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DOCTORAL THESIS

Search for the Standard Model Higgs boson produced in association with a top quark pair in multilepton final states at $\sqrt{s} = 13$ TeV with the ATLAS detector

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for the degree of Doctor of Philosophy*

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Dedicated to my parents and my late grandmother

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Abstract

This thesis presents the results of a search for the Standard Model Higgs boson produced in association with a pair of top quarks, $t\bar{t}H$, in multilepton final states. The search is performed using a dataset corresponding to an integrated luminosity of 36.1 fb^{-1} of proton-proton collision data recorded by the ATLAS experiment at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ at the Large Hadron Collider in 2015 and 2016. The search targets Higgs boson to WW^* , $\tau\tau$, and ZZ^* decay modes. Seven final states, categorized by the number and flavor of the charged leptons, are analyzed in the search for $t\bar{t}H$ production.

The thesis focuses on the analysis of the final state with exactly two same-charge light leptons and one hadronically decaying tau lepton, $2\ell\text{SS}1\tau_{\text{had}}$. The multivariate technique boosted decision tree is used to discriminate the $t\bar{t}H$ signal from backgrounds, the latter being dominated by $t\bar{t}$ production with leptons from heavy-flavor hadron decays. A data-driven method is used to estimate the reducible background events. A profile likelihood fit is performed to extract the ratio of the measured $t\bar{t}H$ signal cross-section to the Standard Model prediction ($\mu_{t\bar{t}H}$). The observed best-fit value of $\mu_{t\bar{t}H}$ is $3.5^{+1.7}_{-1.3}$, with an observed (expected) significance of 3.4 (1.1) standard deviations. A cross-check analysis using a simple cut-and-count categorization is also reported.

The combination of all seven $t\bar{t}H$ multilepton final states gives the best-fit value of the $t\bar{t}H$ signal strength of $\mu_{t\bar{t}H} = 1.6^{+0.5}_{-0.4}$. An excess of events over the expected Standard Model background is found with an observed (expected) significance of 4.1 (2.8) standard deviations. The cross section for $t\bar{t}H$ production corresponding to the best-fit value of the signal strength is $\sigma(t\bar{t}H) = 790^{+230}_{-210} \text{ fb}$, as compared to the Standard Model prediction of $507^{+35}_{-50} \text{ fb}$.

Furthermore, the performance of the ATLAS tau trigger is presented based on the 2015 proton-proton collision data recorded by the ATLAS experiment at $\sqrt{s} = 13 \text{ TeV}$. A study of the Medipix-2 silicon pixel devices used as a luminosity monitoring system is also presented for the data taken in 2012 at $\sqrt{s} = 8 \text{ TeV}$.

Abstrakt

V této dizertaci jsou prezentovány výsledky hledání Higgsova bosonu, předpovězeného ve Standardním modelu, produkovaného asociovaně s párem top kvarků, $t\bar{t}H$, v multileptonových finálních stavech. Analýza je provedena s využitím dat odpovídajících integrální luminositě $36,1 \text{ fb}^{-1}$ proton-protonových srážek s těžišťovou energií $\sqrt{s} = 13 \text{ TeV}$ zaznamenaných experimentem ATLAS na Large Hadron Collideru v letech 2015 a 2016. Výzkum se týká rozpadových módů Higgsova bosonu na WW^* , $\tau\tau$ a ZZ^* . Pro účely hledání událostí $t\bar{t}H$ je analyzováno sedm finálních stavů, které jsou roztrženy podle počtu a vůně nabitých leptonů.

Práce se zaměřuje na analýzu finálních stavů s právě dvěma lehkými leptony se stejným elektrickým nábojem a jedním tau leptonem rozpadajícím se na hadrony, $2\ell\text{SS}1\tau_{\text{had}}$. Multivariační technika vylepšeného rozhodovacího stromu je použita k odlišení $t\bar{t}H$ signálu od pozadí, kterému dominuje produkce $t\bar{t}$ s leptony pocházejícími z rozpadů těžkých hadronů. K odhadu reducibilních pozadových událostí je použita daty řízená metoda. K určení podílu měřeného účinného průřezu produkce $t\bar{t}H$ a předpovědi Standardního modelu ($\mu_{t\bar{t}H}$) je použit fit profilové věrohodnostní funkce. Je pozorována hodnota nejlepšího fitu $\mu_{t\bar{t}H} = 3,5_{-1,3}^{+1,7}$, s pozorovanou (očekávanou) věrohodností 3,4 (1,1) směrodatných odchylek. V práci je také prezentována kontrolní analýza založená na jednoduché cut-and-count kategorizaci.

Kombinace všech sedmi $t\bar{t}H$ multileptonových finálních stavů dává pro nejlepší fit síly signálu $\mu_{t\bar{t}H} = 1,6_{-0,4}^{+0,5}$. Byl nalezen přebytek událostí nad očekávaným pozadím Standardního modelu s pozorovanou (očekávanou) věrohodností 4,1 (2,8) směrodatných odchylek. Účinný průřez produkce $t\bar{t}H$ odpovídající nejlepšímu fitu síly signálu je $\sigma(t\bar{t}H) = 790_{-210}^{+230} \text{ fb}$, předpověď Standardního modelu $507_{-50}^{+35} \text{ fb}$.

Dále je v práci prezentována efektivita ATLAS tau triggeru, založená na datech proton-protonových srážek s $\sqrt{s} = 13 \text{ TeV}$ zaznamenaných experimentem ATLAS v roce 2015. Práce také obsahuje studii využití pixelových detektorů Medipix-2 pro monitorování luminosity pro data naměřená v roce 2012 při $\sqrt{s} = 8 \text{ TeV}$.

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Introduction

The ATLAS and CMS Collaborations at the Large Hadron Collider discovered a new particle consistent with the Standard Model (SM) Higgs boson in 2012. The discovery was an important landmark that completed the decades-long search for the SM Higgs boson. Since then, its properties have been probed deeply using proton-proton collision data produced by the LHC. The precise measurements of the coupling properties of the Higgs boson to other SM particles can provide stringent tests of the validity of the Higgs mechanism. The coupling of the Higgs boson to the bosonic sector ($\gamma\gamma$, ZZ^* , WW^*) has been well established and entered an era of precision measurements. The Yukawa coupling of the Higgs boson to fermions ($\tau\tau$, $b\bar{b}$) has been observed, while only upper limits exist on the Higgs boson coupling to muons.

The top quark is the heaviest particle in the SM with a mass of (173.0 ± 0.4) GeV. The Yukawa coupling of the Higgs boson to the top quark is the largest among the other fermion couplings and could be sensitive to new physics phenomena beyond the SM. Indirect measurements of this coupling were made using the top quark contribution to gluon-gluon fusion production and diphoton decay loops, assuming no contribution from unknown particles in the loop. A direct measurement of the coupling can be obtained through the production of the Higgs boson in association with a top quark pair, $t\bar{t}H$, which is a tree-level process. Although the $t\bar{t}H$ production cross section at the LHC is two orders of magnitude smaller than the total Higgs boson production cross section, it could provide a clean measurement of the top quark Higgs boson Yukawa coupling. This would allow to constrain effects of new physics beyond the Standard Model.

The $t\bar{t}H$ production gives rise to several final state event topologies. The ATLAS Collaboration has searched for $t\bar{t}H$ production in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow b\bar{b}$ decay channels, and in multilepton final states. This thesis describes the search for $t\bar{t}H$ production in multilepton final states, targeting Higgs boson decays $H \rightarrow WW^*$, $H \rightarrow \tau^+\tau^-$, and $H \rightarrow ZZ^*$ excluding $ZZ^* \rightarrow 4\ell$. The search is performed using a dataset corresponding to an integrated luminosity of 36.1 fb^{-1} of proton-proton collision data recorded by the ATLAS detector at $\sqrt{s} = 13 \text{ TeV}$ in 2015 and 2016. The search uses seven final states categorized by the number and flavor of charged leptons (electron, muon, or hadronically decaying tau lepton).

This thesis concentrates on the final state with exactly two light leptons with same-sign electric charges and one hadronically decaying tau lepton, denoted as $2\ell\text{SS}1\tau_{\text{had}}$. The $2\ell\text{SS}1\tau_{\text{had}}$ final state is primarily sensitive to the $H \rightarrow \tau^+\tau^-$ with hadronically and leptonically decaying τ leptons and $H \rightarrow WW^*$ decays. The analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ final state aims to maximize the sensitivity to the $t\bar{t}H$ signal. The main challenge for the analysis is the large backgrounds to the signal from $t\bar{t}$ production with non-prompt leptons from heavy-flavor hadron decays and from the production of a top quark pair in association with a W or Z boson. Many efforts are put into the analysis optimization to enhance the sensitivity and to reduce the impact of the systematic uncertainties. More refined selections compared to previous analyses are used to suppress the backgrounds. A new trigger strategy is employed to improve the signal acceptance. A boosted decision tree is trained to discriminate the $t\bar{t}H$ signal from the background processes. Backgrounds are estimated with a combination of data-driven techniques and Monte Carlo simulation. A fit to the observed data is performed to extract the best estimate for the $t\bar{t}H$ production rate. As a cross-check a separate analysis, where cuts on basic kinematic variables are applied, is carried out. The results of the $2\ell\text{SS}1\tau_{\text{had}}$ final state is combined with other $t\bar{t}H$ multilepton final states. The $t\bar{t}H$ multilepton results are combined with other ATLAS $t\bar{t}H$ results.

The aims of the presented thesis are:

- Performing a search for the $t\bar{t}H$ production in multilepton final states using 36.1 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV collected by the ATLAS detector in 2015 and 2016. In particular, the task was to perform the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ final state.
- Estimation of the tau trigger performance in Run-2 with simulation and its application on the 2015 data, in order to fulfill the ATLAS authorship qualification task.
- Performing studies on luminosity determination using Medipix-2 silicon pixel detectors, which were installed in the ATLAS cavern, as a service work (useful for all members of the ATLAS Collaboration).

Outline of the thesis

The thesis is organized as follow.

Chapter 1 gives a brief overview of the Standard Model and the theoretical motivation for the search of $t\bar{t}H$ production.

Chapter 2 introduces the Large Hadron Collider and the ATLAS detector. It describes the reconstruction and identification of physics objects in ATLAS.

Chapter 3 presents the study of the Medipix-2 silicon pixel devices used as a luminosity monitoring system.

Chapter 4 outlines the performance of the ATLAS tau trigger in Run-2.

Chapter 5 details the main topic of this thesis, the search for the $t\bar{t}H$ production in multilepton final states. The chapter focuses on the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ final state. The event selection and the multivariate technique to separate the signal from the background processes are detailed. The chapter also describes the techniques used to estimate the backgrounds. Then, the different sources of systematic uncertainties are discussed.

Chapter 6 summarizes the results of the analysis and the combination with other ATLAS searches for $t\bar{t}H$ production.

Chapter 1

Theoretical overview

The elementary particles are defined as being point-like, i.e., without any internal structure and make up the ordinary matter of our universe. The fundamental forces are responsible for the interactions between these elementary particles. There are four types of fundamental forces: electromagnetic, weak, strong, and gravitational. The theory that describes the properties of the elementary particles and their interactions¹ is known as the Standard Model of particle physics. It was developed in the early 1970s and has explained so far all experimental results accurately. Over time and through many experiments, the Standard Model has become a well-tested physics theory.

1.1 The Standard Model

The Standard Model (SM) [1–4] is a quantum field theory that describes not only the dynamics of elementary particles but also particle decays and the production of new particles out of a vacuum, which corresponds to the energy ground state of the theory. The elementary particles are characterized by their mass, electric charge, and spin angular momentum $s\hbar$ ($\hbar \equiv h/2\pi$), where s is the spin quantum number or spin for short and h is Planck’s constant. In the SM, particles are divided into two categories: particles with half-integer spin are called *fermions*, and those with integer spin are called *bosons*. There are three types of families (generation) of particles: two types of fermions called *leptons* and *quarks* with spin- $\frac{1}{2}$, and one family of bosons called *gauge bosons* with spin-1. The gauge bosons are sometimes referred to as “force particles” since they mediate the fundamental forces. The elementary particles of the SM are shown in Figure 1.1.

The dynamics and interactions of the elementary particles are derived from the SM Lagrangian and its symmetries. The Lagrangian is invariance under local transformations of the gauge group. In the SM the gauge symmetry group is $SU(3)_C \times SU(2)_L \times U(1)_Y$, which describes the strong, weak, and electromagnetic interactions. The strong interaction results from an $SU(3)_C$ symmetry group, where “C” stands for the conserved charge of interaction referred to as *color*. It is also known as *Quantum Chromo Dynamics* (QCD). The group implies 8 massless generators known as *gluons*, which mediate the interaction between colored particles by carrying the color charges. The electroweak interaction can be obtained from an $SU(2)_L$ symmetry group in the space of weak isospin and a $U(1)_Y$ symmetry group related to the electric charge. The generators of this group corresponds to four spin-1 vector bosons, two of which carry electric charge and two are neutral. The L subscript indicates that the vector bosons only couple to the left-handed component of the fermions leaving the right-handed component unchanged. The Y subscript represents the hyper-charge quantum number, which is a linear combination of electric charge and the third component of the weak isospin.

The gauge symmetries lead to the presence of gauge bosons. The symmetry strictly requires these gauge bosons to be massless. This is true for photons (electromagnetic force mediators) and gluons but not for the weak force mediators, $W^\pm, Z$, which are massive. This implies that $SU(2)_L \times U(1)_Y$ gauge symmetry is not preserved. It explains the coupling structure of the electroweak force, however,

¹ The gravitational force is not part of the Standard Model.

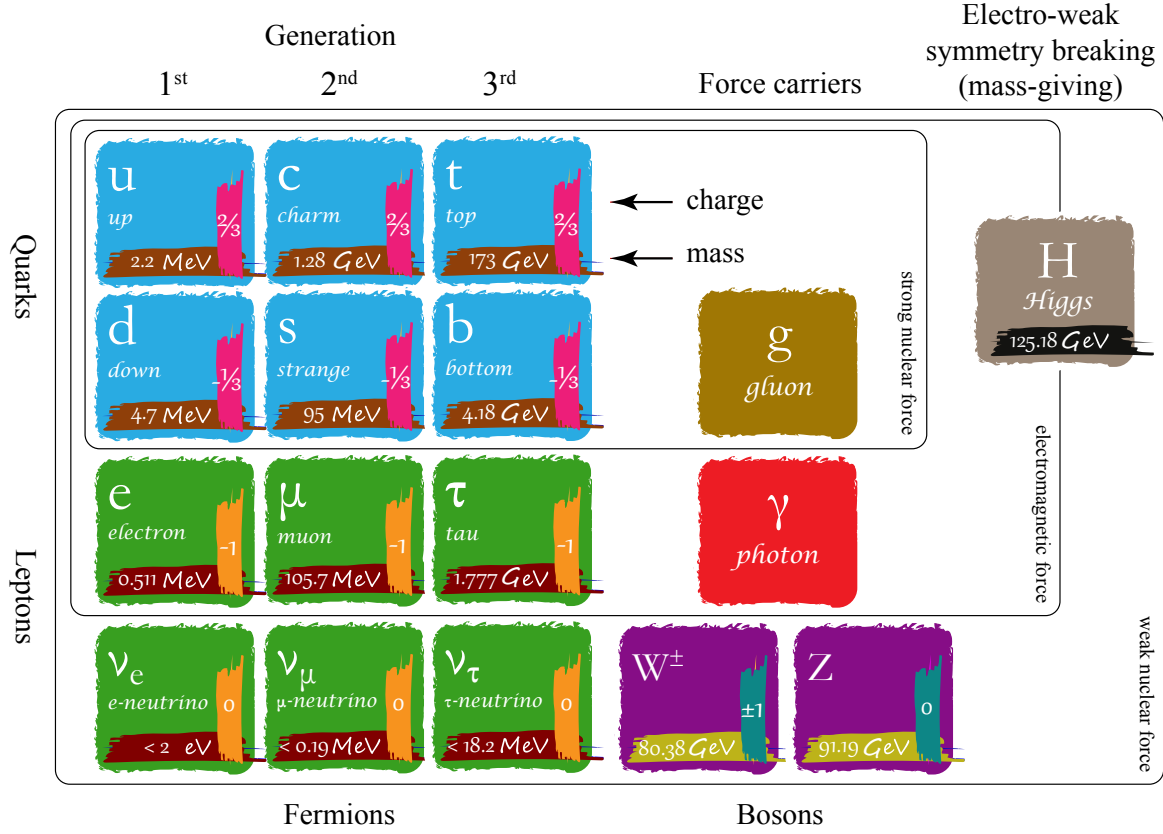


FIGURE 1.1: Elementary particles in the Standard Model.

it contradicts the fact that the $W^\pm$ and Z bosons as well as fermions have a non-vanishing mass [5, 6].

1.2 Spontaneous symmetry breaking

In the SM, the mechanism of electroweak symmetry breaking is responsible for generating mass of $W^\pm$ and Z gauge bosons, and fermions. A new field known as the Higgs field (Φ) is introduced with a characteristic of self-coupling, which leads to an energy potential that is symmetric in the complex plane of Φ . The scalar potential is

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi \Phi^\dagger)^2, \quad (1.1)$$

where the Higgs field Φ is a self-interacting complex scalar doublet $SU(2)_L$ with weak hypercharge of $Y = 1$. Thus,

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}, \quad (1.2)$$

where Φ^+ and Φ^0 are the complex charged and the neutral components of the Higgs doublet, respectively. In the case the coefficient μ^2 at the quadratic term is negative, the neutral component acquires a non-zero vacuum expectation value v , and thus inducing *spontaneous symmetry breaking* of the SM gauge symmetry group. This implies that there is a symmetry of the system that is not respected by

the ground state. The vacuum expectation value becomes non-zero

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (1.3)$$

where v is

$$v = \sqrt{\frac{-\mu^2}{\lambda}}. \quad (1.4)$$

The gauge bosons acquire mass from their interaction with the non-zero vacuum state of the scalar field. This idea was introduced by Higgs, Englert, Brout and others independently in the 1960s, and it is referred to as the Higgs mechanism [7–12].

1.3 The Higgs boson

The Higgs mechanism preserved the electroweak gauge symmetry. Four new degrees of freedom are introduced as a consequence of introducing the Higgs field. The three degrees of freedom correspond to the massive gauge bosons. The fourth degree of freedom leads to postulation of a new particle, the Higgs boson. The Higgs boson has spin-0 and it is electrically neutral. Its mass is given by $m_H = \sqrt{2\lambda}v$, where λ is the Higgs self-coupling parameter in the potential $V(\Phi)$. The value of the vacuum expectation v is fixed by the Fermi coupling G_F :

$$v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}, \quad (1.5)$$

which is determined from precise measurements of muon decays. Moreover, the quartic coupling λ is a free parameter in the SM, and therefore the mass of the Higgs boson is not predicted *a priori*. Experimentally, the Higgs mass has been measured to be $125.18 \pm 0.16 \text{ GeV}$ [13].

The coupling of the Higgs boson to the $W^\pm$ and Z bosons is proportional to the square of their masses. In contrast, fermions can also couple to the Higgs field and acquire masses. This is achieved by a Yukawa interaction term between the Higgs and the fermion fields. The mass term for fermions is

$$m_f = y_f \frac{v}{\sqrt{2}}, \quad (1.6)$$

where f represents any fermion, and y_f is the Yukawa coupling constant that describes the strength of the coupling of the fermion to the Higgs field. The fermion masses are free parameters and can only be measured from experiments since the Yukawa couplings are unknown.

A prominent prediction from the Higgs mechanism is the linearity between mass and coupling. This can be experimentally tested.

1.3.1 Higgs production and decay mechanisms

At the Large Hadron Collider (LHC), there are four main production mechanisms through which the SM Higgs boson can be produced:

- Gluon-gluon fusion (ggF).
- Vector boson fusion (VBF).
- Associated production with W/Z gauge boson (VH).
- Associated production with a pair of top-antitop quarks ($t\bar{t}H$).

Figure 1.2 shows the Feynman diagrams for these Higgs production processes.

