Search for the production of the Higgs boson in association with top quarks (t̅tH) in γγ and multi-lepton channels at CMS

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on behalf of the CMS collaboration
INTRODUCTION

• Production of the Higgs boson in association with a pair of top quarks (ttH) probes the ttH coupling
  ➣ Direct handle on the ttH vertex at tree level: gluon fusion involves a loop
  ➣ Cross-section of ttH is ~508 fb at 13 TeV, roughly 4 times the value at 8 TeV, increased potential for discovery

• Searches for ttH at CMS in Run 2: based on decay channel of the Higgs
  ➣ H→γγ: small branching ratio, but clean final state (low systematic uncertainties)
  ➣ Multi-leptonic (H→ZZ*, H→WW*, H→ττ): higher rate, multi-lepton final state with low background
  ➣ H→b̅b: high branching ratio, but complex multi-jet final state
SUMMARY OF RUN-1 RESULTS

- Studies of the $t\bar{t}H$ production in LHC Run-1 at CMS were based on the different Higgs decay channels: $\gamma\gamma$, $b\bar{b}$, $\tau\tau$ (hadronic) and multi-leptonic ($H\rightarrow ZZ^*$, $H\rightarrow WW^*$, $H\rightarrow \tau\tau$ with multi-lepton final states).

- **Combination** of different Higgs decay channels:
  
  - $t\bar{t}H$ combination from Run1 CMS measurements:
    
    - $\mu_{t\bar{t}H} = 2.8 \pm 1.0$
    
    - 95% CL limit = 4.5

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**Best fit signal strength : $\mu_{t\bar{t}H}$**

**95% CL upper limit $\mu_{t\bar{t}H}$**
• A part of the general $H \rightarrow \gamma \gamma$ analysis

- Events with two high $p_T$ isolated photons selected
- Narrow peak around $m_H$ on top of the falling $m_{\gamma \gamma}$ distribution
- Different production modes ($t\bar{t}H$, VBH, VH) identified based on additional final state objects
- Signal, background extraction from fit to $m_{\gamma \gamma}$ distribution

• Overview of the $H \rightarrow \gamma \gamma$ analysis:

- **Event categorisation** based on
  - additional final state objects to tag production modes
  - mass resolution and kinematics for the 'Untagged' categories

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**m_{\gamma \gamma} distribution (weighted)**

- **Talk by Louis Corpe**

**CMS Preliminary**

- 12.9 fb$^{-1}$ (13 TeV)
- All categories
- $S/(S+B)$ weighted
- $m_{\gamma \gamma}$ distribution (weighted)
- Signal extraction; Bkg extraction; Stat analysis
• 2 categories corresponding to tH based on the decay of the top quarks

• TTH Leptonic Tag:

\[ \bar{t}t \rightarrow bl\nu_l\bar{b}q\bar{q}' \quad \text{or} \quad \bar{t}t \rightarrow bl\nu_l\bar{b}'\nu_l \]

- At least 1 isolated lepton (muon or electron)
- At least 2 jets
- At least 1 B-tagged jet
- Diphoton BDT cut

• TTH Hadronic Tag:

\[ \bar{t}t \rightarrow bq\bar{q}' \bar{b}q\bar{q}' \]

- No leptons
- At least 5 jets
- At least 1 B-tagged jet
- Diphoton BDT cut

**Expected signal for tH categories**: very pure in tH contribution

<table>
<thead>
<tr>
<th>Event Categories</th>
<th>SM 125GeV Higgs boson expected signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>TTH Hadronic Tag</td>
<td>2.42</td>
</tr>
<tr>
<td>TTH Leptonic Tag</td>
<td>1.12</td>
</tr>
</tbody>
</table>
**RESULTS**

- Results based on **12.9 fb^{-1}** of data at **13 TeV** collected during 2016

**Signal strength for each process**

- **H → γγ**
  - Combined ± 1σ
  - μ_{SM} ± 1σ
  - μ_{combined} = 0.95 ± 0.21
  - m_{H} Profiled
  - μ_{VH} = 1

