS extension with $|\cos\theta^*|$



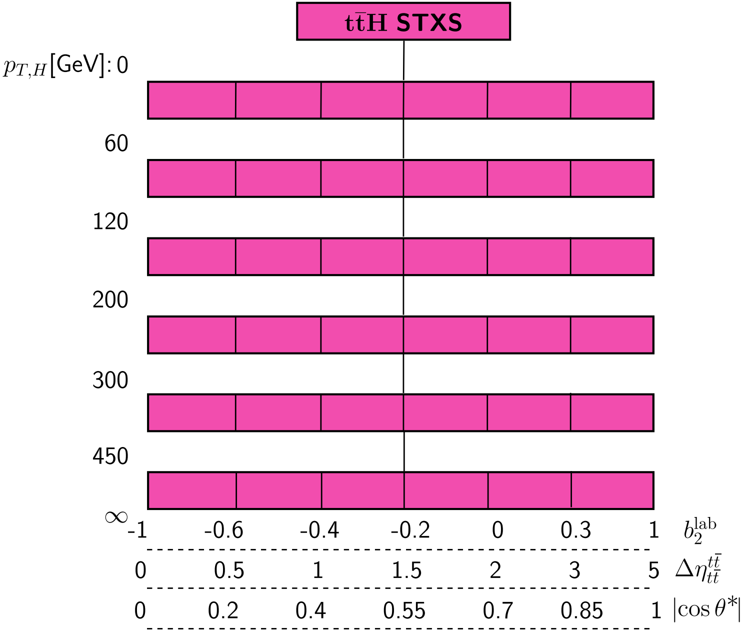
- Expected exclusion limits considering our model use 300 fb^{-1}
- Final limit at $\kappa_t' = 1$, $|\alpha| \lesssim 36°$ at 68% CL $\to$ **12% better with respect to not using** $|\cos\theta^*|$
- Maximum improvement of **40% at** $\kappa_t' = 1.24$
- Results are similar combining $p_{T,H}$ with b_2^{lab} and $\Delta\eta_{t\bar{t}}^{t\bar{t}}$

Expected exclusion limit at High-Luminosity LHC



- constraints in the (g_t, α) plane for (blue) $\mathcal{L} = 300 fb^{-1}$ and (red) $\mathcal{L} = 3000 fb^{-1}$ at the 95 % CL using the one-dimensional $p_{T,H}$ distribution
- Evaluation using 6 (dotted line) and 36 (dashed line) bins and the two-dimensional $(p_{T,H}, |\cos\theta^*|)$ distributions (solid line, 6 × 6 bins)
- $\mathcal{L} = 3000 fb^{-1}$ also presented with the $\mathcal{L} = 300 fb^{-1}$ contour

Extended proposition for STXS in $t\bar{t}H$



Conclusion

Recap and outlook

Recap

- We presented a study to extend STXS targeting CP in $t\bar{t}H$ using three channels
- The sensitivity based on 2 suitable variables is similar to that of a multivariate analysis
- Our sensitivity study shows that b_2^{lab}, $\Delta\eta_{t\bar{t}}^{t\bar{t}}$, and $|\cos\theta^*|$ are similarly good 2nd variables, in combination with $p_{T,H}$
- Up to 40% improvement in some area of the phase space

Recap

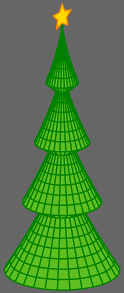
- We presented a study to extend STXS targeting CP in $t\bar{t}H$ using three channels
- The sensitivity based on 2 suitable variables is similar to that of a multivariate analysis
- Our sensitivity study shows that b_2^{lab}, $\Delta\eta_{t\bar{t}}^{t\bar{t}}$, and $|\cos\theta^*|$ are similarly good 2nd variables, in combination with $p_{T,H}$
- Up to 40% improvement in some area of the phase space

Outlook

- The full study is **published: link**
- To implement the proposal $\rightarrow$ parton level top quark definition needs to be added to the STXS framework

