Measurement of the top quark pair-production in association with a W or Z boson in pp collisions at 13 TeV with full 2016 dataset at CMS

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Illia Khvastunov
on behalf of the CMS Collaboration
University of Ghent (Belgium), CEA Saclay (France)

Les Rencontres de Physique de la Vallee d’Aoste 2018

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Strategy and event selection

- The observed yields and measured cross-sections could be altered by new physics, the main background for $t\bar{t}H$ and for BSM processes.
- Strength of the electromagnetic coupling of top quark and Z boson can be probed.

$t\bar{t}W$, SS2$\ell$
- $p_T > 40, 25(27)$GeV
- at least 2 jets, 1 b-tag jet

$t\bar{t}Z$, 3$\ell$
- $p_T > 40, 20, 10$ GeV
- at least 2 jets
- $|m_{\ell\ell} - M_Z| < 10$ GeV

$t\bar{t}Z$, 4$\ell$
- $p_T > 40$ and 10 GeV for others
- at least 2 jets
- $|m_{\ell\ell} - M_Z| < 20$ GeV

- The number of jets and b-tagged jets are used to form signal regions
**ttW in SS 2ℓ**

- For ttW the MVA analysis a Boost Decision Tree (BDT) classifier was developed.
  - BDT input:
    - Number of jets; number of medium b-tagged jets; the sum of $p_T$ of the jets
    - Leading and trailing lepton $p_T$, transverse invariant mass of both leptons
    - Leading and subleading jet $p_T$, missing transverse energy
    - $\Delta R$ between the trailing lepton and the nearest selected jet

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**Event selection and categorisation**

- BDT > 0
- Further split in number of jets, b-tag jets
- Split in $++$ and $--$

**Backgrounds**

- misidentified leptons, tt
- ttZ and ttH
Nonprompt lepton background

- Nonprompt leptons are expected to come mostly from $t\bar{t}$ and Drell-Yan production: an additional nonprompt lepton from the semi-leptonic decay of a $b$-hadron, additional jets misidentified as leptons, etc.

- The probability of a loosely identified lepton to pass the full set of identification/isolation requirements is calculated in respective enriched region and validated in Monte-Carlo simulation and data:
  - $2\ell$: $D < 0$
  - $3\ell$: absence of an same flavour opposite-charge lepton pair or invariant mass of 2 leptons is far from $Z$ boson mass
WZ and ZZ background

- Main backgrounds for $t\bar{t}Z$ in $3\ell$ and $4\ell$ final states
- We rely on MC simulation for yield estimation and validate in enriched control regions:
  - 3 leptons (4 leptons), 2 of the form an (2)SFOC pair close to Z peak mass
  - in $3\ell$ the cut that excludes b-tag jets is used

3\ell

4\ell
**ttV: systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty range</th>
<th>Impact on ttW cross-section</th>
<th>Impact on ttZ cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.5%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Jet Energy Scale/Resolution</td>
<td>2-5%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>2-4%</td>
<td>4-5%</td>
<td>5%</td>
</tr>
<tr>
<td>B tagging</td>
<td>1-5%</td>
<td>2-5%</td>
<td>4-5%</td>
</tr>
<tr>
<td>PU modeling</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Lepton ID, efficiency</td>
<td>2-7%</td>
<td>3%</td>
<td>6-7%</td>
</tr>
<tr>
<td>$\mu_R/\mu_F$ scale choice</td>
<td>1%</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>PDF choice</td>
<td>1%</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>Nonprompt background</td>
<td>30%</td>
<td>4%</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>WZ cross section</td>
<td>10-20%</td>
<td>&lt;1%</td>
<td>2%</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>20%</td>
<td>-</td>
<td>1%</td>
</tr>
<tr>
<td>Charge misidentification</td>
<td>20%</td>
<td>3%</td>
<td>-</td>
</tr>
<tr>
<td>Rare SM background</td>
<td>50%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>ttX background</td>
<td>10-15%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Stat. unc. for nonprompt</td>
<td>5-50%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>Stat. unc. rare SM processes</td>
<td>20-100%</td>
<td>1%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Total systematic</td>
<td>-</td>
<td>14%</td>
<td>12%</td>
</tr>
</tbody>
</table>

- Uncertainties on the lepton reconstruction, b tagging and trigger efficiency have the greatest effect both on the $\text{ttW}$ and $\text{ttZ}$ cross-section measurement.

- The uncertainty on nonprompt background gives a significant contribution to the systematic uncertainty of $\text{ttW}$ cross section measurement.

