Rare top quark production at the LHC

Results on $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, $tZq$, $t\gamma q$, and $t\bar{t}t\bar{t}$ with the ATLAS and CMS experiments

Joscha Knolle
on behalf of the ATLAS and CMS collaborations

WG5: Physics with Heavy Flavours
XVII International Workshop on Deep Inelastic Scattering
April 8th–12th, 2019, Torino
Top quark production at the LHC

March 2019

CMS Preliminary

7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 137 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV

• Top quark pairs and single tops produced plentiful.
• Rare top production modes become fully accessible with full run-2 data.
ttW and ttZ production

- ttZ cross section sensitive to tZ coupling, first direct test
- important backgrounds for measurements with leptons and b-quarks, e.g. ttH

arXiv:1901.03584 (submitted to PRD)

JHEP 1808 (2018) 011

ttW and ttZ with 2016 data

CMS-PAS-TOP-18-009

ttZ with 2016 & 2017 data
**ttW & ttZ measurement**

arXiv:1901.03584 (submitted to PRD)

**ttW:** analysis regions for SS dilepton and trilepton channels

**ttZ:** analysis regions for OS dilepton, trilepton and tetralepton channels

simultaneous **template fit** to signal and control regions

- BDT for OS dilepton channel
- \((N_j, N_b)\) categories for other channels
- control regions for \(t\bar{t}, WZ+\)jets, \(ZZ\)
- nonprompt leptons & charge-flip from data

main systematics: signal modeling, backgrounds (modeling, normalization, statistics)
**ttW & ttZ cross section results**

*arXiv:1901.03584 (submitted to PRD), JHEP 1808 (2018) 011*

### ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- **Best fit**
- 68% CL
- 95% CL
- NLO prediction

### CMS

- **Events**
- 35.9 fb$^{-1}$ (13 TeV)

#### Data
- ttW
- ttZ
- Nonprompt
- WZ
- tt(X)
- Rare
- Charge mis-ID

#### Control region

#### Signal region

**22% and 13% precision**

$\sigma$($ttW$) = 0.87 ± 0.13 (stat) ± 0.14 (syst) pb

$\sigma$($ttZ$) = 0.95 ± 0.08 (stat) ± 0.10 (syst) pb

⇒ in good agreement with SM prediction:

$\sigma$($ttW$) = 0.628 ± 0.082 pb

$\sigma$($ttZ$) = 0.839 ± 0.101 pb
**New inclusive \( t\bar{t}Z \) result**

**CMS-PAS-TOP-18-009**

\[ \sigma(t\bar{t}Z) = 1.00^{+0.06}_{-0.05} \text{ (stat)} +^{0.07}_{-0.06} \text{ (syst)} \text{ pb} \]

\( \Rightarrow \) more precise than NLO prediction

\( \Rightarrow \) main systematics: lepton ID, background normalization

**Nonprompt \( \ell \) from data**

**WZ constraints from \( N_b = 0 \)**

**WZ, X_{\gamma}, ZZ validated in control regions**

**most important background: tZq**
First differential $t\bar{t}Z$ result

**CMS-PAS-TOP-18-009**

**parton-level** cross section, from cut-based measurement in 3-lepton channel

main systematics: lepton ID, jet energy, nonprompt background

⇒ good agreement with shape of SM prediction

EFT interpretation of $t\bar{t}Z$ measurement available, see [talk by Brieuc François](#) for details
tZq production

- t-channel production of single top quark in association with Z boson
- sensitive to tZ coupling, as well as to triboson WWZ coupling
- important feature: recoiling light jet (not present in FCNC scenario)


arXiv:1812.05900 (accepted by PRL)
**tZq measurement**


Train **neural network** to separate trileptonic **tZq** signal from backgrounds

**Template fit** to NN output to extract cross section

- Most discriminating input: $|\eta(\text{light jet})|
- Reconstructed Z boson and top quark
- WZ, ZZ, $t\bar{t}$+fake normalized in control regions
- Z+fake from data

$\sigma(tZq) = 600 \pm 170 \text{ (stat)} \pm 140 \text{ (syst)} \text{ fb}$

4.2 $\sigma$ (5.4 $\sigma$) obs. (exp.) significance

$\Rightarrow$ evidence for tZq production

$\Rightarrow$ in agreement with SM prediction: $800 \text{ fb}^{+6.1\%}_{-7.4\%}$
train **BDT** to separate trileptonic tZq signal from backgrounds

simultaneous **template fit** to BDT output and yields of control regions

- separate BDTs for \((N_j, N_b)\) categories
- most discriminating input: \(|\eta|\) (light jet)
- control regions for WZ, ZZ, Xγ
- nonprompt background from data
- \(\bar{t}tZ\) constrained in low-BDT bins of high-multiplicity categories

