Using associated production of top quarks and neutral bosons to probe Standard Model couplings and search for new physics

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on behalf of the ATLAS Collaboration

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Introduction to top+boson processes

• Unique role in the SM due to its large mass (173 GeV)
  • Yukawa coupling-strength parameter close to unity
  • Short lifetime (ca. $10^{-25}$ s) → decay before hadronisation

• Generalised, effective Lagrangian for the $t \bar{t} V$ coupling vertex:

$$\Gamma_{\mu}^V(q^2) = \gamma_{\mu} F_1^V(q^2) + \frac{i \sigma_{\mu\nu} q^\nu}{2m_t} F_2^V(q^2) + \gamma_{\mu} \gamma_5 F_3^V(q^2) + \frac{i \sigma_{\mu\nu} q^\nu}{2m_t} \gamma_5 F_4^V(q^2)$$

  • Photon coupling: purely "vectorial" coupling at tree level in the SM
  • $Z$ boson coupling: components from EW mixing (hypercharge, weak isospin)
  • Both: only minor tensor-like components with higher-order loop corrections

• Couplings accessible through: top quarks in association with photon or $Z$ boson

• First ATLAS papers with full Run 2 data: stringent tests of theory predictions

→ Presented here: ATLAS measurements of $t \bar{t} \gamma$, $t \bar{t} Z$ and $t Z q$ production

$t \bar{t} \gamma$: arXiv:2007.06946  
ttZ: ATLAS-CONF-2020-028  
tZq: arXiv:2002.07546
Detection with the ATLAS detector

- Onion-shell-like structure
- High-precision components: tracker, calorimeters, muon spectrometer
- Large coverage up to $|\eta| < 5.0$
- 139 fb$^{-1}$ of data “good for physics”
**$t\bar{t}\gamma$ production in the $e\mu$ channel**

- Top-photon coupling accessible in production of $t\bar{t}\gamma$ final states
- $t\bar{t}\gamma$: photon radiation possible by any of the charged particles involved → Combination is measured experimentally as “$t\bar{t}\gamma$ production”
- Earlier measurements (36 fb$^{-1}$) with Run 2 data published by ATLAS [EPJC 79 (2019) 382]
  - Both lepton+jets and dilepton channels
  - Fiducial inclusive and differential cross-sections
- Now: precision measurement in $e\mu$ channel
  - Fiducial inclusive and differential cross-sections in several observables to test theory prediction
  - Comparison with fixed-order calculation (NLO in QCD): [JHEP 1810 (2018) 158]
**$t\bar{t}\gamma$ production in the $e\mu$ channel**

- Fixed-order computation includes all off-shell contributions and interference effects
  - Perform combined $t\bar{t}\gamma + tW\gamma$ measurement
  - Fiducial phase space aligned with computation
- Binned profile likelihood fit of observable $S_T$ (scalar sum of all transverse momenta, incl. $E_T^{\text{miss}}$)
- Measured fiducial cross-section (approx. 6% unc.):
  $$\sigma^{\text{fid}}(t\bar{t}\gamma \rightarrow e\mu) = 39.6 \pm 0.8 \text{ (stat) } \pm^{2.6}_{2.2} \text{ (syst) fb}$$
- To be compared against theory value:
  $$\sigma^{\text{NLO}}_{\text{fid}} = 38.50 \pm^{0.56}_{2.18} \text{ (scale) } \pm^{1.04}_{1.18} \text{ (PDF) fb}$$
- Dominant uncertainties: signal and background modelling, luminosity
**$t\bar{t}\gamma$ production in the $e\mu$ channel**

- ATLAS data unfolded to parton level
- Compared against fixed-order NLO theory and LO+PS Monte Carlo simulation:
  - $p_T$ and absolute rapidity of the photon
  - $|\Delta\eta|$ and $|\Delta\phi|$ between the two leptons
  - $\Delta R$ between photon and closest lepton
- NLO theory in good agreement with data
**$t\bar{t}\gamma$ production in the $e\mu$ channel**

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- Compared against fixed-order NLO theory and LO+PS Monte Carlo simulation:
  - $p_T$ and absolute rapidity of the photon
  - $|\Delta\eta|$ and $|\Delta\phi|$ between the two leptons
  - $\Delta R$ between photon and closest lepton
- NLO theory in good agreement with data
- LO+PS MC simulation with difficulties to describe some of the observables

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$/ndf</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG5 + Pythia8</td>
<td>30.8/9</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>MG5 + Herwig7</td>
<td>31.6/9</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Fixed-order NLO</td>
<td>5.8/9</td>
<td>0.76</td>
</tr>
</tbody>
</table>
$t\bar{t}Z$ production in $3\ell/4\ell$ final states

- Earlier ATLAS measurements at 13 TeV (36 fb$^{-1}$): inclusive cross-sections of $t\bar{t}W/t\bar{t}Z$ production

→ Measurement of $t\bar{t}Z$ with full Run 2 data
  - Focus on trilepton and tetralepton final states
  - Inclusive & differential cross-section measurements in several observables (parton and particle level)

- Trilepton channels – different usage in incl./diff.:
  - One region for unfolding → maximum statistics
  - Two $b$-tag regions for inclusive measurement → maximum precision & $WZ$ background suppression

- Tetralepton channels – four signal regions:
  - Same-flavour/opposite-flavour lepton pairing
  - Different $b$-tag multiplicities

- Control regions for $ZZ$ and $WZ$ backgrounds
$t\bar{t}Z$ production in $3\ell/4\ell$ final states

