Top quark rare production and decay processes
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On behalf of the ATLAS and CMS Collaborations
Rare top processes status

Sensitivity and precision in top quark measurements increased over the years

Former rare processes ($t\bar{t}+X$) are now background for new measurements and searches

Approaching the fb frontier

Covered in this talk:
- Latest observation: $tZj$
- Latest evidences: $t\bar{t}t\bar{t}$, $t\gamma$ (CMS)
- Searches:
  - flavour-changing neutral currents
  - lepton flavour violation

$t\bar{t}+X$ covered by J. Thomas-Wilsker
Measurements
Rare top production: $t\bar{t}t\bar{t}$

Massive final state $\sim 700$ GeV
Sensitive to magnitude and CP nature of top quark Yukawa coupling
Sensitive to presence of New Physics e.g. 2HDM
Small predicted $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4$ fb at 13 TeV, NLO in QCD+EW ([JHEP 02 (2018) 031])
Various lepton ($\ell = e, \mu$) multiplicity final states probed by ATLAS and CMS

Same-charge di-lepton pair ($2\ell SS$), multi-lepton (ML)
small branching fraction (12%)
lower backgrounds:
\[ t\bar{t}W, t\bar{t}Z, \text{non-prompt leptons, charge mis-identification} \]

Single lepton ($1\ell$), opposite-charge pair ($2\ell OS$)
larger branching fraction (56%)
large irreducible background:
\[ t\bar{t} + \text{additional jets} \]
Signal region (SR)
≥4 jets, ≥2 b-jets, $H_{T}^\text{jets} > 300$ GeV, $E_{T}^\text{miss} > 50$ GeV, Z-veto in ML channel

Background modelling
$t\bar{t}Z$, $t\bar{t}W$ corrections:
- $N_{\text{jets}}$ based on dilepton $t\bar{t}$ data/MC
- heavy flavour jet multiplicity (also $t\bar{t}H$) from $\sigma(t\bar{t}bb) / \sigma(t\bar{t}jj)$
- $t\bar{t}Z$, $t\bar{t}W$ constrained by the fit

Data-driven estimation of non-prompt leptons

Signal extraction
SR divided in 17 regions depending on the BDT score
Simultaneous fit of CRZ and SR(s): measured $\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}$ fb

Dominant uncertainties:
- additional $b$-jets modelling (11% impact on $\sigma(t\bar{t}t\bar{t}))$, JES (9%), JER (6%)
**Dominant uncertainty:**

- Measured
- Simultaneous SR+CR fit
- Data-driven charge mis-identification estimation
- Background modelling

**Signal region**

≥6 jets, ≥2 b-jets, \(H_T > 500\) GeV, Z-veto in ML channel

**Background modelling**

Five control regions to normalise

- the non-prompt lepton background
- the \(\bar{t}\bar{t}W\) background

Data-driven charge mis-identification estimation

**Signal extraction**

Simultaneous SR+CR fit

BDT discriminant distribution fit in SR

Measured \(\sigma(\bar{t}\bar{t}t) = 24^{+7.6}_{-5.0}\) fb (1.7σ compatible with SM)

Dominant uncertainty:

modelling of \(\bar{t}\bar{t}W(≥7\) jets), \(\bar{t}\bar{t}W(≥3\) b-jets)
**Region definition**

1\(\ell\), \(\geq 7\) jets or 2\(\ell OS\) (Z-veto), \(\geq 4\) jets.  
Always \(\geq 2\) b-jets, \(H_{Tj} > 500\) GeV

**Strategy**

BDTs to reconstruct the top quarks from jet triplets  
BDTs to discriminate signal from background  
Simultaneous fit of 1\(\ell\) and 2\(\ell\) BDT scores \(D_{ttt\ell}^{SL}\) and \(D_{ttt\ell}^{DL}\)

**Results**

\(\sigma(t\bar{t}t) < 48\) fb 95%CL  
Statistical uncertainty ~ systematic uncertainty
**t̅t̅t̅ 1ℓ and 2ℓOS**

Full-Run 2 search: 1.9σ obs. (1.0σ exp.) [139 fb⁻¹]  
(ATLAS-CONF-2021-013)

Region definition

≥ 2 b-jets, (1ℓ, ≥ 7 jets) or (2ℓOS, Z-veto, ≥ 5 jets)

