Top quark pair production in association with bosons ($t\bar{t}V$, $V=W/Z/photon$) at the LHC

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Introduction

- Measurement of $t\bar{t}Z$ and $t\bar{t}\gamma$ is a direct test of the top-EWK couplings (EWK gauge boson couplings are poorly known; their deviation from SM is a signature to new physics)
- $t\bar{t}V$ is an important background for the top-Higgs coupling measurements and many BSM analyses (especially those searching for signals with two or more leptons)

$t\bar{t}W$  

$t\bar{t}Z/\gamma$
Run 1 $t\bar{t}V$ analyses

Published:

- ATLAS 8 TeV $t\bar{t}W/Z$ analysis (JHEP 11 (2015) 172)
- CMS 8 TeV $t\bar{t}W/Z$ analysis (JHEP 01 (2016) 096)
- ATLAS 7 TeV $t\bar{t}\gamma$ analysis (PRD 91 (2015) 072007)

Preliminary:

- CMS 8 TeV $t\bar{t}\gamma$ analysis (CMS-PAS-TOP-13-011)
Run 1 $t\bar{t}W/Z$ analysis

ATLAS 8 TeV analysis (20.3 fb$^{-1}$)

- Four final states: 2LOS, 2LSS, 3L, 4L
  - 2LOS: split regions by $Z$/noZ, $N_{\text{jets}}$, $N_{\text{bjets}}$, train neural network for each region
  - 2LSS: split into $ee$, $e\mu$, $\mu\mu$, bin by $N_{\text{jets}} \otimes E_{\text{T}}^{\text{miss}}$
  - 3L: split regions by $Z$/noZ, $N_{\text{jets}}$, $N_{\text{bjets}}$
  - 4L: choose the best $Z$ candidate, split regions by $N_{\text{bjets}}$ and relative flavour of two remaining leptons
- Control regions are defined to constrain main backgrounds: $t\bar{t}$ (2LOS), $Z+$jets (2LOS), $WZ$ (3L) and $ZZ$ (4L)

CMS 8 TeV analysis (19.5 fb$^{-1}$)

- Four final states: 2LOS, 2LSS, 3L, 4L
  - 2LOS: split regions by lepton flavour, $N_{\text{jets}}$
  - 2LSS: split regions by lepton flavour, $N_{\text{jets}}$
  - 3L: split regions by $Z$/noZ, $N_{\text{jets}}$
  - 4L: split regions by number of $Z$ candidates (1, $\geq 2$)
- For each region, train BDT using a linear discriminant that matches leptons and jets to $t\bar{t}W/Z$ system, and other kinematic variables
**σ_{t\bar{t}W}** and **σ_{t\bar{t}Z}** are simultaneously extracted using a maximum likelihood fit over 5 control regions and 15 signal regions.

\[ \sigma_{ATLAS \ t\bar{t}W} = 369^{+100}_{-91} \text{ fb} \ (\sigma_{NLO}^{t\bar{t}W} = 232 \pm 32 \text{ fb}) \]

\[ \sigma_{ATLAS \ t\bar{t}Z} = 176^{+58}_{-52} \text{ fb} \ (\sigma_{NLO}^{t\bar{t}Z} = 215 \pm 30 \text{ fb}) \]

Statistical uncertainties dominate.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( t\bar{t}W ) significance</th>
<th>( t\bar{t}Z ) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>2\ell OS</td>
<td>0.4\sigma</td>
<td>0.1\sigma</td>
</tr>
<tr>
<td>2\ell SS</td>
<td>2.8\sigma</td>
<td>5.0\sigma</td>
</tr>
<tr>
<td>3\ell</td>
<td>1.4\sigma</td>
<td>1.0\sigma</td>
</tr>
<tr>
<td>4\ell</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Combined</td>
<td>3.2\sigma</td>
<td>5.0\sigma</td>
</tr>
</tbody>
</table>
CMS Run 1 $t\bar{t}W/Z$ analysis: JHEP 01 (2016) 096

> Extract $t\bar{t}W$ cross section using 2LSS and 3L noZ regions

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross sections (fb)</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$\ell$SS</td>
<td>$414^{+135}_{-112}$</td>
<td>3.4</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>$210^{+117}_{-203}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Combined</td>
<td>$382^{+117}_{-102}$</td>
<td>3.5</td>
</tr>
</tbody>
</table>

> Extract $t\bar{t}Z$ cross section using 2LOS, 3L Z and 4L regions

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross sections (fb)</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$\ell$OS</td>
<td>$257^{+158}_{-129}$</td>
<td>1.8</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>$257^{+85}_{-67}$</td>
<td>4.6</td>
</tr>
<tr>
<td>4$\ell$</td>
<td>$228^{+150}_{-107}$</td>
<td>2.7</td>
</tr>
<tr>
<td>Combined</td>
<td>$242^{+65}_{-55}$</td>
<td>5.7</td>
</tr>
</tbody>
</table>

> Extract both cross sections using all regions

Statistical uncertainties dominate
Study constraints on 5 dimension-six operators, which affects $t\bar{t}W/Z$ cross sections

For each operator $c_j$, define a profile likelihood, and fit with measured $t\bar{t}W/Z$ cross sections
Run 1 $t\bar{t}\gamma$ analysis

