Top quark and heavy vector boson associated production at the ATLAS experiment
Modelling, measurements and effective field theory

Olga Bessidskaia Bylund

Academic dissertation for the Degree of Doctor of Philosophy in Physics at Stockholm University to be publicly defended on Thursday 2 November 2017 at 09.30 in sal FA32, AlbaNova universitetscentrum, Roslagstullsbacken 21.

Abstract
The Standard Model (SM) of particle physics describes the elementary particles that constitute matter and their interactions. The predictions of the SM have been confirmed by numerous experimental results. However, several questions of particle phenomena in the Universe remain unaddressed by the Standard Model, which suggests that the SM can be extended to a more complete theory. One approach to search for extensions of the SM is to test the predictions of the Standard Model in high precision measurements and see whether the results falsify the SM. For this reason, production of the $t\bar{t}Z$ and $tW$ processes at the ATLAS experiment at CERN is studied. It is investigated whether the SM gives correct predictions for these processes and how much room there is for contributions from new physics that give similar final states.

Three measurements of $t\bar{t}Z$ and $tW$ production are performed. The first measurement is performed at 8 TeV collision energy. The next measurement uses data collected in 2015 at 13 TeV collision energy, when the production cross sections for these processes are considerably larger. The third measurement uses ten times as much data at 13 TeV collision energy. This analysis is not public at the time of writing, so only preliminary results for the expected sensitivity are presented.

The new physics affecting $t\bar{t}Z$ production is parametrised in the model-independent framework of Effective Field Theory. Five effective operators that can affect $t\bar{t}Z$ production are studied and their coefficients are constrained in a fit to simulated data for the third measurement.

The major background process $tWZ$ is modelled at NLO in QCD. In order to avoid overlaps with $t\bar{t}Z$, the Diagram Removal (DR) method is employed in two versions: one where the quantum interference is neglected (DR1) and another where it is modelled (DR2). The differences between the two predictions are explored and enter the measurement as a modelling uncertainty.

Stockholm 2017
http://urn.kb.se/resolve?urn=urn:nbn:se:diva-147262

ISBN 978-91-7649-343-4
ISBN 978-91-7649-344-1

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Contents

1 Preface 5
   1.1 Introduction ................................... 5
   1.2 Structure of the thesis ........................... 5
   1.3 Contributions of the author ..................... 6

2 Theory 8
   2.1 The Standard Model and Quantum Field Theory .... 8
      2.1.1 Particle content of the Standard Model ....... 8
      2.1.2 S-matrix expansion .......................... 11
      2.1.3 Cross sections ............................... 13
      2.1.4 Renormalisability and gauge invariance ...... 15
      2.1.5 Structure of the Lagrangian .................. 16
      2.1.6 QED ........................................ 17
      2.1.7 QCD ........................................ 18
      2.1.8 Weak interactions ............................ 20
      2.1.9 Electroweak interactions ........................ 22
      2.1.10 Electroweak symmetry breaking ............... 22
   2.2 Tests of the Standard Model ..................... 23
   2.3 Questions not answered by the Standard Model ..... 24
   2.4 Motivation for \( t\overline{t}V \) searches ............. 25
   2.5 The treatment of the \( Wt \) and \( tWZ \) processes with Diagram Removal ......................... 26
   2.6 Effective Field Theory ............................ 28

3 Experimental setup 32
   3.1 The Large Hadron Collider ....................... 32
   3.2 The ATLAS experiment ............................. 33
      3.2.1 Inner Detector ................................ 34
      3.2.2 Liquid Argon Calorimeter .................... 36
      3.2.3 The Tile Calorimeter .......................... 37
      3.2.4 Muon system .................................. 39
      3.2.5 Magnet system ............................... 41
      3.2.6 Trigger system ................................ 41

4 Measurements of the \( t\overline{t}V \) production cross sections 43
   4.1 Object definitions ............................... 44
      4.1.1 Jets ........................................ 44
      4.1.2 Electrons .................................... 45
      4.1.3 Muons ........................................ 46
      4.1.4 B-jets ....................................... 46
      4.1.5 Missing \( E_T \) ................................ 47
      4.1.6 Overlap removal ................................ 47
Acknowledgements

I would like to thank my supervisor Jörgen Sjölin for helping me choose the subject and to find my niches in the field, which have been more to the phenomenological side. I am grateful to my co-supervisor Sten Hellman and my team leader David Milstead for their feedback and support in the writing of this thesis. I am happy to be part of a supportive and positive group in Stockholm. Katarina in particular has been a rock. Many thanks to the colleagues and friends who helped proof read sections of my thesis.

All the publications that this thesis is based on are the result of collaborative work. In this thesis I highlight my contributions while also giving the overall context and results. Below, I acknowledge the contribution of my collaborators in the cases where we were working on closely related subjects.

Hovhannes Khandanyan (Stockholm) developed the software and defined the signal regions of the trilepton channel that were used for the $t\bar{t}V$ analysis I. I evaluated the systematic uncertainty on the $WZ$ background for analysis I together with Kerim Suruliz (Sussex) and Jörgen Sjölin. Kerim provided the simulations in SHERPA, which I used to compute transfer factors and the largest extrapolation uncertainties for the $WZ$ process for analysis I.

For the $t\bar{t}V$ analyses II and III, the $WZ$ extrapolation uncertainties were evaluated by Kerim; I cite these results for completeness. The fake rates for analysis II and III were derived by Jörgen Sjölin. I was involved in the validation of the fake rates for analysis III.

The final results for the $t\bar{t}V$ analyses that are shown in this thesis were obtained by Tamara Vasquez Schroeder in analysis I and by Maria Moreno Llacer (CERN) for analysis II. Maria also redefined the regions in the same sign dilepton channel for analysis III, which gave us a higher expected sensitivity for the $t\bar{t}W$ measurement.

The fake factors used to scale the $\gamma + X$ background for analysis III were derived by Alexandra Schulte (Mainz).

I would like to thank Kerim for demonstrating the functionality of the software for analysis III, which allowed me to design the fit for the EFT coefficients in a nice way. Many thanks to Karl Gellerstedt (Stockholm) for dressing the $t\bar{t}l^+l^-$ EFT samples so that I could derive the parameters for the EFT fit for analysis III in regions that closely resemble the signal regions of our analysis.

I am grateful to Fabio Maltoni (UCLouvain) who welcomed me to his team and to the MCnet studentship program, which allowed me to spend three and a half months in Belgium, learning about Effective Field Theory and the Diagram Removal methods. For the EFT phenomenological analysis that I performed when I was based in Louvain, I worked together with Ioannis Tsinikos on simulating the $tt\mu^+\mu^-$ process. We discussed the strategy together with my supervisor for the time Fabio Maltoni and collaborators Eleni Vryonidou and Cen Zhang. Cen had provided the code describing
the top quark interactions in the framework of Effective Field Theory and patiently answered my questions that arose while I was working on he EFT fit for analysis III. I learned the Diagram Removal 2 method from Federico Demartin (UCLouvain) and had many discussions with him.

On a more personal level, I would like to thank Ioannis for being my gym buddy and Joze for cooking for me while I was in Belgium, you made my stay more enjoyable.

Thank you to my figure skating coach Susanne and skating friends Natasja and Camilla for the mental training and a great summer.

Thank you to Henrik Åkerstedt for the photos with the ATLAS detectors and for many memorable adventures.

I am very grateful for my big loving family and happy to have great friends. Thank you for helping me through the tougher periods and for lifting me up higher in good times. An extra high five goes to Ea, Mike, Lotta, Mariana, Surre, Tomas K. and Stefan. To my husband Tomas, you have been incredible.
1 Preface

1.1 Introduction

The Standard Model (SM) of particle physics [1], [2] describes our best understanding of particle physics at present. The predictions of the Standard Model have been confirmed by the discoveries of the particles it predicts and by measuring their interactions. Some notable examples of this are the confirmation of electroweak unification by the discoveries of the W and Z bosons 1982 and 1983 [3] and the discovery of the sixth and heaviest quark, namely the top quark, by the CDF and D0 experiments at the Tevatron in 1995 [4].

In order to produce the heaviest particles of the SM and to study their properties, large energies are required. For this purpose, proton beams are accelerated to close to the speed of light inside the Large Hadron Collider (LHC) [5] and brought to collide at the centre of the ATLAS experiment [6]. The protons scatter against each other, creating new particles, which are registered in the ATLAS detector and then the collision events are analysed.

In this thesis, the physics of top quarks is explored. The LHC acts as a top quark factory, producing millions of top quark pairs each year. The main focus of this thesis is on the production of top quark pairs in association with a vector boson (Z or W) at the ATLAS experiment. In order to model an important background to $t\bar{t}Z$, namely single top associated $tWZ$ production, at next-to-leading order in QCD, the resulting overlap with other processes needs to be removed. Two varieties of the Diagram Removal method are used for this purpose. The Standard Model hypothesis for $t\bar{t}Z$ and $t\bar{t}W$ production is tested against data.

The scenario where $t\bar{t}Z$ production is affected by the presence of new physics is also explored, using the Effective Field Theory (EFT) approach [7], [8], [9]. Effective Field Theory is a model-independent framework that parametrises the new physics in terms of different operators that give rise to various of interactions of the SM particles. No particles beyond the SM are assumed to be produced at the energies accessible at the LHC. Instead, the interactions of known particles are assumed to be modified by the effective operators. The coupling constants for the effective operators are constrained using the expected sensitivity of a measurement of $t\bar{t}Z$ production performed by ATLAS.

1.2 Structure of the thesis

This thesis is structured as follows. Section 2 gives a theoretical background for the work presented in this thesis, covering the Standard Model, the Diagram Removal methods and Effective Field Theory. In Sec. 3, an overview of the experimental apparatus is given, with the Large Hadron Collider and the
ATLAS experiment described. It should be noted that this section overlaps considerably with the licentiate thesis in Ref. [10].

Three measurements of $t\bar{t}Z$ and $t\bar{t}W$ production at ATLAS are presented in Sec 4. The first measurement [11], referred to as analysis I, was performed on data from collisions with a center of mass energy of 8 TeV. In analysis II the measurement was carried out at a higher collision energy of 13 TeV, at an integrated luminosity of 3.2 fb$^{-1}$ [12]. The measurement of $t\bar{t}Z$ and $t\bar{t}W$ production was then extended for analysis III, adding the 2016 dataset to give a total of 36 fb$^{-1}$. This analysis is not yet public, at the time of writing, instead the currently expected results are quoted. At the start of Sec. 4, an overview is given of the strategy and the physics objects that the three analyses have in common. Here Sec. 4.1 intersects with the licentiate thesis, Ref. [10]. After a common description, the specific methods and results for each analysis are presented in Secs. 4.6-4.8.

In the modelling of the $t\bar{t}Z$ signal, the $Z$ boson is required to decay into two charged leptons. The contribution and interference of an off-shell photon $t\bar{t}\gamma^*$ giving rise to the same final state is taken into account by specifying $t\bar{t}l^+l^-$ in the simulation (without specifying requirements on the intermediate boson). In the last chapter, Sec. 5, distributions in $t\bar{t}l^+l^-$ in the presence of effective operators are shown. Fits for the coefficients are performed to data. First a toy global fit is done, using several measurements at once to fit several coefficients, while making broad assumptions about the correlations between the uncertainties, as is described in Sec. 5.2. Next, in Sec. 5.4, fits to one coefficient at a time are performed, using the framework for analysis III.

1.3 Contributions of the author

My contributions to the different projects are summarised below.

For analysis I, my focus was on trilepton channel, targeting $t\bar{t}Z$ and $t\bar{t}W$ production; this is the most sensitive channel for $t\bar{t}Z$. I studied the fake lepton background and the $WZ$ background for this channel and maintained and synchronised our software to the other groups within ATLAS and, at a later stage, with CMS. The treatment of fake leptons is described in detail in my licentiate thesis [10] and only mentioned briefly here. For $WZ$ production, the central value is measured in a dedicated control region. The uncertainty from the measurement is referred to as the normalisation uncertainty. Additionally, extrapolating the $WZ$ production from the control region into the signal regions is associated with systematic uncertainties. I evaluated the normalisation uncertainty and used one of the two alternative methods to evaluate the extrapolation uncertainties for analysis I.

The central value and normalisation uncertainty for the $WZ$ production cross section were determined with the same method in analyses II and III, with some minor modifications to the definition of the relevant control
region. Additionally, for both of these analyses, I provided the prediction and modelling uncertainty for the $tWZ$ background. I simulated this process at next-to-leading order in QCD using the Diagram Removal 1 method and assessed the uncertainty by comparing inclusively with the Diagram Removal 2 prediction. Using the DR1 prediction resulted in a 20% lower predicted yield for the background process $tWZ$ than one would obtain at LO (as was done in analysis I). By studying the DR1 and DR2 predictions for $tWZ$ it became apparent that this process was not well understood, which served as an argument against lowering the assigned systematic uncertainty on $tWZ$ for analyses II and III. The Diagram Removal methods applied to $tWZ$ as well as $Wt$ were presented in Ref. [13] and summarised in the conference proceedings [14] for the International Top Workshop 2016. For the work described in Ref. [13], I was responsible for the chapter on Diagram Removal. I also generated DR1 and DR2 simulations of $Wt$ production for ATLAS in MG5\_aMC@NLO.

For analysis III, I worked on the same sign and trilepton channels and for six months of the analysis, I was one of the two main editors of the internal documentation and combined the results from the different channels. Moreover, I provided $tt\bar{t}l^+l^-$ predictions, modified by five different effective operators and performed a fit for the coefficients. The effects of the operators on various top quark physics processes was presented in Ref. [15]. My contribution to this paper was discussing the strategy, giving the experimental perspective, simulating the $tt\bar{t}l^+l^-$ process and looking into many distributions for this process. I also performed a fit, constraining all relevant coefficients at the same time (using some simplified assumptions) to measurements performed at the LHC (by 2015), but this was not included in the paper; this work is described in Sec. 5.2.

In addition to this, as part my PhD programme, I studied the electronic noise in the Tile Calorimeter. This work is described in Ref. [10] and is not repeated here. I also spent one month in 2013 replacing power supplies and doing consolidation work for the Tile Calorimeter.
2 Theory

In this chapter, the Standard Model (SM) is described in Sec. 2.1. Successful tests of the SM are mentioned in Sec. 2.2. Problems with the Standard Model are highlighted in Sec. 2.3 and the measurements of $t\bar{t}Z$ and $t\bar{t}W$ production are motivated in Sec. 2.4. The Diagram Removal methods are introduced in Sec. 2.5 and in Sec. 2.6, the effective operators of interest for $t\bar{t}l^+l^-$ production are shown.

2.1 The Standard Model and Quantum Field Theory

The Standard Model of particle physics [1], [2] describes the particle content of the universe and the interactions of the particles. It is a theory of quantum mechanical fields $\phi_i(x)$, with particles described as the quanta of the fields. The energy density of the system is given by the Lagrangian density $L(x)$, which is a function of different fields $\phi_i(x)$ and their derivatives $\partial_\mu \phi_i(x)$. Integrating the Lagrangian density over the space coordinates $d^4x$ gives the Lagrangian. The Lagrangian density consists of a free field part $L_0(x)$, which includes a kinetic and a potential term, and an interaction part $L_I(x)$, which describes interactions of different kinds of fields.

In this thesis, charges are given in units of the elementary charge (the magnitude of the charge of the electron) and natural units are employed, where $c = \hbar = 1$. In natural units, the dimensions of mass $m$ and energy $E$ are the same and equal to the dimension of length $L$ inverted $[m] = [E] = [L]^{-1}$. The action, from which the interactions of the particles can be derived, is given by:

$$S = \int d^4x \mathcal{L}(x),$$

which is dimensionless. The SM Lagrangian density has mass dimension 4.

2.1.1 Particle content of the Standard Model

Elementary particles can be grouped by their spin number. Spin 0 particles are described by scalar fields; the Higgs boson is the only elementary particle with spin 0 in the Standard Model. The presence of a scalar field allows the generation of mass for elementary particles through the Brout-Englert-Higgs mechanism [16], [17]. Particles with spin 1/2 are called fermions. Fermions obey the Pauli exclusion principle and follow Fermi-Dirac statistics [18], [19]. According to the Pauli exclusion principle, two identical fermions at the same location cannot occupy the same quantum mechanical state, which explains the structure of atomic orbitals which determines the chemical properties of the elements. The elementary fermions are grouped into leptons and quarks. Vector fields correspond to bosons of spin 1, namely $Z$ and $W$ bosons, which
mediate the weak force, photons $\gamma$ that mediate the electromagnetic force and gluons $g$ that bring about strong interactions. Contrary to fermions, particles with integer spin, known as bosons, can be in the same quantum mechanical state and they follow Bose-Einstein statistics [20].

The SM particles are listed in Table 1. The fermions are ordered in three generations by mass, with the third generation holding the most massive particles. For atomic physics, only the first generation of quarks and leptons is relevant, with the up and down quarks constituting the protons and neutrons in the nucleus, and with electrons orbiting the nucleus.

There are six types, or flavours, of quarks: up, down, charm, strange, top and bottom. The three up-type quarks (u, c, t) have charge +2/3 while the three down-type quarks (d, s, b) have charge -1/3. Quarks can interact by the strong, electromagnetic and weak forces. They do not exist in isolation, but form bound states called hadrons, such as protons and neutrons.

Charged leptons interact electromagnetically and weakly and their couplings to the bosons that mediate these interactions are the same – this is referred to as lepton universality. Each charged lepton also has an associated neutrino, which has no electric charge and only interact weakly via Z or W bosons. While neutrinos also are leptons, for the purposes of this work, the term is reserved for charged leptons: electrons, muons and tau leptons.

Table 1: The particle content of the Standard Model. The value to the bottom left specifies the charge and the number to the bottom right gives the mass of the particle in units of [GeV]. The values are obtained from Ref. [21].
### Table 2

<table>
<thead>
<tr>
<th>Particle</th>
<th>Spin</th>
<th>Charge $[e]$</th>
<th>Mass [GeV]</th>
<th>Decay modes</th>
<th>Br [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top quark</td>
<td>1/2</td>
<td>±2/3</td>
<td>173.1 ± 0.6</td>
<td>$t \rightarrow Wb$</td>
<td>~100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t \rightarrow WbZ$</td>
<td>$2 \cdot 10^{-4}$ [22]</td>
</tr>
<tr>
<td>$Z$ boson</td>
<td>1</td>
<td>0</td>
<td>91.1876 ± 0.0021</td>
<td>$Z \rightarrow l^+l^-$</td>
<td>3.3658 ± 0.0023</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Z \rightarrow q\bar{q}$</td>
<td>69.91 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Z \rightarrow \nu\bar{\nu}$</td>
<td>20.00 ± 0.06</td>
</tr>
<tr>
<td>$W$ boson</td>
<td>1</td>
<td>±1</td>
<td>80.385 ± 0.015</td>
<td>$W \rightarrow q\bar{q}$</td>
<td>67.41 ± 0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$W^+ \rightarrow l^+\nu$</td>
<td>10.86 ± 0.09</td>
</tr>
</tbody>
</table>

Table 2: The basic properties of top quarks, $Z$ bosons and $W$ bosons. The values are obtained from Ref. [21], unless stated otherwise. The top quark mass listed here is obtained from direct measurements. In the analyses presented in the work, a central value of 172.5 GeV for the top quark mass was used. The leptonic decay modes for the $W$ and $Z$ boson are given as an average over the three lepton flavours. Br stands for branching ratio, the fraction of decays that occur via the mode in question.

Each particle also has an anti-particle with the same properties, except that the charge has an opposite sign. For example, positrons have the same properties as electrons, except that electrons have charge -1 while positrons have charge +1. The anti-particle to the top quark, which has a charge of 2/3, is the anti-top quark with charge -2/3. The anti-particle to the $W^-$ boson is the $W^+$ boson. A neutral particle can be its own anti-particle, which is the case for e.g. $Z$ bosons and photons. For the purpose of this work, the name of a particle can refer also to its anti-particle, e.g. “electron” also refers to positrons and “top quarks” also refers to anti-top quarks.

Some basic properties for the particles that are the main object of study in this thesis (top, $Z$ and $W$) are given in Table 2. These are among the heaviest particles of the Standard Model; they have a mean lifetime of a few times $10^{-25}$ s and so decay at the proton-proton interaction point. The Feynman diagrams with the most relevant decay channels for these particles are shown in Fig. 1. The leptonic decay mode of $Z$ gives a distinct signature in the ATLAS detector. This is the mode targeted in the $t\bar{t}Z$ analyses. The leptonic and hadronic decay modes of $W$ are also shown. The most common decay mode for the top quark, which is into a $W$ boson and a $b$ quark, is illustrated.

In the $t\bar{t}Z$ and $t\bar{t}W$ analyses, the signal regions are split into different channels by lepton multiplicity. In practice, the decay modes of the $W$ bosons, including those produced from top quark decays, determine the number of real leptons in the signal. Leptonic decays of the $Z$ boson in $t\bar{t}Z$ associated production is targeted.
Figure 1: The top left diagram shows the most common decay mode of the top quark: into a $W$ boson and a $b$ quark. The top right diagram shows the leptonic decay mode of the $Z$ boson. The leptonic decay mode of a $W^-$ boson is shown on the bottom left. The hadronic decay channel of a $W^+$ boson is shown on the bottom right, the resulting quarks form hadrons.

2.1.2 S-matrix expansion

In order to describe the interactions of the SM particles, one needs to expand the $S$-matrix from the relevant interaction part of the Lagrangian and then compute the scattering amplitudes. The expansion needs to be performed iteratively, with each new term having an additional interaction vertex present. The first two terms (or orders) of the expansion have the following form:

$$S^{(1)} = i \int T(L_I(x))dx,$$

$$S^{(2)} = \frac{i^2}{2!} \int T(L_I(x_1)L_I(x_2))dx_1dx_2.$$

Here $T$ denotes time ordering, and $x$ is the space-time coordinate for the interaction vertex. For the second order term, there are two such coordinates $x_1$ and $x_2$. An example of a first order $S^{(1)}$ interaction and of a second order interaction $S^{(2)}$ in Quantum Electrodynamics (QED) are shown in Fig. 2.

From the terms in the expansion, the matrix element $S_{fi} = \langle f | S^{(i)} | i \rangle$ can be computed, where $|i\rangle$ is the initial state, $|f\rangle$ is the final state and $S^{(i)}$ is a term of order $i$ from the interaction part of the Lagrangian that can mediate the transition from $|i\rangle$ to $|f\rangle$. From $S_{fi}$, the scattering amplitude
\[ \mathcal{M} \] can be found. In order to compute the probability for an interaction to occur, \(|\mathcal{M}|^2\) needs to be computed, as described in Sec. 2.1.3.

By Wick’s theorem \[23\], one can express a time ordered product of fields as the sum all possible normal ordered terms, containing the allowed contractions over the fields. For example, the time ordered product of the four fields \(A, B, C\) and \(D\) can be rewritten as below.

\[
T(ABC) = N(ABC) + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD} + \overbrace{ABCD}
\]

A contraction over the \(A\) and \(B\) fields is denoted \(AB\). The number of uncontracted fields gives the number of external particles (which can be either in the initial or the final state). A contraction over two fields corresponds to a propagator - the exchange of an intermediate virtual particle. Only fields that are of the same kind can be contracted. While real (or on-shell) particles fulfill the energy-momentum relation:

\[
p_\mu p^\mu = E^2 - |p|^2 = m^2,
\]

this relation does not hold for virtual particles, which are said to be off-shell. Such particles are usually denoted with a star, e.g. \(\gamma^*\) for off-shell photons.

There is an infinite number of orders in the S-matrix expansion. Each interaction vertex contains a coupling constant \(\alpha\) for the interaction. If \(\alpha \ll 1\), terms corresponding to higher orders of the interaction will be suppressed. Therefore, for a well behaved perturbative theory, the lowest orders dominate and the higher orders form smaller corrections.