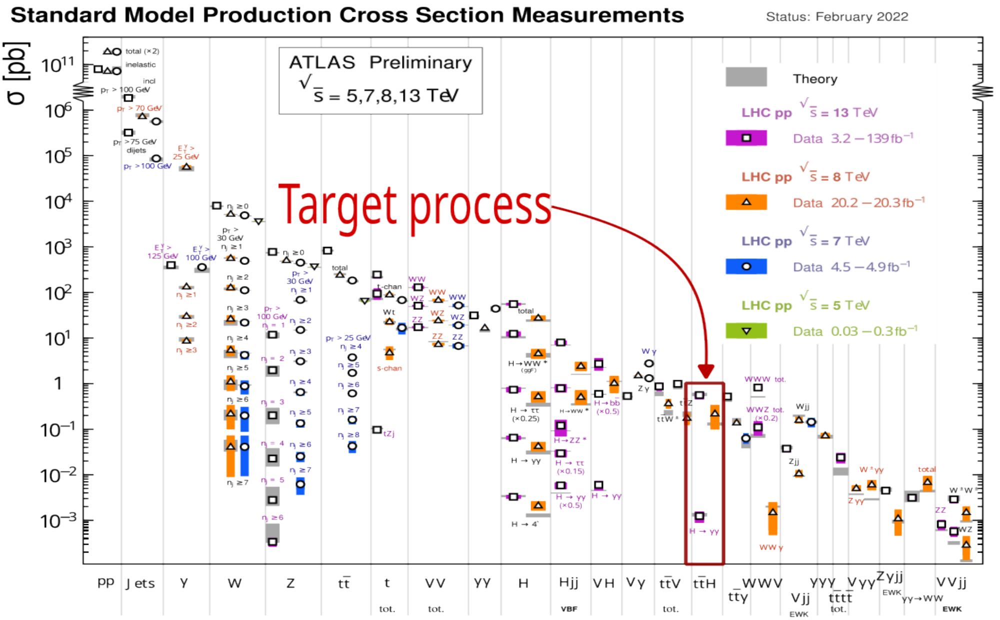
Thank you for your attention

and happy holidays !!



BACKUP

$t\bar{t}H$ in the Standard Model

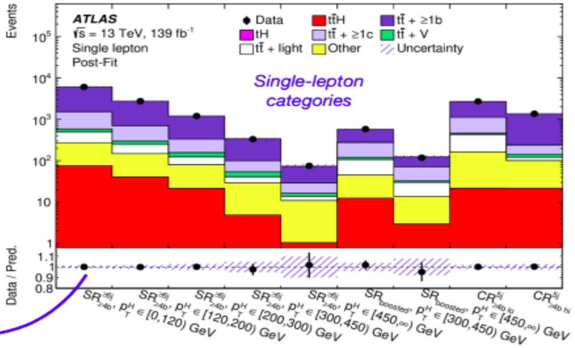


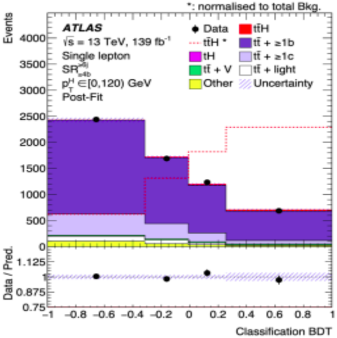
tt̄H (H→bb)

JHEP 06 (2022) 97

Analysis Strategy (at 139 fb^{-1})

- Results in the STXS formalism; **5 STXS Higgs p_T bins**
- Two main analysis channels; **single-lepton** or **dilepton**
- Signal/control regions defined by number of jets, b-tagged jets
  - Additional **boosted Higgs** categories for single-lepton





- Different MVAs used for reconstructing Higgs boson candidate and event classification
- Large irreducible background mainly from **tt+≥1b** constrained by dedicated Control regions (CRs)

