Rare top quark production at CMS

$ttW, ttZ, tty, tZq, t\gamma q, tttt$

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On behalf of the CMS Collaboration

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Run II dataset allows to probe top quarks in its rarest production modes

- $t\bar{t} + W$ (36 fb$^{-1}$) JHEP08(2018)011
- $t\bar{t} + Z$ (78 fb$^{-1}$) arXiv:1907.11270
- $t\bar{t} + \gamma$ (20 fb$^{-1}$) JHEP10(2017)006
- 4 top (137 fb$^{-1}$) CMS-TOP-18-003
- $tZq$ (36 fb$^{-1}$) CMS-TOP-17-019
- $t\gamma q$ (36 fb$^{-1}$) PRL122(2019)132003
- $t\gamma q$ (36 fb$^{-1}$) PRL 121 (2018)221802
**$t\bar{t} + W$ production**

- 2 leptons with same charge
- $p_T(\ell) > 25 / 40$ GeV
- veto Z candidate
- At least two jets

**Results**

$$\sigma(t\bar{t}W) = 0.77 \pm 0.11\text{(stat)} \pm 0.13\text{(syst)}\text{ pb}$$

25% precision

- Large bkg. from nonprompt leptons, ttH
- BDT classifier for S/B separation
- Binned ML fit to all signal & background control regions
- Main syst. from backgrounds
- Next : Full Run II data & detailed studies of charge asymmetries

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**$t\bar{t} + Z$ production**

- 3/4 leptons
- $p_T(\ell) > 10, 15, 25$ GeV
- $Z$ candidate $|m_{\ell\ell} - m_Z| < 15$ GeV

Best process to probe top-Z coupling and its structure

- Events categorized in jet bjet multiplicity $\rightarrow$ good S/B separation
- Simultaneous fit in Signal & bkg. enriched regions with nuisance parameters

8% precision !!!

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

- Main systematic uncertainty modelling of signal acceptance related to leptons and $ttX$ bkg.

$$\sigma(t\bar{t}Z)^{NLO} = 0.85 \pm 0.10$$
• Events with at least 1 bjet and 3 jets are used to measure the differential cross sections

• $Z$ boson $p_T$ and $\cos\theta^*$ sensitive to new physics effects!
**t\bar{t} + Z**: EFT interpretation

- $Z p_T$ and $\cos \theta^*$ are explored to probe anomalous top-Z couplings & top EW dipole moments

SMEFT interpretation to constraint four Wilson coefficients

**EW dipole interactions**

$$\mathcal{L} \equiv e \bar{u}_t \left[ \gamma^\mu (C_{1,V} + \gamma_5 C_{1,A}) + \frac{i \sigma^{\mu\nu} p_\nu}{m(Z)} (C_{2,V} + i \gamma_5 C_{2,A}) \right] \nu_t \cdot Z_\mu$$
Sensitive to top Higgs Yukawa coupling & NP via BSM particles ie. a heavy (pseudo)scalar boson in association with a ttbar pair in 2HDM

- Rare process with a predicted cross section: $12.0^{+2.2}_{-2.5} \text{ fb}$
- Spectacular experimental signature, but small cross section
- Most sensitive channel: same-sign dileptons and multileptons

Using BDT analysis
- Measured cross section is $12.6^{+5.8}_{-5.2} \text{ fb}$
- Obs. significance of $2.6 \sigma$

Combination with other channels important
Single top-quark production

- Production via EWK interaction
  - smaller cross sections, large backgrounds
- Precise determination of $|V_{tb}|$, constrain PDFs, FCNC

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Single top-quark production

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$\sigma(tq) = 136 \pm 1 \pm 22 \text{ pb}$

$\sigma(\bar{t}q) = 82 \pm 14 \text{ pb}$
Single top-quark production

• Production via EWK interaction
  → smaller cross sections, large backgrounds
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Single top-quark production

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Single top-quark production

**ATLAS+CMS Preliminary**

**LHCTopWG**

**Single top-quark production**

November 2018

- **t-channel**
  - $\sigma(tq) = 136 \pm 1 \pm 22 \text{pb}$
  - $\sigma(t\bar{q}) = 82 \pm 1 \pm 14 \text{pb}$

- **tW-channel**
  - $\sigma(tW) = 63 \pm 2 \pm 7 \text{pb}$

- **S-channel**

  $\sigma(tZq) \sim 1 \text{pb}$

  $\sigma(t\gamma q) \sim 3 \text{pb}$

**Rare!!!**
single-top + Z production

- Unique sensitivity to some EFT operators due to $Wb \rightarrow tZ$ vertex
- FCNC
single-top + Z production