Including only the simplest form of diagrams that allow a specific process to occur is referred to as Leading Order (LO) calculations. Allowing
one additional Quantum Chromodynamical (QCD) vertex to be present is referred to as next-to-leading order (NLO) in QCD: this includes the contribution from the emission of one additional quark or gluon, or an internal QCD loop.

Often, the same final state can be obtained by different production mechanisms. For example, from an initial state containing a quark, a lepton pair of opposite sign charge \((l^+l^-)\) can be produced, mediated by either an intermediate \(Z\) boson or an off-shell photon \(\gamma^*\). The scattering amplitude will then contain both terms corresponding to the \(Z\) channel and the \(\gamma^*\) channel. When evaluating the cross section, the modulus of the amplitude is squared. The cross terms between the \(Z\) and \(\gamma^*\) terms describe the quantum interference. Some methods to include the quantum interference relevant for top quark physics are described in Sec. 2.5.

2.1.3 Cross sections

The differential cross section for the scattering of two particles, denoted by index 1 and 2, is given by:

\[
d\sigma = \frac{1}{(2E_1)(2E_2)|\mathbf{v}_1 - \mathbf{v}_2|} |M|^2 d\Pi_{\text{LIPS}}
\]

(5)

with \(E\) being the energies of the particles, \(v\) the velocities, \(M\) the Feynman amplitude and

\[
d\Pi_{\text{LIPS}} = \prod_{\text{final states } j} \frac{d^3p_j}{(2\pi)^3} \frac{1}{2E_{pj}} \frac{1}{(2\pi)^4} \delta^4(\sum p)
\]

(6)

being the Lorentz-invariant phase space. The \(\delta\)-function in \(d\Pi_{\text{LIPS}}\) ensures the conservation of energy and momentum between the final and initial states. Integrating over phase space gives the inclusive cross section \(\sigma\).

For experimental purposes, event generations, such as for example \(\text{MG5}_\text{aMC@NLO} [24]\), are employed to simulate the scattering of quarks or gluons in the proton-proton collisions.

While cross section serves as a measure of probability for an interaction, it is given in dimensions of area, expressed in units of picobarn (pb) or femtobarn (fb) for the processes considered here. One barn equals \(10^{-28}\) cm\(^2\). The cross section is related to the rate \(R\) for an interaction by

\[
R = \frac{dN}{dt},
\]

(7)

with \(N\) being the number of interactions:

\[
N = \sigma \int L dt.
\]

(8)
Here $L$ is the instantaneous luminosity and $\int L dt$ is referred to as the integrated luminosity, which is given in units of $\text{fb}^{-1}$ and serves as a measure of the amount of interactions in the collider experiment. For a collider accelerator, the instantaneous luminosity is obtained as:

$$L = \frac{n_b f N^2}{4\pi \sigma_x \sigma_y}, \quad \text{(9)}$$

with $f$ being the frequency for the bunch crossing, $N$ the number of particles in each bunch, $n_b$ the number of bunches that are brought to collide from each direction, and $\sigma_x$ and $\sigma_y$ give the size of the beams in the transverse plane.

For the observed number of interactions, Eq. 8 the expression is modified by a factor for the acceptance $A$:

$$N_{\text{obs}} = A \sigma L, \quad \text{(10)}$$

which includes both geometrical detector effects and efficiencies from reconstruction of the physics objects.

The decay rate $\Gamma$, describing the rate of transition of a single particle into a state of two or more particles, is given by:

$$\Gamma = \frac{1}{2E_1} |\mathcal{M}|^2 d\Pi_{\text{LIPS}}. \quad \text{(11)}$$

The total decay rate is related to the lifetime of a particle $\tau$ as

$$\Gamma = \frac{1}{\tau}. \quad \text{(12)}$$

The probability of a particle to decay into a particular final state, or decay mode, is called the branching ratio.

The heaviest particles in the SM, such as top quarks, $Z$ and $W$ bosons are unstable and decay into lighter particles before reaching the detector. The energy-momentum conservation is employed to define the invariant mass:

$$m = \sqrt{\left(\sum_f E_f\right)^2 - \left|\sum_f p_f\right|^2}, \quad \text{(13)}$$

where the sum is over the particles in the final state. The invariant mass is a conserved quantity that is useful for searching or selecting for heavy particles. If the heavy mother particle was produced on-shell, the invariant mass of the daughter particles should be equal to the mass of the mother particle. This can be observed as a peak at the mass of the $Z$ boson in the invariant mass spectrum of a lepton pair of the same flavour and opposite sign.
2.1.4 Renormalisability and gauge invariance

Quantum field theory is required to be local, renormalisable and gauge invariant.

Locality is imposed in order to ensure causality by expressing the Lagrangian density as a function of just one point in space-time: \( x \). This implies that particle interactions are described by point interactions and propagators between the different coordinates \( x_i \).

A theory is renormalisable if it can be described by a finite set of parameters and that any divergences present cancel to give a finite prediction. Examples of divergences are ultraviolet divergences, appearing in loop diagrams at high energies, and infrared divergences, appearing in collinear emissions of quarks or gluons. These are treated with renormalisation and factorisation procedures, as described briefly in Sec. 2.1.7.

Gauge invariance means that if a field undergoes a transformation, e.g.

\[
\phi(x) \rightarrow e^{-i\alpha(x)}\phi(x),
\]

the Lagrangian retains the original form. Introducing an interaction term \( \mathcal{L}_I(x) \) between the complex field \( \phi(x) \) and \( A_\mu(x) \), e.g. of the form

\[
\phi(x)A_\mu(x)\partial_\mu\phi(x)
\]

results in an expression that is not invariant. If \( A_\mu \) undergoes a local gauge transformation, e.g.

\[
A_\mu(x) \rightarrow A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x),
\]

(\( e \) being a coupling constant), an additional degree of freedom is added to the interaction Lagrangian. In order to ensure gauge invariance of the interaction term and preserve the number of degrees of freedom, \( \phi \) is required to transform as

\[
\phi(x) \rightarrow e^{-ie\alpha(x)}\phi(x).
\]

This also ensures gauge invariance of the mass term, which is of the form \( m^2\phi^\dagger(x)\phi(x) \). However, the kinetic term, of form \( |\partial_\mu\phi(x)|^2 \), is not gauge invariant. To amend this, the partial derivative \( \partial_\mu\phi(x) \) is replaced by the covariant derivative \( D_\mu\phi(x) \):

\[
D_\mu\phi(x) = (\partial_\mu + ieA_\mu(x))\phi(x).
\]

This expression transforms as

\[
e^{-i\alpha(x)}D_\mu\phi(x)
\]

and hence \( D_\mu\phi(x)D^{\mu}\phi(x) \) becomes gauge invariant – the desired interaction term is thus embedded in the kinetic term.
2.1.5 Structure of the Lagrangian

The Lagrangian consists of the following four parts: the gauge part that contain the field strength tensors for the vector fields, the fermionic part is described in Sec. 2.1.6 for electromagnetic interactions, Sec. 2.1.7 for strong interactions and in Sec. 2.1.8 for weak interactions. A description of the unification of the electromagnetic and weak forces into an electroweak theory can be found in Ref. 2.1.9. The Higgs sector of the Lagrangian are described in Sec. 2.1.10. The gauge and Yukawa parts are below.

The Yukawa part of the Lagrangian provides mass terms for the quarks and the charged leptons, with higher values of Yukawa couplings corresponding to a higher mass for the fermion. The top quark is the heaviest elementary particle and has a Yukawa coupling with a magnitude near one.

The interactions in the Standard Model are described by different Lie algebras corresponding to Lie groups. Strong interactions are described by the SU(3) group. The electroweak interactions are described by SU(2)xU(1)Y, where Y denotes hypercharge.

According to Noether’s theorem [25], a symmetry of the Lagrangian corresponds to a conserved current and to a conserved quantity. For example, the conservation of electric charge can be described as invariance under local U(1) transformations $\phi(x) \to e^{i\alpha} \phi(x)$.

In SU(n) theory, the number of generators of the group is given by $n^2 - 1$. The number of generators corresponds to the number of mediators for the interaction. The SU(2) generators are associated with the three gauge fields $W^i_\mu(x)$, $i = 1, 2, 3$. The gauge field for U(1)Y is called $B_\mu(x)$. In the electroweak unification, the SU(2)xU(1)Y symmetry is broken into U(1)EM (electromagnetic) and the gauge fields mix to give the fields for Z bosons and photons, this is described in Sec. 2.1.10. The strong force has eight generators and the associated gluon fields $G^i_\mu(x)$, $i = 1, 2, 8$.

The gauge field part of the Lagrangian density is given by:

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_\mu(x) B^\mu(x) - \frac{1}{4} W^i_\mu(x) W^{ij\mu}(x) - \frac{1}{4} G^i_\mu(x) G^{ij\mu}(x).$$  \hspace{1cm} (20)

The field strength tensors have the form:

$$B_\mu(x) = \partial_\nu B_\mu(x) - \partial_\mu B_\nu(x)$$

$$W^i_\mu(x) = \partial_\nu W^i_\mu(x) - \partial_\mu W^i_\nu(x) + g e^{ijk} W^j_\mu(x) W^k_\nu(x)$$

$$G^i_\mu(x) = \partial_\nu G^i_\mu(x) - \partial_\mu G^i_\nu(x) + g' f^{ijk} G^j_\mu(x) G^k_\nu(x).$$

Here $f^{ijk}$ and $e^{ijk}$ are antisymmetric structure constants. The fact that SU(2) and SU(3) are non-Abelian groups\(^1\) gives rise to the last term for $W^i_\mu$ and $G^i_\mu$, which describes self-interactions of gluons or the SU(2) fields.

\(^1\)Abelian groups have commuting generators, while the generators for non-Abelian groups do not commute.
2.1.6 QED

Quantum Electrodynamics describes electromagnetic interactions of electrically charged fermions with photons.

The electric charges are screened by the polarisation of the vacuum, such diagrams are illustrated in Fig. 3. Therefore the interaction appears stronger at short distances, or correspondingly at high energies $Q$ of the exchanged photon. The effective electromagnetic coupling $\alpha$ is related to the effective charge $q$ of the electron by $\alpha = q^2 / 4\pi$. This has a dependence on energy $Q$, as is illustrated in Fig. 4. It is measured to be around $1/127$ at the scale of the $Z$ boson and $1/137$ at the energy scale relevant for atomic physics.

![Figure 3: The vacuum polarisation diagrams provide shielding of the electric charge.](image)

![Figure 4: The radial dependence of the inverse of the electric effective coupling $1/\alpha$ [26]. The effective QED coupling increases at higher energies, or correspondingly short distances.](image)
The Lagrangian density for free fermions is:

$$\mathcal{L} = \bar{\psi}(x)(i\partial_\mu \gamma^\mu - m)\psi(x).$$  \hspace{1cm} (24)

Here \(\gamma^\mu (\mu = 0, 1, 2, 3)\) is an extension of the Pauli spin matrices \(\tau^i\) to four dimensions and \(\psi\) denotes \(\psi^\dagger \gamma^0\). The fermionic field is denoted by \(\psi(x)\) and \(m\) is the mass of the fermion in question. QED interactions are introduced by replacing the partial derivative in Eq. (24) by:

$$D_\mu \psi(x) = \partial_\mu \psi(x) + ieA_\mu(x)\psi(x),$$

with \(A_\mu(x)\) being the photon field. From the interaction part of the Lagrangian, it can be seen that the building blocks for QED have two fermionic fields and one photon field. Interactions from the first term of the S-matrix expansion \(S^{(1)}\) are forbidden in vacuum because of energy-momentum conservation. In the presence of a magnetic field or matter, as in a particle detector, energy can be supplied by an external source and first order interactions such as Bremsstrahlung and photon conversions can occur, these interactions are illustrated in Fig. 5.

![Figure 5: Bremsstrahlung (left) and photon conversions (right).](image)

2.1.7 QCD

Quantum Chromodynamics describes the interactions of quarks and gluons via the strong force, which holds together atomic nuclei and nucleons. Quarks are confined, forming bound states called hadrons. Each quark carries a quantum number called colour, which can take on the values red, green or blue. The hadrons, meanwhile, are colour neutral. The only quark that does not hadronise is the top quark, which has a lifetime that is an order of magnitude smaller than the time it takes for a hadron to form. The hadronisation of quarks created in particle collisions need to be simulated; for this purpose programs for parton showering, such as Pythia8 [27], can be used.

Contrary to QED, QCD is a non-Abelian theory and thus has a presence of self-interaction terms for gluons in the Lagrangian. While some screening
of the colour charge is provided by quark loops, as is the case for QED, gluon loops with the opposite effect also appear. The net effect is an anti-screening – the strong interactions become weaker at small distances or at large energies. Some diagrams that contribute to the strong force are shown in Fig. 6.

Figure 6: Example loop diagrams contributing to the running of the strong coupling $\alpha_S$.

The dependence of the QCD effective coupling $\alpha_S$ on the energy $Q$ is shown in Fig. 7. At ranges much smaller than 1 fm, we have a small $\alpha_S$ and a perturbative theory for quarks and gluons. At ranges of the order of 1 fm, the coupling is strong, perturbation theory breaks down and the system is described by hadrons.

Two kinds of divergences appear in QCD: divergences from loops at high energies, referred to as ultraviolet divergences, and those from the emission of a low-energy quark or gluon, known as infrared divergences. The renormalisation procedure is used to factor out the ultraviolet divergences, absorbing them into the mass and effective charge of a particle, while redefining these quantities. An unphysical parameter – the renormalisation scale $\mu_R$ – is introduced when applying a cut-off to regularise the diverging integral. Requiring that the physical observables have no dependence on $\mu_R$ results in the running of the effective charge, as shown in Fig. 7.

To avoid the infrared divergences, a lower cut-off, called factorisation scale $\mu_F$, is introduced. The interactions of quarks and gluons (known as partons) below $\mu_F$ are described by parton distribution functions (pdfs), see for example Ref. [28]. The pdfs give the probability that a quark of a certain flavour or a gluon will participate in the scattering at some momentum transfer $Q$ as a function of the fraction of the momentum of the proton $x$ carried by the parton. The DGLAP equation quantifies the dependence of the pdfs on the momentum scale [29], [30], [31], [32].

When simulating a process, theoretical uncertainties are often estimated
Figure 7: The dependence of the effective coupling $\alpha_s$ on the momentum transfer $Q$ [21]. The coupling decreases at high energies, or short distances.

by varying the renormalisation scale, factorisation scale and choice of pdfs. Typically variations by a factor of 1/2 and 2 are performed for the scales. While the renormalisation scale is an unphysical property, it is used to assess the uncertainty from neglecting higher order terms in the S-matrix expansion – the more orders that are included, the smaller the dependence of the cross section on the renormalisation scale.

2.1.8 Weak interactions

Prior to the emergence of the picture where the weak force is mediated by the exchange of massive $W$ or $Z$ boson, the Fermi theory [33] was used to describe weak interactions. In this picture, instead of a $W$ propagator, an effective coupling constant is introduced to the Lagrangian for a point interaction with four external fermions, as shown in Fig. 8 (left).

This model works well to describe low-energy processes such as the muon decay. However, the approximation breaks down at higher energy transfers as the effects of a massive intermediate $W$ boson become apparent.

The $W$ boson also mediates the decays of quarks. The mass eigenstates and flavour eigenstates for quarks are not the same and the flavour of a quark can be changed in weak interactions. The operation for transforming a quark from the mass eigenstate into the weak interaction eigenstate is given in Eq. (25), the weak eigenstates are denoted with a prime and the mass eigenstates without primes. The values of the CKM matrix, which describes the mixing of the quarks, are shown in Eq. (26). It can be seen
Figure 8: The decay of muons is illustrated in two different pictures. In Fermi theory, this is modelled as a four point fermion interaction (left). The same process with an intermediate vector boson is illustrated to the right.

that the CKM matrix has an approximately diagonal form, implying that decays within the same generation are favoured (provided that it is allowed by energy-momentum conservation).

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

(25)

\[
\begin{pmatrix}
    |V_{ud}| & |V_{us}| & |V_{ub}| \\
    |V_{cd}| & |V_{cs}| & |V_{cb}| \\
    |V_{td}| & |V_{ts}| & |V_{tb}|
\end{pmatrix} =
\begin{pmatrix}
    0.97417 \pm 0.00021 & 0.2248 \pm 0.0006 & (4.09 \pm 0.39) \cdot 10^{-3} \\
    0.220 \pm 0.005 & 0.995 \pm 0.016 & (40.5 \pm 1.5) \cdot 10^{-3} \\
    (8.2 \pm 0.6) \cdot 10^{-3} & (40.0 \pm 2.7) \cdot 10^{-3} & 1.009 \pm 0.031
\end{pmatrix}
\]

(26)

The numbers are obtained from Ref. [21]. \( V_{ij} \) is proportional to the transition amplitude from state \( i \) to state \( j \). \( |V_{tb}| \) has been measured to be near 1 – the most common decay mode by far for a top quark is into a \( b \) quark and a \( W \) boson.

Fermions are chiral particles and can be either left-handed or right-handed. The weak force only acts on left-handed fermions and right-handed anti-fermions. To include this behaviour in the SM description, left-handed fermions are organised into doublets, which can be acted on by SU(2) transformations:

\[
\begin{pmatrix}
    \nu_e \\
    e
\end{pmatrix}_L, \begin{pmatrix}
    \nu_\mu \\
    \mu
\end{pmatrix}_L, \begin{pmatrix}
    \nu_\tau \\
    \tau
\end{pmatrix}_L,
\begin{pmatrix}
    u \\
    d
\end{pmatrix}_L, \begin{pmatrix}
    c \\
    s
\end{pmatrix}_L, \begin{pmatrix}
    t \\
    b
\end{pmatrix}_L.
\]

(27)

(28)
The right-handed fermions on the other hand are represented by singlets:

\[ e_R, \mu_R, \tau_R, u_R, d_R, c_R, s_R, t_R, b_R. \]  

Right-handed neutrinos have not been observed.

2.1.9 Electroweak interactions

The weak and electromagnetic forces are unified into the electroweak force, described by \( SU(2) \times U(1)_Y \). The interaction eigenstates \( W^3_\mu(x) \) and \( B_\mu(x) \) mix to give the mass eigenstates \( Z_\mu(x) \) and \( A_\mu(x) \) for Z bosons and photons. The mixing is specified by the Weinberg angle \( \theta_W \), with \( \sin^2 \theta_W = 0.231 \) [21] at the scale of the Z boson:

\[
W^3_\mu(x) = \cos \theta_W Z_\mu(x) + \sin \theta_W A_\mu(x) \quad \text{(30)} \\
B_\mu(x) = -\sin \theta_W Z_\mu(x) + \cos \theta_W A_\mu(x). \quad \text{(31)}
\]

For the W bosons the mass eigenstates are \( W_\mu(x) \) and \( W_\mu^\dagger(x) \), related to the interaction eigenstates \( W^{1,2}_\mu(x) \) as:

\[ W_\mu(x) = \frac{1}{\sqrt{2}}(W^{1}_\mu(x) - iW^{2}_\mu(x)). \quad \text{(32)} \]

2.1.10 Electroweak symmetry breaking

Giving the W and Z bosons a mass term by inserting an expression like \( m_W^2 W_\mu^\dagger(x) W^\mu(x) \) into the Lagrangian results in a term that is not renormalisable. Instead a mechanism was proposed by Robert Brout and Francois Englert [16] and by Peter Higgs [17] in 1964, here referred to as the BEH mechanism. A scalar field \( \phi(x) \) with a potential of the form \( \mu \phi^2(x) + \lambda \phi^4(x) \) is introduced. If \( \mu < 0 \), the potential does not have a unique minimum and has a shape that can be described as a Mexican hat, with a local maximum on the axis of symmetry and a continuous set of minimal occurring at the same radius from the centre. Choosing one unique minimum and expressing the theory in terms of it breaks the symmetry.

The scalar field is constructed to be an SU(2) doublet. In the unitary gauge, the complex Higgs field can be expressed as:

\[ \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \sigma(x) \end{pmatrix}. \quad \text{(33)} \]

Here \( v \) is the non-zero vacuum expectation value of the Higgs field (represented by the radius from the center) and \( \sigma(x) \) corresponds to radial displacements away from the minimum, which requires energy.

The covariant derivative for the Higgs field \( \phi(x) \) is

\[ D^\mu \phi(x) = (\partial^\mu \phi(x) + ig\tau^i W^\mu_i(x)/2 + ig' Y B^\mu(x))\phi(x) \quad \text{(34)} \]
The value of the hypercharge $Y$ for the Higgs field is $1/2$. The coupling constants $g$ and $g'$ are related by

$$g \sin \theta = g' \cos \theta = e,$$  \hspace{1cm} (35)

with $e$ being the electric charge.

Evaluating the kinetic term $D_\mu \phi(x) D^\mu \phi(x)$ at the minimum of the potential and changing basis from interaction eigenstates to mass eigenstates results in mass terms for $W$ and $Z$ bosons and massless photons. The mass terms contain the constant part of the Higgs field $v$ and appear as a consequence of the minimum not being unique. Additionally a mass term for the $\sigma(x)$ field appears and a massive scalar boson, called the Higgs boson, is predicted. From the kinetic term, interactions of the Higgs field with the $W^*_\mu(x)$ and $B_\mu(x)$ fields can also be deduced.

The BEH mechanism was confirmed by the discovery of the Higgs boson by ATLAS and CMS in 2012 [34], [35]. The Nobel prize for the prediction was awarded to Francois Englert and Peter Higgs in 2013; Robert Brout had passed away a few years earlier. Since the discovery, the properties of the Higgs boson, such as spin and couplings, have been measured. So far, all measured properties agree with the SM prediction.

### 2.2 Tests of the Standard Model

The Standard Model has been successfully tested throughout the decades. Weak neutral currents were observed at Gargamelle at CERN in 1973 [36], interpreted as interactions of neutrinos with electrons via the neutral $Z$ bosons. The $W$ and $Z$ bosons were discovered 1983 by UA1 and UA2 experiments at CERN. The top quark was discovered in 1995 at CDF and D0 at the Tevatron, thus completing the third quark generation.

The most accurate test of the SM comes from the studying the quantity $g/2$ for the electron, which is related to the electron spin $S$ and its dipole moment $\mu$ as:

$$\mu = g \mu_B S,$$  \hspace{1cm} (36)

$$\mu_B = e/2m_e.$$  \hspace{1cm} (37)

Here $e$ is the magnitude of the electric charge and $m_e$ is the mass of the electron. In the absence of interactions with the vacuum, $g/2$ would be exactly 1. However, due corrections from fluctuations of the vacuum, a small deviation from 1 is expected. The theoretical value of $g/2$ has been computed, including 10 orders of the QED expansion [37], to be:

$$g_{th}/2 = 1.00115965218178(77).$$  \hspace{1cm} (38)
This quantity has been measured to an accuracy of 0.28 parts in $10^{12}$ [38]:

$$g_{\text{exp}}/2 = 1.00115965218073(28)$$

and is in good agreement with the theoretical prediction.

Other tests include electroweak precision measurements, as in Ref. [39]. Here fits are performed with and without for instance the masses of top quarks, $W$ bosons and Higgs bosons as inputs. All such measurements are seen to agree with each other within uncertainties.

### 2.3 Questions not answered by the Standard Model

Despite the many successes of the Standard Model, several fundamental questions of particle nature remain unaddressed by it.

The SM does not describe the force of gravity. At energies of the order of the Planck scale $\sim 10^{19}$ GeV, if not at lower scales, gravitational effects need a quantum mechanical description. In calculating the Higgs mass, radiative corrections to the bare mass from bosonic and fermionic loops are integrated up to a cut-off $\Lambda$ above which the SM is no longer valid. If $\Lambda$ is of the order of the Planck mass, these loop corrections need to cancel too one part in $10^{33}$ to be consistent with the observed Higgs boson mass. With no symmetry ensuring such a cancellation, this high level of fine-tuning is often considered to indicate that our understanding of the particle physics is not complete. It is referred to as the fine-tuning problem, also known as the hierarchy problem or the naturalness problem [40],[41]. The largest loop corrections to the Higgs boson mass come from the heaviest particles. As the top quark has the largest Yukawa coupling by far, it is of interest to study top quark physics to search for a solution to the hierarchy problem.

