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

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10/04/2024, Top LHC France 2024 - LPNHE Paris

This project has received funding from the European Union's Horizon 2020 research and innovation program under grantagreement No. 800945 NUMERICS—H2020-MSCA-COFUND-2017.

This work was supported by ANRPIA funding ANR-20-IDEES-0002.

Summary*

1 *Introduction*

2 *Observable definition & phenomenological model*

3 *Results*

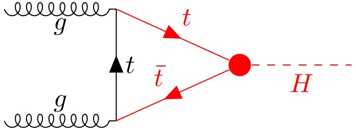
4 *Conclusions*

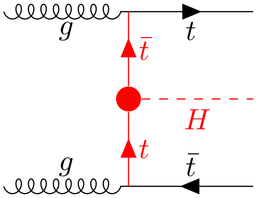
*The work presented here will be published soon

Introduction

CP structure of the Higgs couplings

- Yukawa interactions account for fermion masses, SM expectation: coupling proportional to mass, order of unity for the top quark
- Only $t\bar{t}H$ can directly probe the top-Higgs coupling at tree level
- Sensitive to effects beyond the SM e.g. CP violation
- SM CP violation insufficient to explain baryon asymmetry of the Universe



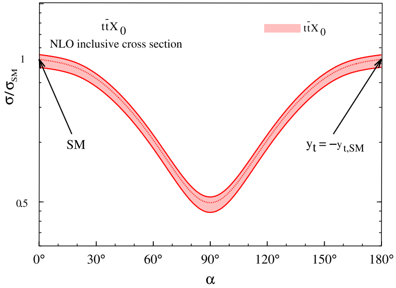


Parametrization and current framework

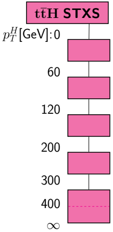
The CP structure of the top-Higgs coupling can be parametrized as a complex phase in SM Lagrangian:

$$\mathcal{L}_{\text{top-Yuk}} = \frac{y_t^{\text{SM}} g_t}{\sqrt{2}} \bar{t} \left(\cos\alpha_t + i\gamma_5 \sin\alpha_t \right) tH$$

Where α mixing angle (effect on shape), g_t scaling factor (effect on normalization), link

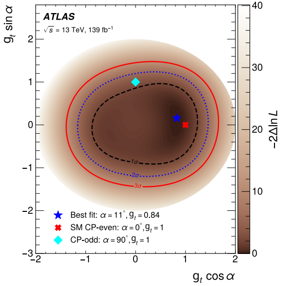


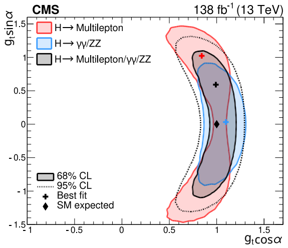
- Established framework currently used: **Simplified template cross-section framework** (STXS - link)



- simplify combination between channels/measurements
- minimize the dependence on theory uncertainties
- maximize the experimental sensitivity
- isolate possible BSM effects
- limit the number of bins to match the experimental sensitivity

We present a **possible extension** that enhances the CP sensitivity of STXS





- **Indirect constrains** from other measurement $\rightarrow$ depends on model/methodologies (e.g., electric dipole moment)
- **Multivariate techniques**, like boosted decision trees (BDT) $\rightarrow$ relies on algorithm and assumptions
- Use of **CP observables**:
  - CP-odd observables $\rightarrow$ hard to construct, information not currently easy to get (e.g., top polarization)
  - CP-even observables $\rightarrow$ global fits

Top fig. ATLAS $t\bar{t}H(H\rightarrow b\bar{b})$ (link) performed using CP-even observables

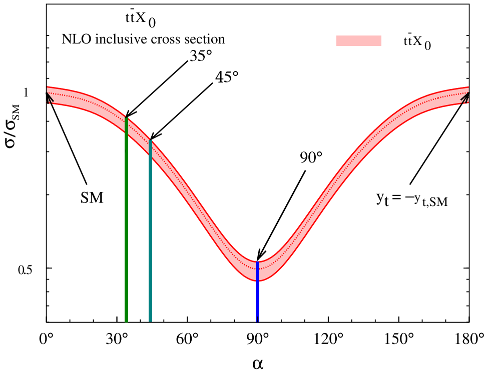
Bottom fig. CMS $t\bar{t}H$ (link), partial combination, BDT trained to separate CP-even/odd