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**tZq measurement**

arXiv:1812.05900 (accepted by PRL)
First tZq observation

arXiv:1812.05900 (accepted by PRL)

train BDT to separate trileptonic tZq signal from backgrounds
simultaneous template fit to BDT output and yields of control regions

15% precision

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

⇒ first observation with observed significance \( > 5 \sigma \)
⇒ in agreement with SM prediction:
94.2 \pm 3.1 \text{ fb}
⇒ main systematics:
  – nonprompt lepton background
  – lepton ID
  – FSR modeling
  – jet energy
Top quarks with a photon

- photon radiation off top quarks sensitive to $t\gamma$ coupling
- also contributions from initial and final state radiation
- fiducial phase space definition requires tightly isolated photon

arXiv:1812.01697 (submitted to EPJC)
$t\bar{t}\gamma$ with 2015 & 2016 data

$t\gamma q$ with 2016 data
**ttγ measurement**

arXiv:1812.01697 (submitted to EPJC)

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Single-lepton

Post-fit

- Data
- $t\bar{t}\gamma$

Had-fake

e-fake

Fake lepton

$W\gamma$

Other prompt

Uncertainty

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Dilepton

Post-fit

- Data
- $t\bar{t}\gamma$

Had-fake

e-fake

$\gamma Z$

Other prompt

Uncertainty

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**train neural network** to separate

$tt\gamma$ signal from backgrounds

**template fit** to NN output

- single-lepton & dilepton channel
- fake photons & fake leptons estimated from data
- $W\gamma$, $Z\gamma$ validated in control regions

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**Inclusive $t\bar{t}\gamma$ cross section**

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

**ATLAS**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Total</th>
<th>Statistical</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e+\text{jets}$</td>
<td>1.07</td>
<td>+0.09 (+0.03 +0.08)</td>
<td>-0.08 (-0.03 -0.08)</td>
</tr>
<tr>
<td>$\mu+\text{jets}$</td>
<td>1.01</td>
<td>+0.09 (+0.03 +0.09)</td>
<td>-0.09 (-0.03 -0.08)</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>1.11</td>
<td>+0.13 (+0.09 +0.10)</td>
<td>-0.12 (-0.08 -0.08)</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>1.09</td>
<td>+0.08 (+0.05 +0.06)</td>
<td>-0.08 (-0.05 -0.06)</td>
</tr>
<tr>
<td>$ee$</td>
<td>1.00</td>
<td>+0.14 (+0.10 +0.10)</td>
<td>-0.13 (-0.09 -0.09)</td>
</tr>
</tbody>
</table>

**Single-lepton channel:**

- **521 \pm 9 (stat) \pm 41 (syst) fb**
- **8% precision**

**Dilepton channel:**

- **69 \pm 3 (stat) \pm 4 (syst) fb**
- **7% precision**

**SM prediction**

\[ \sigma(t\bar{t}\gamma, 1\ell) = 495 \pm 99 \text{ fb} \]
\[ \sigma(t\bar{t}\gamma, 2\ell) = 63 \pm 9 \text{ fb} \]

\[ \frac{\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}\gamma}^{NLO}}{\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}\gamma}^{NLO}} \]

\[ \Rightarrow \text{in agreement with and more precise than NLO prediction} \]

\[ \Rightarrow \text{main uncertainties:} \]
- statistics (2\ell only)
- background modeling
- jet systematics
particle-level cross sections, from cut-based measurement in both channels

good agreement in all observables with SM prediction

- sensitive to $t\gamma$ coupling: $p_T(\gamma), |\eta(\gamma)|, \Delta R(\gamma, \ell)$
- sensitive to $t\bar{t}$ spin correlations: $\Delta \phi(\ell\ell), |\Delta \eta(\ell\ell)|$ (2\ell only)
- main systematics: $t\bar{t}$ modeling (1\ell), $Z\gamma$ modeling (2\ell)
First evidence for $t\gamma q$


Train BDT to separate $t\gamma q$ from backgrounds, template fit to BDT output

- only decay channel: $t \rightarrow \mu \nu b$

Fiducial cross section:

$$\sigma(t\gamma q) = 115 \pm 17 \text{ (stat)} \pm 30 \text{ (syst)} \text{ fb}$$

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

⇒ first evidence for $t\gamma q$ production

⇒ in agreement with SM prediction:

$$81 \pm 4 \text{ fb}$$
Search for $t\bar{t}t\bar{t}t$ production

- sensitive to top quark Yukawa coupling
- many BSM models predict enhanced $t\bar{t}t\bar{t}t$ cross section

