Evidence of $t\bar{t}H$ production in final states with electrons, muons and hadronically decaying $\tau$ with 2016 CMS data at $\sqrt{s}=13$ TeV

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Higgs Hunting 2018
pp → ttH production

Measurement of top Yukawa coupling \( y_t \propto m_t/v \approx 1 \):
- extraordinary large mass: special role in EWSB mechanism?
- indirect sensitivity from \( ggF / H \to \gamma\gamma \) (loop)
- direct measurement from ttH production

small cross section (x4 from 8 TeV to 13 TeV) \( \propto \) cover as many decay channels as possible = Observation of ttH production by CMS

\[ \sigma_{ttH, 13 \text{ TeV}} \sim 510 \text{ fb} \]

This talk: ttH with H → WW*, H → ZZ*, H → ττ, with 2016 data (35.9 fb\(^{-1}\)) at CMS at \( \sqrt{s} = 13 \text{ TeV} \)
Higgs to leptons and hadronic $\tau$’s

6 orthogonal categories based on number of leptons ($e, \mu$) and hadronic $\tau$’s ($\tau_h$).

**Pure multilepton final states**

- $H \rightarrow WW^*$
- $H \rightarrow ZZ^*$

**2$\ell$SS**

**3$\ell$**

**4$\ell$**

**Final states with $\tau_h$’s**

$H \rightarrow \tau\tau$

- **1$\ell$+2$\tau_h$**
- **2$\ell$SS+1$\tau_h$**
- **3$\ell$+1$\tau_h$**

- Looking for 2 tops + 1 Higgs:
  - $t \rightarrow b \ell \nu$ 1 b-jet + 1 lepton + MET
  - $t \rightarrow b qq$ 1 b-jet + 2 light jets

- $H \rightarrow WW/ZZ$ leptons (+ jets + MET)
- $H \rightarrow \tau\tau$ 1-2 $\tau_h$ (+ lepton + MET)

- Complex event reconstruction (large multiplicity of objects in the final state).

- Extensive use of MVA discriminants for object identification ($b$-jets, leptons, $\tau_h$) and signal extraction (MEM, BDT).

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Event reconstruction

Leptons \((e, \mu)\)

Dedicated MVA to discriminate prompt leptons (from W, Z, \(\tau\) decays) against non-prompt (fake) leptons from B or light mesons.

Hadronic \(\tau\)

- Reconstructed with HPS algorithm based on decay mode
- \(\Delta R = 0.3\) isolation MVA (vs. q/g jets)

Jets

- PF reconstructed jets (anti-\(k_T\) clustering algorithm) with \(p_T > 25\) GeV, \(|\eta| < 2.4\)
- MVA algorithm to identify (tag) b-jets

Narrow cone centered on the lepton direction which shrinks with increasing lepton \(p_T\):
- high hadronic activity
- reduce PU effect

\[ I_\ell = \sum_{\text{charged}} p_T + \max \left(0, \sum_{\text{neutral}} p_T - \rho \ A \left[ \frac{R}{0.3} \right]^2 \right) \]

\(E_T^{\text{miss}}\)

- PF reconstructed \(E_T^{\text{miss}}\)
- \(H_T^{\text{miss}}\): worse resolution but pileup resilient

\[ H_T^{\text{miss}} = \left| \sum_{\ell, \text{leptons}} \vec{p}_{T\ell} + \sum_{\tau, \text{hadrons}} \vec{p}_{T\tau} + \sum_{\text{jets}} \vec{p}_{Tj} \right| \]

- Combine into a linear discriminator (LD) to reduce instrumental effects:

\[ E_T^{\text{miss}} \text{LD} = 0.6 \times E_T^{\text{miss}} + 0.4 \times H_T^{\text{miss}} \]
Background estimation

**Irreducible background** (modelled from simulation):
- **ttV**: ttZ, ttW(W), ttγ* MadGraph @NLO
- **Di-boson+jets**: WW, WZ, ZZ
- **Rare processes**: VVV, tttt, tZq, WWqq
- **tH**: tHq, tHW

**Reducible background** (estimated from data):

**Misidentification** ("Fakes")
- Non-prompt lepton / hadron → lepton or jet (q,g) → τh
- Estimated in events that fail the tight lepton selection (lepton mis-id probability from *multijet* and tt+jets events for leptons and τh’s, respectively)

**Charge misassignment** ("Flips")
- 2ℓSS and 2ℓSS+1τh: charge of one of the leptons *mismeasured* (negligible for muons)
- Estimated in opposite-sign events (charge flip probability from Z → ee events)