- Simultaneous profile likelihood fit of all trilepton and tetralepton signal regions + $WZ$ and $ZZ$ control regions
- Cross-check of fit results with individual channel fits

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>$\mu_{t\bar{t}Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trilepton</td>
<td>$1.17 \pm 0.07$ (stat.) $^{+0.12}_{-0.11}$ (syst.)</td>
</tr>
<tr>
<td>Tetralepton</td>
<td>$1.21 \pm 0.15$ (stat.) $^{+0.11}_{-0.10}$ (syst.)</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.19 \pm 0.06$ (stat.) $\pm 0.10$ (syst.)</td>
</tr>
</tbody>
</table>

- Measured inclusive $t\bar{t}Z$ cross-section:
  \[ \sigma(t\bar{t}Z) = 1.05 \pm 0.05 \text{ (stat.)} \pm 0.09 \text{ (syst.) \ pb} \]
- In agreement with NLO+NNLL prediction:
  \[ \sigma(t\bar{t}Z) = 0.863^{+0.07}_{-0.09} \text{ (scale)} \pm 0.03 \text{ (PDF+}\alpha_S\text{) \ pb} \]

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Associated production of top quarks and neutral bosons
**$ttZ$ production in $3\ell/4\ell$ final states**

- Unfolding done to both parton and particle level
- Differential results dominated by statistical uncertainties and those on signal modelling and $b$-tagging

**$p_T(Z)$ at particle level** (combined $3\ell/4\ell$ regions)

**$N_{\text{jets}}$ at particle level** (combined $4\ell$ regions)

\[ \Delta \phi(Z, t_{\text{lep}}) \] at parton level, normalised ($3\ell-2b3j$ region)
Observation of $tZq$ production

- Measurement of a single top quark in association with a $Z$ boson ($tZq$ production)
  - Evidence seen by ATLAS (2015/16 data) \( \text{PLB 780 (2018) 557} \)
  - Observed by CMS (2016/17 data) \( \text{PRL 122 (2019) 132003} \)
- Best signal significance in the trilepton channel → Use only this channel!
- Include non-resonant lepton pairs ($t\ell^+\ell^-q$)
- Multiple tree-level diagrams, measurement includes both $t-Z$ and $Z-W$ couplings
- Two signal regions (2j1b, 3j1b) plus additional control regions for the largest backgrounds ($t\bar{t}Z$, diboson, $t\bar{t}$)
Observation of $tZq$ production

**Basic pre-selection:**
- Three leptons with large $p_T$
  - $\geq$ one OSSF lepton pair
  - $|m_{ll} - m_Z| < 10$ GeV  
    $\rightarrow \mu\mu e$ and $e\mu\mu$ unambiguous, for $\mu\mu\mu$ and $e\mu\mu$ take pair with the smallest difference to the $Z$ mass
- Signal regions: additional forward jet with large $|\eta|$  

**Number of jets**

- Normalisation of backgrounds determined through control regions in the fit $\rightarrow$ free floating
- Statistics of fake-lepton estimate (e.g. $t\bar{t}, Z +$ jets) enriched from dilepton + two $b$-tag regions  
  $\rightarrow$ replace one of the $b$-jets with a lepton (+ energy and polar angle replacement)
Observation of $tZq$ production

- Neural networks employed in both signal regions to perform binary event classification
  - 15 input variables
  - One hidden layer with 25 nodes
- Best separating input variables:
  - Inv. mass of b-jet and untagged jet
  - Reconstructed top-quark mass
- Simultaneous profile-likelihood fit of all signal and control regions
- Dominant uncertainties: statistics, modelling + rate of prompt-lepton background

- Fitted cross-section: $97 \pm 13$ (stat.) $\pm 7$ (syst.) fb
- Compatible with NLO theory prediction: $102^{+5}_{-2}$ fb
Summary & Conclusions

• Run 2 dataset enables precision measurements in top+boson topologies
• Rich program of ATLAS top-quark analyses: [full list of public results]
• Analyses presented today (using full Run 2 data):
  • $t\bar{t}\gamma$ production measurements in $e\mu$ final states
  • $t\bar{t}Z$ production measurements in trilepton and tetralepton final states
  • Observation of single top-quark production with a $Z$ boson ($tZq$)
• Good agreement in inclusive and differential spectra with SM predictions
  • State-of-the-art fixed-order computations and NLO+PS Monte Carlo simulations provide good description of data spectra
  • LO+PS MC simulations describe some of the observables insufficiently
• First round of ATLAS Run 2 measurements = stringent tests of SM prediction
→ More ATLAS Run 2 measurements to come in the top-quark sector!

$tt\gamma$: arXiv:2007.06946  
$t\bar{t}Z$: ATLAS-CONF-2020-028  
$tZq$: arXiv:2002.07546
Backup
$tt\gamma$ production in the $e\mu$ channel
 Associated production of top quarks and neutral bosons

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**tty – pre-fit plots of unfolded variables**

**ATLAS**
- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- **Data**
  - $t\bar{t}_\gamma \, \gamma$
  - $t\bar{t}_\gamma \, e\mu$
  - $tW_\gamma \, e\mu$
  - Other $t\bar{t}_\gamma/tW_\gamma$
  - $h$-fake
  - $e$-fake
  - Prompt $\gamma$ bkg.
  - Uncertainty

**Events / GeV**
- $p_T(\gamma)$ [GeV]
- $|\eta(\gamma)|$
- $\Delta R(\gamma,l_{\text{min}})$

**Associated production of top quarks and neutral bosons**

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$t\bar{t}\gamma$ – pre-fit plots of unfolded variables (2)
**ttγ – migration matrix and efficiencies**

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV} \)

