



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

Henning Bahl, Alberto Carnelli, Frederic Deliot, Elina Fuchs, Anastasia Kotsokechagia, Marco Menen, Matthias Saimpert, Laurent Olivier Schoeffel

IRN Terascale, Montpellier
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Introduction

Study setup

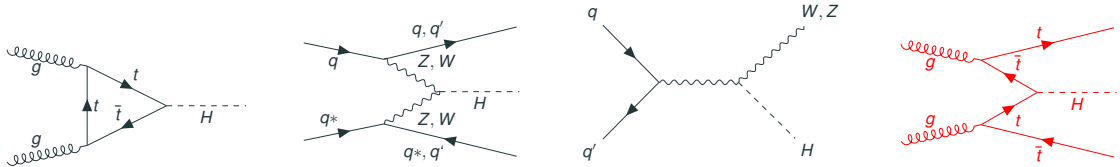
Analysis strategy

Initial results and optimization

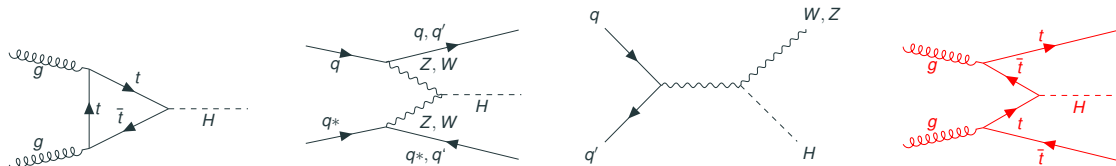
Final result and proposed STXS extension

Conclusion

Introduction

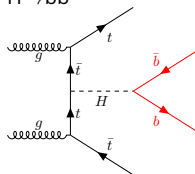


Decreasing cross-section

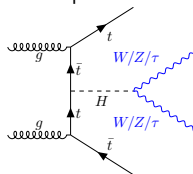


Decreasing cross-section →

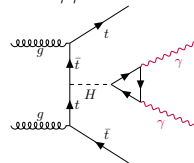
$H \rightarrow b\bar{b}$

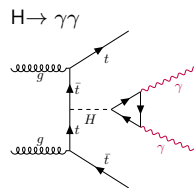
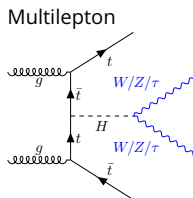
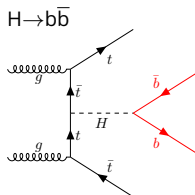
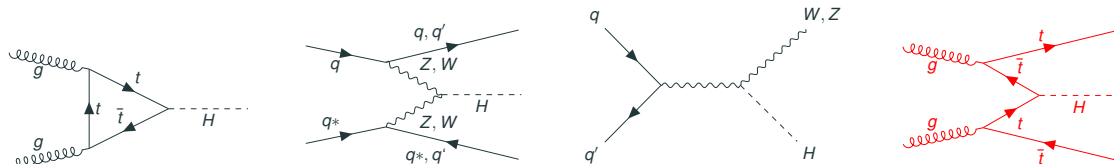


Multilepton



$H \rightarrow \gamma\gamma$





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

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

- There is not enough CP to match observed matter predominance

Yukawa interaction:

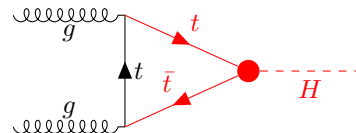
$$\mathcal{L}_{\text{Y.-fermion}} = - \left(\bar{\psi}_{\ell,L}^i y_{ij}^{\ell} \varphi \psi_{\ell,R}^j + \bar{\psi}_{q,L}^i y_{ij}^u \bar{\varphi} \psi_{u,R}^j + \bar{\psi}_{q,L}^i y_{ij}^d \varphi \psi_{d,R}^j + \dots \right)$$

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

Charge symmetry



Parity symmetry



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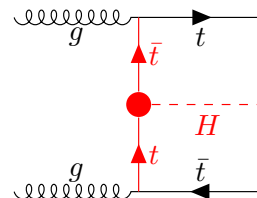
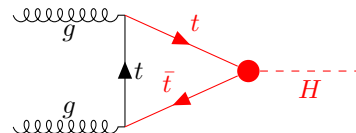
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- **Yukawa interactions account for fermion masses** in the SM
- Measurement of Yukawa couplings (y_{ij}^k) to fermions important probe for new physics $\rightarrow$ could behave different from SM expectations
- **Top quark** Yukawa coupling: largest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

Charge symmetry



Parity symmetry



- CP parametrization in the top Yukawa coupling:

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

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

Model information:

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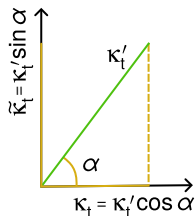
$$\mathcal{L}_{Y\text{-top, CP}} = - \left(y_t \kappa'_t \cos(\alpha) \bar{\psi}_t \psi_t \varphi + i \kappa'_t \sin(\alpha) y_t \bar{\psi}_t \gamma_5 \psi_t \varphi \right)$$

