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

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Seminar on Particle Physics Phenomenology and Experiments

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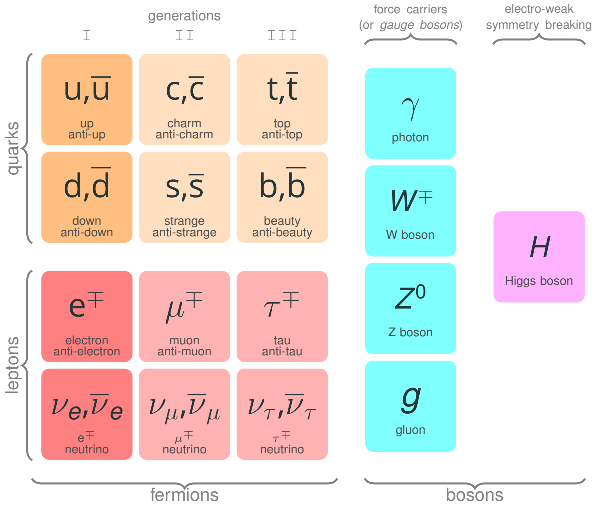
Summary

Introduction – Preamble

The Standard Model of elementary particles

- Universe composition described by **Standard Model (SM)** of elementary particles



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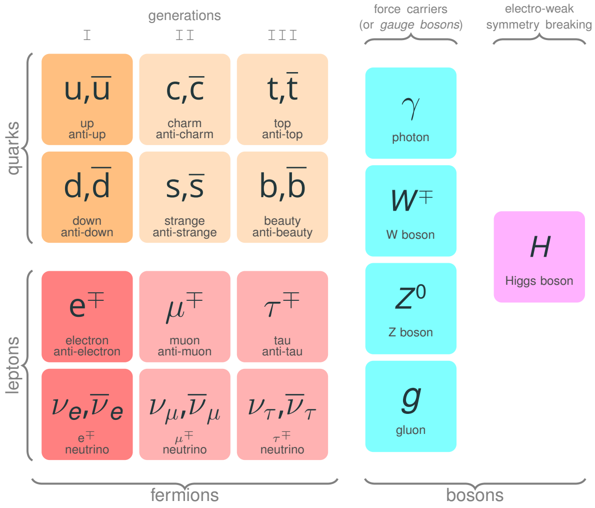
  - Quarks-Leptons (matter+antimatter)
  - Gauge Bosons: interactions
  - Higgs Boson: mass generation



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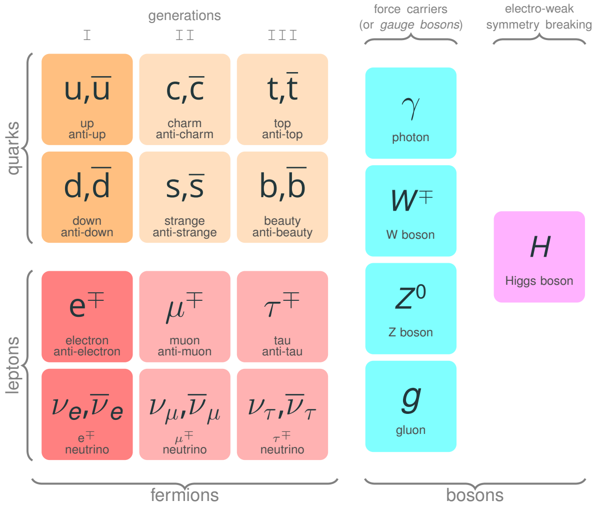

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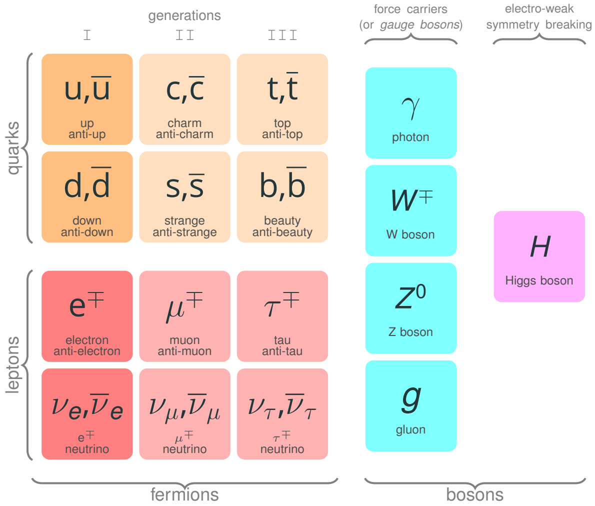
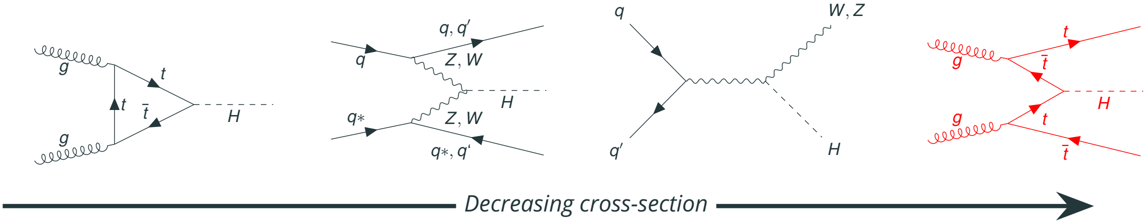
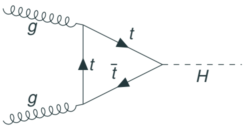


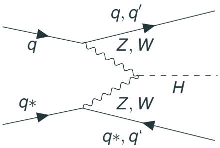
Higgs boson discovered in 2012, still to characterize

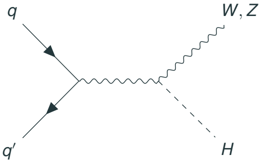
SM alone can’t explain some observation like matter-antimatter asymmetry

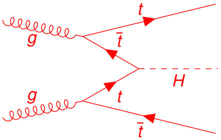
Higgs decays and $t\bar{t}H$ process







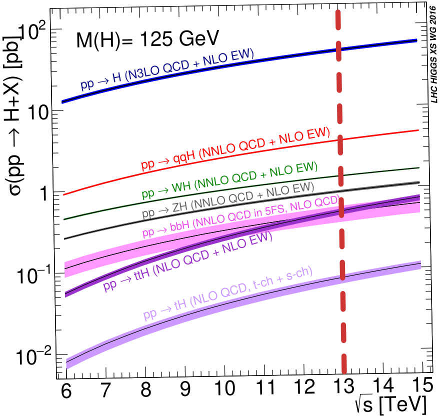


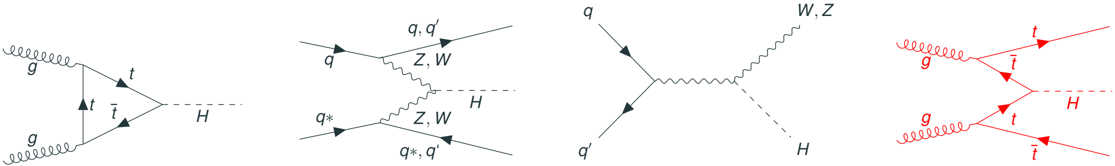


Decreasing cross-section

Higgs production at pp colliders:

- Gluon-gluon fusion (ggH)
- Vector boson fusion (VBF)
- Higgs-Strahlung
- tH and the t$\bar{t}$H processes $\rightarrow$ Focus of this work





