Higgs boson production in association with top quark at CMS

Clara Ramón Álvarez*
(on behalf of the CMS Collaboration)

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Higgs boson production

At LHC gg fusion is the dominant H production mode - $\sigma_{H,ggF} \sim 49\text{ pb @ 13 TeV}$

Top associated production, much lower rates:

- $t\bar{t}H - \sigma_{t\bar{t}H} \sim 0.5\text{ pb @ 13 TeV}$
- $tH - \sigma_{tH} \sim 0.07\text{ pb @ 13 TeV}$

Challenging but interesting:

- **Direct probe** of top-Higgs Yukawa coupling
  - $y_t \sim 1$ (largest in the SM)
  - BSM $y_t = -1 \rightarrow$ constructive interference $\rightarrow \sigma_{tH} \sim 0.8\text{ pb}$
- Probe EFT
Final states to study ttH+tH

**tt decays x Higgs decays**
\( t \rightarrow Wb \)

Branching ratio is not the end of the story...

**H → bb**
- Large number of events
- Large \( t\bar{t}+\text{jets} \) background contribution

**H → WW/ZZ/\( \tau\tau \)**
- Multileptonic
- \( \mu+\text{jets} \) and \( \tau+\text{jets} \)

**H→γγ/4\( \ell \)**
- Lower number of events
- Clear signature
- Resonant channels (peak)

- \( t\bar{t}H \) observed in 2018 (combining all channels) & observation in \( \gamma\gamma \)
- \( tH \) not yet observed
- \( t\bar{t}H \) recent updates: CP measurements, STXS studies
- Higgs Couplings and non-resonant HH Combination

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H 81, 378 (2021)

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JHEP 07, 27 (2021)


Nature 607, 60–68 (2022)
Final states to study ttH+tH

**tt decays x Higgs decays**  
t→ Wb

Branching ratio is not the end of the story...

**H → bb**
- Large number of events
- Large t̅t+jets background contribution

**H→ WW/ZZ/ττ**
- H and t leptonic decays
- Multiple leptons in the final state

**H→ γγ /4ℓ**
- Lower number of events
- Clear signature
- Resonant channels (peak)

- tH observed in 2018 (combining all channels) & observation in γγ
- tH not yet observed
- tH recent updates: CP measurements, STXS studies
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**HIG-18-030**

**Covered in this talk**

- EPJC 81, 378 (2021)
- JHEP 07, 27 (2021)
- Phys. Rev. Lett. 125, 061801
- Nature 607, 60–68 (2022)
Selection:
100 GeV < $m_{\gamma\gamma}$ < 180 GeV
2 high $p_T\gamma$ + additional jets and leptons

Two categories depending on final state objects:
- Hadronic: 0 Leptons & $\geq$ 3Jet & $\geq$ 1 btag
- Leptonic: $\geq$ 1 Lepton & $\geq$ 1Jet

- MVA (BDT-bkg) in each category to separate signal from background
- Simultaneous maximum likelihood (ML) fit performed using the $m_{\gamma\gamma}$

Results
First observation in a single H decay channel!
Observed significance of 6.6 s.d. (4.7 s.d.)

\[
\sigma_{ttH} B_{\gamma\gamma} = 1.56^{+0.34}_{-0.32} \text{ fb}
\]
\[
\mu_{ttH} = 1.38^{+0.36}_{-0.29}
\]
ttH→γγ: CP Interpretation

Kinematic info in ttH production is very rich, angular variables and reconstructed ttH mass sensitive to modification in the Htt coupling

MVA to reconstruct D0- operator

Fitting 12 categories: 2 (BDT-bkg) x 3 (D0-) x 2 (final state)
- Yields parametrized using $\kappa_t$ and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)

$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

$$f_{Htt}^{CP} = 0.00 \pm 0.33$$

$$|f_{CP}^{Htt}| < 0.67\text{ @ 95\%CL}$$

First CP measurement of Htt coupling
CP constrain dominated by statistical uncertainty
Pure Pseudo Scalar CP odd coupling excluded at 3.2 s.d.
**ttH → γγ STXS**