- eµ
- \( t\bar{t}\gamma + tW\gamma \)

### Data Table

<table>
<thead>
<tr>
<th>Reconstruction-level ( p_T(\gamma) ) [GeV]</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>1.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Efficiency**

\( 1 - f_{out} \)

**C**

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV} \)

- eµ
- \( t\bar{t}\gamma + tW\gamma \)

**Associated production of top quarks and neutral bosons**
**ttγ** – pre-fit/post-fit distributions of fit variable

\[
\text{Events / GeV} \\
\begin{array}{c}
\text{Data} \\
\text{tγμ} \\
\text{tWγ μμ} \\
\text{Other tγ/tWγ} \\
\text{h-fake} \\
\text{e-fake} \\
\text{Prompt γ bkg.} \\
\text{Uncertainty}
\end{array}
\]

\[
\begin{array}{c}
\text{Pre-Fit} \\
\text{Post-Fit}
\end{array}
\]
**ttγ** – normalised unfolded cross-sections

ATLAS

- **ATLAS**: $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- **Normalised cross-section**
- **Unfolded data**: $t\bar{t} + Wgamma$ (MG5_aMC+Pythia8)
- **Theory NLO**: $t\bar{t} + Wgamma$
- **Stat. & Syst.**

- **Unfolded data**: $t\bar{t} + Wgamma$ (MG5_aMC+Herwig7)
- **Stat. & Syst.**

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- **Unfolded data**: $t\bar{t} + Wgamma$ (MG5_aMC+Herwig7)
- **Stat. & Syst.**
$t\bar{t}y$ – normalised unfolded cross-sections (2)
$tt\gamma$ – absolute unfolded cross-sections

**ATLAS**

- **$\sqrt{s} = 13$ TeV, 139 $fb^{-1}$**
- **Absolute cross-section $\mu_e$**

**ATLAS**

- **$\sqrt{s} = 13$ TeV, 139 $fb^{-1}$**
- **Absolute cross-section $\phi_\mu$**

**ATLAS**

- **$\sqrt{s} = 13$ TeV, 139 $fb^{-1}$**
- **Absolute cross-section $\phi_\mu$**

**Associated production of top quarks and neutral bosons**

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Associated production of top quarks and neutral bosons
**ttγ – absolute unfolded cross-sections (2)**

![Graph 1](#)

*ATLAS* 
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Absolute cross-section \( \sigma_{\mu} \)

Unfolded data

Theory NLO

Stat.

Stat \( \oplus \) Syst.

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![Graph 2](#)

*ATLAS* 
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Absolute cross-section \( \sigma_{\mu} \)

Unfolded data

Theory NLO

Stat.

Stat \( \oplus \) Syst.
ttγ – uncertainties on normalised cross-sections

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

- Statistical
- Statistical + Systematic

- \( t\bar{t}/tW' \) modelling
- \( t\bar{t}/tW' \) plus systematic
- Bkg. modelling

\[ p_{T}(\gamma) \text{ [GeV]} \]
\[ |\eta(\gamma)| \]
\[ |\Delta R(\gamma/J)_{\text{min}}| \]
\[ |\Delta \phi(\gamma/J)| \]
$tt\gamma$ – uncertainties on absolute cross-sections
**ttγ – pre-fit yield table**

Table 1: Event yields before the profile likelihood fit of the signal and background processes to data after the full selection. All categories are estimated from MC simulation and include correction factors for detector effects as described in Section 6. The combination of all $t\bar{t}\gamma$ and $tW\gamma$ categories is scaled to match the event yields in data. The quoted uncertainties correspond to the total statistical and systematic uncertainties (cf. Section 6) added in quadrature.

<table>
<thead>
<tr>
<th>Events</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}\gamma e\mu$</td>
<td>2391 ± 130</td>
</tr>
<tr>
<td>$tW\gamma e\mu$</td>
<td>156 ± 15</td>
</tr>
<tr>
<td>Other $t\bar{t}\gamma/tW\gamma$</td>
<td>279 ± 15</td>
</tr>
<tr>
<td>h-fake</td>
<td>78 ± 40</td>
</tr>
<tr>
<td>e-fake</td>
<td>23 ± 12</td>
</tr>
<tr>
<td>Prompt $\gamma$ bkg.</td>
<td>87 ± 40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3014 ± 160</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>3014</strong></td>
</tr>
</tbody>
</table>
### $tt\gamma$ – impact of systematic uncertainties

Table 2: Illustrative summary of the systematic uncertainties on the fiducial inclusive cross-section measurement grouped into different categories and their relative impact on the measurement (symmetrised). The categories ‘$tt\gamma/tW\gamma$ modelling’ and ‘Background modelling’ include all corresponding systematic uncertainties described in Section 6.2. The ‘$tW\gamma$ parton definition’ uncertainty is listed separately since it does not enter the profile likelihood fit directly as described in Section 6.3. The category ‘Photons’ corresponds to the uncertainties related to photon identification and isolation as well as photon energy scale and resolution. ‘Jets’ includes the total uncertainty from the JES, JER and JVT discriminant, while the $b$-tagging-related uncertainties are given in a separate category (‘Flavour-tagging’). The category ‘Leptons’ represents the uncertainties related to lepton identification, isolation and energy/momentum calibration.