Both contributions comparable in 2ℓSS (+1τh), 3ℓ (+1τh)  
Irreducible ttV: dominant in 4ℓ  
Reducible tt: dominant in 1ℓ+2τh (mainly from fake τh)

Modelling of the data by the simulation validated in ttZ / ttW / WZ+jets enriched CRs
Signal extraction

- $1\ell + 2\tau_h$, $2\ell\text{SS}(+1\tau_h)$, $3\ell(+1\tau_h)$: use of MVA discriminants (MEM, BDT)
- $4\ell$: cut-and-count

Matrix Element Method (MEM)

\[ LR(y) = \frac{w_{t\bar{t}H}(y)}{w_{t\bar{t}H}(y) + \sum_{B} \kappa_B w_B(y)} \]

**Subcategorization:**
- "no-missing-jet": $t\bar{t}H \rightarrow bW\bar{b}W\tau\tau \rightarrow b\bar{b}j\bar{j}b\bar{b}l\bar{\ell}l\ell\nu_\tau\tau\tau\tau$ pair of jets reconstructed (improved separation of $t\bar{t}H$ signal)
- "missing-jet": otherwise

**Post-fit distributions**

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Signal extraction

- $1\ell + 2\tau_h$, $2\ell$ SS($+1\tau_h$), $3\ell$($+1\tau_h$): use of MVA discriminants (MEM, BDT)
- $4\ell$: cut-and-count

2 Boosted Decision Trees (BDTs)

1 BDT: $t\bar{t}H$ vs. $t\bar{t}V$
1 BDT: $t\bar{t}H$ vs. $t\bar{t}$+jets

2 $\ell$ SS and 3 $\ell$ subcategorization: lepton flavor and charges, b-tagging requirements

Post-fit distributions with floating signal strength

- LR ($3\ell$): MEM $t\bar{t}H$ vs. $t\bar{t}Z + t\bar{t}W$
- Hadronic top tagger ($2\ell$ SS): jet-triplet compatible with hadronic top decay products
- Hj tagger ($2\ell$ SS): jet originating from Higgs decay
Results

Signal rates $\mu$ in each category individually and for the combination of all six:

### Main systematic uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\Delta\mu/\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e, \mu$ selection efficiency</td>
<td>2–4</td>
<td>11</td>
</tr>
<tr>
<td>$\tau_h$ selection efficiency</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>b tagging efficiency</td>
<td>2–15</td>
<td>6</td>
</tr>
<tr>
<td>Reducible background estimate</td>
<td>10–40</td>
<td>11</td>
</tr>
<tr>
<td>Jet energy calibration</td>
<td>2–15</td>
<td>5</td>
</tr>
<tr>
<td>$\tau_h$ energy calibration</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Theoretical sources</td>
<td>$\approx$10</td>
<td>12</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Combined (syst.) $\mu = 1.23^{+0.45}_{-0.43}$

Observed (expected) local significance of $3.2\sigma$ ($2.8\sigma$)
Summary

- **Search** of associated production of a Higgs boson with a top quark pair in final states with $e$, $\mu$ and $\tau_h$, with pp data recorded by CMS in 2016 at $\sqrt{s} = 13 \text{ TeV}$ (35.9 fb$^{-1}$).

- **Strategy** of challenging analysis:
  - 6 mutually exclusive event **categories** (lepton and $\tau_h$ multiplicity).
  - Sensitivity enhanced by using **advanced MVA techniques** (BDTs and MEM).

- Measured observed (expected) signal rate of $1.23_{-0.43}^{+0.45}$, corresponding to an observed (expected) local significance of $3.2\sigma$ ($2.8\sigma$), in agreement with SM expectation

  $\rightarrow$ **Evidence** of associated production of a Higgs boson with a top quark pair in final states with $e$, $\mu$ and $\tau_h$.

- Result included in the $t\bar{t}H$ combination which led to the **observation** of the $t\bar{t}H$ process by CMS with a $5.2\sigma$ significance, where it played an crucial role.

- Combination with 2017 data coming soon…
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BACK-UP
Prompt-lepton MVA

Separate lepton MVAs are trained for electrons and muons, using simulated samples of prompt leptons in $t\bar{t}H$ signal events and non-prompt leptons in $t\bar{t}$+jets background events.