**STXS** (Simplified template cross section) **approach.** Categories targeting all H production modes, in particular $t\bar{t}H$ and $tH$

$t\bar{t}H$: 5 bins in $p_T^H$

tH: 1 category

Selection: the one in previous slide + NN to discriminate $t\bar{t}H$ vs $tH$

**Results**

- First channel to perform $t\bar{t}H$ measurement differentially!
- Good agreement with SM
- Upper limit on the $tH$ cross section is 14 (8 exp.) times the SM expectation
Categorize events depending on the **lepton multiplicity**

Dedicated **MVA to select isolated leptons** from H, W and \( \tau \)

Dedicated selection on each category. Using Jet and b-tagging multiplicities.

**Backgrounds:**

**Reducible backgrounds:**
- Non prompt leptons
- Electron charge miss ID.
- Photon Conversions

**Irreducible backgrounds:**
- \( t\bar{t}Z, \ t\bar{t}W \)
- Dibosons

Estimated with data-driven techniques

Control regions to constrain these backgrounds
**ttH → ml event classification**

- In each signal categories **Neural Network trained** to discriminate signal vs. background
- Dedicated **node to target** $t\bar{t}W$ in $2\ell ss+0\tau$ category
- Further classification depending on flavor, $b$-tag multiplicity...

Simultaneous **maximum likelihood fit** in the signal region categories as well as the control regions
- $t\bar{t}W$ and $t\bar{t}Z$ signal strengths ($\mu$) freely floated in the fit
ttH → ml results

- Signal strengths in good agreement with SM
  \[ \mu_{t\bar{t}H} = 0.92^{+0.26}_{-0.23} \] observed (expected) significance: 4.7 (5.2) s.d.
  \[ \mu_{tH} = 5.7^{+2.8}_{-2.7} \text{(stat.)}^{+3.0}_{-3.0} \text{(syst)} \] observed (expected) significance: 1.4 (0.3) s.d.

- Study Top-Higgs ($\kappa_t$) and Higgs-W ($\kappa_{V}$) coupling:
  - $-0.9 < \kappa_t < -0.7$ or $0.7 < \kappa_t < 1.1$ at 95 % C.L.
ttH → ml: CP interpretation

- Kinematic differences between ttH CP-even and CP-odd components
- Dedicated BDT in each of the 3 most sensitive ttH enriched categories
- Yields parametrized using: $\kappa_t$ and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)

\[ f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2} \]

ML fit profiling $\mu_{ttH}$
Good agreement with SM

\[ f_{CP}^{Htt} = 0.28 \text{ within } (-0.55, 0.55) \]

at 68% CL

\[ |f_{CP}^{Htt}| = 1 \text{ excluded with 3.7 s.d.} \]
Nature combination

Using all published results. Including $b\bar{b}$, $\gamma\gamma$, 4l and multileptons final states.

$k$ modifier affects $H$ decay but also production

$k_V$ and $k_f$ measured with $< 10\%$ unc.
Summary

Two of the most challenging H production modes had been studied during Run 2:
• $t\bar{t}H$ observation in 2018! ★
• $t\bar{t}H$ observation in $\gamma\gamma$
• Have seen improvements on the control of backgrounds
• Differential measurements in some channels

The amount of data taken during Run 2 allowed us to study Top-Higgs coupling:
• Good agreement with SM
• CP interpretations

Still analyzing Run 2 dataset
Run 3 already started:
• increase statistic a factor of $\sim 3!$
• Work ongoing on how to improve modelling of $t\bar{t}W$ ($H\to$ multilepton) and $t\bar{t}b\bar{b}$ ($H\to b\bar{b}$).
Back-up
**ttH → 4ℓ**

Use full Run 2 dataset

**Selection:** 4 isolated leptons that are opposite sign and same flavour -> used to reconstruct the ZZ pair

**STXS approach.** Categories targeting all H production modes, in particular ttH (little sensitivitiy to tH), binned in pTH