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt\gamma/tW\gamma$ modelling</td>
<td>3.8%</td>
</tr>
<tr>
<td>Background modelling</td>
<td>2.1%</td>
</tr>
<tr>
<td>Photons</td>
<td>1.9%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.8%</td>
</tr>
<tr>
<td>Jets</td>
<td>1.6%</td>
</tr>
<tr>
<td>Pile-up</td>
<td>1.3%</td>
</tr>
<tr>
<td>Leptons</td>
<td>1.1%</td>
</tr>
<tr>
<td>Flavour-tagging</td>
<td>1.1%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.4%</td>
</tr>
<tr>
<td>Soft term $E_T^{\text{miss}}$</td>
<td>0.2%</td>
</tr>
<tr>
<td>$tW\gamma$ parton definition</td>
<td>2.8%</td>
</tr>
<tr>
<td>Total syst.</td>
<td>6.3%</td>
</tr>
</tbody>
</table>
**ttγ – compatibility tests for differential cross-sections**

### Normalised Cross-Sections

| Predictions                          | $p_T(\gamma)$ $\chi^2$/ndf | $p$-value | $|\eta(\gamma)|$ $\chi^2$/ndf | $p$-value | $\Delta R(\gamma, \ell)_{\text{min}}$ $\chi^2$/ndf | $p$-value | $\Delta\phi(\ell, \ell)$ $\chi^2$/ndf | $p$-value | $|\Delta\eta(\ell, \ell)|$ $\chi^2$/ndf | $p$-value |
|--------------------------------------|-------------------------------|-----------|-------------------------------|-----------|-----------------------------------------------|-----------|-----------------------------------------------|-----------|-----------------------------------------------|-----------|
| $t\bar{t}\gamma + tW\gamma$ (MG5_aMC+PYTHIA8) | 6.3/10                       | 0.79      | 7.3/7                         | 0.40      | 20.1/9                                        | 0.02      | 30.8/9                                        | <0.01    | 6.5/7                                         | 0.48      |
| $t\bar{t}\gamma + tW\gamma$ (MG5_aMC+HERWIG7) | 5.3/10                       | 0.87      | 7.7/7                         | 0.36      | 18.9/9                                        | 0.03      | 31.6/9                                        | <0.01    | 6.8/7                                         | 0.45      |
| Theory NLO                          | 6.0/10                       | 0.82      | 4.5/7                         | 0.72      | 13.5/9                                        | 0.14      | 5.8/9                                         | 0.76      | 5.6/7                                         | 0.59      |

### Absolute Cross-Sections

| Predictions | $p_T(\gamma)$ $\chi^2$/ndf | $p$-value | $|\eta(\gamma)|$ $\chi^2$/ndf | $p$-value | $\Delta R(\gamma, \ell)_{\text{min}}$ $\chi^2$/ndf | $p$-value | $\Delta\phi(\ell, \ell)$ $\chi^2$/ndf | $p$-value | $|\Delta\eta(\ell, \ell)|$ $\chi^2$/ndf | $p$-value |
|-------------|-------------------------------|-----------|-------------------------------|-----------|-----------------------------------------------|-----------|-----------------------------------------------|-----------|-----------------------------------------------|-----------|
| Theory NLO  | 6.1/11                        | 0.87      | 4.5/8                         | 0.81      | 11.7/10                                       | 0.31      | 5.8/10                                        | 0.83      | 6.2/8                                         | 0.62      |
$ttZ$ production in 3l/4l final states
**ttZ – definition of trilepton SRs**

<table>
<thead>
<tr>
<th>Variable</th>
<th>3ℓ-Z-1b4j-PCBT (inclusive)</th>
<th>3ℓ-Z-2b3j-PCBT (inclusive)</th>
<th>3ℓ-Z-2b3j (differential)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_\ell (\ell = e, \mu) )</td>
<td>( = 3 )</td>
<td>( \geq 1 ) OSSF lepton pair with (</td>
<td>m_{\ell\ell}^Z - m_Z</td>
</tr>
<tr>
<td>( p_T (\ell_1, \ell_2, \ell_3) )</td>
<td>( &gt; 27, 20, 20 \text{ GeV} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{\text{jets}} )</td>
<td>( \geq 4 )</td>
<td>( \geq 3 )</td>
<td>( \geq 3 )</td>
</tr>
<tr>
<td>( N_{b-\text{jets}} )</td>
<td>( = 1@60% )</td>
<td>( \geq 2@70% )</td>
<td>( \geq 2@85% )</td>
</tr>
<tr>
<td>veto add. ( b )-jets@70%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### ttZ – definition of tetralepton SRs

<table>
<thead>
<tr>
<th>Variable</th>
<th>$4\ell$-SF-1$b$</th>
<th>$4\ell$-SF-2$b$</th>
<th>$4\ell$-DF-1$b$</th>
<th>$4\ell$-DF-2$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\ell(\ell = e, \mu)$</td>
<td>$\geq 4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥1 OSSF lepton pair with $</td>
<td>m_{\ell\ell}^Z - m_Z</td>
<td>&lt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for all OSSF combinations: $m_{\text{OSSF}} &gt; 10$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T(\ell_1, \ell_2, \ell_3, \ell_4)$</td>
<td>$&gt; 27, 20, 10, 7$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ell\ell^{\text{non-Z}}$</td>
<td>$e^+e^-$ or $\mu^+\mu^-$</td>
<td>$e^+e^-$ or $\mu^+\mu^-$</td>
<td>$e^\pm\mu^\mp$</td>
<td>$e^\pm\mu^\mp$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>&gt; 100 GeV, if $</td>
<td>m_{\ell\ell}^{\text{non-Z}} - m_Z</td>
<td>\leq 10$ GeV</td>
<td>&gt; 50 GeV, if $</td>
</tr>
<tr>
<td></td>
<td>&gt; 50 GeV, if $</td>
<td>m_{\ell\ell}^{\text{non-Z}} - m_Z</td>
<td>&gt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>$N_{\text{jets}}$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$N_{b-\text{jets @85%}}$</td>
<td>$= 1$</td>
<td>$\geq 2$</td>
<td>$= 1$</td>
<td>$\geq 2$</td>
</tr>
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</table>
ttZ – control plots in WZ CR