- 3 leptons
- $p_T(\ell) > 10, 15, 25$ GeV
- Z candidate $|m_{\ell\ell} - m_Z| < 15$ GeV
- At least two jets with $p_T > 25(60)$ GeV

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2-3

=0

2-3 ≥4

N(jet)

N(b-jet)

signal region with large ttZ

best signal region

signal region with large ttZ

Background control region (WZ/ZZ)

≥2

=1

=0
single-top + Z production

- 3 leptons
- $p_T(\ell) > 10,15,25$ GeV
- Z candidate $|m_{\ell\ell} - m_Z| < 15$ GeV
- At least two jets with $p_T > 25(60)$ GeV

Train BDT in each signal category
single-top $+ Z$ production

- Binned ML fit to all signal & bkg. control regions
  - obs.(exp.) significance $8.2 (7.7) \sigma$
  - First observation!

Measured cross section

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

- 15% precision

NLO SM prediction $94.2 \pm 3.1 \text{ fb}$


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single-top + Z production

- Binned ML fit to all signal & bkg. control regions

\[ \text{obs.(exp.) significance } 8.2(7.7)\sigma \]

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15% precision

NLO SM prediction \[ 94.2 \pm 3.1\,\text{fb} \]


- Relatively pure signal sample → next the differential measurement!
single-top + γ production

- Sensitive to the top quark charge and the top quark electric and magnetic dipole moments
  - Single-muon, $p_T > 30$ GeV
  - Photon $p_T > 30$ GeV, 2 jets, 1 bjet
  - BDT to discriminate signal from backgrounds

- largest background from $t\bar{t}\gamma$, template from 2 b-tag data
- misidentified photons predicted from data by measuring jet misidentification rate as a function of $p_T$

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single-top + $\gamma$ production

Binned likelihood fit is performed to the BDT in the SR and the tt+\gamma CR

obs.(exp.) significance 4.4(3.0)$\sigma$

First evidence!

Measured cross section in a fiducial region:

$p_T(\gamma) > 25$GeV, $|\eta(\gamma)| < 1.44$, $\Delta R(X,\gamma) > 0.5$

$\sigma(t\gamma q) \times BR(t \rightarrow \mu \nu b) = 115 \pm 17$ (stat) $\pm 30$ (syst) fb

30% precision

NLO SM prediction

$\sigma_{t\gamma}(\text{NLO}) = 81 \pm 4$ (scale+PDF) fb
• $tt+V$ measurements are becoming precise and challenge the theoretical precision

• First differential measurements of $ttZ$

• Observation of $tZq$ and evidence for $t\gamma q$

• EFT interpretations play more central role in using top events to look for new physics effects! → More systematic results to come
$t\bar{t} + \gamma$ production

- Only one lepton ($p_T(e, \mu) > 35, 26$ GeV), at least 3 jets ($p_T > 30$ GeV)
- one b-tagged, MET $> 20$ GeV and at least one photon ($p_T > 25$ GeV)
Vtb extraction

\[ \sigma(tj + \bar{t}j) = \sum_{q=b,d,s} \alpha_{tq} \cdot |V_{tq}|^2 \cdot B(t \rightarrow Wq) \]

Deviations from the SM are parameterized with \( f_{LV} \)

\[ |f_{LV} \cdot V_{tb}| = \sqrt{\frac{\sigma_{\text{measured}}}{\sigma_{\text{predicted}}}} \]

Best measurement is obtained from 7 & 8 TeV combination with \(~4\%\) uncertainty

- Expect to improve with luminosity
- limited by theory (\(~3\%\) at NNLO)
Single-top t-channel production

\[ R_1 = \frac{\sigma_{tot}(tq)}{\sigma_{tot}(\bar{t}q)} = 1.66 \pm 0.02 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

- At higher \( \sqrt{s} \), \( R_1 \) approaches 1
- As “sea quarks” become important

arXiv:1812.10514
Lepton identification

- Dedicated lepton selection using MVA for this analysis
- Crucial for reducing backgrounds from nonprompt leptons
- Input variables: jets closest to lepton, impact parameters, isolation, lepton $p_T$, $\eta$, +usual identification variables

- 8-12% gain per signal lepton efficiency
- Factor 2(8) reduction in nonprompt electron (muon) background
tZq event candidate
Most sensitive kinematic variables:

- Maximum di-jet invariant mass
- $\eta$ of the jet recoiling top
- $N_{jets} = 2, 3 \quad N_{bjets} = 1$