- **tH**
  - 1.91 ± 1.5

- **Uncertainties are statistics dominated**
• Multi-lepton final states from $H \rightarrow WW^*$, $H \rightarrow ZZ^*$, $H \rightarrow \tau\tau$

• Event selection:

**Same-sign dilepton channel (2LSS):**
- 2 leptons with same sign: further categorisation into $ee$, $\mu\mu$, $e\mu$ channels
- At least 4 jets

**Three lepton channel (3L):**
- 3 leptons or more
- At least 2 jets

**B Tag jets:** at least 1 jet passing medium WP or 2 jets passing loose WP of B tag algorithm

**Z veto:** based on $m_{\ell\ell}$, $E_T^{miss}$, $H_T^{miss}$
**t\bar{t}H MULTI-LEPTONIC : LEPTON SELECTION**

- Important source of to **background** coming from **non-prompt** leptons (from b jets in t\bar{t}, misidentified jets, decay-in-flight, photon conversions)

- Dedicated **multivariate discriminant** to reject **non-prompt** leptons. Inputs for the MVA:
  - Lepton **isolation** observables, impact parameter wrt vertex
  - **Ratio** of lepton and jet \( p_T \), \( p_T \) wrt direction of jet

![Opposite sign probe (prompt enriched)](image1)

![Same sign probe (non-prompt enriched)](image2)

- Performance is **validated** in data control region. **Data control region** also used to estimate residual **non-prompt background** using loose-to-tight extrapolation.
Expected and observed yields after the selection in 2LSS and 3L final states

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu$</th>
<th>ee</th>
<th>e$\mu$</th>
<th>$3\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W$</td>
<td>18.3 ± 0.9</td>
<td>6.8 ± 0.6</td>
<td>24.5 ± 1.1</td>
<td>12.2 ± 0.7</td>
</tr>
<tr>
<td>$t\bar{t}Z/\gamma^*$</td>
<td>5.8 ± 0.6</td>
<td>7.4 ± 0.6</td>
<td>15.3 ± 1.3</td>
<td>22.6 ± 1.0</td>
</tr>
<tr>
<td>Di-boson</td>
<td>1.4 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>2.6 ± 0.3</td>
<td>5.7 ± 0.4</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
<td>0.8 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>1.5 ± 0.2</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>$tqZ$</td>
<td>0.2 ± 0.3</td>
<td>0.4 ± 0.4</td>
<td>0.6 ± 0.6</td>
<td>2.7 ± 0.8</td>
</tr>
<tr>
<td>Rare SM bkg.</td>
<td>1.6 ± 0.3</td>
<td>0.5 ± 0.1</td>
<td>1.8 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Charge mis-meas.</td>
<td></td>
<td>6.7 ± 0.1</td>
<td>10.0 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Non-prompt leptons</td>
<td>33.4 ± 1.2</td>
<td>23.1 ± 1.1</td>
<td>61.9 ± 1.7</td>
<td>51.0 ± 1.8</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>61.5 ± 1.7</td>
<td>46.4 ± 1.5</td>
<td>118.0 ± 2.5</td>
<td>95.7 ± 2.3</td>
</tr>
<tr>
<td>$t\bar{t}H$ ($H \rightarrow WW^*$)</td>
<td>6.3 ± 0.2</td>
<td>2.6 ± 0.1</td>
<td>8.5 ± 0.2</td>
<td>8.0 ± 0.2</td>
</tr>
<tr>
<td>$t\bar{t}H$ ($H \rightarrow \tau\tau$)</td>
<td>1.6 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>2.5 ± 0.1</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>$t\bar{t}H$ ($H \rightarrow ZZ^*$)</td>
<td>0.2 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.3 ± 0.0</td>
<td>0.5 ± 0.0</td>
</tr>
<tr>
<td>Data</td>
<td>74</td>
<td>45</td>
<td>154</td>
<td>105</td>
</tr>
</tbody>
</table>