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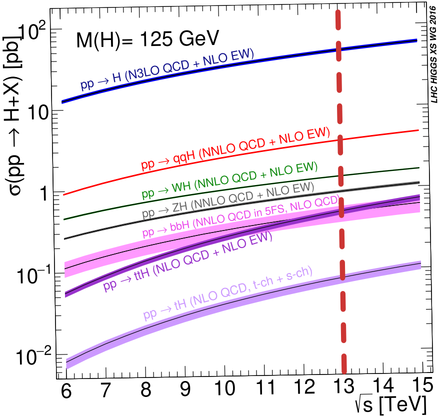
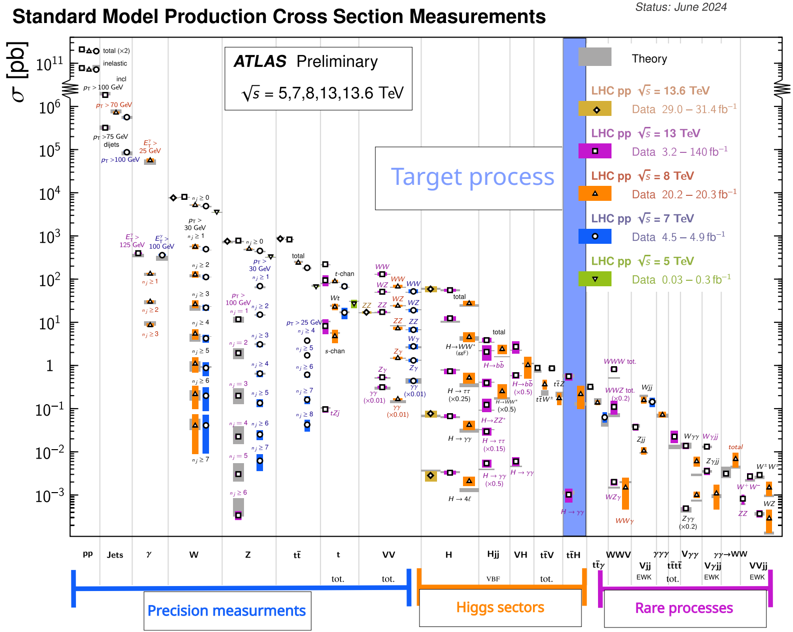
Higgs decay:

Higgs decay channel	Branching ratio
$H \rightarrow b\bar{b}$	57.7%
$H \rightarrow W^+W^-$	21.5%
$H \rightarrow \tau^+\tau^-$	6.32%
$H \rightarrow ZZ$	2.64%
$H \rightarrow \gamma\gamma$	0.23%
$H \rightarrow Z\gamma$	0.15%
$H \rightarrow \mu^+\mu^-$	$\sim$ 0.02%



Top quark decay: $\sim$ 99.9% to Wb

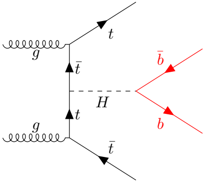
$t\bar{t}H$ in the Standard Model



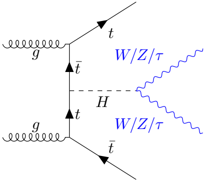
$t\bar{t}$H analysis: decay channels

$t\bar{t}$H decay channels according to H decays:

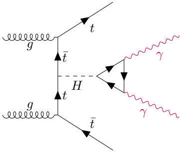
H→$b\bar{b}$



Multilepton



H→ $\gamma\gamma$



Decreasing cross-section →

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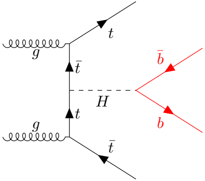

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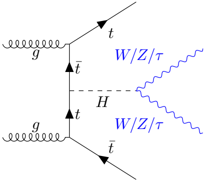

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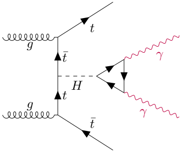

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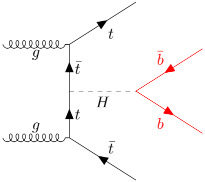

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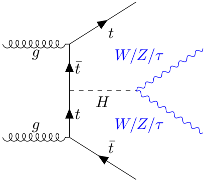

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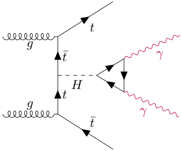
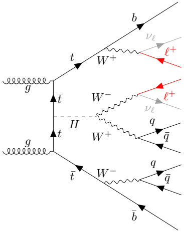
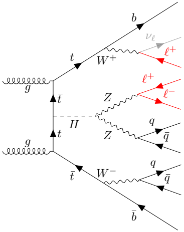
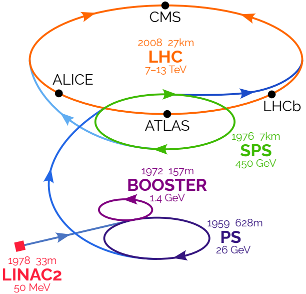


Multilepton: H→ZZ, H→ W^+W^-,H→ $\tau^+\tau^-$ → **Main BRs:** 2ℓSS and 3ℓ final state, no τ_{had}





LHC accelerator complex



Large Hadron Collider (LHC) at CERN near Geneva (Switzerland)

Main experiments at LHC that can perform the measurment:

- **ATLAS** (A Toroidal Lhc ApparatuS): general purpose detector
- **CMS** (Compact Muon Solenoid): general purpose detector

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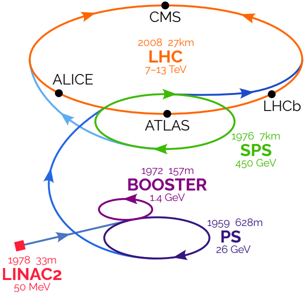

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- Run 1 (2010–2012) $\sqrt{s} = 7$–8 TeV
- Run 2 (2015–2018) $\sqrt{s} = 13$ TeV, used for this work
- Run 3 ongoing $\sqrt{s} = 13.6$ TeV

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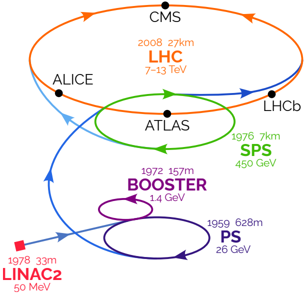

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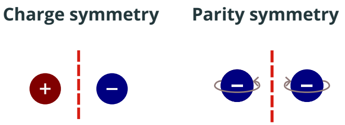
Observation of the process:

- 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

Introduction – CP

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**



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

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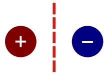
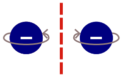


Parity symmetry



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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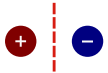
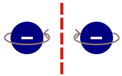
Charge symmetry



Parity symmetry



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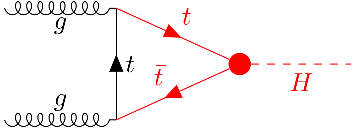

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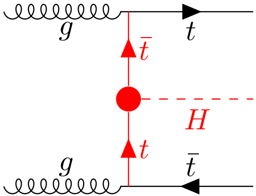
- $t\bar{t}H$: **allow probe top-Higgs coupling at tree level**
- **Ideal to test possible CP violation in Yukawa interaction**



- CP parametrization in the top Yukawa coupling:

