Anomalous and rare top quarks in CMS

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on behalf of the CMS Collaboration

LPCC Seminar - 3 July 2018
indico.cern.ch/event/719632/
The Top Quark

The heaviest fundamental particle, so far
\[ m_{\text{top}} \sim 173 \text{ GeV} \]

The only naked quark, decays weakly before hadronizing
\[ \tau \sim 5 \times 10^{-25} \text{ s} \]
- Allows to probe quark properties directly: mass, couplings, spin, charge

Strongly interacting with the electroweak sector and the Higgs
\[ m_{\text{top}} = y_t v / \sqrt{2} \rightarrow y_t \sim 1 \]
- Direct top-Higgs coupling in ttH observed by both CMS and ATLAS!

Inspiring us to look Beyond the Standard Model
- Hierarchy problem: divergent top corrections to the Higgs mass
  - Supersymmetry, vector-like fermions
- First place to look for new particles that couple to mass
  - Heavy partners of the Higgs
How does the top quark interact with other SM particles?

What is the **strength of the top quark coupling** with the gluon and the W?
- Measure $t\bar{t}$ and single-top cross-sections [not discussed today]

What is the **structure of its weak coupling**, the $Wtb$ vertex?
- Is it SM-like (left-handed vector), or does it have BSM components?
  - Study $W$ helicity in $t\bar{t}$, search among angular correlations in single-top

![Diagram showing production cross section](image-url)

*20 fb$^{-1}$, 8 TeV*
How does the top quark interact with other SM particles?

How does it couple to the $Z/H/\gamma$?

... when does the top quark radiate $Z/H/\gamma$?

- Measure (SM) $ttZ$, $tZ$, $tty$, $ty$. [For $tH$ and $tH$, see recent CMS LPCC seminar by A. Gilbert]
- Constrain coefficients of Effective Field Theory couplings ($ttW$, $ttZ$)

... or can it decay to $Z/H/\gamma$ in a Flavor Changing Neutral Current?

- Search for (BSM) FCNC decays in $tt$ and single top ($t\rightarrow H, Z, \gamma, g$)

CMS Preliminary

June 2018

Production Cross Section, $\sigma$ [fb]

7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
13 TeV CMS measurement ($L \leq 35.9$ fb$^{-1}$)
Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

20 fb$^{-1}$, 8 TeV
36 fb$^{-1}$, 13 TeV

All results at: http://cern.ch/qo/pNj7
How do these interactions affect the $t\bar{t}$ coupling at high energies?

- Measure the SM four top process ($pp \rightarrow t\bar{t}t\bar{t}$), where LO electroweak corrections can become as large as NLO strong corrections.

These fundamental questions define a rich research program!
**Status after LHC Run 1: Rare Top**

**Rare**, but within LHC reach: SM cross section larger than $O(fb)$
- Measurements: $t\bar{t}W$ ($\pm30\%$), $t\bar{t}Z$ ($\pm27\%$), $t\gamma$ ($\pm22\%$), $tZ$ ($\pm80\%$)
- Limits: $t\bar{t}t\bar{t}$ (95% CL upper limit: $\sigma_{t\bar{t}t\bar{t}} < 25*\sigma_{SM}$)

**Very Rare**: FCNC, $\sigma_{SM}$ smaller than $O(10^{-6} \text{ fb})$, but large BSM enhancements
- Limits on top BR ($t\rightarrow H$, $\gamma$, $g$, $Z$) between $10^{-2}$ and $10^{-5}$

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**Flavor Changing Neutral Currents**

<table>
<thead>
<tr>
<th>Theory predictions</th>
<th>CMS Preliminary</th>
<th>February 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\rightarrow H_c$</td>
<td>95% CL upper limits</td>
<td>[1] arXiv:1610.04857 subm. to JHEP</td>
</tr>
<tr>
<td>$t\rightarrow H_u$</td>
<td>[2] JHEP 04 (2016) 035</td>
<td></td>
</tr>
<tr>
<td>$t\rightarrow \gamma c$</td>
<td>[3] arXiv:1610.03545 subm. to JHEP</td>
<td></td>
</tr>
<tr>
<td>$t\rightarrow g u$</td>
<td>[4] arXiv:1702.01404 subm. to JHEP</td>
<td></td>
</tr>
<tr>
<td>$t\rightarrow Z c$</td>
<td>Theory predictions from arXiv:1311.2028</td>
<td></td>
</tr>
<tr>
<td>$t\rightarrow Z u$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Each limit assumes that all other processes are zero.

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All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
Status after LHC Run 1: Anomalous Top

Anomalous couplings: Wtb vertex can include BSM terms
\[
\mathcal{L} = \frac{g}{\sqrt{2}} b \gamma^\mu \left( f_V^L P_L + f_V^R P_R \right) t W^-_\mu - \frac{g}{\sqrt{2}} b \frac{\sigma^{\mu \nu} \partial_\nu W^-_\mu}{M_W} \left( f_T^L P_L + f_T^R P_R \right) t + \text{h.c.}
\]

- Left-handed vector: \( f_V^L = V_L = V_{tb} \sim 1 \) in the Standard Model
- Right-handed vector, and left/right-handed tensors: \( f_V^R, f_T^L, f_T^R \) (aka \( V_R, g_L, g_R \)). 0 in SM.

Two 8 TeV analyses: t-channel single top and top pair

**single top**: generate samples with anomalous couplings \( (f_V^R, f_T^L, f_T^R) \), train Neural Networks on each
- Assume real couplings, and constrain \( (f_V^L, f_V^R, f_T^L, f_T^R) \) in 2D or 3D

**top pair**: measure helicity fractions of the \( W \) (\( F_0, F_L, F_R \))
- Assume real couplings, \( f_V^L = 1 \) and \( f_V^R = 0 \). Constrain \( (f_T^L, f_T^R) \)
Today: Results with 36 fb^{-1} of 13 TeV data

Run 2 results in Rare top:
\(\text{ttW (5}\sigma\), \text{ttZ (5}\sigma\), \text{t}\gamma (4.4}\sigma\), \text{tZ (3.7}\sigma\), \text{tttt (1.6}\sigma\)}

Run 2 results in Very Rare (FCNC) top:
\(\text{t}\rightarrow\text{H (H}\rightarrow\text{bb})\) and \(\text{t}\rightarrow\text{Z}\)

Newest (June 2018)

Highest luminosity results on these processes @ 13 TeV LHC

Flavor Changing Neutral Currents

All results at: http://cern.ch/go/pNj7
Taking full advantage of the CMS detector: the ingredients for rare/anomalous top

Lepton triggers: e (Tracker and ECAL) μ (Tracker and Muon Chambers)

Full event reconstruction: rely on high granularity to identify and reconstruct each individual particle, classified into mutually exclusive categories. Ingredients to define e, μ, γ, jets and MET

b-tagging: Pixels supply additional resolution to tag secondary vertices
New at 13 TeV: leptons and b-jets

Lepton selection optimized for high multiplicity environments

Combine three simple variables with square cuts

- (i) Large cone isolation: strongest background rejection, but loses efficiency in dense environments
- (ii) Small cone isolation and (iii) lepton momentum w.r.t. surrounding jet: recover leptons overlapping with jets due to boost or multiplicity