CP-odd excluded by various studies at 4σ, the mixing angle is currently expected to be $|\alpha| < 45^\circ$ $\rightarrow$ New target to probe around 35°

Phenomenological model & observables definition

Event generation

- Generating $t\bar{t}H$ events in the "Higgs Characterization" (HC) model (link), with MadGraph5_aMC@NLO, $m_b = 0$ in the 5 flavor scheme
- LO plus scale factor to take into account for NLO effects



- The pure CP-odd scenario is excluded by previous studies $\rightarrow$ need new benchmarks
- Probing the $35°$, $45°$ scenarios ($90°$ for reference)
- Studied a group of possible discriminating observables

Observables considered

- Set of observables considered for the studies based on phenomenology and previous analysis works.
- These assume H, t and t̄ reconstructed, with no need to distinguish t/t̄

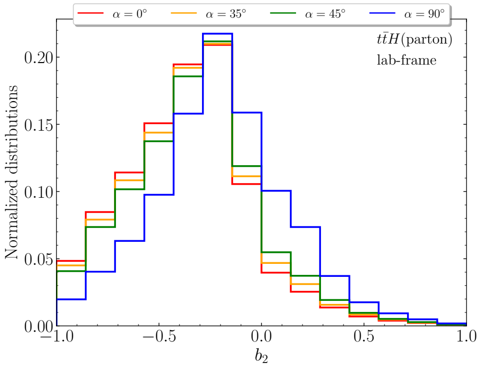
Rest-frames considered:

- 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**).

observable	definition	frame	reference
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	link
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	link
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	link
b_3	$\frac{p_t^x\ p_{\bar{t}}^x}{p_T^t p_T^{\bar{t}}}$	all	link
b_4	$\frac{p_t^z\ p_{\bar{t}}^z}{\lvert\mathbf{p}_t\rvert\ \lvert\mathbf{p}_{\bar{t}}\rvert}$	all	link
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	link

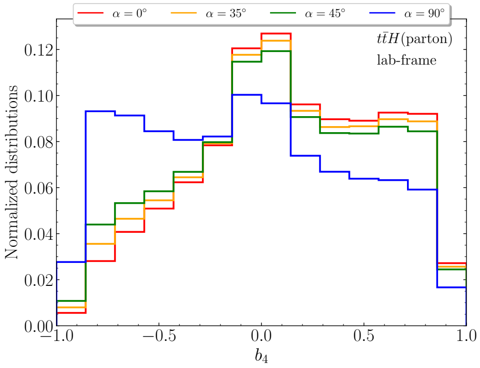
Distributions at the parton-level

$$b_2 = \frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{|\mathbf{p}_t|\ |\mathbf{p}_{\bar{t}}|}$$



Lab frame

$$b_4 = \frac{p_t^z\ p_{\bar{t}}^z}{|\mathbf{p}_t|\ |\mathbf{p}_{\bar{t}}|}$$

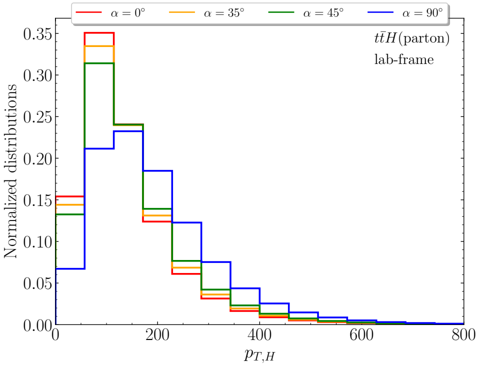


Lab frame

- Some example of the observables distributions at parton level
- Normalized distributions at parton level
- All observables were studied, showing here b_4, b_2

