Rare top quark production in CMS: ttZ, ttW, ttγ, tZq, tγq and tttt

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On behalf of the CMS Collaboration

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Introduction

Rare top production is fully accessible with Run 2 data: $t\bar{t}W$, $t\bar{t}Z$, $tZq$, $t\gamma$, $\gamma q$, $t\bar{t}t\bar{t}$.

What we expect to learn:

- top coupling to $Z$ and $\gamma$ bosons.
- $t\bar{t}V$: one of the most massive signatures that can be studied with high precision.
- Searches for four top quark production starting to be sensitive at LHC.

All results at: http://cern.ch/go/pNj7
• Cross sections that allow high precision measurements
• **Important background** process for searches as $t\bar{t}H$ in multilepton final states
• $t\bar{t}Z$ is sensitive to the direct **coupling of the top quark to the Z boson**
• Production would be enhanced in BSM models
2016 data
Baseline Selection:
• 2 leptons of same charge
• $m_{ll} > 12$ GeV (excluding Z mass window)
• $N_{\text{Jet}} \geq 2$
• $N_{\text{B-tag}} \geq 1$

Analysis strategy:
• BDT to discriminate signal vs. bkg. Most discriminant variables: $N_{\text{jet}}, N_{\text{B-tag}}, H_T$.
• Categories in BDT score, lepton charge, $N_{\text{jet}}$ and $N_{\text{B-tag}}$

Main systematics:
Luminosity, trigger, non-prompt bkg.

$$\mu = 1.23^{+0.19}_{-0.18} (\text{stat})^{+0.20}_{-0.18} (\text{syst})^{+0.13}_{-0.12} (\text{theo})$$

$$\sigma(pp \rightarrow t\bar{t}W) = 0.77^{+0.12}_{-0.11} (\text{stat})^{+0.13}_{-0.12} (\text{syst}) \text{ pb}$$

$$\sigma (\text{NLO}) = 0.628 \pm 0.082 \text{ pb}$$

Observed (expected) significance = 4.5(5.3) $\sigma$
Inclusive $t\bar{t}Z$ Measurement

2016 and 2017 data

Baseline Selection:
- 3 or 4 leptons
- A pair of leptons is OSSF with $m_{ll}$ in the Z mass window
- $N_{\text{Jet}} > 0$

$N_{\text{Jet}}$ and $N_{B}$ Classification

Improvements with respect to JHEP 08 (2018) 011 $t\bar{t}Z$ measurement:
- More inclusive trigger
- Lepton ID

Main Backgrounds:
- at least one top quark in association with a W, Z or H

$$\sigma(pp \rightarrow t\bar{t}Z) = 0.95 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ pb}$$

$$\sigma \text{ (NLO)} = 0.839 \pm 0.101 \text{ pb}$$

Precision comparable to NLO th. prediction
Differential cross section is also measured as a function of $p_T$ of the Z boson and of the cosine of the angle between the negative charged lepton and the Z candidate in the Z rest frame.

A signal enriched sample is used:

- 3 leptons
- $N_{\text{B-tags}} > 1$
- $N_{\text{Jets}} > 3$

- Unfolding by $\chi^2$ minimization without regularization
- aMC@NLO generator describes the shape well
t\bar{t}Z - EFT Interpretation

- Regions defined using $p_T(Z)$ and $\cos(\theta^*_Z)$
- 59 Wilson coefficients of dimension 6 → 4 relevant, sensitive to t-Z coupling
- New stringent limits on the anomalous couplings of t-Z and estimates of the Wilson Coefficients of SM EFT are obtained

Good agreement with SM
Sensitive to several SM interaction via triple gauge boson (WWZ), tbW and top-Z couplings. Also sensitive to tbW → tZ scattering amplitude.

- Might be affected by modified interaction even if ttZ and single top production are not.
- Could indicate the presence of flavour-changing neutral currents

Presence of a forward jet is a significant difference with respect to background processes
tZq - Observation

2016 and 2017 data

Baseline Selection:
- 3 isolated leptons
- A pair of leptons is OSSF with $m_{ll}$ in the Z mass window

Improvements with respect to PLB 779 (2018) 358:
- Luminosity increase
- Non-prompt lepton discrimination
- New analysis strategy: more inclusive categorization

Backgrounds:
- Diboson ($WZ, ZZ$) → CR for WZ and ZZ are implemented $ttX$ and $tX$ (mainly $ttZ$)
- Non-prompt lepton production ($DY$ and $tt$)
tZq - Observation