Update b-tagging of jets, using deep learning

Based on Run 1 tagger ("CSV"), but using more tracks and featuring 4 hidden layers
New at 13 TeV: background estimates

Many rare top analyses reject \( tt \) by requiring 2 same-sign or \( \geq 3 \) leptons

\( tt \) events can still pass the selection, due to different sources of “nonprompt” leptons

- Leptons from decays of heavy-flavor and light-flavor hadrons
- Hadrons misidentified as leptons
- Conversions of \( \gamma \) in jets

Even after strongly reducing it, still need dedicated methods to estimate it

Basic estimate is based on “fake rate” method (aka ABCD)

- Measure a Tight/Loose ratio in a control region, apply it to signal region
New at 13 TeV: background estimates

ABCD works well, as long as two axes are uncorrelated, i.e. the transfer factor applies to SR:

\[ TF \equiv \frac{C}{D} \overset{?}{=} \frac{SR}{B} \]

Any biases should be understood and parametrized
- 1st order bias (well understood): lepton kinematics
- 2nd: \( p_T \) and flavor (b/c/light) of lepton’s parton parent (p)

Two strategies to avoid the “2nd order” effects:
- Tune the Loose selection to avoid the flavor bias
- Combine \( p_T^{\text{lepton}} \) and \( p_T^{\text{parton}} \): \( p_T^{\text{cone}} = p_T^l (1 + \text{RelIso}) \)

With these improvements, ABCD works out of the box across samples with different kinematics and flavor compositions
- Left: measure TF in QCD MC, and apply it to tt MC
Measurement of the cross section for top quark pair production in association with a W or Z boson in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration
arXiv:1711.02547, submitted to JHEP

![Feynman diagrams for top quark pair production](image)

The t\(t\)Z cross section was measured by the CMS collaboration at $p_\text{s} = 7$ TeV with a precision of $\pm 50\%$ [4]. At $p_\text{s} = 8$ TeV CMS used multivariate techniques in events containing two, three, or four charged leptons to measure the t\(t\)W and t\(t\)Z cross sections with a precision of 30 and 25%, respectively [5, 6]. The t\(t\)Z process was observed with a significance of 6.4 standard deviations, and evidence for t\(t\)W production was found with a significance of 4.8 standard deviations. The ATLAS Collaboration analyzed events containing two and three charged leptons for its t\(t\)W measurement, and using two, three, and four charged leptons for the t\(t\)Z channel, achieving a similar precision [7]. In a more recent publication, the ATLAS Collaboration reported the first measurement of the t\(t\)W and t\(t\)Z production cross sections at $p_\text{s} = 13$ TeV [8] with a significantly smaller data set than the one considered here.

In this paper we present measurements of the t\(t\)Z and t\(t\)W production cross sections at $p_\text{s} = 13$ TeV with a data set corresponding to an integrated luminosity of 35.9 fb\(^{-1}\). The measurements are performed using events in which at least one of the W bosons, originating from a top quark decay, further decays to a charged lepton and a neutrino, and the associated W or Z boson decays to a charged lepton and a neutrino or a charged lepton pair, where the charged lepton (\(\ell\)) refers to an electron or a muon. The contribution from t\(t\) leptons are included through their decays to electrons and muons. The analysis is performed in three exclusive final states, in which events with two leptons of same charge, denoted as same-sign (SS) dileptons, are used to extract the t\(t\)W signal, while events with three or four charged leptons that include a lepton pair of opposite charge and same flavor (OSSF) are used to measure the t\(t\)Z signal yield. In addition to the individual t\(t\)W and t\(t\)Z cross section measurements, a fit is performed in all three final
Use same-sign dileptons (ttW) and 3 or 4-lepton (ttZ) to reject most of the tt background

Train a kinematic BDT (“D”) to separate ttW from nonprompt leptons

- Variables: $N_{\text{jets}}$, $N_{b}$-tags, $H_T$, $p_T^{\text{lep1}}$, $p_T^{\text{lep2}}$, MET, $m_T(W)$, $p_T^{j1}$, $p_T^{j2}$, $\Delta R(\text{lep2, j})$

Categorize in $N_{b}$-jets, $N_{\text{jets}}$ to reject prompt backgrounds

Main backgrounds:

- Nonprompt leptons: data-driven
- WZ, ZZ: control regions

Data-driven:

- Events

CMS

- 14
- 20
- 40
- 60

Data

CMS

- 1
- 10
- 100
- 1000

Events

CMS

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35

Events

CMS

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35

Events

CMS

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

CMS

- 35.9 fb$^{-1}$ (13 TeV)
ttW, ttZ: results

Good agreement with theory prediction

- 5 std. dev. significance in both ttW and ttZ

Stat. and syst. uncertainties smaller than 15%

Dedicated developments needed to improve uncertainties further.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{tZ}$ (%)</th>
<th>$\sigma_{ttW}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Trigger</td>
<td>5</td>
<td>4-5</td>
</tr>
<tr>
<td>B tagging</td>
<td>4-5</td>
<td>2-5</td>
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<td>PU modeling</td>
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<tr>
<td>Lepton ID efficiency</td>
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<tr>
<td>Choice in $\mu_R$ and $\mu_F$</td>
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<td>&lt;1</td>
</tr>
<tr>
<td>PDF</td>
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<td>&lt;1</td>
</tr>
<tr>
<td>Nonprompt background</td>
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<td>4</td>
</tr>
<tr>
<td>WZ cross section</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Charge misidentification</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>Rare SM background</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>t($t$+$t$)X background</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Stat. unc. in nonprompt background</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Stat. unc. in rare SM backgrounds</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Statistical uncertainty 12 15

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

$$\sigma(pp \rightarrow t\bar{t}Z) = 0.99^{+0.09}_{-0.08} \,(\text{stat})^{+0.12}_{-0.10} \,(\text{syst}) \,\text{pb}.$$
BSM physics at energy scale $\Lambda$ may alter cross-sections and kinematics

Parametrize as a function of dimension-6 operators, $O_i$ with coefficient $c_i$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i O_i + \cdots$$

Identify 8 EFT operators mainly affecting $\sigma(ttW)$ and $\sigma(ttZ)$

Use inclusive cross sections to set limits (individually) on $c_i/\Lambda^2$

**Figure 12:** Result of the simultaneous fit for $t\bar{t}W$ and $t\bar{t}Z$ cross sections (denoted as star), along with its 68 and 95% CL contours are shown on the left panel. The right panel presents the individual measured cross sections along with the 68 and 95% CL intervals and the theory prediction [1] with their respective uncertainties for $t\bar{t}W$ and $t\bar{t}Z$.

8 Effective field theory interpretation

Within the framework of effective field theory, cross section measurements can be used to search for NP in a model-independent way at energy scales that are not yet experimentally accessible. Using this approach, the SM Lagrangian is extended with higher-order operators that correspond to combinations of SM fields. The extended Lagrangian is a series expansion in the inverse of the energy scale of the NP, $1/\Lambda [50]$, hence operators are suppressed as long as $\Lambda$ is large compared with the experimentally-accessible energy.

The effective Lagrangian is (ignoring the single dimension-five operator, which violates lepton number conservation [50])

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i O_i + \cdots,$$

where $\mathcal{L}_{\text{SM}}$ is the dimension-four SM Lagrangian, $O_i$ are dimension-six operators, and the ellipsis symbol represents higher-dimension operators. The dimensionless Wilson coefficients $c_i$ parameterize the strength of the NP interaction.