Regions defined by jet and b-jet multiplicities

Different b-tagging requirements to resolve the flavour composition

Background (= t̅t̅+jets) modelling

- Flavour rescaling. Dedicated fit in ≥8(6) jets for 1(2)ℓ and ≥2 b to normalise: tt̅+light, t̅t̅+≥1c, tt̅+≥1b
- Kinematic reweighting derived in 2 b-jets region

Strategy

BDTs trained in 6 different regions (3 bins in Njets × Nℓ)

6 SRs for 1L, 4 SRs for 2ℓOS

Simultaneous fit of BDT shape in SRs and Ητ shape in CRs
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**tt̅tt̅ 1ℓ and 2ℓOS, combination**

Full-Run 2 search: 1.9σ obs. (1.0σ exp.) [139 fb⁻¹]

(Atlas-Conf-2021-013)

### Measured σ(tt̅) = 26⁺¹⁷₋₁₅ fb

### Dominant uncertainties:
- $tt$+≥1$b$ modelling, (±8 fb), $tt$+≥1$c$ cross-section (±5 fb)

**ATLAS+CMS Preliminary**

Run 2, $\sqrt{s} = 13$ TeV, May 2021

**Background Unc.**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cross-section (fb)</th>
<th>Obs. (Exp.) Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, 2LSS/3L, 139 fb⁻¹</td>
<td>26⁺¹⁷₋₁₅ fb</td>
<td>1.9 (1.0) σ</td>
</tr>
<tr>
<td>ATLAS, 1L/2LOS, 139 fb⁻¹</td>
<td>24⁺⁷₋₉ fb</td>
<td>4.7 (2.6) σ</td>
</tr>
<tr>
<td>ATLAS, comb., 139 fb⁻¹</td>
<td>24⁺⁷₋₉ fb</td>
<td>4.7 (2.6) σ</td>
</tr>
<tr>
<td>CMS, 2LSS/3L, 137 fb⁻¹</td>
<td>12.6⁺⁵₋₈ fb</td>
<td>2.6 (2.7) σ</td>
</tr>
<tr>
<td>CMS, 1L/2LOS, 35.8 fb⁻¹</td>
<td>0⁺²⁰₋₂⁰ fb</td>
<td>0.0 (0.4) σ</td>
</tr>
</tbody>
</table>

*Preliminary
**Motivation**
Sensitive to $WWZ$, $t\bar{t}Z$, $tbW$ couplings, $bW \rightarrow tZ$

**Selection**
3$\ell$, 1 $Z$ candidate, 1 forward jet, 1 $b$-jet

**Backgrounds**
Non-prompt leptons
- suppressed with object-level MVA
- data-driven estimation. Dedicated CR.
- MC-based shape ("embedded" lepton), normalised in CR $WZ+\text{jets}, t\bar{t}Z$
  - constrained in CR$WZ$, CR$t\bar{t}Z(4\ell)$, low BDT score
  - normalised in CRs

**Strategy**
One BDT / NN per SR, simultaneous fit with CRs
**tZq cross section measurement**

*Observation paper [139 fb⁻¹]*

*ATLAS Experiment*  
*(JHEP 07 (2020) 124)*

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**Figure 3.** Comparison between data and prediction (“Pred.”) after the fit to data (“Post-Fit”) under the signal-plus-background hypothesis for the fitted distributions of the neural network output $O_{NN}$ in the SRs (a) 2j1b and (b) 3j1b. The uncertainty band includes both the statistical and systematic uncertainties as obtained by the fit. The lower panels show the ratios of the data to the prediction.

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**Result**

$\sigma(pp \rightarrow t\ell^+\ell^-q)_{ATLAS} = 97 \pm 13 \text{ (stat)} \pm 7 \text{ (syst)} \text{ fb (±14%)}$

Dominant uncertainties:  
non-prompt leptons (3%), JES (2%), lepton selection (2%)

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SM prediction

$\sigma(pp \rightarrow t\ell^+\ell^-q) = 94.2 \pm 3.1 \text{ fb}$
**tZq cross section measurement**

New preliminary result [138 fb⁻¹]
(CMS-PAS-TOP-20-010)

**Result**

\[
\sigma(pp \rightarrow t\bar{t}q)_{\text{CMS}} = 87.9 \pm 7.5_{-3.6}^{+7.3}\text{(stat)} \pm 6.0\text{(syst)} \text{ fb (±11%)}
\]

\[
\frac{\sigma(t)}{\sigma(\bar{t})} = 2.4 \pm 0.6_{-0.4}^{+0.7}\text{(stat)} \pm 0.3_{-0.1}^{+0.3}\text{(syst)}
\]

