Evidence of the four-top-quark production at the LHC
Top-quark

- Top-quark is the **heaviest** of all known fundamental particles $m_{\text{top}} \sim 170$ GeV
  - a bizarrely steep mass hierarchy
  - Even heavier than the **Higgs boson**
  - Unique role as a result of its mass
  - Many models predict that the top is special in order to explain its mass

- Leaves us wondering:
  - Is the top mass from the Higgs mechanism?
  - Is there a hidden connection with the EWSB mechanism?
  - Does it have any connection to Higgs compositeness?
Top-quark

- Strongly interacts with the Higgs sector

- Large top yukawa coupling $y_t \sim 1$

Thanks for popping me out of the vacuum!

No Problem! Have you seen any new physics down there?
Top-quark

- Short-lived, it decays before hadronizing
  - $\tau_{\text{had}} \approx 2 \times 10^{-24}\text{s}$
  - $\tau_{\text{top}} \approx 0.5 \times 10^{-24}\text{s}$
- Possible to study the properties of a bare quark
- LHC is a top factory & many top-quarks are produced at the LHC
  - About 25,000 $t\bar{t}$ events are produced every hour
- Gateway to **New Physics**
  - Precision SM top-quark properties measurements
  - Search for non-SM top-quark interactions
  - Searches of top-quark partners and other states
Top-quark Production Cross-section Measurements

Run 1 @ 7 TeV  Run 1 @ 8 TeV  Run 2 @ 13 TeV  Theory

Status: May 2021

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 5, 7, 8, 13$ TeV

Different processes
• $t\bar{t}$ production is produced abundantly at the LHC and extremely well studied (total and differential cross sections)
Top-quark Production Cross-section Measurements

- $t\bar{t}+X$ events are related to new physics and important backgrounds for rare SM processes
- Rare top production modes become fully accessible with Run 2 data

![Graph showing top quark production cross-section measurements](image-url)

**Different processes**

- $t\bar{t}W$
- $t\bar{t}Z$
- $t\bar{t}H$
- $t\bar{t}\gamma$
- $tZj$
- $4t$
Top-quark Production Cross-section Measurements

- $t\bar{t}Z/t\bar{t}W$ are among the most massive signatures that can be studied at the LHC with high precision

- Important backgrounds for searches and measurements
• $t\bar{t}H$ was recently observed using $80 \text{ fb}^{-1}$ of Run 2 data-set [ATLAS-CONF-2019-045]
Top-quark Production Cross-section Measurements

- Today I will talk about $t\bar{t}t\bar{t}$

- Very tiny cross section in the SM

$$\sigma_{SM}(t\bar{t}t\bar{t}) = 11.97 \text{ fb at NLO QCD + NLO QED at } 13 \text{ TeV} \quad \text{JHEP 02, 031 (2018)}$$
Predictions for four-tops

- **Rare process** predicted by the SM and has **never been observed**

- Very complicated process: 72 $gg$ + 12 $q\bar{q}$ initiated diagrams at LO

- Sensitive to top-Yukawa coupling ($y_t$)
  - A non-SM value of $y_t$ can change dramatically the production via an off-shell Higgs
Predictions for four-tops

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![Diagram](image)

**Leading:** $O(\alpha_s^4)$

arXiv:1611.05032 [hep-ph]
Predictions for four-tops

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The production of $t\bar{t}t\bar{t}$ is predominantly a QCD process of order $O(\alpha_s^4)$

arXiv:1611.05032 [hep-ph]
Predictions for four-tops

• Rare process predicted by the SM and has never been observed

• Very complicated process: 72 $gg + 12 \bar{q}q$ initiated diagrams at LO

• Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson
  • four top quarks can be produced via an offshell SM Higgs boson

The production of $t\bar{t}t\bar{t}$ is predominantly a QCD process of order $O(\alpha_s^4)$

A sub-leading Higgs boson exchange contribution of order $O(\alpha_s^2 y_t^4)$
Predictions for four-tops

- Sensitive to many BSM models

Four-fermion contact interaction

New Particles

2HDM scalar/pseudoscalar

SUSY
Signatures

• We have **four-tops** in our final state

• Each **top** decays to $Wb$ and the detector signature is defined by:
  
  • The presence of four b-quarks
  
  • The decays of the W bosons
Signatures

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- $W \rightarrow q\bar{q} \quad 2/3$
- $W \rightarrow \tau\nu \quad 1/9$
- $W \rightarrow e\nu \quad 1/9$
- $W \rightarrow \mu\nu \quad 1/9$
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\end{align*}
\]

\[
\begin{align*}
\tau &\rightarrow q\bar{q} \quad (65\%) \\
\tau &\rightarrow \mu\nu \quad (17.5\%) \\
\tau &\rightarrow e\nu \quad (17.5\%)
\end{align*}
\]
Signatures

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\end{align*}
\]

\[~75\% \text{ hadronically}\]

\[~25\% \text{ e or } \mu\]
Signatures

- We have four-tops in our final state
- Each top decays to \( Wb \) and the detector signature is defined by:
  - The presence of four b-quarks
  - The decays of the W bosons

The branching ratios are as follows:

- \( 0l: (75\%)^4 \sim 32\% \)
- \( 1l: (25\%) \times (75\%)^3 \times 4 \sim 42\% \)
- \( \geq 3l: 5\% \)
- \( 2lSS: (25\%)^2 \times (75\%)^2 \times 2 \sim 7\% \)
- \( 2lOS: (25\%)^2 \times (75\%)^2 \times 4 \sim 14\% \)
Signatures

• Channels are split according to:

  • \textbf{2\ell\ell SS/3\ell: 2\ell SS} (7\%) / \textbf{3\ell} (5\%) \textbf{2\ell SS} (7\%) / \textbf{3\ell} (5\%)

    • Small branching fraction

    • Small background (ttW, ttZ, non-prompt leptons, charge misidentification)

    • Most sensitive channel

  • \textbf{1\ell/2\ell OS: 1\ell} (42\%) / \textbf{2\ell OS} (14\%)

    • Dominant branching fraction

    • Large irreducible background from tt+jets (tt+heavy flavour jets)

  • \textbf{0\ell} (32\%)