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$$\mathcal{L}_{Y\text{-top, CP}} = \mathcal{L}_{Y\text{-top, CP-Even}} + \mathcal{L}_{Y\text{-top, CP-Odd}}$$

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- Usually use $\kappa_t, \tilde{\kappa}_t \rightarrow$ **direct CP visualization**



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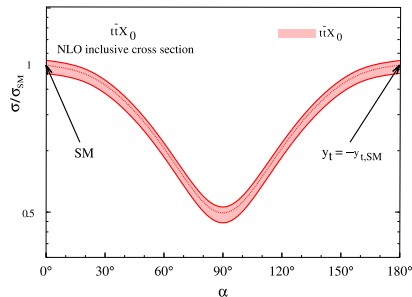
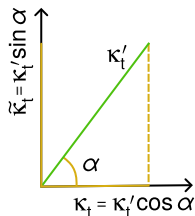
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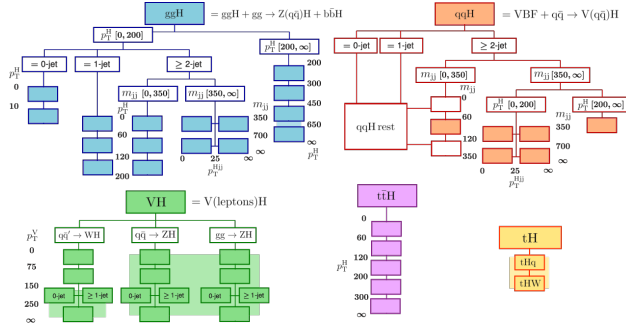
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The plots set Higgs-top coupling to reproduce the SM gluon-fusion cross section for every value of α ([link](#))

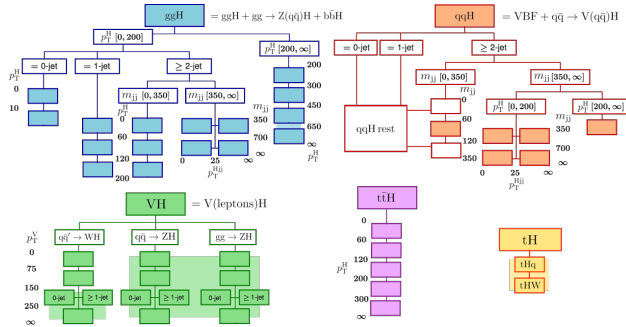
Model consequences:

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



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

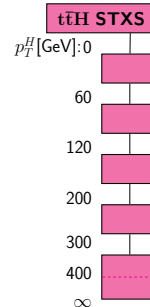
- simplify combination between channels/measurements
- minimize the dependence on theory uncertainties
- maximize the experimental sensitivity
- isolate possible BSM effects



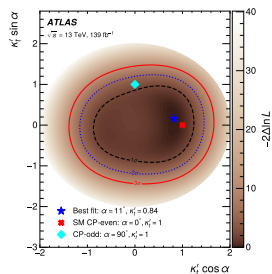
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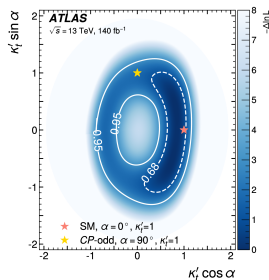
- **Goal:** developing an STXS extension targeting better $t\bar{t}H$ CP sensitivity
- CP-odd excluded by various studies at $4\sigma \rightarrow$ Obtained without the STXS framework
- $|\alpha| < 45^\circ \rightarrow$ decide to target 35°



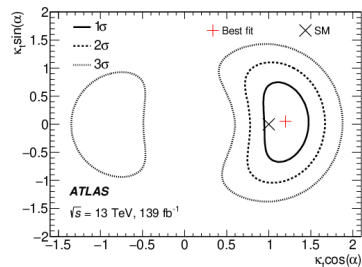
Methods currently in use relies on machine learning techniques or using CP-observables



ATLAS $t\bar{t}H(H \rightarrow b\bar{b})$ [\(link\)](#) performed using CP-observables