**tZq** is observed with a significance well above 5 $\sigma$, result in good agreement with SM prediction

$$\sigma(pp \rightarrow tZq \rightarrow t\ell^+\ell^-q) = 111^{+13}_{-13} \text{ (stat)}^{+11}_{-9} \text{ (syst)} \text{ fb}$$

$$\sigma(\text{NLO}) = 94.2 \pm 3.1 \text{ fb}$$

$$m(\ell^+\ell^-) > 30 \text{ GeV/c}^2$$

Main systematics: non-prompt background, lepton ID, FSR modeling, jet energy
2012 data @ 8TeV

Top selection:
- 1 lepton \((e, \mu, \tau \rightarrow e, \mu)\)
- \(N_{\text{Jet}} \geq 3\)
- \(N_{\text{B-tag}} \geq 1\)
- \(p_T^{\text{miss}} > 20\) GeV

Photon selection:
- \(\geq 1\) isolated prompt photon

Main backgrounds:
1) \(t\bar{t} +\) fake \(\gamma\)
2) \(V+\gamma\) \((V=Z/W)\)

Main Systematics:
- fit stats., JES, modeling...
- Evaluate photon purity using MC truth information
- Top reconstruction using \(M_3\)

---

**Table:**

<table>
<thead>
<tr>
<th>Category</th>
<th>(R)</th>
<th>(\sigma^{\text{fid}}_{t\bar{t}+\gamma}) (fb)</th>
<th>(\sigma_{t\bar{t}+\gamma}B) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>((5.7 \pm 1.8) \times 10^{-4})</td>
<td>138 \pm 45</td>
<td>582 \pm 187</td>
</tr>
<tr>
<td>(\mu)+jets</td>
<td>((4.7 \pm 1.3) \times 10^{-4})</td>
<td>115 \pm 32</td>
<td>453 \pm 124</td>
</tr>
<tr>
<td>Combination</td>
<td>((5.2 \pm 1.1) \times 10^{-4})</td>
<td>127 \pm 27</td>
<td>\textbf{515 \pm 108}</td>
</tr>
<tr>
<td>Theory</td>
<td>—</td>
<td>—</td>
<td>\textbf{592 \pm 71} (scales) \pm 30 (PDFs)</td>
</tr>
</tbody>
</table>

---

**Graph:**

- Data
- \(t\bar{t}+\gamma\)
- \(t\bar{t}+\)jets
- \(V+\gamma\)
- \(W/Z+\gamma\)
- \(W/Z+\)jets
- Multijet
- Uncertainty

- CMS: Inv. mass of the 3-jet combination with highest sum of \(p_T\)
2016 data

Selection:
- 1 muon & 1 isolated photon
- \(N_{\text{Jet}} \geq 2\)
- 1 \(N_{\text{B-tag}}\)
- \(p_T^{\text{miss}} > 30\) GeV

Strategy:
- **BDT** constructed based on topological and kinematic properties

Main backgrounds:
1) fake \(\gamma\) background: data-driven estimation using photon isolation and shower shape
2) \(t\bar{t}\gamma\): CR defined with 2 b-tagged jets.

\[
\sigma(pp \to t\gamma q) \text{ BR}(t \to \mu \nu b) = 115 \pm 17 \text{ (stat.)} \pm 30 \text{ (syst.)} \text{ fb}
\]

Fiducial Region:
- \(p_T^\gamma > 25\) GeV
- \(|\eta_\gamma| < 1.44\)
- \(\Delta R \left(\{\mu, b, j\}, \gamma\right) > 0.5\)

\[
\sigma_{\text{fiducial}}^{\text{SM}} \text{(scale + pdf)} = 81 \pm 4 \text{ fb}
\]

Observed (expected) significance of 4.4 (3.0) \(\sigma\)

**First evidence of the process**
• Very low cross section process $\sigma$(NLO) = 12.0 $^{+2.0}_{-2.5}$ fb
• The cross section can be used to constrain the magnitude and CP properties of the **Yukawa coupling** of the **top to the Higgs**.
• Can be enhanced due to **BSM particles** such as a heavy pseudoscalar or scalar boson produced in association with $t\bar{t}$ pair in 2HDM
Baseline Selection:
2\ell SS and 3\ell final states
Selection: \( H_T > 300 \text{ GeV}, p_T^{\text{miss}} > 50 \text{ GeV}, N_{\text{Jet}} \geq 2, N_{\text{B-tag}} \geq 2 \)

Two approaches: cut-based and BDT
variables: \( N_{\text{jet}}, N_{\text{B-tag}}, N_{\text{lep}}, H_T, p_T^{\text{jet}} \)...