    • Experimentally very challenging

      • Large multi-jet background

    • Not yet explored in ATLAS
Search Strategy

Event Selection and Analysis regions

**Control Region** to estimate the main background

**Use BDT in the Signal Region** to separate the signal from the background

**Validation Region** to validate the model

\( \bar{t}t + b\bar{b} \)

\( \bar{t}t + W \)

Perform a fit in the Control and Signal Regions to extract the signal strength

\[ \mu = \frac{\sigma_{\bar{t}t\bar{t}t}}{\sigma_{\bar{t}t\bar{t}t}^{SM}} \]

Extract measured cross section and compare to theory!
Event Selection

**Event Selection and Analysis regions**

Control Region to estimate the main background

Use BDT in the Signal Region to separate the signal from the background

Validation Region to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{\text{TTT}} / \sigma_{\text{TTT}}^{\text{SM}}$

Extract measured cross section and compare to theory!
Event Selection

- Focus on interesting events & maximize the statistical significance of a potential signal excess
- Reduce major backgrounds (maximizing the significance of an excess)
- **Using full Run 2 dataset: 139 fb⁻¹**
- Selection requirements in the **2ℓSS/3ℓ** (signal region):
  - **2 same-sign leptons** or **3 leptons** (ℓ=e,μ)
  - **≥ 6 jets** \(p_T > 25\) GeV
  - **≥ 2 b-tagged jets**
    - efficiency of identifying b-jets is 77%
  - \(H_T > 500\) GeV ; \(H_T = \sum P_T + \sum P_T\)
Event Selection

- Selection requirements in the $1\ell/2\ell$OS:
  - Expect 10 (8) jets in 1L (2L)OS and 4 b-jets at truth level
  - Targeting events with high jet and b-jet multiplicities

- Event pre-Selection:
  - 1 e/µ or 2 e/µ
  - $N_{\text{jets}} \geq 7$ (1L), $N_{\text{jets}} \geq 5$ (2L)
  - $N_{\text{b}} \geq 2$

Example from the 1l channel
Analysis regions

Event Selection and Analysis regions

**Control Region** to estimate the main background

**Use BDT in the Signal Region** to separate the signal from the background

**Validation Region** to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{\text{Signal}} / \sigma_{\text{Control}}$

Extract measured cross section and compare to theory!
Control Regions

Event Selection and Analysis regions

Control Region to estimate the main background

Use BDT in the Signal Region to separate the signal from the background

Validation Region to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength \( \mu = \frac{\sigma_{\text{signal}}}{\sigma_{\text{SM}}} \)

Extract measured cross section and compare to theory!
Backgrounds in 2ℓSS/3ℓ Channel

- **Irreducible backgrounds:**
  - Leptons from W, Z or leptonic τ decays
    - $t\bar{t}W$ (37%), $t\bar{t}Z$ (17%), and $t\bar{t}H$ (14%)
    - Others (10%): Diboson, triboson, VH+jets, ttWW, tWZ, tZq
    - $ttt$ (1%)
  - Evaluated using MC normalised to SM cross sections, except $t\bar{t}W$ which is floating in the fit

- **Defined a dedicated Control Region for $t\bar{t}W$**
Backgrounds in 2ℓSS/3ℓ Channel

- The motivation to float the $t\bar{t}W$ background comes from:
  
  - the large $t\bar{t}W$+jets background normalisation factor found in recent measurements in a similar phase space $ttH(H\rightarrow\text{multi-leptons})$
  
  - the effect of missing electroweak corrections in the MC simulation

ATLAS-CONF-2019-045
Backgrounds in 2ℓSS/3ℓ Channel

- **Reducible backgrounds** (3 dedicated control regions):
  - **Charge mis-assignment (6%)** and relevant for the 2ℓSS channel
    - Charge of electron is mis-measured, caused by:
      - Bremsstrahlung photon emission followed by its conversion
      - Mis-measured track curvature

![ATLAS Detector diagram](image)

- **Charge Mis-assignment**
  - Bremsstrahlung
  - Mis-measured curvature

- **Beam Pipe**
  - ℓ+: prompt lepton from W
  - ℓ+: lepton from instrumental effect

- **Other distributions**
  - ttW
  - ttZ
  - ttH
  - Other
  - tt
  - Fake
  - Q misID

- **Breakdown**
  - ttW: 37%
  - ttZ: 15%
  - ttH: 14%
  - Other: 10%
  - tt: 1%
  - Fake: 6%
  - Q misID: 1%
Backgrounds in $2\ell SS/3\ell$ Channel

- Fake and non-prompt backgrounds (15%):
  - electrons from $\gamma$ conversion in detector
  - a virtual photon $\gamma^*$ leading to an $e^+e^-$ pair (Low $M_{ee}$)
  - electrons (muons) from heavy-flavour (HF) decay
Backgrounds in 2ℓSS/3ℓ Channel

- **Template Method** is used to determine the major backgrounds
  - Background shapes are estimated from MC
  - Normalisation is obtained from the fit
  - Fit is performed in 1 Signal Region 4 Control regions
    - Dedicated Control Regions are defined to constrain normalisation factors and the modeling is validated in the validation regions

Electron from Heavy Flavour

Muon from Heavy Flavour
• **Template Method** is used to determine the major backgrounds

- Background shapes are estimated from MC
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- Fit is performed in 1 Signal Region 4 Control regions

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**Low-mass $e^+e^-$**

**Material Conversion**

$\bar{t}tW$
Results of the Template Fit

The factors are compatible with unity except for $NF_{ttW}$ and $NF_{Material\ Conversion}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$NF_{ttW}$</th>
<th>$NF_{Mat.\ Conv.}$</th>
<th>$NF_{Low\ M_{ee}}$</th>
<th>$NF_{HF\ e}$</th>
<th>$NF_{HF\ \mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$1.6 \pm 0.3$</td>
<td>$1.6 \pm 0.5$</td>
<td>$0.9 \pm 0.4$</td>
<td>$0.8 \pm 0.4$</td>
<td>$1.0 \pm 0.4$</td>
</tr>
</tbody>
</table>