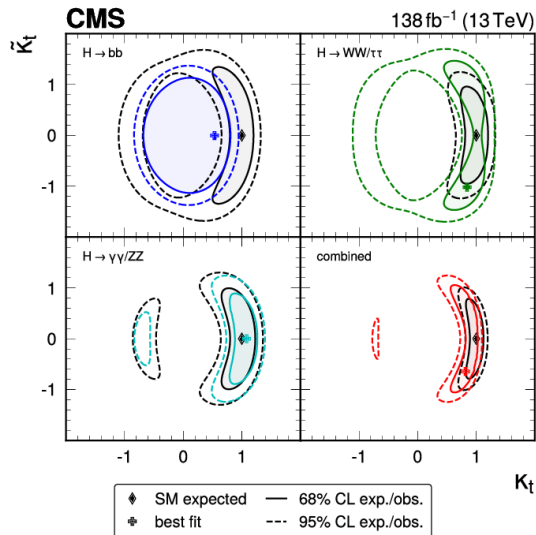


ATLAS $t\bar{t}H \rightarrow$ ML [\(link\)](#) performed using combined

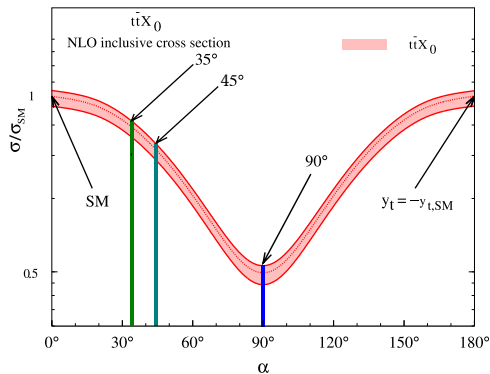


ATLAS $t\bar{t}H(H \rightarrow \gamma\gamma)$ [\(link\)](#), BDT trained to separate CP-even/odd

First performed combination with full Run 2, machine learning techniques to separate the SM from BSM

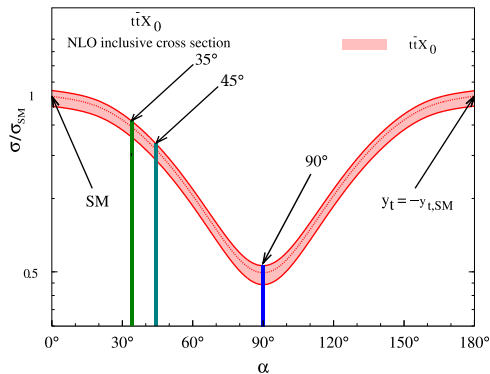


Study setup



- 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

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



Rest-frames considered:

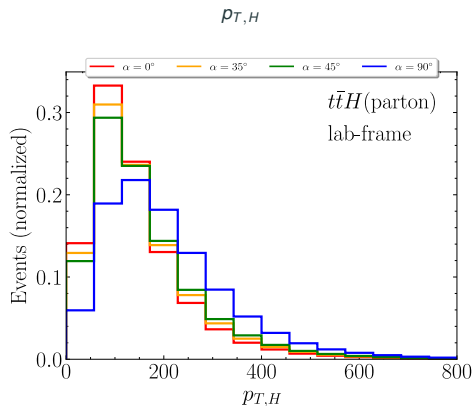
- laboratory frame (**lab frame**),
- $t\bar{t}$ rest frame, where $\mathbf{p}_t + \mathbf{p}_{\bar{t}} = \mathbf{0}$ (**$t\bar{t}$ frame**),
- $t\bar{t}H$ rest frame, where $\mathbf{p}_t + \mathbf{p}_{\bar{t}} + \mathbf{p}_H = \mathbf{0}$ (**$t\bar{t}H$ frame**),
- H rest frame, where $\mathbf{p}_H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

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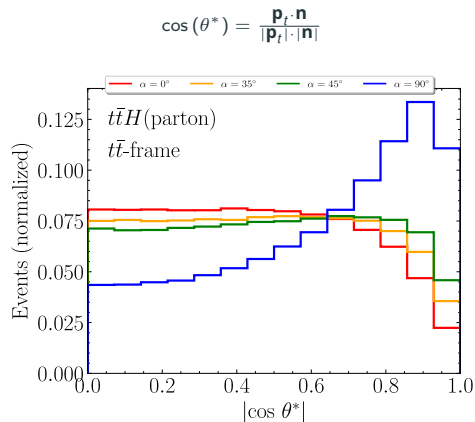
$$N(\kappa'_t, \alpha_t) = \kappa'_t{}^2 \left[N_{\text{SM}} \cos^2 \alpha_t + N_{\text{odd}} \sin^2 \alpha_t \right]$$

- Studied a group of possible discriminating observables
- Assume H , t and $\bar{t}$ reconstructed

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



Lab frame

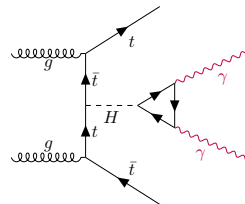
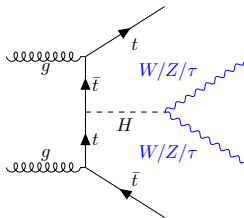
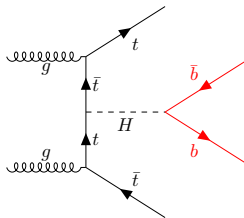


$t\bar{t}$ frame

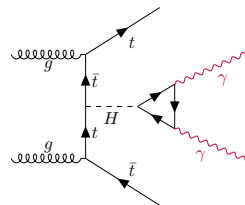
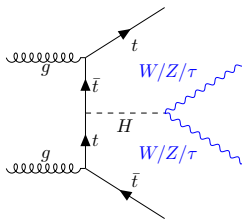
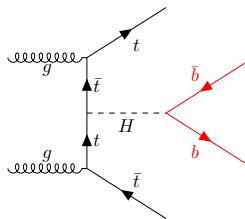
- Normalized distributions for some examples of observables
- Here the t and $\bar{t}$ kinematics is needed (no need to distinguish them)