Another question not answered by the Standard Model is the nature of dark matter. From studies of galactic rotation curves, it is evident that the amount and distribution of visible matter in most galaxies is not consistent with Kepler’s laws [42]. Other observations, such as that of the Bullet Cluster [43] and of the cosmic microwave background [44], point to that this discrepancy is explained by the presence of non-luminous matter, called dark matter, that only interacts gravitationally and possibly weakly. Dark matter constitutes 27% of the energy content of the universe, while ordinary matter only makes up 5%, the rest being dark energy [45]. The SM lacks a particle candidate that could explain the amount of dark matter observed in the Universe. Theories such as Supersymmetry [46] and Large Extra Dimensions [47] [48] attempt to resolve the hierarchy problem and also predict particles that could be candidates for dark matter.

The SM does not address why the electric charge is quantised or why the charges of the proton and the electron are of the same magnitude. Neither does it explain why the number of generations is the same for leptons and quarks. Grand Unified Theories (GUTs) [21] seek to address these issues
by suggesting that the particle interactions can be described by a higher order Lie group, which could be decomposed into SU(3)xSU(2)xU(1), the structure of the SM. This would introduce additional symmetries to describe features that appear accidental in the SM.

In the original form of the SM, neutrinos are massless. We now know that this is not the case. However, the SM could be extended to accommodate massive neutrinos that acquire their mass through interaction with the Higgs field, for example through the see-saw mechanism [49]. The neutrino sector is not considered in this work.

In summary, these theoretical questions motivate searches of physics beyond the Standard Model.

2.4 Motivation for $t\bar{t}V$ searches

In search of physics beyond the Standard Model, one approach is to study SM particles and test whether their interactions agree with the SM prediction. Top quark physics in particular is of interest because it is believed to play an important role in symmetry breaking, and a solution to the hierarchy problem would likely appear in the properties of the most massive particles, which have largest couplings to the Higgs boson.

Top quarks are produced in great amounts in the LHC, with the dominant production mode being the fusion of gluons to produce a top anti-top quark pair. Production of $t\bar{t}Z$ is a process of interest because it allows one to constrain the coupling between top quarks and Z bosons, see Figure 9 (left). Constraining this coupling allows one to probe new physics that would modify the coupling. This is explored in this work in the framework of Effective Field Theory, which is introduced in Sec. 2.6. For $t\bar{t}W$, production from proton-proton collisions at tree level can only occur with the $W$ radiated from the initial state, as shown in Fig. 9 (right). Measurements of $t\bar{t}W$ production allows one to probe signatures that are similar to those resulting from new physics scenarios involving heavy partners to the top quark [50], [51]. For instance, hypothetical vector-like quarks can mix with SM quarks, modifying their couplings to Z and W bosons. Such partners to top and bottom quarks could have exotic charges of $+5/3$ and $-4/3$ respectively, and would have decay modes into $W^+t$ and $W^-b$. Pair production of such exotic particles, or production in association with a SM top quark would give rise to similar final states as $t\bar{t}W$.

Both $t\bar{t}Z$ and $t\bar{t}W$ production also form important backgrounds to many searches for supersymmetry and to $t\bar{t}H$, so understanding how these processes look in ATLAS would allow for more accurate such measurements. From here on, these two processes together are referred to as $t\bar{t}V$, where $V$ denotes vector boson.
Figure 9: Production of $t\bar{t}Z$ through gluon fusion is illustrated to the left. In the production of $ttW$ at tree level, the $W$ boson is radiated from the initial state, while the $t\bar{t}$ pair is formed from the collision. This is shown to the right.

2.5 The treatment of the $Wt$ and $tWZ$ processes with Diagram Removal

In order to compare the $ttV$ measurement to the Standard Model prediction, the signal and important background processes need to be simulated. One important background is $tWZ$ production. At NLO in QCD, this process overlaps with $ttZ$ production. Several schemes exist to handle the overlap, thus avoiding the double counting of diagrams arising at LO for single top processes in the $Wt$ channel and those at NLO for $tt$-like processes. The available methods that are utilised in this work are Diagram Removal of two forms [52] and Diagram Subtraction [53], [54]. The methods are described below in the context of $Wt$ production. The Diagram Removal methods are then extended to $tWZ$ in Sec. 4.5, where results from simulations of $Wt$ and $tWZ$ production are also presented.

The five flavour scheme is used in the event generation, meaning that the $b$ quark is included in the pdfs. Generating single top production in the $Wt$ channel at NLO in QCD gives rise to diagrams that overlap with $tt$ production. In Fig. 10 (right), a diagram is shown that appears both for $Wt$, allowing for an additional $b$ quark, and for LO $t\bar{t}$ production, with one of the top quarks decaying as $t \to Wb$. In the simulation, the particles specified in the final state in the computation of the matrix element ($W, t$) are required to be on shell, while intermediate particles, such as a top quark propagator, can be on-shell or off-shell. The overlap occurs when the intermediate top propagator is allowed to be on shell by the energy-momentum relation. Diagrams with exactly one top quark present are referred to as singly resonant (sr) while diagrams including an additional top propagator that can be on shell are called doubly resonant (dr).

The Feynman amplitude $\mathcal{M}$ can be written in terms of singly-resonant
Figure 10: Diagrams appearing at the NLO generation of $Wt$ production. The diagram to the left is singly resonant. The diagram to the right is doubly resonant and overlaps with $t\bar{t}$ production followed by the decay of a top quark $t \rightarrow Wb$.

and overlapping doubly resonant contributions in Eq. (40):

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_{\text{sr}} + \mathcal{M}_{\text{dr}}.$$  \hfill (40)

The modulus squared of the Feynman amplitude appears in the production cross section and is split in terms of singly resonant and doubly resonant contributions in Eq. (41). In the Diagram Removal 1 scheme (commonly referred to as just Diagram Removal), the Feynman amplitudes for doubly resonant diagrams are set to zero. As a consequence, only the first term in Eq. (41) is included in the prediction and the interference of $Wt$ and $t\bar{t}$ is neglected. The alternative method Diagram Removal 2 retains the interference term by subtracting the modulus squared of the amplitude for doubly resonant diagrams from Eq. (41).

$$|\mathcal{M}_{\text{tot}}|^2 = |\mathcal{M}_{\text{sr}}|^2 + 2\text{Re}(\mathcal{M}_{\text{sr}}^*\mathcal{M}_{\text{dr}}) + |\mathcal{M}_{\text{dr}}|^2. \hfill (41)$$

DR1

DR2

These two DR methods to model $Wt$ and $tWZ$ are the focus for the single-top processes in this work. Another method, called Diagram Subtraction (DS), removes the overlap at the level of the cross section, while including the interference in the prediction. This method is gauge invariant by construction, but relies upon momentum reshuffling, which introduces uncertainties and dependence on unphysical parameters to the prediction. A more proper way than both DR and DS to assess this final state would be generating $WbWb(Z)$ at NLO. While such efforts are progressing for the former process [55], particularly using the POWHEG generator [56], this is still far from realisation for $WbWbZ$ production.

In Ref. [57], it is shown that applying DR2 to $Wt$ and $tWH$ production in MG5_aMC@NLO [24] yields results that are consistent with gauge invariant predictions that assess the interference. Comparing DR1 and DR2
predictions, one can assess the magnitude of the interference. The DR2 method has been validated against gauge invariant predictions at LO for the $Wt$ and $tWH$ processes in Ref. [57].

2.6 Effective Field Theory

Effective Field Theory (EFT) is a model-independent framework that parametrises new physics up to some energy scale $\Lambda$ [7], [8], [9]. The parametrisation describes how the physics of SM particles can be modified at energies below $\Lambda$. In the description, no particles from beyond the SM can be produced in this regime. Similarly to Fermi theory for weak interactions, the effect of new physics is approximated to a contact interaction at low energies – no model-dependent propagators are introduced in the description.

In the top-down approach to EFT, the complete theory is known. To simplify it, the masses of the heavy new particles are integrated away and the effects at low energies can be expressed in terms of effective operators. In the bottom-down approach, followed here, no full theory is constructed. The operators under study describe generic interactions between SM particles that can be mediated in the presence of new physics. They modify the SM Lagrangian density as:

$$L_{\text{EFT}} = L_{\text{SM}} + \frac{C_i}{\Lambda^4} O_{iD5} + \frac{C_i}{\Lambda^2} O_{iD6} + \frac{C_i}{\Lambda^4} O_{iD7} + \frac{C_i}{\Lambda^4} O_{iD8} + ...$$  \hspace{1cm} (42)

Here $O_i$ are the Wilson operators, which contain the structure of the interaction, while their coefficients $C_i$ determine the coupling strength for a given value of $\Lambda$. $DX$ gives the dimension of the effective operators. The operators appear together with some power of $\Lambda$ in the denominator in such a way that all terms have mass dimension 4.

EFT is not a renormalisable theory. Operators of an infinite number of dimensions modify the SM Lagrangian. However, at energy transfers below the cut-off, terms from higher-order operators are suppressed by higher powers of $\Lambda$ so it can be argued that they can be neglected. The number of effective operators at any given dimension is finite.

Operators of dimension 5 that are relevant for top quark physics mediate flavour changing neutral currents (these are forbidden at tree level in the SM) and are not considered here. In this work, operators of dimension 6 affecting $t\bar{t}Z$ production [51], [58] are studied. Following the notation used in Ref. [58], they are defined as:
Here $y_t$ is the Yukawa coupling for the top quark, $\phi$ is the Higgs field, $\overrightarrow{D}_\mu$, $\overrightarrow{D}_I^\mu$ are covariant derivatives acting both to the left and right, $Q$ is the left-handed third generation quark doublet, and $t$ is the right-handed top singlet. It is worth noting that the two least massive generations of quarks are decoupled from these operators in this definition. The effects of these operators is studied with the event generator MG5_aMC@NLO in Ref. [15]. Only the constant part of the Higgs field $v$ is considered.

The $Z$ boson appears in all operators except in $O_{tG}$, either in the the covariant derivatives or from the gauge fields $W_{\mu\nu}^I$, $B_{\mu\nu}$ – all these five operators modify the $ttZ$ vertex. The $tt\gamma$ vertex is also modified by $O_{tW}$ and $O_{tB}$. The $O_{tG}$ operator instead appears in the $ttb$ vertex. Some Feynman diagrams illustrating which vertices are affected are shown in Fig. 11.

The coefficients employed in the model are renormalised to NLO in QCD:

$$C_i^0 \to Z_{ij}C_j = \left(1 + \frac{1}{2} \Gamma(1 + \epsilon) (4\pi)^\epsilon \frac{1}{\epsilon_{UV}} \gamma \right)_{ij} C_j,$$  \hspace{1cm} (49)

For $O_{tG}$, $O_{tW}$ and $O_{tB}$, the components of the anomalous dimension matrix $\gamma$ are non-zero:

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} 1/6 & 0 & 0 \\ 1/3 & 1/3 & 0 \\ 5/9 & 0 & 1/3 \end{pmatrix}.$$  \hspace{1cm} (50)

One can express the $ttZ$ coupling in terms of these EFT operators:

$$\mathcal{L}_{ttZ} = \bar{e}u(p_t) \left[ \gamma^\mu \left(C_{1,V}^Z + \gamma_5 C_{1,A}^Z\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_Z} \left(C_{2,V}^Z + i\gamma_5 C_{2,A}^Z\right) \right] v(p_t) Z_\mu, \hspace{1cm} (51)$$
Figure 11: Some Feynman diagrams illustrating the different vertices that are affected by the effective operators considered here. The blob illustrates that an effective operator enters the vertex. The $t\bar{t}g$ vertex is modified by $\mathcal{O}_{tG}$. The $t\bar{t}\gamma$ vertex is affected by $\mathcal{O}_{tW}$ and $\mathcal{O}_{tB}$. The $t\bar{t}Z$ vertex is affected by all operators considered here, except $\mathcal{O}_{tG}$.

As can be seen above, the operators $\mathcal{O}_{\phi Q}^{(1)}$ and $\mathcal{O}_{\phi Q}^{(3)}$ enter the $t\bar{t}Z$ vertex in the combination $\mathcal{O}_{\phi Q}^{(3)} - \mathcal{O}_{\phi Q}^{(1)}$, so it is only possible to constrain the difference $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$ by measuring $t\bar{t}Z$ production.

It is worth noting that the effective operators enter processes besides $t\bar{t}Z$, such as $t\bar{t}\gamma$, $tt$ and $Wt$ production. A strength in constraining effective operators rather than anomalous couplings is that for the EFT approach, measurements of different processes could be combined to place better limits using all the available information.

The operators modify the SM Lagrangian density $\mathcal{L}_{SM}$, appearing in it together with their Hermitian conjugates:

\begin{align}
C_{1,V}^Z &= \frac{1}{2} \left( C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)} - C_{\phi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W} \\
C_{1,A}^Z &= \frac{1}{2} \left( -C_{\phi Q}^{(3)} + C_{\phi Q}^{(1)} - C_{\phi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W} \\
C_{2,V}^Z &= \left( C_{tW} c_W^2 - C_{tB} s_W^2 \right) \frac{2m_t m_Z}{\Lambda^2 s_W c_W} \\
C_{2,A}^Z &= 0
\end{align}

(52) (53) (54) (55)
\[ \Delta \mathcal{L} = \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i + h.c. \] (56)

The cross section for the process is modified as:

\[ \sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/\text{TeV})^2} \sigma_i^{(1)} + \sum_{i \leq j} \frac{C_i C_j}{(\Lambda/\text{TeV})^4} \sigma_{ij}^{(2)}. \] (57)

The term \( \sum_i \frac{C_i}{(\Lambda/\text{TeV})^2} \sigma_i^{(1)} \) is referred to as the interference term, as it corresponds to the interference of the SM operators and the effective operators. The term \( \sum_{i \leq j} \frac{C_i C_j}{(\Lambda/\text{TeV})^4} \sigma_{ij}^{(2)} \) is referred to as the quadratic term.

Distributions for the \( t\bar{t}l^+l^- \) processes (\( l \) denoting leptons) with the effective operators are shown, as well as fits to data to constrain the coefficients \( C_i \) are presented in Sec. 5.
3 Experimental setup

The experimental results presented in this thesis are based on data collected and processed by the ATLAS experiment. The particle collisions that are analysed in ATLAS are produced by the Large Hadron Collider (LHC). An overview of the LHC and the ATLAS experiment is given below.

3.1 The Large Hadron Collider

The Large Hadron Collider [60] is the largest machine and the most powerful particle accelerator in the world. It accelerates proton beams to up to 99.9999991 % of the speed of light and collides them at a collision energy of 13 TeV. It is situated at the European Organization for Nuclear Research (CERN) on the border between Switzerland and France, outside of Geneva. The circumference of the circular tunnel holding the LHC is 27 kilometres. It is located 100 metres underground. Superconducting magnets with a strength of 8 T are employed to bend the proton beams to follow the trajectory of the LHC. A section of the LHC is shown in Fig. 12.

The protons are collected in bunches with an order of $10^{11}$ protons present in each bunch. The bunches form so called bunch trains, with an order of 100 bunches in each train. They are brought to collide pairwise at the centres of several experiments positioned along the LHC, with up to 50 pairs colliding per bunch crossing [61]. The LHC can also circulate and collide lead ions, but such collisions are not considered in this work. The four major experiments at the LHC are ATLAS [6], CMS [62], ALICE [63]
and LHCb [64]. ATLAS and CMS are multipurpose experiments, famous for the discovery of the Higgs boson in 2012. ALICE is an experiment where quark-gluon plasma is studied from the collision of lead ions. LHCb is an asymmetric detector with full $\eta$ coverage in one end. Here the physics of hadrons containing $b$ quarks is studied.

3.2 The ATLAS experiment

The ATLAS experiment (A Toroidal LHC ApparatuS) [6] is a multipurpose experiment and is the result of a large collaborative effort, currently involving over 3000 physicists. The detector is cylindrical in shape, around 44 metres long and with a diameter (or height) of 25 metres and has a mass of 7000 tonnes. A photograph of a part of the ATLAS experiment is shown in Fig. 13. A schematic picture is shown in Fig. 14.

Figure 13: A view of the ATLAS detector [65]. The brown cylinder is one of the end barrels of the Tile Calorimeter, adjacent to a yellow muon wheel. The barrel has been extracted from within the toroid to facilitate repair work. The grey tubes with orange stripes are part of the toroidal magnet system.

In the coordinate system used in the ATLAS detector, the origin is located at the point of interaction. A right-handed coordinate system is used,
with the positive $x$-axis pointing toward the centre of the LHC, the $y$-axis going upward and the $z$-axis along the beam pipe. Using angular coordinates, the azimuthal angle $\phi$ runs from the positive $x$-axis upward and around the beam pipe. The polar angle $\theta$ is defined with respect to the $z$-axis with $\theta = \pi/2$ along the $y$-axis. In practice, the pseudorapidity $\eta$ is used in place of $\theta$; the two are related by $\eta = -\ln(\tan \frac{\theta}{2})$. A quantity that is often used to quantify the spatial separation of two objects in ATLAS is $\Delta R$, defined as $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$.

The main components of ATLAS are the Inner Detector, which measures the position and momentum of charged particles, the electromagnetic and hadronic calorimeters, the Muon Spectrometer and the magnet system, which provides a field that bends the trajectories of charged particles. These components are described in Secs. 3.2.1 - 3.2.4.

### 3.2.1 Inner Detector

The Inner Detector (ID) [6], [67] measures tracks from charged particles, which ionise the detector material. A solenoid magnet surrounds the ID, generating a magnetic field of 2 T to deflect the charged particles. The curvature of a track registered in the ID provides information about the sign of the charge of the particle and its momentum.
The interaction point for a specific collision gives rise to a primary vertex, from which the tracks originate. The creation and subsequent decays of heavy particles with a lifetime of the order of $10^{-13} - 10^{-12}$ s, such as $\tau$ leptons, and $b$- and $c$-hadrons, give rise to secondary vertices. The location of the primary vertices is important for associating particles with the correct interaction and information about tracks from the primary and secondary vertices are important for reconstructing the process that took place. The very large density of tracks near the interaction point places high demands on the granularity of the ID. The momenta of the particles that leave tracks in the ID need to be known to a high precision for further analyses of the collision events.

The ID is located closest to the beam pipe. It consists, from the inside and out, of the Insertable B Layer (in place since 2014), the pixel detector, the SemiConductor Tracker (SCT) and the Transition Radiation Tracker (TRT), see the schematic picture in Fig. 15. The pixel detector and the SCT provide high-precision tracking within $|\eta| < 2.5$. The subdetectors in the ID complement each other and together provide a robust combined estimate of the momentum of the particles.

Figure 15: A schematic view of the Inner Detector [6].

The subdetector that was originally the innermost one is the silicon-based pixel detector [68]. It consists of three concentric layers in the barrel and three disks each in the end caps. The read-out is performed by front-end chips that are resistant to radiation, with 80.4 million read-out channels in
total. The granularity is very high, the size of a pixel is typically 50 μm by 400 μm. The b-hadrons and τ leptons decay in the pixel detector and are first detected here. Above an adjustable threshold, usually of the order of 4000 times the elementary charge, the pixels are read out. The pulse is digitised, based on the time for which the threshold is exceeded, which is typically around 30 bunch crossings. This time is proportional to the pulse amplitude and hence the energy.

Moving outward, the next subdetector is the SemiConductor Tracker (SCT) with 6.4 million read-out channels. It is arranged in four concentric layers in the barrel and nine disks each in the end-caps. Ideally, in the barrel region, four measurements per track are provided. It stores binary information, with the pulse height required to exceed what usually corresponds to a charge of 1 pC.

The outermost subdetector is the Transition Radiation Tracker (TRT) [69], which consists of gas-filled drift tubes that have a wire at the centre. The gas is a mixture of xenon, carbon dioxide and oxygen. A charged particle that crosses the TRT ionises the gas. The free electrons drift towards the wire, where the current is amplified and read out. Between the tubes, polymer fibres (in the barrel) or foils (in the end-caps) are placed. When these are traversed by highly relativistic particles, transition radiation is emitted. The amplitude of the emitted radiation is proportional to the Lorentz boost factor $\gamma = \frac{E}{m}$, which is higher for electrons than for massive hadrons and can thus be used to distinguish between them. The TRT has 351,000 read-out channels in total. Each track is built from on average 36 hits in the TRT.

The Insertable B-Layer (IBL) [70] was added during the long shutdown in 2014. It is located closest to the beam pipe, inside of the pixel layer. It was inserted in order to improve reconstruction of vertices and the identification of b-jets, while withstanding high luminosity and radiation levels. The IBL has a comparatively low occupancy and a higher bandwidth than the pixel detector.

### 3.2.2 Liquid Argon Calorimeter

The Liquid Argon Calorimeter (LAr) [72] consists of an electromagnetic (EM) calorimeter and hadronic end-caps. The EM part is designed to measure energy depositions from electrons and photons. The active material is liquid argon, which is resistant to radiation. The electron or photon that enters the LAr initiates a chain reaction of pair production and Bremsstrahlung in the passive material. Electrons from the shower ionise the material in the active layer. This creates a current, which is read out, digitised and converted to an energy.

The central part of the EM LAr, called the barrel, covers ranges of up to $|\eta| = 1.475$. End-caps cover the range $1.375 < |\eta| < 3.2$. The
energy resolution of the EM calorimeter is energy-dependent: \( \sigma_E/E = 10%/\sqrt{E/\text{GeV}} \oplus 0.7\% \). The passive layer in the barrel is made of lead, clad in steel.

The Forward Calorimeter (FCal) is integrated into the cryostat. It consists of a copper layer followed by two tungsten layers, which constitute the passive material.

The hadronic end-caps of LAr measure hadrons emitted at a small angle to the beam pipe, thus complementing the Tile Calorimeter. The hadrons initiate a nuclear chain reaction known as hadronic shower in the passive layer. The HEC consists of two copper wheels with a radius of 2 m. The absorber material is copper.

3.2.3 The Tile Calorimeter

The Tile Calorimeter [73] (TileCal) is a hadronic calorimeter, covering ranges the range of \( |\eta| < 2.5 \). The extended barrels and the two halves of the barrel in TileCal are each divided azimuthally (in \( \phi \)) into 64 modules. One module is illustrated in Fig. 17. In addition, the calorimeter is segmented longitudinally into three layers of cells, having approximately 5000 cells in total. The cells are read out by one Photomultiplier Tubes (PMTs) from each \( \phi \) side of the cell in order to achieve better uniformity and redundancy. The granularity of TileCal is \( \Delta\eta \times \Delta\phi = 0.1 \times 0.1 \) in the inner two layers and \( 0.2 \times 0.1 \) in the outer layer.

TileCal measures the energy and the position of absorbed particles, de-
Figure 17: A schematic picture [74] of a module in the Tile Calorimeter. Wavelength shifting fibres transporting light from the plastic tiles in a module to the PMTs.

tecting jets and other energy depositions from which one can derive the missing transverse energy $E_T^{miss}$ - a quantity that measures the apparent momentum imbalance in the transverse plane, see Sec. 4.1.5. TileCal also shields the muon system from hadrons and assists the muon spectrometer in identifying muons. The energy resolution of TileCal is $\sigma_E/E = 50%/\sqrt{E/\text{GeV}} \oplus 3\%$.

TileCal is a sampling calorimeter, containing scintillating plastic tiles embedded in steel absorber plates. The tiles are oriented radially, perpendicularly to the beam line to facilitate readout and connecting the optical fibres to the scintillator. The ionising radiation from the hadronic shower reaches the tiles, making the material luminous. This light is read out from both sides of the scintillating plastic tiles. The signal is transported by wavelength shifting fibres to PMTs on the periphery of TileCal.