The high $NF_{ttW}$ is compatible with previous ATLAS $ttH(H\rightarrow$ multi-leptons) results and results from CMS.
2ℓSS/3ℓ Channel: $t\bar{t}W$ Validation Region

- Use Validation Region to check $t\bar{t}W$+jets normalisation and modeling

- **Additional jets**: Uncertainty of 125% is assigned to events with 7 jets and 300% is assigned to events with $\geq 8$ jets

- Based on Validation Region mismodeling

$t\bar{t}W$ Validation Region: $\geq 4$ jets $\geq 2$ b-tagged
Backgrounds in the 1\ell/2\ell\text{OS} Channel

- Dominated by background coming from $t\bar{t}$+jets; mainly $t\bar{t}$+$b\bar{b}$
- Small contribution from non-ttbar background:
  - Single-top, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$, V+jets, VV, $t\bar{t}WW$, ttt, tZ, and tWZ

\[ \begin{array}{c}
\text{8j,3bL} \\
\geq \text{8j,3bH} \\
\geq \text{8j,4b} \\
\geq \text{5b} \\
\geq 8j, 5b \\
\geq 9j, 5b \\
\geq 10j, 5b \\
\geq \text{5b} \\
\end{array} \]

\[ \begin{array}{c}
\text{Relative contribution} \\
1 \\
0.8 \\
0.6 \\
0.4 \\
0.2 \\
0 \\
\end{array} \]

\textbf{ATLAS Simulation} \\
$\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$

\[
\begin{align*}
\text{1L} & : t\bar{t}t \\
\text{ttf} & : t\bar{t}+\text{light} \\
\text{ttf+1c} & : t\bar{t}+3b \\
\text{ttf+bb} & : t\bar{t}+bb \\
\text{non-tt} & : t\bar{t}+b \\
\end{align*}
\]
Backgrounds in the 1ℓ/2ℓOS Channel

- $t\bar{t}$+jets is a challenging background to model
- Many additional jets are produced in the parton shower with limited precision
- Modelling of HF jets (b/c) is even more challenging

$\bar{t}t+b\bar{b}$ is underestimated by the current MC simulations
Events are categorized according to the number of jets and different b-tagging requirements.

- Both number of b-tags & their quality (Low or High)

Example from the 1l channel

<table>
<thead>
<tr>
<th>Number of b-tagged jets</th>
<th>Number of jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥5b</td>
<td>7j</td>
</tr>
<tr>
<td>4b</td>
<td>8j</td>
</tr>
<tr>
<td>3bV</td>
<td>9j</td>
</tr>
<tr>
<td>3bH</td>
<td>≥10j</td>
</tr>
<tr>
<td>3bL</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td></td>
</tr>
</tbody>
</table>
• Events are categorized according to the number of jets and different $b$-tagging requirements

• Both number of $b$-tags & their quality (Low or High)

### Example from the $1\ell/2\ell$OS Channel

<table>
<thead>
<tr>
<th>Name</th>
<th>$N_b^{60%}$</th>
<th>$N_b^{70%}$</th>
<th>$N_b^{85%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2b</td>
<td>-</td>
<td>= 2</td>
<td>-</td>
</tr>
<tr>
<td>3bL</td>
<td>$\leq 2$</td>
<td>= 3</td>
<td>-</td>
</tr>
<tr>
<td>3bH</td>
<td>= 3</td>
<td>= 3</td>
<td>= 3</td>
</tr>
<tr>
<td>3bV</td>
<td>= 3</td>
<td>= 3</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>$\geq 4b$ (2LOS)</td>
<td>-</td>
<td>$\geq 4$</td>
<td>-</td>
</tr>
<tr>
<td>4b (1L)</td>
<td>-</td>
<td>= 4</td>
<td>-</td>
</tr>
<tr>
<td>$\geq 5b$ (1L)</td>
<td>-</td>
<td>$\geq 5$</td>
<td>-</td>
</tr>
</tbody>
</table>

![Background model derivation regions](image-url)
• 12 **Signal** and **Control** regions will be used as input for the binned profile likelihood fit

• $H_T^{\text{all}}$ (lepton+jets activities) distributions are used in Control Regions
Events with 2-bjets are used to derive pre-fit corrections factors applied to the $t\bar{t}$+jets MC simulations.
1ℓ/2ℓOS Channel: $t\bar{t}$+jets Backgrounds

- MC known to mismodel the $t\bar{t}$+jets background at high-$H_T$ and high-b jet multiplicity (mostly noticeable in $N_{\text{jets}}$ and $H_T$)
- Developed techniques to tackle MC mismodeling in 2 b-tagged regions
- Derived rescaling factors at pre-fit level
- Designed a 3-step sequential re-weighting to target different type of mismodeling

$N_{\text{jet}} \rightarrow H_T^{\text{all}} \rightarrow \Delta R_{\text{avg}}^{\text{jets}}$
1ℓ/2ℓOS Channel: $t\bar{t}$+jets Backgrounds

- Better Data/MC agreement after correcting the $t\bar{t}$+jets background
**Signal Separation**

**Event Selection and Analysis regions**

- **Control Region** to estimate the main background
- **Use BDT in the Signal Region** to separate the signal from the background
- **Validation Region** to validate the model

\[
\begin{align*}
\bar{t}t + b\bar{b} \\
\bar{t}t + W
\end{align*}
\]

Perform a fit in the Control and Signal Regions to extract the signal strength
\[
\mu = \frac{\sigma_{\bar{t}t + \bar{t}t}}{\sigma_{SM}^{\bar{t}t + \bar{t}t}}
\]

Extract measured cross section and compare to theory!
Use of BDT in the Signal Region

- Signal is separated from background based on a multivariate discriminant built in the signal region by combining many **input observables** into a BDT:

- **Observables** are selected based on their **discrimination power** and the requirement of good modelling

- **b-tagging information**: **Sum of the pseudo-continuous b-tagging discriminant score**

- **Lepton and jet kinematics**

\[ \text{ATLAS Simulation} \quad \text{SR} \]

<table>
<thead>
<tr>
<th>Arbitrary units</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of b-tag scores</td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arbitrary units</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T(j_5) ) (GeV)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\[ \text{Sum of b-tag scores} + \quad p_T(j_5) + \ldots \]
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- Signal is separated from background based on a multivariate discriminant built in the signal region by combining many **input observables** into a BDT:

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- **Lepton and jet kinematics**

![Graphs and diagrams showing the use of BDT in the Signal Region](image)

\[
\text{Sum of b-tag scores} + p_T(j_5) + \ldots = \text{BDT score}
\]
Profile Likelihood Fit

Event Selection and Analysis regions

Control Region to estimate the main background

Use BDT in the Signal Region to separate the signal from the background

Validation Region to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \frac{\sigma_{\text{t\bar{t}t\bar{t}}}}{\sigma_{\text{SM}_{\text{t\bar{t}t\bar{t}}}}}$

Extract measured cross section and compare to theory!
Results: post-fit plots

- A simultaneous profile likelihood fit is performed in the Control Regions and Signal Regions
- The systematic uncertainties in both the signal and background predictions are included as nuisance parameters in the likelihood function
• The measured $t\bar{t}t\bar{t}$ signal strength is found to be:

$$\mu = 2.0^{+0.4}_{-0.4} (\text{stat}) \, +^{0.7}_{-0.5} (\text{syst}) = 2.0^{+0.8}_{-0.6}$$
The measured $t\bar{t}t\bar{t}$ signal strength is found to be:

$$\mu = \frac{\sigma_{t\bar{t}t\bar{t}}}{\sigma_{t\bar{t}t\bar{t}}^{SM}} = 2.0^{+0.4}_{-0.4}(\text{stat}) \times 0.7(\text{syst}) = 2.0^{+0.8}_{-0.6}$$

Cross section:

$$\sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(\text{stat}) \times 4(\text{syst}) \text{ fb} = 24^{+7}_{-6} \text{ fb}$$

Compared to the theoretical predication of $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2 \text{ fb}$
Results: 2ℓSS/3ℓ Channel

- The measured $t\bar{t}t\bar{t}$ signal strength is found to be:
  \[ \mu = \frac{\sigma_{t\bar{t}t\bar{t}}}{\sigma_{t\bar{t}t\bar{t}}^{SM}} = 2.0^{+0.4}_{-0.4}(\text{stat}) \, +^{0.7}_{-0.5}(\text{syst}) = 2.0^{+0.8}_{-0.6} \]

- Cross section:
  \[ \sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(\text{stat}) \, +^{5}_{-4}(\text{syst}) \, fb = 24^{+7}_{-6} \, fb \]

- Compared to the theoretical predication of $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2 \, fb$

\textbf{Strong 4.3σ (2.4σ expected) evidence!!!}
The measured $t\bar{t}t\bar{t}$ signal strength is found to be:
\[ \mu = \frac{\sigma_{t\bar{t}t\bar{t}}}{\sigma_{t\bar{t}t\bar{t}}^{SM}} = 2.0^{+0.4}_{-0.4}(stat) \cdot ^{+0.7}_{-0.5}(syst) = 2.0^{+0.8}_{-0.6} \]

Cross section:
\[ \sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(stat) \cdot ^{+5}_{-4}(syst) \text{ fb} = 24^{+7}_{-6} \text{ fb} \]

Compared to the theoretical predication of $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2 \text{ fb}$

Strong $4.3\sigma$ ($2.4\sigma$ expected) evidence

Consistent to $1.7\sigma$ with the Standard Model

Extensive tests were done to check the stability & consistency of the result
The dominant systematics uncertainties on the signal strength are:

- **Theoretical uncertainty on the signal**
- **Data statistics**
- **$t\bar{t}W$ modeling**
- **$ttt$ modeling**
- **Instrumental**
  - B-tagging and Jet Energy Scale
  - Non-prompt lepton normalisation and modelling

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal modelling</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$ cross section</td>
<td>+0.56</td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$ modelling</td>
<td>+0.15</td>
</tr>
<tr>
<td>Background modelling</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}W$ modelling</td>
<td>+0.26</td>
</tr>
<tr>
<td>$t\bar{t}t$ modelling</td>
<td>+0.10</td>
</tr>
<tr>
<td>Non-prompt leptons modeling</td>
<td>+0.05</td>
</tr>
<tr>
<td>$t\bar{t}H$ modelling</td>
<td>+0.04</td>
</tr>
<tr>
<td>$t\bar{t}Z$ modelling</td>
<td>+0.02</td>
</tr>
<tr>
<td>Charge misassignment</td>
<td>+0.01</td>
</tr>
<tr>
<td>Instrumental</td>
<td></td>
</tr>
<tr>
<td>Jet uncertainties</td>
<td>+0.12</td>
</tr>
<tr>
<td>Jet flavour tagging (light-jets)</td>
<td>+0.11</td>
</tr>
<tr>
<td>Simulation sample size</td>
<td>+0.06</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.05</td>
</tr>
<tr>
<td>Jet flavour tagging (b-jets)</td>
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<tr>
<td>Other experimental uncertainties</td>
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<tr>
<td>Jet flavour tagging (c-jets)</td>
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<tr>
<td>Total systematic uncertainty</td>
<td>+0.69</td>
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<tr>
<td>Statistical</td>
<td>+0.42</td>
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<tr>
<td>Non-prompt leptons normalisation(HF, material conversions)</td>
<td>+0.05</td>
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<tr>
<td>$t\bar{t}W$ normalisation</td>
<td>+0.04</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+0.82</td>
</tr>
</tbody>
</table>
Results: $1\ell/2\ell$OS Channel

- The measured $t\bar{t}t\bar{t}$ signal strength is found to be:
  \[ \mu = \frac{\sigma_{t\bar{t}t\bar{t}}}{\sigma_{t\bar{t}t\bar{t}}^{SM}} = 2.2^{+0.7}_{-0.7} \text{(stat.)} \pm 1.5 \text{(syst.)} = 2.2^{+1.6}_{-1.2} \]

- Cross section:
  \[ \sigma(t\bar{t}t\bar{t}) = 26 \pm 8 \text{(stat.)} \pm 15 \text{(syst.)} \text{ fb} = 26^{+17}_{-15} \text{ fb} \]

- Compared to the theoretical predication of
  \[ \sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4 \text{ fb} \]

- Observed (expected) significance: 1.9 (1.0) $\sigma$
The dominant systematics uncertainties are coming from the four-top signal and $t\bar{t}+\text{jets}$ background modelling uncertainties.