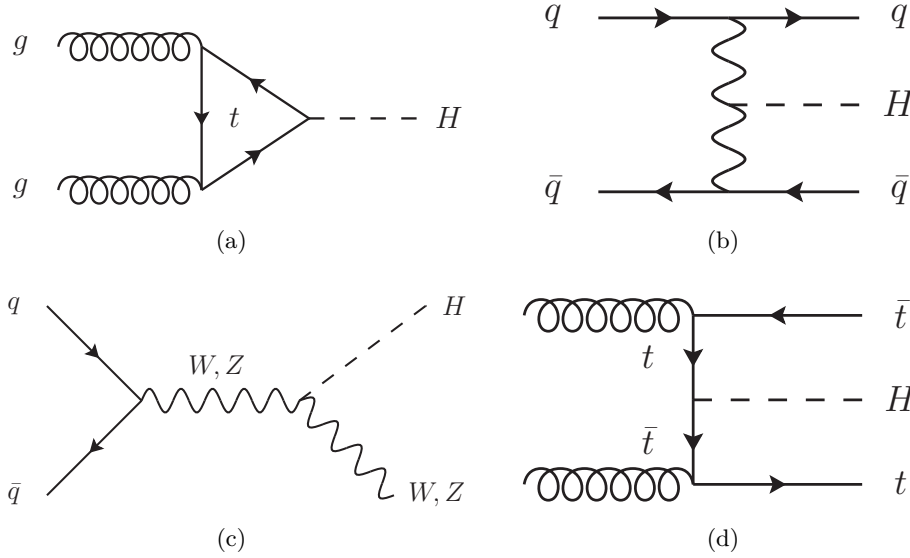


FIGURE 1.2: Leading order Feynman diagrams contributing to the Higgs boson production modes in (a) ggF , (b) VBF , (c) VH , and (d) $t\bar{t}H$.

The production mechanism with the largest cross section is the gluon-gluon fusion process. The coupling of the Higgs boson with gluons is through the exchange of a virtual heavy top quark. The VBF process involves the scattering of two quarks (anti-quarks) mediated by the exchange of a W or Z boson, with the Higgs boson radiated off the vector boson propagator. In the final state the scattered quarks give rise to two well separated jets in the forward and backward direction of the detector. The cross section of this process is smaller than the ggF production. The third most relevant production mechanism is the Higgs-strahlung mechanism, where the Higgs boson radiated off a virtual gauge boson. The VH production mode provides a relatively clean environment for studying the decay of the Higgs boson into a pair of bottom quarks. The $t\bar{t}H$ production mode has the smallest cross section compared with the other production modes. However, it provides a direct probe of the top-Higgs Yukawa coupling. Other production mechanisms at the LHC include the Higgs production in association with a single top quark pair, and with bottom quarks. These production mechanisms are quite rare but can be accessible at high energy. Figure 1.3 (a) summarizes the SM Higgs boson production cross sections as a function of the center-of-mass energy $\sqrt{s}$.

The branching ratios for the main decay modes of the SM Higgs boson are summarized in Figure 1.3 (b). The dominant decay modes are $H \rightarrow b\bar{b}$ and $H \rightarrow WW^*$ for a Higgs boson mass of 125 GeV. With smaller branching ratios, follow the decay modes $H \rightarrow gg$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow c\bar{c}$, $H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$, and $H \rightarrow \mu\mu$. The Higgs decays into gluons, and a $c\bar{c}$ pair are less accessible at the LHC due to overwhelming QCD background production. The Higgs boson decays into a $\tau^+\tau^-$ pair has a small branching ratio, but it allows for probing the coupling of the Higgs field to the fermions. The $H \rightarrow \gamma\gamma$ decay (through loop) offers a clean experimental signature as it only involves two energetic photons. This decay mode has a low branching ratio but a high signal over background ratio.

1.4 The top quark

The top quark is the heaviest quark in the SM with a mass of 173.0 ± 0.4 GeV [13]. It is the only quark in the SM whose Yukawa coupling to the Higgs boson, y_t , is close to unity. Such particular value implies that the top quark plays a special role in the SM and many scenarios beyond the SM. At the LHC, top quarks are produced in pairs through the process $gg \rightarrow t\bar{t}$. The top quark has a very short lifetime and decays before hadronization can occur. Being heavier than the W boson, it decays

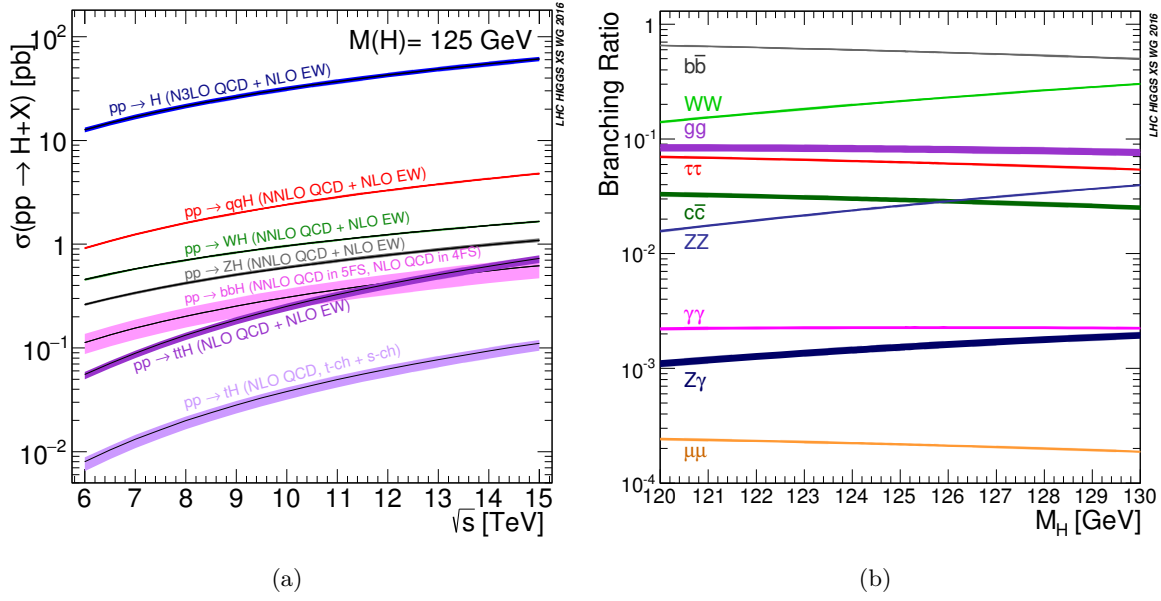


FIGURE 1.3: (a) SM Higgs boson production cross sections as a function of the center-of-mass energy $\sqrt{s}$. (b) Branching ratios for the main decay modes as a function of the Higgs boson mass M_H . The SM Higgs boson has a mass of 125.18 ± 0.16 GeV [13].

into a W boson and a b quark. The final states of a $t\bar{t}$ production are divided into three categories based on the decay of the two W bosons.

- **Dilepton:** the two W bosons decay leptonically into a lepton and a neutrino. This includes the leptonic decay of the tau lepton². The final state is characterized by the presence of two oppositely charged leptons from the W decays.
- **Hadronic:** both W bosons decay hadronically into a quark pair. The quarks in the final state emerge as jets of hadrons.
- **Leptons+Jets (semileptonic):** one of the W boson decays leptonically, while the other hadronically.

Many properties of the top quark, such as differential production cross section, spin correlation, forward-backward or charge asymmetry, have been measured with precision. Details of these measurements can be found in Ref. [13].

1.5 Theoretical motivation for the $t\bar{t}H$ measurement

The discovery of a Higgs boson with a mass of about 125 GeV by the ATLAS [14] and CMS [15] Collaborations was an important milestone in the particle physics. Following the discovery, the properties of the Higgs boson have been measured at different runs of the LHC at $\sqrt{s} = 7, 8$, and 13 TeV [16–19]. No significant deviations from the SM predictions were found.

The Yukawa coupling of the Higgs boson to the top quark is expected to have a value of the order of unity. Any deviations found between measurements and the expected values of the top Yukawa coupling would be a strong evidence for the new physics beyond the SM (BSM). A measurement of the ratio of the top Yukawa coupling to the SM prediction has been obtained from the combined fit of the ATLAS and CMS Higgs boson measurements [20]. This indirect measurement was made using the

² Hadronically decaying tau leptons are considered separately.

ggF production process, since the ggF loop is dominated by the top quarks, and assumes no beyond the SM contributions. However, the new particles predicted by BSM theories could be present in the loop. Thus, a direct measurement of the top Yukawa coupling is preferable to disentangle any deviation due to coupling to new particles and to significantly reduce the model dependence in the extraction of the top Yukawa coupling. A direct test of this coupling can be achieved via the $t\bar{t}H$ production, as shown in Figure 1.2 (d).

Although the $t\bar{t}H$ production has the smallest cross section, the characteristic signatures from the top quarks in the final state give access to several Higgs boson decay modes. The evidence [21] of the $t\bar{t}H$ production was found in 2017 by the ATLAS Collaboration. Later in June 2018, the coupling of the Higgs boson to top quarks was directly observed by the ATLAS and CMS Collaborations through the observation of the associated production of a Higgs boson and a top quark pair [22, 23].

Chapter 2

The Large Hadron Collider and the ATLAS detector

This chapter summarizes at first the world's largest and most powerful particle accelerator, the Large Hadron Collider, and then focuses on the ATLAS detector, one of the four main experiments which study the collisions produced by the collider.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [24] is a circular particle accelerator, based at the European Organization for Nuclear Research (CERN), near Geneva in Switzerland. It is hosted in the same tunnel of the CERN's previous accelerator the Large Electron Positron collider (LEP), which operated from 1989 to 2000, and has the same geometry as the LEP collider with eight arcs and eight straight sections. It is situated about 100 m underground and consists of a 27 kilometer ring of superconducting magnets and accelerating structures. The LHC is designed to provide proton-proton (pp) collisions with a center-of-mass energy of $\sqrt{s} = 14$ TeV and an unprecedented luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. In addition, the LHC can also collide heavy lead (Pb) ions with an energy of 2.8 TeV per nucleon and a peak luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

A schematic view of the LHC ring and the layout of the accelerator complex at CERN is shown in Figure 2.1. Before being injected into the LHC ring, protons are pre-accelerated by a chain of linear and synchrotron accelerators. Protons, obtained from the ionization of hydrogen gas, are first accelerated by a linear accelerator (LINAC 2) to an energy of 50 MeV. The protons are then injected to the proton synchrotron booster which accelerate them to an energy of 1.4 GeV. They are then injected into proton synchrotron which in turn increases their energy to 25 GeV. After that, protons are sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV.

The protons from the SPS are transferred to the two beam pipes of the LHC. The proton beam in one pipe circulates clockwise while the beam in the other pipe circulates anticlockwise. Two beams of protons are intersect at four interaction points, where the collisions occur. The proton beams are kept on their nearly circular orbits by means of 1232 dipole magnets with field strength of up to 8.3 T, which are cooled by superfluid helium down to 1.9 K. In addition, 392 quadrupole magnets are used to focus the beams. Just prior to collision, final focus magnets are used to squeeze the particles closer together to maximize the collision rate. The protons are injected in bunches into the LHC with a bunch spacing as low as 25 ns. It takes about 4 minutes to fill each LHC ring. Each bunch contains about 10^{11} protons and the LHC is designed to be loaded with 2808 bunches. Once completely filled, the beams are accelerated to 6.5 TeV using superconducting Radio Frequency (RF) cavity system. The RF cavities are located at four different places around the ring. An uninterrupted period with beams circulating in the LHC machine is called a LHC *fill*. Usually a LHC fill lasts for several hours up to the point when the beam intensity is reduced down to a threshold due to the collisions with the remaining beam-gas, or the beam-wall, and other effects along the trajectory. Although most protons

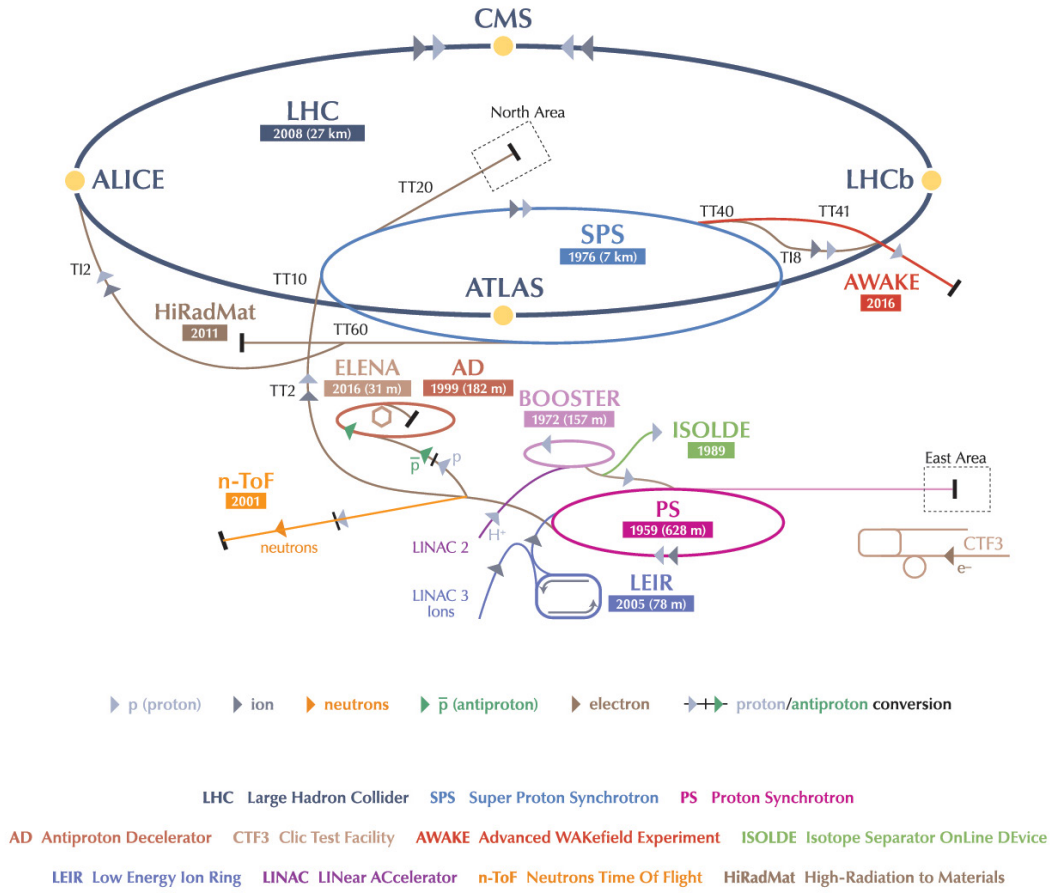


FIGURE 2.1: The CERN accelerator complex [32]. The four main experiments are indicated as yellow dots.

are lost due to bunch-bunch interactions (“burn-off”). At that point, the beams are dumped from the machine to allow for a new cycle to start.

There are four main experiments installed at the LHC:

- A Toroidal LHC ApparatuS (ATLAS) [25].
- Compact Muon Solenoid (CMS) [26].
- Large Hadron Collider beauty (LHCb) [27].
- A Large Ion Collider Experiment (ALICE) [28].

ATLAS and CMS are general-purpose detectors designed to cover the widest possible range of physics at the LHC, including tests of the Standard Model and searches for new physics beyond the Standard Model. The LHCb focuses on the precision measurements of CP violation and rare decays of b-hadrons. ALICE is dedicated to heavy ion physics. In addition, there are three smaller and very specialized experiments situated close to the ATLAS and CMS experiments:

- TOTal Elastic and diffractive cross section Measurement (TOTEM) [29].
- Large Hadron Collider forward (LHCf) [30].
- Monopole and Exotics Detector At the LHC (MoEDAL) [31].

The number of events generated in the LHC collisions is given by

$$N = \sigma_{\text{event}} \int \mathcal{L} \, dt, \quad (2.1)$$

where σ_{event} is the cross section of the process under study and $\mathcal{L}$ is the instantaneous luminosity that is integrated over the data collection time. The cross section is expressed in units of area called barns ($1 \text{ barn} = 10^{-24} \text{ cm}^2$). The integrated luminosity is measured in units of inverse barn b^{-1} , and it represents a measurement of the collected data sample. The integrated luminosity is often referred to simply as the luminosity. The instantaneous luminosity, $\mathcal{L}$, depends only on the beam parameters and can be written for a Gaussian beam distribution as

$$\mathcal{L} = \frac{f n_b N_p^2 \gamma}{4\pi \varepsilon \beta^*} F, \quad (2.2)$$

where f is the revolution frequency, N_p is the typical number of protons per bunch, n_b is the number of bunches per beam, γ is the relativistic factor, ε is the normalized transverse beam emittance, β^* is the beta function at the collision point, and F is a geometric luminosity reduction factor due to the crossing angle at the interaction point. For head on collision the value of the factor F is 1 and it becomes smaller when the crossing angle increases. The product $\varepsilon \beta^*$ is directly related to the beam size at the interaction point, and it is a measurement of the beam's squeezing. In order to achieve high luminosity, more high population bunches need to collide at high frequency with the beam size as low as possible [24].

The LHC first started its operations in September 2008. After an incident related to the main dipoles it took almost one year to recover, the LHC resumed its operations for data taking in 2009. The first collisions at $\sqrt{s} = 7 \text{ TeV}$ took place in spring 2010. The data-taking period from 2010 to 2012 is referred to as Run-1. The LHC delivered pp collisions at $\sqrt{s} = 7$ in 2010 and 2011, and $\sqrt{s} = 8$ in 2012. After Run-1, the machine and its experiments went into a planned first long shutdown (LS1) of about two years to upgrade and prepare for higher energies and luminosities. The LHC restarted its operations in early 2015 reaching a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. During this second run from 2015 to 2018 (Run-2), the LHC performed beyond expectations producing five times more data than during Run-1 at the unprecedented energy of 13 TeV. The LHC delivered collisions at record instantaneous luminosities up to $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and surpassed the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ due to a very small transverse beam emittances and β^* of 30 cm. The total integrated luminosity delivered to the ATLAS detector¹ in Run-2 was 156 fb^{-1} , as shown in Figure 2.2 and given in Table 2.1.

On 3rd December 2018, the LHC was shut down again for about two years for major improvements and upgrades. This shutdown is called the long shutdown 2 (LS2). During the LS2, the accelerator complex and detectors will be reinforced and upgraded in preparation for Run-3 starting in 2021 and for the High-Luminosity (HL-LHC) project [35], which will start its operation after 2025. The dataset collected for the analyses presented in this thesis corresponds to the years 2015 and 2016 of the LHC operations.

TABLE 2.1: Total integrated luminosity delivered by the LHC at $\sqrt{s} = 13 \text{ TeV}$ in Run-2 [33].

Year	2015	2016	2017	2018
Total delivered integrated luminosity (fb^{-1})	4.0	38.5	50.2	63.4

¹ In Run-2, the total integrated luminosity recorded by the ATLAS detector was 139.0 fb^{-1} [33].

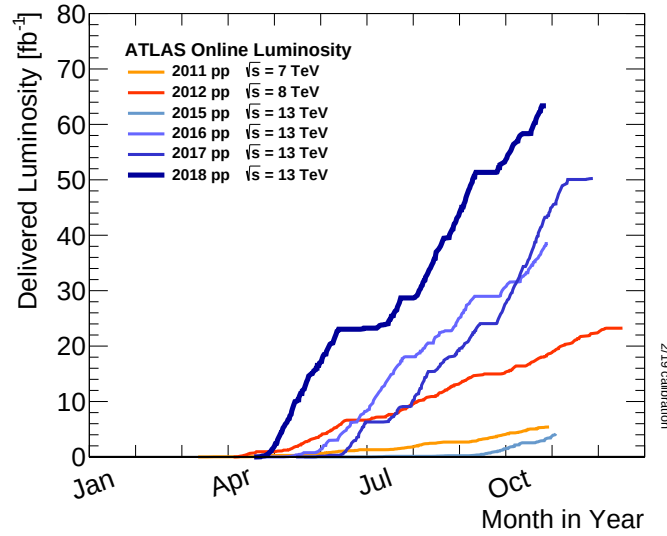


FIGURE 2.2: Cumulative luminosity versus day delivered to the ATLAS detector during stable beam conditions and for high energy pp collisions, separately for years between 2011 and 2018 [34].

2.2 The ATLAS detector

The ATLAS detector [25] is situated at one of the four interaction points of the LHC collider. It is a multipurpose detector designed to explore a wide range of physics processes, from high precision measurements to searches for new phenomena. A schematic view of the detector is shown in Figure 2.3. It is 44 m in length, 25 m in height, and is hosted in a cavern 100 m below ground. The overall weight of the detector is approximately 7000 tonnes, similar to the weight of the Eiffel Tower. It has a symmetric cylindrical geometry which covers nearly 4π in solid angle. The detector is comprised of four main components: the inner detector, the electromagnetic and hadron calorimeters, the magnet system, and the muon spectrometer. The subdetectors are arranged in concentric layers around the beam pipe to record the trajectory, momentum, and energy of different particles. This allows identification of individual particles.