The signal is widened by a shaper and digitised by an ADC into seven samples spaced 25 ns apart, as shown in Fig. 18. From the area under such a pulse, the deposited energy can be derived, while the position of the peak gives the timing of the signal. The digital signals are stored in front-end pipeline memories, where they await the decision from the Level 1 trigger.
Signals that receive an accept from the L1 trigger are transported from the pipeline memory to the Read Out Drivers (RODs) for further processing.

![Graph showing ADC counts, phase, amplitude, and pedestal over time in nanoseconds.](Image)

Figure 18: After shaping and digitisation, each signal consists of seven samples, 25 ns apart [75].

The charge of the analog signal is related to energy by using conversion constants between MeV and pC derived from calibrations using electron test beams. This gives the energy on the so-called electromagnetic scale. Further calibrations are needed to relate the energy at this scale to the energy of the jets that deposit energy in TileCal.

One challenge for the Tile Calorimeter is pile-up. With an average 25 interactions per bunch crossing, decay products from different collisions in a bunch crossing can leave energy depositions in the same cells in TileCal. This is known as in-time pile-up. Additionally, the bunch spacing is 25 ns (50 ns for data collected at 8 TeV collision energy), while each signal is read out for 175 ns. The overlap in the read-out of events from different bunch crossings is referred to as out-of-time pile-up. To reconstruct jets from depositions in TileCal, the pile-up needs to be accounted for.

### 3.2.4 Muon system

One of the main purposes of the ATLAS detector is to provide efficient identification and accurate momentum measurement of muons. The Muon Spectrometer (MS) [76], [77], [6] is the outermost component of the ATLAS detector. It consists of high-resolution tracking chambers and a trigger system. The components are marked out in Fig. 19. The barrel chambers of the muon system are arranged into three concentric cylinders and cover the
central pseudorapidity range $|\eta| < 1$. The chambers in the End-Cap are positioned on wheels orthogonal to the beam pipe and reach $|\eta| = 2.7$.

A system of large superconducting toroid magnets provides the magnetic field to deflect the muons, to enable measurements of their momentum. Triggering is enabled by Resistive Plate Chambers (RPCs) in the barrel. The RPCs [78] are gas based and detect ionisation created when muons ionise the gas in the presence of an electric field, applied by electrodes. The gas is a mixture of carbon dioxide and $\text{n}$-pentane. The RPCs in ATLAS are 2 mm thick and placed at a distance of 2 mm from each other. They operate in avalanche mode: drifting electrons collide with the gas and produce further ionisation. RPCs have a fast response and a spatial resolution of around 5-10 mm. In the end caps that cover the forward region, communication with the muon trigger is instead handled by Thin Gap Chambers.

High precision measurements of the momenta of the muons are performed by Monitored Drift Tubes (MDTs). They consist of aluminum tubes with a diameter of 3 cm and a length between 0.9 m and 6.2 m. The MDTs are filled by a mixture of argon and carbon dioxide gas and operate under a pressure of 3 bar. The muons ionise the gas, with the electrons collected on a wire, which is read out by electronics. At high $|\eta|$, the measurement of muon momenta is instead performed by Cathode Strip Chambers (CSC), which are multi-wire proportional chambers.

The resolution is 80 $\mu$m for MDTs and 60 $\mu$m for CSC system. The resolution is higher in the end-caps to manage the higher backgrounds near the beam-pipe.
3.2.5 Magnet system

Figure 20: The winding of the coils of the toroid magnet (barrel and end-caps) [79]. The solenoid is located in the centre.

The magnet system of ATLAS [6], [79] consists of a solenoid around the Inner detector and an outer toroidal part. The winding of the coils is shown in Fig. 20. The solenoid is aligned on the beam axis and provides an axial magnetic field that reaches 2 T for the ID. The toroid consists of a barrel and two end caps. It provides magnetic fields over the Muon Spectrometer of approximately 0.5 T in the barrel and 1 T in the end-caps. Over one hundred kilometres of superconducting wire is used and the magnet system operates at 4.5 K.

3.2.6 Trigger system

With a bunch crossing rate of 40 MHz and up to 50 collisions per bunch crossing, it is not feasible or desirable to retain data from more than a small fraction of the total number of collisions. The trigger system [80] at ATLAS selects collision events that are relevant for physics analyses. There are three consecutive levels of triggers.

The trigger system makes a selection of which events to store and record based on a large (around 100) set of conditions that are based on the con-
tent of physics objects in the event. To make the selection, preliminary identification of physics objects such as muons, electrons, photons and jets is performed on the fly. Intermediate storage of the collision data for the trigger analysis is achieved by using buffers.

The Level-1 trigger analyses fragments of event data from the calorimeter and the muon detectors. Less than 100000 out of 40 million bunch crossings a second are kept and the decision is taken within 2 $\mu$s. The Level-2 trigger analyses the regions of interest from partial event data in more detail, using a large number of processors that run fast algorithms. A few thousand events of the ones forwarded from the previous stage are selected by the Level-2 trigger and forwarded to a third level called the Event Filter, which consists of a large amounts of CPUs that can perform a detailed analysis of the events. At this stage, around 200 events per second are selected to be stored for offline analysis. In Run 2, the Event Filter is replaced by the High Level Trigger (HLT), which is merged with the Level-2 trigger.

For the $t\bar{t}V$ measurements, the conditions for triggering require the presence of at least one charged electron or muon above some threshold. This threshold is set to a transverse momentum above 24 GeV for the data collected for analysis I and II, and at 26 GeV for the additional data collected for analysis III.
4 Measurements of the $t\bar{t}V$ production cross sections

The measurements of the $t\bar{t}V$ production cross sections are presented in this chapter. Three analyses are covered:

I The first measurement at $\sqrt{s} = 8$ TeV collision energy [11], using an integrated luminosity of $20.3 \text{ fb}^{-1}$.

II An analysis using the first data available at $\sqrt{s} = 13$ TeV [12], with an integrated luminosity of $3.2 \text{ fb}^{-1}$.

III An analysis at $\sqrt{s} = 13$ TeV using all data available at the time, with an integrated luminosity of $36 \text{ fb}^{-1}$. This material is not yet in print, expected results are presented.

The general strategy is the similar for all three analyses. A number of signal regions are defined, with the selection based on the number of observed leptons, their charge and the multiplicities of jets and $b$-jets. $\tau$ leptons decay via a $W$ boson before reaching the calorimeters. They can enter the analysis either as charged lighter leptons if they decay leptonically, or as jets if they decay hadronically. Some regions are optimised for sensitivity to $t\bar{t}Z$ production and others for $t\bar{t}W$ production. The regions are sensitive to different backgrounds and so are optimised for the signal over background individually. Control regions are defined to constrain several major backgrounds.

A profile likelihood fit is then performed using all signal and control regions, to extract the cross sections for $t\bar{t}Z$ and $t\bar{t}W$ production. The systematic uncertainties enter the fit as nuisance parameters. The cut and count method is used in most signal regions except in opposite sign (OS) dilepton channel, which has very high backgrounds and is evaluated with multivariate techniques. For analysis II some of the less sensitive regions were omitted from the measurement due to limited statistics.

In the regions optimised for $t\bar{t}Z$, leptonic decays of the $Z$ boson are targeted. While the branching ratio of $Z$ to charged leptons is low, it has a distinct signature with two leptons of opposite sign charge and same flavour (OSSF). If the $Z$ boson was created on-shell, the invariant mass registered for the OSSF lepton pair should be near the mass of the $Z$ boson. In the modelling of this signal, the production of a top quark pair in association with an off-shell photon that converts into a lepton pair is also included. By specifying the final state $t\bar{t}l^+l^-$ when simulating the process, both of these production modes as well as the interference between them is taken into account.

This chapter is organised as follows. In Secs. 4.1-4.5, the general definitions and strategies common to all three analyses are listed, starting with
the definition of physics objects, proceeding to describe the signal and control regions, and finishing with outlining the strategy for fake leptons and the methods for assessing the $tWZ$ background. Next, the more specific methods and the results are presented analysis by analysis, with analysis I summarised in Sec. 4.6, analysis II in Sec. 4.7 and analysis III in Sec. 4.8.

4.1 Object definitions

Here the detection and reconstruction of the physics objects that enter the analysis is briefly explained. Data from the different detector systems needs to be assembled into objects that are relevant for physics analysis. A high efficiency for reconstructing the physics objects needs to be weighed against the risk of misidentification. The background resulting from misidentified electrons and muons for the $t\bar{t}V$ analyses is examined in Sec. 4.4.

4.1.1 Jets

Hadrons can be created from quark or gluon emissions. The hadrons form collimated sprays that are called jets [81], which deposit their energy in the Tile and Liquid Argon calorimeters. The cells in the calorimeters that get energy depositions are collected into so-called topological clusters, or topo-clusters. The topo-clusters are built in three steps. First, seed cells in the calorimeters are identified as the cells in which the energy deposition exceeds the noise by a factor of 4. Next, for the cells adjacent to the growing cluster, those that exceed the noise by a factor of 2 are added to the cluster until no more such cells are found. Finally, all cells neighbouring to the cluster after the previous step are added to the cluster. The noise, which is used to define the threshold, has one component from pile-up and another from electronic noise – these effects are of the same magnitude and are added in quadrature. The energy estimates of the clusters are calibrated, making use of properties such as energy density, depth in the calorimeter and isolation. The calibrated cluster are used as input to the anti-kt algorithm [82] to reconstruct the jets.

For jets with $p_T > 25$ GeV, the efficiency for jet reconstruction is 1.0 when using the anti-$k_T$ algorithm with distance parameter $R = 0.4$ [83]. The uncertainty on the jet energy resolution for jets with $p_T > 20$ GeV reconstructed with the anti-kt algorithm with $R=0.4$ is less than 3 %. The uncertainty on the jet energy scale is below 1 % for jets with $100 < p_T < 1500$ GeV.

The Jet Vertex Fraction (JVF) [84] is a discriminant that gives the probability of a jet to have originated from a specific vertex, used for jets with $p_T > 60$ GeV. It is measured by combining the tracks and their vertices with jets in the calorimeter and has an efficiency of 93.8 %. Lower bounds on the JVF are used to suppress the contribution of pile-up to jets. For analyses
II and III (performed in Run 2), the Jet Vertex Tagger (JVT) discriminant [85] is used in place of JVF. JVT is a multivariate algorithm, that makes use of track-based variables to suppress jets from pileup. JVT is required to have values above 0.59 for jets with a transverse momentum below 60 GeV.

4.1.2 Electrons

Electrons are absorbed by the LAr calorimeter, creating an EM shower there, and also leave a track in the ID. Reconstruction of electrons [86] is based on matching the energy depositions in the LAr calorimeter to the tracks in the ID. Isolated electrons are well identified up to pseudorapidities of $|\eta| = 2.5$.

The electrons that are of interest in the analysis are those produced in the decays of top quarks, $W$ and $Z$ bosons and in pair production from off-shell photons in the signal process $t\bar{t}l^+l^-$, as well as leptons from $\tau$ decays, where the $\tau$ has one of these origins. Such electrons are referred to as prompt in these analyses. Examples of non-prompt leptons are those created in the decays of $b$ hadrons decays and photon conversions from processes other than $t\bar{t}l^+l^-$, referred to as $\gamma+X$. Non-prompt electrons as well as jets can be misidentified as prompt leptons, such objects are referred to as fake leptons.

To distinguish isolated electrons from the backgrounds several criteria are employed, such as conditions on the shape of the electromagnetic shower, the quality of the associated track and the matching of the cluster in the LAr calorimeter to a track in the ID. At least one track matching a cluster is required in order to reconstruct the electron.

The reconstructed electrons can be classified in different ways, as described in detail in Ref. [86]. One way to classify leptons is by applying different sequential cuts to define so-called loose, medium and tight electrons. Increasing tightness indicates a subset of the looser one with more requirements on the electrons. Another way to classify electrons is based on a multivariate likelihood approach, with the categories LHLOOSE, LHmedium and LHverytight. This approach is designed to greatly reduce the background contamination. In order two estimate the contribution of fake leptons with the Matrix Method [87], the analysis definition of the electrons (or muons) needs to be relaxed. This relaxed definition is referred to as loose in the context of the Matrix Method. The definitions for both the electrons of the analysis (called Tight) and the loose electrons are listed in Table 3. The requirements for analysis III in regions targeting $t\bar{t}W$ production are motivated by the need to reduce the background from fake leptons.

Isolation requirements within a cone of $\Delta R = 0.2$ are imposed on both loose and Tight electrons, which has the implications that electrons that are within a distance of $\Delta R = 0.2$ of each other can not be resolved in the reconstruction.


<table>
<thead>
<tr>
<th>Analysis I</th>
<th>Tight electrons</th>
<th>loose electrons</th>
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<tbody>
<tr>
<td>Analysis II</td>
<td>LHmedium medium++</td>
<td></td>
</tr>
<tr>
<td>Analysis III, $t\bar{t}Z$</td>
<td>LHmedium LooseAndBLayerLH</td>
<td></td>
</tr>
<tr>
<td>Analysis III, $ttW$</td>
<td>LHTight LooseAndBLayerLH</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: The electron definitions used for the $ttV$ measurements in the trilepton and same sign dilepton channels, as described in Ref.[86]. For analysis III, different definitions for electrons are used depending on whether the region has been optimised for $t\bar{t}Z$ or for $ttW$.

4.1.3 Muons

The measurements of muons [77] are made by the Muon Spectrometer and the ID, achieving a reconstruction efficiency of around 99 % up to $|\eta| < 2.5$. Combined Muons have reconstruction performed independently in the ID and MS and thereafter combined; this method ensures the highest purity of muons. The resolution of momentum is between 1.7 % for low $p_T$ and low rapidity and 4 % at $p_T \sim 100$ GeV and high rapidity. The uncertainty on the momentum scale is 0.2 % or lower.

For muons, the same origins as for electrons are used to define prompt leptons. The muons of the analyses are required to pass the MEDIUM selection defined in [88] and to have $|\eta| < 2.4$. For the purpose of the Matrix Method, the loose definition is given by LOOSE from Ref. [88]. Isolation criteria for muons are defined within a cone of $\Delta R = 0.3$, so muons with a smaller separation than this can not be resolved.

4.1.4 B-jets

Bottom quarks that are created in collisions hadronise and then decay. As the lifetime of $b$-hadrons is of the order of 1.5 ps, they will travel some distance in the detector before decaying, forming a secondary vertex. Multivariate algorithms are employed to distinguish $b$-jets from jets containing $c$ quarks or light flavour jets. The procedure is called $b$-tagging [89] and is particularly important for analysing events involving top quarks, since each top decay produces a $b$ quark.

The multivariate MV1 algorithm based on neural networks is used for the $ttV$ analysis to tag $b$-jets while rejecting jets of other origins. MV1 combines the IP3D, SV1 and JetFitterCombNN algorithms, which are described in Ref. [90]. The properties of the $b$ quark, such as a mass of 5 GeV and its lifetime are exploited to discriminate between $b$-jets and light flavour jets. The MV1 algorithm returns a weight that is high for real $b$ jets and close to zero for jets from light quarks and gluons. The contamination from $c$ jets is
reduced by exploiting properties of the tracks and vertices of the hadrons. In analysis I, the 70 % working point of the MV1 analysis is used, meaning that the efficiency for $b$-tagging a jet that originates from a $b$ quark is 70 %. For the analyses II and III, the next version MV2c10 [91] is used at the working point of 77 % efficiency in $t\bar{t}$.

4.1.5 Missing $E_T$

Due to conservation of momentum, the total momentum in the transverse plane should be zero after a collision. In practice, due to non-perfect energy resolution and limited efficiency of the detector, the measured momentum in the transverse plane is generally non-zero. The apparent non-conservation of momentum is described by the quantity missing transverse momentum $E_T^{\text{miss}}$ [92], [93]. Computation of $E_T^{\text{miss}}$ is done by calculating the negative vector sum of the momenta in the transverse plane $p_T$ of all calibrated hard objects: photons, electrons, muons, jets, $\tau$ leptons, as well as a soft term. The soft term is obtained from energy depositions in the calorimeter associated with an event that are not part of the reconstructed calibrated objects. A large $E_T^{\text{miss}}$ could indicate the presence of particles that do not interact via the strong or electromagnetic force, such as neutrinos or possibly more exotic particles from beyond the SM. For the $t\bar{t}V$ analyses, cuts on $E_T^{\text{miss}}$ are employed to define control regions and some of the signal regions.

4.1.6 Overlap removal

In order to avoid double counting of objects, such as objects that are reconstructed as both electrons and jets, the following overlap removal scheme is applied:

- Electron candidates that share a track with a muon candidate are removed.
- If the angular separation $\Delta R$ between a jet and an electron is below 0.2, then the jet is dropped. If multiple jets are found with this requirement, only the closest one is dropped.
- If the distance in $\Delta R$ between a jet and an electron is $0.2 < \Delta R < 0.4$, then the electron is dropped.
- If the distance in $\Delta R$ between a jet and a muon is $\Delta R < 0.4$, then: if the jet has more than 2 associated tracks then the muon is dropped, otherwise the jet is removed.

4.2 Signal regions

In this section, an overview is given of the signal regions used for the $t\bar{t}V$ measurements. The definitions listed here apply for analysis III, but are

47
in general similar for analyses I and II. For the definitions valid there, please see Ref. [11] and Ref. [12]. The major changes between the analyses are summarised after the channels have been presented. When discussing the leptons and jets in the analysis, as they are sorted in terms of transverse momentum $p_T$, the “leading lepton” or “first lepton” refers to the lepton with the highest transverse momentum etc.

- The opposite sign dilepton (OS) channel is optimised for $t\bar{t}Z$ production. Two leptons of opposite sign charge are required together with at least five jets of which at least two are $b$-tagged. The large backgrounds in this region make multivariate techniques, such as a Boosted Decision Tree, to select for the signal necessary. The OS channel is divided into three regions by jet multiplicity. The definitions are given in Table 4.

- The same sign (SS) dilepton channel is optimised for $t\bar{t}W$. Two leptons of same sign charge are required together with at least one $b$-tagged jet. The SS region is split by lepton flavour, lepton charge and $b$-jet multiplicity into twelve regions. For more details, see Table 5.

- The trilepton (3L) channel is optimised for both $t\bar{t}Z$ and $t\bar{t}W$ production and split into five regions. Three of these regions target on shell $t\bar{t}Z$ production, for this reason a lepton pair with an invariant mass near the mass of the $Z$ boson is required. These three regions differ by jet multiplicity. A fourth region targets off-shell $t\bar{t}(Z^*/\gamma^*)$ production by requiring an OSSF pair outside of the $Z$-mass window and a high jet multiplicity. A fifth region targets $t\bar{t}W$ production by applying a veto against an OSSF pair and requiring a low jet multiplicity. The definitions can be found in Table 6.

- The tetralepton channel (4L) is optimised for $t\bar{t}Z$. At least one OSSF lepton pair is required. The channel is partitioned into four regions by lepton flavour relations and by $b$-jet multiplicity, as shown in Table 7.

The main changes in the definition of the regions between the analyses are as following:

- The treatment of the same sign channel is new for analysis III. While it is split there into 12 regions by lepton flavour, lepton charge and $b$-tag multiplicity, the only partitioning for analysis I was by lepton flavour (three regions) and a minimum of two $b$-tagged jets were required. Out of these, only the dimuon region was used for analysis II.

- The OS channel was not included in analysis II. There were changes in the choice of multivariate techniques between analyses I and III. For analysis I, this channel also had regions targeting $t\bar{t}W$ production.
In analyses II and III, the two trilepton regions that have veto against an OSSF lepton pair in the $Z$ window were treated as one region, targeting $ttW$ only.

<table>
<thead>
<tr>
<th>Variable</th>
<th>2l-Z-6j1b-SR</th>
<th>2l-Z-5j2b-SR</th>
<th>2l-Z-6j2b-SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton multiplicity</td>
<td>$= 2$</td>
<td>same flavour</td>
<td>opposite sign</td>
</tr>
<tr>
<td>Lepton flavour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m(l,l)$</td>
<td>$</td>
<td>m_\mu - m_Z</td>
<td>&lt; 10$ GeV</td>
</tr>
<tr>
<td>$p_T$ (1st lepton)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T$ (2nd lepton)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_{b-jets}$</td>
<td>$= 1$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$n_{jets}$</td>
<td>$\geq 6$</td>
<td>$= 5$</td>
<td>$\geq 6$</td>
</tr>
<tr>
<td>BDT output</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0$</td>
</tr>
</tbody>
</table>

Table 4: Summary of the event selection in the opposite sign dilepton signal regions used in Analysis III. A BDT is trained to separate the $ttZ$ signal from background.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two same-sign leptons</td>
<td>all</td>
</tr>
<tr>
<td>$n_{b-jets} \geq 2$</td>
<td>$* 2b$ channels</td>
</tr>
<tr>
<td>$n_{b-jets} = 1$</td>
<td>$* 1b$ channels</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 20$ GeV</td>
<td>$2\mu$ channels</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 40$ GeV</td>
<td>$e\mu$ and $2e$ channels</td>
</tr>
<tr>
<td>$H_T$ (sum of electron, muon and jet $p_T$) &gt; 240 GeV</td>
<td>all</td>
</tr>
<tr>
<td>$p_T$ (1st lepton) &gt; 27 GeV</td>
<td>all</td>
</tr>
<tr>
<td>$p_T$ (2nd lepton) &gt; 27 GeV</td>
<td>all</td>
</tr>
<tr>
<td>$n_{Jets} \geq 4$</td>
<td>$e\mu$ and $2e$ channels</td>
</tr>
<tr>
<td>$Z$-veto</td>
<td>$2\mu$ and $2e$ channels</td>
</tr>
</tbody>
</table>

Table 5: Summary of the event selection in the same-sign dilepton regions for analysis III. These criteria define a total of 12 regions.
Variable 3LZ1b4j 3LZ2b3j 3LZ2b4j 3LnoZ2b4j 3LnoZ2b2j

Leptons = 3
Leading lepton $p_T > 27$ GeV
Second and third lepton $p_T > 20$ GeV
One OSSF lepton pair required required vetoed vetoed
Z-like OSSF pair required required vetoed vetoed
Sum of lepton charges = 1 ≥ 2 ≥ 2 ≥ 2
$n_{b-jets}$ ≥ 4 ≥ 3 ≥ 4 ≥ 4

Table 6: Summary of the event selection in the trilepton signal regions for analysis II. For analyses I and II, the cut on the leptons is instead at 25 GeV. Also, for these two analyses there was only one 3LnoZ region, with at least 2 jets of which 2 are $b$-tagged and without a requirement on the presence of an OSSF pair.

<table>
<thead>
<tr>
<th>Region</th>
<th>Z2 leptons</th>
<th>$p_T$</th>
<th>$p_T$</th>
<th>$E_T^{miss}$</th>
<th>N b-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>4L-DF-1b</td>
<td>$e^\mp \mu^\mp$</td>
<td>$&gt;$ 7</td>
<td>$&gt;$ 35</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>4L-DF-2b</td>
<td>$e^\mp \mu^\mp$</td>
<td>$&gt;$ 10</td>
<td>-</td>
<td>-</td>
<td>$\geq$ 2</td>
</tr>
<tr>
<td>4L-SF-1b</td>
<td>$e^\pm e^\mp$ or $\mu^\pm \mu^\mp$</td>
<td>$&gt;$ 7</td>
<td>$&gt;$ 25</td>
<td>$&gt;$ 40 or $&gt;$ 80*</td>
<td>1</td>
</tr>
<tr>
<td>4L-SF-2b</td>
<td>$e^\pm e^\mp$ or $\mu^\pm \mu^\mp$</td>
<td>$&gt;$ 10</td>
<td>-</td>
<td>- or $&gt;$ 40*</td>
<td>$\geq$ 2</td>
</tr>
</tbody>
</table>

Table 7: Definitions of the four tetralepton signal regions for analysis III. The definitions in analysis I and II are similar. Four leptons are required with $p_T > 7$ GeV. Out of the four leptons, the OSSF pair that has the invariant mass closest to the mass of the $Z$ boson is called $Z_1$, the remaining lepton pair is referred to as $Z_2$. *The first requirement listed for $E_T^{miss}$ is applied if the $Z_2$ lepton pair has an invariant mass in the $Z$-mass window, otherwise the second listed requirement on $E_T^{miss}$ is applied.
4.3 Control regions

The main background to $t\bar{t}Z$ in the trilepton channel is $WZ$ production. While the total theoretical cross section for $WZ$ production is known to a high precision, the prediction in a region where a high jet multiplicity is required is much less certain. The trilepton signal regions require either three or at least four jets, so an estimate that is valid in these regions is needed.