Associated production of top quarks and neutral bosons
**ttZ – trilepton post-fit distributions**

![Graphs showing distributions](attachment:image.png)

**ATLAS Preliminary**

\( \bar{\gamma}s = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

3l-Z-1b4j-PCBT

Post-fit

**ATLAS Preliminary**

\( \bar{\gamma}s = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

3l-Z-2b3j-PCBT

Post-fit

**Data / SM**

Events / 30 GeV

Leading lepton \( p_T \) [GeV]
**ttZ** – tetralepton post-fit distributions

**ATLAS Preliminary**
\[\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}\]

4l SR combination
Post-fit

<table>
<thead>
<tr>
<th>Events</th>
<th>Data / SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\text{jets}})</td>
<td>2</td>
</tr>
<tr>
<td>Data</td>
<td>80</td>
</tr>
<tr>
<td>ttZ</td>
<td>50</td>
</tr>
<tr>
<td>ZZ+jets</td>
<td>30</td>
</tr>
<tr>
<td>tWZ</td>
<td>10</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>30</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>5</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**
\[\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}\]

4l SR combination
Post-fit

<table>
<thead>
<tr>
<th>Events / 50 GeV</th>
<th>Data / SM</th>
</tr>
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<tr>
<td>Leading lepton (p_T) [GeV]</td>
<td>0</td>
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<td>70</td>
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<td>ttZ</td>
<td>50</td>
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<tr>
<td>ZZ+jets</td>
<td>30</td>
</tr>
<tr>
<td>tWZ</td>
<td>10</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>30</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>5</td>
</tr>
</tbody>
</table>
$ttZ$ – combined-channel post-fit distributions

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
3l + 4l SR combination
Post-fit

Data / SM

Events / 50 GeV

$\not{E}_T$ [GeV]

$\gamma^* = 13$ TeV, 139 fb$^{-1}$
3l + 4l SR combination
Post-fit

Data / SM

Events / 0.5

$\gamma^*$
# $ttZ$ – fit results and systematic uncertainties

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>$\mu_{ttZ}$</th>
<th>Uncertainty</th>
<th>$\Delta \sigma_{ttZ}/\sigma_{ttZ}$ [%]</th>
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</thead>
<tbody>
<tr>
<td>Trilepton</td>
<td>$1.17 \pm 0.07$ (stat.) $^{+0.12}_{-0.11}$ (syst.)</td>
<td>$t\bar{t}Z$ parton shower</td>
<td>3.1</td>
</tr>
<tr>
<td>Tetralepton</td>
<td>$1.21 \pm 0.15$ (stat.) $^{+0.11}_{-0.10}$ (syst.)</td>
<td>$tWZ$ modelling</td>
<td>2.9</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.19 \pm 0.06$ (stat.) $\pm 0.10$ (syst.)</td>
<td>$b$-tagging</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$WZ/ZZ$ + jets modelling</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$tZq$ modelling</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lepton</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Luminosity</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jets + $E_T^{\text{miss}}$</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-prompt/fake leptons</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t\bar{t}Z$ A14 tune</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t\bar{t}Z$ $\mu_f$, $\mu_r$ scales</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Other backgrounds</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pile-up</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t\bar{t}Z$ PDF</td>
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<td></td>
<td></td>
<td>Total systematics</td>
<td>8.4</td>
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<td></td>
<td></td>
<td>Data statistics</td>
<td>5.2</td>
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<tr>
<td></td>
<td></td>
<td>Total</td>
<td>9.9</td>
</tr>
</tbody>
</table>
## $ttZ$ – unfolding variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3$\ell$</td>
<td></td>
</tr>
<tr>
<td>$p_T^{Z}$</td>
<td>Transverse momentum of the $Z$ boson</td>
</tr>
<tr>
<td>$</td>
<td>y^{Z}</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>Number of selected jets with $p_T &gt; 25$ GeV and $</td>
</tr>
<tr>
<td>$N_{jets}$</td>
<td>Transverse momentum of the lepton which is not associated with the $Z$ boson</td>
</tr>
<tr>
<td>$p_T^{\ell,non-Z}$</td>
<td>Azimuthal separation between the $Z$ boson and the top quark (antiquark) featuring the $W \rightarrow \ell\nu$ decay</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi (Z, l_{lep})</td>
</tr>
<tr>
<td>4$\ell$</td>
<td>Number of selected jets with $p_T &gt; 25$ GeV and $</td>
</tr>
<tr>
<td>$N_{jets}$</td>
<td>Azimuthal separation between the two leptons from the $t\bar{t}$ system</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi (\ell_T^+, \ell_T^-)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi (t\bar{t}, Z)</td>
</tr>
<tr>
<td>$p_T^{t\bar{t}}$</td>
<td>Transverse momentum of the $t\bar{t}$ system</td>
</tr>
</tbody>
</table>
**ttZ – unfolded number of jets (3l)**

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, \, 139 \text{ fb}^{-1} \]

3l-Z-2b3j

- Data
- MG5_aMC@NLO + Pythia8
- MG5_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**Chart 1:**
- **Theory/Data**
  - Stat.
  - Stat. + Syst.