Assuming baryon and lepton number conservation, there are fifty-nine independent dimension-six operators [51]. Thirty-nine of these operators were chosen for study in Ref. [52] because they include at least one Higgs field; the four-fermion operators were omitted. Constraints on the Wilson coefficients of some dimension-six operators have been reported in Refs. [2, 6, 53–59].

To investigate the effects of NP on any given process, it is necessary to calculate the expected cross section as a function of the Wilson coefficients. The matrix element can be written as the sum of SM and NP components:

$$M = M_0 + \sum_i c_i M_i.$$
BMS physics at energy scale $\Lambda$ may alter cross-sections and kinematics

Parametrize as a function of dimension-6 operators, $\mathcal{O}_i$ with coefficient $c_i$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i + \cdots$$

Identify 8 EFT operators mainly affecting $\sigma(\text{ttW})$ and $\sigma(\text{ttZ})$

Use inclusive cross sections to set limits (individually) on $c_i/\Lambda^2$

**Fit $c_{\text{uG}}$ to $\sigma_{\text{observed}}$**

**Limits on individual coefficients**

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>95% CL [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\text{uW}}/\Lambda^2$</td>
<td>$[-2.9, 2.9]$</td>
</tr>
<tr>
<td>$</td>
<td>c_{\text{H}}/\Lambda^2 - 16.8$ TeV$^{-2}$</td>
</tr>
<tr>
<td>$</td>
<td>c_{3G}/\Lambda^2</td>
</tr>
<tr>
<td>$c_{3G}/\Lambda^2$</td>
<td>$[-0.7, 1.0]$</td>
</tr>
<tr>
<td>$c_{\text{uG}}/\Lambda^2$</td>
<td>$[-1.0, -0.9]$ and $[-0.3, 0.4]$</td>
</tr>
<tr>
<td>$</td>
<td>c_{\text{uB}}/\Lambda^2</td>
</tr>
<tr>
<td>$c_{\text{Hu}}/\Lambda^2$</td>
<td>$[-11.1, -6.5]$ and $[-1.6, 3.0]$</td>
</tr>
<tr>
<td>$c_{2G}/\Lambda^2$</td>
<td>$[-1.1, 0.8]$</td>
</tr>
</tbody>
</table>
Measurement of the associated production of a single top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration
tZ: analysis strategy

Signature: 3 leptons, one Z candidate, at least 2 jets of which 1 or 2 b-tagged

Use 2 BDTs (for 1bjet and 2bjet regions) to separate signal and sum of backgrounds

- Kinematics: lepton, jet, Z, reconstructed top quark, b-tagging discriminants
- Matrix Element Method (MEM) to separate signal from ttZ and WZ (20% gain)

**ΔR(b-jet, light jet)**

**MEM discriminant**
tZ: results

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Background normalizations based on a simultaneous fit in 3 regions
- N_{b-jets} = 1, BDT distribution: extract signal
- N_{b-jets} = 2, BDT distribution: constrain ttZ, some signal
- N_{b-jets} = 0, m_T(W) distribution: constrain WZ and nonprompt leptons

![Graphs showing CMS 1bjet, 2bjets, and 0bjet distributions](image-url)
tZ: results

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- \( N_{b-jets} = 0 \), \( m_T(W) \) distribution: constrain WZ and nonprompt leptons

Main systematics:
- Backgrounds: nonprompt lepton and ttZ
- Detector effects: b-tagging
- Signal modelling: parton shower scales

<table>
<thead>
<tr>
<th></th>
<th>Significance</th>
<th>( \sigma(pp \to tZq \to t\ell\ell q) ), with ( m_{\ell\ell} &gt; 30 ) GeV [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pred.</td>
<td>3.1</td>
<td>94.2 ± 3.1</td>
</tr>
<tr>
<td>Meas.</td>
<td>3.7</td>
<td>123 ( ^{+33}<em>{-31} ) (stat) ( ^{+29}</em>{-23} ) (syst)</td>
</tr>
</tbody>
</table>
Search for top+photon production in pp collisions at 13 TeV in the muon+jets channel

The CMS Collaboration
CMS-PAS-TOP-17-016

The study of top quark production in association with a photon is an important test of the standard model (SM) description of top quark interactions with gauge bosons, and is sensitive to physics beyond the SM. The cross section for the single top quark production in association with a photon is sensitive to the top quark charge as well as the top quark electric and magnetic dipole moments [1, 2].

The cross section for the production of a top quark-antiquark pair and a photon ($t\bar{t}g$) was measured by the CDF Collaboration at the Tevatron in $p\bar{p}$ collisions at $p_s=1.96$ TeV [3], and by the ATLAS and CMS Collaborations in pp collisions at the LHC at $p_s=8$ TeV [4, 5]. So far, all measurements are in agreement with the SM predictions within the uncertainties.

The SM predicts three different mechanisms for the production of a single top quark in association with a photon ($t\gamma$) at the LHC: $t$-channel, $s$-channel, and $tW$ production, where the largest contribution comes from the $t$-channel. This letter presents the first evidence for single top quark production in association with a photon in the $t$-channel, using data collected in 2016 by the CMS experiment at $p_s=13$ TeV and corresponding to an integrated luminosity of 35.9 fb$^{-1}$.

The search targets events with a top quark, a photon, and at least a jet in the final state ($t\gamma j$), where the top quark decays into a W boson and a b quark, followed by a W boson decay into a muon and a neutrino. Figure 1 shows representative Feynman diagrams for the $t\gamma j$ process including the leptonic decay of the W boson in the top quark decay. The photon can be emitted either from initial state or final state particles.

One of the distinctive signatures of the signal is the presence of a forward light energetic jet in the final state which is due to the W boson involved in the single top quark production being space-like. The analysis focuses on the muon decay channel since it allows for a good signal efficiency with low background contamination. The final state includes possible contributions from $W!^\tau t$, where the $t$ lepton decays to $\mu\nu$.

The kinematic and topological properties of the signal are exploited in a multivariate technique to discriminate the background processes. There are two main kinds of background: those with a jet misidentified as a photon, like $t\bar{t}$, $W+\text{jets}$ and $Z+\text{jets}$, and those with a real photon, such as $t\bar{t}g$, $Wg+\text{jets}$ and $Zg+\text{jets}$ processes.

Monte Carlo (MC) simulated samples for the $t\gamma j$ signal are generated at next-to-leading order (NLO) using MAdGraph5 aMC@NLO v2.2.2 event generator [6], with a minimum transverse momentum requirement of $p_T>10$ GeV and $|\eta|<2.6$ for the associated photon. The NNPDF3.0 [7] parton distribution functions (PDFs) are used and the top quark mass is set to 172.5 GeV. The angular separation between the photon and all other particles is required to be $D_R>0.05$, where $D_R=\frac{p(D_h)^2}{p(D_h)^2+(D_f)^2}$.

After these requirements, an inclusive cross section of $2.95\pm0.13$ (factorization/renormalization scales) $\pm0.03$ (PDF) pb is obtained with MAdGraph5 aMC@NLO.