Analysis strategy

- Channels considered: $t\bar{t}H(H \rightarrow \gamma\gamma)$, $t\bar{t}H(H \rightarrow b\bar{b})$ and $t\bar{t}H \rightarrow \text{multilepton final states}$
- 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:

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

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

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

Initial results and optimization

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

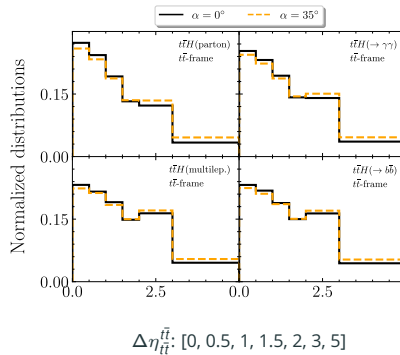
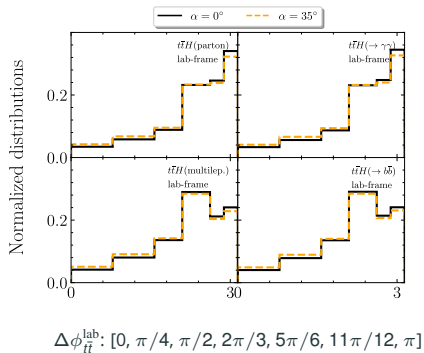
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- The highest significance is obtained when combining $\Delta\phi_{\ell\bar{\ell}}$ and b_4 in the lab frame
- **Decided to use $p_{T,H}$ with a second observable** (to build on the existing STXS setup) $\rightarrow$ combined values similar to the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

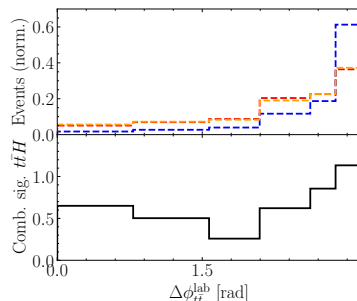
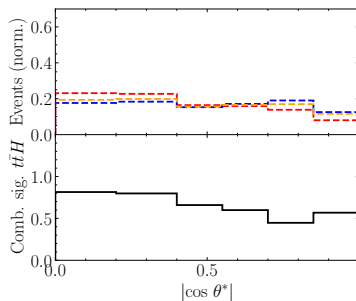
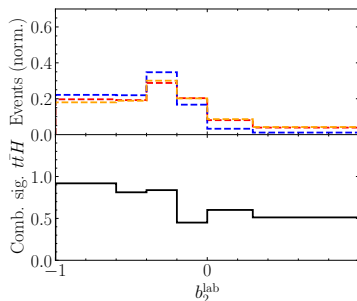
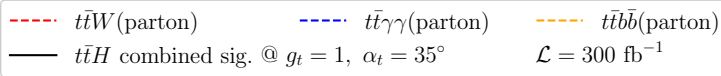
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- **Highest significance from 2D combination of observables**
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	$\alpha_t = 35^\circ$	$t\bar{t}H$ @ $\mathcal{L} = 300 \text{ fb}^{-1}$						14 (6×6) bins for 1d (2d) dist.				comb. w/ $p_{T,H}^{\text{lab}}$			
$H \rightarrow \gamma\gamma$	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
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	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
	lab frame							indep.		$t\bar{t}$ frame					

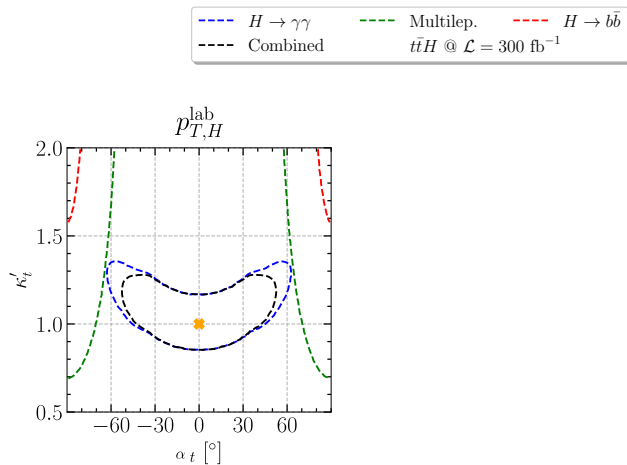
- Best results from combining p_T^H with $\Delta\phi_{t\bar{t}}^{\text{lab}}$, b_1^{lab} , $\Delta\eta_{t\bar{t}}^{\text{t}\bar{t}}$, θ^* , $t\bar{t}$, b_2^{lab} .
- For these pairs: binning optimization performed targeting six bins to determine best pair, distributions presented below (comparing SM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