**Chart 2:**
- **Theory/Data**
  - Stat.
  - Stat. + Syst.

**Particle-level N_{jets} ≥ 5**

Knut Zoch (University of Göttingen)  
Associated production of top quarks and neutral bosons

40
ttZ – unfolded number of jets (4l)

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

4l SR combination

![Graph 1](image1)

![Graph 2](image2)

Associated production of top quarks and neutral bosons
**ttZ** – unfolded absolute distributions (3l)

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

3l-Z-2b3j

- Data
- MG5_aMC@NLO + Pythia8
- MG5_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

- ATLAS Preliminary
- \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

3l-Z-2b3j

- Data
- MG5_aMC@NLO + Pythia8
- MG5_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**Theory**

<table>
<thead>
<tr>
<th>Data</th>
<th>Stat.</th>
<th>Stat. ( \oplus ) Syst.</th>
</tr>
</thead>
</table>

**Associated production of top quarks and neutral bosons**
**ttZ – unfolded normalised distributions (3l)**

**ATLAS Preliminary**  
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**3l-Z-2b3j**

- Data
- \( \text{MG5}_a\text{MC@NLO} + \text{Pythia8} \)
- \( \text{MG5}_a\text{MC@NLO} + \text{Herwig7} \)
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**ATLAS Preliminary**  
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**3l-Z-2b3j**

- Data
- \( \text{MG5}_a\text{MC@NLO} + \text{Pythia8} \)
- \( \text{MG5}_a\text{MC@NLO} + \text{Herwig7} \)
- Sherpa NLO inclusive
- Sherpa NLO multi-leg
- NLO + NNLL JHEP 08 (2019) 039

**Associated production of top quarks and neutral bosons**

Knut Zoch (University of Göttingen)
**ttZ – unfolded absolute distributions (4l)**

**ATLAS Preliminary**
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

4l SR combination

**Energy Spectrum**

- **Theory**
- **Data**

**Stat.**

- **Stat. + Syst.**

**Parton-level**

\( |\Delta \phi(l^+_1, l^-_1)|/\pi \)

**Particle-level**

\( |\Delta \phi(l^+_1, l^-_1)|/\pi \)

**Associated production of top quarks and neutral bosons**
\( ttZ \) – unfolded normalised distributions (4l)

\[
\frac{1}{\sigma} \frac{d\sigma}{d|\Delta\phi(l^+_T, l^-_T)|/\pi}
\]

\( \sqrt{s} = 13 \) TeV, 139 fb\(^{-1} \)

4l SR combination

**ATLAS** Preliminary

Data

- MG5\_aMC@NLO + Pythia8
- MG5\_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**Theor.**

\( \frac{\text{Theory}}{\text{Data}} \)

Stat. \( \oplus \) Stat. \( \oplus \) Syst.

**Theory**

\( \frac{\text{Theory}}{\text{Data}} \)

Stat. \( \oplus \) Stat. \( \oplus \) Syst.

**Data**

\( \sqrt{s} = 13 \) TeV, 139 fb\(^{-1} \)

4l SR combination

**ATLAS** Preliminary

Data

- MG5\_aMC@NLO + Pythia8
- MG5\_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**Theor.**

\( \frac{\text{Theory}}{\text{Data}} \)

Stat. \( \oplus \) Stat. \( \oplus \) Syst.

**Theory**

\( \frac{\text{Theory}}{\text{Data}} \)

Stat. \( \oplus \) Stat. \( \oplus \) Syst.
**ttZ – channel combination (absolute)**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

3l + 4l combination

**Associated production of top quarks and neutral bosons**

Knut Zoch (University of Göttingen)
**ttZ – channel combination (normalised)**

**ATLAS Preliminary**
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**3l + 4l combination**

\[
\frac{1}{\sigma} \frac{d\sigma}{d\pT} \quad \text{[GeV]}
\]

**Theory**
- Data
- MG5_aMC@NLO + Pythia8
- MG5_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg

**Stat. Stat. ⊕ Syst.**

**ATLAS Preliminary**
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**3l + 4l combination**

\[
\frac{1}{\sigma} \frac{d\sigma}{d\pT} \quad \text{[GeV]}
\]

**Theory**
- Data
- MG5_aMC@NLO + Pythia8
- MG5_aMC@NLO + Herwig7
- Sherpa NLO inclusive
- Sherpa NLO multi-leg
- NLO + NNLL JHEP 08 (2019) 039

**Stat. Stat. ⊕ Syst.**
Observation of $tZq$ production
**tZq – NN output distribution in SRs**

![Graph](image_url)

**Data / Pred.**

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

SR 2j1b

Post-Fit

- Events / 0.2

- Data
- tZq
- \(t\bar{t}+tW\)
- Z+jets
- VV+LF
- VV+HF
- tZ+WF
- tW+tH
- Uncertainty

**Data / Pred.**

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

SR 3j1b

Post-Fit

- Events / 0.2

- Data
- tZq
- \(t\bar{t}+tW\)
- Z+jets
- VV+LF
- VV+HF
- tZ+WF
- tW+tH
- Uncertainty

Associated production of top quarks and neutral bosons
**tZq – post-fit control plots with cut on NN**

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1} \)

SR 2j1b, \( O_{\text{NN}} > 0.4 \)

Post-Fit

<table>
<thead>
<tr>
<th>Events / 50 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
</tr>
<tr>
<td>tZq</td>
</tr>
<tr>
<td>t\bar{t}+tW</td>
</tr>
<tr>
<td>Z+jets</td>
</tr>
<tr>
<td>VV+LF</td>
</tr>
<tr>
<td>VV+HF</td>
</tr>
<tr>
<td>t\bar{t}Z+tWZ</td>
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<td>t\bar{t}W+tH</td>
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<tr>
<td>Uncertainty</td>
</tr>
</tbody>
</table>

Data / Pred.