Inputs:

- **isolation of the lepton** with respect to charged and neutral particles, corrected for pileup effects
  \[ I_l = \sum_{\text{charged}} p_T + \max \left( 0, \sum_{\text{neutrals}} p_T - \rho A \left( \frac{R}{0.3} \right)^2 \right) \]
  \[ R = \begin{cases} 
    0.05, & \text{if } p_T > 200 \text{ GeV} \\
    10 \text{ GeV} / p_T, & \text{if } 50 < p_T < 200 \text{ GeV} \\
    0.20, & \text{if } p_T < 50 \text{ GeV} 
  \end{cases} \]

- **ratio of the** $p_T$ **of the lepton to the** $p_T$ **of the nearest jet**

- **b-tagging** discriminant

- the component of the **lepton momentum perpendicular to the jet** axis

- the transverse and longitudinal **impact parameters** of the lepton track with respect to the PV

- **significance of the impact parameter of the lepton track**: impact parameter (in three dimensions) **divided by its uncertainty**.

- $p_T$ and $\eta$ of the lepton

- **electron** identification **MVA** output / **compatibility of track** segments in the **muon** system with the pattern expected from muon ionization
b-tag and $\tau_h$ efficiencies

<table>
<thead>
<tr>
<th>Working point</th>
<th>b-tagging efficiency</th>
<th>Light flavor (udsg) mistag rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose</td>
<td>83%</td>
<td>10%</td>
</tr>
<tr>
<td>Medium</td>
<td>69%</td>
<td>1%</td>
</tr>
<tr>
<td>Tight</td>
<td>49%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

**Graph 1:**
- **Title:** CMS Preliminary
- **Description:** Muon enriched QCD AK4 jets ($50 < p_T < 250$ GeV)
- **Legend:**
  - Data
  - b
  - c
  - udsg
  - b from gluon splitting
- **Axes:** Jets/0.02 vs. CSVv2 Discriminator

**Graph 2:**
- **Title:** CMS Simulation Preliminary
- **Description:**
  - Z $\rightarrow \tau\tau$ MC
  - $p_T^Z$ (GeV)
- **Legend:**
  - VLoose
  - Loose
  - Medium
  - Tight
  - VTight
  - VVTight
- **Axes:** $p_T^Z$ (GeV)

**Graph 3:**
- **Title:** CMS Simulation Preliminary
- **Description:**
  - QCD multi-jet MC ($15 < p_T < 3000$ GeV flat)
  - $p_T^{\text{jet}}$ (GeV)
- **Legend:**
  - $\tau_h$
  - Jets
- **Axes:** MVA output

**Graph 4:**
- **Title:** CMS Simulation Preliminary
- **Description:**
  - Relative yield / bin
- **Legend:**
  - $\tau_h$
  - Jets
- **Axes:** MVA output

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# Event selection

<table>
<thead>
<tr>
<th>Selection</th>
<th>(2\ell ss)</th>
<th>(2\ell ss + 1tH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targeted (t\bar{t}H) decay</td>
<td>(t \rightarrow b\ell v, t \rightarrow bq\nu)</td>
<td>(t \rightarrow b\ell v, t \rightarrow bq\nu)</td>
</tr>
<tr>
<td>(H \rightarrow WW \rightarrow \ell\nu qq)</td>
<td>(H \rightarrow \tau\tau \rightarrow \ell tH + \nu's)</td>
<td></td>
</tr>
</tbody>
</table>

### Trigger
- Single- and double-lepton triggers

<table>
<thead>
<tr>
<th>Lepton (p_T)</th>
<th>(p_T &gt; 25 / 15 \text{ GeV})</th>
<th>(p_T &gt; 25 / 15 \text{ (e)} \text{ or } 10 \text{ GeV (}\mu\text{)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_H p_T)</td>
<td>(p_T &gt; 20 \text{ GeV})</td>
<td></td>
</tr>
</tbody>
</table>