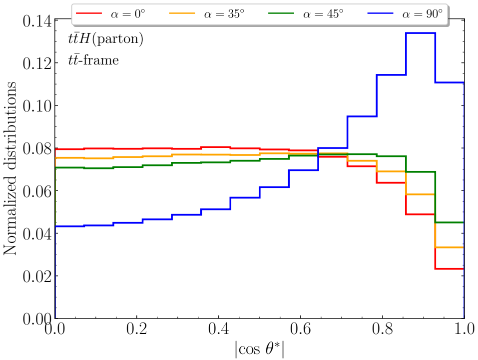
Distributions at the parton-level

p_T^H



Lab frame

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

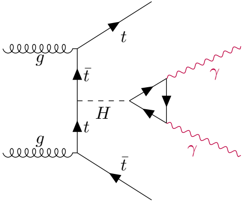


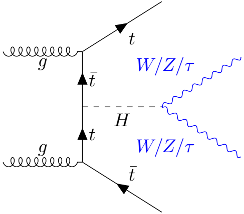
$t\bar{t}$ frame

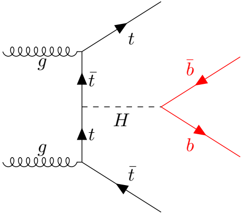
- Two other observables distributions at parton level
- Normalized distributions at parton level
- Further examples: $\cos(\theta^*)$, p_T^H

Detector effects and selection efficiency

- Developed a simplified model that simulate the tt̄H channels studied at LHC
- Channels: tt̄H(H$\rightarrow\gamma\gamma$) and tt̄H(H$\rightarrow$ bb̄) and tt̄H$\rightarrow$ *multilepton final states*
- Took into account: effect from BR, acceptance for efficiency factors, smeared the Higgs and top/Antitop for resolution.
- Numbers are channel-specific (backup) and validated from ATLAS/CMS results







Branching Ratio

	$t\bar{t}H$(parton)	$t\bar{t}H(\rightarrow\gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\rightarrow b\bar{b})$
BR	1	$2.27\cdot10^{-3}$	$6.79\cdot10^{-2}$	$5.81\cdot10^{-1}$

- Example: smearing effect on p_T^H $\rightarrow$ estimated for tt̄H(H$\rightarrow\gamma\gamma$) two orders of magnitude lower than the other two channels thanks to clear signature from photons

Observables combination and ranking

- Quantify and compare the sensitivity of the various observables assuming acceptance, smearing and other factors applied, luminosity of 300 fb^{-1}
- To account for statistical & systematic uncertainty, in each bin σ_i is:

$$\sigma_i = \sqrt{\sigma^2_{\text{sys}} + \sigma^2_{\text{stat}}}$$

- Define *significance* S according to link: metric to evaluate and compare observables, taking n SM and m BSM

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

- Due to systematic uncertainties, apart for the tt̄H(H$\rightarrow \gamma\gamma$) channel, distributions are normalized before S evaluation

Results

Results and 2D combination

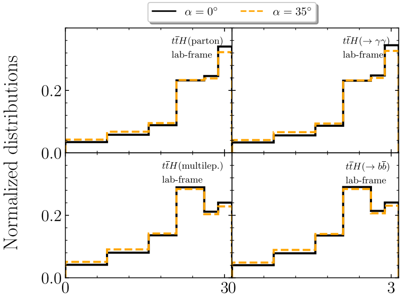
- In total, we considered 31 different observables across the different rest frames and focusing on the best observable
- Considering also two-dimensional distributions taking combinations of 2 observables shows the best discrimination, results on a subset of observables:

$\alpha = 35^\circ$ $\mathcal{L} = 300\ \mathrm{fb}^{-1}$ 14 (6x6) bins for 1d (2d) dist. comb. w/ $p_{T,H}^{\mathrm{lab}}$