Samples of simulated events for the production of $t\bar{t}g$, $W+\text{jets}$, Drell–Yan, $Zg+\text{jets}$, diboson First Evidence!!
**tγ: analysis strategy**

**Signature:** 1 isolated $\gamma$, 1 $\mu$, 1 b-tagged jet and 1 untagged jet

- Use a BDT to separate signal and sum of backgrounds
  - Kinematics: $\eta^{\text{light jet}}$, $\eta^{\mu}$, $\Delta R(\text{light jet}, \gamma)$, $\cos(\theta)$, $m_{\mu vb}$, $N_{\text{jets}}$, $m_T(W)$
  - No b-tagging information: use $N_{b\text{-jets}}$ to build control regions

**Background normalization and shapes from data:**
- Fake photons: use photon ID/isolation sidebands
- $t\gamma$: use data with $N_{b\text{-jets}}=2$

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**Graphs: Data/MC**

- $\theta = \text{angle btw } \mu \text{ and light jet in t frame}$

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**CMS Preliminary**

- $35.9 \text{ fb}^{-1} (13 \text{ TeV})$
Uncertainties dominated by systematics

- jet energy (12%), b-tagging (7%)
- $t\gamma$ modeling (9%): scale, PDF, hadronization/showering
- $Z\gamma$+jets (8%)

Largest backgrounds at high BDT: $W/Z\gamma$+jets

First Evidence!!
Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration
Large theoretical uncertainties in tttt inclusive cross section

QCD NLO/LO k-factor ranges between 1.2 and 2.0, depending on scale and PDF choices

Large effects (up to 40%) from Leading Order EWK diagrams

13 TeV prediction currently used by ATLAS and CMS: $\sigma_{\text{NLO}}(\text{tttt}) = 9.2^{+2.9}_{-2.4} \text{ fb}$ [1]

Most recent prediction, including EWK NLO effects: $12^{+2.2}_{-2.5} \text{ fb}$ [2]

All-hadronic
Powerful in boosted searches for new physics
1 lepton and opposite-sign 2 leptons
Large $t\bar{t}$ pair-production background
2 same-sign or $\geq 3$ leptons
Comparable branching to OS2L, reject $t\bar{t}$ background

Latest CMS combination:

2.6 fb$^{-1}$ (13 TeV)
All-hadronic

Powerful in boosted searches for new physics

1 lepton and opposite-sign 2 leptons
Large tt pair-production background

2 same-sign or ≥ 3 leptons
Comparable branching to OS2L, reject tt background

Total branching ratio: 9%

Baseline selection
- Tight lepton identification
- $N_{\text{jets}} \geq 2$, $N_{\text{b-jets}} \geq 2$
- $H_T > 300$, $\text{MET} > 50 \text{ GeV}$
- DY veto, down to $p_T^{\text{lep}3} > 5(7) \text{ GeV}$ for e(μ)

Total BR * acceptance * efficiency after baseline selection: 1.5%
Rare top processes with $W^\pm W^\pm$ (or $WZ$ with a lost $Z$ lepton) and b-jets
$t\bar{t}+X$: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$ (mainly $H\rightarrow WW$), $t\bar{t}VV$

Single-lepton $t\bar{t}$ with an additional fake/nonprompt lepton

- Reduction and estimate discussed earlier

Opposite-sign dilepton $t\bar{t}$ with a charge-misidentified electron

- Reduced to a rate of $10^{-5}$-$10^{-3}$ with track-quality criteria
- Estimated by reconstructing $Z\rightarrow e^\pm e^\pm$

Simulation, corrected and normalized using data

Data
**ttW CR:**

N\(_{\text{jets}}\) ≤ 5, N\(_{\text{b}}\) = 2
40% ttW

ttW scale: 1.2 ± 0.3

**ttZ CR:**

3 lep, m\(_{ll}\) ~ m\(_{Z}\)
75% ttZ

ttZ scale: 1.3 ± 0.3
Main backgrounds, ttW, ttZ, ttH(WW) have 2 b-jets: why 3 b-tags?

Check ttW at generator level:
- \( N_b = 3 \) region dominated by \( W \rightarrow c \)
- \( N_b = 4 \) region dominated by ttW+bb

Are ttV+jets and ttV+bb well understood?

Use tt+jets and tt+bb as proxy for ttV

- tt+jets measurement is below simulation
- \( \sigma(ttbb)/\sigma(ttjj) \) measurement is 1 \( \sigma \) above simulation (1.7 ± 0.6) [arXiv:1705.10141]

Correct ttV simulation using tt Data/MC
tttt: Signal Regions definitions

tttt at generator level: 2(3) leptons, 8(6) jets of which 4 b-jets

Most discriminant variables: $N_{\text{jets}}$, $N_{b\text{-tags}}$, $N_{\text{leptons}}$

![Graphs showing distributions of $N_{\text{jets}}$, $N_{b\text{-tags}}$, HT, and MET for various signal regions.](image-url)
Use $N_{\text{jets}}$, $N_{\text{b-tags}}$, and separate 2 lepton and $\geq 3$ lepton events. Group regions with similar S/B, avoid regions with $<< 1$ event.

<table>
<thead>
<tr>
<th>$N_{\text{lps}}$</th>
<th>$N_{\text{b}}$</th>
<th>$N_{\text{jets}}$</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>$\leq 5$</td>
<td>CRW</td>
</tr>
<tr>
<td>2</td>
<td>5, 6</td>
<td>$\geq 7$</td>
<td>SR4</td>
</tr>
<tr>
<td>2</td>
<td>$\geq 4$</td>
<td>$\geq 5$</td>
<td>SR6</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>$\geq 2$</td>
<td>$\geq 5$</td>
<td>SR7</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>$\geq 4$</td>
<td>SR8</td>
</tr>
</tbody>
</table>

inverted Z-veto | CRZ

CMS Simulation Supplementary 35.9 fb$^{-1}$ (13 TeV)
Large total uncertainty (±100%)
Expect ~5 signal, ~15 background events

## Systematic uncertainties

- The shape uncertainty resulting from variations of the renormalization and factorization scales is as large as 15% for the $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$ backgrounds, and 10% for the $t\bar{t}t\bar{t}$ signal, while the effect from the PDF is only 1%.
- For the signal, the uncertainty in the acceptance from variations of the scales (PDFs) is 2% (1%).
- In addition, for the $t\bar{t}t\bar{t}$ signal, the scales that determine ISR and final-state radiation (FSR) in the parton shower are also varied, resulting in a 6% change in the acceptance and shape variations as large as 15%.

- For nonprompt and charge-misidentified lepton backgrounds, the statistical uncertainty from the application region depends on the SR considered.
- The background from misidentified charge is assigned a systematic uncertainty of 20%, based on comparisons of the expected number of same-sign events estimated from an OS control sample and the observed same-sign yield in a control sample enriched in $Z\gamma^*+e^+e^-$ events with one electron or positron having a misidentified charge.
- In addition to the statistical uncertainty, the nonprompt lepton background is assigned an overall normalization uncertainty of 30% to cover variations observed in closure tests performed with simulated multijet and $t\bar{t}$ events. This uncertainty is increased to 60% for electrons with $p_T > 50$ GeV, to account for trends observed at high $p_T$ in the closure tests.
- We also include an uncertainty related to the subtraction of events with prompt leptons (from electroweak processes with a W or Z boson) in the measurement region, which has an effect between 1% and 50%, depending on the SR. The prompt lepton contamination was also checked in the application region, where it was found to be below 1%.