### Charge requirements
- 2 same-sign leptons
- and charge quality requirements
  - \(\sum q = \pm 1\)
- \(t_H q = 0\)

### Jet multiplicity
- \(\geq 4\) jets
- \(t_H p_T > 20 \text{ GeV}\)

### b tagging requirements
- \(\geq 1\) tight b-tagged jet or \(\geq 2\) loose b-tagged jets

### Missing transverse momentum
- \(L_D > 30 \text{ GeV}\)

### Dilepton mass
- \(m_{\ell\ell} > 12 \text{ GeV} \text{ and } |m_{ee} - m_Z| > 10 \text{ GeV}\)*

<table>
<thead>
<tr>
<th>Selection</th>
<th>(3\ell)</th>
<th>(3\ell + 1tH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targeted (t\bar{t}H) decays</td>
<td>(t \rightarrow b\ell v, t \rightarrow b\ell v)</td>
<td>(t \rightarrow b\ell v, t \rightarrow b\ell v)</td>
</tr>
<tr>
<td>(H \rightarrow WW \rightarrow \ell\nu qq)</td>
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<td></td>
</tr>
<tr>
<td>(t \rightarrow b\ell v, t \rightarrow bq\nu)</td>
<td>(t \rightarrow b\ell v, t \rightarrow bq\nu)</td>
<td></td>
</tr>
<tr>
<td>(H \rightarrow ZZ \rightarrow \ell\nu qq \text{ or } \ell\nu vv)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Trigger
- Single-, double- and triple-lepton triggers

<table>
<thead>
<tr>
<th>Lepton (p_T)</th>
<th>(p_T &gt; 25 / 15 / 15 \text{ GeV})</th>
<th>(p_T &gt; 20 / 10 / 10 \text{ GeV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_H p_T)</td>
<td>(p_T &gt; 20 \text{ GeV})</td>
<td></td>
</tr>
</tbody>
</table>

### Charge requirements
- \(\sum q = \pm 1\)
- \(\sum q = 0\)

### Jet multiplicity
- \(\geq 2\) jets

### b tagging requirements
- \(\geq 1\) tight b-tagged jet or \(\geq 2\) loose b-tagged jets

### Missing transverse momentum
- No requirement if \(N_{\ell} \geq 4\)
- \(L_D > 45 \text{ GeV}\)*
- \(L_D > 30 \text{ GeV}\) otherwise

### Dilepton mass
- \(m_{\ell\ell} > 12 \text{ GeV} \text{ and } |m_{ee} - m_Z| > 10 \text{ GeV}\)**

* Applied only if both leptons are electrons.
† If the event contains a SFOS lepton pair and \(N_{\ell} \leq 3\).
‡ Applied to all SFOS lepton pairs.
## Event selection

<table>
<thead>
<tr>
<th>Selection</th>
<th>$1\ell + 2\tau_h$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Targeted $ttH$ decays</strong></td>
<td>$t \rightarrow b\ell\nu, t \rightarrow bqq, H \rightarrow \tau\tau \rightarrow \tau_h\tau_h + \nu's$</td>
<td>$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu, H \rightarrow WW \rightarrow \ell\ell\ell\nu$</td>
</tr>
</tbody>
</table>

**Trigger**

<table>
<thead>
<tr>
<th>Lepton $p_T$</th>
<th>$p_T &gt; 25$ (e) or 20 GeV ($\mu$)</th>
<th>$p_T &gt; 25 / 15 / 15 / 10$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h$ $p_T$</td>
<td>$p_T &gt; 30 / 20$ GeV</td>
<td>—</td>
</tr>
</tbody>
</table>

**Jet multiplicity**

- $\geq 3$ jets
- $\geq 2$ jets

**b tagging requirements**

- $\geq 1$ tight b-tagged jet or $\geq 2$ loose b-tagged jets

**Charge requirements**

- $\sum q = 0$ and $\sum q = \pm 1$
- $\sum \ell = 0$ or $\sum \ell = 2$

**Missing transverse momentum**

- No requirement if $N_j \geq 4$
- $L_D > 45$ GeV $^\dagger$
- $L_D > 30$ GeV otherwise

**Dilepton mass**

- $m_{\ell\ell} > 12$ GeV
- $m_{\ell\ell} > 12$ GeV
- and $|m_{\ell\ell} - m_Z| > 10$ GeV $^\ddagger$

**Four-lepton mass**

- —
- $m_{4\ell} > 140$ GeV $^§$

$^\dagger$ If the event contains a SFOS lepton pair and $N_j \leq 3$.

$^\ddagger$ Applied to all SFOS lepton pairs.

$^§$ Applied only if the event contains 2 SFOS lepton pairs.
“Fakes” background estimation

• Non-prompt lepton / hadron → lepton
• Jet \((q,g) → \tau_h\)

Fake factor (FF) method:
  - Same selection as SR but relaxing identification criteria (“tight” to “fakeable”): AR.
  - Estimation of fake background in SR done applying weights to the events in the AR.
  - Weights depend on the probability \(f_i\) of a misidentified lepton or \(\tau_h\) that passes the “fakeable” criteria to pass the “tight” criteria.