Main backgrounds: WZ, ttZ and nonprompt lepton
• Binned maximum-likelihood fit to all three distributions & WZ and ZZ control regions
• Nuisance parameters for normalization and shape uncertainties
• Good agreement between prediction and observed data
**single-top + Z production**

- Binned maximum-likelihood fit to all three distributions & WZ and ZZ control regions

\[
\mu = 1.36^{+0.22}_{-0.20} \text{(stat)}^{+0.14}_{-0.12} \text{(sys)} \quad 2016 \text{ data}
\]

\[
\mu = 1.03^{+0.18}_{-0.17} \text{(stat)}^{+0.14}_{-0.12} \text{(sys)} \quad 2017 \text{ data}
\]

\[
\mu = 1.18^{+0.14}_{-0.13} \text{(stat)}^{+0.11}_{-0.10} \text{(sys)}
\]

observed(expected) significance 8.2(7.7)σ

First observation of tZq process!

**Measured cross section**

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

NLO SM prediction


94.2 ± 3.1 fb

15% precision

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single-top + Z production

Measured cross section

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

15% precision

<table>
<thead>
<tr>
<th>Source</th>
<th>impact (±%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonprompt bkg.</td>
<td>4.1</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>3.2</td>
</tr>
<tr>
<td>Jet Energy Scale 2016(2017)</td>
<td>0.9(3.1)</td>
</tr>
<tr>
<td>Parton Shower Mod.</td>
<td>2</td>
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<tr>
<td>QCD Scale choice (tZq)</td>
<td>2</td>
</tr>
<tr>
<td>Pile Up</td>
<td>1.9</td>
</tr>
<tr>
<td>QCD Scale choice (ttZ)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

- Several improvements in the analysis paid off
- In particular nonprompt lepton background reduction
- Still statistical uncertainties dominate
**Ttgamma systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
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<tbody>
<tr>
<td>Statistical likelihood fit</td>
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<tr>
<td>Top quark mass</td>
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<tr>
<td>JES</td>
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<tr>
<td>Fact. and renorm. scale</td>
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<td>ME/PS matching threshold</td>
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<td>Photon energy scale</td>
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<td>JER</td>
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<tr>
<td>Multijet estimate</td>
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<tr>
<td>Electron misid. rate</td>
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<tr>
<td>Z+jets scale factor</td>
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<tr>
<td>Pileup</td>
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<tr>
<td>Background normalization</td>
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<td>Top quark $p_T$ reweighting</td>
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<td>$b$ tagging scale factor</td>
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<td>Muon efficiency</td>
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<tr>
<td>Electron efficiency</td>
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<td>PDFs</td>
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<tr>
<td>Muon energy scale</td>
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<tr>
<td>Electron energy scale</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20.7</strong></td>
</tr>
</tbody>
</table>
Nonprompt lepton bkg. validation

No OSSF pair or \( m(\ell\ell) \) outside Z mass window

- Low statistics \( \rightarrow \) powerful lepton selection
- 30\% systematic uncertainty + stat uncertainty in the control region
Signal samples & theory cross section

- Signal MC: LO rescaled to NLO.
- Theory cross section:
  - $Z$ boson is forced to be on shell,
  - no cuts are applied,
  - 4-flavour scheme.
- $\sigma_{NLO}(tZq) = 800 \text{ fb}$
  - ±6/7% scale

- Signal MC: NLO.
- Theory cross section:
  - $Z$ boson can be off shell $/gamma^*$ is also included,
  - $m_H > 30 \text{ GeV}$,
  - 5-flavour scheme (4FS for MC generation).
- $\sigma_{NLO}(tllq) = 94 \text{ fb}$
  - ±2% scale
  - ±2.5% PDF

- Tau leptonic decays included.
- Different scale choice between ATLAS and CMS.
  - $\sigma_{NLO}(tZq) \sim 820 \text{ fb}$.
BDT discriminator

Signal & Background discriminating variables

- Maximum di-jet invariant mass
- $\eta$ of the jet recoiling top
- $|\eta| \times \text{charge}(\ell_W)$
- highest btag discriminator
- $\text{max } \Delta \phi(\ell\ell)$
- $\text{min } \Delta R(\text{jet}, \ell_W)$
- $\text{max } p_T(\text{jet,jet})$
- $m(\ell\ell\ell), m_T, H_T, N_{\text{jets}}, ...$

- 6 BDTs in total: 3 for each category and separate for 2016/2017 data
- Training against the sum of all backgrounds
- Good discrimination power in all categories