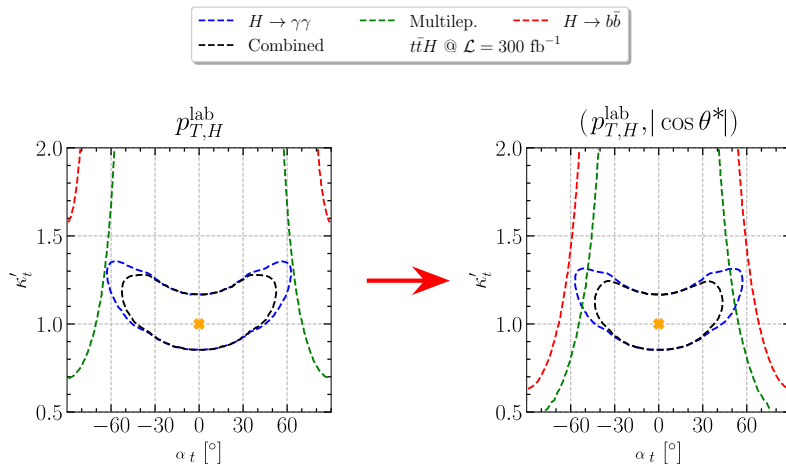
- Sensitivity of the observables in the various bins compared to the background distributions for the most sensitive observables
- Observables where the significance could have been over-estimated due to low signal over background ratio are excluded
- Example on three observables of background shapes



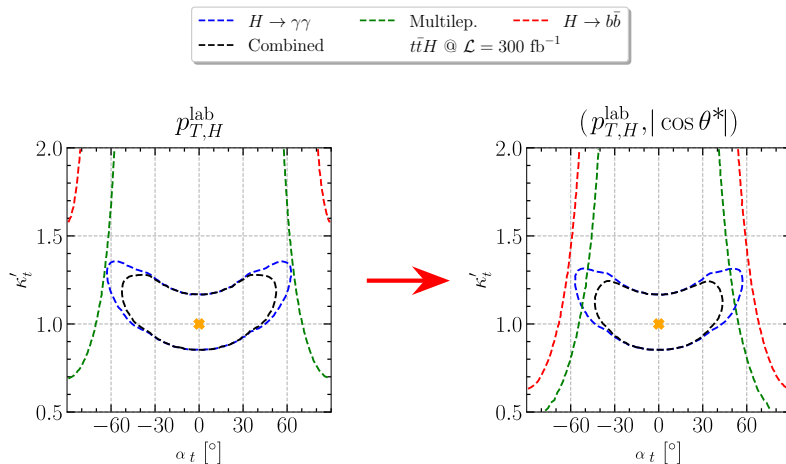
Final result and proposed STXS extension



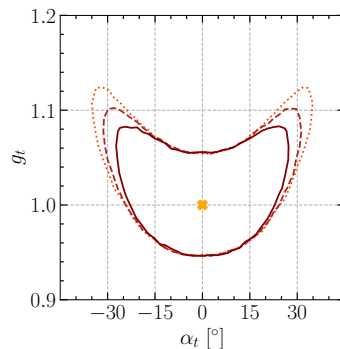
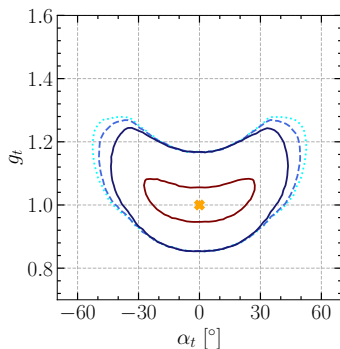
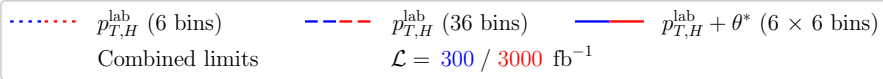
- Expected exclusion limits considering our model use 300 fb^{-1}



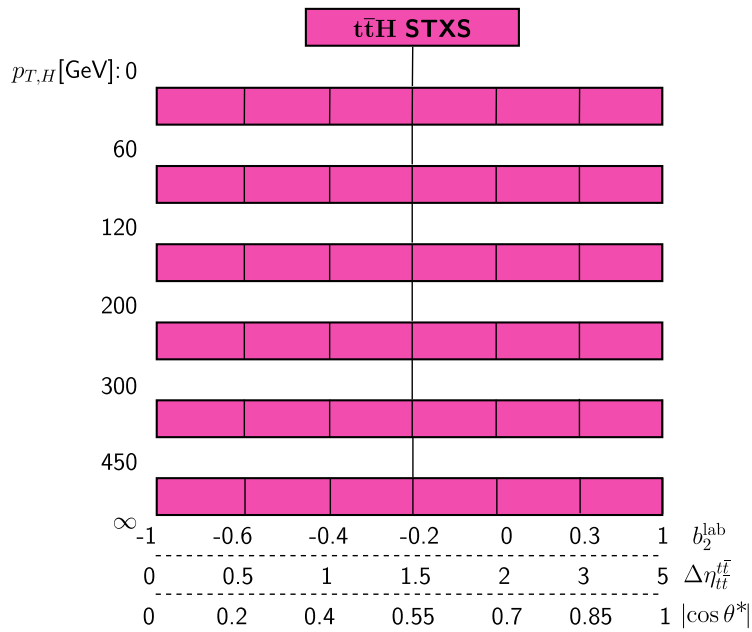
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- Expected exclusion limits considering our model use 300 fb^{-1}
- Final limit at $\kappa'_t = 1$, $|\alpha| \lesssim 36^\circ$ at 68% CL $\rightarrow$ **12% better with respect to not using $|\cos\theta^*|$**
- Maximum improvement of **40% at $\kappa'_t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