For events with 2 objects

\[
w_2 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 1 \\ \frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 0 \end{cases}
\]

For events with 3 objects

\[
w_3 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 2 \\ \frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 1 \\ \frac{f_1 f_2 f_3}{(1-f_1)(1-f_2)(1-f_3)} & \text{if } N_p = 0 \end{cases}
\]

- Measured separately for e / \(\mu\) (multijets), \(\tau_h\) (t\(\bar{t}\)+jets) (DR)
- \(2\ell\)SS+1\(\tau_h\), 3\(\ell\)+1\(\tau_h\): restricted to leptons. \(\tau_h\) contribution estimated from MC. (30% of the t\(\bar{t}\)H signal has fake \(\tau_h\)).
Charge-flip background estimation

$2\ell_{SS}, 2\ell_{SS}+1\tau_h$ categories

- 2IOS prompt leptons $\rightarrow 2\ell_{SS}$ prompt leptons

Fake factor (FF) method:

- Same selection as SR but requiring 2 leptons opposite sign: AR.
- Estimation of fake background in SR done applying weights to the events in the AR.
- Weights depend on the probability $f_i$ to mismeasure the charge of either one of the 2 leptons.

- $2\ell_{SS}$: $\omega = \text{sum of the probabilities to mismeasure the charge of either one of the two leptons}$
- $2\ell_{SS}+1\tau_h$: $\omega = \text{the probability to mismeasure the sign of the lepton with the same sign as the } \tau_h \text{ (charge requirements already applied)}$

- Measured separately for e ($Z/\gamma^* \rightarrow ee$), $\mu$ ($Z/\gamma^* \rightarrow \mu\mu$) (DR) as the ratio between SS and OS leptons.
Hadronic top tagger (2ℓSS)

- Compatibility of jets with a **hadronic decay of a top quark**.
- BDT classifier, evaluated for each possible jet and lepton permutation, using several **kinematic** quantities and **b-tagging** information as inputs.
- The maximum over all those permutations is used as input to the BDT that separates the \( ttH \) signal from the \( tt+\text{jets} \) background.

- Inputs:
  - mass and \( p_T \) of the reconstructed hadronic top
  - mass of the W boson and the CSV discriminator of the b-jet originating from the hadronic top decay
  - \( p_T \) ratio of the lepton from the Higgs to the lepton from the top
  - \( \Delta R \) separation between leptons and b-jets from the top quark pair system.

![Hadronic top tagger BDT score](image)
Hj tagger \((2\ell SS)\)

- Compatibility of jets to originate from \(H \rightarrow WW\) decays in which one \(W\) boson decays leptonically and the other to a pair of quarks.
- BDT classifier, evaluated per jet, using **angular** variables and **jet identification** variables (b tagging and quark-gluon discriminants).
- The maximum over all jets is used as input to the BDT that separates the \(tt\bar{H}\) signal from the \(tt\bar{V}\) background.
- Jets that are compatible with originating from the hadronic decays of top quarks are excluded from the computation.
- Inputs:
  - jet identification (CSV discriminator, quark-gluon jet likelihood)
  - geometric properties (\(\Delta R\) with respect to the leptons)

![Graph showing data and predictions for \(H \rightarrow l\nu+\text{jet(s)}\) tagger BDT score](image)
MEM (2ℓSS+1τ_h)

Compatibility of the event measured with observables \( y \) with the hypothesis that the event is produced by the process \( \Omega \)

\[
\omega_\Omega(y) \propto \sum_p \int dx dx_a dx_b \frac{f_i(x_a, Q)f_j(x_b, Q)}{x_ax_bs} \delta^4(x_ap_a + x_bp_b - \sum p_k) |M_\Omega(x)|^2 W(y|x)
\]

All possible associations between parton-level and reconstructed objects

Bjorken variables (fraction of proton momentum carried by parton)

Energy and momentum conservation (reduce integral dimensionality)

Kinematic variables (4-momenta of partons in initial and final state)

Measured set of observables in the detector.

Transfer function (the probability for measuring a set of observables \( y \) in the detector, given that the corresponding parton-level momenta are equal to \( x \)) -> experimental resolution. Computed with MC simulation.

Hard-scattering matrix element. Computed to LO with MadGaph.

Parton distribution functions (PDF). Computed numerically to LO using CTEQ6.6 and NNPDF3.0.