To get an estimate of the $WZ$ production cross section at high jet multiplicity and with three charged leptons present, a control region is constructed by requiring exactly three jets, none of which are $b$-tagged, and three leptons. Two of the leptons are required to be of the same flavour and opposite sign charge, and have an invariant mass within 10 GeV of the $Z$ boson mass. These requirements define a region that is dominated by $WZ$ production, as is shown in the yield tables in Secs. 4.6-4.8. It is referred to as CRWZ. A fit to data in CRWZ gives a prediction for the $WZ$ cross section in this region of phase space together with a normalisation uncertainty. Moreover, extrapolation uncertainties are derived from this control region into the signal regions by constructing transfer factors under different theoretical assumptions. While the normalisation uncertainty is of the order of 20 % or less, depending on the amount of data available for each analysis, the extrapolation uncertainty can be up to +100 %, depending on the jet multiplicity of the signal region and on the method. A similar procedure is performed for the $ZZ$ background to the tetralepton signal regions. The definitions of the two control regions can be found in Table 8.

| Region | n leptons | n Jets | n b-jets | $E_T^{\text{miss}}$ | $|m_{Z1} - m_Z|$ | $|m_{Z2} - m_Z|$ |
|--------|-----------|--------|----------|-----------------|----------------|----------------|
| CRWZ   | 3         | 3      | 0        | $> 40$ GeV      | $< 10$ GeV    | $< 10$ GeV     |
| CRZZ   | 4         | -      | 0        | $< 40$ GeV      | $< 10$ GeV    | $< 10$ GeV     |

Table 8: The definitions for the control regions CRWZ and CRZZ. $Z_1$ refers to the OSSF pair with the mass closest to the mass of the $Z$ boson. $Z_2$ refers to the other lepton pair in the tetralepton channel.

Control regions to estimate the number of fake leptons are also employed. The method to do so is described below.

4.4 Fake leptons, overview

The background from fake leptons needs to be estimated for the analyses. The data-driven matrix method (MM) [87] is employed for this purpose. As input, the method needs the efficiencies of prompt leptons, also referred to as real leptons ($r$), the probability to misidentify an object as a prompt lepton (called the fake rate $f$), as well as data in the given region, partitioned in Loose (L) and Tight (T). The Tight definition is taken to be the same as the
lepton definition of the analysis. The criteria are relaxed to define a loose selection (l) and the lepton fulfill the loose but not the tight requirements are called Loose (L). From the number of Tight and Loose leptons, knowing the real efficiency $r$ and fake rate $f$, one can change the basis from Loose and Tight to get an estimate for the number of real and fake leptons from inverting the matrix equation.

$$N_i = M_{ij} n_j.$$  \hfill (58)

In this equation, $N_i$ gives the number of leptons partitioned into Loose and Tight, $M_{ij}$ contains the real efficiencies and fake rates, and $n_j$ gives the number of leptons expressed in terms of real and fake leptons. In a region with two loose leptons present, the explicit form of the matrix method is as following:

$$N_i = \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix},$$ \hfill (59)

$$M_{ij} = \begin{pmatrix} r_1 r_2 \\ r_1 (1 - r_2) \\ (1 - r_1) r_2 \\ (1 - r_1)(1 - r_2) \end{pmatrix} \begin{pmatrix} r_1 f_2 \\ r_1 (1 - f_2) \\ (1 - r_1) f_2 \\ (1 - r_1)(1 - f_2) \end{pmatrix} \begin{pmatrix} f_1 r_2 \\ f_1 (1 - r_2) \\ (1 - f_1) r_2 \\ (1 - f_1)(1 - r_2) \end{pmatrix} \begin{pmatrix} f_1 f_2 \\ f_1 (1 - f_2) \\ (1 - f_1) f_2 \\ (1 - f_1)(1 - f_2) \end{pmatrix},$$ \hfill (60)

$$n_j = \begin{pmatrix} N_{LL} \\ N_{RL} \\ N_{LR} \\ N_{FF} \end{pmatrix}. \hfill (61)$$

Here $N_{TL}$, for example, denotes that the leading lepton is Tight and that the second is in Loose. The index 1 in $r_1, f_1$ refers to the efficiencies for the leading lepton and $r_2, f_2$ to the efficiencies for the subleading lepton. The method can be extended to regions containing three leptons.

Before applying the Matrix Method, the parameters $r$ and $f$ need to be determined. For this purpose, a likelihood fit is performed to the matrix equation (58) in a control region orthogonal to the signal regions, containing exactly two loose leptons. The real efficiencies $r$ and fake rates $f$ are treated as free parameters in the fit. Opposite sign charge is required to fit for $r$ and same sign in the fit for $f$. The rates thus derived in control regions are then applied in the other regions relevant for the analysis. The explicit form of the matrix method in a region where three loose leptons are present is given in Ref. [10].

For analysis I, Tight was defined such that is was not a subset of loose and so did not meet the requirements of the matrix method. Therefore the rates derived in this way needed to be corrected, which was done iteratively.
The control regions where the fake rates were measured in analysis I had a requirement of exactly one $b$-tagged jet. In order to assess the uncertainty on the fake lepton background, the definition for the region where the fake rates were derived was varied by changing the jet multiplicity. The resulting difference in fake lepton yields was used as a systematic uncertainty. For analysis II, the same method was applied, but by choosing loose in such a way that Tight is a subset of it, no iterative corrections were needed.

For the analysis III, large amounts of data is available and a control region requiring at least two $b$-tagged jets can be constructed to derive the rates. Comparisons of the rates in a region with exactly one $b$-tagged jet are compared with the rates from region with at least two $b$-tagged jets in Sec. 4.8.

4.5 Background estimation with Diagram Removal

A major background to $t\bar{t}Z$ in the trilepton and tetralepton channel is $tWZ$ production. The assessment of the background is performed at NLO, using the Diagram Removal method, as described below. This method is also used for the evaluation of the minor background $Wt$, which has similarities to $tWZ$ in terms of modelling. Results for studies of both the $Wt$ and $tWZ$ processes are presented here.

For $Wt$, the DR1 and DR2 predictions are compared for $Wt$, using MG5__aMC@NLO [24] for the event generation, with the top quarks and $W$ bosons required to decay leptonically in MadSpin [94] and parton showering provided by HERWIG++ [95]. For comparison, the nominal ATLAS prediction of the time is also shown, which uses POWHEG-BOX [56], [96] with DR1 and interfaced with Pythia6 [97] for parton showering. The Diagram Subtraction prediction with otherwise similar settings as the nominal prediction is also shown. Again, the presence of two charged leptons is required. The resulting total cross sections are shown in Table 9.

In performing the subtraction of the doubly resonant term for the DR2 prediction, a divergence appears when the top quark is on shell. This is regularised by redefining the top quark propagator from the original expression in the MG5__aMC@NLO code:

\[
\frac{1}{p_t^2 - m_t^2} \rightarrow \frac{1}{p_t^2 - m_t^2 + i\Gamma_t},
\]

where $p_t$ is the momentum of the top quark, $m_t$ is its mass and $\Gamma_t$ is its width.

As shown in Table 9, the interference of $Wt$ with $t\bar{t}$ is destructive and found to be of the order of 10 %, in agreement with Ref. [57].

In Fig. 21, the jet multiplicity is compared for $Wt$ modelling between the DR1, DR2 and DS predictions. The selection requires two leptons with $p_T > 20$ GeV, $|\eta| < 2.5$ and that the jets have transverse momentum $p_T > 25$.
<table>
<thead>
<tr>
<th>Method</th>
<th>Total cross section [pb]</th>
<th>Difference w.r.t. DR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG5_aMC@NLO DR1+P6</td>
<td>7.87</td>
<td></td>
</tr>
<tr>
<td>MG5_aMC@NLO DR2+P6</td>
<td>7.09</td>
<td>-10 %</td>
</tr>
<tr>
<td>Powheg-Box DR1+HPP</td>
<td>7.16</td>
<td></td>
</tr>
<tr>
<td>Powheg-Box DS+HPP</td>
<td>6.82</td>
<td>-5 %</td>
</tr>
</tbody>
</table>

Table 9: The cross section for Wt, with the presence of two charged leptons required. Four predictions are compared: DR1 and DS evaluated with Powheg and DR1 and DR2 with MG5\_aMC@NLO. The difference with respect to the DR1 prediction for each generator is shown.

GeV and pseudorapidity $|\eta| < 2.5$. These cuts are designed to be similar to the preselection for the Wt measurement by ATLAS [98]. Lower yields at high jet multiplicity are found for the methods that evaluate the interference (DR2, DS) compared to the DR1 prediction. This is consistent with a destructive interference, as $t\bar{t}$ is characterised by a higher jet multiplicity than Wt – therefore the interference with t\bar{t} should increase at high jet multiplicity.

![Figure 21](image1.png)

Figure 21: The jet multiplicity for Wt production with dileptonic decays [98], shown in a fiducial region. The nominal DR1 Powheg-Box prediction is shown in black, the Powheg-Box DS prediction in purple, the MG5\_aMC@NLO DR1 in blue and the MG5\_aMC@NLO DR2 in red. The ratio is computed with respect to the nominal distribution from Powheg-Box.

For tWZ production, the modelling is more complicated than for Wt. In
addition to the interference with $ttZ$, diagrams that arise from $tt$ production followed by a three-body decay $t \rightarrow WbZ$ appear. The event generation for the $tWZ$ process is performed with MG5_aMC@NLO. It is interfaced with MADSPIN to model the decays of top quarks, $W$ and $Z$ bosons. A requirement is placed on the $Z$ bosons to decay into two charged leptons ($e^+e^-$, $\mu^+\mu^-$ or $\tau^+\tau^-$). The parton showering is simulated with PYTHIA8 [27]. The difference in the total prediction with DR1 and DR2 is considerably larger than for $Wt$: 28 % inclusively, see Table 10. This is of a similar magnitude to the interference of $tWH$ with $ttH$ [57].

<table>
<thead>
<tr>
<th>Method</th>
<th>Cross section [fb]</th>
<th>Difference w.r.t. DR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG5_aMC@NLO DR1 +P8</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>MG5_aMC@NLO DR2+P8</td>
<td>12.2</td>
<td>-28%</td>
</tr>
</tbody>
</table>

Table 10: The total cross section for the two $tWZ$ predictions, with the $Z$ boson required to decay to two charged leptons. The difference with respect to the DR1 prediction is shown.

Figure 22: Jet $p_T$ (left) and leading jet $p_T$ (right) for $tWZ$ production with leptonic $Z$ decays, shown in a fiducial region [13]. The nominal prediction from MG5_aMC@NLO with DR1 is shown in blue and the MG5_aMC@NLO DR2 in red. The ratio is computed with respect to the DR1 prediction.

A couple of distributions are shown for these DR1 and DR2 predictions in Fig. 24, with the modelling of the $p_T$ of the $Z$ boson and the jet multiplicity is examined. A selection is applied for the plots, requiring at least two charged leptons with $p_T > 15$ GeV and $|\eta| < 2.5$ and at least three jets with $p_T > 25$ GeV, $|\eta| < 2.5$. This selection is chosen to be close to the selection for the $ttZ$ analyses by ATLAS, where $tWZ$ appears as a major background. It can be seen in Fig. 24, that if the $Z$ boson has a transverse momentum above around 200 GeV, the difference with respect to the DR1 prediction
is not covered by an overall uncertainty of 28%. It is important to keep such effects in mind in the context of differential measurements in regions where $tWZ$ is present. The jet multiplicity shows a similar behaviour to the corresponding plot for $Wt$ and the same argument applies there.

The diagrams that contribute to the overlap between $tWZ$ and other top quark processes are illustrated in Fig. 23 and can be classified as following:

a) The top propagator undergoes what looks like a top quark decay ($t \rightarrow Wb$).

b) The top propagator emits a Z boson before decaying ($t \rightarrow tZ \rightarrow tWZ$).

c) The top quark propagator seems to undergo a three-body decay ($t \rightarrow bW \rightarrow bWZ$).

These kinds of diagrams are shown in Fig 23. The type a) diagrams overlaps with $t\bar{t}Z$ and type c) with $t\bar{t}$. The b)-type diagram can both be viewed as $t\bar{t}Z$ followed by a top quark decay, or as a three-body decay of the top quark propagator – it overlaps with both $t\bar{t}Z$ and $t\bar{t}$ production. This categorisation is made in order to examine what type of diagrams give the largest contribution to the predicted cross section.

To study the effect of the different kinds of overlapping diagrams, a hybrid form of Diagram Removal was tried by the author. In this approach, a part of the overlapping diagrams are removed with the DR1 method while others are allowed to be present in the interference term (as in DR2). The comparison is performed at parton level (after event generation, before modelling the decay of the top quark and the bosons). At parton level, the difference between DR1 and DR2 is found to be 22% rather than the 28% seen after simulating decays and parton showering.

With the hybrid method, it was evaluated that a)-type diagrams reduce the DR1 prediction by 11%, b)-type diagrams increase it by 6% and c)-type diagrams reduce it by 17%. These results lead to the conclusion that all three kinds of diagrams are important for the DR2 prediction, not least the ones corresponding to rare three-body top decays. The interference of singly resonant diagrams with a)- and c)-type diagrams seems to be destructive while the interference with b)-type diagrams seems constructive.

The DR2 method has been verified for $Wt$ and $tW H$ in Ref. [57]. One of the comparisons performed was simulating $WbWb$ at LO and subtracting $t\bar{t}$ – this leaves $Wt$ production and the interference with $t\bar{t}$. A better agreement was found with DR2 than with DR1 for $Wt$, and similarly for $tW H$. In order to do such a test for $tWZ$, $t\bar{t}Z$ and $t\bar{t}$ followed by a three-body decay would need to be subtracted from $WbWbZ$. It turned out that it was not straightforward to model the three-body decay $t \rightarrow WbZ$ in $\text{MG5}_a\text{MC@NLO}$. Further work is required in order to perform a validation test of the DR2 prediction.
Figure 23: Production diagrams for $tWZ$. The top left diagram shows a singly resonant $tWZ$ diagram. The type a) diagram to the top right overlaps with $ttZ$. The bottom left type b) diagram to the overlaps with both $ttZ$ and with $tt$ production followed by a three-body decay. The bottom right type c) diagram overlaps only with $tt$ production followed by a three-body top quark decay.

A different approach to DR for $tWZ$ production could be to only consider tops that create a $Wb$ pair as doubly resonant, treating the propagators that give rise to $WbZ$ as singly resonant. With the masses of these three particles adding up to only a couple of GeV above the central value of the measured top quark mass, it is not obvious how top propagators of the kind $t \rightarrow bWZ$ should be treated. Ideally, the interference effects would be captured by simulating $WbWbZ$ at NLO in QCD, but such calculations are not available for the time being. Before either of the Diagram Removal schemes are validated, taking the envelope of the available predictions at NLO seems as a reasonable approach.

In summary, the studies described above were used to derive a new baseline for the $tWZ$ background estimate at NLO in QCD for the $ttV$ analysis, using DR1 as the nominal prediction. The uncertainty on the modelling is assessed by the total difference between the DR1 and DR2 prediction. This number was found to be $-22\%$ at parton level – this number was applied for analysis II. After hadronisation and applying the A14 tune [99], the difference was found to be $-28\%$, this number is used as the uncertainty in analysis III. Additionally an uncertainty up of $+10\%$ is applied in both analyses to cover modelling uncertainties related to variations for the DR1
Figure 24: The $p_T$ of the $Z$-boson (left) and the jet multiplicity (right) for $tWZ$ production with leptonic $Z$ decays, shown in a fiducial region [13]. The $Z$ boson is required to originate from the hard scattering process. The nominal prediction from MG5_aMC@NLO with DR1 is shown in blue and the MG5_aMC@NLO DR2 in red. The ratio is computed with respect to the DR1 prediction. The overflow is included in the last bin.

4.6 Analysis I at 8 TeV, 20.3 fb$^{-1}$

The first ATLAS measurement of $t\bar{t}Z$ and $t\bar{t}W$ production [11] was performed at 8 TeV collision energy, using an integrated luminosity of 20.3 fb$^{-1}$.

4.6.1 Event yields I

The estimated signal and background composition and the data collected for analysis I is shown in Table 11 for the SS and trilepton channels. The term yield refers to the number of events predicted or observed.

<table>
<thead>
<tr>
<th>Region</th>
<th>$t + X$ Bosons</th>
<th>MisID</th>
<th>Background</th>
<th>$tW$</th>
<th>$tZ$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$\ell$-SS</td>
<td>0.06±0.13</td>
<td>0.17±0.10</td>
<td>8.9±2.4</td>
<td>9.8±2.6</td>
<td>2.97±0.30</td>
<td>0.95±0.23</td>
</tr>
<tr>
<td>$\mu$-SS</td>
<td>1.9 ± 0.35</td>
<td>0.39 ± 0.28</td>
<td>14.1 ± 4.5</td>
<td>16.4 ± 5.1</td>
<td>8.67 ± 0.76</td>
<td>2.16 ± 0.51</td>
</tr>
<tr>
<td>2$\mu$-SS</td>
<td>0.94 ± 0.17</td>
<td>0.25 ± 0.14</td>
<td>0.93 ± 0.55</td>
<td>2.12 ± 0.86</td>
<td>4.79 ± 0.40</td>
<td>1.12 ± 0.27</td>
</tr>
<tr>
<td>3$\ell$-0b3j</td>
<td>1.11 ± 0.32</td>
<td>0.25 ± 0.14</td>
<td>0.93 ± 0.55</td>
<td>2.12 ± 0.86</td>
<td>4.79 ± 0.40</td>
<td>1.12 ± 0.27</td>
</tr>
<tr>
<td>3$\ell$-1b4j</td>
<td>1.58 ± 0.42</td>
<td>3.8±1.3</td>
<td>2.4±1.1</td>
<td>7.8±1.6</td>
<td>0.14±0.05</td>
<td>7.1±1.6</td>
</tr>
<tr>
<td>3$\ell$-2b3j</td>
<td>1.29 ± 0.34</td>
<td>0.68 ± 0.33</td>
<td>0.19 ± 0.13</td>
<td>2.16 ± 0.42</td>
<td>0.21 ± 0.07</td>
<td>2.76 ± 0.69</td>
</tr>
<tr>
<td>3$\ell$-2b4j</td>
<td>1.00 ± 0.29</td>
<td>0.48±0.24</td>
<td>0.42±0.37</td>
<td>1.93±0.49</td>
<td>0.14±0.07</td>
<td>6.6±1.6</td>
</tr>
<tr>
<td>3$\ell$-noZ-2b</td>
<td>1.06±0.25</td>
<td>0.27±0.17</td>
<td>1.31±0.90</td>
<td>2.7±0.9</td>
<td>3.7±0.9</td>
<td>1.23±0.32</td>
</tr>
</tbody>
</table>

Table 11: The yields of the analysis I. misID refers to both misidentified leptons and leptons with misidentified charge.
4.6.2 The WZ background I

The WZ background is measured in CRWZ, which is defined in Sec. 4.3. In analysis I, no cut on $E_T^{\text{miss}}$ is employed, but instead a cut on transverse mass $^{2}$ of $E_T^{\text{miss}}$ and the lepton that is not associated with the Z-decay or $\gamma^*$ conversion has a cut of $m_T^W > 50$ GeV. The WZ signal strength (the ratio of measured to theoretical cross section) is measured in the control region to be $\mu_{WZ} = 0.98 \pm 0.20$. The distribution in $E_T^{\text{miss}}$ and in lepton flavour is shown in Fig. 25.

![Figure 25: The $E_T^{\text{miss}}$ (left) and lepton multiplicity (right) in CRWZ in analysis I. The WZ process is shown in turquoise. The main background is ZZ production, shown in purple.](image)

Transfer factors from CRWZ to the signal regions are derived using predictions from the Powheg-Box and Sherpa [100] generators. The difference is taken as a systematic uncertainty and found to be in the range 20-35\%, as shown in Table 12. A different method – studying the effect of varying the theoretical input parameters was also employed, which gave an uncertainty of 20\%. The values in Table 12 were used to avoid underestimating the uncertainty.

4.6.3 Results I

A fit to the data considering the $t\bar{t}Z$ and $t\bar{t}W$ processes simultaneously gives a measured $t\bar{t}W$ cross section of $\sigma_{t\bar{t}W} = 339^{+116}_{-90}$ (stat.) $\pm 44$ (syst.) fb $= 369^{+109}_{-91}$ fb. For $t\bar{t}Z$, the measured cross section is $\sigma_{t\bar{t}Z} = 176^{+52}_{-48}$ (stat.) $\pm 24$ (syst.) $= 176^{+52}_{-48}$ fb. The results agree with the SM prediction, shown in Table 13. The significance for the exclusion of the background-only hypoth-

\[M_T^2 = E_{T,1} \cdot E_{T,2}(1 - \cos \phi),\]

where $\phi$ is the azimuthal opening angle between the particles and $E_T$ is the energy in the transverse plane.

---

$^{2}$The transverse mass for two particles, denoted with index 1 and 2, is evaluated as $M_T^2 = \left| E_{T,1} \cdot E_{T,2}(1 - \cos \phi) \right|$, where $\phi$ is the azimuthal opening angle between the particles and $E_T$ is the energy in the transverse plane.
Table 12: The transfer factors for WZ extrapolations, derived by computing the ratio of the yield in the SR over the yield in CRWZ. The differences between the transfer factors from Sherpa and Powheg are taken as a systematic uncertainty.

<table>
<thead>
<tr>
<th></th>
<th>CRWZ</th>
<th>3LZ1b4j</th>
<th>3LZ2b3j</th>
<th>3LZ2b4j</th>
<th>3LnoZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield, Sherpa</td>
<td>58.21</td>
<td>9.72</td>
<td>0.55</td>
<td>0.43</td>
<td>1.26</td>
</tr>
<tr>
<td>Yield, Powheg</td>
<td>37.97</td>
<td>6.13</td>
<td>0.30</td>
<td>0.20</td>
<td>0.74</td>
</tr>
<tr>
<td>Transfer factor, Sherpa</td>
<td>-</td>
<td>0.17</td>
<td>0.0094</td>
<td>0.0074</td>
<td>0.022</td>
</tr>
<tr>
<td>Transfer factor, Powheg</td>
<td>-</td>
<td>0.16</td>
<td>0.0079</td>
<td>0.0053</td>
<td>0.019</td>
</tr>
<tr>
<td>Relative difference</td>
<td>-</td>
<td>0.033</td>
<td>0.16</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>-</td>
<td>0.20</td>
<td>0.26</td>
<td>0.35</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The impact of the systematic uncertainties on the signal uncertainty is shown in Table 14. These are calculated by removing one source of uncertainty at a time, evaluating the resulting uncertainty on the signal and subtracting this number from the total uncertainty in quadrature. As can be seen from Table 14, the precision is limited by the statistical uncertainty. The leading systematic uncertainty for the t\bar{t}Z measurement is related to the modelling of background processes (8.0 %), particularly for WZ and tWZ. It is followed by the uncertainty on reconstructed objects (7.4 %), particularly electrons. The leading systematic uncertainty for t\bar{t}W is the modelling of fake leptons and of leptons with a misidentified charge.
Figure 26: The post-fit yields for analysis I, split by channel. The signal processes are shown in yellow for $t\bar{t}Z$ and in red for $t\bar{t}W$. The $tWZ$ background is included together with $WZ$ and $ZZ$ in what is called $VV$, shown in turquoise. The total uncertainty on the prediction is shown by the shaded bands.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>( \sigma_{t\bar{t}Z} )</th>
<th>( \sigma_{t\bar{t}W} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>4.6 %</td>
<td>3.5 %</td>
</tr>
<tr>
<td>Reconstructed objects</td>
<td>7.4 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Backgrounds from simulation</td>
<td>8.0 %</td>
<td>5.8 %</td>
</tr>
<tr>
<td>Fake leptons and charge misID</td>
<td>3.0 %</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>4.5 %</td>
<td>1.8 %</td>
</tr>
<tr>
<td>Total systematic</td>
<td>13 %</td>
<td>12 %</td>
</tr>
<tr>
<td>Statistical</td>
<td>+30 % / -27%</td>
<td>+24 % / -21%</td>
</tr>
<tr>
<td>Total</td>
<td>+33 % / -29%</td>
<td>+27 % / -24%</td>
</tr>
</tbody>
</table>

Table 14: The impact of the uncertainties on the signal processes in analysis I.
4.7 Analysis II at 13 TeV, 3.2 fb$^{-1}$

Analysis II [12] is performed at a higher collision energy of 13 TeV, with an integrated luminosity of 3.2 fb$^{-1}$. At 13 TeV, the increase in the predicted production cross section is a factor of 3.5 for $t\bar{t}Z$ and 2.4 for $t\bar{t}W$.