- constraints in the (g_t, α) plane for (blue) $\mathcal{L} = 300 \text{ fb}^{-1}$ and (red) $\mathcal{L} = 3000 \text{ fb}^{-1}$ 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)
- $\mathcal{L} = 3000 \text{ fb}^{-1}$ also presented with the $\mathcal{L} = 300 \text{ fb}^{-1}$ contour



Conclusion

Recap

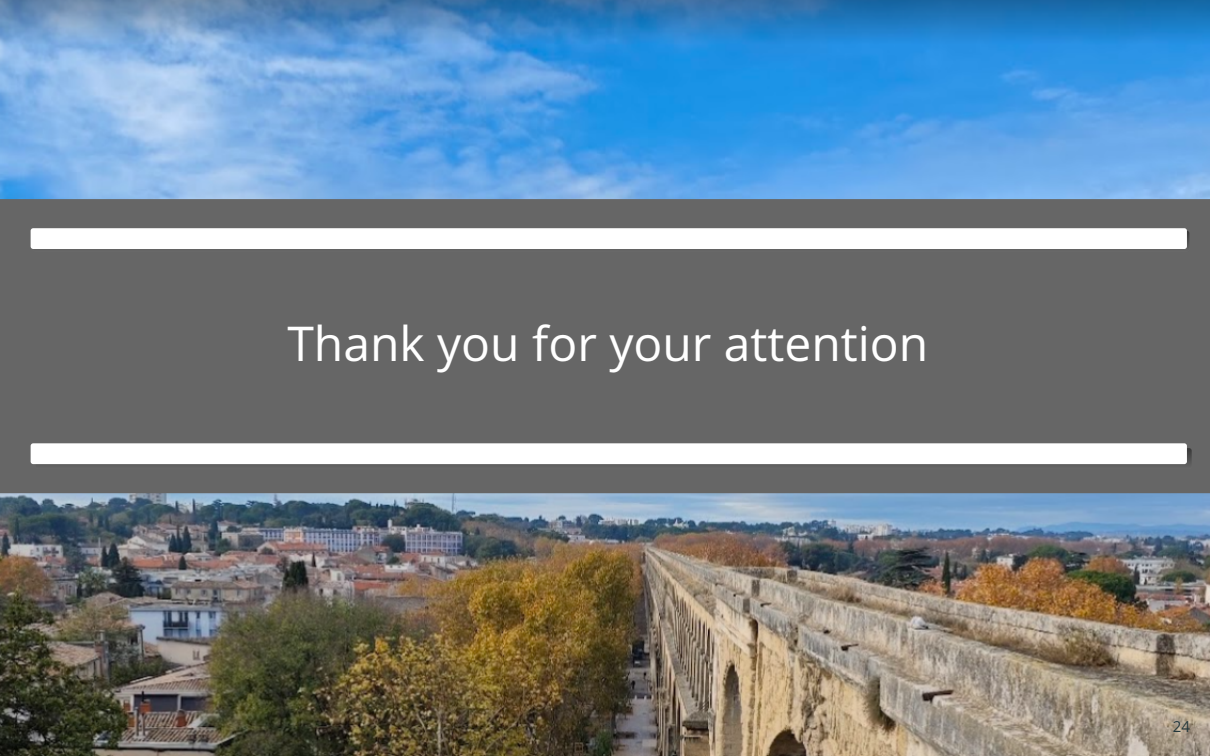
- We presented a study to extend STXS targeting CP in $t\bar{t}H$ using three channels
- The sensitivity based on 2 suitable variables is similar to that of a multivariate analysis
- Our sensitivity study shows that b_2^{lab} , $\Delta\eta_{t\bar{t}}$, and $|\cos\theta^*|$ are similarly good 2nd variables, 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
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Outlook

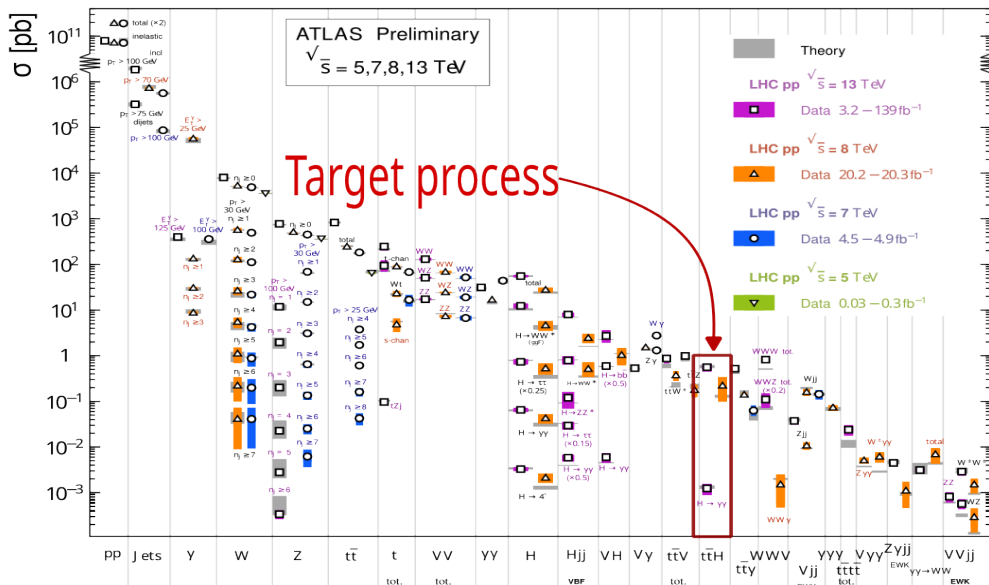
- The full study is **published: [link](#)**
- To implement the proposal $\rightarrow$ parton level top quark definition needs to be added to the STXS framework
- Can be directly tested future CP violation searches in $t\bar{t}H$ channel at the LHC