<table>
<thead>
<tr>
<th>Events / 50 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
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<tr>
<td>tZq</td>
</tr>
<tr>
<td>t\bar{t}+tW</td>
</tr>
<tr>
<td>Z+jets</td>
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<tr>
<td>VV+LF</td>
</tr>
<tr>
<td>VV+HF</td>
</tr>
<tr>
<td>t\bar{t}Z+tWZ</td>
</tr>
<tr>
<td>t\bar{t}W+tH</td>
</tr>
<tr>
<td>Uncertainty</td>
</tr>
</tbody>
</table>

Associated production of top quarks and neutral bosons
**tZq – NN output distribution in CRs (1)**

Data / Pred.

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, \; 139 \text{ fb}^{-1} \]

VR diboson 2j1Lb Post-Fit

Events / 0.3

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, \; 139 \text{ fb}^{-1} \]

VR diboson 3j1Lb Post-Fit

Events / 0.3

Associated production of top quarks and neutral bosons
**tZq – NN output distribution in CRs (2)**

**ATLAS**

\( |\bar{s}| = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

VR \( t\bar{t} + tV \) 2j1b

Post-Fit

- Data
- \( t\bar{t}Z \)
- \( t\bar{t}W \)
- \( Z + \text{jets} \)
- \( VV + \text{LF} \)
- \( VV + \text{HF} \)
- \( t\bar{t}Z + \text{WZ} \)
- \( t\bar{t}W + t\bar{t}H \)

Uncertainty

**Data / Pred.**

Events / 0.3

ATLAS

\( |\bar{s}| = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

VR \( t\bar{t} + tV \) 3j1b

Post-Fit

- Data
- \( t\bar{t}Z \)
- \( t\bar{t}W \)
- \( Z + \text{jets} \)
- \( VV + \text{LF} \)
- \( VV + \text{HF} \)
- \( t\bar{t}Z + \text{WZ} \)
- \( t\bar{t}W + t\bar{t}H \)

Uncertainty

**Data / Pred.**

Events / 0.3

Associated production of top quarks and neutral bosons
### tZq – definition of signal and control regions

Common selections

Exactly 3 leptons ($e$ or $\mu$) with $|\eta| < 2.5$

- $p_T(\ell_1) > 28\text{ GeV}$, $p_T(\ell_2) > 20\text{ GeV}$, $p_T(\ell_3) > 20\text{ GeV}$
- $p_T(\text{jet}) > 35\text{ GeV}$

<table>
<thead>
<tr>
<th>SR 2j1b</th>
<th>CR diboson 2j0b</th>
<th>CR $t\bar{t}$ 2j1b</th>
<th>CR $t\bar{t}Z$ 3j2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1$ OSSF pair</td>
<td>$\geq 1$ OSSF pair</td>
<td>$\geq 1$ OSDF pair</td>
<td>$\geq 1$ OSSF pair</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>&lt; 10\text{ GeV}$</td>
<td>$</td>
</tr>
<tr>
<td>2 jets, $</td>
<td>\eta</td>
<td>&lt; 4.5$</td>
<td>2 jets, $</td>
</tr>
<tr>
<td>1 $b$-jet, $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
<td>0 $b$-jets</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SR 3j1b</th>
<th>CR diboson 3j0b</th>
<th>CR $t\bar{t}$ 3j1b</th>
<th>CR $t\bar{t}Z$ 4j2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1$ OSSF pair</td>
<td>$\geq 1$ OSSF pair</td>
<td>$\geq 1$ OSDF pair</td>
<td>$\geq 1$ OSSF pair</td>
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<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>&lt; 10\text{ GeV}$</td>
<td>$</td>
</tr>
<tr>
<td>3 jets, $</td>
<td>\eta</td>
<td>&lt; 4.5$</td>
<td>3 jets, $</td>
</tr>
<tr>
<td>1 $b$-jet, $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
<td>0 $b$-jets</td>
</tr>
</tbody>
</table>
## tZq – ranking of variables in NNs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rank</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{bj})</td>
<td>1</td>
<td>(Largest) invariant mass of the (b)-jet and the untagged jet(s)</td>
</tr>
<tr>
<td>(m_{\text{top}})</td>
<td>2</td>
<td>Reconstructed top-quark mass</td>
</tr>
<tr>
<td>(</td>
<td>\eta(j_f)</td>
<td>)</td>
</tr>
<tr>
<td>(m_T(\ell, E_T^{\text{miss}}))</td>
<td>4</td>
<td>Transverse mass of the (W) boson</td>
</tr>
<tr>
<td>(b)-tagging score</td>
<td>5</td>
<td>(b)-tagging score of the (b)-jet</td>
</tr>
<tr>
<td>(H_T)</td>
<td>6</td>
<td>Scalar sum of the (p_T) of the leptons and jets in the event</td>
</tr>
<tr>
<td>(q(\ell_W))</td>
<td>7</td>
<td>Electric charge of the lepton from the (W)-boson decay</td>
</tr>
<tr>
<td>(</td>
<td>\eta(\ell_W)</td>
<td>)</td>
</tr>
<tr>
<td>(p_T(W))</td>
<td>9</td>
<td>(p_T) of the reconstructed (W) boson</td>
</tr>
<tr>
<td>(p_T(\ell_W))</td>
<td>10</td>
<td>(p_T) of the lepton from the (W)-boson decay</td>
</tr>
<tr>
<td>(m(\ell\ell))</td>
<td>11</td>
<td>Mass of the reconstructed (Z) boson</td>
</tr>
<tr>
<td>(</td>
<td>\eta(Z)</td>
<td>)</td>
</tr>
<tr>
<td>(\Delta R(j_f, Z))</td>
<td>13</td>
<td>(\Delta R) between the (j_f) jet and the reconstructed (Z) boson</td>
</tr>
<tr>
<td>(E_T^{\text{miss}})</td>
<td>14</td>
<td>Missing transverse momentum</td>
</tr>
<tr>
<td>(p_T(j_f))</td>
<td>15</td>
<td>(p_T) of the (j_f) jet</td>
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<tr>
<td>(</td>
<td>\eta(j_f)</td>
<td>)</td>
</tr>
<tr>
<td>(p_T(Z))</td>
<td></td>
<td>(p_T) of the reconstructed (Z) boson</td>
</tr>
<tr>
<td>(p_T(j_f))</td>
<td></td>
<td>(p_T) of the (j_f) jet</td>
</tr>
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</table>
### $tZq$ – post-fit yields in signal and control regions