### Experimental uncertainties

Experimental uncertainties are treated as correlated among signal regions for all signal and background processes. Systematic uncertainties in data-driven estimates and theoretical uncertainties are treated as uncorrelated between processes, but correlated among signal regions. Statistical uncertainties from the limited number of simulated events or in the number of events in data control regions are considered uncorrelated.

### Table 3: Summary of the sources of uncertainty and their effect on signal and background yields

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
</tr>
<tr>
<td>Pileup</td>
<td>0–6</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>4–10</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1–15</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1–5</td>
</tr>
<tr>
<td>b tagging</td>
<td>1–15</td>
</tr>
<tr>
<td>Size of simulated sample</td>
<td>1–10</td>
</tr>
<tr>
<td>Scale and PDF variations</td>
<td>10–15</td>
</tr>
<tr>
<td>ISR/FSR (signal)</td>
<td>5–15</td>
</tr>
<tr>
<td>$t\bar{t}H$ (normalization)</td>
<td>50</td>
</tr>
<tr>
<td>Rare, $X\gamma$, $t\bar{t}VV$ (norm.)</td>
<td>50</td>
</tr>
<tr>
<td>$t\bar{t}Z$, $t\bar{t}W$ (normalization)</td>
<td>40</td>
</tr>
<tr>
<td>Charge misidentification</td>
<td>20</td>
</tr>
<tr>
<td>Nonprompt leptons</td>
<td>30–60</td>
</tr>
</tbody>
</table>

Combining the effects of systematic uncertainties only increases total uncertainty by ~10%.

- Main background uncertainties constrained by control region statistics.
Results:

- Upper limit: $20.8^{+11.2}_{-6.9}$ fb expected (bkg only), 42 fb observed
- 1.6 sigma significance observed (1.0 expected)
- $\sigma_{tttt} = 16.9^{+13.8}_{-11.4}$ fb ($\sigma_{SM} = 9.2\pm3$ fb or $12 \pm 2$ fb)
tttt: Higgs and BSM interpretations

Constrain the top-Higgs Yukawa coupling [Cao et al., arXiv:1602.01934]

Higgs diagrams are a small contribution O(10%), but proportional to $y_t^4$

$$\sigma(t\bar{t}t\bar{t}) = \sigma_{SM}(t\bar{t}t\bar{t})g+Z/\gamma + \kappa_t^2 \sigma_{int} + \kappa_t^4 \sigma_{SM}(t\bar{t}t\bar{t})_H$$

$$\kappa_t \equiv y_{Htt}/y_{Htt}^{SM}$$

Probe Two-Higgs-doublet models (2HDM) [Craig et al., arXiv:1605.08744]

Introduce a scalar (H) and a pseudoscalar (A), in addition to the SM Higgs (h)

Top-associated production ($pp \rightarrow t\bar{t}H/A$), followed by $H/A \rightarrow t\bar{t}$

Constraining the four fermion EFT operators [ATLAS, arXiv:1803.09678]

Recent ATLAS limits on $L_4t = \frac{C_4t}{\Lambda^2} (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R) : c_{4t}/\Lambda^2 < 1.6 \text{ TeV}^{-2}$

... and more recent proposals from theory community:

Comprehensive EFT constraints from tttt [C. Zhang, arXiv:1708.05928]

Top dipole moments with tttt [M. Malekhosseini et al., arXiv:1804.05598]
Compare UL with predicted $\sigma(\text{tttt})$ as a function of $\kappa_t = |y_t/y_t^{\text{SM}}|$

$$\sigma(\text{tttt}) = \sigma^{\text{SM}}(\text{tttt})_{g+Z/\gamma} + \kappa_t^2 \sigma^{\text{SM}}_{\text{int}} + \kappa_t^4 \sigma^{\text{SM}}(\text{tttt})_H$$

- $\text{ttH}$ background also depends on $y_t$, so $\sigma(\text{tttt})$ upper limit improves at large $y_t$

**Result:**

- $|y_t| < 2.1$ at 95% CL
- **Differences w.r.t. $\text{ttH}$ measurement**
  - probe a higher center of mass
  - no assumption on total Higgs width

![CMS graph]

<table>
<thead>
<tr>
<th>Leading Order</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{\text{SM}}(\text{tttt})_{g+Z/\gamma}$</td>
<td>9,997 fb</td>
</tr>
<tr>
<td>$\sigma^{\text{SM}}(\text{tttt})_H$</td>
<td>1,168 fb</td>
</tr>
<tr>
<td>$\sigma^{\text{SM}}(\text{tttt})_{\text{int}}$</td>
<td>$-1,547$ fb</td>
</tr>
</tbody>
</table>
tttt results: 2HDM heavy (pseudo)scalar *

Compare UL with prediction of top-associated H/A production (ttH / ttA)
Heavy H/A can generate large enhancement (low tanβ, mH/A ≳ 2*mt) where H/A → tt
Exclude mA(H) < 430 (360) GeV for tanβ = 1

• With respect to direct searches for pp→H/A→tt resonances, this strategy has no dependence on the H/A width and does not suffer from large SM interference

* From inclusive 2016 same-sign analysis, arXiv:1704.07323, which inspired the dedicated tttt analysis
Search for flavour changing neutral currents in top quark production and decays with three-lepton final state using the data collected at $\sqrt{s} = 13$ TeV

The CMS Collaboration
CMS-PAS-TOP-17-017

top pair production, tZq decay
tZq single-top production
FCNC $t \rightarrow Zq$

**Signature:** 3 leptons, one $Z$ candidate, $\geq 1$ b-jets, 1-3 jets

2 signal regions: “TT” for $tZq$ decay (2-3 jets) and “ST” for $tZq$ production (1 jet)

Use BDTs to separate signal from prompt lepton backgrounds

- Variables: object kinematics, angles, b-tag discriminant
- Separate trainings for each SRs and each lepton channels ($\mu\mu\mu$, $\mu\mu\epsilon$, …)
- Separate trainings for $t \rightarrow Zu$ and $t \rightarrow Zc$

**Control regions**

- “WZ”: estimate $WZ$ and $DY+\text{nonprompt}$
- “TT” and “ST”: estimate $tt+\text{nonprompt}$ for respective SRs

<table>
<thead>
<tr>
<th></th>
<th>WZ control region (WZCR)</th>
<th>single top quark signal region (STSR)</th>
<th>top quark pair signal region (TTSR)</th>
<th>single top quark control region (STCR)</th>
<th>top quark pair control region (TTCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of jets</td>
<td>$\geq 1, \leq 3$</td>
<td>1</td>
<td>$\geq 2, \leq 3$</td>
<td>1</td>
<td>$\geq 2, \leq 3$</td>
</tr>
<tr>
<td>Number of b jets</td>
<td>0</td>
<td>1</td>
<td>$\geq 1$</td>
<td>1</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$</td>
<td>M(Z_{\text{reco}}) - M_{Z}</td>
<td>&lt; 7.5$ GeV</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Search for $t \rightarrow qZ$ at the LHC (ATLAS and CMS)