2.2.1 The coordinate system

The ATLAS detector uses a right-handed coordinate system. The origin of the coordinate system is at the nominal interaction point (IP) in the center of the detector, where the beams collide, while the direction of the beam pipe defines the z -axis. The positive x -axis points toward the center of the LHC ring from the IP and the positive y -axis points upwards. Cylindrical coordinates are commonly used, ϕ being the azimuthal angle defined in the transverse x - y plane around the z -axis between $-\pi$ and π , and the polar angle $\theta \in [0, \pi]$ is the angle from the beam axis. The pseudorapidity^{2,3} is often used instead of the polar angle θ , which is defined as:

$$\eta = -\ln \tan \frac{\theta}{2}. \quad (2.3)$$

in the range $-\infty < \eta < \infty$.

² In the case of massive objects such as jets, the rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$ is used, where E is the energy and p_z is the momentum component in the z -direction.

³ The pseudorapidity defined in equation 2.3 is approximately equal to the rapidity y for $p \gg m$ and $\theta \gg 1/\gamma$, where γ is the relativistic factor.

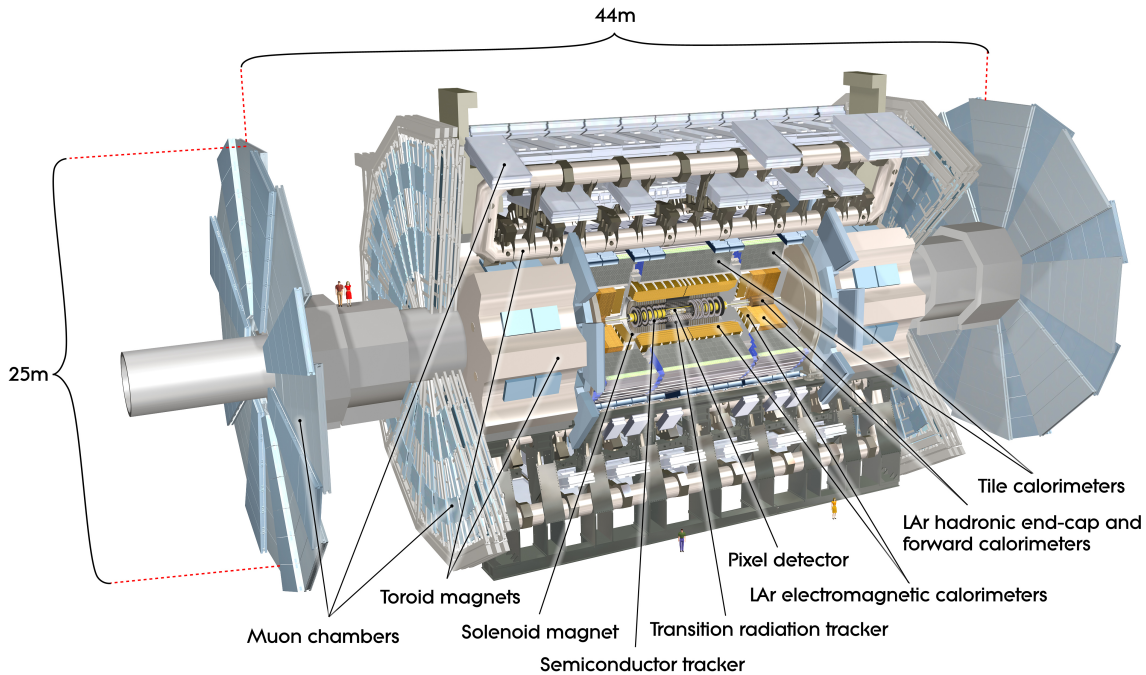


FIGURE 2.3: Cut-away view of the ATLAS detector [36]. The various subdetectors are indicated and labeled.

The difference in pseudorapidity, $\Delta\eta$, is an invariant quantity under a Lorentz boost along the z -axis. This property is useful in hadron colliders such as the LHC, since the partons e.g. gluon or quarks in protons carry fractions of the incoming proton momentum and thus have unknown longitudinal momenta. Furthermore, the composite nature of the colliding protons means that interactions rarely have their center-of-mass frame coincident with the detector rest frame. The angular distance between physics objects in the η - ϕ plane is given by:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}. \quad (2.4)$$

In hadron collider physics, the transverse quantities are often used to describe the kinematics of objects. Such quantities are the transverse momentum (p_T) and energy (E_T) being the component of a particle's momentum and energy in the transverse x - y plane, and can be calculated using the following relations

$$\begin{aligned} p_T &= \sqrt{p_x^2 + p_y^2}, \\ E_T &= \sqrt{p_T^2 + m^2}, \end{aligned} \quad (2.5)$$

where p_x and p_y are the momentum components in the x - and y -direction, respectively.

2.2.2 The magnet system

The magnet system is essential for an accurate measurement of charged particles momenta. It consists of a central solenoid, a barrel toroid and the two endcap toroids, designed to provide magnetic fields that bend the trajectories (tracks) of charged particles. The momentum of charged particles can be measured from the curvature of their trajectories⁴. The stronger the magnetic field, the more

⁴ The momentum component that is perpendicular to the magnetic field can be estimated as p [GeV] = $0.3 B$ [T] R [m], where R is the radius of the charge particle track.

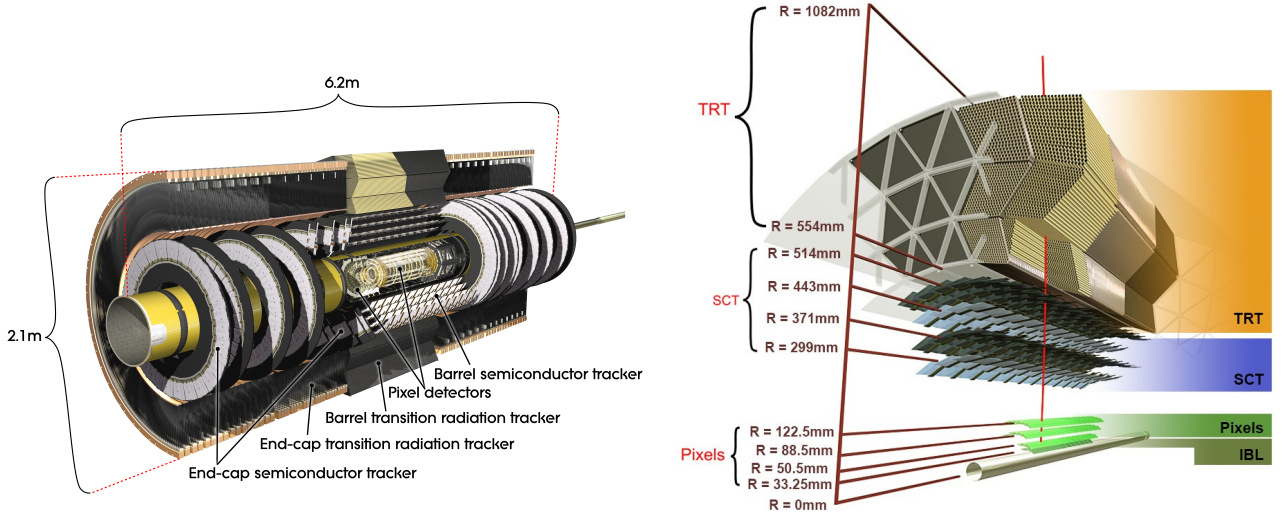


FIGURE 2.4: Schematic view of the ATLAS ID: (a) barrel and endcap sections; (b) barrel section showing the Pixel, SCT, and TRT subdetectors including the IBL. The distances to the interaction point are also shown [25, 38].

pronounced the curvature and the better the accuracy of the momentum measurement.

The solenoid magnet is aligned on the beam axis and provides a 2 T axial magnetic field for the inner detector, bending particles in the ϕ direction. The length of the solenoid is 5.8 m and it has outer radius of 1.28 m. In order to reduce the amount of material in front of the calorimeter, the solenoid and the calorimeter share the same cooling cryostat. The calorimeter and its support structure acts as a return yoke for the solenoid.

The three large superconducting air-core toroids generate a magnetic field of approximately 0.5 T and 1 T for the muon spectrometer in the barrel and endcap regions, respectively. Each of the three toroids consists of eight coils arranged radially around the beam axis. The barrel coils are 25.3 m long with inner and outer diameters of 9.4 m and 20.1 m, respectively. They are encased in individual racetrack-shaped stainless-steel vacuum vessel. The end-cap coils are five meters in length with inner and outer diameters of 1.65 m and 10.7 m, respectively. The end-cap toroids are rotated by 22.5° with respect to the barrel toroid in order to provide the radial overlap and to achieve a higher uniformity of the magnetic field.

2.2.3 The inner detector

The inner detector (ID) [37] provides efficient and robust pattern recognition, good momentum resolution, precise impact parameter measurements, and both primary and secondary vertex measurements for charged particles with $p_T > 0.5$ GeV within the pseudorapidity range $|\eta| < 2.5$. The ID comprises three complementary subdetectors: the Pixel Detector, the SemiConductor Tracker (SCT), and the Transition Radiation Tracker (TRT). The Pixel Detector and SCT are closest to the beam; both detectors are based on semiconductor technology and characterized by high granularity to cope with higher occupancy near the interaction point. At a larger distance to the interaction point, the TRT based on gaseous drift tube technology provides additional track measurements and particle identification. The ID is designed to provide a transverse momentum resolution of $\sigma_{p_T}/p_T = 0.05\% \cdot p_T \oplus 1\%$ by combining the information from the three subdetectors. The layout of the ID is shown in Figure 2.4. It is contained in a 6.2 m long cylinder with a radius of about 1.15 m, within a solenoidal magnetic field of 2 T. It is divided into a barrel and two endcap regions. The barrel is composed of several cylindrical layers of sensors arranged concentrically around the beam pipe, whereas in the endcaps the layers of sensors are mounted as disks or wheels perpendicular to the beam axis.

Pixel detector

The Pixel Detector [39] consists of 1744 silicon pixel modules arranged in three concentric barrel layers at radii $r = 50.5, 88.5, \text{ and } 122.5$ mm and two endcaps of three disks each. Each module has a sensitive area of 16.4×60.8 mm², and a thickness of 250 μm . There are 47232 pixels on each module, and the nominal pixel size in $(r-\phi) \times z$ is 50 $\mu\text{m} \times 400$ μm . A module is readout by 16 radiation-hard front-end chips bump-bonded to the sensor; the total number of readout channels is approximately 80.4 million. Hits in a pixel are read out if the signal exceeds a tunable threshold. The pulse height is measured using the Time-over-Threshold (ToT) technique [39]. The Pixel Detector has an intrinsic accuracy of 10 μm in $r-\phi$, and 115 μm both in z and r in the barrel and endcap regions, respectively. During LS1, a fourth layer, the so-called Insertable B-Layer (IBL) [40, 41], was installed at a radius of 33.25 mm between the first pixel layer (B-layer) and a new smaller radius beam pipe, as shown in Figure 2.4. The new beam pipe was inserted together with the IBL, and mainly consists of a 0.8 mm thick beryllium pipe with an inner radius of 23.5 mm. The IBL improves the tracking and vertexing performance of the current pixel detector.

SemiConductor Tracker

The SemiConductor Tracker [42, 43] consists of 4088 modules of silicon-strip detectors arranged in four coaxial cylindrical layers in the barrel region and two endcaps of nine disks on each side. The strips in the barrel are approximately parallel to the magnetic field and beam axis, and have a constant pitch of 80 μm , while in the endcaps the strip direction is radial and of variable pitch. Each module consists of four rectangular silicon-strip sensors; two sensors on each side are daisy-chained together to give a total of 768 strips of approximately 12 cm in length. A second pair of identical sensors is glued back-to-back with the first pair at a stereo angle of 40 mrad to provide space points. The strips are readout by radiation-hard front-end chips, each chip reading out 128 channels. The total number of readout channels in the SCT is approximately 6.3 million. The spatial resolution in the barrel (endcaps) is 17 μm in $r-\phi$, and 580 μm in z (r). The Pixel and SCT detectors cover the region $|\eta| < 2.5$.

Transition Radiation Tracker

The Transition Radiation Tracker [44, 45] consists of thin-walled proportional drift tubes (straws) with a diameter of 4 mm that are filled with a gas mixture of 70% Xe, 27% CO₂, and 3% O₂. In the center of each straw, there is a gold-plated tungsten anode wire of 31 μm diameter. The TRT barrel region contains 52544 straws of 144 cm in length, oriented parallel to the beam. The central anode wires are electrically split and readout at both ends of the straw. The two endcaps each contain 122880 straws 37 cm in length radially aligned to the beam axis. The endcap straws are read out at their outer end. The TRT straw layout is designed so that charged particles with $p_T > 0.5$ GeV and with pseudorapidity $|\eta| < 2$ cross typically more than 30 straws, providing continuous tracking at larger radii of the ID. When a charged particle traverses the TRT, it ionizes the gas inside the straws. The resulting free electrons drift towards the central anode wire, where they are amplified and readout by the radiation-hard front-end electronics. The total number of TRT readout channels is approximately 351000. The TRT only provides $r-\phi$ information, it has an intrinsic accuracy of 130 μm per straw.

The TRT straws are interleaved with polypropylene fibres (barrel) and foils (endcaps) to provide transition radiation, which may be emitted by highly relativistic charged particles as they traverse a material boundary. This effect depends on the relativistic factor $\gamma = E/m$ and it is strongest for electrons. For instance a 1 GeV electron has $\gamma \sim 2000$, whereas a pion with same energy only has a $\gamma \sim 7$. Typical energy of the transition radiation photons are about 6 keV, compared with the few hundred eV deposited by an ionizing particle in the Xe, CO₂, and 3% O₂ gas. These photons can be absorbed by Xe atoms, depositing additional energy in the gas and leading to significantly higher readout signals. Such signals are detected by a second, high-threshold, discriminator in the

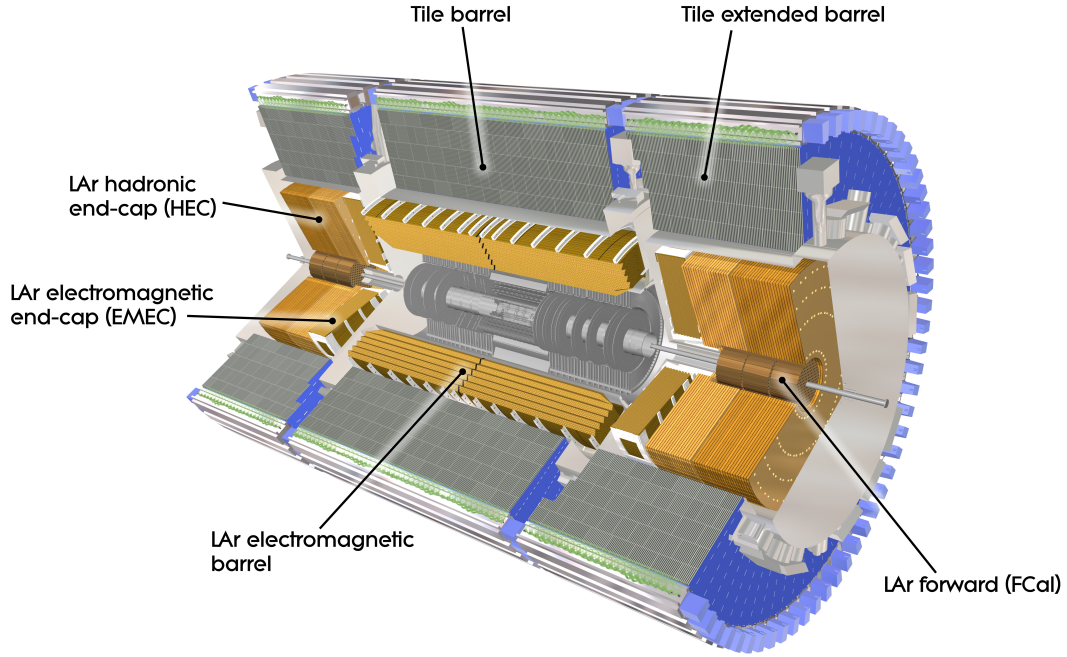


FIGURE 2.5: Cut-away view of the ATLAS calorimeter system with the various components indicated [46].

radiation-hard front-end electronics. Thus, the TRT provides electron identification via transition radiation complementary to that of the calorimeter over a wide range of energies.

2.2.4 The calorimeter system

The ATLAS calorimeter system [25] is illustrated in Figure 2.5. It comprises several calorimeters with various granularities and with different technologies. These calorimeters cover the pseudorapidity range $|\eta| < 4.9$ and provide accurate energy measurements of all particles. They are divided into two types: the electromagnetic calorimeter with fine granularity for precise measurements of electrons and photons, and the hadronic calorimeter designed with coarser granularity to measure the energy of hadrons. The ATLAS calorimeters are sampling calorimeters consist of alternating layers of absorbing (passive) and active materials. As particles from the hard-scatter processes interact with the absorbing material of the calorimeter, they create either an electromagnetic or hadronic shower. The layers of active material are designed to accurately measure the amount of energy in the shower. This alternating design allows for creating compact calorimeters with excellent shower containment, but at the cost of energy lost in the layers of absorbing material. The energy resolution of a sampling calorimeter can be parameterized as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2.6)$$

where a is the stochastic term related to the sampling, b is the noise term, and c is the constant term which takes into account the non-uniformity of the calorimeter and of its response. The symbol $\oplus$ indicates that the three terms are added in quadrature.

The electromagnetic calorimeter

The ATLAS electromagnetic (EM) calorimeter [47] is a high-granularity sampling calorimeter, which uses liquid argon (LAr) as active material and lead plates as the passive absorber. The liquid argon was chosen for its linear behavior, stability, and radiation hardness. The readout electrodes consist of kapton clad with copper are located in the gaps between the absorbers. The EM calorimeter has an accordion-shaped structure, which provides full ϕ symmetry without azimuthal cracks and facilitates fast readout. It is divided into a barrel region, covering the pseudorapidity range $|\eta| < 1.475$, and two endcaps covering $1.375 < |\eta| < 3.2$ in two coaxial wheels. The crack region between $1.375 < |\eta| < 1.52$ is affected by additional material needed to cool the inner detector, and it is normally excluded from physics analyses that require a precise measurement of electrons. The calorimeter barrel is segmented into three longitudinal layers with different granularities for $|\eta| < 2.5$, as shown in Figure 2.6. The first layer is finely segmented in strips of $\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$ to provide γ/π^0 separation and measurement of electromagnetic shower direction. The second layer collects most of the shower energy and has a granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$. The third layer is coarsely segmented in η to collect the shower tail but it gives the calorimeter extra depth. In front of the calorimeter, a thin presampler, covering the region $|\eta| < 1.8$, is used to correct for the energy lost by incident particles traversing the upstream material (e.g. the inner detector and the solenoid coil). The presampler consists of an active LAr layer with a thickness of 1.1 cm (0.5 cm in the barrel (endcap) region). The total thickness of EM calorimeter is more than 22 radiation lengths⁵ (X_0) in the barrel, and more than 24 X_0 in the endcaps. The energy resolution of the EM calorimeter was measured in test-beam by fitting the functional form in equation 2.6. The energy resolution obtained after the noise subtraction is

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%, \quad (2.7)$$

where E is expressed in GeV [25].

The hadronic calorimeter

The hadronic calorimeter is placed directly outside the EM calorimeter envelope and consists of the tile calorimeter (TileCal) [48], the hadronic endcap calorimeter (HEC), and the forward calorimeter (FCal) [49]. The TileCal is a sampling calorimeter using scintillating tiles as the active material and steel as the absorber. It is subdivided into a central barrel covering the range $|\eta| < 1.0$, and the two extended barrels covering $0.8 < |\eta| < 1.7$. Both the barrel and extended barrels are divided azimuthally into 64 wedges (modules) corresponding to size $\Delta\phi \sim 0.1$. Radially, each module is segmented into three layers that are approximately 1.5, 4.1, and 1.8 interaction lengths (λ) thick for the barrel, and 1.5, 2.6, and 3.3 for the extended barrel. The scintillator tiles are arranged radially and normal to the beam axis. Wavelength shifting fibres coupled to each edge of the scintillating tiles collect the produced light, and readout by two different photomultiplier tubes (PMTs) each linked to one readout channel. The fibres are grouped to define a three dimensional cell geometry. The resulting cell dimensions are $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two radial layers and 0.2×0.1 in the third layer. As the hadronic showers tend to be less compact than electromagnetic showers, this coarser granularity provides suitable precision, and thus high granularity is less important. The total thickness of the TileCal at the outer edge is 9.7λ at $\eta = 0$, guaranteeing full containment of hadronic showers.