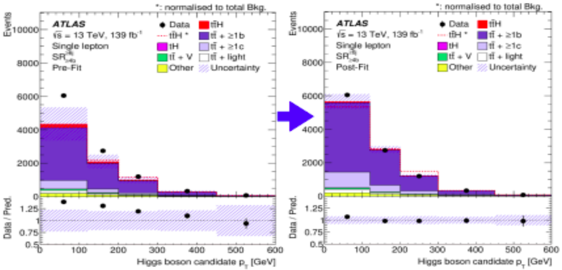
From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

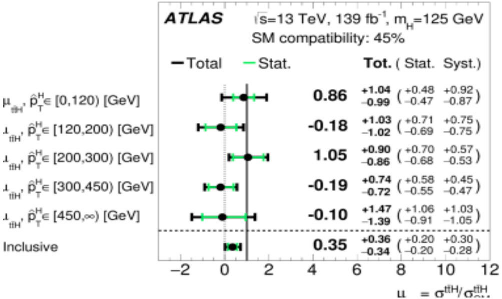
$t\bar{t}H$ ($H \rightarrow bb$)

JHEP 06 (2022) 97

Background modeling

- **tt+bb** background modelled with 4 flavour-scheme NLO QCD accuracy
- Main shape systematic uncertainties: Initial and final state radiation, parton shower, NLO matching, relative fractions of tt+heavy flavor components
  - Additional uncertainty to account for mis-modeling observed in reconstructed $p_{T,\text{higgs}}$





- **Inclusive results:**

$$\mu = 0.35 \pm 0.20\,(\text{stat.})\,{}^{+0.30}_{-0.28}\,(\text{syst.}) = 0.35^{+0.36}_{-0.34}$$

Z= 1.0σ (2.7σ exp.)
(139 fb⁻¹)

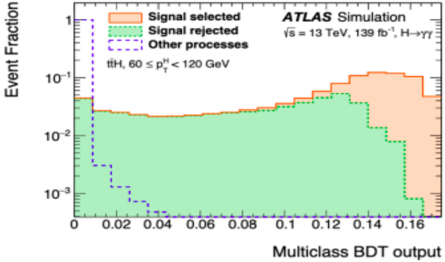
- Measured μ for five separate $p_{T,\text{higgs}}$ bins
- Sensitivity dominated by large theoretical uncertainties on irreducible tt+≥1b background

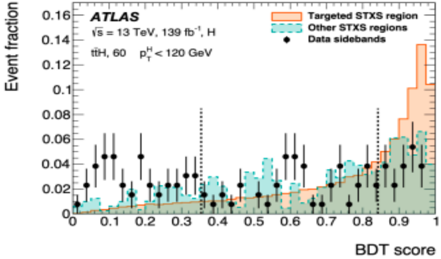
From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

$t\bar{t}H/tH$ ($H \rightarrow \gamma\gamma$)

Analysis Strategy (at 139 fb-1)

- targets $t\bar{t}H/tH$ production along w/other Higgs productions through **Simplified Template Cross Sections (STXS)** formalism where cross-section is measured as a function of truth p_{TH}
- In total 45 STXS regions defined
  - based on targeted production, Higgs p_T and number of jets





STXS category assignment:

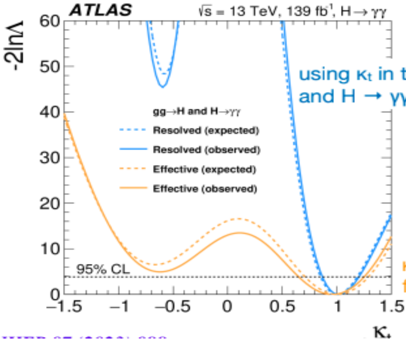
- Multi-classifier BDT sensitive to particular STXS regions + additional binary BDT trained to distinguish signal from background
- $tHqb$ class divided into two sub-classes using a neural network to distinguish between κ_t = 1 and κ_t = -1, and further categorization done to separate signal from background events