- The $tZq$ vertex can be probed both in $tt$ events (where $t \rightarrow qZ$) and $tZ$ production via FCNC
- The present talk will focus on the comparison of the ATLAS and CMS results at 13 TeV:
  - **CMS**: PAS TOP-17-017 → production+decay

**Signature**: 3 leptons, one Z candidate, $\geq 1$ b-jets, 1-3 jets

- 2 signal regions: “TT” for $tZq$ decay (2-3 jets) and “ST” for $tZq$ production (1 jet)
- Use BDTs to separate signal from prompt lepton backgrounds

**Main background**: nonprompt (‘NPL’)

**tt production, $tZq$ decay**

**tZq single-top production**
Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s} = 13$ TeV
Single lepton events, classify in $N_{\text{jets}}, N_{\text{b-jets}}$

Main backgrounds: $t\bar{t}+bb/cc/light$

BDT1: assign b-jets to initial particles (top or Higgs)
- $\sim75\%$ correct assignment

BDT2: ($t\rightarrow Hu$ or $t\rightarrow Hc$) vs sum of backgrounds
- Most important variables: BDT1, b-jet discriminant and $m_{bb}$ of b-jets assigned to H, lepton charge

Data / MC

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

CMS

BDT1 (assign b-jets)

Events / $0.07$

BDT discriminant

$0.5$ $1$ $1.5$ $2$ $2.5$ $3$

Data / MC

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

CMS

b3j3

b-discriminant (b-jet assigned to H)

$b$ jet CSVv2 discriminant

$0.85$ $0.9$ $0.95$ $1$

Data / MC

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

CMS

b3j3

$m_{bb}$ of b-jets assigned to H

$m_{bb}$ [GeV]
Single lepton events, classify in $N_{\text{jets}}, N_{\text{b-jets}}$

Main backgrounds: $tt+bb/cc/light$

**BDT1:** assign b-jets to initial particles (top or Higgs)
- ~75% correct assignment

**BDT2:** ($t\rightarrow Hu$ or $t\rightarrow Hc$) vs sum of backgrounds
- Most important variables: BDT1, b-jet discriminant and $m_{bb}$ of b-jets assigned to H, lepton charge

![Data](https://example.com/data1.png)  
**ST($\kappa_{\text{Hut}}=1$)  
**ST($\kappa_{\text{Hct}}=1$)  
**TT($\kappa_{\text{Hut}}=1$)  
**TT($\kappa_{\text{Hct}}=1$)
Good agreement with SM, interpreted as 95% CL limits on top branching fractions.

\( t \to Zq \): significant improvement in expected limits, observed comparable with Run 1.

\( t \to Hq \): \( H \to bb \) Run2 result is comparable to full Run1 combination (multilepton, bb, \( \gamma\gamma \)).

<table>
<thead>
<tr>
<th>Branching (%)</th>
<th>( t \to Zu )</th>
<th>( t \to Zc )</th>
<th>( t \to Hu )</th>
<th>( t \to Hc )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>0.024(0.015)</td>
<td>0.045(0.037)</td>
<td>0.47(0.34) (bb)</td>
<td>0.47(0.44) (bb)</td>
</tr>
<tr>
<td>Run 1</td>
<td>0.022(0.027)</td>
<td>0.049(0.118)</td>
<td>0.55(0.40)</td>
<td>0.40(0.43)</td>
</tr>
</tbody>
</table>

Large FCNC program for Run 2 has just started. Already surpassing Run 1, with several more channels to explore, and \( x^4 \) statistics expected.
Summary

CMS has taken advantage of the first 36 fb$^{-1}$ of Run 2 data to explore rare SM top processes, reaching new frontiers and finding good agreement with SM predictions

- New results in ttW ($5\sigma$), ttZ ($5\sigma$), $t\gamma$ ($4.4\sigma$), tZ ($3.7\sigma$), tttt ($1.6\sigma$)
- Several results systematics limited → strategies will need to evolve to keep improving

The search for Flavor Changing Neutral Currents at 13 TeV has started

- New results in $t\rightarrow Zq$ and $t\rightarrow Hq$ with H(bb), already surpassing Run 1

Rare and anomalous top offer a complementary program to direct searches for BSM
Backup
# CMS and ATLAS analyses

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dataset</td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>36 fb⁻¹, 13 TeV</td>
<td><a href="https://arxiv.org/abs/1803.09678">arXiv:1803.09678 (BSM only)</a></td>
</tr>
<tr>
<td>FCNC: t → Zq</td>
<td>36 fb⁻¹, 13 TeV</td>
<td><a href="https://arxiv.org/abs/1803.09923">arXiv:1803.09923</a></td>
</tr>
</tbody>
</table>
New at 13 TeV: background estimates

ABCD works well, as long as two axes are uncorrelated, i.e. the transfer factor applies to SR:

$$TF \equiv \frac{C}{D} = \frac{SR}{B}$$

Differences can be understood and parametrized

- 1\textsuperscript{st} cause of difference: lepton kinematics: $TF(p_T^l, \eta^l)$
- 2\textsuperscript{nd}: $p_T$ and flavor (b/c/light) of lepton’s parton parent (p)
  - Could be solved by: $TF(p_T^l, \eta^l, p_T^p, f^p)$

Example: pick muons with: $20 < p_T^l < 25$ GeV, $|\eta^l| < 0.9$, $f^p = b$

TF($p_T^p$) plot shows clear dependence

And $p_T^p$ is different for QCD and tt
ttW/ttZ: nonprompt lepton control regions

2 same-sign leptons:  
BDT determining signal and control regions

3-lepton, nonprompt-enriched:  
Either no OSSF pair or |m$_{ll}$ - m$_Z$| > 10 GeV

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

Events

Data  ttW  ttZ  Nonprompt  WZ  t($\bar{t}$)X  Rare  Charge mis-ID

Control region  Signal region

CMS  Supplementary arXiv:1711.02547  35.9 fb$^{-1}$ (13 TeV)

Events

N$_b$ = 0  N$_b$ = 1  N$_b$ > 1

N$_j$

4.2 Three-lepton analysis

The production rate of ttZ events is measured in the final state with three leptons. We select events that contain exactly three leptons (µµµ, µµe, µee, or eee), requiring the leading, subleading, and trailing lepton $p_T$ to be above 40, 20, and 10 GeV, respectively. To reduce backgrounds from multilepton processes that do not contain a Z boson, we require at least one OSSF lepton pair with invariant mass, $M(\gamma\gamma)$, consistent with the Z boson hypothesis, namely $|M(\gamma\gamma) - M(Z)| < 10$ GeV. Signal events are expected to have at least four jets, two of which originate from b quarks. When the events pass the jet and b jet requirements defined in the previous section, one obtains a sample of events enriched in signal, with minimal background contribution. However, nearly 70% of the signal events fail the requirement of having four jets with two of them identified as b jets. We therefore make use of lower jet and b jet multiplicities to form nine exclusive event categories to include a larger fraction of the signal events. These nine categories are formed using events with $N_j = 2, 3,$ and $>3$, where each jet multiplicity gets further split according to the b jet multiplicity, $N_b = 0, 1,$ and $>1$.