Dominant uncertainties:

- tZq modelling (3%), non-prompt leptons (2%), WZ normalisation (2%)

SM prediction

\[
\sigma(pp \rightarrow t\bar{t}q) = 94.2 \pm 3.1 \text{ fb}
\]
Parton & particle level, 9 variables: \( p_T(t) \), \( p_T(Z) \), \( p_T(l) \), \( m(3l) \), \( \Delta \Phi(l,l') \), \( \cos(\theta_{\text{pol}}) \), \( m(t,Z) \), \( p_T(j') \), \( |\eta|(j') \)

tZq divided into generator-level bin: 4 for lepton variables, 3 for hadronic variables

tZq detector response matrix determined with simulation

Fit of NN output determines the normalisation of the generator-level bins

**Results**

- Similar goodness-of-fit of 4FS and 5FS in all variables
- Spin asymmetry

\[
\frac{d\sigma}{d \cos(\theta_{\text{pol}})} = c_{tZq} \left( \frac{1}{2} + A_t \cos(\theta_{\text{pol}}) \right)
\]

\( A_t = 0.58_{-0.16}^{+0.15} \pm 0.06 \)

compatible with SM prediction \( A^4/5FS = 0.437 / 0.454 \pm 0.005 \)
ty evidence

First evidence: 4.4σ obs. (3.0σ exp.) [35.9 fb⁻¹]

Motivation: sensitive to magnetic dipole moment

Selection: 1µ, 1γ, 1 b-jet, 1 forward jet

Backgrounds
ttγ (×9 ty), Vγ (×2 ty)

Signal extraction
BDT shape fit
σ(pp → tyj)B(t→µνb) = 115 ± 17 (stat) ± 30 (syst) fb
Expected ty events 154 ± 24, observed 220 ± 63
Dominant uncertainty: JES(12%)
Searches
Search for the FCNC $tHq$ interaction

$tHq (q = u, c)$, production & decay, $H \rightarrow \gamma \gamma$ [137 fb$^{-1}$]

(CMS-PAS-TOP-20-007)

**Motivation:** SM prediction $B(t \rightarrow Hq) \sim 10^{-16}$, any excess = evidence for new physics

**Signal region**

2 photons, $100 < m_{\gamma\gamma} < 180$ GeV

- **leptonic:** $\geq 1$ jet, $\geq 1\ell$
- **hadronic:** $\geq 3$ jet, $\geq 1$ $b$-jet

**Backgrounds**

- resonant: $t\bar{t}H$, $VH$, VBF, $ggH$, $b\bar{b}H$, $tH$
- non-resonant: $\gamma(\gamma)+\text{jets}$, $t\bar{t}+\gamma(\gamma)$, $V+\gamma$

**Strategy**

8 BDTs: $(u, c) \times (\text{lep, had}) \times (\text{res, non-res bkg})$
7 categories defined by BDT score per $q = u, c$ flavour
14 $m_{\gamma\gamma}$ distributions to fit
Search for the FCNC $tHq$ interaction

$tHq$ ($q = u, c$), production & decay, $H \rightarrow \gamma \gamma$ [137 fb$^{-1}$]

(CMS-PAS-TOP-20-007)

**Results**

Data compatible with absence of signal

95% CL upper limits:

- $B(t \rightarrow Hu) < 1.9 \times 10^{-4}$ (exp. $3.1 \times 10^{-4}$)
- $B(t \rightarrow Hc) < 7.3 \times 10^{-4}$ (exp. $5.1 \times 10^{-4}$)

Dominant uncertainties:
- $b$-tagging, $\gamma$ identification

**References**

- M. Kobayashi and T. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interaction",
  Prog. Theor. Phys. 49 (1973) 652–657,
- S. Glashow, J. Iliopoulos, and L. Maiani, "Weak Interactions with Lepton-Hadron Symmetry",
  Phys. Rev. D 2 (1970) 1285–1292,
**FCNC tHq summary**

**Searches with 36 fb\(^{-1}\)**
- \(t \to H(\gamma\gamma)q\) (JHEP 10 (2017) 129)
- \(t \to H(ML)q\) (Phys. Rev. D 98, 032002)
- \(t \to H(b\bar{b}, \tau\tau)q\) (JHEP 05 (2019) 123)