From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

$t\bar{t}H/tH$ ($H\to\gamma\gamma$)

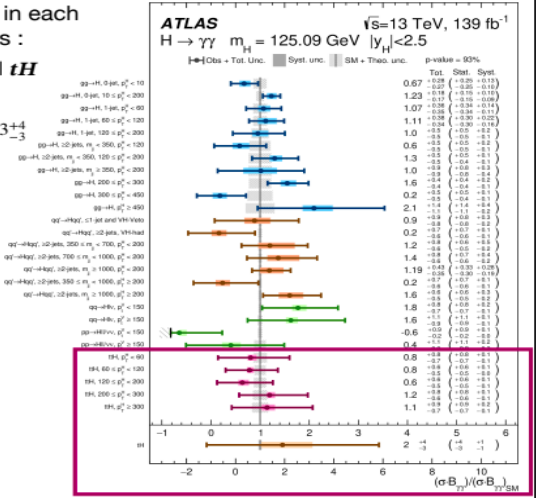
- Results for **STXS** parameters in each of the 28 phase-space regions :
  - 5 $t\bar{t}H$ p_T bins and additional *tH* category (p_T inclusive)
- **Inclusive:** $\mu_{t\bar{t}H} = 0.89^{+0.32}_{-0.30}$, $\mu_{tH} = 3^{+4}_{-3}$

- Interpretation of the results in **κ-framework**; sensitivity to sign of κ_t thanks to tH categories → **$\kappa_t < 0$** excluded at **2.2σ**



using κ_t in the ggF and $H\to\gamma\gamma$ loops

κ_g and κ_γ fixed to the SM prediction



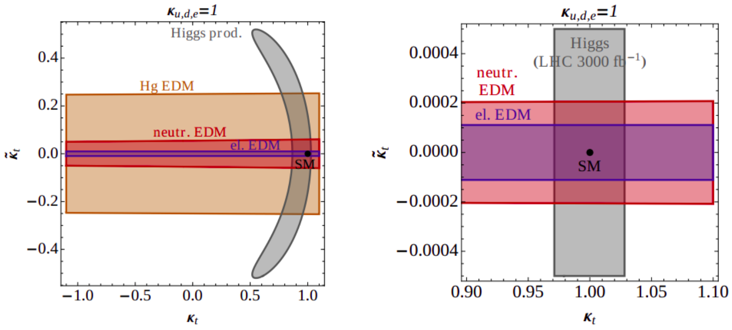
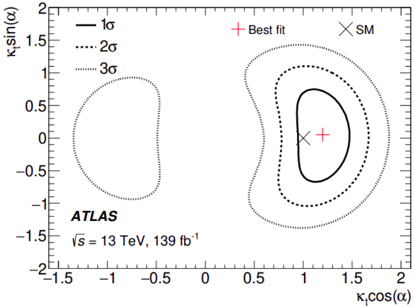


Figure 2. Left: Present constraints on κ_t and $\tilde{\kappa}_t$ from the electron EDM (blue), the neutron EDM (red), the mercury EDM (brown), and Higgs physics (gray). Right: Projected future constraints on κ_t and $\tilde{\kappa}_t$, see text for details.

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

where $f = t, b, \tau$ and $y_f = \sqrt{2} m_f / v$ is the SM Yukawa coupling with m_f the fermion mass and $v \simeq 246\text{GeV}$ the electroweak symmetry breaking vacuum expectation value of the Higgs field. The couplings $\tilde{\kappa}_f$ are CP violating, while κ_f parametrize CP-conserving NP (see link)

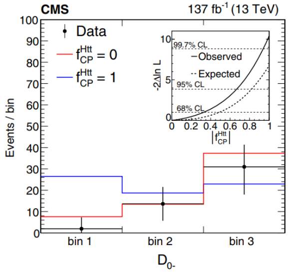
$t\bar{t}H$, H $\rightarrow \gamma\gamma$ results CP