The HEC consists of two independent wheels per endcap, covering the range $1.5 < |\eta| < 3.2$. Each wheel is built from 32 identical wedge-shaped modules. It uses LAr technology similar to that of the EM calorimeter, but have copper rather than lead as the absorbing material. The geometrical arrangement of the layers also differs, where a simple design of flat copper plates is used. The readout cells have granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the region $|\eta| < 2.5$ and 0.2×0.2 for larger η .

⁵ The radiation length is the mean path length over which a high-energy ($E \gg 2m_e$) electron loses all but 1/e of its energy due to bremsstrahlung.

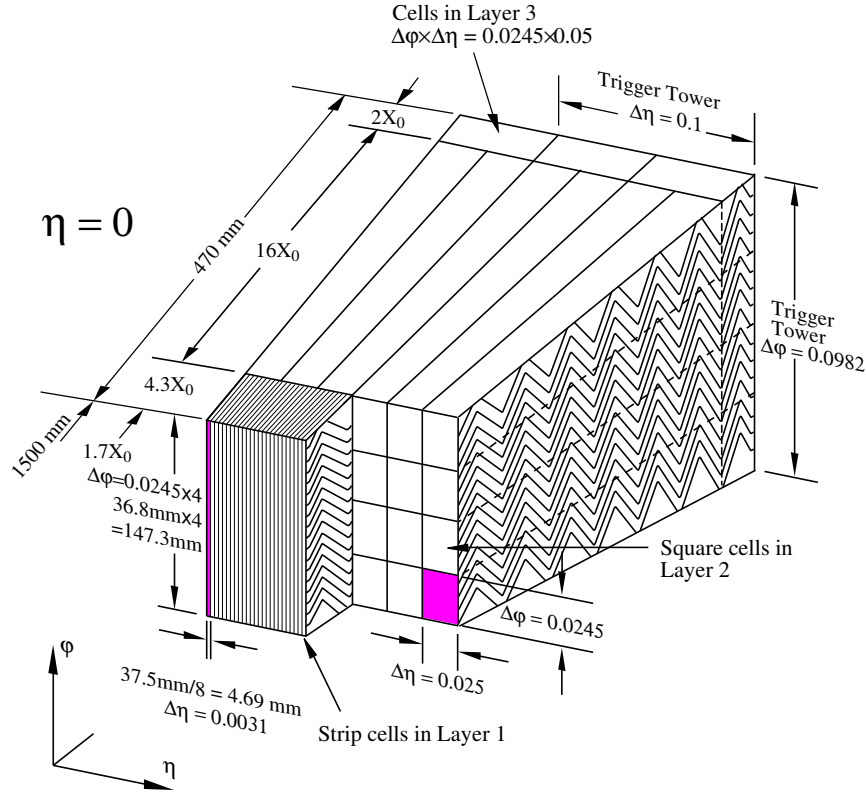


FIGURE 2.6: Schematic view of a section of the EM barrel calorimeter, showing the accordion structure and the granularity of each of the three layers [25].

The FCal is a liquid argon and copper/tungsten detector placed 4.7 m away from the interaction point on each side, designed to measure both electromagnetic and hadronic showers. It is located in the same cryostats as the endcap calorimeters and extends the ATLAS calorimeter system up to $|\eta| < 4.9$. The FCal consists of three separate modules; the first is optimized for electromagnetic measurements, and the remaining two measure predominantly the energy of hadronic interactions. The active medium for all three modules is LAr, while the absorbing medium is copper for the first and tungsten for the latter two. The total depth of the FCal is approximately 10 interaction lengths.

2.2.5 The muon spectrometer

The muon spectrometer (MS) [50] is the outermost ATLAS subdetector that surrounds the calorimeters. It is designed to detect muons, and provides a standalone measurement of the muon momentum in the pseudorapidity range of $|\eta| < 2.7$ with the transverse momentum resolution varying from 3% at 100 GeV to about 10% at 1 TeV. It is also designed to trigger on muons with varying transverse momentum thresholds down to a few GeV in the region $|\eta| < 2.4$. The muon momentum is determined by measuring the track curvature in a toroidal magnetic field. In the barrel ($|\eta| < 1.4$) the magnetic field is provided by the large barrel toroid, while in the endcap ($1.6 < |\eta| < 2.7$) two smaller magnets inserted into both ends of the barrel toroid generate the field. In the transition region ($1.4 < |\eta| < 1.6$), magnetic deflection is provided by a combination of barrel and endcap fields. The layout of the ATLAS muon spectrometer is shown in Figure 2.7. The MS employs four different chamber technologies: Monitored Drift Tubes (MDTs), Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs), and Thin Gap Chambers (TGCs). The chambers are arranged in three concentric cylindrical layers around the beam axis in the barrel region. In the two endcap regions, the chambers form large wheels perpendicular to the beam, also in three layers.

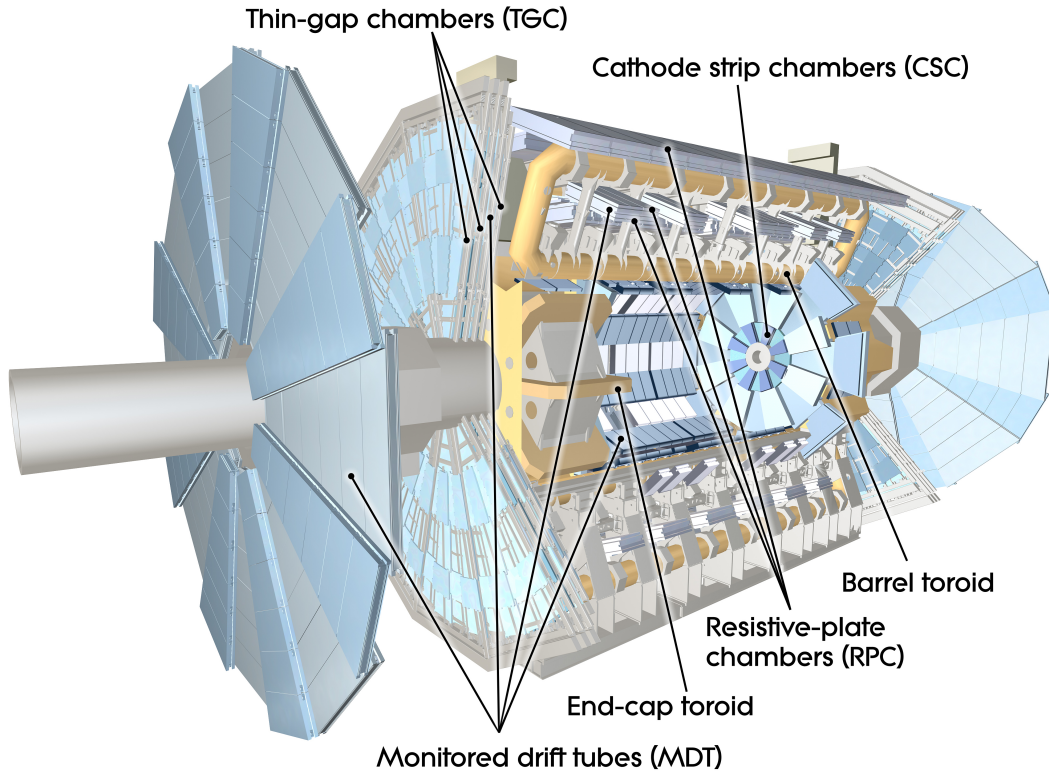


FIGURE 2.7: Cut-away view of the ATLAS muon spectrometer and its main components [51].

A precise momentum measurement for muons is provided by the MDTs. The MDT chambers are composed of two multi-layers of drift tubes. Each drift tube is 30 mm in diameter and filled with a Ar/CO₂ gas mixture. The electrons resulting from ionization are collected at the central tungsten-rhenium wire with a diameter of 50 μm . The orientation of the tubes in the barrel and endcaps is along ϕ . The MDTs are located in the barrel and endcap regions of the MS covering the region up to $|\eta| < 2.7$. They are used to measure the track coordinates in the bending plane of the magnetic field, i.e., in the r - z plane, with an average resolution of about 35 μm per chamber. In the forward region ($2 < |\eta| < 2.7$), CSCs are used to cope with higher rates. The CSC chambers are multiwire proportional chambers with cathode planes segmented into strips in orthogonal directions. This allows both η and ϕ coordinates to be measured from the induced-charge distribution. The position of the track is obtained by interpolation between the charges induced on neighboring cathode strips. Typical resolution of a chamber is 40 μm in the bending plane.

The trigger system of the MS is based on the RPC and TGC chambers. They provide triggering capability to the detector as well as η and ϕ position measurements. In the barrel RPCs are used, which are gaseous parallel-plate detectors. Two resistive plates are kept parallel to each other with a 2 mm gap and filled with a gas mixture. A high voltage creates a uniform electric field between the plates, which allows avalanches to form along the ionizing tracks towards the anode. RPCs are operated in avalanche mode. This means that they can operate at higher rate and with a good timing resolution, which is useful for triggering. The signal from the RPC is readout by two orthogonal sets of pick-up strips. The RPCs are mounted together with MDTs in the barrel and cover the pseudorapidity range of $|\eta| < 1.05$. In the endcap region, TGCs provide the muon trigger capability and the measurement of the azimuthal coordinate. TGCs are multiwire proportional chambers with a very small gap between wire and cathodes compared to the wire-to-wire gap. The high electric field and the small wire-to-wire distance lead to a very good timing resolution. TGCs are mounted on the endcap wheels covering the

region $1.05 < |\eta| < 2.7$ (2.4 for triggering). Both RPCs and TGCs have good timing resolution of the order of few ns, but lower spatial resolution.

2.2.6 The trigger and data acquisition system

The trigger system is a fundamental component of the ATLAS detector, since it is responsible for the real-time selection of the subset of collisions to be recorded and analyzed offline. During Run-1, the trigger system operated efficiently at instantaneous luminosities up to $8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and primarily at center-of-mass energies of 7 and 8 TeV. The trigger and data acquisition (TDAQ) system used during Run-1 is described in detail in Refs. [52, 53]. In Run-2, the increased center-of-mass energy to 13 TeV, higher instantaneous luminosity, and an increased number of pp interactions per bunch crossing (pile-up), lead to higher trigger rates as compared to the Run-1. In addition, the decrease in bunch spacing from 50 to 25 ns also increases the trigger rates. In order to cope with the higher rates and with large number of pile-up (μ), the trigger system was significantly improved for Run-2. Several upgrades and additions were implemented during LS1. A detailed discussion of the trigger improvements for Run-2 is presented in Ref. [54]. The improved trigger system successfully adapted to the challenging running conditions of the LHC Run-2, and collected collision data with high efficiency.

The Run-2 ATLAS TDAQ system consists of a hardware-based first-level trigger (L1) and a software-based high-level trigger (HLT), as shown in Figure 2.8. The L1 trigger is implemented in hardware using custom electronics and makes fast decisions on whether to further process or discard an event. The L1 trigger uses a subset of the information from the calorimeter and muon detectors to reduce the event rate to a design maximum of 100 kHz. It has a fixed 2.5 μs latency after which events are rejected or passed to the HLT. The L1 triggers identify *Region of Interest* (RoI) within the detector to be investigated by the HLT. The L1 trigger decision is formed by the Central Trigger Processor (CTP) based on inputs from the L1 calorimeter (L1Calo) and L1 muon (L1Muon) triggers as well as from several other subsystems. The CTP also applies preventive deadtime by limiting the minimum time between two consecutive L1 accepts to avoid overlapping readout windows. The L1Muon trigger uses information from dedicated muon trigger chambers, the RPC system in the barrel region and the TGC system in the endcap region, to identify muon candidates. The L1Calo trigger make use of reduced granularity information from the electromagnetic and hadronic calorimeters to search for electrons, photons, hadronically decaying tau leptons, jets, as well as missing transverse energy. A new topological trigger (L1Topo) consisting of two FPGA-based (Field Programmable Gate Arrays) processor modules has been added to the L1 trigger system, and became fully operational in 2017. The L1Topo performs selections based on geometric or kinematic association between trigger objects received from the L1Calo or L1Muon systems. Such selections include cuts on the angular distance or on invariant mass of pairs of particle candidates at L1, which are crucial for triggering on low- p_T signatures at an affordable rate. An example for the benefits from the new L1Topo selections is the Higgs boson decays into pairs of hadronically decaying tau leptons event candidates. The di- τ triggers with selection implemented in L1Topo are used to select such event candidates.

After the events accepted by the L1 trigger, they are buffered in the Read-Out System (ROS) and processed by the HLT. The software-based HLT is implemented in a computer farm with about 40000 processing units. It reconstructs the physics objects using finer granularity calorimeter information, precision measurements from MS, and tracking information from the ID, which are not available at L1. At the HLT, the reconstruction algorithms are executed either in the RoI identified at L1 or in the full event, with the data retrieved on demand from the ROS. It uses algorithms and selections that are close to the ones used in the offline reconstruction (Section 2.3). In Run-1, the HLT consisted of separate level-2 (L2) and event filter (EF) farms. For Run-2, the L2 and EF farms were merged into a single homogeneous farm allowing better resource sharing and an overall simplification of both hardware and software. Most HLT triggers use a two-stage approach with a fast reconstruction step to reject the majority of events and a slower precision reconstruction for the remaining events in order to reduce the processing time. However, there is no fixed bandwidth or rate limitation between the

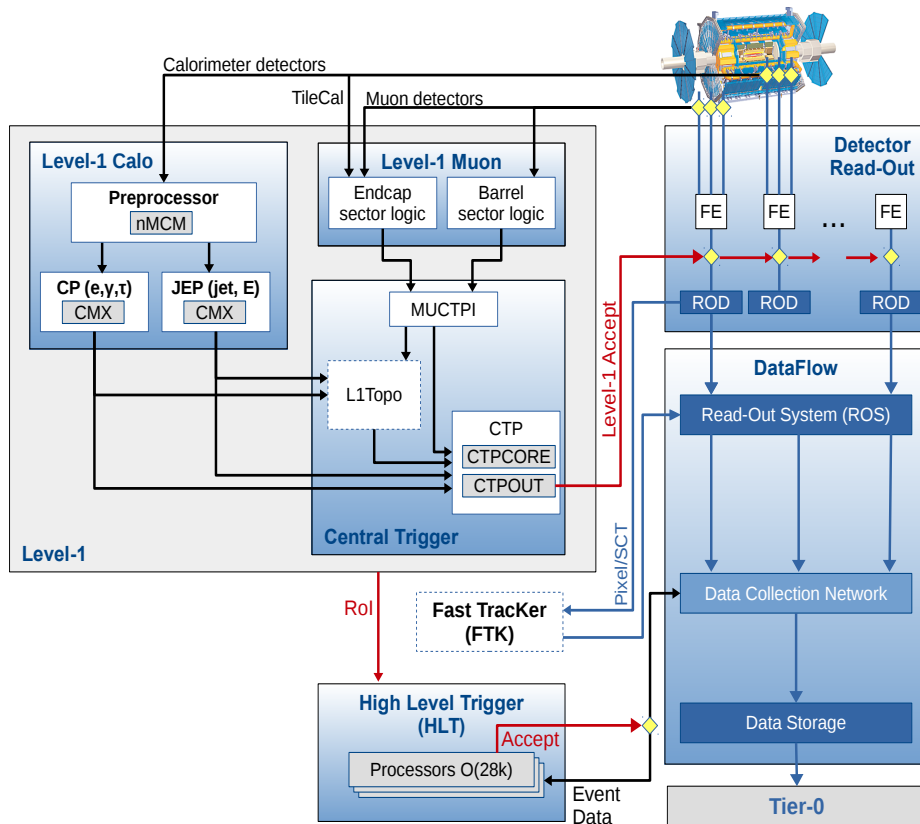


FIGURE 2.8: The ATLAS TDAQ system in Run-2 [54]. The L1Topo and FTK systems were not available during the 2015 and 2016 data-taking periods relevant to this thesis.

two steps thanks to the merging of L2 and EF farms. The HLT selects events at an average rate of 1 kHz during the LHC fill. Figure 2.9 shows the HLT trigger rates during an LHC fill with a peak luminosity of $4.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in 2015. It indicates the priority of the ATLAS physics program; a large fraction of the program is dedicated to physics with electrons and muons. Events accepted by the HLT are stored locally at the experimental site and exported to the Tier-0 facility at the CERN computing center for offline reconstruction. The data flow component of the ATLAS data acquisition (DAQ) system [55] is responsible for buffering and transporting event data from the ROS to the HLT and to the event storage.

A new FastTracker (FTK) system [56], was installed and commissioned, provides global ID track reconstruction at L1 using look up tables stored in associative memory chips for the pattern recognition. It allows the use of tracks at much higher event rates in the HLT than currently affordable using CPU systems.

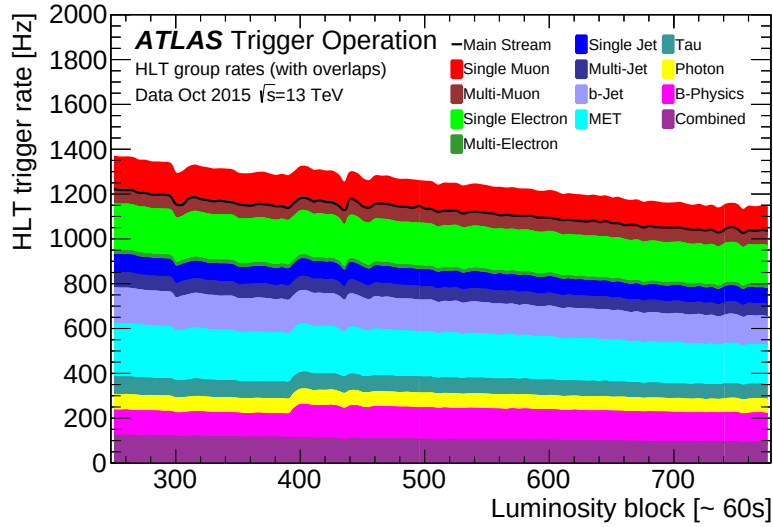


FIGURE 2.9: HLT trigger rates during an LHC fill in October 2015. Owing to overlaps the total HLT output rate (“main stream”) is less than the sum of the individual physics groups, which is shown as black line. The combined group includes multiple triggers combining different trigger signatures such as electrons with muon, taus, jets, or missing transverse energy [54].

2.2.7 Luminosity measurement and pile-up

An accurate measurement of the LHC luminosity delivered to the ATLAS experiment is a key component for any physics analysis. The information of the delivered luminosity is vital to evaluate backgrounds and to determine the sensitivity in searches for new physics. The uncertainty in the luminosity is often one of the major systematic uncertainties for cross section measurements.

ATLAS monitors the delivered luminosity by measuring the observed interaction rate per bunch crossing, μ_{vis} , independently with several detectors and using different algorithms. The luminosity can be written as

$$\mathcal{L} = n_b \cdot \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}} \cdot f_r, \quad (2.8)$$

where $\sigma_{\text{vis}} = \varepsilon \sigma_{\text{inel}}$ is the pp inelastic cross section multiplied by the efficiency ε of a particular detector and algorithm, $\mu_{\text{vis}} = \varepsilon \mu$ where the parameter μ is the average number of inelastic interactions per bunch crossing (i.e., pile-up), n_b is the bunch pairs colliding at the interaction point, and f_r is the bunch revolution frequency [57].

The calibration of the luminosity scale of a particular detector and algorithm is performed using dedicated beam-separation scans, known as van der Meer scans (Section 3.3), where the absolute luminosity is inferred from direct measurements of the beam parameters. This luminosity is then combined with the measured visible interaction rate μ_{vis} to obtain the visible cross section σ_{vis} .