Thank you for your attention

BACKUP

Status: February 2022

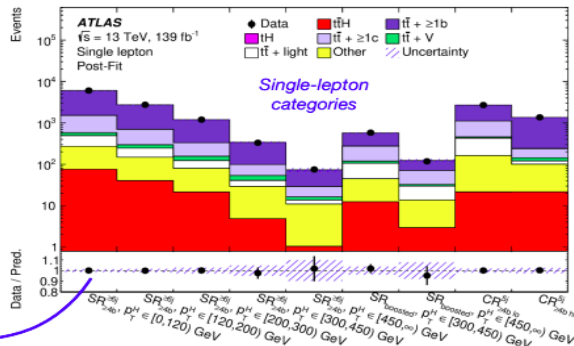
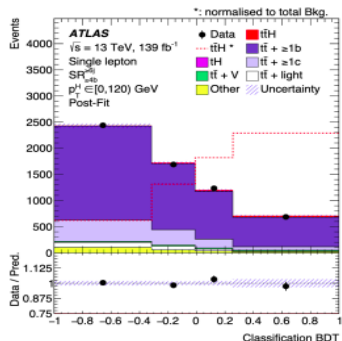


$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

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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 $t\bar{t} + \geq 1b$ constrained by dedicated Control regions (CRs)

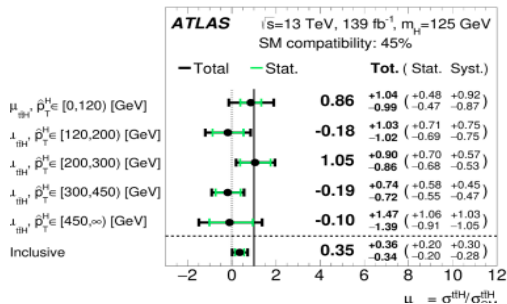
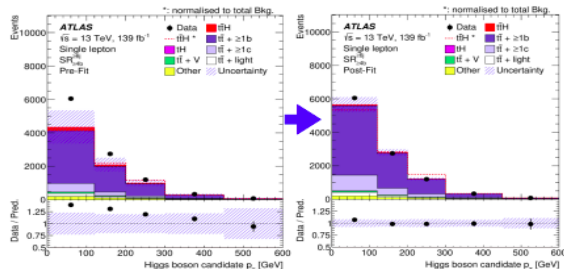
From LHCP2024 talk of Anastasia Anastasia Kotsoskechagia ([link](#))

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

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Background modeling

- $t\bar{t}+b\bar{b}$ 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 $t\bar{t}$ +heavy flavor components
 - Additional uncertainty to account for mis-modeling observed in reconstructed $p_{T,\text{Higgs}}$



Inclusive results:

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

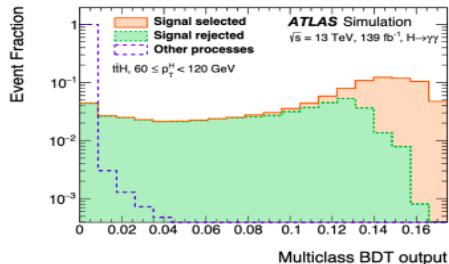
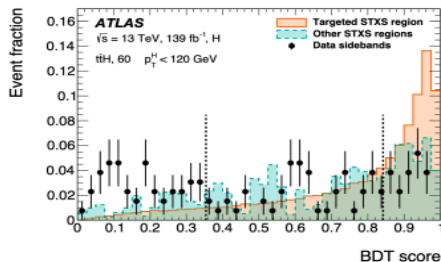
Z = 1.0 σ (2.7 σ exp.)
(139 fb⁻¹)

- Measured μ for five separate $p_{T,\text{Higgs}}$ bins
- Sensitivity dominated by large theoretical uncertainties on irreducible $t\bar{t}+\geq 1b$ background

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

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 $\kappa_t = 1$ and $\kappa_t = -1$, and further categorization done to separate signal from background events