Most stringent bound from \(t \to H(b\bar{b}, \tau\tau)q\)
- \(B(t \to Hu) < 1.2 \times 10^{-3}\)
- \(B(t \to Hc) < 1.1 \times 10^{-3}\)

**New CMS-PAS-TOP-20-007**
- \(B(t \to Hu) < 1.9 \times 10^{-4}\)
- \(B(t \to Hc) < 7.3 \times 10^{-4}\)

Previous bound from \(t \to H(b\bar{b})q\) (JHEP 06 (2018) 102)
- \(B(t \to Hq) < 4.7 \times 10^{-3}\)
Search for CLFV in top production and decay

Motivation: CLFV suppressed in SM with massive neutrinos. LFV underlying mechanism unknown.

Signal process

$t\ell\ell'q$ interaction described by EFT operators such as

$$O^{(1)}_{1q} = (\bar{1}_i \gamma^\mu 1_j)(\bar{q}_k \gamma^\mu q_l)$$

grouped in 3 classes:

- $O_{\text{vector}} = O_{1q} + O_{1u} + O_{eq} + O_{eu}$
- $O_{\text{scalar}} = O^{(1)}_{\text{lequ}}$
- $O_{\text{tensor}} = O^{(3)}_{\text{lequ}}$

No SM interference

$q = u, c$ considered separately

EFT vertex in both single top production and $t\bar{t}$ decay

Signature / SR

Always one hadronic top decay

2$t\ell$OS ($1e, 1\mu$), 1 $b$-jet

Backgrounds

$t\bar{t}$ (90%), $tW$

modelled with MC events
Search for CLFV in top production and decay

$t\ell\ell^\prime q$ interaction $\ell = e, \mu$, $q = u, c$ [137 fb$^{-1}$]

(CMS-PAS-TOP-19-006)

Strategy

One BDT trained in SR for all categories
BDT applied also in CR (2 $b$-jets)
SR+CR BDT shape fit for one operator at a time

Results

Data consistent with SM expectation
Upper limits set on the Wilson coefficients
Dominant uncertainty: $b$-tagging
Results

Limits on the Wilson coefficients translate into

\[ B(t \rightarrow e\mu u/c)_{\text{scalar}} < 0.07 / 0.89 \times 10^{-6} \]
\[ B(t \rightarrow e\mu u/c)_{\text{vector}} < 0.14 / 1.3 \times 10^{-6} \]
\[ B(t \rightarrow e\mu u/c)_{\text{tensor}} < 0.25 / 2.6 \times 10^{-6} \]

to be compared with previous ATLAS result
\[ B(t \rightarrow e\mu q) < 6.6 \times 10^{-6} \]
Summary

New results in the investigation of SM rare top processes:

- $t\bar{t}t\bar{t}$ evidence
- $tZq$ differential measurement
- $ty$ evidence

Still to do: $tH$, $tWZ$

Top processes as fertile ground for BSM searches:

- FCNC
- CLFV
- LFU (previous talk by Svan Menke)

All results at: http://cern.ch/go/pNj7
First evidence: 4.3σ obs. (2.4σ exp.)

(80:1085)

<table>
<thead>
<tr>
<th>Region</th>
<th>Channel</th>
<th>$N_J$</th>
<th>$N_b$</th>
<th>Other requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>2LSS/3L</td>
<td>≥ 6</td>
<td>≥ 2</td>
<td>$H_T &gt; 500$</td>
</tr>
<tr>
<td>CR Conv.</td>
<td>$e^+e^-</td>
<td></td>
<td>e^+e^-\mu^\pm$</td>
<td>$4 \leq N_J &lt; 6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR HF e</td>
<td>$eee \parallel eee\mu$</td>
<td>–</td>
<td>= 1</td>
<td>$100 &lt; H_T &lt; 250$ GeV</td>
</tr>
<tr>
<td>CR HF $\mu$</td>
<td>$e\mu\mu \parallel \mu\mu\mu$</td>
<td>–</td>
<td>= 1</td>
<td>$100 &lt; H_T &lt; 250$ GeV</td>
</tr>
<tr>
<td>CR ttW</td>
<td>$e^\pm\mu^\pm</td>
<td></td>
<td>\mu^\pm\mu^\pm$</td>
<td>≥ 4</td>
</tr>
</tbody>
</table>