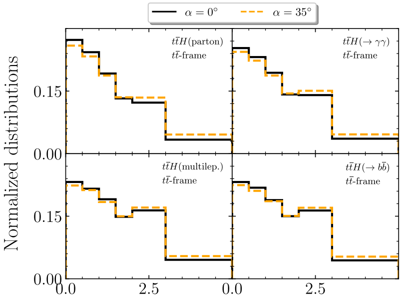
	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\|\cos\theta^*\|$	b_1	b_2	b_3
$H \to \gamma\gamma$	1.41	1.45	1.42	1.43	1.42	1.41	1.44	1.36	1.38	1.41	1.46	1.46	1.4	1.46	1.41
Multilep.	0.38	0.48	0.64	0.62	0.63	0.49	0.51	0.37	0.37	0.38	0.5	0.6	0.35	0.59	0.39
$H \to b\bar{b}$	0.26	0.29	0.35	0.34	0.36	0.31	0.3	0.24	0.24	0.23	0.29	0.36	0.21	0.35	0.24
Combined	1.49	1.56	1.6	1.59	1.6	1.52	1.56	1.43	1.44	1.48	1.58	1.62	1.46	1.62	1.48

Best pairs & Optimized binning

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

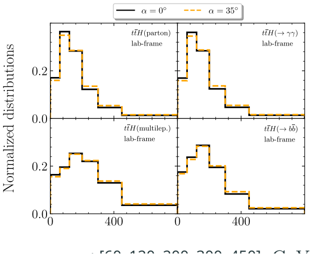


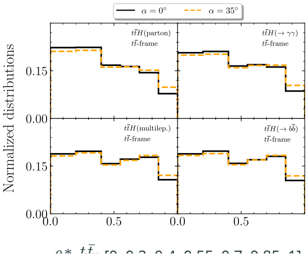
$\Delta\phi_{t\bar{t}}^{\text{lab}}$: [0, $\pi/4$, $\pi/2$, $2\pi/3$, $5\pi/6$, $11\pi/12$, π]

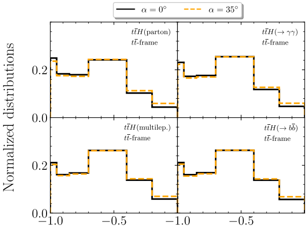


$\Delta\eta_{t\bar{t}}^{t\bar{t}}$: [0, 0.5, 1, 1.5, 2, 3, 5]

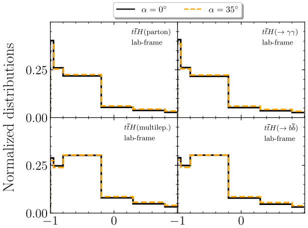
Optimized binning for other observables







$b_2^{t\bar{t}}$: [-1, -0.95, -0.85, -0.7, -0.4, -0.2, 0]

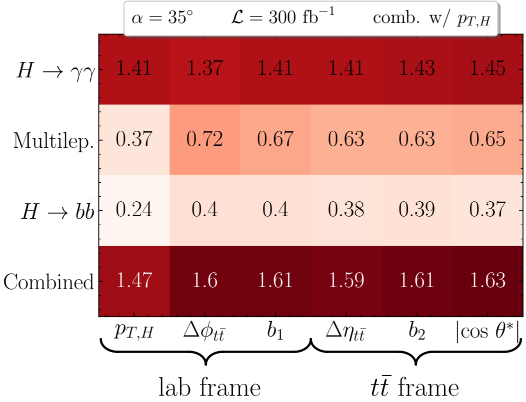


b_1^{lab}: [-1, -0.95, -0.8, -0.2, 0.3, 0.8, 1.0]