- Main sources of background:
  - **Signal like final states**: $t\bar{t}V$ (estimated from MC), Di-boson (validated in data)
  - **Others**: Non-prompt leptons (largely from $t\bar{t}$), charge mis-measured leptons: Data driven estimation
  - Multivariate BDT is used to separate the different types of backgrounds, use for signal extraction
Multivariate **BDT** discriminants trained in simulated events to separate the **signal** from **t\(\bar{t}\)V** backgrounds and also **non-prompt** (\(t\bar{t}\)) backgrounds.

- 2 separate BDTs trained using kinematical observables.
  - \(\eta\) of leptons, jet multiplicity, distance between lepton & jet, \(m_T^{\text{miss}}\)
  - For **t\(\bar{t}\)**: \(E_T^{\text{miss}}, H_T^{\text{miss}}\), distance between jets
  - For **t\(\bar{t}\)V**: leading, trailing lepton \(p_T\), for 3L category: matrix element weight (MEM weight):

\[
    w_{i,a}(\Phi') = \frac{1}{\sigma_a} \int d\Phi \cdot \delta^4(p_1^\mu + p_2^\mu - \sum_{k>2} p_k^\mu) \cdot \frac{f(x_1, \mu_F) f(x_2, \mu_F)}{x_1 x_2^s} \cdot |M_a(p_k^\mu)|^2 \cdot W(\Phi' | \Phi_a)
\]

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**BDT vs t\(\bar{t}\)**

**BDT vs t\(\bar{t}\)V**

**MEM Weight**

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**CMS Preliminary**

12.9 fb\(^{-1}\) (13 TeV)

**Data**

- t\(\bar{t}\)H
- TTW
- TTZ
- Fakes

**Pre-fit,\(\mu=1\)**

**Fit**

- t\(\bar{t}\)H
- TTW
- TTZ
- Rares
- Fakes

**Stat. Unc.**

**Total Unc.**

**MEM Weight**

**Events**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40

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Search for $t\bar{t}H$ in $\gamma\gamma$ & multi-lepton channels at CMS

Saranya Ghosh | Higgs Couplings, 2016

2 Dimensional fit to the two BDT discriminators is performed for signal extraction
• Events in the 2LSS and 3L categories are further categorised before the final signal extraction
  ➡ Whether the b - tagged jets pass a tighter WP
  ➡ Sum of leptonic charges is + or -
  ➡ Presence of hadronic τ for 2LSS

• Main sources of systematic uncertainties:
  ➡ Lepton selection efficiency
  ➡ Fake rate measurement for background estimate

![Graphs showing post fit yields in different categories]

**Event Categories**

- **μ±μ±**
  - b tight
  - b loose

- **e±μ±**
  - b tight
  - b loose

- **e±e±**
  - b tight

- **3L**
  - b tight
  - b loose

**SS2L with hadronic tau**
• Results based on \(12.9 \text{ fb}^{-1}\) of data collected during 2016 and combination with \(2.3 \text{ fb}^{-1}\) collected in 2015

<table>
<thead>
<tr>
<th>Category</th>
<th>Obs. limit</th>
<th>Exp. limit ±1σ</th>
<th>Best fit (\mu) ±1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same-sign dileptons</td>
<td>4.6</td>
<td>1.7(+0.9)(-0.5)</td>
<td>2.7(+1.1)(-1.0)</td>
</tr>
<tr>
<td>Trileptons</td>
<td>3.7</td>
<td>2.3(+1.2)(-0.7)</td>
<td>1.3(+1.2)(-1.0)</td>
</tr>
<tr>
<td>Combined categories</td>
<td>3.9</td>
<td>1.4(+0.7)(-0.4)</td>
<td>2.3(+0.9)(-0.8)</td>
</tr>
<tr>
<td>Combined with 2015 data</td>
<td>3.4</td>
<td>1.3(+0.6)(-0.4)</td>
<td>2.0(+0.8)(-0.7)</td>
</tr>
</tbody>
</table>

