Search for Higgs bosons produced in association with top quarks in the CMS detector

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Introduction

- Probing the **ttH coupling** at LHC:
  - via gluon fusion cross section, assuming no BSM particles running in the loop
  - **directly at tree level,** via associated production

- $\sigma$ for $ttH \sim 510 \text{ fb}$ at 13 TeV
- BR to $bb \sim 60\%$, $WW^* \sim 20\%$, smaller for other final states
- **Challenging due to the presence of additional jets and leptons from top decay**
Searches for ttH at CMS

- **tt + b-jets**, targeting Higgs decay to bb
  - high cross section x BR, but complex multi-jet final state
  - reduce tt+jets using kinematic variables and MEM (details in C. Palmer’s talk)

- **tt + leptons**, targeting Higgs decays to WW*, ZZ*, ττ
  - lower rate, low background multi-lepton final state

- **tt + γγ**, targeting Higgs decay to γγ
  - small branching ratio, but very clean final state (small systematic uncertainty)
Results with 2015 data

- Higgs to $bb$  
  \[ \hat{\mu}_{\text{obs}} = -2.0^{+1.8}_{-1.8} \]

- Higgs to $\gamma\gamma$  
  \[ \hat{\mu}_{\text{obs}} = 3.8^{+4.5}_{-3.6} \]

- Multi-lepton  
  \[ \hat{\mu}_{\text{obs}} = 0.6^{+1.4}_{-1.1} \]

CMS PAS HIG-16-004  
CMS PAS HIG-15-005  
CMS PAS HIG-15-008

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Results with 2015 data

- Result of the combination of ttH searches with 2015 data: compatible with the SM
- Sensitivity is about 1 x SM

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Updates with 2016 data

- **ttH, Higgs to $\gamma\gamma$** (details in V. Tavolaro’s talk):
  - tagged $H \rightarrow \gamma\gamma$ categories selecting hadronic and leptonic top decays

- **New ttH multi-lepton result**, presented in the following

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ttH in multi-lepton final states

- Target multi-lepton final states from Higgs decays to $WW^*$, $ZZ^*$, $\tau\tau$
- Channels:
  - two same-sign leptons + 4 jets
  - at least three leptons (with Z veto) + 2 jets
- At least 2 loose or 1 medium b-tagged jets

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Event yields

<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>$ttt$</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>6.7 ± 0.1</td>
<td></td>
<td></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>

12.9 fb$^{-1}$, stat. unc. only

- Main sources of background:
  - **irreducible**: $ttV$ (from MC), di-boson (validated in data)
  - **reducible**: non-prompt leptons in $tt$ events and charge mis-ID, data-driven
Lepton selection

- Goal: **reject non-prompt leptons** (mainly from b-jets in tt, but also mis-identified light jets and decay-in-flight)
- **Multivariate discriminant based on isolation, vertex and identification lepton observables**
- Performance validated in data control regions
- **Data-driven** estimate of residual background using a **tight-to-loose method**

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Kinematic discrimination

- Using **kinematic observables to improve discrimination against tt and ttV events:** jet multiplicity, lepton/jet angular separation, MET, lepton $p_T$
- New for 2016 analysis **in 3l:** **matrix element weights for ttH and ttV hypotheses**

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

- Separate **BDT discriminators** against tt and ttV:

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The signal is extracted via a 2-dimensional fit to the BDT discriminators:
Event categorization

- **Post-fit yields** in each category:
- **Main systematic uncertainties:**
  - lepton selection efficiency
  - fake rate measurement for background estimate

**Further categorization** based on lepton flavor, presence of b-jets, hadronically-decaying $\tau$, lepton charge.

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Results

- Results with **2016 dataset** and from the **combination with the ttH multi-lepton 2015 result**:

<table>
<thead>
<tr>
<th>Category</th>
<th>Obs. limit</th>
<th>Exp. limit ±1σ</th>
<th>Best fit μ ±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>
Outlook

• We have presented studies of associate production of the Higgs boson and top quarks with the CMS experiment

• **Probing the Higgs coupling** with the top quark at tree level

• **Challenging final states** with jets and leptons from top decay

• **Advanced methods** are used to improve the signal purity and discriminate it from tt+jets and ttV background processes

• Combination of 2015 results is in agreement with the SM expectation

• Updated results:
  
  • **ttH multi-lepton:** $\mu = 2.0 \pm^{0.8}_0.7$ (2015 + 2016 combination)
  
  • **ttH, $H \rightarrow \gamma\gamma$:** $\mu = 1.9^{+1.5}_{-1.2}$ (2016 dataset)

  Further discussion in E. Ntomari’s poster later this week.