ATLAS uses several independent luminosity detectors, which are characterized by different acceptance, response to pile-up, and sensitivity to instrumental effects and beam-induced backgrounds. The systematic uncertainties affecting the absolute luminosity determination are controlled by comparing the measurements of different luminometers. For LHC Run-1, the two primary luminometers were the BCM (Beam Conditions Monitor) [58] and LUCID (LUMinosity measurement using a Cherenkov Integrating Detector). For LHC Run-2, the primary luminometer was the LUCID-2 [59] Cherenkov detector, upgraded from its Run-1 configuration. The BCM consists of four $8 \times 8 \text{ mm}^2$ diamond sensors arranged around the beam pipe in a cross pattern on each side of IP at a distance of $z = \pm 184 \text{ cm}$. LUCID is a Cherenkov detector made up of 16 aluminum tubes filled with C_4F_{10} gas surround

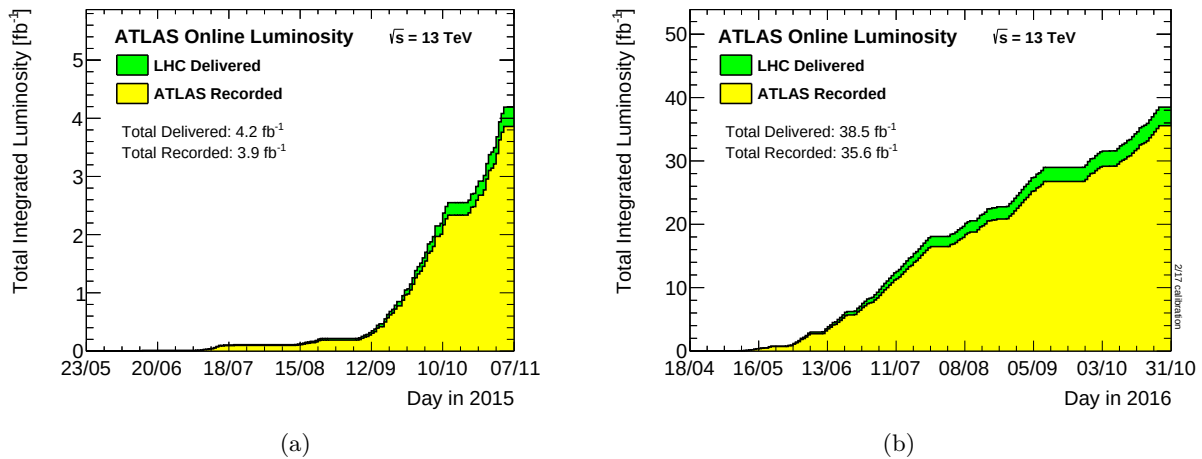


FIGURE 2.10: Time history of the integrated luminosity delivered by the LHC and recorded by the ATLAS detector during stable beams for pp collisions at $\sqrt{s} = 13$ TeV in (a) 2015 and (b) 2016 [34].

the beam pipe on each side of the IP at a distance of 17 m, covering the pseudorapidity range of $5.6 < |\eta| < 6.0$. Charged particles produce Cherenkov photons in the gas which are reflected by the tube walls until they are detected by the PMTs at the back end of the tubes. Both detectors are equipped with electronics capable of making precise bunch-by-bunch luminosity measurements. A brief description of the detectors and algorithms used for luminosity determination in ATLAS can be found in Refs. [33, 57].

The basic unit for storing luminosity information for physics analyses use is a luminosity block (LB). The boundaries of each LB are defined by the CTP to ensure that the data-taking configurations are constant. Configuration changes such as a trigger prescale adjustment can only happen at the boundaries of the LB. Thus, each LB contains data taken under uniform conditions and in general the duration of each LB is one minute. The instantaneous luminosity from each detector averaged over the LB. A variety of general ATLAS data-quality information is also stored for each LB. In order to define a data sample for physics analyses, quality criteria are applied to select LBs where conditions related to beam and detector are good. The instantaneous luminosity in the selected LB is multiplied by the LB duration to provide the integrated luminosity delivered in that LB. Additional corrections can be made for trigger deadtime and trigger prescale factors. The sum of the integrated luminosity delivered in a specific set of LBs provides the integrated luminosity of the entire data sample. This information of the integrated luminosity is needed for most physics analyses.

The cumulative luminosity delivered to ATLAS during stable beams for pp collisions in 2015 and 2016 is shown in Figure 2.10. The integrated luminosity recorded by the ATLAS detector is reported in yellow. The inefficiency in recording data arises due to the so-called warm start procedure in which the tracking detectors undergo a ramp up of the high voltage and become fully operative after LHC declared the stable beams, and because of deadtime problems in the trigger and data acquisition system. Typically ATLAS records data continuously during a single LHC fill. The data-taking is subdivided into runs and data periods. A run is the collection of luminosity blocks corresponding to continuous data-taking. This allows the exclusion of single problematic data-taking periods with minimal impact on the overall data-taking efficiency. Data periods are collections of runs that have similar data-taking configurations in terms of trigger and detector conditions, which are named alphabetically. The data used for the analysis presented in this thesis comprises the full 2015 and 2016 datasets collected by the ATLAS detector. It corresponds to an integrated luminosity of 36.1 fb^{-1} after data quality assessment.

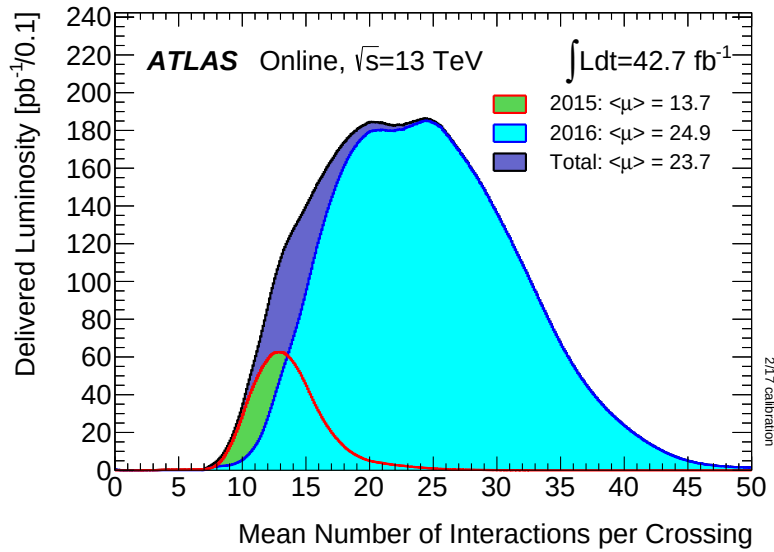


FIGURE 2.11: Delivered luminosity weighted distribution of the mean number of interactions per crossing for the combined 2015 and 2016 pp collision data. The mean number of interactions per crossing corresponds to the mean of the Poisson distribution of the number of interactions per crossing calculated for each bunch [34].

The number of inelastic interactions per bunch crossing follows a Poisson distribution with mean value μ , which is calculated from the instantaneous luminosity per bunch according to equation 2.8. The inelastic cross section, σ_{inel} , is taken to be 80 mb for 13 TeV collisions, based on van der Meer beam-separation scans performed in 2016 [34]. The luminosity weighted distribution of the mean number of interactions per crossing measured by the ATLAS detector during 2015 and 2016 is shown in Figure 2.11. The maximum number of interactions per bunch crossing reached up to 50 in 2016. The multiple interactions per crossing produce two types of effects: in-time and out-of-time pile-up. The in-time pile-up refers to additional pp collisions occurring in the same bunch crossing as the collision of interest. The out-of-time pile-up is due to additional collisions occurring in bunch crossings before and after the collision of interest. Such collisions can leave signals in the subdetectors during their readout because the electronics integration time is significantly larger than the interval between bunch crossings, which is 25 ns for Run-2.

2.3 Object reconstruction

Particles stemming from the pp collisions or from the subsequent decays interact with the ATLAS detector when traversing the detector volume. Each particle leaves a characteristic signature inside the various subdetectors. The output information from all subdetectors is combined forming basic quantities such as tracks and energy clusters. The reconstruction algorithms are employed to reconstruct objects from these quantities. The object reconstruction is a multi-stage process and the final output is the collection of objects (also referred to as physics objects) such as electrons, muons, hadronically decaying tau leptons, jets and missing transverse energy. These physics objects are used in the various physics searches. The reconstruction of physics objects that are relevant to the $t\bar{t}H$ search presented in this thesis is described in the following. The reconstruction of photons is not considered since they are not explicitly used in this thesis. Details of the photon reconstruction and identification algorithms can be found in Ref. [60].

2.3.1 Tracks and primary vertices

Charged particle trajectories or tracks are reconstructed in the ID within the pseudorapidity range $|\eta| < 2.5$ [61, 62]. The reconstruction begins by assembling clusters from the raw data (hits) in the Pixel and SCT detectors and subsequently converting the clusters into three-dimensional measurements referred to as space-points⁶. In the Pixel detector, each cluster corresponds to a single space-point. In the SCT, a three-dimensional space-point is obtained by combining the clusters from both sides of the strip module in a layer. Track seeds are formed from the sets of three space-points. The properties of a track seed are estimated by performing fit to a perfect helical trajectory in a uniform magnetic field. After the fit, a track is fully characterized by the following parameters:

- Transverse (d_0) and longitudinal (z_0) impact parameters.
- Polar (θ) and azimuthal (ϕ) angles.
- Charge over momentum q/p .

The transverse impact parameter is defined as the shortest distance between a track and the beam line in the transverse plane. The longitudinal impact parameter is defined as the distance in z (along the beam line) between the point on the track where d_0 is measured and the primary vertex. The purity of seeds that result in good quality tracks depends on which subdetector space-points are used in the seed. Three types of seed are considered: SCT-only, pixel-only, and mixed-detector seeds. The momentum and impact parameters requirements are placed on seeds to maximize purity, which is also improved by requiring one additional space-point that is compatible with the particle's trajectory estimated from the seed. A combinatorial Kalman filter [63] is used to build track candidates from the chosen seeds by incorporating additional space-points from the remaining layers of the silicon detectors.

The collection of tracks found in the combinatorial pattern recognition stage contains track candidates where space-points overlap, or have been incorrectly assigned. Ambiguities are solved using a track scoring strategy. The track candidates are scored in a reward-penalty schema with respect to one another, penalizing less precise track candidates. Clusters assigned to a track increase the track score, whereas holes reduce the score. A hole is defined as intersection of the reconstructed track with a sensitive detector element that does not contain a cluster. The χ^2 of the track fit is also considered to penalize poor quality candidates. A track candidate is rejected in the ambiguity solving procedure if it fails to meet any of the following quality criteria:

- Minimum of seven pixel and SCT clusters ('silicon hits').
- Maximum of either one shared pixel cluster or two shared SCT clusters in a given layer.
- No more than two holes in the combined Pixel and SCT detectors, and no more than one hole in the Pixel detector.
- Transverse momentum $p_T > 400$ MeV and the pseudorapidity $|\eta| < 2.5$.

Finally, the successful track candidates are extrapolated into the TRT volume and a track refit is performed using the drift circles found in the TRT. This leads to the final collection of tracks used as input to the object reconstruction.

Primary vertices are reconstructed from a collection of reconstructed tracks. For tracks to be considered in the construction of a vertex, they must pass the above requirements. Additional requirements are also applied: the minimum number of silicon hits are increased to nine and at least one hit on one of the two innermost Pixel layers (including the new IBL) is required. Moreover, the number of holes in the SCT is reduced to one and the tracks with a pixel hole are vetoed [64]. The procedure

⁶ A space-point represents the point where the charged particle traversed the active material of the ID.

of primary vertex reconstruction is divided into two stages: vertex finding and vertex fitting [65]. In the former stage, the reconstructed tracks are associated to the vertex candidates. The vertex fitting stage deals with reconstruction of the actual vertex position. Vertex seeds are obtained from the z_0 of the reconstructed tracks. An iterative χ^2 fit is made using the tracks and seed to estimate the best vertex position. Depending on the χ^2 of the fit, less compatible tracks are down-weighted in each iteration. After the position is determined, tracks that are incompatible with the vertex are removed from it and allowed to be used in the determination of another vertex. The procedure is repeated with the remaining set of tracks in the event. During reconstruction only vertices with at least two associated tracks are considered. The output of the vertex reconstruction algorithm is a set of three dimensional vertex positions and their corresponding uncertainties. The primary vertex of an event is defined as the vertex with the highest sum of squared transverse momenta of the associated tracks. All the other vertices are assumed to be due to pile-up interactions.

2.3.2 Electrons

Electrons are reconstructed in the central region of the ATLAS detector ($|\eta| < 2.47$) from energy clusters in the electromagnetic calorimeter matched to reconstructed tracks in the ID [66]. A schematic illustration of the elements that enter into the reconstruction as well as the identification of an electron is shown in Figure 2.12.

The $\eta \times \phi$ space of EM calorimeter is divided into a grid of 200×256 towers of size 0.025×0.025 , corresponding to the granularity of the second layer of the calorimeter. The energy of a tower is formed by summing up the energy of cells in all layers of the calorimeter including the presampler. The energy of cells spanning over several towers distributed uniformly among the towers. The EM clusters are reconstructed using sliding-window algorithm [67], which searches for seed clusters of towers with total cluster transverse energy above 2.5 GeV. The window size is 3×5 towers in η - ϕ space.

Electron track candidates are reconstructed in two steps: pattern recognition and track fit. The pattern recognition uses the pion hypothesis for the model of energy loss due to interactions of the particle with the detector material. However, if the pion hypothesis fails, a second attempt is made with the new pattern recognition using an electron hypothesis that allows up to 30% energy loss at each intersection of the track with the detector material to account for bremsstrahlung. Track candidates are fit either with the pion hypothesis or the electron hypothesis using the ATLAS global χ^2 track fitter [68]. Resulting tracks are extrapolated to the second layer of the calorimeter and loosely matched to the EM clusters. The matching conditions account for energy loss due to bremsstrahlung and the number of hits in the silicon detector. A subsequent fitting procedure is used for tracks with at least four silicon hits, and are loosely associated to EM clusters. This procedure employed an optimized Gaussian Sum Filter (GSF) [69], which takes into account the non-linear bremsstrahlung effects.

The matching of the GSF fitted track candidate to the seed cluster completes the electron reconstruction procedure. If several tracks are matched to a cluster, a primary track is selected based on an algorithm that takes into account the distance between the extrapolated tracks and the cluster barycentres measured in the second layer of the calorimeter, the number of hits in the silicon detector as well as the presence of a hit in the innermost silicon layer. Electron candidates without any associated tracks are considered to be photons. The energy of the clusters is calibrated using multivariate techniques based on MC samples and validated with data [70]. The electron energy is computed from the calibrated cluster, while the η and ϕ coordinates are taken from the corresponding track parameters.

The electron reconstruction efficiency is defined as the ratio of the number of reconstructed electron candidates to the number of EM cluster candidates. The reconstruction efficiency is measured from $Z \rightarrow ee$ events using tag-and-probe method [66]. Figure 2.13 (a) shows the reconstruction efficiency as a function of transverse energy E_T measured in data and simulation. The efficiency ranges from approximately 97 to 99% for electrons with $E_T > 15$ GeV. The uncertainty in the efficiency in data is

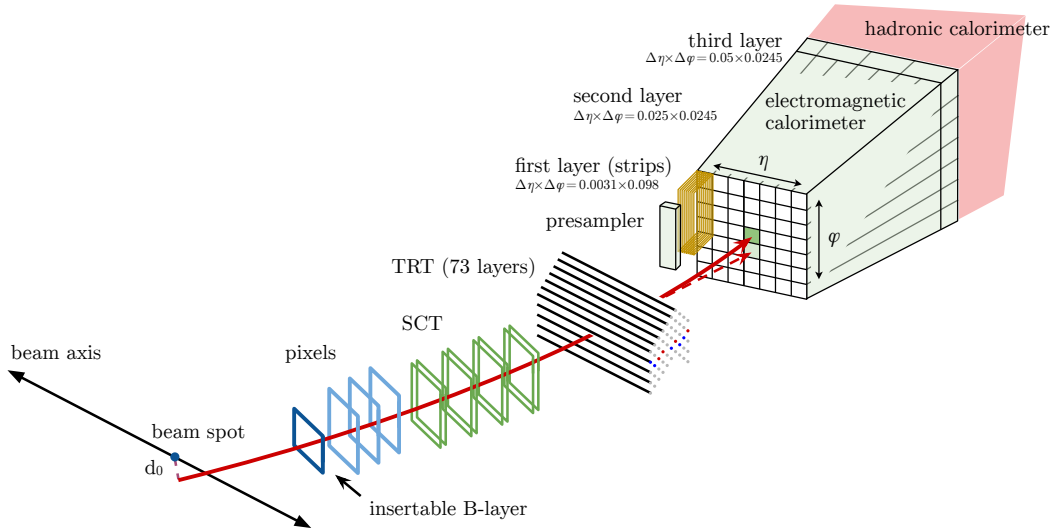


FIGURE 2.12: Depiction of an electron path through the ATLAS detector. The red trajectory shows the hypothetical path of an electron, which traverses the inner detector and typically hits the IBL pixel layer, 3 pixel layers, 4 double-sided silicon strips and approximately 73 TRT layers before entering the electromagnetic calorimeter. The electron deposits its energy in four successive calorimeter layers. The dashed red trajectory indicates the path of a photon produced by the interaction of the electron with the ID material [66].

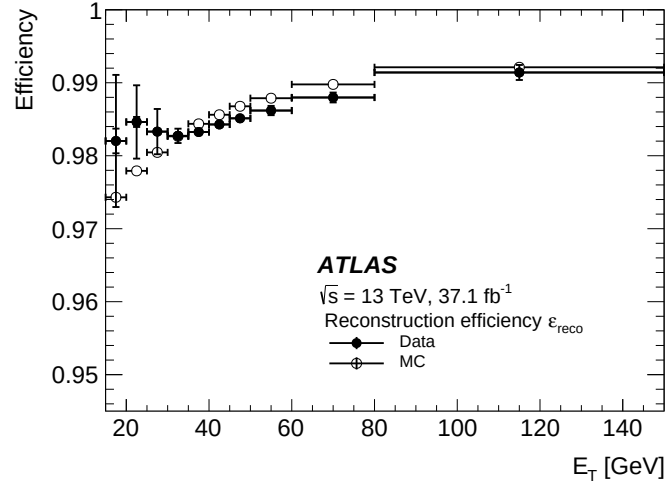
typically 1% for $E_T = 15 - 20$ GeV and reaches the per mille level at higher E_T . The uncertainty in simulation is almost an order of magnitude smaller than data.

Electron identification algorithms are applied to the reconstructed electrons to distinguish prompt⁷ electrons from background-like objects such as hadronic jets or converted photons. The identification algorithm uses a likelihood-based (LH) multivariate discriminant to reject these backgrounds [66]. The inputs to the LH include calorimeter shower shapes, information from the TRT, track-cluster matching related quantities, track properties including the number of hits in the IBL, and variables measuring bremsstrahlung effects. Three identification operating points are provided for electron identification. These are referred to as *loose*, *medium* and *tight*, which correspond to increasing background rejection. Benchmark efficiency measurements of the LH-based electron identification for three identification operating points for data are shown in Figure 2.13 (b). The efficiencies are measured from the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ events using the tag-and-probe method. The efficiencies for identifying a prompt electron with $E_T = 40$ GeV are 93%, 88% and 80% for the *loose*, *medium* and *tight* operating points, respectively [66]. Differences in the efficiencies between data and simulation are taken into account, and the simulated events are corrected. The ratio of the efficiency measured in data to that determined from simulated events is used as a multiplicative correction factor for simulation. These correction weights are normally close to unity; deviations from unity stem from mismodeling in simulation. In order to further reject the background objects an isolation requirement is applied to the electrons. More details can be found in Ref. [66].

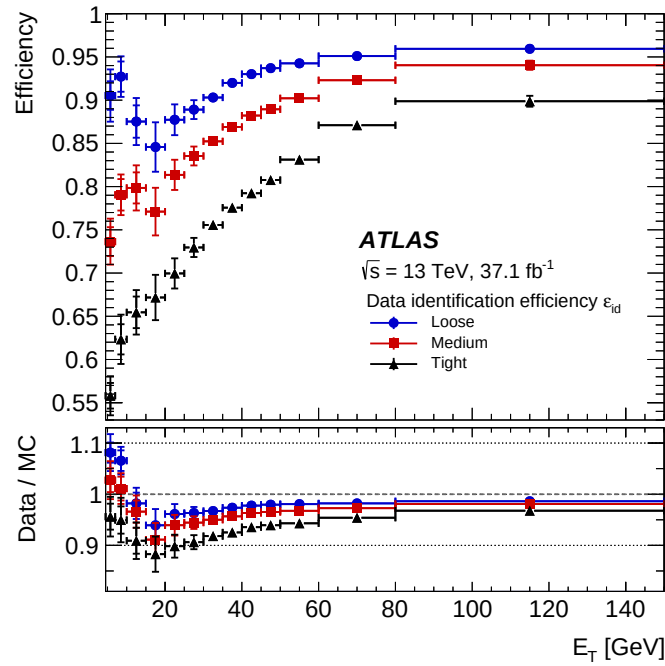
2.3.3 Muons

Muons are reconstructed by combining tracks from the inner detector with those in the muon spectrometer. In the MS, reconstruction starts with a search for hit patterns inside each muon chamber to form segments. The MDT segments are reconstructed by performing a straight line fit to the hits found in each layer. In the CSC, segments are built using a combinatorial search in the η - ϕ plane. The RPC

⁷ Originating from the hard-scattering vertex or from the decay of Higgs, or W , and Z bosons.