- Optimized binning is chosen to maximize the significance for various channels

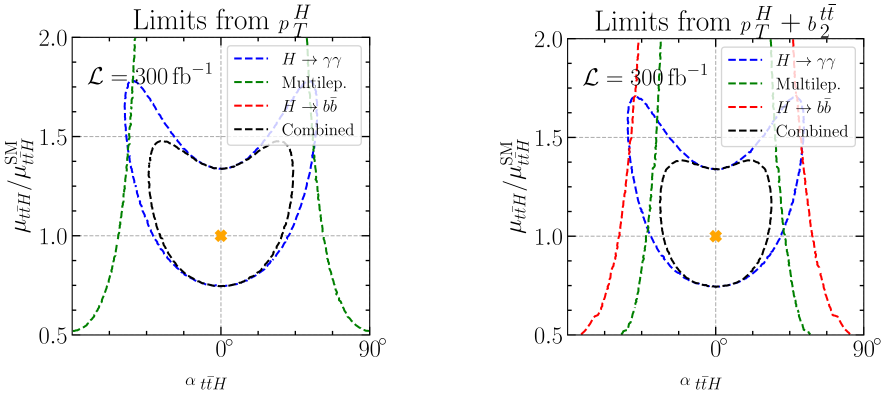
Final significance estimation

- The combination using the optimized binning allows us to choose the best observables combination in the various channels
- For these final observables $\rightarrow$ qualitative background study carried out to verify that the background distribution are not reducing the sensitivity
- In addition to p_T^H two candidates are observed to be equally good for extending the STXS framework, $b_2^{t\bar{t}}$, $\theta^{*,t\bar{t}}$



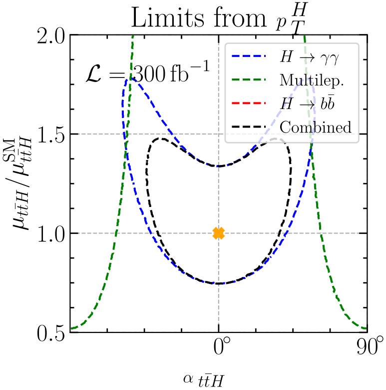
Expected sensitivity to CP, STXS extension with $b_2^{t\bar{t}}$

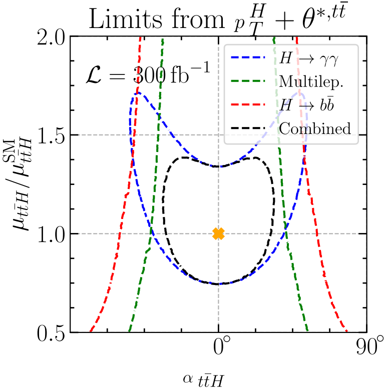
- Expected exclusion limit with our simplified model taking p_t^H only (left) and together with the best observable (right) at 300 fb^{-1}
- The final combinations make a large improvement in the CP sensitivity
- p_t^H in combination with $b_2^{t\bar{t}}$



Expected sensitivity to CP, STXS extension $\theta^{*,t\bar{t}}$

- Expected exclusion limit with our simplified model taking p_t^H only (left) and together with the best observable (right) at 300 fb^{-1}
- The final combinations make a large improvement in the CP sensitivity
- p_t^H in combination with $\theta^{*,t\bar{t}}$





Conclusions

Recap and outlook

Recap:

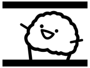
- We presented a study of the CP measurement in $t\bar{t}H$, using three different channels, offering a solid alternative to multivariate studies
- Performing a detailed sensitivity study for various CP-sensitive observables, we conclude that both $\boldsymbol{b_2^{t\bar{t}}}$ **and** $\boldsymbol{\theta^{*,t\bar{t}}}$ are equally good candidates, in combination with p_T^H
- The final proposal is a **feasible extension of the current STXS framework, facilitating combination between channels, experiments and future reinterpretations**

Prospect:

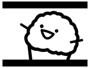
- **Published soon**
- Application to next CP measurements already under consideration

CP violation in the Higgs sector is still to be thoroughly explored!

Thanks for your attention!

