MEASUREMENT OF $t\bar{t}H$ PRODUCTION AT CMS
**INTRODUCTION**

- **ttH production** provides a direct measurement of the Yukawa coupling of the top to the Higgs.
- Other ways to probe the Yukawa coupling. Some examples:
  - Four top production ([CMS-PAS-18-003](#)).
  - Differential $t\bar{t}$ production ([CMS-PAS-TOP-17-004](#)).
  - $t\bar{t}Hq$ production ([CMS-PAS-HIG-17-005](#)).
  - Also sensitive to the sign of the coupling.
  - Very rich signatures due to the different decays of the Higgs.
  - Also very challenging because of the low production cross-section.
DECAYS TARGETED

- Focusing in the latest results in multilepton channels (HIG-18-019)
- Sensitive to the ZZ, WW and $\tau\tau$ decays
- Reasonably large branching ratio
- Moderate amount of background

- This talk will focus on the analysis with 2017 data
  - Will also cover the combination with other datasets
- Searches exist focusing in the $b\bar{b}$ and $\gamma\gamma$ channels
- Search targeting $H \rightarrow ZZ \rightarrow 4\ell$ also not covered
**EVENT SELECTION AND CATEGORIZATION**

- Events are categorized based on the number of light leptons (e and $\mu$) and hadronic $\tau$.
- Different jet and $b$ jet multiplicity criteria are applied to each of the regions.

- Further categorization is made according to
  - $b$ jet multiplicity
  - lepton charge and flavor
  - dedicated MVA discriminants for each region
BACKGROUND ESTIMATION

Main backgrounds

- Top quark pair production associated with a vector boson (ttW, ttZ)
  - Similar kinematics to the signal
  - Estimated with Monte Carlo simulations
  - Control regions are used in the fit to constrain these processes
  - ttZ and ttW are parameterized with signal strength modifiers in the signal extraction

- Processes with leptons not coming from W, Z or \( \tau \) decays
  - Dedicated MVA for the identification of prompt leptons
  - Data-driven estimation for this background

<table>
<thead>
<tr>
<th>Category</th>
<th>2( \ell )ss</th>
<th>3( \ell )</th>
<th>4( \ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH</td>
<td>43.0 ± 7.1</td>
<td>18.8 ± 4.8</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>ttW + ttWW</td>
<td>218.5 ± 13.7</td>
<td>51.0 ± 5.3</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>tH</td>
<td>2.4 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>WZ + ZZ</td>
<td>&lt; 0.05</td>
<td>12.0 ± 1.7</td>
<td>0.15 ± 0.10</td>
</tr>
<tr>
<td>ttZ/( \gamma^* )</td>
<td>138.2 ± 7.6</td>
<td>74.1 ± 6.3</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>Misidentified</td>
<td>132.1 ± 10.0</td>
<td>26.8 ± 4.0</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Conversions</td>
<td>11.6 ± 3.0</td>
<td>6.6 ± 1.3</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Signal flip</td>
<td>22.8 ± 2.3</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Other</td>
<td>26.7 ± 3.9</td>
<td>9.7 ± 2.2</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>SM expectation</td>
<td>595.3 ± 20.6</td>
<td>200.0 ± 10.8</td>
<td>5.0 ± 0.7</td>
</tr>
<tr>
<td>Observed data</td>
<td>614</td>
<td>195</td>
<td>6</td>
</tr>
</tbody>
</table>
2LSS REGION

- Requiring at least 4 jets and at least one tight* or two loose $b$ tagged jets
- In the ee channel, a Z mass veto is applied and $L_D > 30$ GeV
- Events categorized in lepton flavor and charge, and $b$ jet multiplicity
- Dedicated discriminants used to discriminate ttH from $t\bar{t}$ and ttZ and ttW

- Discriminants use kinematic variables, hadronic top tagger ($t\bar{t}$) and Higgs jet tagger (ttW, ttZ)
- Discriminants are merged into a single discriminant using clustering techniques

- ttW control region is defined relaxing the jet multiplicity cut

* Loose (tight) $b$ tagged jet: 10% (1%) misidentification probability
3L REGION

- Events are required to have at least 2 jets and one tight or two loose b* tagged jets
- Events with an OSSF lepton pair compatible with a Z are vetoed
- $L_D$ cut depending on jet multiplicity and lepton flavor
- Categories based on $b$ jet multiplicity and charge

- Discriminants use kinematic variables
- Discriminants are merged into a single discriminant using clustering techniques