Substantial impact from JES uncertainties and from the $b$-tagging efficiencies on light jets.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]</th>
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</thead>
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<tr>
<td><strong>Signal Modelling</strong></td>
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<tr>
<td>$t\bar{t}t\bar{t}$ modelling</td>
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<tr>
<td><strong>Background Modelling</strong></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}+\geq 1b$ modelling</td>
<td>+8</td>
</tr>
<tr>
<td>$t\bar{t}+\geq 1c$ modelling</td>
<td>+5</td>
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<tr>
<td>$t\bar{t}$+jets reweighting</td>
<td>+4</td>
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<tr>
<td>Other background modelling</td>
<td>+4</td>
</tr>
<tr>
<td>$t\bar{t}$+light modelling</td>
<td>+2</td>
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<tr>
<td><strong>Experimental</strong></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+6</td>
</tr>
<tr>
<td>$b$-tagging efficiency and mis-tag rates</td>
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<tr>
<td>MC statistical uncertainties</td>
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<tr>
<td>Luminosity</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Other uncertainties</td>
<td>&lt; 1</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>+15</td>
</tr>
<tr>
<td><strong>Statistical uncertainty</strong></td>
<td>+8</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td>+17</td>
</tr>
</tbody>
</table>
Combination of 2ℓSS/3ℓ and 1ℓ/2ℓOS Channels

- The combined four-top cross-section:
  \[ \sigma(t\bar{t}t\bar{t}) = 25^{+7}_{-6} \text{ fb} \]

- To be compared to
  \[ \sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4 \text{ fb} \]

- Compatible with the SM prediction within 2.0 \( \sigma \)

- Observed (expected) significance: 4.7 (2.6) \( \sigma \)
Combination of 2ℓSS/3ℓ and 1ℓ/2ℓOS Channels

• The combined four-top cross-section:
  \[ \sigma(t\bar{t}t\bar{t}) = 25^{+7}_{-6}\ fb \]

• To be compared to
  \[ \sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4\ fb \]

• Compatible with the SM prediction within 2.0 \( \sigma \)

• Observed (expected) significance:
  \[ 4.7\ (2.6)\ \sigma \]

ATLAS finds further confirmation of evidence for four top-quark process
Results from CMS

- Similarly CMS published results for $2\ell SS/3\ell$ channel using the full run 2 data-set (Eur. Phys. J. C 80 (2020) 75)
  
- Used BDTs to separate signal from background

- Events split in many signal regions

- Observed (expected) significance: $2.6 \ (2.7) \ \sigma$

- Measured cross-section: $12.6^{+5.8}_{-5.2} \ \text{fb}$

Limits on top-Yukawa coupling

$$|y_t/y_t^{SM}| < 1.7$$

upper limit ranges from $[1.4, 2.0]$
Results from CMS

• Also published results for the 1\ell/2\ell OS Channel using 36 fb^{-1} of run 2 data-set (JHEP 11 (2019) 082)

• Events split in several categories for 1\ell and 2\ell OS
  
  • using (b-)jet multiplicity and different b-tagging working points
  
  • BDT discriminants in signal regions to separate signal from backgrounds
    
    • includes a BDT identifying 3-jets groups from hadronic top, N_{jets}, topology variables

• Observed (expected) significance: 0.0 (0.4) \sigma
Summary of ATLAS and CMS measurements

**ATLAS+CMS Preliminary**

LHCTopWG

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

\[ \sigma_{\text{Hf}} = 12.0_{-2.5}^{+2.2} \text{ (scale) fb} \]

JHEP 02 (2018) 031

NLO QCD+EW

---

**ATLAS, 2LSS/3L, 139 fb^{-1}**

EPJC 80 (2020) 1085

\[ 24_{-6}^{+7} \ (5_{-4}^{+5}) \text{ fb} \]

4.3 (2.4) $\sigma$

**ATLAS, 1L/2LOS, 139 fb^{-1}**

arXiv:2106.11683

\[ 26_{-15}^{+17} \ (8_{-13}^{+15}) \text{ fb} \]

1.9 (1.0) $\sigma$

**ATLAS, comb., 139 fb^{-1}**

arXiv:2106.11683

\[ 24_{-6}^{+7} \ (4_{-4}^{+5}) \text{ fb} \]

4.7 (2.6) $\sigma$

**CMS, 2LSS/3L, 137 fb^{-1}**

EPJC 80 (2020) 75

\[ 12.6_{-5.2}^{+5.8} \text{ fb} \]

2.6 (2.7) $\sigma$

**CMS, 1L/2LOS, 35.8 fb^{-1}**

JHEP 11 (2019) 082

\[ 0_{-0}^{+20} \text{ fb} \]

0.0 (0.4) $\sigma$
Search for heavy resonances in four-top-quark final state

ATLAS-CONF-2021-048
**Motivation**

- In many BSM theories, new “top-philic” vector resonances are predicted
  - Associated production $t\bar{t}Z'$ is then favored over $q\bar{q}$ annihilation
  - Decay of the resonance to $t\bar{t}$ leads to $t\bar{t}t\bar{t}$ final states
- Consider a color singlet vector particle ($Z'$) which dominantly couple to $t\bar{t}$

\[
\mathcal{L}_{int} = c_1 \gamma_\mu (\cos \theta P_L + \sin \theta P_R) tZ'^\mu
\]

$Z'$-top coupling  Chirality parameter

Free parameters:

- **Resonance mass**: $m_{Z'} = [1, 1.25, 1.5, 2.0, 2.5, 3.0]$ TeV
- **Coupling to top quarks**: $c_1 = 1$ (4% relative width)
- **Chirality parameter**: $\theta = \pi/4$ ($t\bar{t}Z'$ production insensitive to $\theta$)  
- Loop-induced production of the $Z'$ resonance is strongly suppressed
Reconstruction

- Focus on **1 lepton** channel using ATLAS 139 fb⁻¹ Run-2 data

- Strategy: Use reclustered large-R jets to reconstruct the resonance, targeting **fully hadronic decay**