4.7.1 Yields II

The yields of analysis II are given in Table 15 for the trilepton and same sign dilepton channels.

4.7.2 WZ II

The $WZ$ signal strength is measured to be $\mu_{WZ} = 1.11 \pm 0.30$. The shape uncertainties on the $WZ$ background are rederived at 13 TeV and a conservative estimate of $+100\% -50\%$ in all trilepton regions is assigned.

4.7.3 Results II

The measured cross sections are $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3\,pb$ and $\sigma_{t\bar{t}W} = 1.5 \pm 0.8\,pb$. This agrees with the SM prediction within uncertainties, as shown in Table 16. Again the central value for the measured $t\bar{t}W$ cross section is higher than expected. The measurement is limited by statistical uncertainties, as seen in Table 16. The correlation between the measured $t\bar{t}Z$ and $t\bar{t}W$ cross sections is 0.13.

The observed significance over the null hypothesis 3.9 $\sigma$ for $t\bar{t}Z$ and 2.2 $\sigma$ for $t\bar{t}W$, while the expected sensitivities are 3.4 $\sigma$ and 1.0 $\sigma$ respectively. In the trilepton channel, the observed significance for $t\bar{t}Z$ is 3.3 $\sigma$ (3.7 $\sigma$ expected). The significance in this channel for $t\bar{t}W$ is 1.0 $\sigma$ (1.4 $\sigma$ expected).

The post-fit yields of all the signal and control regions are shown in Fig. 27.

The impact of the systematic uncertainties on the signal is shown in Table 17. This measurement is statistically limited. The uncertainty on reconstructed objects, especially electrons, is dominating the systematic uncertainty for $t\bar{t}Z$. The modelling of fake leptons dominates the systematic uncertainty for $t\bar{t}W$. 
Figure 27: The post-fit yields of analysis II. The signal processes are shown in blue for $t\bar{t}Z$ and in red for $t\bar{t}W$. The fake lepton background is shown in yellow, the $WZ$ background in magenta, $ZZ$ in orange and other processes in green. The total uncertainty on the prediction is shown by the shaded bands.
Table 15: The yields of analysis II.

<table>
<thead>
<tr>
<th>Region</th>
<th>t + X</th>
<th>Bosons</th>
<th>Fakes</th>
<th>Background</th>
<th>ttW</th>
<th>ttZ</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2μ−SS</td>
<td>0.94 ± 0.08</td>
<td>0.12 0.05</td>
<td>1.5 ± 1.3</td>
<td>2.5 ± 1.3</td>
<td>2.32 0.33</td>
<td>0.70 0.10</td>
<td>9</td>
</tr>
<tr>
<td>CRWZ</td>
<td>0.51 ± 0.13</td>
<td>26.9 ± 2.2</td>
<td>2.2 ± 1.8</td>
<td>29.5 ± 2.8</td>
<td>0.015 ± 0.004</td>
<td>0.80 ± 0.13</td>
<td>33</td>
</tr>
<tr>
<td>3LZ1b4j</td>
<td>1.14 ± 0.24</td>
<td>3.3 ± 2.2</td>
<td>2.2 ± 1.7</td>
<td>6.7 ± 2.8</td>
<td>0.036 ± 0.011</td>
<td>4.3 ± 0.6</td>
<td>7</td>
</tr>
<tr>
<td>3LZ2b3j</td>
<td>0.58 ± 0.19</td>
<td>0.22 ± 0.18</td>
<td>&lt;0.001</td>
<td>0.80 ± 0.26</td>
<td>0.083 ± 0.014</td>
<td>1.93 ± 0.28</td>
<td>4</td>
</tr>
<tr>
<td>3LZ2b4j</td>
<td>1.08 ± 0.25</td>
<td>0.5 ± 0.4</td>
<td>&lt;0.001</td>
<td>1.6 ± 0.5</td>
<td>0.065 ± 0.013</td>
<td>5.5 ± 0.7</td>
<td>8</td>
</tr>
<tr>
<td>3LnoZ</td>
<td>0.95 ± 0.11</td>
<td>0.14 ± 0.12</td>
<td>3.6 ± 2.2</td>
<td>4.7±2.2</td>
<td>1.59 ±0.28</td>
<td>1.45 ± 0.20</td>
<td>10</td>
</tr>
</tbody>
</table>
### Table 16: The expected and observed results for analysis II. The uncertainty on the measurement is broken down into a systematic uncertainty (stated first) and a statistical uncertainty (stated second). Significance refers to the rejection of the null hypothesis.

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}Z$ cross section [pb]</td>
<td>$0.84 \pm 0.09$</td>
<td>$0.92 \pm 0.29$ (stat) $\pm 0.10$ (syst)</td>
</tr>
<tr>
<td>$t\bar{t}Z$ significance</td>
<td>$3.4\sigma$</td>
<td>$3.9\sigma$</td>
</tr>
<tr>
<td>$t\bar{t}W$ cross section [pb]</td>
<td>$0.60 \pm 0.08$</td>
<td>$1.50 \pm 0.72$ (stat) $\pm 0.33$ (syst)</td>
</tr>
<tr>
<td>$t\bar{t}W$ significance</td>
<td>$1.0\sigma$</td>
<td>$2.2\sigma$</td>
</tr>
</tbody>
</table>

### Table 17: The impact of the uncertainties on the signal for analysis II.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\sigma_{t\bar{t}Z}$</th>
<th>$\sigma_{t\bar{t}W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.6 %</td>
<td>3.1 %</td>
</tr>
<tr>
<td>Reconstructed objects</td>
<td>8.3 %</td>
<td>9.3 %</td>
</tr>
<tr>
<td>Backgrounds from simulation</td>
<td>5.3 %</td>
<td>3.1 %</td>
</tr>
<tr>
<td>Fake leptons and charge misID</td>
<td>3.0 %</td>
<td>19 %</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>2.3 %</td>
<td>4.2 %</td>
</tr>
<tr>
<td>Total systematic</td>
<td>11 %</td>
<td>22 %</td>
</tr>
<tr>
<td>Statistical</td>
<td>31 %</td>
<td>48 %</td>
</tr>
<tr>
<td>Total</td>
<td>32 %</td>
<td>53 %</td>
</tr>
</tbody>
</table>

Table 17: The impact of the uncertainties on the signal for analysis II.
4.8 Analysis III at 13 TeV, 36 fb$^{-1}$

4.8.1 Yields III

The expected yields for the analysis in the trilepton regions and for the SS regions and are shown in Tables 18 and 19. The background that is denoted $\gamma + X$ consists of background processes that give rise to fake leptons through photon conversions. This prediction is taken from simulation and rescaled by fake factors that have been derived in control regions.

<table>
<thead>
<tr>
<th></th>
<th>3LZ1b4j</th>
<th>3LZ2b3j</th>
<th>3LZ2b4j</th>
<th>3LnoZ2b4j</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttZ$</td>
<td>29.88 ± 3.72</td>
<td>5.90 ± 0.97</td>
<td>16.63 ± 3.71</td>
<td>12.71 ± 3.67</td>
</tr>
<tr>
<td>$tW$</td>
<td>0.35 ± 0.40</td>
<td>0.52 ± 0.58</td>
<td>0.83 ± 0.86</td>
<td>3.67 ± 3.80</td>
</tr>
<tr>
<td>$WZ$</td>
<td>17.84 ± 5.89</td>
<td>7.05 ± 3.76</td>
<td>3.32 ± 1.59</td>
<td>1.05 ± 0.33</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.70 ± 0.40</td>
<td>0.53 ± 0.08</td>
<td>0.68 ± 0.23</td>
<td>0.33 ± 0.16</td>
</tr>
<tr>
<td>$tZ$</td>
<td>1.95 ± 0.64</td>
<td>3.41 ± 1.11</td>
<td>3.66 ± 1.17</td>
<td>0.32 ± 0.13</td>
</tr>
<tr>
<td>$tWZ$</td>
<td>4.03 ± 1.77</td>
<td>5.77 ± 2.15</td>
<td>2.07 ± 0.51</td>
<td>0.67 ± 0.29</td>
</tr>
<tr>
<td>$tH$</td>
<td>0.85 ± 0.12</td>
<td>1.42 ± 0.19</td>
<td>0.51 ± 0.08</td>
<td>4.87 ± 0.63</td>
</tr>
<tr>
<td>Other</td>
<td>0.14 ± 0.08</td>
<td>0.37 ± 0.37</td>
<td>0.87 ± 0.84</td>
<td>2.13 ± 1.08</td>
</tr>
<tr>
<td>DD fakes</td>
<td>4.39 ± 1.80</td>
<td>4.01 ± 1.60</td>
<td>1.17 ± 0.82</td>
<td>3.16 ± 1.44</td>
</tr>
<tr>
<td>$\gamma + X$ fakes</td>
<td>1.31 ± 0.99</td>
<td>0.49 ± 0.42</td>
<td>0.62 ± 0.81</td>
<td>4.88 ± 1.98</td>
</tr>
<tr>
<td>Total</td>
<td>62.43 ± 8.12</td>
<td>80.57 ± 9.51</td>
<td>30.36 ± 4.90</td>
<td>33.78 ± 6.31</td>
</tr>
</tbody>
</table>

Table 18: The expected yields for the trilepton channel in analysis III. The $\gamma + X$ background has been scaled by fake factors. The 3LnoZ2b2j region is still subject to change and is not included here.
Table 19: Yield table for the same sign dilepton channel. FakeMM give the estimate of fake leptons through the matrix method. The fake factor prediction in this channel is not used in the analysis, but is included for comparison to FakeMM+DDCF+γ+X. The γ+X prediction has been scaled by fake factors. Statistical and systematic uncertainties are included. In the names of the signal regions, MM denotes that the charge of both leptons is negative and PP that it positive. The number of b-tagged jets is specified by the ending of the name, with “one” referring to exactly one b-tagged jet and “twob” to at least two b-tagged jets.

| Signal Region | SSsemuMMoneb | SSsemuMMtwob | SSsemalPoneb | SSsemalPtwob | SSsemalMMoneb | SSsemalMMtwob | SSSsemalPoneb | SSSsemalPtwob | SSsemalMMoneb | SSsemalMMtwob | SSsemalPoneb | SSsemalPtwob | SSsemalMMoneb | SSsemalMMtwob | SSsemalMMoneb | SSsemalMMtwob | SSsemalPoneb | SSsemalPtwob | SSsemalMMoneb | SSsemalMMtwob |
|---------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 3F | 3.01 ± 0.46 | 3.69 ± 0.45 | 4.12 ± 0.59 | 4.17 ± 0.58 | 1.92 ± 0.32 | 1.95 ± 0.31 | 1.37 ± 0.24 | 1.35 ± 0.23 | 1.20 ± 0.24 | 1.21 ± 0.23 | 1.32 ± 0.23 | 1.31 ± 0.23 | 1.23 ± 0.22 | 1.22 ± 0.22 | 1.24 ± 0.23 | 1.23 ± 0.23 | 1.22 ± 0.23 | 1.23 ± 0.23 |
| WW  | 14.70 ± 1.50 | 17.02 ± 2.02 | 8.76 ± 1.07 | 5.88 ± 1.25 | 3.01 ± 0.64 | 14.40 ± 3.60 | 7.24 ± 1.82 | 12.83 ± 3.23 | 6.83 ± 1.73 | 4.39 ± 1.12 | 2.41 ± 0.62 |
| ZZ  | 0.55 ± 0.15 | 0.30 ± 0.08 | 0.98 ± 0.37 | 0.31 ± 0.11 | 0.37 ± 0.23 | 0.13 ± 0.07 | 7.57 ± 0.94 | 5.42 ± 0.77 | 4.71 ± 1.13 | 2.75 ± 0.46 | 1.10 ± 0.25 | 0.59 ± 0.22 |
| ZZ  | 0.01 ± 0.01 | 0.03 ± 0.01 | 1.01 ± 0.01 | 0.02 ± 0.01 | < 0.01 | < 0.01 | 0.27 ± 0.06 | 0.23 ± 0.07 | 0.12 ± 0.04 | 0.09 ± 0.04 | 0.04 ± 0.02 | 0.03 ± 0.02 |
| tZ  | 0.39 ± 0.14 | 0.14 ± 0.07 | 0.47 ± 0.16 | 0.13 ± 0.05 | 0.13 ± 0.06 | 0.05 ± 0.02 | 0.98 ± 0.32 | 0.45 ± 0.16 | 0.24 ± 0.09 | 0.22 ± 0.08 | 0.09 ± 0.04 | 0.08 ± 0.04 |
| WW  | 0.34 ± 0.25 | 0.34 ± 0.13 | 0.35 ± 0.18 | 0.28 ± 0.10 | < 0.01 | < 0.01 | 0.47 ± 0.20 | 0.52 ± 0.19 | 0.45 ± 0.13 | 0.39 ± 0.17 | 0.20 ± 0.11 | 0.19 ± 0.11 |
| tH  | 3.42 ± 0.33 | 2.74 ± 0.35 | 4.18 ± 0.49 | 4.29 ± 0.50 | 1.57 ± 0.22 | 2.36 ± 0.32 | 2.31 ± 0.27 | 3.10 ± 0.38 | 3.23 ± 0.37 | 1.21 ± 0.17 | 1.40 ± 0.15 |
| Other | 1.10 ± 0.57 | 0.93 ± 0.48 | 1.54 ± 0.78 | 1.66 ± 0.84 | 0.74 ± 0.42 | 0.62 ± 0.31 | 1.78 ± 1.07 | 1.99 ± 1.19 | 1.43 ± 0.81 | 1.71 ± 0.96 | 0.70 ± 0.43 | 0.23 ± 0.12 |
| FakeMM | 11.21 ± 4.70 | 12.95 ± 6.62 | 15.35 ± 4.24 | 12.75 ± 3.74 | 4.23 ± 1.33 | 3.58 ± 1.21 | 19.94 ± 6.66 | 17.81 ± 4.51 | 14.09 ± 3.67 | 8.18 ± 2.32 | 1.03 ± 0.49 | 1.2 ± 0.44 |
| DDCF | 0.14 ± 0.01 | 0.14 ± 0.01 | 2.93 ± 0.30 | 2.93 ± 0.30 | 2.17 ± 0.23 | 2.17 ± 0.23 | 0.20 ± 0.02 | 0.20 ± 0.02 | 2.30 ± 0.24 | 2.30 ± 0.24 | 1.77 ± 0.19 | 1.77 ± 0.19 |
| γ+X | undefined | undefined | 6.48 ± 2.29 | 2.28 ± 1.40 | 2.08 ± 1.52 | 2.96 ± 1.41 | undefined | undefined | 4.50 ± 1.63 | 4.66 ± 1.77 | 5.30 ± 2.34 | 3.29 ± 1.54 |
| FakeF | 4.89 ± 2.59 | 3.03 ± 1.20 | 13.44 ± 3.77 | 17.91 ± 4.39 | 7.49 ± 2.36 | 5.21 ± 1.72 | 19.09 ± 4.03 | 11.34 ± 2.17 | 16.36 ± 3.29 | 14.38 ± 2.83 | 12.04 ± 3.05 | 7.41 ± 2.40 |
| Total | 33.87 ± 5.11 | 25.47 ± 5.78 | 54.34 ± 5.63 | 57.61 ± 4.39 | 18.57 ± 2.46 | 18.22 ± 2.09 | 47.84 ± 6.12 | 39.19 ± 5.40 | 47.17 ± 5.44 | 35.90 ± 5.69 | 17.51 ± 2.74 | 12.36 ± 1.86 |
4.8.2 Redefinition of trilepton regions for analysis III

As the ratio of the $t\bar{t}Z$ to $t\bar{t}W$ yield increased between the 8 TeV and 13 TeV analyses and the total expected number of events increases for analysis III, the 3LnoZ region previously used is revisited. In the region that was used in analyses I and II, exactly three leptons and 2-4 jets, of which at least 2 are $b$-tagged, were required. At 13 TeV, it is found that there was a high presence of $t\bar{t}Z^*/\gamma^*$ at high jet multiplicity. Therefore the 3Lon region was split into one region with two or three jets targeting $t\bar{t}W$ and another with four jets or more, targeting off-shell $t\bar{t}Z^*/\gamma^*$ production. As before, a total lepton charge of $\pm 1$ is required and a veto is applied against an OSSF pair in the $Z$-mass window. Moreover, for the 3LnoZ2b4j region, the presence of an OSSF pair is required. The redefinition was partly motivated by the search for a region sensitive to off-shell $t\bar{t}Z^*/\gamma^*$ production for the purpose of constraining Wilson coefficients in a region where the invariant mass of the OSSF pair is far from the mass of the $Z$ boson. In Fig. 28, the jet multiplicity is shown for the 3LnoZ2b4j region, with the cut on jet multiplicity removed.

The jet multiplicity in the original region and in the two new regions is shown in Fig. 28. In Fig. 29, distributions of the transverse momentum $p_T$ and invariant mass of the OSSF pair closest to the mass of the $Z$ boson ($Z_1$) is shown. Distributions of $p_{Tz_1}$ and $E_{T\text{miss}}$ in the 3LZ2b4j region are shown in Fig. 30.
Figure 28: The jet multiplicity in the 3LnoZ2b4j region, where the requirement on jet multiplicity has been removed. The $t\bar{t}Z$ signal is shown in blue, the $t\bar{t}W$ signal in red, fake leptons in grey, non-prompt leptons from photon conversions in yellow, $WZ$ in magenta and other processes in green. The statistical uncertainty on the expectation for the total yield is shown by the shaded band.

Figure 29: Distributions in the 3LnoZ2b4j signal region: the transverse momentum of the OSSF pair $p_Tz_1$ (left) and the invariant mass of the OSSF pair $m_{z_1}$ (right). The statistical uncertainty on the expectation for the total yield is shown by the shaded band.
Figure 30: Distributions in the 3LZ2b4j signal region: the transverse momentum $p_{Tz1}$ (left) of the OSSF pair with the invariant mass closest to the mass of the $Z$ boson and $E_{T}^{\text{miss}}$ (right). The $t\bar{t}Z$ signal is shown in blue, the $t\bar{t}W$ signal in red, fake leptons in grey, non-prompt leptons from photon conversions in yellow, $WZ$ in magenta, $tWZ$ in black and other processes in green. The statistical uncertainty on the expectation for the total yield is shown by the shaded band.
4.8.3 The WZ background III

The expected signal strength for the WZ process is $\mu_{WZ} = 1.00 \pm 0.08$. The distributions in lepton flavour $E_T^{\text{miss}}$ are shown in Fig. 31. CRWZ is dominated by WZ production while the main background is ZZ.

The uncertainties on the extrapolation of WZ from the CRWZ to the signal regions were rederived more carefully for analysis III, resulting in the values summarised in Table 20.

<table>
<thead>
<tr>
<th>Region</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>3LZ1b4j</td>
<td>30 %</td>
</tr>
<tr>
<td>3LZ2b3j</td>
<td>45 %</td>
</tr>
<tr>
<td>3LZ2b4j</td>
<td>50 %</td>
</tr>
<tr>
<td>3LnoZ2b4j, 3LnoZ2b2j</td>
<td>42 %</td>
</tr>
</tbody>
</table>

Table 20: The systematic uncertainty on the extrapolation of the WZ production cross section from CRWZ, where it is measured, to the signal regions.
4.8.4 Fake leptons III

For analysis III, the probability to misidentify a jet (e.g.) as a lepton is measured separately in regions with exactly one $b$-tagged or at least 2 $b$-tagged jets. This distinction is important for the $t\bar{t}W$ measurement. The rates are shown in Fig. 32. To assess the systematic uncertainty on the fake rates, the estimate of the number of real leptons obtained from simulation, that is present in the CR where the fake rates are derived is varied up and down by 30% and the fake rates are rederived in these modes. The envelope of this shift and the uncertainty from the fit is taken, separately for the shift up and the shift down, as the total systematic uncertainty on fake rates.

![Figure 32: The real efficiencies $r$ for electrons (black) and muons (red) and fake rates $f$ for electrons (blue) and muons (green) used for analysis III are shown. The plots to the left show the rates derived in a CR with one $b$-tagged jet, while the plots to the right show the rates derived in a CR with two $b$-tagged jets. The lepton definitions for the regions targeting $t\bar{t}Z$ are used for the rates shown in the top row and the lepton definitions for regions targeting $t\bar{t}W$ are used for the lepton definitions used for the bottom row. The dashed lines show the systematic uncertainties associated with the rates.](image)

The predictions from these fake rates are verified in validation regions that are orthogonal to the signal and control regions. This is shown in Fig. 32.
33 for the 1-\(b\) rates and in Fig. 34 for the \(\geq 2-b\) rates.

Figure 33: The 1-\(b\) fake rates are validated in a region with one \(b\)-tagged jet. The fake leptons are shown in grey, \(WZ\) in purple, \(ZZ\) in orange, leptons with misidentified charge in dark green, the signal process \(t\bar{t}W\) in red, \(\gamma+X\) in yellow, \(t\bar{t}Z\) in blue and other processes in green. The jet multiplicity is shown for the \(ee\) (top left), \(e\mu\) (top right) and \(\mu\mu\) (bottom) channels.
Figure 34: The $\geq 2$-b fake rates are validated in a regions at least two b-tagged jets and with two leptons. The background from fake leptons is shown in grey, the signal $t\bar{t}W$ process in green, leptons with misidentified charge in dark blue, $t\bar{t}Z$ in light blue, Higgs production in yellow and other processes in white. The invariant mass of the lepton pair is shown for the $ee$ (top left), $e\mu$ (top right) and $\mu\mu$ channels (bottom).
4.8.5 Results III

The fit results to simulated data is $\mu_{t\bar{t}Z} = 1.00^{+0.14}_{-0.13}$. Simulating the measurement in the trilepton channels only gives $\mu_{t\bar{t}Z} = 1.00^{+0.18}_{-0.17}$.

The correlation matrix for the parameters entering the fit and the ranking plot showing the systematic uncertainties with the highest impact are shown in Fig. 35. The highest correlations are observed between the $t\bar{t}Z$ signal strength and uncertainties on the $b$-tagging (35 %), followed by anti-correlations between the signal strength and the extrapolation uncertainties on the $WZ$ background (at most -28 %). These uncertainties also have the largest impact on the observed signal strength, followed by the normalisation of the $tZ$ background and the modelling of $tWZ$.