**Signal strength for 2016 analysis**

- CMS Preliminary \(12.9 \text{ fb}^{-1}\) (13 TeV)
  - \(m_H = 125\text{ GeV}\)
  - Combined \(\mu = 2.3\)^{+0.9}_{-0.8}\)

- Dilepton
  - \(\mu = 2.7\)^{+1.1}_{-1.0}\)

- Trilepton
  - \(\mu = 1.3\)^{+1.2}_{-1.0}\)

**Signal strength for 2016+2015 analysis**

- CMS Preliminary \(2.3+12.9 \text{ fb}^{-1}\) (13 TeV)
  - \(m_H = 125\text{ GeV}\)
  - Combined \(\mu = 2.0\)^{+0.8}_{-0.7}\)

- Dilepton
  - \(\mu = 1.9\)^{+0.9}_{-0.8}\)

- Trilepton
  - \(\mu = 2.5\)^{+1.4}_{-1.2}\)
SUMMARY & OUTLOOK

- Studies of the associated production of the Higgs boson and top quarks with the CMS experiment with data collected in early 2016 (2015) have been presented for the $H \to \gamma\gamma$ and multi-leptonic channels.

- Probes of the top-Higgs coupling directly at the tree level

- Studies involve complex final states with leptons, jets etc. Special methods are used to improve signal purity and to reduce backgrounds.

- Current measurements are consistent with SM expectation:
  
  - $t\bar{t}H$ multi-leptonic: $\mu = 2.0^{+0.8}_{-0.7}$ (2015 + 2016 combination: 2.3+12.9fb$^{-1}$)
  
  - $t\bar{t}H$ with $H \to \gamma\gamma$: $\mu = 1.9^{+1.5}_{-1.2}$ (2016: 12.9fb$^{-1}$)

- Analyses to be updated with the full dataset collected during 2016 (~3 times the data presented here)

THANK YOU!
ttH WITH H→γγ: RESULTS (2015 DATA)

Signal strength for 2015 analysis

CMS Preliminary

2.7 fb⁻¹ (13 TeV)

H→γγ

Combined ± 1σ

Untagged 0

Untagged 1

Untagged 2

Untagged 3

VBF Tag 0

VBF Tag 1

TTH Tags

μ = 0.69 ± 0.47

m_H = 125.09 GeV

Per category ± 1σ

μ = μ_SM

Signal strength for 2016 analysis

CMS Preliminary

12.9 fb⁻¹ (13 TeV)

H→γγ

Combined ± 1σ

μ = μ_SM

Untagged 0

Untagged 1

Untagged 2

Untagged 3

VBF Tag 0

VBF Tag 1

TTH Hadronic Tag

TTH Leptonic Tag

μ_comb = 0.95 ± 0.21

m_H Profiled

Per category ± 1σ

μ = μ_SM

μ = 125.09 GeV

Combined

σ ± 1σ

Per category

μ = μ_SM

Combined

σ ± 1σ

Per category
Sources of Uncertainty

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>$\hat{r} = 2.0 \pm 0.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tight lepton selection efficiency</td>
<td></td>
</tr>
<tr>
<td>2. Muon fake rate, normalization</td>
<td></td>
</tr>
<tr>
<td>3. 2016 luminosity calibration</td>
<td></td>
</tr>
<tr>
<td>4. $ttH$ theoretical uncertainty (scale)</td>
<td></td>
</tr>
<tr>
<td>5. Jet energy scale</td>
<td></td>
</tr>
</tbody>
</table>

Pull | $+\sigma$ Impact | $-\sigma$ Impact

Jet energy scale

-2 | -1 | 0 | 1 | 2 | -0.2 | 0 | 0.2

$\Delta \hat{r}/\sigma_r$