(a)



(b)

FIGURE 2.13: (a) Reconstruction efficiency as a function of electron transverse energy E_T for $Z \rightarrow ee$ events, comparing data with simulation. (b) Electron identification efficiencies in $Z \rightarrow ee$ events for the *loose* (blue circle), *medium* (red square) and *tight* (black triangle) operating points as a function of E_T . The results are based on 37.1 fb^{-1} of data collected in 2015 and 2016 [66].

or TGC hits measure the coordinate orthogonal to the bending plane of the detector. Muon tracks are built by fitting together hits from segments in different layers. The reconstruction algorithm performs a segment-seeded search for this task. The initial seeds to the algorithm are the segments found in the middle layers of the MS where more trigger hits are available. The segments are selected based on hit multiplicity and the fit quality, and are matched using their relative positions and angles. At least two segments are required to build a track. In the barrel-endcap transition region, a single high quality segment with η and ϕ information can be used to build a track. The combined ID-MS muon reconstruction is performed based on the information provided by the ID, MS and the calorimeters. This leads to four types of muons depending on which subdetectors are used in the reconstruction: combined muons, segment-tagged muons, calorimeter-tagged muons and extrapolated muons [71].

For combined muons, tracks are reconstructed independently in ID and MS before being combined. A global fit is performed using the hits from both the ID and MS subdetectors. During the fit, hits from MS may be added or removed from the track to improve the fit quality. Most muon candidates are reconstructed using an outside-in pattern recognition algorithm in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track. A complementary approach in which ID tracks are extrapolated outward and matched to MS tracks is also employed. Segment-tagged muons require a track in the ID extrapolated to the MS and associated with at least one local track segment in MDT or CSC chambers. Such muons are used when muons that pass only one layer of MS chambers, either because of low p_T or because they fall in regions with reduced acceptance. Calorimeter-tagged muons are formed by matching an ID track to an energy deposit in the calorimeter consistent with the passage of a minimum-ionizing particle. These muons have the lowest purity but allow to recover acceptance in the partially instrumented MS region ($|\eta| < 0.1$). Finally, extrapolated muons are reconstructed based only on the MS track and a loose requirement on compatibility with originating from the IP, taking into account the estimated energy loss in the calorimeters. These muons are used to extend the acceptance into the region $2.5 < |\eta| < 2.7$, which is not covered by the ID. Overlaps between different muon types are resolved before producing the final collection of muons to be used by physics analyses [71].

In order to suppress the background muon candidates, mainly coming from pion and kaon decays, muon identification is performed by applying quality requirements and selecting prompt muons with high efficiency. Additional requirements on the number of hits in the ID and MS are used to ensure a robust muon momentum measurement. Four identification selections are provided for muon identification. These are referred to as *loose*, *medium*, *tight* and *high- p_T* . The *medium* identification criteria provide the default selection for muons in ATLAS, which include only combined and extrapolated muons. Loose muons take into account all types of muons, where the segment- and calorimeter-tagged muons are restricted to the $|\eta| < 0.1$ region. Tight muons include only combined muons. The *high- p_T* selection aims to maximize the momentum resolution for tracks with transverse momentum above 100 GeV [71].

Muon reconstruction efficiency in the $|\eta| < 2.5$ region is obtained with the tag-and-probe method. The $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events are used to measure the efficiencies in data and simulation. The efficiency at low p_T is measured from $J/\psi \rightarrow \mu\mu$ events in addition to $Z \rightarrow \mu\mu$. Figure 2.14 shows the muon reconstruction efficiency as a function of η for the *loose*, *medium* and *tight* muon selections. The reconstruction efficiencies of the loose and medium muons are almost stable at 99% with the exception of the region $|\eta| < 0.1$ due to the MS acceptance gap⁸. The muon momentum scale and resolution are studied using $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ decays. A set of correction factors is applied to the simulated muon momentum to improve the level of agreement between data and simulation. [71].

In order to reject the non-prompt muons arising from semileptonic decays of heavy-flavor hadrons, muons are required to satisfy an isolation criteria. More details can be found in Ref. [71].

⁸ In the $|\eta| < 0.1$ region, the ATLAS muon spectrometer is only partially instrumented to allow for cabling and services to the calorimeters and inner detector.

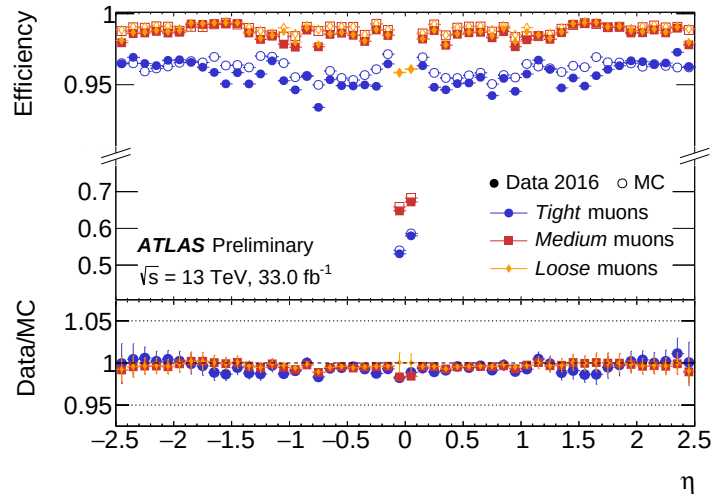


FIGURE 2.14: Muon reconstruction efficiency as a function of η measured in $Z \rightarrow \mu\mu$ events for muons with $p_T > 10$ GeV shown for *loose* (diamond), *medium* (square) and *tight* (circle) muon selections. The results are based on 33.0 fb^{-1} of data collected in 2016 [72].

2.3.4 Jets

Jets are collimated sprays of hadrons produced by the hadronization process of quarks and gluons due to color confinement. They are reconstructed using the anti- k_t jet clustering algorithm [73] with a radius parameter of $R = 0.4$. The clusters of topologically connected calorimeter cells (topoclusters) are employed as input to the jet reconstruction algorithm. Topoclusters are formed by a growing-volume algorithm that starts from a calorimeter seed cell with a sufficiently high signal compared to noise and then grouping the neighboring cells into a cluster as long as the signal in the cells are above a noise threshold [74]. Calorimeter cells with insignificant signals are considered noise and discarded from jet reconstruction. Each topocluster is calibrated at the electromagnetic scale corresponding to the energy deposited by electromagnetically interacting particles.

The calibration of reconstructed jets consists of several consecutive stages, and derived from a combination of simulation based methods and *in situ* techniques. First, a jet is corrected to point to the hard-scatter vertex. Next, the effect of pile-up is removed using an area-based subtraction procedure and residual corrections. The simulation based calibration then corrects the reconstructed jet four-momentum to that of truth jets reconstructed at the particle-level energy scale. Further improvements to the reconstructed jet energy are achieved through the use of calorimeter, muon-segment and track based variables in the global sequential calibration. Finally, *in situ* techniques are used to measure the difference in jet response between data and simulation with calibration is applied to correct jets in data [75, 76].

In order to reduce the contamination from jets arising from pile-up, a requirement is applied on the Jet Vertex Tagger (JVT) [77] output. The JVT algorithm combines tracking information into a multivariate algorithm to reject jets which do not originate from the primary vertex, and is applied to jets with $p_T < 60$ GeV and $|\eta| < 2.4$. Jets with $p_T > 60$ GeV are assumed to be originated from the primary vertex.

Jets containing b -hadrons can be identified by using b -tagging algorithms [78, 79]. Such jets originate from b -quarks fragmentation and typically contain b -flavored hadrons which decay via weak interactions. The dominant decay mode of a b -quark is $b \rightarrow cW^{*-}$, where the virtual W materializes either into a pair of leptons (semileptonic decay), or into a pair of quarks which then hadronizes [13]. b -hadrons have unique properties that can be exploited in order to be identified in data. For instance,

their relatively long lifetime allows them to travel several millimeters in the transverse direction before decaying⁹. This gives rise to topologies with at least one vertex displaced from the point where the hard-scatter collision occurred. In addition, their high mass lead to decay products with a larger transverse momentum relative to jet axis¹⁰ with respect to the ones found in jets originating from light quarks (u, d, s), gluons (light-flavor jets) and jets originating from c -quarks (c -jets).

b -tagging algorithms aim to identify b -quark jets (b -jets) and separate them from c - and light-flavor jets by exploiting the long lifetime, high mass and decay multiplicity of b -hadrons. There are three basic b -tagging algorithms:

- Impact parameter-based algorithms.
- An inclusive secondary vertex reconstruction algorithm.
- A decay chain multi-vertex reconstruction algorithm.

The output of these algorithms are combined in a multivariate discriminant (MV2) [78, 79], which provides the separation between the different jet flavors. The training of the discriminant is performed on jets from the simulated $t\bar{t}$ events with b -jets classed as signal and c - and light-flavor jets as background. The specific algorithm used in $t\bar{t}H$ to multileptons analysis to identify b -jets is called the MV2c10 tagger [79]. The MV2c10 BDT output for the signal and background is shown in Figure 2.15. Four working points are defined by a single cut value on the MV2c10 output. The working point used for the analysis in this thesis corresponds to a b -jet efficiency of 70%, and c - and light-flavor jets rejection factors of 12 and 381, respectively. Several methods are used to calibrate the b -tagging efficiency and the light-flavor jet and c -jet mistag rates. In order to compensate for differences between data and simulation in the b -tagging efficiencies and mistag rates, correction factors are applied to the simulated samples [78, 80].

2.3.5 Hadronically decaying tau leptons

The tau lepton is the heaviest known charged lepton with a mass of 1.777 GeV [13]. Tau leptons decay hadronically in about 65% of all possible decay modes. The hadronic decay products typically contain one or three charged pions in 72% and 22% of all cases, respectively. Charged kaons are present in the remaining hadronic decays. At least one neutral pion is also produced in 68% of all hadronic decays. The neutral and charged hadrons stemming from the tau lepton decay make up the visible part of the decay ($\tau_{\text{had-vis}}$). The identification of $\tau_{\text{had-vis}}$ candidate is done through their decay products inside the detector. The main sources of background to hadronic tau decays are jets of energetic hadrons produced via fragmentation of quarks and gluons. The rejection against jets is achieved using discriminating variables based on the information from the calorimeter and tracking in the identification step of the $\tau_{\text{had-vis}}$ candidates. Electrons also form an important background and can mimic the signature of tau lepton decays with one charged hadron. A specific method is used to suppress this background [81].

The $\tau_{\text{had-vis}}$ candidates are reconstructed from energy clusters in the calorimeters and associated ID tracks [81, 82]. The reconstruction algorithm is seeded by jets formed using the procedure described in Section 2.3.4. Additionally, jets are required to have $p_T > 10$ GeV and $|\eta| < 2.5$. The $\tau_{\text{had-vis}}$ candidate vertex is defined as the vertex candidate with the largest p_T -weighted fraction of all tracks in the region $\Delta R < 0.2$ around the jet seed direction. This vertex is then used to determine the direction of the $\tau_{\text{had-vis}}$ candidate, and to associate tracks. The pseudorapidity and azimuthal angle of the $\tau_{\text{had-vis}}$ candidate are calculated using the vectorial sum of the topoclusters within $\Delta R < 0.2$ of the seed jet barycentre, and using the tau vertex as the origin. The $\tau_{\text{had-vis}}$ mass is defined to be zero.

⁹ A B^+ or B^- hadron has a mean life $c\tau$ of 0.4911 mm and mass of 5.279 GeV [13]. Such hadron with p_T of 100 GeV travel a distance of approximately $\langle l \rangle = \beta\gamma c\tau \approx 10$ mm in the detector, which is a measurable distance given the resolution of the Pixel detector.

¹⁰The jet axis is defined as the energy-weighted barycentre of all associated topoclusters [74].

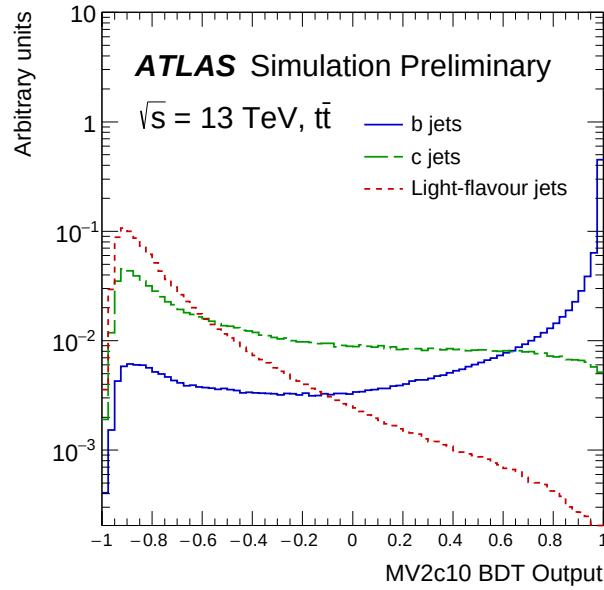


FIGURE 2.15: MV2c10 BDT output for b -jets, c -jets and light-flavor jets evaluated on simulated $t\bar{t}$ events [79].

Tracks are associated to the $\tau_{\text{had-vis}}$ candidate in the *core* ($\Delta R < 0.2$) and *isolation* ($0.2 < \Delta R < 0.4$) regions around the $\tau_{\text{had-vis}}$ direction; depending on their p_T , the number of hits in the silicon detectors, and their transverse and longitudinal impact parameters with respect to the tau vertex. The number of core tracks defines the number of prongs. The hadronic tau decays to one (“1-prong” decay) and three (“3-prong” decay) charged pions are reconstructed as 1-track and 3-track $\tau_{\text{had-vis}}$ candidates, respectively.

The energy calibration of the $\tau_{\text{had-vis}}$ candidates is described in detail in Ref. [82]. The tau energy scale consists of two additional corrections which calibrate the tau energy back to the true visible energy¹¹. A response correction and a pile-up subtraction are applied to the sum of the energy of all topoclusters, which are calibrated using a local hadronic calibration [83] within $\Delta R < 0.2$ of the tau candidate axis. This corrected energy is used with information from tau particle flow method [84] and with additional calorimeter and tracking information in a multivariate technique known as boosted regression tree to calculate the final energy of the $\tau_{\text{had-vis}}$ candidate.

The reconstruction of $\tau_{\text{had-vis}}$ candidates provides no rejection against backgrounds from quark- and gluon-initiated jets. An identification algorithm is used to discriminate $\tau_{\text{had-vis}}$ candidates from jets. The tau identification is based on boosted decision tree (BDT) methods [85–87]. A set of BDTs is trained separately for 1-track and 3-track $\tau_{\text{had-vis}}$ decays on simulated $Z/\gamma^* \rightarrow \tau\tau$ events for signal and dijet events from data for background. The BDT uses a collection of discriminating variables based on the tracks and topoclusters found in the core or isolation region around the $\tau_{\text{had-vis}}$ candidate, as described in Ref. [81], and produces an output score used for the final tau identification. Three working points labeled *loose*, *medium* and *tight* are provided for tau identification corresponding to different tau identification efficiency values. The combined reconstruction and identification efficiencies for these working points are 60% (50%), 55% (40%) and 45% (30%) for 1-track (3-track) τ decays, respectively [82].

The tau identification efficiency measurement is performed using a tag-and-probe method with a data sample enriched in $Z \rightarrow \tau_\mu \tau_{\text{had}}$, where one tau lepton decays to a muon and the other

¹¹The true visible energy is defined as the energy of the generated tau decay products including the final state radiation, but excluding the contribution from the neutrinos.

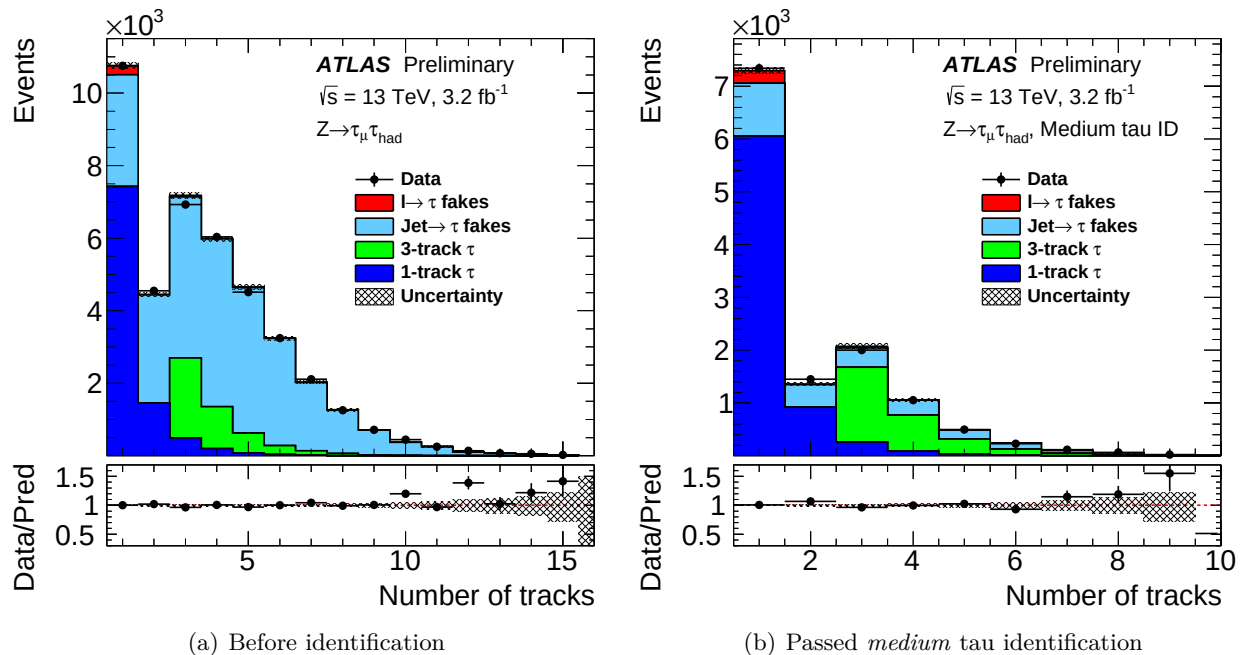


FIGURE 2.16: Distributions of the track multiplicity (a) before, (b) after applying the *medium* tau identification. The Jet $\rightarrow \tau$ fakes component is fitted to data while lepton (l) $\rightarrow \tau$ fakes component is fixed to simulation prediction [82].

decays hadronically with associated neutrinos. A template fit is performed using the track multiplicity variable to estimate the background contamination in data. The track multiplicity is defined as the sum of the number of core ($\Delta R < 0.2$) and outer ($0.2 < \Delta R < 0.6$) tracks associated to the $\tau_{\text{had-vis}}$ candidate. The outer tracks are required to satisfy the track separation criteria, $D_{\text{outer}} = \min([p_{\text{T}}^{\text{core}}/p_{\text{T}}^{\text{outer}}], \Delta R(\text{core}, \text{outer})) < 4$. The signal¹² contribution to data before applying the tau identification requirement is estimated directly from the fit, whereas the signal contribution after the application of the various tau identification working points is extracted by subtracting the estimated backgrounds from the data. The efficiency for a given working point is calculated by taking the ratio of the extracted number of signal events before and after applying the identification criteria. The track multiplicity distributions before and after applying the *medium* identification requirement are shown in Figure 2.16. Corrections (scale) factors are derived by taking the ratio of the efficiency measured in data to the efficiency in the simulation. These factors are needed to bring the tau identification efficiency in simulation to the level measured in data. Figure 2.17 shows the correction factors for one and three track $\tau_{\text{had-vis}}$ candidates. The uncertainties in the correction factor measurements are approximately 5% (6%) for one (three) track, respectively [82].

A likelihood-based discriminator is used to discriminate $\tau_{\text{had-vis}}$ candidates from electrons. The reconstructed tau candidates associated with a single track are geometrical matched to a reconstructed electron within the region of $\Delta R < 0.4$. These candidates are rejected if the electron passes the *loose* working point of the likelihood-based identification algorithm (Section 2.3.2). The cut values on the likelihood score are tuned to yield a constant efficiency of 95% for $\tau_{\text{had-vis}}$ candidates depending on the p_{T} and $|\eta|$ of the tau candidate. The probability of misidentifying an electron as a tau candidate is measured using a tag-and-probe method in the $Z \rightarrow ee$ events. The misidentification probability ranges between 0.5 and 2.5%, and the corresponding correction factors are measured with a precision of 3-14% depending on the $|\eta|$ of the tau candidate [82].