ATLAS 7 TeV analysis (4.59 fb$^{-1}$)

- $t\bar{t}$ events are preselected by requiring exactly one electron or muon, and at least four jets (including one $b$-jet)
- $t\bar{t}\gamma$ events are the subset of $t\bar{t}$ events with at least one photon of $p_T \geq 20$ GeV
- Also define fiducial phase space to be similar to the $t\bar{t}\gamma$ event selection
- $t\bar{t}\gamma$ cross section is extracted using a template-based profile likelihood fit, using photon track-isolation as discriminant

CMS 8 TeV analysis (19.7 fb$^{-1}$)

- $t\bar{t}$ events are preselected by requiring exactly one muon, and at least four jets (including one $b$-jet)
- $t\bar{t}\gamma$ events are the subset of $t\bar{t}$ events with at least one photon of $p_T \geq 25$ GeV
- The number of real/fake photon events is estimated by a template-based likelihood fit, using charged hadron isolation of photon as discriminant
Extract $t\bar{t}\gamma$ cross section in electron and muon channels

The observed significance of $t\bar{t}\gamma$ is 5.3σ

$\sigma_{t\bar{t}\gamma}^{fid} \times BR(t\bar{t} \rightarrow \ell j) = 63 \pm 8 \text{ (stat.)} +17^{+17}_{-13} \text{ (syst.)} \pm 1 \text{ (lumi.)} \text{ fb}$

(the NLO prediction is 48 fb)

Systematic uncertainties (jet modeling) dominate
CMS Run 1 $t\bar{t}\gamma$ analysis: CMS-PAS-TOP-13-011

- Template fit using charged hadron isolation as discriminant

- The observable $R = \sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ is calculated using number of real photon events, and parameters of event selection

  $R = (1.07 \pm 0.07 \text{ (stat.)} \pm 0.27 \text{ (syst.)}) \times 1\%$

- $t\bar{t}\gamma$ cross section is obtained from multiplying $R$ by $\sigma_{t\bar{t}}^{CMS}$

  $\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \text{ pb}$

  (the NLO prediction is 1.8 pb)

Systematic uncertainties (background modeling) dominate
Run 2 $t\bar{t}V$ analyses

Preliminary:

- ATLAS 13 TeV $t\bar{t}W/Z$ analysis (ATLAS-CONF-2016-003)
- CMS 13 TeV $t\bar{t}Z$ analysis (CMS-PAS-TOP-16-009)
Run 2 $t\bar{t}W/Z$ analysis

ATLAS 13 TeV analysis (3.2 fb$^{-1}$)

- Three final states: 2µSS, 3L, 4L
  - 2µSS: require $N_{bjets} \geq 2$
  - 3L: split regions by Z/noZ, $N_{jets}$, $N_{bjets}$
  - 4L: choose the best Z candidate, split regions by $N_{bjets}$ and relative flavour of two remaining leptons

- Control regions are defined to constrain main backgrounds: $WZ$ (3L) and $ZZ$ (4L)

CMS 13 TeV analysis (2.7 fb$^{-1}$)

- Two final states: 3L, 4L
  - 3L: require exactly 1 Z candidate, split regions by $N_{jets}$, $N_{bjets}$
  - 4L: require exactly 1 Z candidate, split regions by $N_{bjets}$
ATLAS Run 2 $t\bar{t}W/Z$ analysis: ATLAS-CONF-2016-003

- Extract $t\bar{t}Z$ cross section using 3L-$Z$, 4L signal regions, and $WZ$, $ZZ$ control regions

- Extract $t\bar{t}W$ cross section using 2$\mu$SS, 3L-no$Z$ signal regions, and $WZ$, $ZZ$ control regions

\[ \sigma_{ATLAS}^{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb} \]
\[ (\sigma_{NLO}^{t\bar{t}Z} = 0.76 \pm 0.08 \text{ pb}) \]

\[ \sigma_{ATLAS}^{t\bar{t}W} = 1.4 \pm 0.8 \text{ pb} \]
\[ (\sigma_{NLO}^{t\bar{t}W} = 0.57 \pm 0.06 \text{ pb}) \]

Statistical uncertainties dominate
CMS Run 2 $t\bar{t}Z$ analysis: CMS-PAS-TOP-16-009

- Extract $t\bar{t}Z$ cross section using 3L and 4L signal regions

$\sigma_{CMS}^{t\bar{t}Z} = 1065^{+352}_{-313} (\text{stat.})^{+168}_{-142} (\text{syst.}) \text{ fb}$

Statistical uncertainties dominate

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<tr>
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<th>Observed</th>
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<tbody>
<tr>
<td>$3\ell$</td>
<td>2.9</td>
<td>3.5</td>
</tr>
<tr>
<td>$4\ell$</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Combined</td>
<td>3.1</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Conclusion

Run 1 $t\bar{t}V$ analyses:
- $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$ were all observed for the first time
- All measurements are consistent with the NLO calculations

Run 2 $t\bar{t}V$ analyses:
- Some preliminary measurements have been published
- More statistics are needed to study $t\bar{t}V$ differentially, which will be very helpful to constrain certain EFT operators (http://arxiv.org/pdf/1601.08193.pdf)