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

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

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

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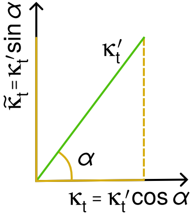
- Usually **use** $\kappa_t, \tilde{\kappa}_t \rightarrow$ **direct CP visualization**



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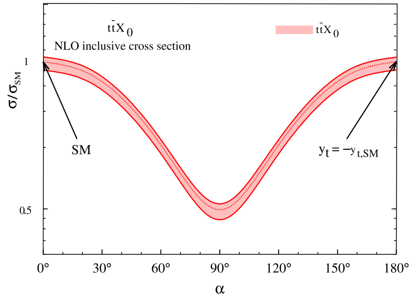

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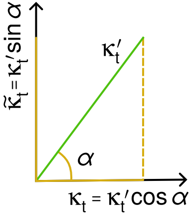
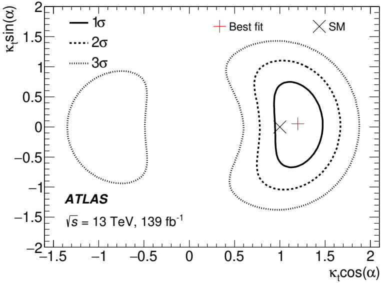
The plots set Higgs-top coupling to reproduce the SM gluon-fusion cross section for every value of α (link)



Model consequences:

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

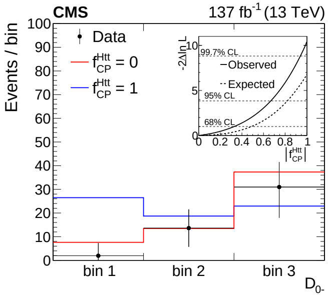
$t\bar{t}H$, H $\rightarrow \gamma\gamma$ CP results



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

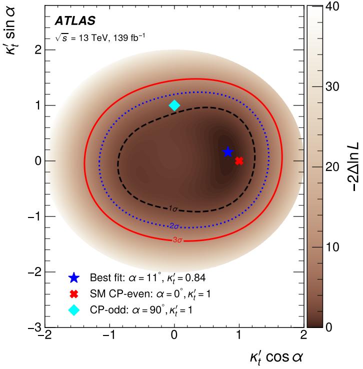


CMS analysis (link):

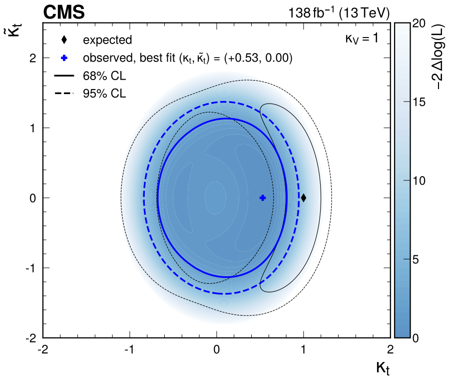
- Same strategy using MVAs to separate BKGs and CP-odd from CP-even
- Use of the parametrization:
  $$f_{CP}^{t\bar{t}H} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \, \mathrm{sign}\left(\tilde{\kappa}_t/\kappa_t\right).$$
- Observed $f_{CP}^{t\bar{t}H} = 0.00 \pm 0.33$ at 95%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

$t\bar{t}H$, $H \to b\bar{b}$ CP results

Currently instead of machine learning techniques, recent results started using directly CP-observables



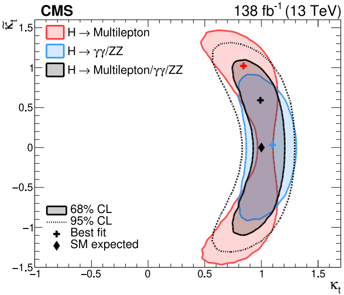
ATLAS $t\bar{t}H(H \to b\bar{b})$ (link) performed using CP-observables



CMS $t\bar{t}H$ (link), $H \to b\bar{b}$, from cross-section measurement

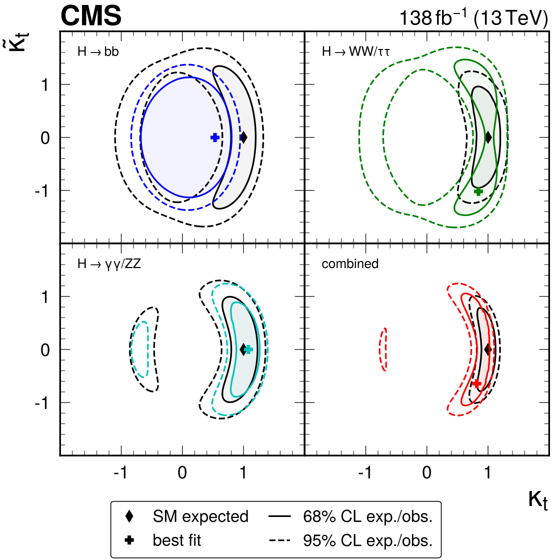
$t\bar{t}H$, other channels CP results and combination

Very active field $\longrightarrow$ still requires a final combination



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

CMS $t\bar{t}H$ combination (link)

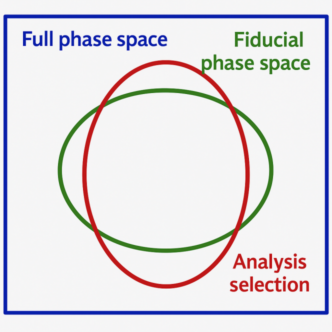


Introduction – STXS

- **Differential:** Measure cross-section in bins of observables
- **Fiducial:** Extrapolate the measurement to a restricted phase space matching experimental selections.

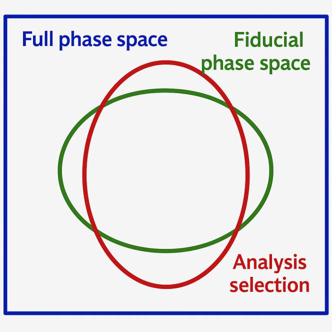
Fiducial differential cross–section measurements provide:

- A fundamental test of the SM predictions;
- A probe of phase spaces sensitive to BSM effects.



Fiducial Differential Cross–Section Measurements

- **Differential:** Measure cross-section in bins of observables
- **Fiducial:** Extrapolate the measurement to a restricted phase space matching experimental selections.



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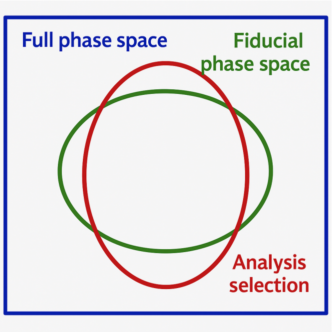

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- Long measurement lifetime and easy comparison with different theories

- Limited to few variables at the same time
- Hard to combine different channels without extrapolating to full phase space
- Non-trivial to include complex variables (e.g. DNNs) in fiducial phase space

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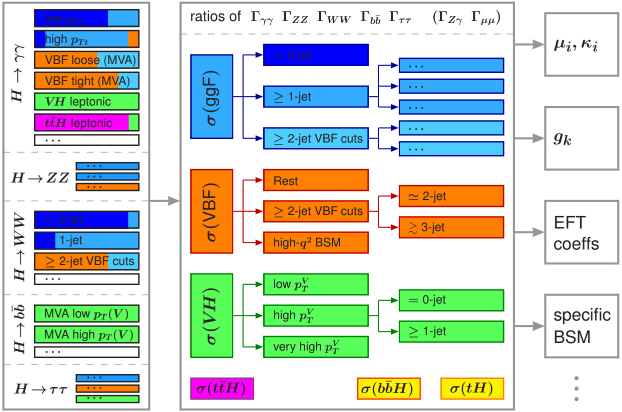
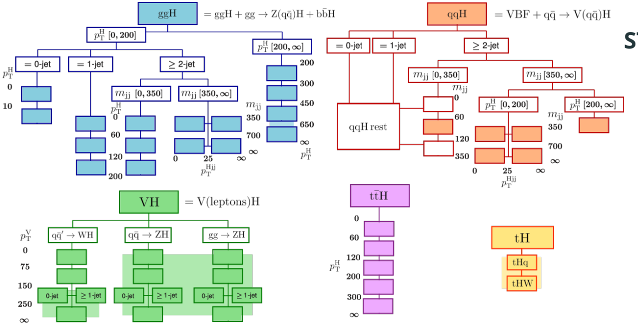
- **Supports and improves global combination** across all Higgs decay channels.