¹²The signal refers to a reconstructed $\tau_{\text{had-vis}}$ candidate geometrically matched to the true (i.e., at generator level) $\tau_{\text{had-vis}}$.

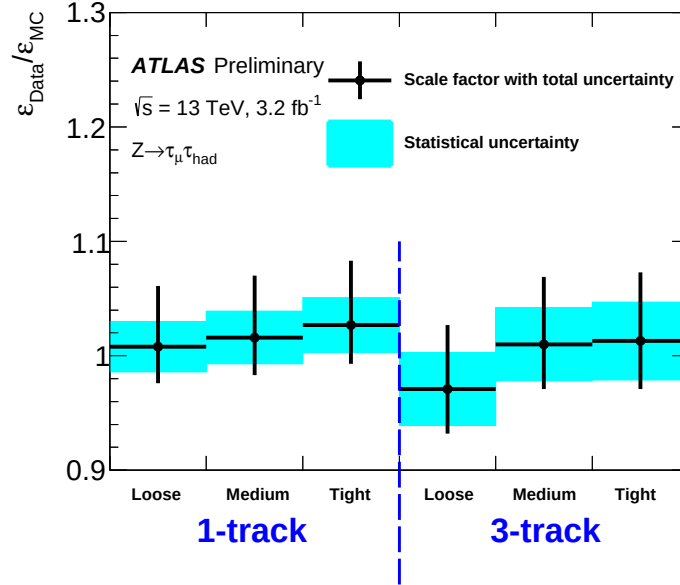


FIGURE 2.17: Scale factors for 1-track and 3-track $\tau_{\text{had-vis}}$ candidates with $p_T > 20$ GeV and for all tau identification working points [82].

The $\tau_{\text{had-vis}}$ reconstruction at the trigger level is modified compared to the offline reconstruction. More details about the ATLAS tau trigger are given in Chapter 4.

2.3.6 Missing transverse energy

Momentum conservation in the transverse plane implies that the transverse momentum of the collision products should sum to zero. A value incompatible with zero may indicate the production of Standard Model neutrinos or the production of new particles, which do not interact with the detector, suggested in models for physics beyond the SM. These particles escape the ATLAS detector without leaving a signal, and their presence can be inferred indirectly from the imbalance in the transverse momentum, which is known as “missing transverse momentum” (E_T^{miss}).

The E_T^{miss} reconstruction uses all the reconstructed and calibrated objects to measure the missing transverse momentum in an event [88, 89]. The components of E_T^{miss} in the two transverse directions are calculated as

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,e}} + E_{x(y)}^{\text{miss,\gamma}} + E_{x(y)}^{\text{miss,\tau}} + E_{x(y)}^{\text{miss,\mu}} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,soft}}, \quad (2.9)$$

where each term is obtained from the negative sum of the transverse momenta of the calibrated objects. The magnitude of the missing transverse momentum is calculated as:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}. \quad (2.10)$$

The soft term in equation 2.9 takes into account the energy deposited in the detector that is not associated to any reconstructed object. It is measured from the reconstructed tracks in the ID that are associated with the hard-scatter vertex. Tracks are required to have a p_T of 0.5 GeV or greater, and lie within the acceptance of the ID. The soft term may also be reconstructed from the energy deposits in calorimeter cells, grouped into topoclusters, which are not matched to the reconstructed objects. More details can be found in Ref. [89].

2.4 Event generation and simulation

Monte Carlo (MC) simulation plays a key role in the ATLAS experiment. It is an important tool to predict the response of the detector for a wide range of physics processes. In ATLAS, the majority of analyses rely on simulations to compare experimental results with theoretical predictions. Simulations are used for the modeling of the signal and background processes with sufficient precision. They also provide input for the design of new experiments or allow the study of new detector layouts and planning for a detector upgrade.

The ATLAS simulation framework is described in detail in Ref. [90]. The simulation is divided into three steps: event generation, simulation of the detector and the interactions of particles with the detector, and digitization of the energy deposited in the sensitive regions of the detector into voltages and currents. Each step in the simulation is carried out by specific programs interfaced with each other. The output of the simulation chain is stored in a format identical to that of the DAQ system. Thus, both the simulated and real data from the detector are processed through the same particle reconstruction algorithms.

A Monte Carlo event generator [91] is capable of simulating a wide range of physical processes that occur in the pp collisions at the LHC. Event generators usually rely on the factorization of a pp collision event into different well-defined phases corresponding to different kinematic regimes. The different phases involved in the simulation are illustrated in Figure 2.18 for a $t\bar{t}H$ event. In the description of each of these phases different approximations are employed, and different generators are developed to model the underlying physics. The first stage consists of simulation of the hard scattering process (red blob in the figure), which describes the physics process; in this case a $t\bar{t}H$ production. The parton distribution function (PDF) [92] describes the momentum distribution of quarks and gluons within a proton, which is employed in the simulation of hard process. A PDF gives the probability of finding a parton (quarks or gluons) within the proton carrying a fraction of the proton's momentum at the energy scale of the hard process. The PDFs are measured experimentally in deep inelastic scattering and collider experiments. The matrix elements of the interactions in the hard scatter are calculated to a fixed order in perturbation theory. The matrix element, PDF and phase space of the interaction are used to calculate the cross section of the process. In the second stage, the evolution of the outgoing particles from the hard process is simulated. The partons in the initial and final state can radiate gluons (red curly lines), which can further radiate gluons or produce quark-antiquark pairs generating showers of outgoing partons with progressively lower energy. This process of particle showering stops at a non-perturbative energy scale where the transition to hadrons occurs. At this hadronization scale, the partons are transformed into colorless hadrons (light green ovals) due to color confinement. The formation of hadrons is described by phenomenological models. The hadrons are usually unstable and decay into particles that can be observed in detectors (dark green blobs). In the last stage of the event generation of a hard process, the underlying event is simulated as well. It represents the remnants of the incoming partons that may experience secondary hard interactions (purple blob). The phenomenological models are used to simulate the underlying event and parameters are tuned by using comparisons with experimental data. The photon radiation (yellow lines) can occur at any stage.

The ATLAS detector is simulated using the **GEANT4** simulation toolkit [94]. The **GEANT4** uses a full description of the detector geometry and provides a framework for simulating the interaction of the particles with the material. The outcome of the event generation is the list of stable particles which are then read into the **GEANT4** simulation. Each particle is propagated through the full ATLAS detector. The energies deposited in the sensitive parts of the detector are recorded as hits containing the total energy deposit, position and time. In addition, the truth information¹³ is recorded for each event.

¹³The truth information is a history of the interactions from the generator, including incoming and outgoing particles.

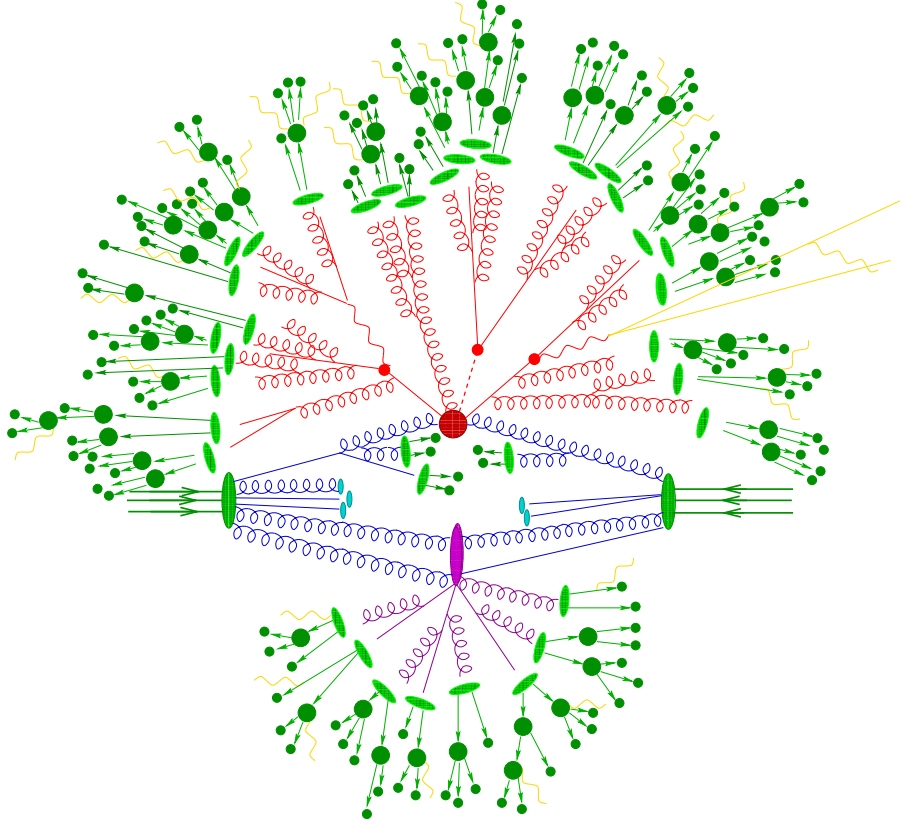


FIGURE 2.18: Representation of a $t\bar{t}H$ event as produced by an event generator [93].

Finally, the hits produced by the simulation are converted into detector responses, i.e., digits. A digit is produced when the voltage or current on a particular readout channel rises above a threshold within a particular time window. During digitization, various types of events (hard-scatter or minimum bias) are overlayed to simulate the effect of pile-up. The complex detector geometry and detailed physics description used by the ATLAS **GEANT4** simulation are computationally expensive.

In addition to the full ATLAS simulation, a fast simulation known as **ATLFAST-II** (**AFII**) is often used that speeds up the simulation by an order of magnitude. The fast simulation aims to provide large statistics for many physics studies [90].

2.5 Software and computing

The ATLAS software framework is called **Athena** [95], which is based on **Gaudi** framework [96]. An efficient distributed computing system is required to process the data recorded by the ATLAS detector and to distribute the production of simulated data. This is achieved through the LHC World-wide Computing Grid (WCG), which is composed of four “Tiers” (0, 1, 2, and 3) [97]. The recorded data is initially processed at CERN’s Tier-0 data center and then distributed to the other Grid sites around the world. The Tier Grid sites provide computing power for data analysis tasks. A single task on the Grid is split into many jobs depending on the complexity of the task. The output of every Grid job is registered with the ATLAS distributed data management system, which is known as **Rucio** [98].

Chapter 3

Medipix-2 detectors as luminosity monitor

A network of sixteen Medipix-2 detectors was installed and successfully operated in the ATLAS cavern from 2008 to 2013. The study presented in this chapter demonstrates that the network can be used as a self-sufficient luminosity monitoring system. Results from the luminosity monitoring are presented for proton-proton collision data taken in 2012 at a center-of-mass energy of $\sqrt{s} = 8$ TeV.

3.1 Introduction

The luminosity detectors BCM [58] and LUCID [59] were used by the ATLAS experiment for Run-1 data-taking, as described in Section 2.2.7. Both detectors use event counting algorithms to measure the luminosity on a bunch-by-bunch basis. The baseline luminosity algorithm is known as the EventOR algorithm, which requires that at least one hit be recorded anywhere in the detector considered. Additional algorithms have been developed which do not depend on event counting, but rather upon measuring detector currents that are proportional to the particle flux from proton-proton collisions in specific regions of the ATLAS calorimeters. The first technique measures the particle flux as reflected in the current drawn by the photomultiplier tubes of the tile calorimeter (TileCal) [48]. This flux is also monitored by the total ionization current flowing through the liquid-argon electromagnetic endcap (EMEC) [47] and the forward calorimeters (FCal) [49]. A third technique uses Medipix radiation monitors and measures the average particle flux observed in these devices, as described in detail in this chapter. These techniques measure the total instantaneous luminosity, summed over all bunches, and allow independent checks of the linearity and long-term stability of the BCM and LUCID algorithms as well as the track-counting algorithm. A brief overview of the detectors and algorithms used for luminosity determination in ATLAS for Run-1 can be found in Ref. [57].

The Medipix-2 (MPX) detectors are hybrid silicon pixel devices, which are primarily designed to measure the composition and spectral characteristics of the radiation environment within the ATLAS detector and its surrounding cavern. A network of 16 MPX detectors was installed at different locations in the ATLAS detector and in its cavern. Their positions are illustrated in Figure 3.1. The primary goal of the network was to provide information on the radiation composition within the ATLAS cavern. The MPX detectors also allow the measurement of beam-induced radioactivity during and after collisions. This real-time measurement of the LHC-generated background radiation allows the validation of background radiation simulation studies [99].

The use of the MPX network for luminosity measurements has been studied in detail in Refs. [100, 101] and the results are summarized in this chapter. Sixteen installed MPX detectors collected data independently of the ATLAS data-recording chain. Two detectors were noisy due to radiation damage. One detector was located too far away from the interaction point. Thus, only thirteen detectors were used for the analysis. The locations of the MPX detectors with respect to the interaction point (IP) are given in Table 3.1.

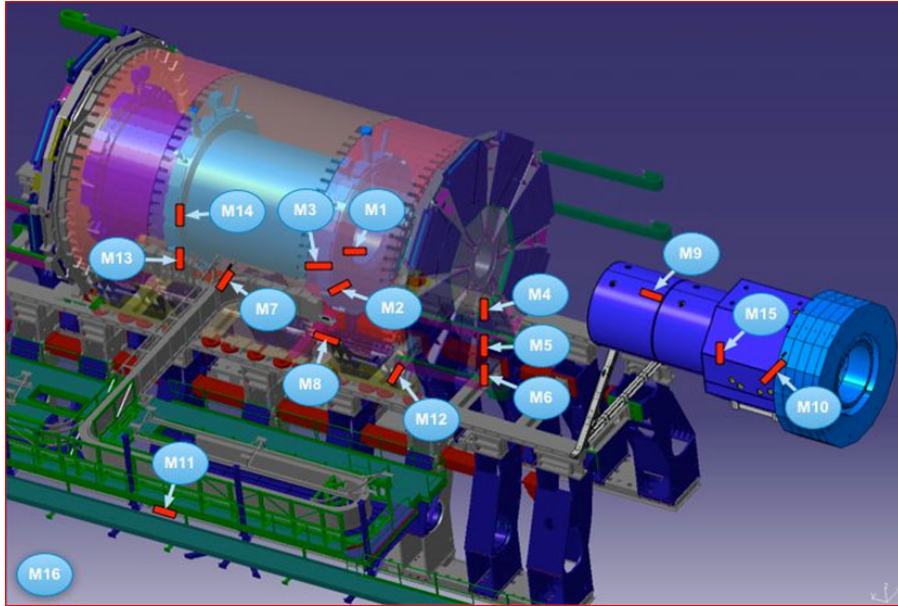


FIGURE 3.1: Overview of the MPX detector positions in the ATLAS detector. The precise locations of these detectors are given in Table 3.1 [99].

TABLE 3.1: MPX detector locations with respect to the interaction point. Z is the longitudinal distance from the interaction point and R is the distance from the beam axis. The MPX07–12 detectors with lower cluster rates are used for the thermal neutron counting analysis (Section 3.5) [99, 100].

Device name	Z [m]	R [m]	Clusters per unit sensor area per unit luminosity [$\text{cm}^{-2}/\text{nb}^{-1}$]
MPX01	3.42	0.77	55000
MPX02	3.42	2.50	230
MPX03	2.94	3.57	31
MPX04	7.12	1.30	110
MPX05	7.20	2.36	47
MPX06	7.20	3.36	20
MPX07	0.35	4.59	0.45
MPX08	4.02	4.40	1.2
MPX09	15.39	1.56	5.8
MPX10	22.88	5.19	1.0
MPX11	4.86	16.69	0.30
MPX12	7.23	6.25	3.9
MPX13	-3.42	2.44	380

3.2 The ATLAS-MPX detector

The ATLAS-MPX detectors are based on the Medipix-2 hybrid silicon pixel detector. Each detector consists of a 300 μm thick silicon sensor matrix of 256×256 pixels, each with an area of $55 \times 55 \mu\text{m}^2$, bump-bounded to a readout chip. The total sensitive area of sensor is about 2 cm^2 . A counter in each pixel records interacting quanta of radiation with energy deposits falling within the preset energy window. An incoming particle upon hitting the silicon sensor creates free charge carriers. If the charge-generated signal exceeds the threshold, the pixel is activated and the counter is incremented by one. All pixels are exposed simultaneously with a common electronically adjustable shutter that allows the precise selection of exposure times. The resulting signals are amplified and counted during this adjustable exposure time window (frame) for each pixel. Particle hits outside the active exposure time are simply not recorded in the counters. After exposure, the counters of all pixels readout in about 6 s to obtain a snapshot. The electronic shutter is closed and the detector is not sensitive during this readout process (deadtime). The data is then stored frame-by-frame [99].

The ATLAS-MPX detectors can detect the charged particles, including minimum ionizing particles (MIPs) and heavy ions. The detection of charged particles is based on the ionization energy deposited by particles passing through the silicon sensor. Neutrons, X-rays and gamma rays are detected indirectly by first converting them into charged particles. For neutron detection, each detector is covered by a mask of neutron converting materials ^6LiF and polyethylene (PE). These converting materials and their overlaps with the aluminum support foil divide the sensitive area of each detector into six different regions as shown in Figure 3.2. The ^6LiF region (1) is used for thermal neutron detection, exploiting the large cross-section of the $^6\text{Li}(n, \alpha)^3\text{H}$ reaction. Fast neutron detection is based on the detection of proton recoiling from the PE region (2). Fast neutrons can also be directly detected via their nuclear reactions in silicon itself and in the surrounding materials. The PE+Al region (3) allows the measurement of recoiling protons which penetrate the Al support. Here the aluminium foils act as a energy threshold. The Al foil region (4) serves as an attenuator of low energy muons, electrons and X-rays. Thick Al foils (5) achieve further electron and X-ray attenuation. The remaining uncovered area (6) is directly exposed to all incoming radiation, and is almost insensitive to thermal neutrons.

The detection efficiency for neutrons, X-rays and gamma rays is reduced by the efficiency of converting them into detectable charged particles. The typical detection efficiencies for different types of radiations for the 300 μm thick silicon sensor are [99, 102]:

- Charges particles ($> 8 \text{ KeV}$): 100%.
- X-rays ($\sim 10 \text{ KeV}$): $\sim 90\%$.
- Gamma rays ($\sim 1 \text{ MeV}$): $\sim 0.1\%$.
- Thermal neutrons (^6LiF region, $< 1 \text{ eV}$): $\sim 1\%$.
- Fast neutrons (PE region, MeV range): $\sim 0.1\%$.

The ATLAS-MPX detectors can be operated in two modes, tracking or hit counting mode. The tracking mode is based on the visualization of tracks of individual quanta of radiation in the sensitive silicon pixel detector volume. A track is composed of pixels where energy deposited by charged particle is above the threshold. The characteristic shape of a track depends on the type of radiation as well as the energy threshold settings [99, 102, 103]. Examples of different types of radiation as they are registered by the MPX detector can be seen in Figure 3.3 (a).

In the tracking mode of operation the acquisition time is set to be short to avoid the overlap of tracks generated by the interacting particles. These tracks are identified and sorted into several categories according to their characteristic shapes.

The following categories are defined:

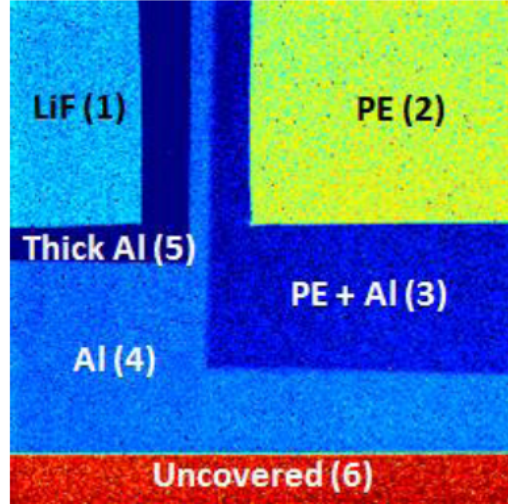


FIGURE 3.2: X-ray image of the six different detection regions of the MPX detector [99].

- *Dot*: one pixel size track (e.g., low energy photons or electrons).
- *Small blob*: round cluster of 2-4 pixels (e.g., X-ray photon or electron).
- *Curly track*: one pixel thick long curved line (e.g., electrons of keV to MeV range).
- *Heavy blob*: circular cluster of more than 5 pixels (e.g., alpha particles, heavy ions).
- *Heavy track*: thick straight track with a minimal width of three pixels (e.g., energetic heavy charged particles, protons of MeV range).
- *Straight track*: long straight clusters with more than 20 pixels length and less than three pixels width (e.g., MIPS, muons).