JHEP 1812 (2018) 039
$t\bar{t}t\bar{t}$ with 2015 & 2016 data

CMS-PAS-TOP-17-019
$t\bar{t}t\bar{t}$ with 2016 data

CMS-PAS-TOP-18-003
$t\bar{t}t\bar{t}$ with 2016–2018 data
jets reclustered into mass-tagged large-R jets

**template fit** to hadronic activity distribution in signal regions

- \((N_j, N_b, N_J)\) categories for both channels
- nonprompt lepton and \(\bar{t}t\) background from data
- dominant systematic: \(\bar{t}t\) modeling

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**Single Lepton**

\[ H_T^{\text{had}} \text{ [GeV]} \]

\[ \begin{array}{c|c|c|c}
\text{Events / bin} & \text{Data} & \text{\(t\bar{t}\) (SM)} & \text{\(t\bar{t}\) + jets (data-driven)} \\
\hline
\geq 10j, 3 b, \geq 2 J & 30 & 10 & 20 \\
\geq 9 j, 3 b, \geq 2 J & 20 & 10 & 10 \\
0.5 & 0.75 & 1 & 1.25 \\
\end{array} \]

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**Dilepton**

\[ H_T^{\text{had}} \text{ [GeV]} \]

\[ \begin{array}{c|c|c|c}
\text{Events / bin} & \text{Data} & \text{\(t\bar{t}\) (SM)} & \text{\(t\bar{t}\) + jets (data-driven)} \\
\hline
\geq 8 j, 3 b, \geq 1 J & 8 & 6 & 2 \\
\geq 7 j, 4 b, \geq 1 J & 10 & 5 & 5 \\
0.5 & 0.75 & 1 & 1.25 \\
\end{array} \]
cut-based search for new phenomena in events with leptons and b-jets
interpreted as \( t\bar{t}t\bar{t} \) search

- \( N_b \) categories for different signals
- high MET & hadronic activity
- nonprompt lepton & charge-flip backgrounds from data

**combination** of both searches

obs. (exp.) significance: \( 2.8 \sigma \) (1.0 \( \sigma \))
**tttt search in 1ℓ, 2ℓ OS channels**


Train BDT to separate tttt signal from background

Template fit to BDT output in signal regions
- BDT-based top tagging
- \((N_j, N_b)\) categories
- Main background: t\(\bar{t}\)+jets

EFT interpretation of tttt search available, see talk by Brieuc François

**Combination** with previous 2ℓ SS & 3ℓ search (also 2016 data)

Obs. (exp.) significance: 1.1 \(\sigma\) (1.4 \(\sigma\))
Both **cut-based** and **BDT**-based analysis performed, with compatible results

Simultaneous **template fit** to signal and control regions

- Cut-based categories in \((N_\ell, N_j, N_b)\)
- Control regions for \(t\bar{t}Z, t\bar{t}W\) normalization
- Nonprompt lepton and charge-flip backgrounds from data

Main systematics: \(t\bar{t}+b\bar{b}\) normalization, jet energy, b-tagging
**tttt search with full run-2 data**

2ℓ SS, 3ℓ channels, CMS-PAS-TOP-18-003

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**CMS Preliminary**

**BDT (postfit)**

137 fb⁻¹ (13 TeV)

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**CMS Preliminary**

137 fb⁻¹ (13 TeV)

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Result with BDT-based analysis

obs. (exp.) significance: 2.6 σ (2.7 σ)

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Constraint on Yukawa coupling

95 % CL limit: |y_t/y_t^{SM}| < 1.7
Summary

- Large amount of run-2 data and refined analysis techniques allowed for measurements of several rare top quark production processes.
- All results are in good agreement with standard model predictions.
- Stay tuned: New results with more data are on their way!

Some highlights:
- Differential $t\bar{t}Z$ and $t\bar{t}\gamma$ cross section measurements
- First observation of $tZq$
- First evidence for $t\gamma q$
- First $t\bar{t}t\bar{t}$ search results with full run-2 dataset

$tZq$ candidate event:
Backup: Why study rare tops?

Test of SM Couplings
e.g. $t\bar{t}\gamma$: direct probe of top quark’s electric charge

Flavor-Changing Neutral Currents
e.g. $tZ$: presence of FCNC vertex changes experimental signature

EFT Constraints
e.g. $ttt\bar{t}$: constrains 4-fermion operators

Important Backgrounds
e.g. $t\bar{t}W$, $t\bar{t}Z$: relevant backgrounds to $t\bar{t}H$ in multilepton final states

CMS

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CMS

CMS PAS-FTR-18.031

CMS-PAS-FTR-18.031


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