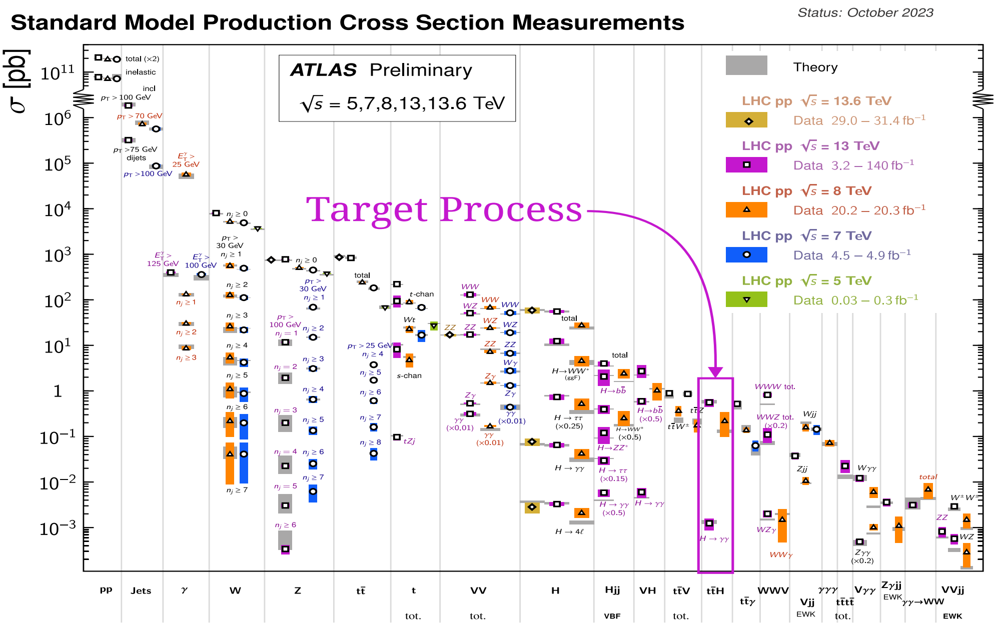


BACKUP

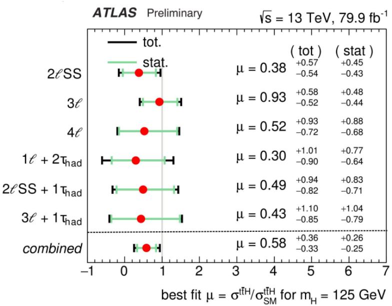


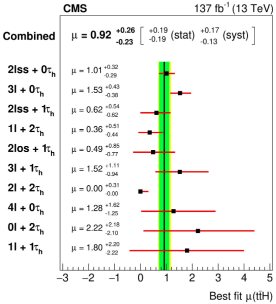
$t\bar{t}H$ channel summary

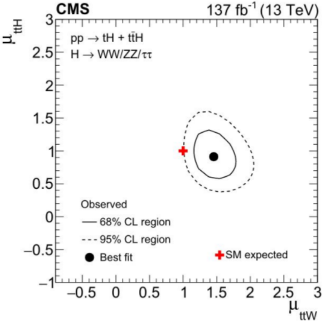
tt̄H in the SM link



- $t\bar{t}H$ observation by ATLAS (link) and CMS (link) with partial Run 2 datasets with a significance of 6.3 and 5.2 σ respect to background-only hypotesis
- $t\bar{t}H$ still currently under combination with run 2 datasets.

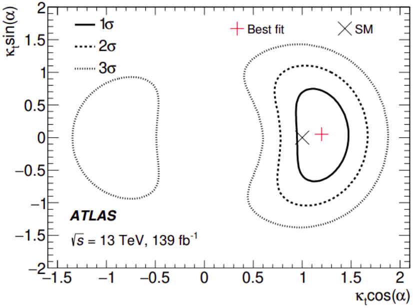






Latest CP measurements in $t\bar{t}H$

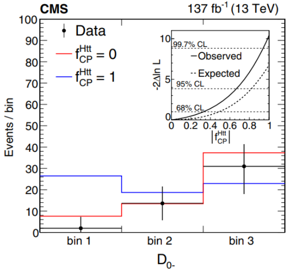
$t\bar{t}H$, $H \to \gamma\gamma$ results

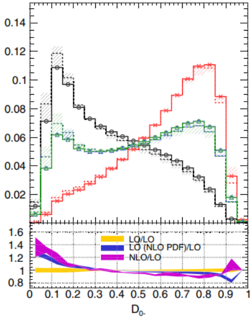


ATLAS analysis (link):

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

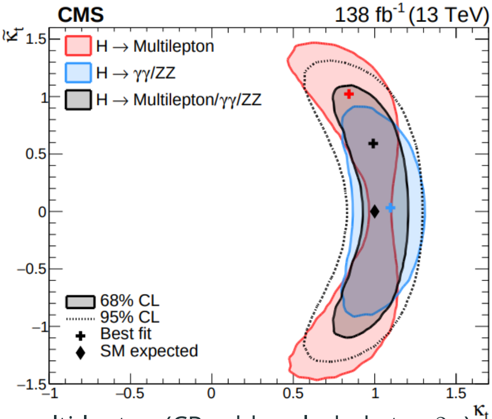




CMS analysis (link):

- Same strategy using MVAs to separate BKGs and CP-odd from CP-even
- Use of the parametrization: $f_{CP}^{t\bar{t}H} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \,\mathrm{sign}\left(\tilde{\kappa}_t/\kappa_t\right).$
- Observed $f_{CP}^{t\bar{t}H} = 0.00 \pm 0.33$ at 95% and pure CP-odd coupling excluded at 3.2σ.