- **Invariant mass** of the top candidates ($m_{JJ}$) is the main discriminant
Background Estimation

- Region definition based on number of **additional jets** ($N_{\text{add.-jets}}$) and number of **b-jets** ($N_{\text{b-jets}}$)

- Functional form fit to data $m_{JJ}$ distribution in source region, extrapolated to signal regions by ratios of fits to MC $m_{JJ}$ distributions
Results

• Good agreement between data and estimated background

• no significant **bumps detected**

• Limits set on simplified model as a function of $Z'$ mass

• Observed (expected) limits range from $65 \ (54) \ fb$ at 1 TeV to $12 \ (11) \ fb$ at 3 TeV
Outlook

- We’ve found exciting results using the full run 2 data-set

- A slight excess in the measured four-top cross section, but still compatible with the SM prediction within 2 $\sigma$

- Efforts have started to both improve upon the latest result
  - Run 3 will double our dataset, and could lead to discovery (5 $\sigma$) of the four-top process
  - Will greatly benefit from better modeling of $t\bar{t}W$ & $t\bar{t}bb$ processes, & from new techniques to better constrain these backgrounds

- Have started exploring Beyond-the-SM interpretations such as EFT or new resonances
SS $e\mu$
7 jets
4 b-jets
$H_T = 723 \text{ GeV}$

Thank you!
Beyond the tttt measurement back-up
Top-Higgs Yukawa Coupling

- Sensitive to top Yukawa coupling
- off-shell Higgs does not depend on the Higgs width/BR assumptions
- Sources of CP violation?

- The general top-quark Yukawa coupling is parameterized as following

\[ \mathcal{L}_{Htt} = - \frac{m_t}{v} H\bar{t}(a_t + i b_t \gamma_5) t \]

\[ \sigma_{(t\bar{t}t\bar{t})_{13}} \text{ TeV} = 9.998 - 1.522a_t^2 + 2.883b_t^2 + 1.173a_t^4 + 2.713a_t^2b_t^2 + 1.827b_t^4 \]
• Effective operators as higher dimensional terms

\[ \mathcal{L}_{EFT} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} \mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} \mathcal{O}_k^{(6)} + \ldots \]

• Dimension 6-operators that mainly contribute to tttt production

\[
\begin{align*}
\mathcal{O}_{tt}^1 &= (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma^\mu t_R) \\
\mathcal{O}_{QQ}^1 &= (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L) \\
\mathcal{O}_{tt}^2 &= (\bar{t}_R \gamma^\mu L)(\bar{Q}_L \gamma^\mu t_R) \\
\mathcal{O}_{QQ}^2 &= (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L) \\
\end{align*}
\]

• Also sensitive to heavy-light type operators

• Full set of 14 operators

\[
\begin{align*}
\mathcal{O}_{Qq}^{(8,3)} &= (\bar{Q}_L \gamma^\mu T^a \tau^i Q_L) (\bar{q}_L \gamma^\mu T^a \tau^i q_L) \\
\mathcal{O}_{Qq}^{(8,1)} &= (\bar{Q}_L \gamma^\mu T^a Q_L) (\bar{q}_L \gamma^\mu T^a q_L) \\
\mathcal{O}_{td}^{(8)} &= (\bar{t}_R \gamma^\mu T^a t_R) (\bar{d}_R \gamma^\mu T^a d_R) \\
\mathcal{O}_{tu}^{(8)} &= (\bar{t}_R \gamma^\mu T^a t_R) (\bar{u}_R \gamma^\mu T^a u_R) \\
\mathcal{O}_{tq}^{(8)} &= (\bar{t}_R \gamma^\mu T^a t_R) (\bar{q}_L \gamma^\mu T^a q_L) \\
\mathcal{O}_{Qd}^{(8)} &= (\bar{Q}_L \gamma^\mu T^a Q_L) (\bar{d}_R \gamma^\mu T^a d_R) \\
\mathcal{O}_{Qu}^{(8)} &= (\bar{Q}_L \gamma^\mu T^a Q_L) (\bar{u}_R \gamma^\mu T^a u_R) \\
\mathcal{O}_{Qq}^{(1,3)} &= (\bar{Q}_L \gamma^\mu T^a T^a \tau^i Q_L) (\bar{q}_L \gamma^\mu T^a T^a \tau^i q_L) \\
\mathcal{O}_{Qq}^{(1,1)} &= (\bar{Q}_L \gamma^\mu T^a Q_L) (\bar{q}_L \gamma^\mu T^a q_L) \\
\mathcal{O}_{Qd}^{(1)} &= (\bar{Q}_L \gamma^\mu Q_L) (\bar{d}_R \gamma^\mu d_R) \\
\mathcal{O}_{Qu}^{(1)} &= (\bar{Q}_L \gamma^\mu Q_L) (\bar{u}_R \gamma^\mu u_R) \\
\end{align*}
\]

EFT past results

• CMS has set limit on four major dimension-6 operators that mainly contribute to $t \bar{t} t \bar{t}$

• using 36 fb$^{-1}$ of run 2 data (arxiv.1906.02805)

• observed (expected) 95% CL upper limit on cross-section, 33 (20) fb

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected $C_k / \Lambda^2$ (TeV$^{-2}$)</th>
<th>Observed (TeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_{t t}^1$</td>
<td>$[-2.0, 1.9]$</td>
<td>$[-2.2, 2.1]$</td>
</tr>
<tr>
<td>$\mathcal{O}_{Q Q}^1$</td>
<td>$[-2.0, 1.9]$</td>
<td>$[-2.2, 2.0]$</td>
</tr>
<tr>
<td>$\mathcal{O}_{Q t}^1$</td>
<td>$[-3.4, 3.3]$</td>
<td>$[-3.7, 3.5]$</td>
</tr>
<tr>
<td>$\mathcal{O}_{Q t}^8$</td>
<td>$[-7.4, 6.3]$</td>
<td>$[-8.0, 6.8]$</td>
</tr>
</tbody>
</table>

• ATLAS set limit on the pure right-handed operator $\mathcal{O}_{t t}^1$ using 36 fb$^{-1}$ of run 2 data (JHEP12(2018)039)

• observed (expected) limit on Wilson coefficient $|C_{4t}| / \Lambda^2 < 1.9$ TeV$^{-2}$ (1.6 TeV$^{-2}$)
2ℓSS/3ℓ Channel back-up
### 2ℓSS/3ℓ Channel: Selection in the different regions

The variable $m_{ee}^{CV}$ ($m_{ee}^{PV}$) is defined as the invariant mass of the system formed by the track associated with the electron and the closest track at the conversion (primary) vertex. $N_j$ ($N_b$) indicates the jet ($b$-tagged jet) multiplicity in the event. $H_T$ is defined as the scalar sum of the transverse momenta of the isolated leptons and jets.