For $N_b = 2$, $H_T < 500$ GeV or $N_J < 6$
For $N_b \geq 3$, $H_T < 500$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NF$_{tW}$</th>
<th>NF$_{\text{Mat. Conv.}}$</th>
<th>NF$_{\text{Low } m(y)}$</th>
<th>NF$_{\text{HF } e}$</th>
<th>NF$_{\text{HF } \mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.6 ± 0.3</td>
<td>1.6 ± 0.5</td>
<td>0.9 ± 0.4</td>
<td>0.8 ± 0.4</td>
<td>1.0 ± 0.4</td>
</tr>
</tbody>
</table>

\[ \text{Post-Fit} \]

**ttW Validation Region**

- **Data**
- **tW**
- **tW**
- **ttW**
- **Q mis-id**
- **HF e**
- **HF \( \mu \)**
- **Others**
- **Uncertainty**
First evidence: $4.3\sigma$ obs. ($2.4\sigma$ exp.) [139 fb$^{-1}$]

Full-Run 2 search: $1.9\sigma$ obs. ($1.0\sigma$ exp.) [139 fb$^{-1}$]
(ATLAS-CONF-2021-013)

$\mu_{tt} = 2.9^{+1.8}_{-1.5}$
$\mu_{2\tau OS} = 1.3^{+1.7}_{-1.5}$
Figure 9: Distributions at the detector level of some of the important variables used in the tZq analysis. The panels show the ratio of the data to the predictions. The vertical lines on the data points represent the statistical uncertainty in the data; the shaded area corresponds to the total uncertainty.

The variables shown are as follows: upper left: transverse momentum of the lepton associated with the decay of the top quark, upper right: number of muons in the event, lower left: reconstructed transverse momentum of the Z boson, lower right: transverse mass of the W boson. The lower panels show the number of events as a function of various kinematic variables along with the requirement that the event BDT discriminant be large than 0.5. The variables with uncertainty include the transverse momentum of the Z boson and the transverse mass of the W boson.
### $tZq$ differential

**New preliminary result [138 fb$^{-1}$]**

(CMS-PAS-TOP-20-010)

#### $\chi^2$ test p-values

<table>
<thead>
<tr>
<th>Observable</th>
<th>parton level</th>
<th>particle level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>absolute</td>
<td>normalized</td>
</tr>
<tr>
<td></td>
<td>4FS</td>
<td>5FS</td>
</tr>
<tr>
<td>$p_T(Z)$</td>
<td>97.0</td>
<td>81.8</td>
</tr>
<tr>
<td>$\Delta\phi(\ell, \ell')$</td>
<td>70.1</td>
<td>47.2</td>
</tr>
<tr>
<td>$p_T(\ell_1)$</td>
<td>95.0</td>
<td>72.0</td>
</tr>
<tr>
<td>$m(3\ell)$</td>
<td>6.4</td>
<td>1.8</td>
</tr>
<tr>
<td>$p_T(t)$</td>
<td>80.8</td>
<td>69.6</td>
</tr>
<tr>
<td>$m(t, Z)$</td>
<td>67.5</td>
<td>49.1</td>
</tr>
<tr>
<td>$\cos(\theta^*_\text{pol})$</td>
<td>82.3</td>
<td>56.0</td>
</tr>
<tr>
<td>$p_T(j')$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>(j')$</td>
</tr>
</tbody>
</table>

#### Table

- $p_T(Z)$
- $\Delta\phi(\ell, \ell')$
- $p_T(\ell_1)$
- $m(3\ell)$
- $p_T(t)$
- $m(t, Z)$
- $\cos(\theta^*_\text{pol})$
- $p_T(j')$
- $|\eta|(j')$

#### Diagram

- CMS Preliminary
- Measurement
- aMC@NLO, 4FS
- aMC@NLO, 5FS

- $p_T^{0.5} = 80.8\%$
- $p_T^{0.5} = 79.2\%$
- $p_T^{0.5} = 72.4\%$

- Parton level $p_T(t)$ [GeV]
- Particle level $p_T(t)$ [GeV]
Figure 11: Response matrices of the $p_T(Z)$ at parton level (left) and $p_T(t)$ at particle level (right) for $tZq$ events in the full and visible phase space, respectively. The expected number of reconstructed events is given for each bin. The color indicates the transition probability for an event in a generator-level bin, to have a reconstructed value corresponding to a given detector-level bin. The efficiency $\times$ acceptance values of reconstructing events are plotted in the middle panel. The lower panel plots the stability and purity values as they are defined in the text.