CMS $t\bar{t}H \to$ Multilepton and combination



- Similar methodology in multi-lepton (CP-odd excluded at $> 2\sigma$) and H→VV→4ℓ channels (CP-odd excluded at 3.1σ) (link and link)
- Observed combined result of $|f_{CP}^{t\bar{t}H}| < 0.55$ at 68% and pure CP-odd scenario excluded at 3.7σ.

Simplified model factors

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

	$t\bar{t}H(\text{parton})$	$t\bar{t}H(\to\gamma\gamma)$	$t\bar{t}H(\text{multilep.})$	$t\bar{t}H(\to b\bar{b})$
$\alpha = 0°$	1	$2.5\cdot10^{-1}$	$3.6\cdot10^{-2}$	$5.0\cdot10^{-3}$
$\alpha = 35°$	1	$2.5\cdot10^{-1}$	$3.6\cdot10^{-2}$	$5.2\cdot10^{-3}$
$\alpha = 45°$	1	$2.7\cdot10^{-1}$	$3.8\cdot10^{-2}$	$5.4\cdot10^{-3}$
$\alpha = 90°$	1	$3.2\cdot10^{-1}$	$4.2\cdot10^{-2}$	$6.5\cdot10^{-3}$

Smearing factors

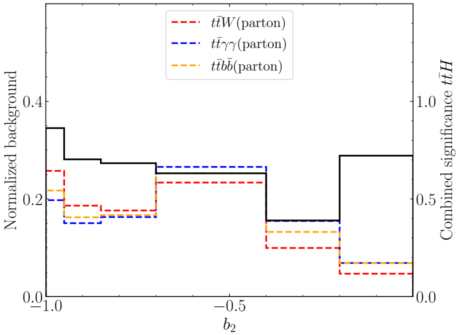
	$t\bar{t}H(\text{parton})$	$t\bar{t}H(\to\gamma\gamma)$	$t\bar{t}H(\text{multilep.})$	$t\bar{t}H(\to b\bar{b})$
$\Delta p_{T,H}$	None	4 GeV	120 GeV	80 GeV
$\Delta p_{T,t}$	None	40 GeV	70 GeV	70 GeV
$\Delta\eta_t$	None	0.5	0.8	0.8
$\Delta\phi_t$	None	None	20°	20°

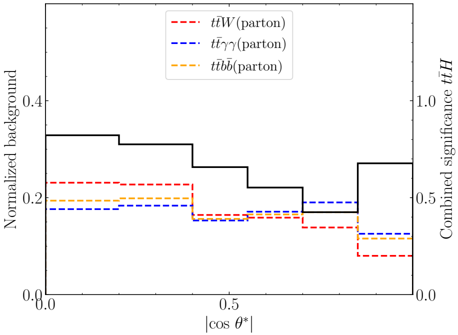
Normalization factors + Branching Ratio

	$t\bar{t}H(\text{parton})$	$t\bar{t}H(\to\gamma\gamma)$	$t\bar{t}H(\text{multilep.})$	$t\bar{t}H(\to b\bar{b})$
BR	1	$2.27\cdot10^{-3}$	$6.79\cdot10^{-2}$	$5.81\cdot10^{-1}$
$\alpha = 0°$	Normalized	93	401	473
$\alpha = 35°$	Normalized	77	328	397
$\alpha = 45°$	Normalized	69	290	358
$\alpha = 90°$	Normalized	45	180	244

Qualitative background study

- Sensitivity of the observables in the various bins compared to the background distributions for the most sensitive observables





- Sensitivity of the observables in the various bins compared to the background distributions for other optimized observables