STXS and extension idea targeting CP violation in the top Yukawa coupling



STXS main points:

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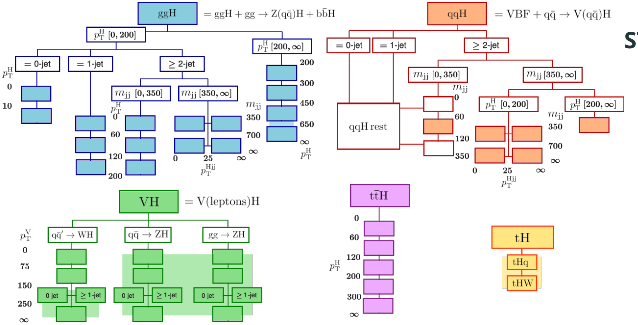

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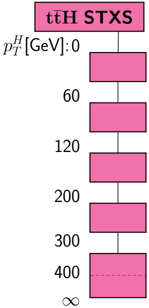
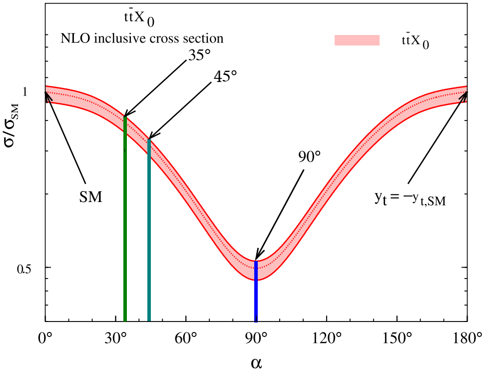
- **Goal:** developing an STXS extension targeting better tt̄H CP sensitivity
- CP-odd excluded by various studies at $4\sigma \rightarrow$ Obtained without the STXS framework
- $|\alpha| < 45^\circ \rightarrow$ decide to target 35°

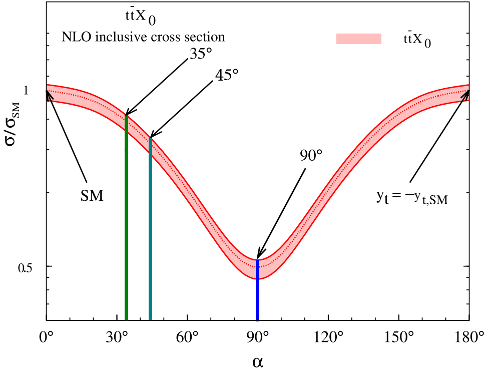


Study setup



- 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

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



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

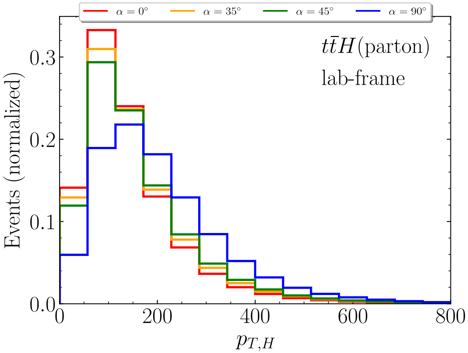
observable	definition	frame
p_T^H	-	lab, $t\bar{t}$, $t\bar{t}H$
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
$\cos(\theta^*)$	$\frac{\mathbf{p}_t \cdot \mathbf{n}}{\lvert\mathbf{p}_t\rvert \cdot \lvert\mathbf{n}\rvert}$	$t\bar{t}$
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**),
- $t\bar{t}$ 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**)

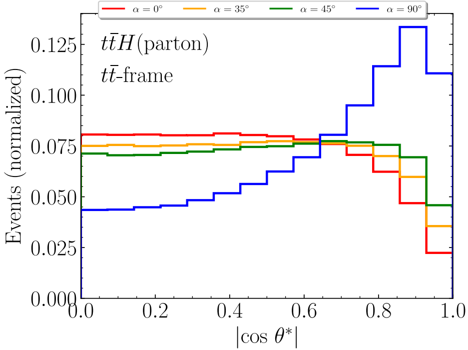
Examples of distributions at parton-level

$p_{T,H}$



Lab frame

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

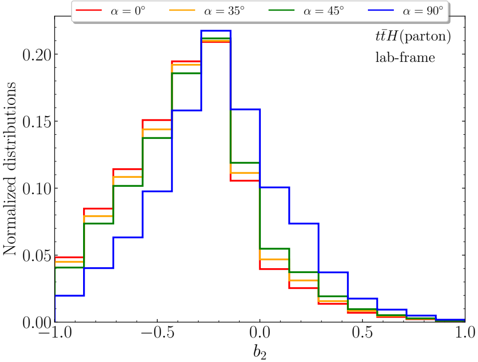


$t\bar{t}$ frame

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

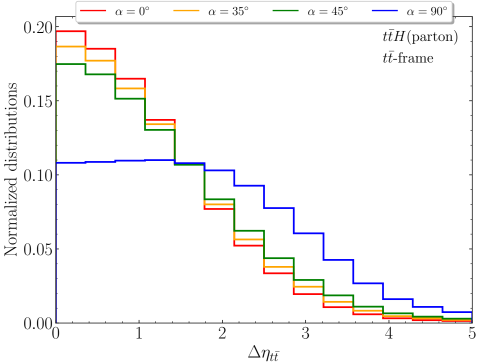
Examples of distributions at parton-level – other observables

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



Lab frame

$$\Delta\eta_{t\bar{t}}$$



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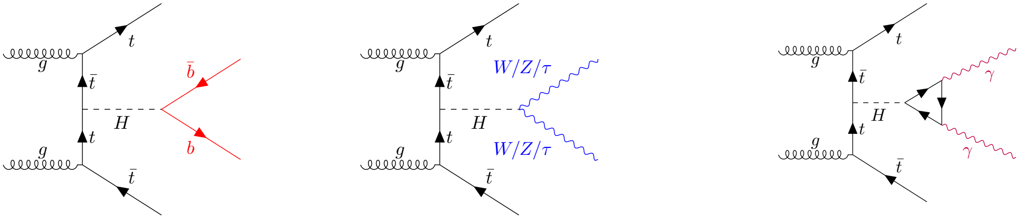
Analysis strategy