- The systematic uncertainty for $\text{ttW}$ and $\text{ttZ}$ becomes dominant!
ttV results

2L

3L

4L
⇒ First time a single experiment achieves $>5\sigma$ for both processes simultaneously at 13 TeV
⇒ First time $t\bar{t}V$ reaches $>5\sigma$ at 13 TeV
**ttV: EFT interpretations**

**EFT Lagrangian:**
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2} \sum_j c_j \mathcal{O}_j + \cdots \]

- \[ \mathcal{M} = \mathcal{M}_0 + \sum c_j \mathcal{M}_j \], consider one operator at a time
- Do not consider all NP couplings to the first two generations, as well operators which caused significant cross section scaling for tt, inclusive Higgs, WW or WZ
- Considered NP effects on ttH as well as ttW and ttZ
- Construct a profile likelihood test statistic \[ q(c_j) \], maximize to find the asymptotic best-fit \[ c_j \]

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>Best fit [TeV(^{-2})]</th>
<th>68% CL [TeV(^{-2})]</th>
<th>95% CL [TeV(^{-2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{c}_{uW}/\Lambda^2 )</td>
<td>1.7</td>
<td>[−2.4, −0.5] and [0.4, 2.4]</td>
<td>[−2.9, 2.9]</td>
</tr>
<tr>
<td>(</td>
<td>\bar{c}_H/\Lambda^2 − 16.8\text{ TeV}^{-2}</td>
<td>)</td>
<td>15.6</td>
</tr>
<tr>
<td>(</td>
<td>\bar{c}_{3G}/\Lambda^2</td>
<td>)</td>
<td>0.5</td>
</tr>
<tr>
<td>( \bar{c}_{3G}/\Lambda^2 )</td>
<td>−0.4</td>
<td>[−0.6, 0.1] and [0.4, 0.7]</td>
<td>[−0.7, 1.0]</td>
</tr>
<tr>
<td>( \bar{c}_{uG}/\Lambda^2 )</td>
<td>0.2</td>
<td>[0, 0.3]</td>
<td>[−1.0, −0.9] and [−0.3, 0.4]</td>
</tr>
<tr>
<td>(</td>
<td>\bar{c}_{uB}/\Lambda^2</td>
<td>)</td>
<td>1.6</td>
</tr>
<tr>
<td>( \bar{c}_{Hu}/\Lambda^2 )</td>
<td>−9.3</td>
<td>[−10.3, −8.0] and [0, 2.1]</td>
<td>[−11.1, −6.5] and [−1.6, 3.0]</td>
</tr>
<tr>
<td>( \bar{c}_{2G}/\Lambda^2 )</td>
<td>0.4</td>
<td>[−0.9, −0.3] and [−0.1, 0.6]</td>
<td>[−1.1, 0.8]</td>
</tr>
</tbody>
</table>
Conclusions

- The measurement of $t\bar{t} + V$ cross-section is done at 13 TeV with statistical uncertainty $O(15\%)$ and systematic uncertainty $O(15\%)$
- Next step is to measure differential cross-section for $t\bar{t}Z$ and the $tZ$ coupling
- We are excited to have more data already in 2017-2018!
ttbar MC closure test

- Tight-to-loose prediction vs. MC observed
- CMS Simulation Supplementary arXiv:1711.02547

Histograms for:
- N_j: 2 to 6 a.u.
- Leading lepton p_T (GeV): 10 to 200
- Trailing lepton p_T (GeV): 10 to 30
- MVA score: -0.5 to 1 a.u.
DY control region in data

$3\ell$ channel, OSSF pair, 0-1 jets, 0 b jets, $E_{T}^{\text{miss}} < 30$ GeV
WZ+jets split in flavour

CMS Supplementary arXiv:1711.02547 35.9 fb⁻¹ (13 TeV)

![Diagram showing event distribution based on Nb and N_j categories.]

- Data
- t\(\bar{t}\)Z
- t(\(\bar{t}\))X
- WZ + light
- WZ + c
- WZ + b
- Rare
- Nonprompt
same-sign $2\ell$ channel in enriched $t\bar{t}W$ region: $\geq 3$ jets, $\geq 2$ b jet
$t\bar{t}Z$ in $3\ell$

$3\ell$ channel in enriched $t\bar{t}Z$ region: $\geq 3$ jets, $\geq 1$ b jet

![Graphs showing event distributions for $t\bar{t}Z$ in $3\ell$ channel.](image)