Main Backgrounds:
\( \ttW, \ttZ, \ttH, \ttt \) (with a misidentified charge of one of the leptons)

Main syst:
jet energy, b-tagging, \( \ttH \) normalization

\[ \sigma = 12.6^{+5.8}_{-5.2} \text{ fb} \]
Observed (expected) significance = 2.6 (2.7) \( \sigma \)
A constrain on the Yukawa coupling is imposed: $|\frac{y_t}{y_t^{SM}}| < 1.7$ with a 95% confidence level.

Limits also set on the production of heavy scalar and pseudoscalar boson in a type II 2HDM scenario.
• LHC is now capable of measuring **rare SM** processes **with top quarks**.
• These processes are **sensitive to beyond the SM** interactions.
• Most of the analyses are not using the full Run 2 data sample yet.
• Some of the processes are studied for the first time are the LHC.
• All presented results show good agreement with the SM.

**Highlights:**
- Differential $t\bar{t}Z$
- First observation of $tZq$
- First evidence of $t\gamma$
- 4-top search increase in sensitivity

**Stay tuned!**
Back up
Summary of sources of systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty from each source (%)</th>
<th>Impact on the measured $t\bar{t}W$ cross section (%)</th>
<th>Impact on the measured $t\bar{t}Z$ cross section (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Jet energy scale and 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>Choice in $\mu_R$ and $\mu_F$</td>
<td>1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>PDF</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>t($\bar{t}$)X background</td>
<td>10–15</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Stat. unc. in nonprompt background</td>
<td>5–50</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Stat. unc. in rare SM backgrounds</td>
<td>20–100</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>—</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>
## t\bar{t}Z Inclusive

### Summary of sources of systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty range (%)</th>
<th>Correlated between 2016 and 2017</th>
<th>Impact on the t\bar{t}Z cross section (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>PU modeling</td>
<td>1–2</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Trigger</td>
<td>2</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>Lepton ID efficiency</td>
<td>4.5–6</td>
<td>√</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1–9</td>
<td>√</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0–1</td>
<td>√</td>
<td>&lt;1</td>
</tr>
<tr>
<td>b tagging light flavor</td>
<td>0–4</td>
<td>×</td>
<td>&lt;1</td>
</tr>
<tr>
<td>b tagging heavy flavor</td>
<td>1–4</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>Choice in $\mu_R$ and $\mu_F$</td>
<td>1–4</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>PDF choice</td>
<td>1–2</td>
<td>√</td>
<td>&lt;1</td>
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<tr>
<td>Color reconnection</td>
<td>1.5</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Parton shower</td>
<td>1–8</td>
<td>√</td>
<td>&lt;1</td>
</tr>
<tr>
<td>WZ cross section</td>
<td>10</td>
<td>√</td>
<td>3</td>
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<tr>
<td>WZ high jet multiplicity</td>
<td>20</td>
<td>√</td>
<td>1</td>
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<tr>
<td>WZ + heavy flavor</td>
<td>8</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>10</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>t(\bar{t})X background</td>
<td>10–15</td>
<td>√</td>
<td>2</td>
</tr>
<tr>
<td>Xγ background</td>
<td>20</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Nonprompt background</td>
<td>30</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Rare SM background</td>
<td>50</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Stat. unc. in nonprompt bkg.</td>
<td>5–50</td>
<td>×</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Stat. unc. in rare SM bkg.</td>
<td>5–100</td>
<td>×</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>8</td>
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</tbody>
</table>
t\bar{t}Z - EFT Interpretation