- ttZ control region is defined inverting the Z candidate veto
- WZ control region defined further inverting the $b$ jet requirement
- 4l category requiring 4 leptons instead of three $\Rightarrow$ no categorization
**Categories with 1 \( \tau \)**

- **2lss + 1\( \tau \)**
  - Sum of lepton and \( \tau \) charge equal to \( \pm 1 \)
  - At least three jets
  - At least one tight or two loose \( b \) jet
  - \( L_D \) cut and \( Z \) mass veto in the ee channel

- **3l + 1\( \tau \)**
  - Sum of charges equal to 0
  - At least two jets
  - At least one tight or two loose jets
  - Events with an OSSF lepton pair compatible with a \( Z \) are vetoed

- BDTs trained against \( \bar{t}t \), \( ttZ \) and \( ttW \). Some categories use hadronic top reconstruction
**CATEGORIES WITH 2 $\tau$**

- **1l + 2$\tau$**
  - At least 3 jets, at least one tight or 2 loose $b$ tagged jets
  - $\tau$ are required to have opposite charge

- **2l + 2$\tau$**
  - Sum of the charges of leptons and taus must be 0
  - At least 2 jets, at least one tight or 2 loose $b$ jets
  - $L_D$ cut depending on jet multiplicity and lepton flavor

- BDTs trained against $t\bar{t}$, ttZ and ttW. Some categories use hadronic top reconstruction
**RESULTS**

**Signal strength**

- $\mu = 0.75^{+0.46}_{-0.43}$ (observed)
- $\mu = 1.00^{+0.39}_{-0.35}$ (expected)

**Significance**

- $2.7 \sigma$ observed and expected

**Best fit for ttZ and ttW**

- $\mu_{ttZ} = 1.69^{+0.39}_{-0.33} (1.00^{+0.24}_{-0.21})$
- $\mu_{ttW} = 1.42^{+0.34}_{-0.33} (1.00^{+0.27}_{-0.24})$

- Result consistent with the $\mu = 1$ hypothesis
- About 40% uncertainty with the 2017 only
**COMBINATION WITH 2016**

- Result has been combined with the equivalent 2016 result ([JHEP 08 (2018) 066](https://jhep.org/))
- Signal strength
  - \( \mu = 0.96^{+0.34}_{-0.31} \) (observed)
  - \( \mu = 1.00^{+0.30}_{-0.27} \) (expected)
- Significance
  - 3.2 \( \sigma \) observed and 4.0 \( \sigma \) expected

- Uncertainty on signal strength largely reduced in the combination
- Uncertainty on \( \mu \) dominated by \( ttH \) cross-section calculation uncertainty and fake lepton estimation
COMBINATION WITH OTHER CHANNELS

- Combination performed with other analyses targeting different signatures
- Only 2016 result used so far

\( H \rightarrow \gamma\gamma \)
- Clean final state and Higgs mass resolution
- Low statistics available
- Using semileptonic and fully hadronic channel
- JHEP 11 (2018) 185

\( H \rightarrow ZZ \rightarrow 4\ell \)
- Clean final state and Higgs mass resolution
- Using semileptonic and fully hadronic channel
- Very low branching ratio
- JHEP 11 (2017) 047
**Combination with other channels**

\( H \to b\bar{b} \) (fully hadronic)

- Overwhelming multijet background
- MEM discriminant used for the signal extraction

\[
w_{\Omega}(y) = \frac{1}{\sigma_{\Omega}} \sum_p \int dx_a dx_a dx_b f_i(x_a, Q) f_j(x_b, Q) \frac{\delta^2(x_a P_a + x_b P_b - \sum p_{E})}{x_a x_b s} |M_{\Omega}(x)|^2 W(y|x)
\]

- JHEP06(2018)101

\( H \to b\bar{b} \) (single and double lepton)

- Challenging due to the irreducible \( t\bar{t} + b\bar{b} \) background
- Elaborated analysis strategy using MEM and DNNs

- JHEP 03 (2019) 026
Combination with Other Channels

- Using data from Run I and 2016
- Signal strength fitted for each branching fraction and year, and combined
- Always consistent with unity

Significance

- $5.2 \, \sigma$ observed
- $4.2 \, \sigma$ expected

Best fit $\mu = 1.26^{+0.31}_{-0.26}$
CONCLUSIONS

- Reviewed the state-of-the-art of measurements of $ttH$ in multileptonic channels
- CMS has provided evidence for $ttH$ in this channel alone
  - Analysis provides $4\,\sigma$ sensitivity to SM Higgs
- Observation of $ttH$ when combining with other channels