**Two categories** depending on top decay:
- **Hadronic:** ≥ 4 Jets, ≥ 1 btag, 0 additional leptons
- **Leptonic:** ≥ 1 additional lepton

**Two Dimesional fit** to m4l and kinematic disceiminat sig. vs bkg

Results

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{ttH,tH}$</td>
<td>$1.00^{+1.23}<em>{-0.77}$ (stat) $^{+0.51}</em>{-0.06}$ (syst)</td>
<td>$0.17^{+0.88}<em>{-0.17}$ (stat) $^{+0.42}</em>{-0.00}$ (syst)</td>
</tr>
</tbody>
</table>
$ttH \rightarrow 4\ell$

Expected

$\mu_{ttH,tH} = 1.00^{+1.23}_{-0.77} \text{ (stat)}^{+0.51}_{-0.66} \text{ (syst)}$

$0.17^{+0}_{-0}$

Observed

$0.17^{+0.88}_{-0.17} \text{ (stat)}^{+0.42}_{-0.00} \text{ (syst)}$

CMS

$137 \text{ fb}^{-1} (13 \text{ TeV})$

$H \rightarrow ZZ$

$m_H = 125.38 \text{ GeV}$

STXS merged Stage 1.2 - $|y_H| < 2.5$
ttH (ml) categories

Maximum Likelihood Fit

* bl (bt): < 2 (≥ 2) tight b-jets

3l – CR
4l – CR
<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mu_{t\bar{t}H}/\mu_{t\bar{t}H} [%]$</th>
<th>$\Delta \mu_{t\bar{t}H}/\mu_{t\bar{t}H} [%]$</th>
<th>$\Delta \mu_{t\bar{t}W}/\mu_{t\bar{t}W} [%]$</th>
<th>$\Delta \mu_{t\bar{t}Z}/\mu_{t\bar{t}Z} [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>2.3</td>
<td>8.1</td>
<td>1.2</td>
<td>1.9</td>
</tr>
<tr>
<td>$e, \mu$ reconstruction and identification efficiency</td>
<td>2.9</td>
<td>7.1</td>
<td>1.7</td>
<td>3.2</td>
</tr>
<tr>
<td>$\tau$ identification efficiency</td>
<td>4.6</td>
<td>9.1</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$b$ tagging efficiency and mistag rate</td>
<td>3.6</td>
<td>13.6</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Misidentified leptons and flips</td>
<td>6.0</td>
<td>36.8</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>3.4</td>
<td>8.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>MC sample and sideband statistical uncertainty</td>
<td>7.1</td>
<td>27.2</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Theory-related sources affecting acceptance and shape of distributions</td>
<td>4.6</td>
<td>18.2</td>
<td>2.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Normalization of MC-estimated processes</td>
<td>13.3</td>
<td>12.3</td>
<td>13.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.2</td>
<td>4.6</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>20.9</td>
<td>48.0</td>
<td>5.9</td>
<td>5.8</td>
</tr>
</tbody>
</table>
ttH ($\gamma\gamma$) syst + STXS

Theoretical:
- ttH normalization (QCD renormalization and factorisation scales)

Experimental:
- b quark and photon identification
- Jet energy scale and resolution
- Integrated luminosity
Lagrangian can be expressed as a superposition of CP-even and a CP-odd terms

\[ \mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2} \bar{\psi}_t (\kappa_t + i \gamma_5 \tilde{\kappa}_t) \psi_t H \]

With:
- \( y_t \) the top-Higgs coupling
- \( \kappa_t \) ratio of the CP-even terms to SM expectation
- \( \tilde{\kappa}_t \) ratio of the CP-odd terms to SM expectation

Defining \( \alpha \) as the CP mixing angle:
- \( \kappa_t \) proportional to \( \cos \alpha \)
- \( \tilde{\kappa}_t \) proportional to \( \sin \alpha \)

Kinematic differences as well as cross-section changes expected depending on the CP scenario

\( tH \) cross section sensitive to the inverted top coupling scenario \( (y_t = -y_t^{SM}) \)