- Regions defined using $p_T(Z)$ and $\cos(\theta_Z^*)$
tZq - Observation

Signal enriched region and summary of most important sources of systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Impact (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>lepton selection</td>
<td>3.2</td>
</tr>
<tr>
<td>trigger efficiency</td>
<td>1.4</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>3.3</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>1.7</td>
</tr>
<tr>
<td>nonprompt normalization</td>
<td>4.1</td>
</tr>
<tr>
<td>ttZ normalization</td>
<td>1.0</td>
</tr>
<tr>
<td>luminosity</td>
<td>1.7</td>
</tr>
<tr>
<td>pileup</td>
<td>1.9</td>
</tr>
<tr>
<td>other</td>
<td>1.3</td>
</tr>
<tr>
<td>Theoretical</td>
<td></td>
</tr>
<tr>
<td>final-state radiation</td>
<td>2.0</td>
</tr>
<tr>
<td>tZq QCD scale</td>
<td>2.0</td>
</tr>
<tr>
<td>ttZ QCD scale</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Table 4: Uncertainties in the cross section ratio $R$ for the combination of the $e+$jets and $\mu+$jets final states.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical likelihood fit</td>
<td>15.5</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>7.9</td>
</tr>
<tr>
<td>JES</td>
<td>6.9</td>
</tr>
<tr>
<td>Fact. and renorm. scale</td>
<td>6.7</td>
</tr>
<tr>
<td>ME/PS matching threshold</td>
<td>3.9</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>2.4</td>
</tr>
<tr>
<td>JER</td>
<td>2.3</td>
</tr>
<tr>
<td>Multijet estimate</td>
<td>2.0</td>
</tr>
<tr>
<td>Electron misid. rate</td>
<td>1.3</td>
</tr>
<tr>
<td>Z+jets scale factor</td>
<td>0.8</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.6</td>
</tr>
<tr>
<td>Background normalization</td>
<td>0.6</td>
</tr>
<tr>
<td>Top quark $p_T$ reweighting</td>
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</tr>
<tr>
<td>b tagging scale factor</td>
<td>0.3</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>0.3</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>0.1</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.1</td>
</tr>
<tr>
<td>Muon energy scale</td>
<td>0.1</td>
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<tr>
<td>Electron energy scale</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>20.7</td>
</tr>
</tbody>
</table>
2016 data
Selection:
• 1 muon & 1 isolated photon
• $N_{\text{Jet}} \geq 2$
• 1 $N_{\text{B-tag}}$
• $p_T^{\text{miss}} > 30$ GeV

Strategy:
BDT constructed based on topological and kinematic properties

Main backgrounds:
1) fake $\gamma$ background: data-driven estimation using photon isolation and shower shape
2) $t\bar{t}\gamma$: CR defined with 2 b-tagged jets.

Main Systematics:
JES (12%), signal modeling (9%), $Z\gamma +$ jets normalization (8%) and b-tagging and mistagging rates (7%)
Summary of sources of systematic uncertainties

Table 2: Summary of the sources of uncertainty, their values, and their impact, defined as the relative change of the measurement of $\sigma(tttt)$ induced by one-standard-deviation variations corresponding to each uncertainty source considered separately. The first group lists experimental and theoretical uncertainties in simulated signal and background processes. The second group lists normalization uncertainties in the estimated backgrounds. Uncertainties marked (not marked) with a † in the first column are treated as fully correlated (fully uncorrelated) across the three years of data taking.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>Impact on $\sigma(tttt)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.3–2.5</td>
<td>2</td>
</tr>
<tr>
<td>Pileup</td>
<td>0–5</td>
<td>1</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2–7</td>
<td>2</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>2–10</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1–15</td>
<td>9</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1–10</td>
<td>6</td>
</tr>
<tr>
<td>b tagging</td>
<td>1–15</td>
<td>6</td>
</tr>
<tr>
<td>Size of simulated sample</td>
<td>1–25</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Scale and PDF variations †</td>
<td>10–15</td>
<td>2</td>
</tr>
<tr>
<td>ISR/FSR (signal) †</td>
<td>5–15</td>
<td>2</td>
</tr>
<tr>
<td>$t\bar{t}H$ (normalization) †</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Rare, $X\gamma$, $t\bar{t}VV$ (norm.) †</td>
<td>11–20</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$t\bar{t}Z$, $t\bar{t}W$ (norm.) †</td>
<td>40</td>
<td>3–4</td>
</tr>
<tr>
<td>Charge misidentification †</td>
<td>20</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Nonprompt leptons †</td>
<td>30–60</td>
<td>3</td>
</tr>
<tr>
<td>$N_{\text{ISR/FSR}}^{\text{jets}}$</td>
<td>1–30</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma(tt\bar{b})/\sigma(t\bar{t}jj)$ †</td>
<td>35</td>
<td>11</td>
</tr>
</tbody>
</table>
2016 data
Baseline Selection:

2ℓOS and single lepton final states

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
<th>e</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{ℓℓ}</td>
<td>&gt;20 GeV + Z veto</td>
<td>&gt;20 GeV</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N_{jet}</td>
<td>≥4</td>
<td>≥8</td>
<td>≥7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N_{B-tag}</td>
<td>≥2</td>
<td>≥2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Strategy:
BDT used to identify hadronic top decays. A second BDT is used to discriminate $tttt$ from $tt$. This takes as input the first BDT, event topology, event activity, $N_{B-tag}$

Combination with **EPJC 78 (2018) 140** (2016 multilepton):

$$\sigma = 13^{+11}_{-9} \text{ fb}$$

Observed (expected) significance = 1.4 (1.1)