Work is currently ongoing to evaluate the sensitivity to $t\bar{t}W$ production.
Figure 35: The correlation matrix (top) and ranking plot (bottom) for the fit for $t\bar{t}Z$ production in the trilepton channel.
5 Effective field theory

In this chapter, the results from simulating the production of $t\bar{t}l^+l^-$ in the presence of effective operators are presented. The code for the modified interactions is implemented in a so-called UFO model [101] and interfaced with the MG5\_aMC@NLO generation. The UFO model, was first verified and its predictions were explored in Ref. [15]. Some of the results from this paper, in the form of cross sections and distributions, are presented in Sec. 5.1. In Sec. 5.2, these results are used as input to a toy fit, in which all operators are constrained simultaneously, using measurements from ATLAS and CMS at 8 TeV collision energy. In Sec. 5.3, the results from the simulation of $t\bar{t}l^+l^-$ processes with effective operators that was produced for ATLAS are described. Finally, in Sec. 5.4, a fit is performed to one coefficient at a time using the settings and the expected sensitivity of analysis III.

5.1 Cross section and distributions with effective operators

The impact of the effective operators listed in Eq. 48 is studied for $t\bar{t}\mu^+\mu^-$, $t\bar{t}Z$, $t\bar{t}$ and $tt\gamma$ in Ref. [15]. In this thesis, the results for $t\bar{t}\mu^+\mu^-$ are presented. Due to lepton universality, and since the couplings to leptons are not affected by these effective operators, this is viewed as being representative for all three lepton flavours of $t\bar{t}l^+l^-$. The MG5\_aMC@NLO generator is used for the predictions, with the fixed order mode employed to obtain the cross sections and the distributions. No decays or parton showering are simulated.

The five flavour scheme is used, with the MSTW2008 [102] set of parton distribution functions, including the recommended variations to assess pdf uncertainties. The mass of the top quark $m_t$ is set to $m_t = 173.3$ GeV. The renormalisation ($\mu_R$) and factorisation ($\mu_F$) scales are fixed to $\mu_R = \mu_F = m_t$. Scale variations are obtained by independently varying $\mu_R$ and $\mu_F$ by a factor of $1/2$ and $2$, which results in nine combinations, and taking the envelope. A minimum invariant mass of 10 GeV for the muon pair is required.

The cross sections for the SM process are given in Table 21; they are listed at LO, at NLO in QCD and the ratio between them, called the $k$-factor, is also given. It is seen that the SM cross section increases by almost a factor of four when the collision energy is increased from 8 TeV to 13 TeV.

The cross section for a process that is affected by one effective operator $O_i$ has the form:

$$\sigma = \sigma_{SM} + \frac{C_i}{(\Lambda/\text{TeV})^2} \sigma_{(1)} + \frac{C_i^2}{(\Lambda/\text{TeV})^4} \sigma_{(2)}.$$  \hspace{1cm} (63)

Here the cross section is shown in terms of the SM prediction, the interfer-
Table 21: The cross sections in [fb] for $t\bar{t}\mu^+\mu^-$ production at LO and NLO, as well as the k-factor, are quoted at 8 TeV and 13 TeV collision energy. The uncertainty stated first is derived from the variation of renormalisation and factorisation scales, while the second one is obtained from variations of the pdfs.

<table>
<thead>
<tr>
<th></th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO cross section [fb]</td>
<td>8.779$^{+40.9%/-2.4%}_{-26.6%/+7.7%}$</td>
<td>31.67$^{+37.4%/-2.1%}_{-25.1%/+9.1%}$</td>
</tr>
<tr>
<td>NLO cross section [fb]</td>
<td>9.827$^{+37.4%/-2.9%}_{-26.4%/+2.6%}$</td>
<td>37.51$^{+9.1%/-2.0%}_{-25.1%/+2.6%}$</td>
</tr>
<tr>
<td>k-factor</td>
<td>1.12</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table 22 and 23 show the inclusive production cross section for $t\bar{t}\mu^+\mu^-$ at 8 TeV and 13 TeV collision energy, respectively. The cross sections are shown for LO and NLO in QCD, separately for the interference term and the quadratic term for the different operators. The NLO prediction is used throughout this chapter and the LO calculation is shown for comparison. The ratio to the SM prediction can be different at NLO than at LO.

It can be seen that $\sigma^{(2)}$ is considerably larger than $\sigma^{(1)}$ for the operators $O_{tW}$ and $O_{tB}$. Moreover, the quadratic term increases with $C_i^2$ while the interference term scales linearly with $C_i$. Hence, limits on the corresponding two coefficients for the $t\bar{t}Z$ measurement are expected to be dominated by the quadratic term. These two operators couple both to $Z$ bosons and to photons. Therefore they also have a contribution in regions where the contribution from $t\bar{t}\gamma^*$ is significant. Studying the contribution of these operators to production of on-shell $t\bar{t}\gamma$ production, it was found that this process is more sensitive to these two operators, see Table 25. The operator $O_{tG}$ affects the $t\bar{t}g$ vertex, the corresponding coefficient is best constrained.
in $t\bar{t}$ production [103]. It should be noted that the results for $\mathcal{O}^{(3)}_{tQ}$ for $t\bar{t}\mu^+\mu^-$ equal the results for $\mathcal{O}^{(1)}_{tQ}$, with a relative sign for the interference term.

<table>
<thead>
<tr>
<th>$8\text{TeV}$</th>
<th>$\mathcal{O}_{tG}$</th>
<th>$\mathcal{O}^{(1)}_{tQ}$</th>
<th>$\mathcal{O}_{dt}$</th>
<th>$\mathcal{O}_{tB}$</th>
<th>$\mathcal{O}_{W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{(1)}_{1,LO}$</td>
<td>$3.07^{+14.1}_{-26.9}$</td>
<td>$0.613^{+4.2}_{-25.6}$</td>
<td>$0.413^{+4.4}_{-23.8}$</td>
<td>$0.0101^{+41.3}_{-26.5}$</td>
<td>$0.0121(6)$</td>
</tr>
<tr>
<td>$\sigma^{(1)}_{2,LO}$</td>
<td>$3.21^{+14.1}_{-10.4}$</td>
<td>$0.683^{+4.4}_{-11.3}$</td>
<td>$0.44^{+4.8}_{-10.9}$</td>
<td>$0.0121(1)$</td>
<td></td>
</tr>
<tr>
<td>$\sigma^{(1)}_{NLO}$</td>
<td>$1.05$</td>
<td>$1.11$</td>
<td>$1.08$</td>
<td>$1.2$</td>
<td>$0.3$</td>
</tr>
<tr>
<td>$\sigma^{(2)}_{1,LO}$</td>
<td>$3.07^{+14.1}_{-26.9}$</td>
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<td>$0.0121(1)$</td>
<td></td>
</tr>
<tr>
<td>$\sigma^{(2)}_{NLO}$</td>
<td>$1.05$</td>
<td>$1.11$</td>
<td>$1.08$</td>
<td>$1.2$</td>
<td>$0.3$</td>
</tr>
</tbody>
</table>

Table 22: The EFT parameters $\sigma_{tG}^{(1)}$ and $\sigma_{tG}^{(2)}$ in [fb] are shown for the $t\bar{t}\mu^+\mu^-$ process at 8 TeV collision energy [15]. The uncertainties listed in per cent correspond to scale variations. The statistical uncertainties are given in brackets.

<table>
<thead>
<tr>
<th>$13\text{TeV}$</th>
<th>$\mathcal{O}_{tG}$</th>
<th>$\mathcal{O}^{(1)}_{tQ}$</th>
<th>$\mathcal{O}_{dt}$</th>
<th>$\mathcal{O}_{tB}$</th>
<th>$\mathcal{O}_{W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{1,LO}^{(1)}$</td>
<td>$11.28^{+32.7}_{-25.2}$</td>
<td>$2.58^{+48.4}_{-26.6}$</td>
<td>$1.70^{+40.1}_{-26.4}$</td>
<td>$0.034^{+36.9}_{-25.1}$</td>
<td>$0.025(3)$</td>
</tr>
<tr>
<td>$\sigma_{2,LO}^{(1)}$</td>
<td>$12.5^{+6.7}_{-10.3}$</td>
<td>$2.97^{+6.7}_{-12.4}$</td>
<td>$1.89^{+10.1}_{-10.1}$</td>
<td>$0.040(2)$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{NLO}^{(1)}$</td>
<td>$1.11$</td>
<td>$1.15$</td>
<td>$1.11$</td>
<td>$1.3$</td>
<td>$1.7$</td>
</tr>
<tr>
<td>$\sigma_{1,LO}^{(2)}$</td>
<td>$8.95^{+49.3}_{-30.2}$</td>
<td>$0.10^{+49.4}_{-26.6}$</td>
<td>$0.099^{+46.0}_{-26.6}$</td>
<td>$0.107^{+44.3}_{-28.5}$</td>
<td>$0.74^{+44.4}_{-29.4}$</td>
</tr>
<tr>
<td>$\sigma_{2,LO}^{(2)}$</td>
<td>$8.49^{+4.1}_{-4.7}$</td>
<td>$0.116^{+7.1}_{-11.0}$</td>
<td>$0.112^{+3.5}_{-11.0}$</td>
<td>$0.123^{+6.2}_{-28.5}$</td>
<td>$0.8^{+5.9}_{-28.5}$</td>
</tr>
<tr>
<td>$\sigma_{NLO}^{(2)}$</td>
<td>$0.56^{+0.0}_{-0.2}$</td>
<td>$0.08^{+0.2}_{-2.0}$</td>
<td>$0.05^{+0.1}_{-2.0}$</td>
<td>$0.001^{+0.0}_{-0.1}$</td>
<td>$0.000^{+0.0}_{-0.1}$</td>
</tr>
<tr>
<td>$\sigma_{1,LO}^{(3)}$</td>
<td>$3.07^{+4.2}_{-26.6}$</td>
<td>$0.613^{+4.4}_{-23.8}$</td>
<td>$0.413^{+4.4}_{-23.8}$</td>
<td>$0.0101^{+41.3}_{-26.5}$</td>
<td>$0.0121(6)$</td>
</tr>
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<td>$\sigma_{2,LO}^{(3)}$</td>
<td>$3.21^{+4.4}_{-10.9}$</td>
<td>$0.683^{+4.8}_{-10.9}$</td>
<td>$0.0121(1)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{NLO}^{(3)}$</td>
<td>$1.05$</td>
<td>$1.08$</td>
<td>$1.08$</td>
<td>$1.2$</td>
<td>$0.3$</td>
</tr>
</tbody>
</table>

Table 23: The EFT parameters $\sigma_{tG}^{(1)}$ and $\sigma_{tG}^{(2)}$ in [fb] are shown for the $t\bar{t}\mu^+\mu^-$ process at 13 TeV collision energy [15]. The uncertainties listed in per cent correspond to scale variations. The statistical uncertainties are given in brackets.

The corresponding numbers for $t\bar{t}Z$ production at 8 TeV collision energy can be found in Table 24. The total predictions for $t\bar{t}Z$ and $t\bar{t}\gamma$ are used as inputs to the toy fit described in Sec. 5.2.

Several distributions for $t\bar{t}\mu^+\mu^-$ have been studied. Some of those found to have the highest sensitivity to the effective operators are shown below. The invariant mass $m_{ll}$ and the azimuthal separation $\Delta \phi$ for the muon pair are shown at 8 TeV and 13 TeV in Figs. 36-38 for $\mathcal{O}_{tG}$, $\mathcal{O}_{tQ}$ and $\mathcal{O}_{tB}$. The variable $\Delta \phi$ is anti-correlated with the transverse momentum of the lepton pair. For $\mathcal{O}_{tG}$, the new physics contribution is enhanced when the muons have a small angular separation in $\phi$. For $\mathcal{O}_{tQ}^{(1)}$ (and consequently $\mathcal{O}_{tQ}^{(3)}$),
<table>
<thead>
<tr>
<th>STev</th>
<th>$O_{tG}$</th>
<th>$O_{tB}^{[1]}$</th>
<th>$O_{tW}$</th>
<th>$O_{tB}^{[2]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{t,LO}^{[1]}$</td>
<td>76.1$^{+41.9}_{-27.1}$</td>
<td>18.6$^{+45.2}_{-28.6}$</td>
<td>12.5$^{+44.6}_{-28.3}$</td>
<td>0.077(8)$^{+46.6}_{-43.2}$</td>
</tr>
<tr>
<td>$\sigma_{t,LO}^{(1)}$</td>
<td>78.1$^{+4.4}_{-10.0}$</td>
<td>20.8$^{+5.6}_{-11.5}$</td>
<td>13.5$^{+4.9}_{-10.7}$</td>
<td>-0.32(2)$^{+39.1}_{-67.3}$</td>
</tr>
<tr>
<td>K-factor</td>
<td>1.03</td>
<td>1.12</td>
<td>1.08</td>
<td>-4.2</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{[2]}$</td>
<td>39.9$^{+53.6}_{-31.8}$</td>
<td>0.73(2)$^{+46.3}_{-28.8}$</td>
<td>0.73(2)$^{+46.3}_{-28.8}$</td>
<td>4.14$^{+6.2}_{-30.7}$</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{(2)}$</td>
<td>39.8$^{+4.7}_{-9.4}$</td>
<td>0.8(2)$^{+5.4}_{-9.1}$</td>
<td>0.8(2)$^{+7.4}_{-8.3}$</td>
<td>4.81$^{+12.5}_{-6.2}$</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{[1]}$</td>
<td>0.368$^{+0.4}_{-0.3}$</td>
<td>0.0895$^{+2.7}_{-2.5}$</td>
<td>0.0604$^{+2.3}_{-2.0}$</td>
<td>0.00037(4)$^{+33.6}_{-42.9}$</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{(1)}$</td>
<td>0.345$^{+1.3}_{-2.8}$</td>
<td>0.0918$^{+0.6}_{-1.0}$</td>
<td>0.059$^{+10.8}_{-4.2}$</td>
<td>-0.0014(1)$^{+31.4}_{-56.8}$</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{[2]}$</td>
<td>0.524$^{+8.2}_{-6.5}$</td>
<td>0.039(1)$^{+4.3}_{-0.3}$</td>
<td>0.058(2)$^{+4.2}_{-0.7}$</td>
<td>54(6)$^{+84.7}_{-29.1}$</td>
</tr>
<tr>
<td>$\sigma_{t,NLO}^{(2)}$</td>
<td>0.509$^{+1.4}_{-8.4}$</td>
<td>0.037(8)$^{+4.7}_{-4.5}$</td>
<td>0.06(1)$^{+3.2}_{-5.9}$</td>
<td>-15(1)$^{+36.9}_{-41.5}$</td>
</tr>
</tbody>
</table>

Table 24: The EFT parameters $\sigma_{t}^{[1]}$ and $\sigma_{t}^{(2)}$ in [fb] are shown for the $t\bar{t}Z$ process at 8 TeV collision energy [15]. The uncertainties listed in per cent correspond to scale variations. The statistical uncertainties are given in brackets. To obtain the prediction for $O_{tB}$, $\sigma_{t}^{[1]}$ can be scaled by $-\tan^2\theta_{tW}$ to give $\sigma_{tB}^{[1]}$ and $\sigma_{t}^{(2)}$ by $-\tan^4\theta_{tW}$ to give $\sigma_{tB}^{(2)}$.

The effect is enhanced at the mass of the $Z$ boson while it is not seen below an invariant mass of around 50 GeV: at low values, off-shell $\gamma^{*}$ dominates the production and these operators do not couple to photons. For $O_{tB}$ an enhancement is seen at low azimuthal separations and at high invariant masses.
Table 25: The EFT parameters $\sigma_{i,LO}^{(1)}$ and $\sigma_{i,NLO}^{(1)}$ in [fb] are shown for the $t\bar{t}\gamma$ process at 8 TeV collision energy [15]. The uncertainties listed in percent correspond to scale variations. The statistical uncertainties are given in brackets. The parameters for $O_{tW}$ turn out to have the same values as the ones for $O_{tB}$.
Figure 36: Distributions in $t\bar{t}\mu^+\mu^-$ production with $CtG = 1, \Lambda = 1$ TeV, showing $m(\mu^+, \mu^-)$ (left) and $\Delta\phi(\mu^+, \mu^-)$ (right) at 8 TeV (top) 13 TeV (bottom) collision energy [15]. The SM prediction is shown in black, the interference term in blue and the quadratic term in red; these are stacked in this order.
Figure 37: Distributions in $t\bar{t}\mu^+\mu^-$ production with $C^{(1)}_{\phi Q} = 2, \Lambda = 1$ TeV, showing $m(\mu^+, \mu^-)$ (left) and $\Delta\phi(\mu^+, \mu^-)$ (right) at 8 TeV (top) 13 TeV (bottom) collision energy [15]. The SM prediction is shown in black, the interference term in blue and the quadratic term in red; these are stacked in this order.
Figure 38: Distributions in $t\bar{t}\mu^+\mu^-$ production with $C_{tB} = 4, \Lambda = 1$ TeV, showing $m(\mu^+,\mu^-)$ (left) and $\Delta\phi(\mu^+,\mu^-)$ (right) at 8 TeV (top) 13 TeV (bottom) collision energy [15]. The SM prediction is shown in black, the interference term in blue and the quadratic term in red; these are stacked in this order.
5.2 EFT limits, simultaneous fit

A toy fit is performed to constrain the five coefficients: \( C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}, C_{\phi t}, C_{tW}, C_{tB} \) and \( C_{tG} \). Constraints are obtained from measurements by both ATLAS and CMS at 8 TeV of \( t\bar{t}, t\bar{t}Z \) and \( t\bar{t}\gamma \). These input values are shown in Table 26.

Table 26: The input ATLAS and CMS measurements for the toy fit for the Wilson coefficients. The uncertainties are split into a statistical and a systematic component, presented in this order. The uncertainties have been symmetrised by taking the average of the upper and lower uncertainty.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( t\bar{t}Z ) [pb]</th>
<th>( t\bar{t}\gamma ) [pb]</th>
<th>( t\bar{t} ) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>( 0.176 \pm 0.030 \pm 0.024 ) [11]</td>
<td>-</td>
<td>( 232.4 \pm 1.7 \pm 9.3 ) [104]</td>
</tr>
<tr>
<td>CMS</td>
<td>( 0.242 \pm 0.043 \pm 0.042 ) [105]</td>
<td>( 2.4 \pm 0.2 \pm 0.6 ) [106]</td>
<td>( 239.0 \pm 2.6 \pm 13.4 ) [104]</td>
</tr>
<tr>
<td>ATLAS+CMS</td>
<td>-</td>
<td>( 1.8 \pm 0.5 ) [106]</td>
<td>( 241.5 \pm 1.4 \pm 5.95 ) [104]</td>
</tr>
<tr>
<td>Theory</td>
<td>( 0.206 \pm 0.0215 ) [107]</td>
<td>-</td>
<td>( 252.89 \pm 11.67 ) [108]</td>
</tr>
</tbody>
</table>

Correlations between the different measurements need to be known and included in order to combine the measurements and assess the limits properly. As these are not publicly available, two different simplified assumptions on the correlations are made. The case where no uncertainties are assumed to be correlated between the measurements is described first.

The coefficients enter the fit as free parameters while measurements of \( tt, t\bar{t}Z \) and \( t\bar{t}\gamma \) and the SM predictions for these processes enter the fit as parameters with Gaussian constraints. The total experimental uncertainty on the measurements listed in Table 26 is included in this fit. More explicitly, the following terms enter the logarithm of the likelihood function. The measurement constrains the prediction as:

\[
\ln L_{\text{meas},X} = -\left( \sigma_{\text{pred},X} - \sigma_{\text{meas},X} \right)^2 / (2(\Delta \sigma_{\text{meas},X})^2), \tag{65}
\]

where \( X \) denotes one of the processes \( tt, t\bar{t}Z \) or \( t\bar{t}\gamma \). For measurements of \( t\bar{t}Z \) and \( tt \) production, results from both the ATLAS and CMS experiments are included. Hence there are two terms of the form of Eq. (65) for \( tt \) and \( t\bar{t}Z \) production, with both terms having the same predicted cross section.

The total prediction is denoted \( \sigma_{\text{pred}} \) and includes both the SM part, as given in Table 26, and the contribution from the EFT operators from Tables 24, 25 and Ref. [109], where it is found that \( \sigma_{tG} = 72.62 \) pb and \( \sigma_{tG}^2 = 11.8 \) pb for \( tt \) production. No cross terms between effective operators are included in the fit. For \( tt \), the total prediction is modelled as:

\[
\sigma_{\text{pred},tt} = \sigma_{SM,tt} + \frac{C_{tG} \sigma_{tG,tt}^{(1)}}{\Lambda^2} + \frac{C_{tG}^2 \sigma_{tG,tt}^{(2)}}{\Lambda^4}. \tag{66}
\]

For the \( t\bar{t}\gamma \) process, the measured cross section as well as the SM pre-
diction are scaled by the factor $R = 0.4531$:

$$\ln L_{\text{meas},t\bar{t}\gamma} = -\frac{(\sigma_{\text{pred},t\bar{t}\gamma} - R \cdot \sigma_{\text{meas},t\bar{t}\gamma})^2}{(2(\Delta \sigma_{\text{meas},t\bar{t}\gamma})^2)}, \quad (67)$$

$$\sigma_{\text{pred},t\bar{t}\gamma} = R \cdot \sigma_{\text{SM},t\bar{t}\gamma} + \sum_i (\frac{C_i}{X^2} \sigma_i^{(1)} + \frac{C_{ii}^2}{X^4} \sigma_i^{(2)}). \quad (68)$$

The factor $R$ is derived in Ref. [15], and it is used to translate between the values for $\sigma_i^{(1)}$ and $\sigma_i^{(2)}$ for $t\bar{t}\gamma$ in Table 25, and the definition of the signal process $(W^+ b W^− b \gamma)$ that is used for the measurement by the CMS. In the latter definition, the photon can also be radiated from the decay partners of the top quark or from the initial state. In the approach employed in Eq. (67), the simplified assumption is made that the ratios $\sigma_i^{(1)}/\sigma_{\text{SM}}$ and $\sigma_i^{(2)}/\sigma_{\text{SM}}$ would be the same both for $t\bar{t}\gamma$ and $W^+ b W^− b \gamma$.

The SM prediction is constrained by the theoretical uncertainty, explicitly:

$$\ln L_{\text{SM},X} = -\frac{(\sigma_{\text{SM},X} - \hat{\sigma}_{\text{SM},X})^2}{(2(\Delta \hat{\sigma}_{\text{SM},X})^2)}, \quad (69)$$

with $\Delta \hat{\sigma}_{\text{SM},X}$ being the theoretical uncertainty on the SM estimate $\hat{\sigma}_{\text{SM}}$ for the process $X$. No theoretical uncertainty is applied to the terms arising from the effective operators in the toy fit: $\sigma_i^{(1)}$ and $\sigma_i^{(2)}$ are treated as constants. The log likelihood expression thus becomes:

$$\ln L_{\text{tot}} = \sum_X (\ln L_{\text{meas},X} + \ln L_{\text{SM}}). \quad (70)$$

Next, the case with all systematic uncertainties are considered correlated between the ATLAS measurements and between the CMS measurements is studied. Then Eq. (65) is modified to read:

$$\ln L_{\text{meas},X} = -\frac{(\sigma_{\text{pred},X} - \sigma_{\text{meas},X}(1 + \alpha))^2}{2(\Delta \sigma_{\text{meas},X})^2} - \frac{\alpha^2}{2(\Delta \alpha)^2_X}. \quad (71)$$

Here $\alpha$ is a parameter that quantifies the systematic shift from the central value in the measurements. To fully correlate the systematic uncertainties, $\alpha_{\text{CMS}}$ is required to be the same for all three CMS measurements in the fit and similarly for $\alpha_{\text{ATLAS}}$ for the two ATLAS measurement. $(\Delta \alpha)_X$ is evaluated as the systematic uncertainty on the measurement of $X$, normalised to the central value of the measurement:

$$(\Delta \alpha)_X = \frac{\Delta \sigma_{\text{syst}}}{\sigma_{\text{meas},X}} \quad (72)$$

The Migrad algorithm in the Minuit library [110] is used for the minimisation. The 95% confidence limits for both the uncorrelated and correlated scenario are listed in Table 27. For the correlated fit, the output for
the systematic shift is $\alpha_{ATLAS} = (-0.1 \pm 3.4)\%$ and $\alpha_{CMS} = (0.0 \pm 4.3)\%$. A value of the magnitude of 100 % would imply an overall systematic shift of the order of the systematic uncertainties in the measurements.