Detector effects and significance evaluation

- Channels considered: $t\bar{t}H(H\to\gamma\gamma)$, $t\bar{t}H(H\to b\bar{b})$ and $t\bar{t}H\to$ *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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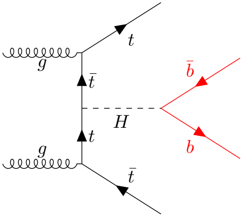

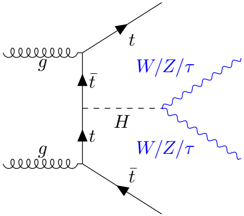

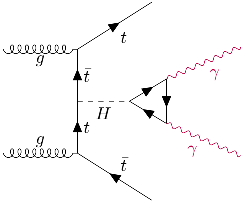

- Metric to judge the sensitivity of the various observables assuming acceptance, smearing, luminosity of 300 fb^{-1}
- Account for statistical and systematic uncertainty, in each bin σ_i is:

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

- 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

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

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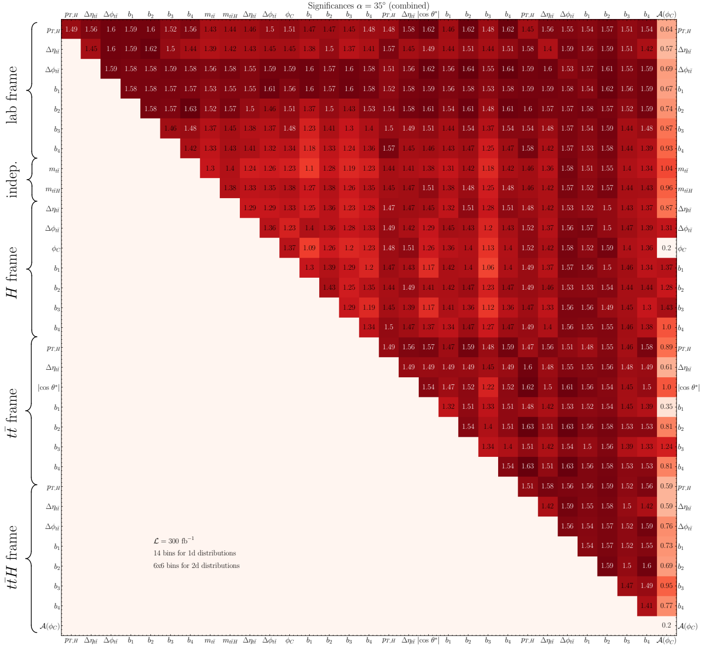

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$\alpha_t = 35°$ $t\bar{t}H$ @ $\mathcal{L} = 300$ fb^{-1} 14 (6 × 6) bins for 1d (2d) dist. **comb. w/ $p_{T,H}^{\text{lab}}$**

	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}.

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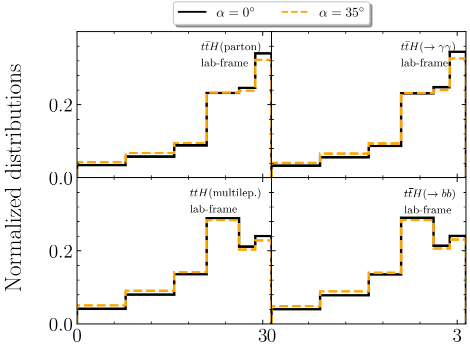
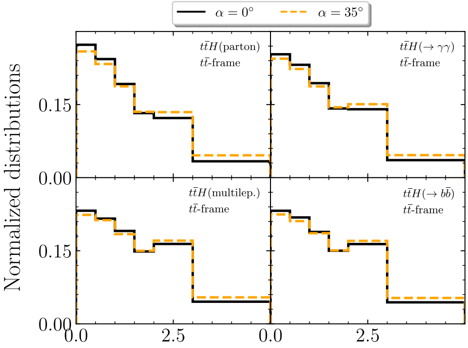
- Here showing $\Delta\phi_{t\bar{t}}^{\mathrm{lab}}$ and $\Delta\eta_{t\bar{t}}^{t\bar{t}}$



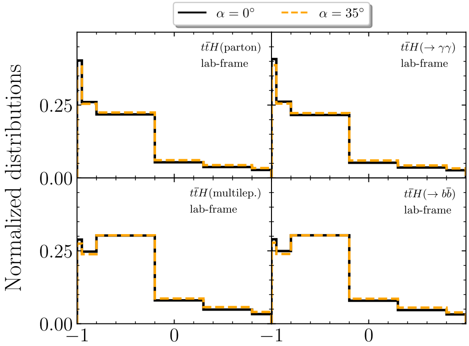
$\Delta\phi_{t\bar{t}}^{\mathrm{lab}}$: [0, $\pi/4$, $\pi/2$, $2\pi/3$, $5\pi/6$, $11\pi/12$, π]



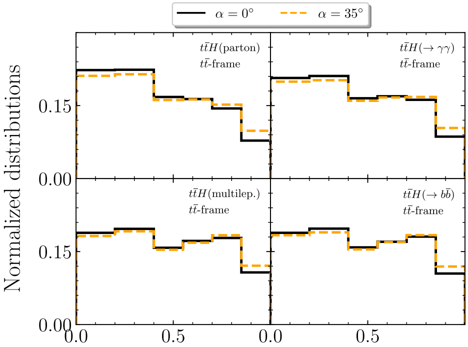
$\Delta\eta_{t\bar{t}}^{t\bar{t}}$: [0, 0.5, 1, 1.5, 2, 3, 5]

Best pairs & Optimized binning

- Other two examples below: b_1^{lab} and $\theta^{*,t\bar{t}}$



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



$\theta^{*,t\bar{t}}$: [0, 0.2, 0.4, 0.55, 0.7, 0.85, 1]

Best pairs significance results

- Results of significance after bin optimization: **very close performances**
- No clear winning and preferred candidate between them

$\alpha_t = 35^\circ$ $t\bar{t}H$ @ $\mathcal{L} = 300\ \mathrm{fb}^{-1}$ **comb. w/ $p_{T,H}^{\mathrm{lab}}$**

	lab frame				$t\bar{t}$ frame	
	$p_{T,H}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$
$H \to \gamma\gamma$	1.51	1.57	1.56	1.57	1.58	1.59
Multilep.	0.49	0.94	0.93	0.92	0.81	0.83
$H \to b\bar{b}$	0.31	0.55	0.55	0.55	0.51	0.52
Combined	1.61	1.91	1.9	1.9	1.85	1.87

background distribution study

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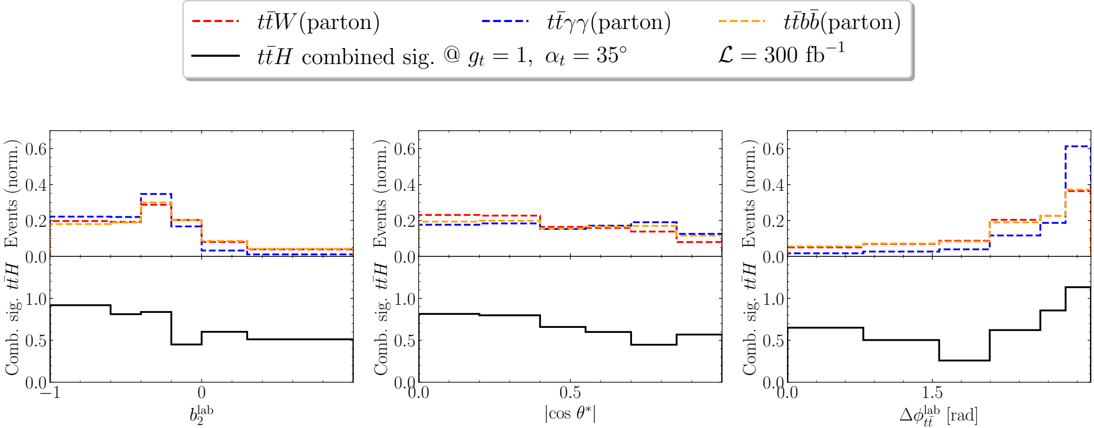
- Example on three observables of background shapes