High-dimensional integrals, poorly measured. Numerical integration (VEGAS, MC-chain)

Energy and momentum conservation (reduce integral dimensionality)

The coefficients \( \kappa_B \) that quantify the relative importance of different background processes \( B \) are determined by a numerical optimization, in order to achieve the maximal separation of the \( ttH \) signal from all background processes.
In the 3L event category only, the kinematic variables listed above are complemented by matrix element weights. A weight $w_{i,a}$ is computed for each hypothesis $a$ (where $a$ is either $\ttH$, $\ttW$, or $\ttZ$) and for the event $i$ as follows:

$$w_{i,a}(\Phi') = \frac{1}{\sigma_a} \int d\Phi_a \cdot \delta^4\left(p_{t1}^a + p_{t2}^a - \sum_{k>2} p_{k}^a\right) \cdot \frac{f(x_1, \mu_F) f(x_2, \mu_F)}{x_1 x_2 s} \cdot |M_a(p_k^a)|^2 \cdot W(\Phi'|\Phi_a),$$

where $\sigma_a$ is the cross section; $\Phi'$ are the 4-momenta of the reconstructed particles; $d\Phi_a$ is the element of phase space corresponding to unmeasured quantities with momentum conservation enforced; $f(x, \mu_F)$ are the parton density functions, computed using NNPDF3.0 LO [26]; $|M_a|^2$ is the squared matrix element, computed with MADGRAPH 5_AMC@NLO standalone [27] at LO in the narrow-width approximation for $t$, $\bar{t}$ and $H$, and $W$ are the transfer functions for jet energy and $E_{T}^{\text{miss}}$, relating parton to reconstructed quantities, estimated from simulated $\ttH$ events.

The two jets with the highest CSV tagging output are assigned to the two $b$ quarks in the matrix element. Among the remaining jets, the pair with dijet mass closest to $m_{W}$ is selected. In $\ttH$, for semileptonic decays of the Higgs daughters, the pair with lowest dijet mass is selected. If one or two jets needed to evaluate $|M_a|^2$ fail to be reconstructed, the weight is recovered by extending the integration phase space for the missing jets.

The final weight for each hypothesis $a$ is taken as the average of the weights computed for each lepton and jet permutation. The MEM weights of signal and backgrounds are combined in a likelihood ratio that is used as an input variable to the BDT. Including the MEM weights in the BDT training against $\ttW/\ttZ$ improves the background rejection power by about 10% for the three lepton category.
Subcategory distributions in $2\ell$SS
Signal extraction

1\ell + 2\tau_h  

1 BDT  

ttH vs. t\bar{t}+jets

Background dominated by t\bar{t}+jets

Post-fit distributions with floating signal strength

\begin{array}{c|c}
\text{Observable} & 1\ell + 2\tau_h \\
\hline
\Delta R(\ell_1,j) & - \\
\Delta R(\ell_2,j) & - \\
\langle \Delta R_{\ell j} \rangle & \checkmark \\
\Delta R_{\tau\tau} & \checkmark \\
\text{max} (|\eta^{\ell_1}|,|\eta^{\ell_2}|) & - \\
H_{\text{miss}} & \checkmark \\
N_j & \checkmark \\
N_{b} & \checkmark \\
m_{\text{miss}} & - \\
m_{t} & - \\
p_T^{\ell_1} & - \\
p_T^{\ell_2} & - \\
p_T^{\tau_1} & - \\
p_T^{\tau_2} & - \\
LR(3\ell) & \checkmark \\
MVA_{\text{max}}^{\tau_h} & - \\
MVA_{\text{max}}^{tH} & - \\
\end{array}

Events

Data - Expectation

Expectation

Discriminant

CMS  
35.9 fb^{-1} (13 TeV)

\begin{itemize}
\item Observed
\item ttH (\hat{\mu}=1.23)
\item Misid. leptons
\item t\bar{t}W + ttWW
\item WZ + ZZ
\item Rare + ttH
\item Uncertainty
\end{itemize}

Events

selected Events

Data - Expectation

Expectation

CMS  
35.9 fb^{-1} (13 TeV)

\begin{itemize}
\item Observed
\item ttH (\hat{\mu}=1.23)
\item WZ + ZZ
\item Rare + ttH
\item tH
\item Uncertainty
\end{itemize}

Background dominated by t\bar{t}+jets

Low number of events

Higgs Hunting 2018 - Cristina Martin Perez
Additional signal extraction distributions