<table>
<thead>
<tr>
<th></th>
<th>SR 2j1b</th>
<th>CR diboson 2j0b</th>
<th>CR $t\bar{t}$ 2j1b</th>
<th>CR $t\bar{t}Z$ 3j2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tZq$</td>
<td>79 ± 11</td>
<td>53.1 ± 7.5</td>
<td>0.2 ± 0.1</td>
<td>12.9 ± 2.0</td>
</tr>
<tr>
<td>$t\bar{t} + tW$</td>
<td>23.8 ± 4.8</td>
<td>13.7 ± 2.7</td>
<td>33.3 ± 6.3</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td>Z + jets</td>
<td>28 ± 13</td>
<td>181 ± 82</td>
<td>&lt; 0.1</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>VV + LF</td>
<td>19.7 ± 7.9</td>
<td>2000 ± 100</td>
<td>&lt; 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>VV + HF</td>
<td>101 ± 22</td>
<td>383 ± 78</td>
<td>0.4 ± 0.1</td>
<td>5.2 ± 1.7</td>
</tr>
<tr>
<td>$t\bar{t}Z + tW$</td>
<td>96 ± 11</td>
<td>63.2 ± 7.0</td>
<td>4.8 ± 0.5</td>
<td>59.3 ± 7.1</td>
</tr>
<tr>
<td>$t\bar{t}H + t\bar{t}W$</td>
<td>6.5 ± 1.0</td>
<td>3.0 ± 0.5</td>
<td>12.4 ± 1.9</td>
<td>2.8 ± 0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>354 ± 16</td>
<td>2697 ± 56</td>
<td>51.1 ± 6.1</td>
<td>83.5 ± 6.4</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>359</td>
<td>2703</td>
<td>49</td>
<td>92</td>
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<table>
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<tr>
<th></th>
<th>SR 3j1b</th>
<th>CR diboson 3j0b</th>
<th>CR $t\bar{t}$ 3j1b</th>
<th>CR $t\bar{t}Z$ 4j2b</th>
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<tbody>
<tr>
<td>$tZq$</td>
<td>43.4 ± 6.2</td>
<td>21.2 ± 3.3</td>
<td>0.2 ± 0.1</td>
<td>8.0 ± 1.3</td>
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<tr>
<td>$t\bar{t} + tW$</td>
<td>11.0 ± 2.2</td>
<td>6.9 ± 1.3</td>
<td>15.4 ± 3.1</td>
<td>1.0 ± 0.2</td>
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<tr>
<td>Z + jets</td>
<td>12.8 ± 6.0</td>
<td>53 ± 23</td>
<td>&lt; 0.1</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>VV + LF</td>
<td>10.1 ± 4.2</td>
<td>624 ± 53</td>
<td>&lt; 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>VV + HF</td>
<td>58 ± 17</td>
<td>186 ± 51</td>
<td>0.3 ± 0.1</td>
<td>3.4 ± 1.0</td>
</tr>
<tr>
<td>$t\bar{t}Z + tW$</td>
<td>132 ± 12</td>
<td>61.9 ± 6.2</td>
<td>3.9 ± 0.5</td>
<td>58.1 ± 5.3</td>
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<tr>
<td>$t\bar{t}H + t\bar{t}W$</td>
<td>4.7 ± 0.7</td>
<td>1.7 ± 0.3</td>
<td>8.2 ± 1.3</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>272 ± 12</td>
<td>955 ± 29</td>
<td>28.0 ± 3.0</td>
<td>72.8 ± 5.0</td>
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<tr>
<td><strong>Data</strong></td>
<td>259</td>
<td>949</td>
<td>31</td>
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## $t\bar{t}Zq$ – impact of systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\sigma/\sigma$ [%]</th>
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<tr>
<td>Prompt-lepton background modelling and normalisation</td>
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<tr>
<td>Jets and $E_T^{\text{miss}}$ reconstruction and calibration</td>
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<tr>
<td>Lepton reconstruction and calibration</td>
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<tr>
<td>Luminosity</td>
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<td>Pile-up modelling</td>
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<td>MC statistics</td>
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<td>$t\bar{t}Zq$ modelling (QCD radiation)</td>
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<tr>
<td>$t\bar{t}Zq$ modelling (PDF)</td>
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<tr>
<td>Jet flavour tagging</td>
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</tr>
</tbody>
</table>

Total systematic uncertainty: 7.0%

Data statistical: 12.6%

$\bar{t}t$ and $Z +$ jets normalisation: 2.1%

Total statistical uncertainty: 12.9%