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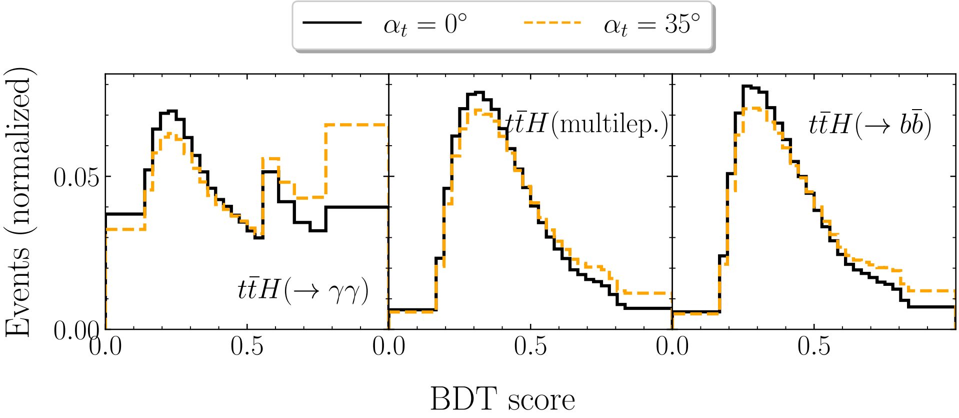

BDT results versus 2D combinations

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Channel	Significance (BDT)	Significance (2D)
$t\bar{t}H(\rightarrow \gamma\gamma)$	1.75	1.57
$t\bar{t}H$ (multilep.)	1.17	0.94
$t\bar{t}H(\rightarrow bb)$	0.69	0.55
Combined	2.21	1.91

- Significances from the BDT method are higher, **only moderately**:
  - $\sim$10% improvement for $H \rightarrow \gamma\gamma$
  - $\sim$17% improvement for $H \rightarrow$ multilepton
  - $\sim$25% improvement for $H \rightarrow b\bar{b}$

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- **Greater BDT sensitivity in**:
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- These channels benefit from selecting more $t\bar{t}H$ events and exploiting kinematic shapes.

BDT results versus 2D combinations

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Channel	Significance (BDT)	Significance (2D)
$t\bar{t}H(\to \gamma\gamma)$	1.75	1.57
$t\bar{t}H$ (multilep.)	1.17	0.94
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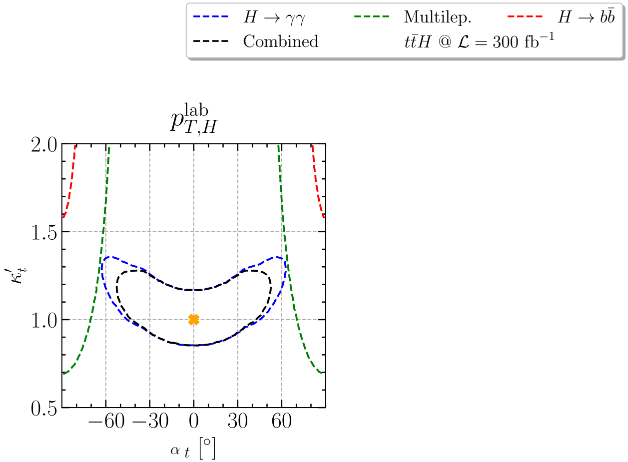
- These channels benefit from selecting more $t\bar{t}H$ events and exploiting kinematic shapes.
- Conclusion: **two-dimensional distributions are sufficient to reach near-optimal sensitivity** for probing CP violation in the top-Yukawa coupling.

Final result and proposed STXS extension

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



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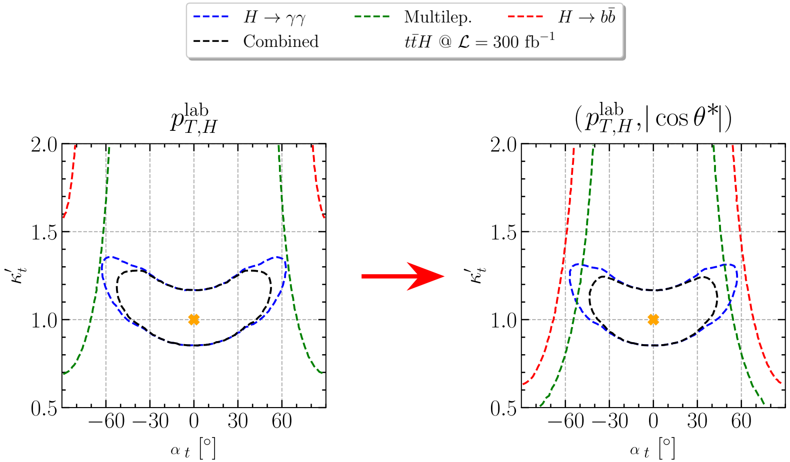
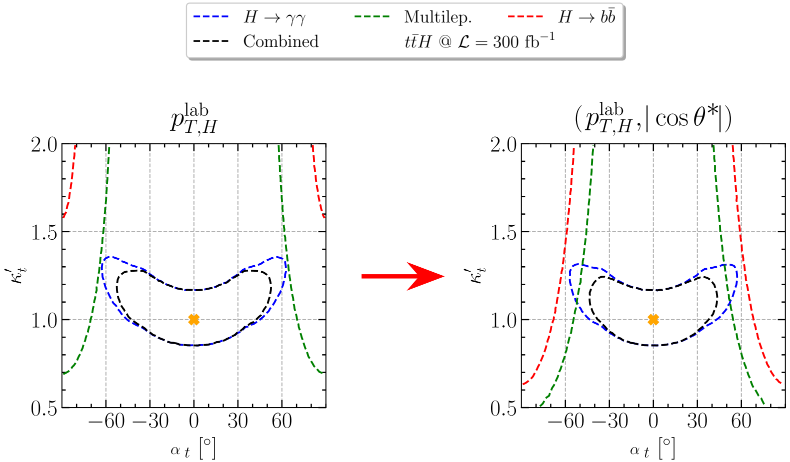