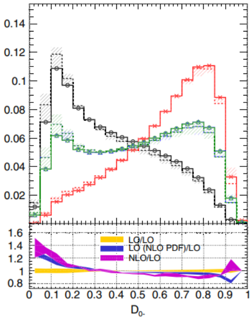


ATLAS analysis (PRL 125, 061802):

1. train BDT to separate $t\bar{t}$H from background (BKG Discriminant)
2. BDT trained to separate CP-even from CP-odd couplings (CP Discriminant)

CP-odd excluded with 3.9σ, $|\alpha| >$ 43 at 95% CL



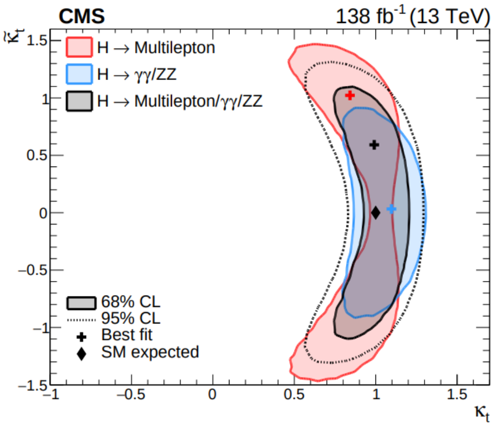


CMS analysis (PRL 125, 061801):

- Same strategy using MVAs to separate BKGs and CP-odd from CP-even
- Use of the parametrization:

$$f_{CP}^{t\bar{t}H} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{ sign}\left(\tilde{\kappa}_t / \kappa_t\right).$$

- Observed $f_{CP}^{t\bar{t}H} = 0.00 \pm 0.33$ at 95% and pure CP-odd coupling excluded at 3.2σ.



- Similar methodology in multilepton (CP-odd excluded at $> 2\sigma$) and $H \rightarrow VV \rightarrow 4\ell$ channels (CP-odd excluded at 3.1σ) (arXiv:2208.02686 and PRD 104, 052004)
- Observed combined result of $|f_{CP}^{t\bar{t}H}| < 0.55$ at 68% and pure CP-odd scenario excluded at 3.7σ.
- Will soon be available from ATLAS

Various channels info

- Various factor utilized to scale the distributions for the three channels
- They were taken from available info from published papers in the three channels

Acceptance factors

	$t\bar{t}H$(parton)	$t\bar{t}H(\to \gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\to b\bar{b})$
$\alpha = 0°$	1	$2.5 \cdot 10^{-1}$	$3.6 \cdot 10^{-2}$	$5.0 \cdot 10^{-3}$
$\alpha = 35°$	1	$2.5 \cdot 10^{-1}$	$3.6 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$
$\alpha = 45°$	1	$2.7 \cdot 10^{-1}$	$3.8 \cdot 10^{-2}$	$5.4 \cdot 10^{-3}$
$\alpha = 90°$	1	$3.2 \cdot 10^{-1}$	$4.2 \cdot 10^{-2}$	$6.5 \cdot 10^{-3}$

Smearing factors

	$t\bar{t}H$(parton)	$t\bar{t}H(\to \gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\to b\bar{b})$
$\Delta p_{T,H}$	None	$4 GeV$	$120 GeV$	$80 GeV$
$\Delta p_{T,t}$	None	$40 GeV$	$70 GeV$	$70 GeV$
$\Delta \eta_t$	None	0.5	0.8	0.8
$\Delta \phi_t$	None	None	$20°$	$20°$

Normalization factors + Branching Ratio

	$t\bar{t}H$(parton)	$t\bar{t}H(\to \gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\to b\bar{b})$
BR	1	$2.27 \cdot 10^{-3}$	$6.79 \cdot 10^{-2}$	$5.81 \cdot 10^{-1}$
$\alpha = 0°$	Normalized	93	401	473
$\alpha = 35°$	Normalized	77	328	397
$\alpha = 45°$	Normalized	69	290	358
$\alpha = 90°$	Normalized	45	180	244