Table 27: Summary table of the fit results from measurements at 8 TeV by ATLAS and CMS, either assuming no correlations between the measurements (left), or assuming full correlation for the measurements by ATLAS and CMS internally (right). The quoted interval is defined by the central value $\pm$ the errors (68 % C.L.) from the toy fit.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Assumed uncorrelated</th>
<th>Correlations assumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/(\Lambda/1\text{ TeV})^2$</td>
<td>[-20,18]</td>
<td>[-20,18]</td>
</tr>
<tr>
<td>$C_{\phi t}/(\Lambda/1\text{ TeV})^2$</td>
<td>[-16,13]</td>
<td>[-15,12]</td>
</tr>
<tr>
<td>$C_{tW}/(\Lambda/1\text{ TeV})^2$</td>
<td>[-18,20]</td>
<td>[-17,19]</td>
</tr>
<tr>
<td>$C_{tB}/(\Lambda/1\text{ TeV})^2$</td>
<td>[-3.3,23]</td>
<td>[-3.9,24]</td>
</tr>
<tr>
<td>$C_{tG}/(\Lambda/1\text{ TeV})^2$</td>
<td>[-0.33,0.02]</td>
<td>[-0.39,0.06]</td>
</tr>
</tbody>
</table>

The correlation between $C_{tG}$ and the SM prediction for the $t\bar{t}$ cross section is found to be of the order of -(70-90) %. Large anti-correlations were also observed for the coefficients: almost -90% between $C_{tW}$ and $C_{tB}$. Finding observables where the contributions from the different operators can be distinguished from one another could reduce the correlations between the Wilson coefficients in the fit. The correlation matrices for the two fits are listed in Appendix A1.

For completeness, the limits from LEP, electroweak precision measurements and $t\bar{t}$ production at the LHC at 8 TeV are listed in Table 28. These limits are derived allowing only one coefficient at a time to be zero, contrary to the approach taken for this toy fit. Moreover, a common practice to place limits on EFT coefficients has been to use only the interference term as the prediction and the quadratic term as an uncertainty. Adding the constrains from Table 28 to the toy fit in a consistent way is not straightforward and has only been done for $C_{tG}$, where the limit comes from measurements of $t\bar{t}$ production at the LHC.

It is worth noting that the experimental measurements are only sensitive to the region in phase space where it is measured. For an inclusive measurement, such as the $t\bar{t}V$ measurements described in this work, an extrapolation is then performed to give a prediction for the total production cross section. The acceptance and shape for the SM process is generally assumed for such an extrapolation, which is not necessarily the same for the EFT prediction. This can introduce a bias if such an extrapolation is performed before setting limits on the Wilson coefficients for the effective operators. This speaks in favour of making a fiducial measurement and computing the EFT prediction when applying the cuts that are used to define the signal regions. For the
Coefficient Limit (95 % C.L.) [ TeV$^{-2}$] Source

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Limit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C^{(3)}<em>{\phi Q} + C^{(1)}</em>{\phi Q})/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-0.026, 0.059]</td>
<td>Ref. [109]</td>
</tr>
<tr>
<td>$C^{(3)}_{\phi Q}/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-3.4,7.5]</td>
<td>Refs. [109], [111]</td>
</tr>
<tr>
<td>$C_{\phi t}/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-2.5, 7]</td>
<td>Ref. [109]</td>
</tr>
<tr>
<td>$C_{tW}/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-0.15, 1.9]</td>
<td>Refs. [112], [111]</td>
</tr>
<tr>
<td>$C_{tB}/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-16.43]</td>
<td>Refs. [109], [111]</td>
</tr>
<tr>
<td>$C_{tG}/(\Lambda/1 \text{ TeV})^2$</td>
<td>[-0.42,0.3]</td>
<td>Ref. [103]</td>
</tr>
</tbody>
</table>

Table 28: The limits available on the coefficients for the effective operators at the time of performing the toy fit.

5.3 EFT simulations for ATLAS

Next, simulations of the $t\bar{t}l^+l^-$ processes including effective operators are performed for the use in analysis III. The event generation is performed in MG5_aMC@NLO with similar settings to those used for the nominal SM prediction. The decays of top quarks, $Z$ and $W$ bosons are performed with MadSpin and Pythia8 with the A14 tune applied is employed for the parton showering. An invariant mass cut of $m_{ll} > 5 \text{ GeV}$ is applied in the generation.

One coefficient at a time is allowed to take on a non-zero value. Two values for $C_i/\Lambda^2$ are used for the prediction for each operator; these values are referred to as $+x$ and $-x$. All other coefficients set to zero in the simulation. From these predictions, $\sigma^{(1)}$ and $\sigma^{(2)}$ can be separated as in Eq. (64) and the prediction can be rescaled to some other value for $C_i/\Lambda^2$.

The total cross sections for the $t\bar{t}l^+l^-$ predictions for ATLAS are summarised in Table 29. The values of $x$ for $C_i/\Lambda^2$ were generally chosen to be near the previous limits on the coefficients. The generation is preformed at truth level – the detector effects are only simulated for the $t\mu^+\mu^-$ process with $C_{tB}/(\Lambda/1 \text{ TeV})^2 = 5$.

Some distributions in $t\bar{t}l^+l^-$ are shown in Figs. 39 - 41, exploring the effects of the different operators. The invariant mass, angular separation ($\Delta\phi$, $\Delta R$) and transverse mass for the OSSF lepton pair with the invariant mass closest to the mass of the $Z$ boson is shown (hence $Z1$ in the variable names). This lepton pair could come from the decay of $Z$ or a photon conversion, but either or both of them could also originate from the decay.
Table 29: The values for $C_i/Λ^2$ chosen for performing the simulations of $t\bar{t}l^+l^-$ including EFT effects, and the total production cross sections obtained for $t\bar{t}l^+l^-$ for these values. The lower cut on invariant mass of the lepton pair is 5 GeV.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$C_i/(Λ/1 \text{ TeV})^2$</th>
<th>$tte^+e^- σ [\text{fb}]$</th>
<th>$ttμ^+μ^- σ [\text{fb}]$</th>
<th>$ttτ^+τ^- σ [\text{fb}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>- (SM)</td>
<td>-</td>
<td>36.3</td>
<td>36.3</td>
<td>36.0</td>
</tr>
<tr>
<td>$C_{φQ}^{(3)}$</td>
<td>+6</td>
<td>55.3</td>
<td>55.3</td>
<td>54.8</td>
</tr>
<tr>
<td>$C_{φt}^{(3)}$</td>
<td>-6</td>
<td>24.4</td>
<td>24.5</td>
<td>24.3</td>
</tr>
<tr>
<td>$C_{φt}$</td>
<td>+6</td>
<td>49.2</td>
<td>49.6</td>
<td>49.3</td>
</tr>
<tr>
<td>$C_{φt}$</td>
<td>-6</td>
<td>30.3</td>
<td>30.4</td>
<td>30.0</td>
</tr>
<tr>
<td>$C_{lw}$</td>
<td>+2</td>
<td>39.1</td>
<td>39.2</td>
<td>39.1</td>
</tr>
<tr>
<td>$C_{lw}$</td>
<td>-2</td>
<td>39.3</td>
<td>39.3</td>
<td>39.1</td>
</tr>
<tr>
<td>$C_{lB}$</td>
<td>+5</td>
<td>39.1</td>
<td>39.2</td>
<td>38.9</td>
</tr>
<tr>
<td>$C_{lB}$</td>
<td>-5</td>
<td>38.6</td>
<td>38.7</td>
<td>38.5</td>
</tr>
<tr>
<td>$C_{lG}$</td>
<td>+0.3</td>
<td>40.6</td>
<td>40.4</td>
<td>40.4</td>
</tr>
<tr>
<td>$C_{lG}$</td>
<td>-0.3</td>
<td>33.4</td>
<td>33.5</td>
<td>33.2</td>
</tr>
</tbody>
</table>

of a top quark or (in the case of $t\bar{t}τ^+τ^-$) from the decay of a τ lepton.

From Fig. 39, showing the invariant mass of the lepton pair, it can be seen that for $C_{φQ}^{(3)}$ and $C_{φt}$, the effect of the operators is concentrated at the mass of the $Z$ boson – these operators do not couple to photons. In Figs. 40 and 41, it is seen that for $C_{lB}$, the enhancement from the effective operator is concentrated at low angular separation ($Δφ, ΔR$). These variables anti-correlate with $p_{Tz1}$. It should be noted, however, that in event reconstruction, electrons are required to be isolated within a cone of 0.2 in $ΔR$ while muons are required to be isolated within a cone of $ΔR < 0.3$.

In order to avoid bias from events from regions with low lepton isolation (in particular for $C_{lB}$) and other regions to which the analysis is not sensitive to, $σ_i^{(1)}$ and $σ_i^{(2)}$ are derived in fiducial signal regions. As the operators have shape in $m_{z1}$, the parameters are derived separately in the 3LZ2b4j and 3LnoZ2b4j regions, which are defined in Table 6. As a reminder, the former has a requirement of an OSSF pair within 10 GeV of the mass of the $Z$ boson, while the latter requires an OSSF with an invariant mass outside of this range.
Figure 39: The distribution of the invariant mass of the lepton pair. The SM prediction is shown in black, the SM and the interference term in blue and the full EFT prediction in red. The effect of $\mathcal{O}_{\phi Q}^{(3)}$ is shown in the top left plot, of $\mathcal{O}_{\phi t}$ to the top right, of $\mathcal{O}_{tW}$ to the bottom left and of $\mathcal{O}_{tB}$ to the bottom right.
Figure 40: The distribution of the azimuthal opening angle $\Delta \phi$ between the lepton pair. The SM prediction is shown in black, the SM and the interference term in blue and the full EFT prediction in red. The effect of $\mathcal{O}^{(3)}_{\phi Q}$ is shown in the top left plot, of $\mathcal{O}_{\phi t}$ to the top right, of $\mathcal{O}_{tW}$ to the bottom left and of $\mathcal{O}_{tB}$ to the bottom right.
Figure 41: The distribution of the angular separation $\Delta R$ between the lepton pair. The SM prediction is shown in black, the SM and the interference term in blue and the full EFT prediction in red. The effect of $\mathcal{O}_{\phi Q}^{(3)}$ is shown in the top left plot, of $\mathcal{O}_{\phi t}$ to the top right, of $\mathcal{O}_{tW}$ to the bottom left and of $\mathcal{O}_{tB}$ to the bottom right.
Figure 42: The $p_T$ of the OSSF lepton pair with an invariant mass closest to the $Z$ boson mass in the signal region 3LZ2b4j. The SM prediction is shown in black, the SM and the interference term in blue and the full EFT prediction in red. The effect of $O_{\phi Q}^{(3)}$ is shown in the top left plot, of $O_{\phi t}$ to the top right, of $O_{tW}$ to the bottom left and of $O_{tB}$ to the bottom right.
5.4 EFT limits from the 13 TeV measurement

Next, the framework for the $t\bar{t}Z$ measurement in analysis III is used to set limits on the coefficients for the effective operators. One coefficient at a time is constrained at this stage. The fit is performed on simulated data, assuming that the measured data will reproduce the SM prediction. Hence, the $t\bar{t}Z$ cross section is fixed to the SM prediction. In addition to the uncertainties from the SM $t\bar{t}Z$ analysis, a theoretical uncertainty of 12% is applied to the SM $t\bar{t}Z$ prediction. The statistical uncertainty on the parameters from Table 30 is also included. The new physics contribution is modelled as:

$$\frac{C_i}{\Lambda^2}\sigma_i^{(1)} + \frac{C_{ii}}{\Lambda^4}\sigma_{ii}^{(2)}.$$  \hspace{1cm} (73)

The parameters $\sigma_i^{(1)}$ and $\sigma_{ii}^{(2)}$ are derived separately in the 3LZ2b4j and 3LnoZ2b4j fiducial regions by making use of Eq. (64), their values are summarised in Table 30. The derivation is performed on the level where the hard scattering, decays and parton shower has been modelled, but no detector effects, such as reconstruction of physics objects and acceptance.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$\sigma_i^{(1)}$ (Z)</th>
<th>$\sigma_{ii}^{(2)}$ (Z)</th>
<th>$\sigma_i^{(1)}$ (noZ)</th>
<th>$\sigma_{ii}^{(2)}$ (noZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\phi Q}$</td>
<td>10.59 ± 0.14</td>
<td>0.39 ± 0.03</td>
<td>5.63 ± 0.27</td>
<td>0.15 ± 0.07</td>
</tr>
<tr>
<td>$C_{\phi t}$</td>
<td>6.91 ± 0.13</td>
<td>0.39 ± 0.03</td>
<td>3.77 ± 0.27</td>
<td>0.20 ± 0.07</td>
</tr>
<tr>
<td>$C_{tW}$</td>
<td>-0.92 ± 0.24</td>
<td>3.11 ± 0.20</td>
<td>-0.76 ± 0.58</td>
<td>2.37 ± 0.47</td>
</tr>
<tr>
<td>$C_{tB}$</td>
<td>-0.01 ± 0.11</td>
<td>0.23 ± 0.04</td>
<td>-0.17 ± 0.29</td>
<td>0.62 ± 0.09</td>
</tr>
</tbody>
</table>

Table 30: The EFT parameters $\sigma_i^{(1)}$ and $\sigma_{ii}^{(2)}$ in the fiducial 3LZ2b4j and 3LnoZ2b4j regions, normalised to the SM prediction in per cent. These numbers are derived at truth level, after simulating the parton shower in Pythia8.

Figure 43 shows the dependence of the signal strength on the value of the EFT coefficients in 3LZ2b4j and 3LnoZ2b4j.

Another uncertainty arises from the lack of modelling of detector effects for the EFT predictions. To assess the uncertainty from parametrising $\sigma_i^{(1)}$ and $\sigma_{ii}^{(2)}$ on truth level and applying the parametrisation to the SM prediction after detector effects have been modelled, the following is done. The $tt\mu^+\mu^-$ prediction with $C_{tB}/\Lambda^2$ set to 5 TeV$^{-2}$ has had detector effects simulated. The fraction of the EFT $tt\mu^+\mu^-$ prediction over the SM prediction for $tt\mu^+\mu^-$ is computed in regions similar to 3LZ2b4j and 3LnoZ2b4j at particle level and on truth level. The difference in this fraction between truth level and detector level is 3.3% in 3LZ2b4 and 0.0% in 3LnoZ2b4j. The envelope 3.3% is applied as an overall reconstruction uncertainty on the EFT prediction in the 3LZ2b4j, 3LZ2b3j and 3LZ1b4j regions.
Figure 43: The signal strength normalised to the SM prediction as a function of the coefficient for \(C^{(3)}_{\phi Q}\) (top left) \(C_{\phi t}\) (top right), \(C_{tW}\) (bottom left) and \(C_{tB}\) (bottom right). The signal strength in the 3LZ2b4j region is shown in red and in the 3LnoZ2b4j in blue.

The results of the fits to the coefficients, using simulated data and all tilepton regions are summarised in Table 31. For the limits on \(C_{tB}\), the 3LnoZ2b4j region is expected to be of importance. The upper limits of \(C^{(3)}_{\phi Q}\), \(C_{\phi t}\) and \(C_{tB}\) are expected to be improved from the limits stated in Eq. (28) if the observed data matches the SM prediction.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Limit (95 % C.L.) from the 3LZ regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C^{(3)}<em>{\phi Q} - C^{(1)}</em>{\phi Q}/(\Lambda/1 \text{ TeV})^2)</td>
<td>([-4.9, 4.6])</td>
</tr>
<tr>
<td>(C_{\phi t}/(\Lambda/1 \text{ TeV})^2)</td>
<td>([-5.8])</td>
</tr>
<tr>
<td>(C_{tW}/(\Lambda/1 \text{ TeV})^2)</td>
<td>([-4.0, 4.3])</td>
</tr>
<tr>
<td>(C_{tB}/(\Lambda/1 \text{ TeV})^2)</td>
<td>([-18, 18])</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Limit (95 % C.L.) from the 3LnoZ2b4j region</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{tB}/(\Lambda/1 \text{ TeV})^2)</td>
<td>([-16, 16])</td>
</tr>
</tbody>
</table>

Table 31: The expected limits for the coefficients, under the assumption that the observation agrees with the SM prediction. The lower limit on \(C_{\phi t}\) could not be determined.
6 Conclusions and outlook

The first measurements of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections by ATLAS have been performed at 8 TeV collision energy, using an integrated luminosity of 20.3 fb$^{-1}$. These production cross sections were then measured at a collision energy of 13 TeV, using a smaller dataset of 3.2 fb$^{-1}$. The results from both measurements are limited by statistical uncertainties. A new measurement at 13 TeV collision energy is ongoing, with ten times as much data available as the previous time, which is expected to reduce the uncertainties on the measured $t\bar{t}Z$ cross section considerably.

In order to better understand the backgrounds and systematic uncertainties on the measurements of $t\bar{t}Z$ production cross sections, the major background $tWZ$ was modelled at NLO in QCD, employing two Diagram Removal schemes. It is the first time that the DR2 method is applied to $tWZ$ and several theoretical questions are raised.

The expected sensitivity of the ongoing measurement of $t\bar{t}Z$ production at 13 TeV collision energy is used to set expected limits to the Wilson coefficients for effective dimension 6 operators, under the assumption that only one coefficient can have a non-zero value. In this mode, an improvement of the limits from the pre-LHC era can be expected for some of the Wilson coefficients. Performing a differential measurement in a variable, for which the distribution looks different for the SM and for the various EFT predictions, could allow one to further distinguish the effect of the operators from the SM background and from each other. A combination of measurements of $t\bar{t}V$ production with measurements of $t\bar{t}\gamma$ and $t\bar{t}$ would be useful to further constrain the operators and for fitting several coefficients at the same time. Moving towards a global fit, adding constraints from measurements of single top production and looking at modification of the Higgs couplings by the effective operators would give a more complete picture.
References


[12] ATLAS Collaboration, *Measurement of the t\bar{t}Z and t\bar{t}W production cross sections in multilepton final states using 3.2 fb^-1 of pp*


[61] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2.


[65] Photographer: Henrik Åkerstedt.


References


A1: Additional material for toy fit

6.1 Uncorrelated systematic uncertainties

The uncertainties on all the parameters in the fit where all uncertainties are uncorrelated are shown below:

The correlation matrix between the parameters for the toy fit, assuming that all measurements have uncorrelated uncertainties. The indexing for the parameters in the matrix is as follows.
1: $C_tG$
2: SM $t\bar{t}$ prediction
3: SM $t\bar{t}Z$ prediction
4: $C_{tQ}^{(3)}$
5: $C_{t\phi}$
6: $C_{tW}$
7: $C_{tB}$
8: SM $t\bar{t}\gamma$ prediction

\[
\begin{bmatrix}
1 & 0.100 & -0.877 & -0.000 & -0.000 & -0.000 & 0.013 & -0.040 & -0.002 \\
2 & -0.877 & 1.000 & 0.000 & 0.000 & 0.000 & 0.011 & 0.035 & 0.001 \\
3 & 0.000 & 0.000 & 1.000 & -0.014 & -0.013 & -0.014 & -0.025 & 0.020 & 0.002 \\
4 & 0.000 & 0.000 & 0.000 & 1.000 & -0.311 & -0.013 & 0.057 & 0.457 & 0.042 \\
5 & -0.000 & 0.000 & 0.000 & 0.000 & 1.000 & -0.590 & 0.476 & 0.044 \\
6 & 0.013 & 0.011 & 0.025 & 0.016 & 0.000 & 0.000 & 0.007 \\
7 & -0.040 & 0.035 & 0.020 & 0.057 & 0.476 & -0.871 & 1.000 & -0.304 \\
8 & 0.002 & 0.001 & 0.002 & 0.042 & 0.044 & 0.007 & 0.304 & 1.000 \\
\end{bmatrix}
\]

6.2 Correlated systematic uncertainties

The correlations of all the parameters in the fit where all systematic uncertainties correlated for the ATLAS and CMS measurements respectively are shown below. The indexing is as above, with following addition.

9: $\alpha_{ATLAS}$
10: $\alpha_{CMS}$

\[
\begin{bmatrix}
1 & 0.100 & -0.731 & -0.000 & -0.003 & -0.003 & -0.010 & -0.031 & -0.001 & 0.408 & 0.311 \\
2 & -0.731 & 1.000 & 0.000 & 0.002 & 0.002 & 0.009 & 0.035 & 0.001 & 0.009 & 0.007 \\
3 & 0.000 & 0.000 & 1.000 & -0.016 & -0.016 & -0.019 & 0.016 & 0.002 & 0.000 & -0.000 \\
4 & -0.003 & 0.002 & -0.016 & 1.000 & -0.439 & -0.515 & 0.422 & 0.043 & 0.000 & -0.005 \\
5 & -0.003 & 0.002 & -0.016 & -0.439 & 1.000 & -0.528 & 0.433 & 0.044 & 0.000 & -0.005 \\
6 & -0.010 & 0.009 & -0.019 & -0.515 & -0.528 & 1.000 & -0.883 & 0.002 & -0.001 & 0.001 \\
7 & 0.031 & 0.035 & 0.016 & 0.422 & 0.433 & -0.883 & 1.000 & -0.287 & -0.006 & 0.040 \\
8 & 0.001 & 0.001 & 0.002 & 0.043 & 0.044 & 0.002 & -0.287 & 1.000 & -0.000 & 0.002 \\
9 & 0.408 & 0.009 & 0.000 & 0.000 & -0.001 & -0.006 & -0.000 & -0.000 & 1.000 & 0.286 \\
10 & 0.311 & 0.007 & -0.000 & -0.005 & -0.005 & 0.001 & 0.040 & 0.002 & -0.286 & 0.100 \\
\end{bmatrix}
\]
7 Sammanfattning

Standardmodellen för partikelfysik beskriver elementarpartiklarna som utgör materia och deras växelverkan. Ett stort antal experimentella mätningar har bekräftat standardmodellens förutsägelser. Dock saknar standardmodellen svar på ett flertal fenomenologiska frågor, vilket antyder att modellen skulle kunna utökas till en mer komplett teori. Ett sätt att söka efter utvidgningar till standardmodellen är att testa dess förutsägelser till hög precision i ett försök att falsifiera den. Produktionen av $t\bar{t}Z$ och $t\bar{t}W$ studeras för detta syfte vid ATLAS-experimentet på CERN. Det undersöks om standardmodellen korrekt beskriver dessa processer och hur mycket utrymme som lämnas för ny fysik som ger liknande sluttillstånd.

Tre mätningar av produktion av $t\bar{t}Z$ och $t\bar{t}W$ har utförts. Den första mätningen baseras på data med en kollisionsenergi på 8 TeV. I nästa mätning används data som samlats in under 2015 med en kollisionsenergi på 13 TeV, vilket medför betydligt större produktionstvärsnitt för dessa processer. Den tredje mätningen är baserat på tio gånger mer data vid 13 TeV kollisionsenergi. Denna mätning är inte publik i skrivande stund, så preliminära resultat som främst använder sig av simulerat data visas.

Den nya fysiken som kan påverka produktion av $t\bar{t}Z$ parametr化eras med effektiv fältteori – ett allmänt ramverk som inte bygger på specifika modeller. Fem effektiva operatorer, som kan påverka produktion av $t\bar{t}Z$, studeras och deras koefficienter begränsas genom en anpassning till simulerat data för den tredje mätningen.

Bakgrundsprocessen $tWZ$ modelleras med två versioner av metoden Diagram Removal (DR). I det ena fallet (DR1) bortses det från interferensen mellan $tWZ$ och $t\bar{t}Z$ medan i det andra fallet (DR2) görs en skattning utav interferensen. Skillnaderna mellan dessa två skattningar undersöks och ingår i mätningarna som en systematisk felkälla.