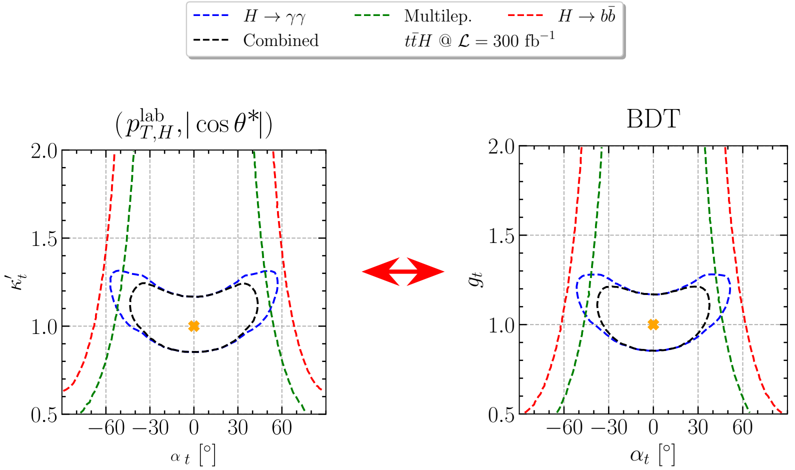
- Expected exclusion limits considering our model use 300 fb^{-1}
- Final limit at $\kappa_t' = 1$, $|\alpha| \lesssim 36^\circ$ at 68% CL $\rightarrow$ **12% better with respect to not using** $|\cos\theta^*|$

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



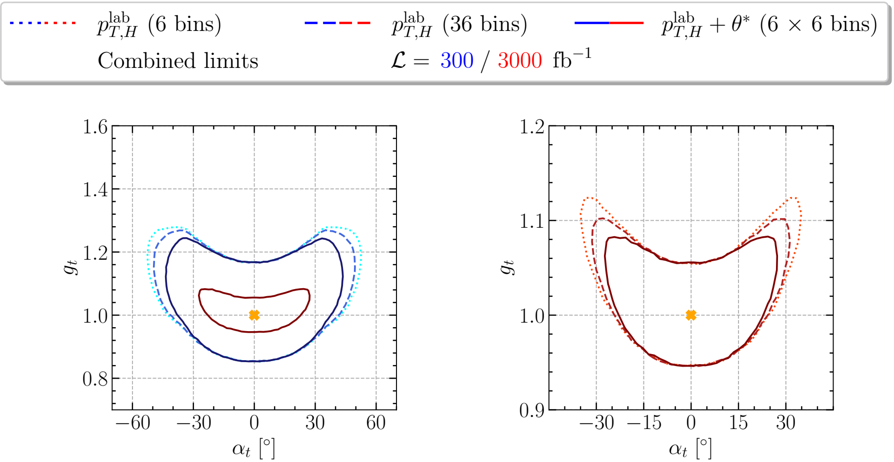
- Expected exclusion limits considering our model use 300 fb^{-1}
- Final limit at $\kappa_t' = 1$, $|\alpha| \lesssim 36°$ at 68% CL $\to$ **12% better with respect to not using** $|\cos\theta^*|$
- Maximum improvement of **40% at** $\kappa_t' = 1.24$
- Results are similar combining $p_{T,H}$ with $b_2^{\rm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

STXS extension, $|\cos\theta^*|$ vs BDT

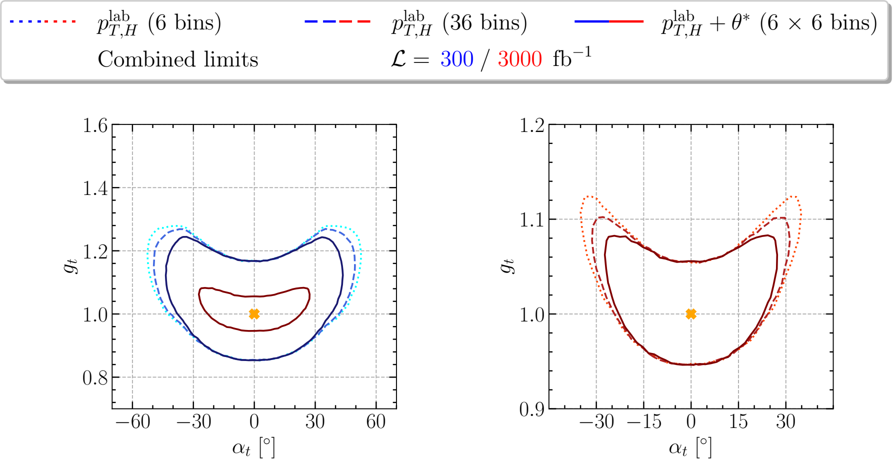


- Expected exclusion limits considering our model use 300 fb^{-1}
- Comparison limits vs the BDT approach shows a **clear but not so drastic improvement**

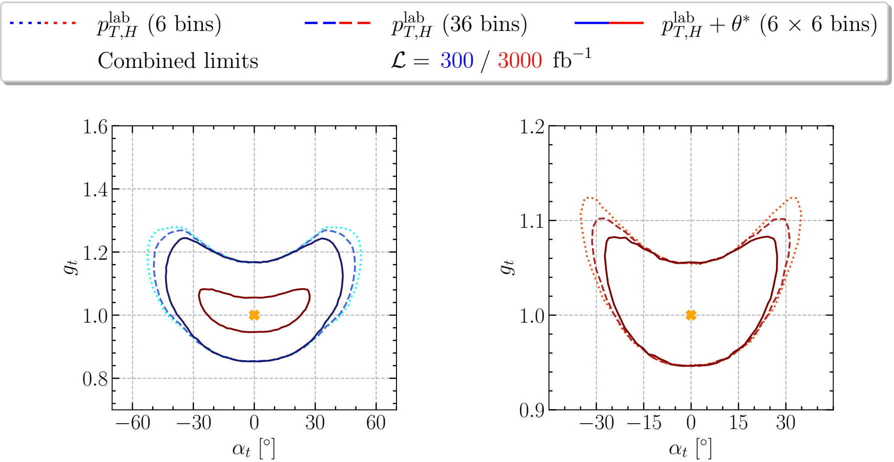
Expected exclusion limit at High-Luminosity LHC



Expected exclusion limit at High-Luminosity LHC



- **Constraints in the** (k_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



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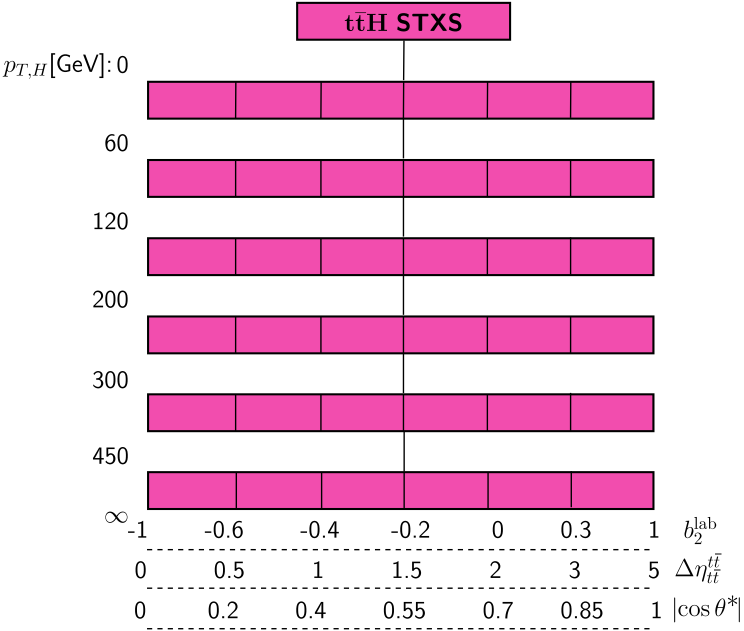
- **Evaluation using 6 (dotted line) and 36 (dashed line) bins and the two-dimensional** $(p_{T,H}, |\cos\theta^*|)$ distributions (solid line, 6 × 6 bins)
- $\mathcal{L} = 3000 fb^{-1}$ also presented with the $\mathcal{L} = 300 fb^{-1}$ contour