Despite the larger background contamination, the $N_j = 3$ categories, especially in bins with larger $N_b$, improve the signal sensitivity, as this category recovers signal efficiency for the jets that fall outside the acceptance. The $N_j = 2$ category provides a background-dominated region that helps to constrain the background uncertainties. We use all nine signal regions to extract the signal significance and the cross section.

4.3 Four-lepton analysis

In addition to the three-lepton final state, events with four leptons are exclusively analyzed for the measurement of the ttZ production rate. The ttZ events in this channel are characterized by the presence of two b jets, $p_T^{miss}$, and four leptons, two of which form an OSSF pair consistent with the Z boson mass. The event selection
Anomalous Couplings (single top). ATLAS/CMS

Wtb vertex general form includes anomalous couplings
- Left-handed vector: $f_V^L = V_L = V_{tb} \sim 1$ in the Standard Model
- Right-handed vector, and left/right-handed tensors: $f_V^R, f_t^L, f_t^R$ (aka $V_R, g_L, g_R$). 0 in SM.

$$\mathcal{L} = \frac{g}{\sqrt{2}} b \gamma^\mu \left( f_V^L P_L + f_V^R P_R \right) t W^{-}_\mu - \frac{g}{\sqrt{2}} b \frac{\sigma^{\mu\nu} \partial_\nu W^{-}_\mu}{M_W} \left( f_T^L P_L + f_T^R P_R \right) t + h.c.$$

8 TeV analyses in t-channel single top in ATLAS and CMS
Use Neural Networks trained on dedicated samples
- Assume real couplings, constrain ($f_V^L, f_V^R, f_t^L, f_t^R$) in 2D or 3D
- Measure angles in t decays to extract helicities and phases
- Allow complex (CP-violating) couplings, constrain ratios

2D limit
5.0 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)

2D projection of 3D limit (including $f_V^L$)
5.0 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)
Simultaneous 2D fits to ttW and ttZ

Good agreement with theory prediction (also ATLAS 3.2 fb\textsuperscript{−1} analysis)

- CMS reaches 5 std. dev. significance in both ttW and ttZ
- About 1 std. dev. higher than \( \sigma_{\text{SM}} \)

\[
\sigma(pp \rightarrow \bar{t}tW) = 0.77^{+0.12}_{-0.11} (\text{stat})^{+0.13}_{-0.12} (\text{syst}) \text{ pb},
\]

\[
\sigma(pp \rightarrow \bar{t}tZ) = 0.99^{+0.09}_{-0.08} (\text{stat})^{+0.12}_{-0.10} (\text{syst}) \text{ pb}.
\]
Scale/PDF choices lead to different NLO/LO k-Factors:

1) Prediction has strong dependence on scale, PDF, EWK diagrams

   [1] 14 TeV, NLO: $\sigma_{\text{NLO}}(ttt) = 15.3^{+4.0}_{-3.8}$ fb
   - NLO/LO k-factor: 1.27

2) 13 TeV, NLO: $\sigma_{\text{NLO}}(ttt) = 9.2^{+2.9}_{-2.4}$ fb
   - NLO/LO k-factor: 2.04

3) 13 TeV, LO: $\sigma_{\text{LO}}(ttt) = 9.6^{+3.9}_{-3.5}$ fb
   - explicitly separate the Higgs diagrams
   - authors apply the 1.27 k-factor from [1] to get: $12.2^{+5.0}_{-4.4}$ fb

Latest calculation with NLO (QCD) and NLO (EWK):

4) 13 TeV, NLO(QCD+EWK): $12^{+2.2}_{-2.5}$ fb
   - NLO/LO k-factor: 1.57

Summary:

1) Prediction has strong dependence on scale, PDF, EWK diagrams
2) Range of NLO/LO k-factor: 1.27 to 2.04
3) Range of NLO ±1 sigma: 6.8 to 14.2 fb

In a similar fashion the NLO corrections and their single perturbative orders can be defined two quantities as

calculational framework for predictions for proton–proton collisions at 13 and 100 TeV. We discuss in detail the impact sec.

The structure of the paper is the following. In sec.

tttt: NLO EWK+QCD

Table 5. Cross section for \( pp \rightarrow tttt \) at 13 TeV in various approximations.

<table>
<thead>
<tr>
<th>( \sigma [fb] )</th>
<th>( \text{LO}_{\text{QCD}} )</th>
<th>( \text{LO}<em>{\text{QCD}} + \text{NLO}</em>{\text{QCD}} )</th>
<th>( \text{LO} )</th>
<th>( \text{LO} + \text{NLO} )</th>
<th>( \text{LO} + \text{NLO} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = H_T/4 )</td>
<td>( 6.89^{+70%}_{-38%} )</td>
<td>( 11.12^{+19%}_{-23%} )</td>
<td>( 7.59^{+64%}_{-36%} )</td>
<td>( 11.97^{+18%}_{-21%} )</td>
<td>( 1.11 (1.08) )</td>
</tr>
</tbody>
</table>

Table 7. \( \text{tttt: } \sigma^\text{(N)LO}/\sigma_{\text{LO}_{\text{QCD}}} \) ratios at 13 TeV, for different values of \( \mu = \mu_r = \mu_f \).

\[
\Sigma_{\text{LO}}(\alpha_s, \alpha) = \alpha_s^4 \Sigma_{4,0} + \alpha_s^3 \alpha \Sigma_{4,1} + \alpha_s^2 \alpha^2 \Sigma_{4,2} + \alpha_s^3 \Sigma_{4,3} + \alpha^4 \Sigma_{4,4}
\]

\[
\equiv \Sigma_{\text{LO}_1} + \Sigma_{\text{LO}_2} + \Sigma_{\text{LO}_3} + \Sigma_{\text{LO}_4} + \Sigma_{\text{LO}_5}.
\]

\[
\Sigma_{\text{NLO}}(\alpha_s, \alpha) = \alpha_s^4 \Sigma_{5,0} + \alpha_s^4 \alpha \Sigma_{5,1} + \alpha_s^3 \alpha^2 \Sigma_{5,2} + \alpha_s^2 \alpha^3 \Sigma_{5,3} + \alpha_s \alpha^4 \Sigma_{5,4} + \alpha^5 \Sigma_{5,5}
\]

\[
\equiv \Sigma_{\text{NLO}_1} + \Sigma_{\text{NLO}_2} + \Sigma_{\text{NLO}_3} + \Sigma_{\text{NLO}_4} + \Sigma_{\text{NLO}_5} + \Sigma_{\text{NLO}_6}.
\]
$\sigma(\text{tttt})$ includes diagrams with off-shell Higgs bosons

Small, but proportional to 4th power of top-Higgs coupling

- Unique: production and decay through same Yukawa
- $|y_t| > |y_t^{\text{SM}}|$ would significantly enhance tttt cross section

Proposal from Cao et al. [PRD 95, 053004 (2017) and FCC Yellow Report]

Combine tttt and ttH measurements to constrain total Higgs width, assuming SM branching ratio to $\mu\mu/ZZ/\gamma\gamma$, or vice-versa
tttt: H/A resonant search (ATLAS)

Two-Higgs-doublet models (2HDM)

Realized in many new physics scenarios, such as SUSY
Lowest mass scalar can match the SM Higgs (“h”), in the “alignment limit”

Introduce a scalar (H) and a pseudoscalar (A)