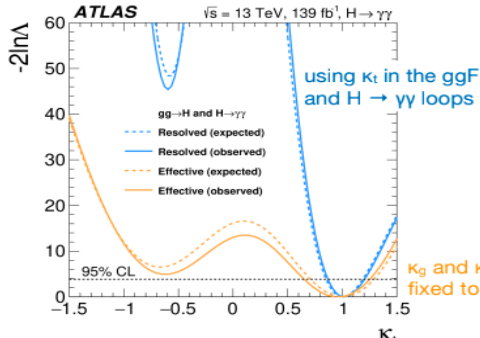
$t\bar{t}H/tH$ ($H \rightarrow \gamma\gamma$)

- Results for **STXS** parameters in each of the 28 phase-space regions :

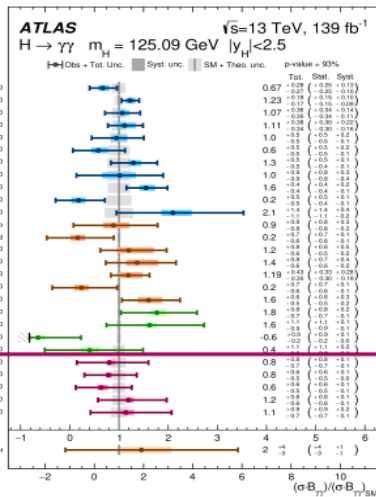
- 5 $t\bar{t}H$ p_T bins and additional tH category (p_T inclusive)

- Inclusive:** $\mu_{i\bar{i}H} = 0.89^{+0.32}_{-0.30}$, $\mu_{tH} = 3^{+4}_{-3}$

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



κ_g and κ_γ
fixed to the SM prediction



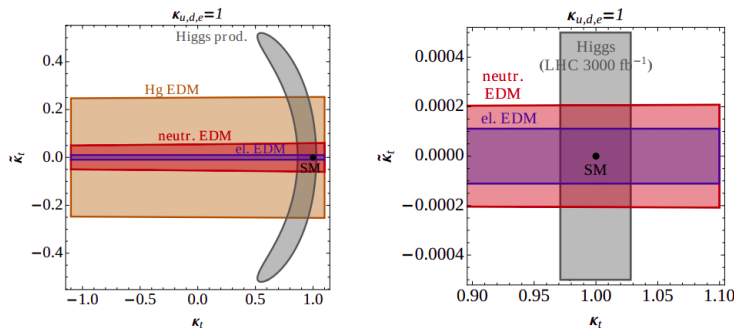
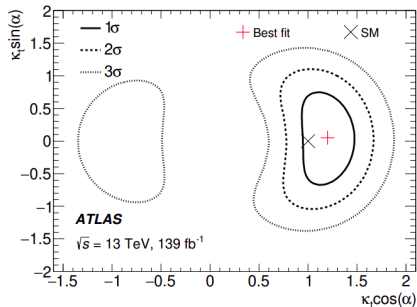


Figure 2. Left: Present constraints on κ_t and $\tilde{\kappa}_t$ from the electron EDM (blue), the neutron EDM (red), the mercury EDM (brown), and Higgs physics (gray). Right: Projected future constraints on κ_t and $\tilde{\kappa}_t$, see text for details.

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

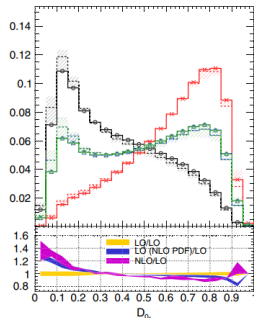
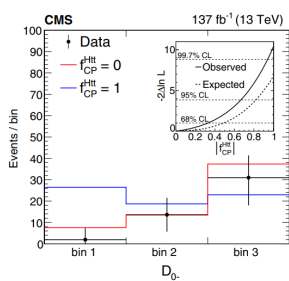
where $f = t, b, \tau$ and $y_f = \sqrt{2}m_f/v$ is the SM Yukawa coupling with m_f the fermion mass and $v \simeq 246\text{GeV}$ the electroweak symmetry breaking vacuum expectation value of the Higgs field. The couplings $\tilde{\kappa}_f$ are CP violating, while κ_f parametrize CP-conserving NP (see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



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



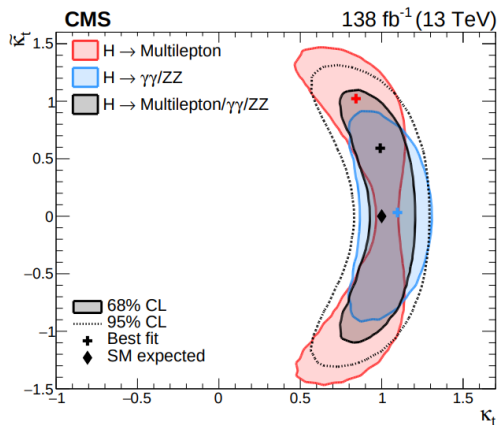
CMS analysis (PRL 125, 061801):

- Same strategy using MVAs to separate BKGs and CP-odd from CP-even

- Use of the parametrization:

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

- 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 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

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

Smearing factors

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

Normalization factors + Branching Ratio

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