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 and outlook

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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
- Have been consider applying this new approach in ongoing measurements

Thank you for your attention

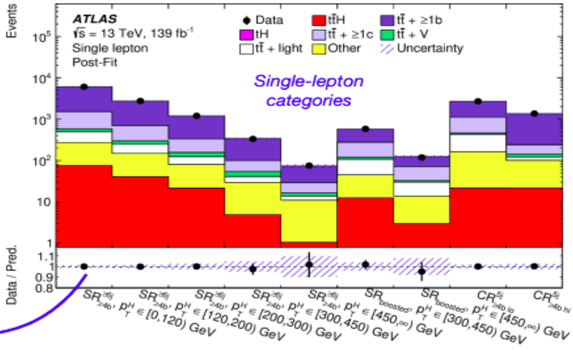
BACKUP

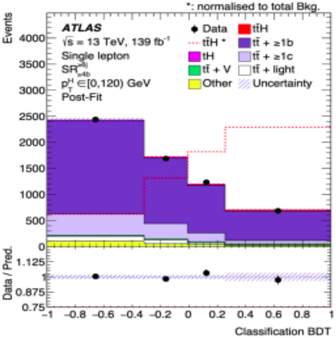
$t\bar{t}H$ ($H\rightarrow bb$)

[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)

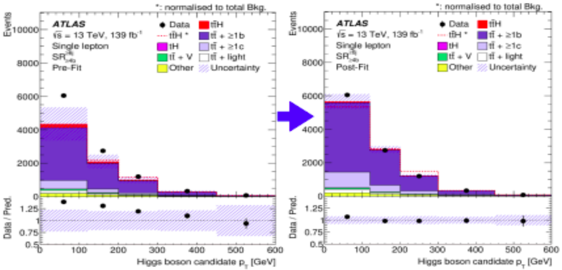
From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

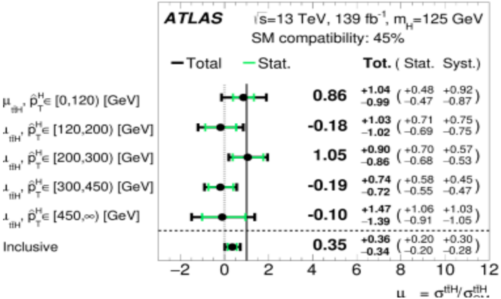
ttH (H→bb)

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 $p_{T,higgs}$





- **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)

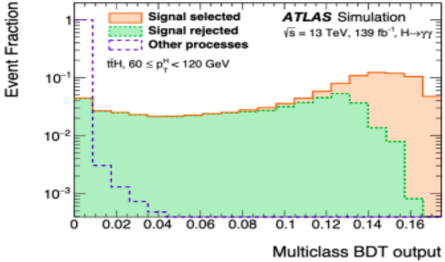
- Measured μ for five separate $p_{T,higgs}$ bins
- Sensitivity dominated by large theoretical uncertainties on irreducible tt+≥1b background

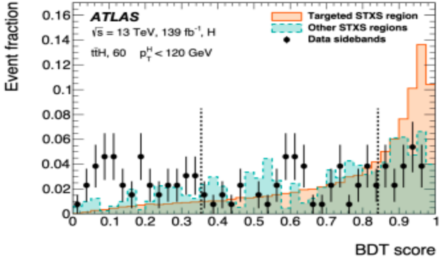
From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

tt̄H/tH (H→γγ)

Analysis Strategy (at 139 fb-1)

- targets tt̄H/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:

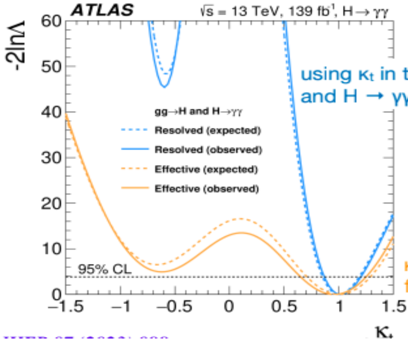
- Multi-classifier BDT sensitive to particular STXS regions + additional binary BDT trained to distinguish signal from background
- $tHqb$ class divided into two sub-classes using a neural network to distinguish between κ_t = 1 and κ_t = -1, and further categorization done to separate signal from background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

From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

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

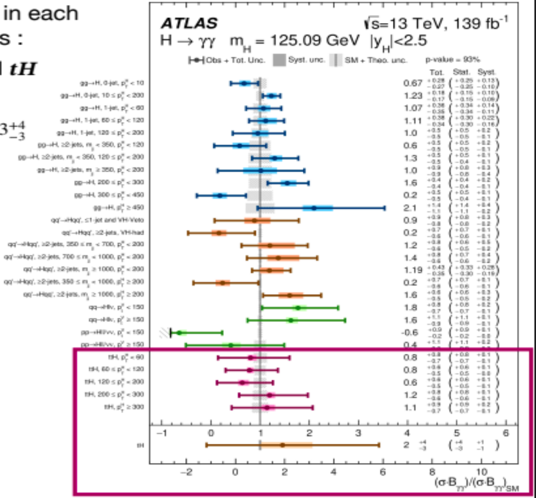
- Results for **STXS** parameters in each of the 28 phase-space regions :
  - 5 $t\bar{t}H$ p_T bins and additional tH category (p_T inclusive)
- **Inclusive:** $\mu_{t\bar{t}H} = 0.89^{+0.32}_{-0.30}$, $\mu_{tH} = 3^{+4}_{-3}$

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



using κ_t in the ggF and H → γγ loops

κ_g and κ_γ fixed to the SM prediction



From LHCP2024 talk of Anastasia Anastasia Kotsokechagia (link)

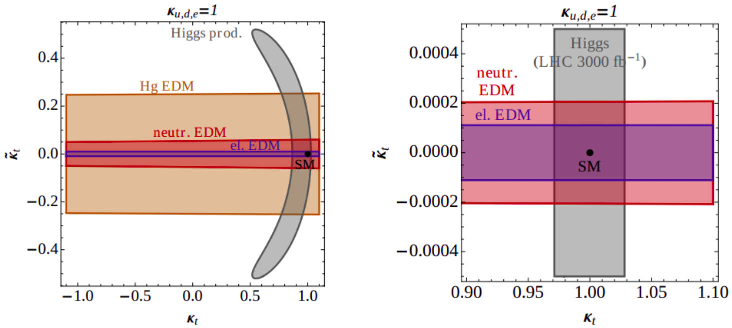


Figure 2. Left: Present constraints on κ_t and $\tilde{\kappa}_t$ from the electron EDM (blue), the neutron EDM (red), the mercury EDM (brown), and Higgs physics (gray). Right: Projected future constraints on κ_t and $\tilde{\kappa}_t$, see text for details.

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

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 $v \simeq 246\mathrm{GeV}$ 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)

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.)	$t\bar{t}H(\to b\bar{b})$
$\alpha = 0^\circ$	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

	$t\bar{t}H$(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	$4GeV$	$120GeV$	$80GeV$
$\Delta p_{T,t}$	None	$40GeV$	$70GeV$	$70GeV$
$\Delta \eta_t$	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	$2.27 \cdot 10^{-3}$	$6.79 \cdot 10^{-2}$	$5.81 \cdot 10^{-1}$
$\alpha = 0^\circ$	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