Currently unprobed region (alignment limit, low $\tan \beta$, $m_{H/A} \approx 2m_t$) where bb/WW couplings are suppressed, and H/A decays preferentially to tt

Largest cross section is direct production $pp \rightarrow H/A \rightarrow tt$

Problem 1: large background (and interference with) QCD $tt$ production
Problem 2: shape of signal mass peak depends on coupling

Signal shape in $m_{tt}$ for different assumptions of signal strength

ATLAS Simulation Preliminary
\( \sqrt{s} = 8 \, \text{TeV}, \int L dt = 20.3 \, \text{fb}^{-1} \)

before det. sim. and event sel.
\( m_t = 500 \, \text{GeV}, \tan \beta = 0.70 \)

http://cds.cern.ch/record/2206229/files/
ATLAS-CONF-2016-073.pdf

before det. sim. and event sel.
\( m_t = 500 \, \text{GeV}, \tan \beta = 9.00 \)
**tttt: H/A resonant search (ATLAS)**

**ATLAS search for m_{tt} features in 8 TeV data [CONF-2016-073]**

- Exclude m_{A(H)}~500 GeV for very small values of tanβ<0.85 (0.45)
  - Expected sensitivity for tanβ ≈ 1.2 (1.0).

Search loses sensitivity quickly as higher tanβ reduces cross section and narrows width

- Searches for this signature are constrained by systematics on reconstructed m_{tt}
- Difficult to probe 350-450 GeV region due to background shape
Contact interactions (explored by ATLAS-CONF-2016-020 and 032)

Generic non-resonant tttt production, as long as $\Lambda$ is much larger than the scale of the process

$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma^\mu t_R)$

Even more generic: Effective Field Theory operators


First: can set limits based on cross-section enhancement

Next (300 fb$^{-1}$): can start studying kinematics

$O_R = (\bar{t}_R \gamma^{\mu} t_R) (\bar{t}_R \gamma^{\mu} t_R)$

$O_L^{(1)} = (\bar{Q}_L \gamma^{\mu} Q_L) (\bar{Q}_L \gamma^{\mu} Q_L)$

$O_L^{(8)} = (\bar{Q}_L \gamma^{\mu} T^A Q_L) (\bar{Q}_L \gamma^{\mu} T^A Q_L)$

$O_B^{(1)} = (\bar{Q}_L \gamma^{\mu} Q_L) (\bar{t}_R \gamma^{\mu} t_R)$

$O_B^{(8)} = (\bar{Q}_L \gamma^{\mu} T^A Q_L) (\bar{t}_R \gamma^{\mu} T^A t_R)$
Dilepton triggers: ee, μμ, eμ
Use non-isolated triggers with $p_{T,lep} > 8$ GeV, $H_T > 300$ GeV
$\diamondsuit > 95\%$ (92\%) for ee, eμ (μμ)

Object kinematics:

<table>
<thead>
<tr>
<th>Object</th>
<th>$p_T$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>$p_T &gt; 20$ GeV</td>
<td>$</td>
</tr>
<tr>
<td>Muons</td>
<td>$p_T &gt; 20$ GeV</td>
<td>$</td>
</tr>
<tr>
<td>Jets</td>
<td>$p_T &gt; 40$ GeV</td>
<td>$</td>
</tr>
<tr>
<td>b-tagged jets</td>
<td>$p_T &gt; 25$ GeV</td>
<td>$</td>
</tr>
</tbody>
</table>

Baseline selection:

tttt: Branching Ratio ~ 9%  Baseline selection ~ 1.5%
Several not-yet-observed rare backgrounds with t’s and V’s

Generate LO samples, use NLO cross-sections

- Largest contribution: ttWW ($\sigma \sim 10$ fb)

Interesting measurements for Run 3 and beyond!

<table>
<thead>
<tr>
<th>13 TeV $\sigma$ [ab]</th>
<th>$t\bar{t}W^+Z$</th>
<th>$t\bar{t}W^-Z$</th>
<th>$t\bar{t}ZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO QCD</td>
<td>+9.9% +2.7%</td>
<td>-10.6% -2.7%</td>
<td>-11.2% -3.7%</td>
</tr>
<tr>
<td>LO</td>
<td>2705(3)</td>
<td>1179(2)</td>
<td>1982(2)</td>
</tr>
<tr>
<td>$K$-factor</td>
<td>1.36</td>
<td>1.40</td>
<td>1.23</td>
</tr>
</tbody>
</table>

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<th>13 TeV $\sigma$ [ab]</th>
<th>$t\bar{t}W^+H$</th>
<th>$t\bar{t}W^-H$</th>
<th>$t\bar{t}ZH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO QCD</td>
<td>+1.8% +2.6%</td>
<td>-5.9% -2.6%</td>
<td>-1.9% +3.0%</td>
</tr>
<tr>
<td>LO</td>
<td>1089(1)</td>
<td>493.0(5)</td>
<td>1535(2)</td>
</tr>
<tr>
<td>$K$-factor</td>
<td>1.09</td>
<td>1.12</td>
<td>1.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>13 TeV $\sigma$ [ab]</th>
<th>$t\bar{t}W^+W^-$</th>
<th>$t\bar{t}W^+W^-$ (4f)</th>
<th>$t\bar{t}HH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO QCD</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LO</td>
<td>8380(5)</td>
<td>11500(10)</td>
<td>756.5(7)</td>
</tr>
<tr>
<td>$K$-factor</td>
<td>1.38</td>
<td>1.38</td>
<td>0.99</td>
</tr>
</tbody>
</table>

arXiv:1610.07922 (Handbook of LHC cross-sections 4)
tttt: $X^+\gamma$ and Rares

$X^+\gamma$: $tt\gamma$, $t\gamma$

- Asymmetric prompt $\gamma \rightarrow$ dilepton, with one lepton lost
  - Internal conversions: $\gamma^* \rightarrow e^+e^-$, $\mu^+\mu^-$
  - External conversions: $\gamma \rightarrow e^+e^-$ interacting with the detector

Estimated from simulation in tttt analysis

- But could also define a $Z \rightarrow ll\gamma^*$ and $\gamma^* \rightarrow ll$ CR, as in arXiv:1709.05406
- CR: $N_{\text{lep}} = 3$, $m_{ll} < 75$ GeV, MET < 50 GeV

Rares:

- $VVV$: $WWW$, $WWZ$, $WZZ$, $ZZZ$, $WW\gamma$, $WZ\gamma$
- $tZq$, $ggH$, $WH$, $ZH$, $W^{\pm}W^{\pm}$, $tttV$, $tttq$
- Estimated from simulation
Charge misidentification is negligible for muons, and for electrons we reduce it by requiring “triple-charge agreement”

Agreement between 3 available charge measurements

- Pion-like track, Electron-like track (with Brehm), $\Delta\phi$ (Pixel hits, Supercluster)

**Estimate based on “ABCD-like” method**

Use Z MC to estimate $TF(p_T^l, \eta^l)$

- Validate TF in Z-enriched (low-MET) data
- Apply TF to OS events in data
Small underestimate when using pre-fit $ttW$, $ttZ$

Interesting excess in $N_b = 3$ bin

Checked individual events, found no suspicious behavior
tttt: post-fit kinematics

Reduced tension in Nb=3 region. Good agreement for leptons.