Figure 3: Distributions in the discriminating observables used for the signal extraction in the "no-missing-jet" (top left) and "missing-jet" (top right) subcategories of the 2ℓss + 1τ_{ll} category, the 3ℓ category (bottom left), and the 3ℓ + 1τ_{ll} category (bottom right), compared to the SM expectation for the tH signal and for background processes. The MEM discriminant LR(2ℓss + 1τ_{ll}) is used in the 2ℓss + 1τ_{ll} subcategories, while a D_{MV} variable, combining the outputs of two BDTs trained to discriminate the tH signal from the ttV and t+ jets backgrounds respectively, is used in the 3ℓ and 3ℓ + 1τ_{ll} categories. The distributions expected for signal and background processes are shown for the values of nuisance parameters obtained from the combined ML fit and μ = β = 1.23, corresponding to the best-fit value from the ML fit. The lowest bin of the MEM discriminant in the "missing-jet" subcategory of the 2ℓss + 1τ_{ll} category collects events for which the kinematics of the reconstructed objects is not compatible with the tH, H → ττ signal hypothesis.
Additional signal extraction distributions

Figure 2: Distributions in the discriminating observables used for the signal extraction in the $1\ell + 2\tau_h$ category (top left) and in different subcategories of the $2\ell_{ss}$ category (top right and bottom row), compared to the SM expectation for the $t\bar{t}H$ signal and for background processes. A BDT trained to separate the $t\bar{t}H$ signal from the $t\bar{t}$+jets background is used in the $1\ell + 2\tau_h$ category, while a $D_{MVA}$ variable, combining the outputs of two BDTs trained to discriminate the $t\bar{t}H$ signal from the $t\bar{t}V$ and $t\bar{t}$+jets backgrounds respectively, is used in the $2\ell_{ss}$ subcategories. The distributions expected for signal and background processes are shown for the values of nuisance parameters obtained from the combined ML fit and $\mu = \hat{\mu} = 1.23$, corresponding to the best-fit value from the ML fit.
Data-to-MC corrections

- **Pileup reweighting**: difference in PU distributions.
- **Trigger efficiency**: measured in $Z/\gamma^* \rightarrow ee$, $Z/\gamma^* \rightarrow \mu\mu$, $Z/\gamma^* \rightarrow \tau\tau$ events
- **e and $\mu$ reconstruction, identification and isolation efficiency**: measured in $Z/\gamma^* \rightarrow ee$, $Z/\gamma^* \rightarrow \mu\mu$ events
- **$\tau_h$ identification efficiency**: measured in $Z/\gamma^* \rightarrow \tau\tau$ events
- **$\tau_h$ energy scale**: measured in $Z/\gamma^* \rightarrow \tau\tau$ events
- **b-tag efficiency and mistag rate**: measured in tt+jets and $Z/\gamma^* \rightarrow \ell\ell$ events, respectively.
- **$E_T^{\text{miss}}$ resolution and response**: measured in $Z/\gamma^* \rightarrow \ell\ell$ and $\gamma+$jets events.
- **Jet energy corrections**.
Event yields