<table>
<thead>
<tr>
<th>Region</th>
<th>Channel</th>
<th>$N_j$</th>
<th>$N_b$</th>
<th>Other requirements</th>
<th>Fitted variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>2LSS/3L</td>
<td>$\geq 6$</td>
<td>$\geq 2$</td>
<td>$H_T &gt; 500$</td>
<td>BDT</td>
</tr>
<tr>
<td>CR Conv.</td>
<td>$e^\pm e^\pm</td>
<td></td>
<td>e^\pm \mu^\pm$</td>
<td>$4 \leq N_j &lt; 6$</td>
<td>$\geq 1$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$200 &lt; H_T &lt; 500 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>CR HF e</td>
<td>$eee</td>
<td></td>
<td>e\mu$</td>
<td>--</td>
<td>$= 1$</td>
</tr>
<tr>
<td>CR HF $\mu$</td>
<td>$e\mu \mu</td>
<td></td>
<td>\mu \mu \mu$</td>
<td>--</td>
<td>$= 1$</td>
</tr>
<tr>
<td>CR ttW</td>
<td>$e^\pm \mu^\pm</td>
<td></td>
<td>\mu^\pm \mu^\pm$</td>
<td>$\geq 4$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>For $N_b = 2$, $H_T &lt; 500 \text{ GeV}$ or $N_j &lt; 6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>For $N_b \geq 3$, $H_T &lt; 500 \text{ GeV}$</td>
<td></td>
</tr>
</tbody>
</table>
$2\ell SS/3\ell$ Channel: Background composition

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV} \]

- CR Conv.
- CR HF $\mu$
- CR HF e
- CR ttW
- SR
2\ell SS/3\ell Channel: Background composition

Charge Mis-identification

- Bremsstrahlung
- Mis-measured curvature

Non-prompt Leptons

- Material conversion
- Semi-leptonic b decay (HF)

\( \bar{t}t \)

ATLAS Detector

Beam Pipe

- \( \ell^+ \): prompt lepton from W
- \( \ell^+ \): lepton from instrumental effect
2\ell SS/3\ell Channel: pre-fit plots (input variables to the BDT)
$2\ell SS/3\ell$ Channel: post-fit plots (input variables to the BDT)
$2\ell SS/3\ell$ Channel: post-fit plots (input variables to the BDT)
2\ell SS/3\ell Channel: ttW Validation Region

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

Data: ttW
Others: Uncertainty

Post-Fit

Number of jets

BDT score

Data / Pred.

140
120
100
80
60
40
20
0

4 5 6 7 \( \geq 8 \)

160
140
120
100
80
60
40
20
0

-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
2\ellSS/3\ell Channel: SR pre-fit

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

SR
Pre-Fit

ATLAS

Data
\tt\tt\tt
\ttW
\ttZ
\ttH
Mat. Conv.
Mat. Conv.
Low m_{\gamma*}
Low m_{\gamma*}
HF e
HF e
HF \mu
HF \mu
Others
Others
\ttt
\ttt
Uncertainty

Events / 0.1

Data / Pred.

BDT score
$2\ellSS/3\ell$ Channel: $ttW$ pre-fit

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

CR $ttW$
Pre-Fit

Events / 20 GeV

Data
$t\bar{t}$
$t\bar{t}W$
$t\bar{t}H$
Mat. Conv.
Low $m_{\gamma\gamma}$
Others
Uncertainty

Data / Pred.

$\sum p_T [\text{GeV}]$
<table>
<thead>
<tr>
<th>$N_\ell$</th>
<th>$N_b$</th>
<th>$N_{jets}$</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>$\leq 5$</td>
<td>CRW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>SR1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>SR2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 8$</td>
<td>SR3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>SR4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>SR5</td>
</tr>
<tr>
<td></td>
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<td>7</td>
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<td>SR8</td>
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<td>$\geq 4$</td>
<td>2</td>
<td>5</td>
<td>SR9</td>
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<td>6</td>
<td>SR10</td>
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<td>SR11</td>
</tr>
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<td>$\geq 3$</td>
<td>4</td>
<td>SR12</td>
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<td>SR14</td>
</tr>
<tr>
<td></td>
<td>Inverted resonance veto</td>
<td></td>
<td>CRZ</td>
</tr>
</tbody>
</table>
1ℓ/1ℓOS Channel back-up
$t\bar{t}+b\bar{b}$ measurements from CMS

Figure 3: Comparison of the measured $t\bar{t}b\bar{b}$ production cross sections (vertical lines) with predictions from several Monte Carlo generators (squares), for three definitions of our $t\bar{t}b\bar{b}$ regions of phase space: fiducial parton-independent (left), fiducial parton-based (middle), total (right). The dark (light) shaded bands show the statistical (total) uncertainties in the measured value. Uncertainty intervals in the theoretical cross sections include the statistical uncertainty as well as the uncertainties in the PDFs and the $\mu_R$ and $\mu_F$ scales.
1ℓ/1ℓ OS Channel: Analysis Regions

The diagram illustrates different analysis regions based on the number of leptons (ℓ) and jets (j). The regions are categorized as:

- **Signal regions**: ≥4b
- **Validation regions**: 3bV
- **Control regions**: 3bH, 3bL
- **Background model derivation regions**: 2b

The regions are further divided into categories based on the number of jets:

- 5j
- 6j
- 7j
- ≥8j
$1\ell/1\ell\text{OS}$ Channel: Analysis Regions

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

2LOS

<table>
<thead>
<tr>
<th>Relative contribution</th>
<th>6j, 3bL</th>
<th>7j, 3bL</th>
<th>$\geq 8j$, 3bL</th>
<th>6j, 3bH</th>
<th>7j, 3bH</th>
<th>$\geq 8j$, 3bH</th>
<th>6j, 3bV</th>
<th>7j, 3bV</th>
<th>$\geq 8j$, 3bV</th>
<th>6j, $\geq 4b$</th>
<th>7j, $\geq 4b$</th>
<th>$\geq 8j$, $\geq 4b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>$t\bar{t}$ + light</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>$t\bar{t}$ + $\geq 1c$</td>
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</tr>
<tr>
<td>$t\bar{t}$ + b</td>
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<td>$t\bar{t}$ + B</td>
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<td>non-$t\bar{t}$</td>
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1\ell/1\ell OS Channel: Effect of the re-weighting

**ATLAS**

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

- **t\bar{t}+jets uncorrected**
  - 1L, \(\geq 8j, \geq 3b\)
- **t\bar{t}+jets corrected**
  - 1L, \(\geq 8j, \geq 3b\)

- **Data**
- **t\bar{t}t\bar{t}**
- **t\bar{t}+light**
- **t\bar{t}+\geq 1c**
- **t\bar{t}+\geq 1b**
- **non-t\bar{t}**
- **Uncertainty**
ATLAS
\(\sqrt{s} = 13\text{ TeV}, \ 139\text{ fb}^{-1}\)

1L,9j,3b
Pre-Fit

\begin{itemize}
\item Data
\item tttt
\item tt+light
\item t\bar{t}+\geq 1c
\item t\bar{t}+\geq 1b
\item non-t\bar{t}
\item Uncertainty
\end{itemize}

*: normalised to tot. bkg.

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

2LOS,7j,3b
Pre-Fit

\begin{itemize}
\item Data
\item tttt
\item tt+light
\item t\bar{t}+\geq 1c
\item t\bar{t}+\geq 1b
\item non-t\bar{t}
\item Uncertainty
\end{itemize}

*: normalised to tot. bkg.
$1\ell/1\ell OS$ Channel: pre-ft plots (input variables to the BDT)
1ℓ/1ℓOS Channel: Ranking of systematics

Pre-fit impact on \( \mu \):  
- \( \theta = \hat{\theta} + \Delta \theta \)  
- \( \theta = \hat{\theta} - \Delta \theta \)

Post-fit impact on \( \mu \):  
- \( \theta = \hat{\theta} + \Delta \hat{\theta} \)  
- \( \theta = \hat{\theta} - \Delta \hat{\theta} \)

- Nuis. Param. Pull

\( \Delta \mu \) vs. \( \frac{\theta - \theta_0}{\Delta \theta} \)

**ATLAS**

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

- t\bar{t}t\bar{t} cross section
- t\bar{t}t\bar{t} PS choice
- tfbb 5FS vs. 4FS
- tf+1c normalisation
- t\bar{t}t \( \mu_F \) and \( \mu_R \)
- b-tagging: light jets mis-tag rates E0
- ttbb generator choice shape
- tf+\geq3b normalisation
- tf+jets reweighting: non-t\bar{t} subtraction
- t\bar{t}f+\geq1c generator choice shape
- tf+\geq3b 5FS vs. 4FS
- t\bar{t}B normalisation
- JES modelling EV1
- JES pile-up \( \rho \)-topology
- t\bar{t}B 5FS vs. 4FS
- t\bar{f}+light generator choice migration
- JES flavour composition t\bar{t}t\bar{f}
- t\bar{t}H + jets cross section
- JES flavour response
- single-top-quark generator choice
BSM 4tops Search back-up
Benchmark Signal Model

- Consider a color singlet vector particle ($Z'$), with mass $\gg m_{\text{top}}$, leading to a narrow resonance: Probing TeV scale Top-Philic Resonances with Boosted Top-Tagging at the High Luminosity LHC
- Using a model independent approach and focus on a two body decay of $Z'$ into $t\bar{t}$ with $M_{Z'}$ in the TeV range
- Can produce top-philic resonances at tree-level and one-loop
- We focus on tree-level production such as: $t\bar{t} + Z'$, $tW + Z'$ and $tj + Z'$ with $Z' \rightarrow t\bar{t}$

![Diagram of $t\bar{t} + Z'$ production](image-url)
The largest contribution at the LHC comes from the four top-quark final state

- \( t\bar{t} + Z' \) production is smaller than \( t\bar{t} + Z' \) roughly by a factor of 2 while \( tW + Z' \) production is smaller by a factor 4

So far only considering \( t\bar{t} + Z' \)
BumpHunter Results

**ATLAS Preliminary**

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

Region 2a, 3b

Expected yield: 427 ± 18

Observed yield: 431

BumpHunter global p-value = 0.79

**ATLAS Preliminary**

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

Region 2a, 3b

Expected yield: 74 ± 6

Observed yield: 82

BumpHunter global p-value = 0.26

**ATLAS Preliminary**

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

Region 3a, 3b

Expected yield: 207 ± 16

Observed yield: 272

BumpHunter global p-value = 0.87

**ATLAS Preliminary**

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

Region 3a, 4b

Expected yield: 65 ± 5

Observed yield: 61

BumpHunter global p-value = 0.66
BumpHunter Results

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

Region \( \geq 4a, 3b \)

Expected yield: 297 \( \pm \) 26
Observed yield: 309

BumpHunter

\[ \text{global p-value} = 0.51 \]

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

Region \( \geq 4a, 4b \)

Expected yield: 82 \( \pm \) 7
Observed yield: 84

BumpHunter

\[ \text{global p-value} = 0.67 \]
## Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty categories</th>
<th>Relative contribution to the total uncertainty [%]</th>
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<tbody>
<tr>
<td></td>
<td>1.5 TeV</td>
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<td>$t\bar{t}$+jets modeling</td>
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<td>Signal bias</td>
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<td>Functional fit and extrapolation</td>
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<td>Jet energy scale and resolution</td>
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<td>Single-top-quark modeling</td>
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<td>Luminosity</td>
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<td><strong>Total systematic uncertainty</strong></td>
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<tr>
<td><strong>Statistical uncertainty</strong></td>
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