<table>
<thead>
<tr>
<th>Process</th>
<th>(1\ell + 2\tau_h)</th>
<th>(2\ell ss)</th>
<th>(2\ell ss + 1\tau_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t}H)</td>
<td>5.8 ± 1.9</td>
<td>53.8 ± 17.0</td>
<td>9.4 ± 2.8</td>
</tr>
<tr>
<td>(t\bar{t}Z/\gamma^*)</td>
<td>6.3 ± 1.1</td>
<td>80.9 ± 10.4</td>
<td>9.2 ± 1.2</td>
</tr>
<tr>
<td>(t\bar{t}W + t\bar{t}WW)</td>
<td>0.5 ± 0.1</td>
<td>150.0 ± 16.9</td>
<td>9.1 ± 1.0</td>
</tr>
<tr>
<td>(WZ + ZZ)</td>
<td>2.1 ± 1.6</td>
<td>16.5 ± 13.1</td>
<td>3.9 ± 3.0</td>
</tr>
<tr>
<td>(t\bar{t}H)</td>
<td>0.4 ± 0.1</td>
<td>2.7 ± 0.2</td>
<td>0.5 ± 0.04</td>
</tr>
<tr>
<td>Conversions</td>
<td>&lt; 0.02</td>
<td>12.1 ± 5.8</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>Sign flip</td>
<td>—</td>
<td>27.5 ± 8.0</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>Misidentified lepton</td>
<td>195.7 ± 13.6</td>
<td>94.2 ± 21.2</td>
<td>8.6 ± 2.1</td>
</tr>
<tr>
<td>Rare backgrounds</td>
<td>1.4 ± 0.7</td>
<td>39.0 ± 21.2</td>
<td>3.1 ± 1.5</td>
</tr>
<tr>
<td>Total expected background</td>
<td>206.3 ± 14.0</td>
<td>423.0 ± 38.0</td>
<td>36.1 ± 4.2</td>
</tr>
<tr>
<td>Observed</td>
<td>212</td>
<td>507</td>
<td>49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>(3\ell)</th>
<th>(3\ell + 1\tau_h)</th>
<th>(4\ell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t}H)</td>
<td>18.5 ± 6.0</td>
<td>2.1 ± 0.7</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>(t\bar{t}Z/\gamma^*)</td>
<td>49.0 ± 6.9</td>
<td>3.4 ± 0.5</td>
<td>2.1 ± 0.4</td>
</tr>
<tr>
<td>(t\bar{t}W + t\bar{t}WW)</td>
<td>35.2 ± 4.2</td>
<td>0.4 ± 0.04</td>
<td>&lt; 2 \times 10^{-3}</td>
</tr>
<tr>
<td>(WZ + ZZ)</td>
<td>9.9 ± 2.4</td>
<td>0.3 ± 0.05</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>(t\bar{t}H)</td>
<td>1.2 ± 0.2</td>
<td>0.1 ± 0.01</td>
<td>&lt; 4 \times 10^{-4}</td>
</tr>
<tr>
<td>Conversions</td>
<td>5.3 ± 2.9</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Misidentified lepton</td>
<td>22.7 ± 6.7</td>
<td>0.9 ± 0.2</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>Rare backgrounds</td>
<td>8.2 ± 13.8</td>
<td>0.2 ± 0.1</td>
<td>0.1 ± 0.2</td>
</tr>
<tr>
<td>Total expected background</td>
<td>131.4 ± 18.2</td>
<td>5.3 ± 0.5</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td>Observed</td>
<td>148</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5: Numbers of events selected in the different categories compared to the SM expectations for the \(t\bar{t}H\) signal and background processes. The event yields expected for the \(t\bar{t}H\) signal and for the backgrounds are shown for the values of nuisance parameters obtained from the ML fit and \(\mu = 1\). Quoted uncertainties represent the combination of statistical and systematic components.
Results

Relative contribution of the $t\bar{t}H$, $H \rightarrow WW$, $ZZ$ and $\tau\tau$ decay modes in the different analysis categories.

Signal rates $\mu$, in units of the SM $t\bar{t}H$ production rate, measured either assuming the same signal strength for all decay modes (combined) or independently for the Higgs boson decays into two electroweak bosons ($t\bar{t}H+H \rightarrow VV$) and into two $\tau$ leptons ($t\bar{t}H+H \rightarrow \tau\tau$).
Table 6: The 95% CL upper limits on the t\(\bar{t}H\) signal rate, in units of the SM t\(\bar{t}H\) production rate, obtained in each of the categories individually and for the combination of all six event categories. The observed limit is compared to the limits expected for the background-only hypothesis (\(\mu = 0\)) and for the case that a t\(\bar{t}H\) signal of SM production rate is present in the data (\(\mu = 1\)). The ±1 standard deviation uncertainty intervals on the expected limits are also given in the table.

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed limit on (\mu) ((\mu = 0))</th>
<th>Expected limit ((\mu = 1))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(\ell) + 2(\tau_h)</td>
<td>2.7</td>
<td>4.1±1.7</td>
</tr>
<tr>
<td>2(\ell)ss</td>
<td>2.8</td>
<td>1.0±0.4</td>
</tr>
<tr>
<td>2(\ell)ss + 1(\tau_h)</td>
<td>2.5</td>
<td>1.4±0.3</td>
</tr>
<tr>
<td>3(\ell)</td>
<td>2.7</td>
<td>1.6±0.8</td>
</tr>
<tr>
<td>3(\ell) + 1(\tau_h)</td>
<td>4.4</td>
<td>2.8±1.3</td>
</tr>
<tr>
<td>4(\ell)</td>
<td>6.5</td>
<td>4.9±2.8</td>
</tr>
<tr>
<td>Combined</td>
<td>2.1</td>
<td>0.8±0.3</td>
</tr>
</tbody>
</table>

Figure 5: Distribution of the decimal logarithm of the ratio between the expected signal and expected background in each bin of the distributions used for the signal extraction. The distributions expected for signal and background processes are shown for the values of nuisance parameters obtained from the combined ML fit and \(\mu = \beta = 1.23\), corresponding to the best-fit value from the ML fit.