Interactions of neutrons are detected via “Heavy blob”. An overview of the definitions and characteristic track shapes is given in Figure 3.3 (b). These definitions of the cluster types are based on the classifications described in Refs. [99, 102, 103].

In the hit counting mode the frames are analyzed by integrating all hits registered in all pixels for the full detector area. This mode is used in radiation environment with high particle flux. In the case of higher count rates, overlapping of the clusters complicates the pattern recognition procedure making the hit counting mode analysis imperative. For a small amount of overlap, a correction factor for the luminosity measurement is applied. Table 3.1 shows the count rates per unit sensor area per unit integrated luminosity for each MPX detector.

3.3 Van der Meer scans

Van der Meer (vdM) scans are used to determine the absolute luminosity calibration scale of the luminosity detector and algorithm. The vdM scan technique was pioneered at CERN in the 1960s to determine the luminosity calibration at the LHC in a simple way [105]. It involves scanning the LHC beams through one another to determine the size of the beams at their point of collision. The scans are performed to determine the horizontal and vertical widths of the beams. These width measurements are then combined with the information on the colliding beams, allowing the determination of an absolute luminosity scale. Three sets of vdM scans were performed during 2012 at $\sqrt{s} = 8$ TeV: in April, July, and November (Table 3.2). The beam conditions during these vdM scans were different from those in normal physics operation, having fewer bunches colliding and lower bunch intensities.

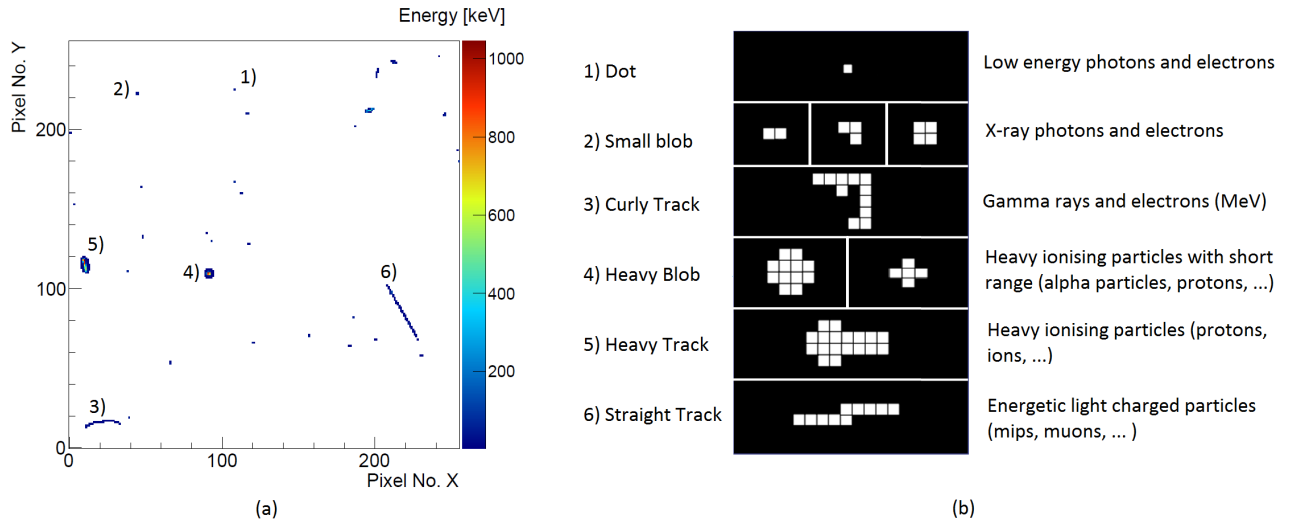


FIGURE 3.3: (a) An exemplary frame of 20 s acquisition time obtained from MPX device. Individual tracks are identified and sorted into categories shown in (b) according to their shapes. These categories allow particle identification and distinction between electrons, photons, alpha particles, heavy ions and MIPs [104].

In terms of colliding-beam parameters, the luminosity $\mathcal{L}$ can be written as

$$\mathcal{L} = \frac{n_b n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y}, \quad (3.1)$$

where n_b is bunch pairs colliding at the interaction point per machine revolution, n_1 and n_2 are the bunch populations (number of protons per bunch) in beam 1 and beam 2, respectively (together forming the bunch population product), and f_r is the machine revolution frequency (11245.5 Hz). The Σ_x and Σ_y are the convoluted horizontal and vertical beam sizes, respectively, as defined in Ref [57].

The product $\Sigma_x \Sigma_y$ is measured directly during a pair of orthogonal vdM (beam-separation) scans. Combining these scans with an external measurement of the bunch population product $n_1 n_2$ provides a direct determination of the luminosity for the case of zero beam separation (unseparated beams). The quantities Σ_x and Σ_y can be determined for any observed luminosity curve and depend only upon the area under the luminosity curve. In the case where the luminosity curve is Gaussian, Σ_x coincides with the standard deviation of that distribution. The measured product of the convoluted beam sizes $\Sigma_x \Sigma_y$ is directly related to the specific luminosity

$$\mathcal{L}_{\text{spec}} = \frac{\mathcal{L}}{n_b n_1 n_2} = \frac{f_r}{2\pi \Sigma_x \Sigma_y}, \quad (3.2)$$

which, together with the bunch currents, determines the absolute luminosity scale. Comparing the specific luminosity values (i.e., the inverse product of the convoluted beam sizes) measured in the same scan by the different detectors and algorithms provides a direct check on the mutual consistency of the absolute luminosity scale.

The study of the MPX data taken during vdM scans in 2012 focuses on the horizontal and vertical width determination of the LHC beams. The data used in this vdM scan study was taken with the MPX01 detector with the highest count rates (Table 3.1). The hit counting mode is used for the analysis of the vdM scan data. The beams are typically scanned transversely across each other in 25 scan steps. During each step, the beam orbits are left untouched (“quiescent beams”) and the luminosity remains constant for approximately 29 s. Since the MPX01 exposure (acquisition) time is about 5 s per frame, followed by a 6 s readout period, two frames typically occur within each (quiescent beam) scan step.

TABLE 3.2: Summary of the main characteristics of the 2012 vdM scans. The fit results for the bunch-averaged horizontal Σ_x and vertical Σ_y convoluted beam sizes are given, as measured with MPX01 detector.

Month	Fill number	Number of bunch pairs colliding	Number of protons per bunch n_1 (n_2) [$\times 10^{11}$]	Scan number	Σ_x [μm]	Σ_y [μm]
April	2520	35	0.540 (0.566)	I	25.9	33.1
				II	26.0	32.6
				III	26.7	33.6
July	2855	35	0.911 (0.968)	IV	120.5	127.6
				V	124.7	127.9
				VI	123.8	128.2
				VIII	120.6	127.1
November	3311	29	0.931 (0.921)	X	121.4	128.2
				XI	129.3	129.6
	3316		0.872 (0.886)	XIV	139.9	131.0
				XV	119.3	133.6

Table 3.2 summarizes the scan results for all 2012 vdM scans registered with the MPX01 detector. The last horizontal and vertical November 2012 scans are used for the absolute luminosity calibration because of its stability with respect to other scans. The parameters for the corresponding LHC fill 3316 [106] are also given in Table 3.2. Figure 3.4 shows the last horizontal scan measured with MPX01 detector. This scan is well described by a single Gaussian. The widths of $119.3 \pm 1.6 \mu\text{m}$ and $133.6 \pm 1.9 \mu\text{m}$ are measured for the horizontal and vertical beam separations, respectively. The resulting MPX luminosity, using equation 3.1, is $\mathcal{L}_{\text{MPX}} = 2.515 \mu\text{b}^{-1}\text{s}^{-1}$.

The corresponding number of MPX hits at the peak is determined from a Gaussian fit plus a constant background (Figure 3.4). The fit provides 1609.34 hits/s at the peak above the background. Thus, the normalization factor n_f between the MPX01 hit rate and the luminosity is:

$$n_f = \frac{2.515 \mu\text{b}^{-1}\text{s}^{-1}}{1609.34 \text{ hits}^{-1}} = 1.5628 \times 10^{-3} \mu\text{b}^{-1}/\text{hit}. \quad (3.3)$$

The normalization factor for the absolute luminosity is only approximate since the MPX acquisition time is much longer than the bunch spacing. Therefore, the bunch-integrated luminosity averages over the different bunch profiles.

3.4 MPX luminosity from hit counting

The six MPX detectors (MPX01-05,13) with highest cluster rate, as specified in Table 3.1, are used for the luminosity determination from the hit counting. Each detector measures the luminosity independently and is cross-checked with the others. This is an intrinsic advantage of the MPX network. The acquisition time window for each MPX detector is different. In order to compare luminosity measurements from different detectors, a common time window equivalent to the time unit used for storing ATLAS luminosity information is introduced called Luminosity Block (LB), which is typically one minute long.

A small number of noisy pixels could have a significant effect on the luminosity measurement. Three independent methods differing in procedure and criteria for noisy pixel removal have been tested. Details of these methods can be found in Ref. [100]. The same noisy pixels are removed for

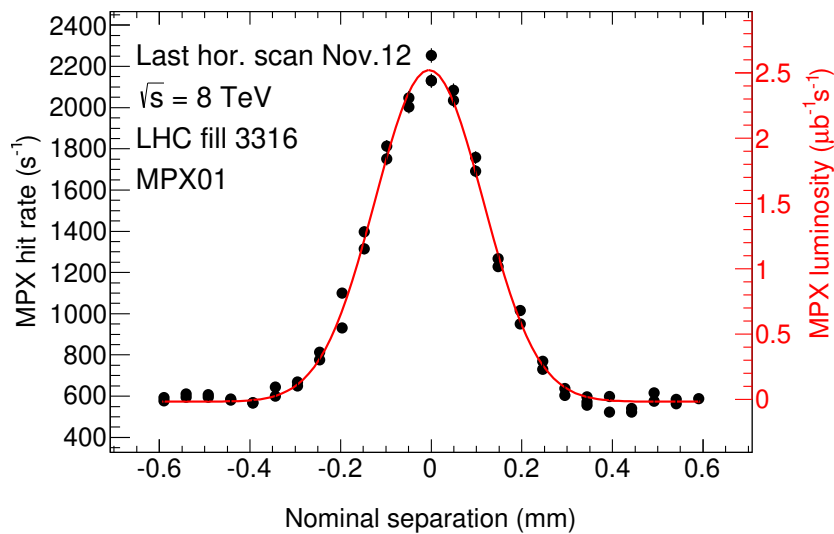


FIGURE 3.4: Luminosity from hit counting (referring to the vertical axis on the right) as a function of nominal beam separation measured with MPX01 detector during the last horizontal vdM scan of November 2012. Each data point shows the measured luminosity before the background subtraction and averaged over one acquisition time. The fit function is the sum of a single Gaussian and a constant term that accounts for instrumental noise and single-beam induced background.

the whole 2012 data-taking period¹. In the process of performing the luminosity determination with MPX detectors, the activation of the ATLAS detector material was investigated and found to have a negligible effect.

The hit rates per frame are converted into hit rates per LB for each MPX detector separately. First, the frames within the time window of LB are selected. The hit rates of these frames are then averaged. Thus, one hit rate is stored per LB. Given that the acquisition times of MPX detectors vary between 5 s and 120 s, the number of frames used per LB varies for the six MPX detectors. If there is no hit rate for a given LB, the previous LB hit rate is used. Finally, only those LBs are used for which all the six MPX detectors were operational. The hit rate for the MPX01 detector is normalized to units of luminosity by multiplying with the normalization factor n_f (equation 3.3). The other detectors (MPX02–05, 13) are normalized to MPX01 based on the average hit rate for the June to November 2012 running period. The MPX detectors have largely different hit rates, however, using the normalization factor each MPX detector obtains an equal weight. Table 3.3 summarizes the normalization factors of MPX detectors.

The long-term time stability of the six MPX detectors is studied. For this study the LBs, for which all the six MPX detectors were operational, are grouped into 14 time periods such that each time period contains the same number of LBs. The luminosity ratio of an individual MPX detector to the average of all the other MPX detectors (MPXav) is calculated for each time period. A normalization is applied such that the ratio is unity in time period 1 for each MPX detector. As an example, Figure 3.5 shows the luminosity ratio versus time for the June to November 2012 data-taking period for the MPX02 and MPX13 detectors. A linear fit is applied to the luminosity ratio (MPX/MPXav). The slope of this linear fit is taken as a measure of time stability. The obtained slope values and their uncertainties for all the MPX detectors are summarized in Table 3.3. The time stability from June to November 2012 is better than 1%. This gives an indication of the time stability of MPX luminosity monitoring.

¹ Method 1 was used for noisy pixel removal (Section II of Ref. [100]).

TABLE 3.3: Normalization factor and slope of time history of the luminosity ratio MPX/MPXav for the six MPX detectors with the highest particle flux (MPX01–05 and MPX13) used for the hit counting analysis. The slope values and their uncertainties are given per second, and in percent for 200 days. For a realistic slope uncertainty determination of an individual detector, the errors are scaled to obtain $\chi^2/\text{ndf} = 1$. The variance of these slope measurements is 0.69 [% per 200 days]². The resulting standard deviation is 0.83 [% per 200 days].

MPX	$1/n_f$ [hit/ μb^{-1}]	Slope [10^{-10} s^{-1}]	σSlope [10^{-10} s^{-1}]	Slope [%/200 days]	σSlope [%/200 days]
01	639.88	3.09	1.94	0.53	0.34
02	4.04	2.10	1.08	0.36	0.19
03	0.51	3.24	1.19	0.56	0.21
04	1.31	−5.95	1.36	−1.03	0.24
05	0.55	−5.06	1.30	−0.87	0.23
13	5.89	2.66	1.10	0.46	0.19

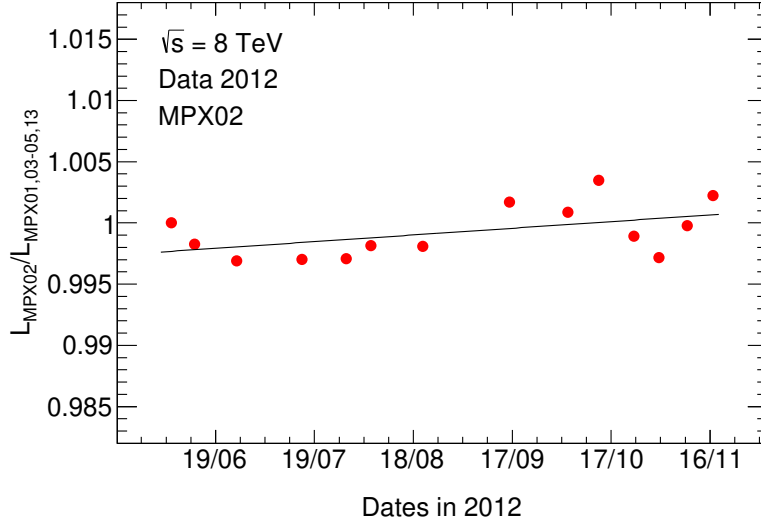
3.5 MPX luminosity from thermal neutron counting

Thermal neutrons are detected by MPX detectors via the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction in a ${}^6\text{LiF}$ converter layer. The tritons and alpha particles from the neutron conversion are registered by Si-sensors as large round-shaped pixel clusters, so-called Heavy-blobs (HB), as described in Section 3.2. The HB (thermal neutron) count rate is used as a measure of instantaneous luminosity since neutrons are generated in the proton-proton collisions at the LHC.

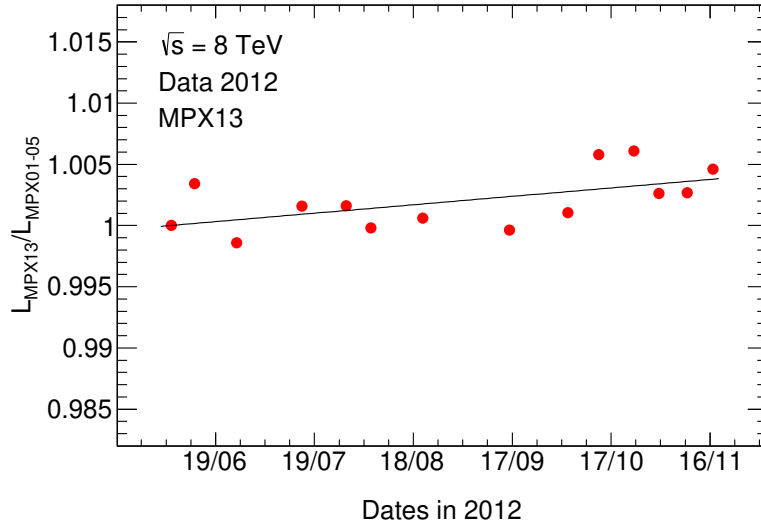
The MPX07 to MPX12 detectors are used for the thermal neutron counting analysis since the pixel matrix occupancy for these detectors is sufficiently small for pattern recognition, and to determine the HB count rate. A dedicated study was performed to determine the misidentification of heavy blobs which are lost due to the overlap with other clusters [99]. The resulting correction factors, specific to each MPX detector, depend on the number of clusters per frame (i.e., on the LHC collision rate, the exposure time and the detector location). The precision of these factors was estimated to be below 1% with the exception of MPX06 detector with the largest pixel occupancy. Therefore, MPX06 detector was not used for this study.

Figure 3.6 shows the distribution of the number of heavy blobs per frame recorded with MPX12 detector within the region covered with a ${}^6\text{LiF}$ converter. The distribution is well described by the Poisson statistics.

For luminosity determination, the number of heavy blobs with overlap corrected (cHB) is used for each MPX detector. The procedure similar to that described in Section 3.4 for the hit counting analysis is used. First, the number of cHB per frame is converted into LBs. Frames which lie within the time window of the LB are selected. The number of cHB of these frames are then averaged for all MPX detectors. Only those LBs are used for which all the MPX detectors (MPX07–12) were operational. These LBs are grouped into 14 time periods such that each time period has an equal number of LBs. For each time period the number of cHB are summed for each MPX detector. The summed cHB are converted into luminosity by using a normalization factor such that the luminosity ratio MPX/MPXav of time period 1 is unity. The weighted luminosity average of all detectors, excluding the detector under consideration, used in MPXav is determined to calculate the luminosity ratio for each time period. For each detector and time period, the statistical uncertainty is given as $1/\sqrt{N_{\text{HB}}}$, where N_{HB} is the summed number of heavy blobs.



(a)



(b)

FIGURE 3.5: Time history of the luminosity ratio MPX/MPXav for the June to November 2012 data-taking period for (a) MPX02 and (b) MPX13 detectors. The MPXav is calculated by excluding the MPX detector which is under consideration. The data is scaled such that the value of the first bin entry is unity. The size of the statistical error bar is below the size of the data point, and it is same for each data point.

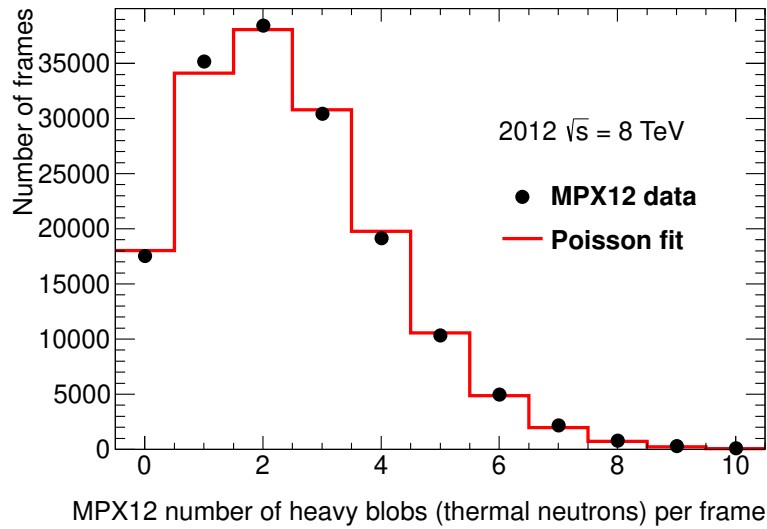


FIGURE 3.6: Distribution of the number of heavy blobs per frame, recorded with MPX12 detector below a ${}^6\text{LiF}$ converter layer, during the 2012 data-taking period. The red solid line shows the histogram with a fitted Poisson distribution.

A linear fit is applied to determine the precision of the time history of the ratio between individual MPX detectors with respect to the weighted average of all the other detectors. Figure 3.7 shows the luminosity ratio versus time for the MPX07 detector. Table 3.4 summarizes the slope values and the uncertainties of the linear fits for all the detectors. In this analysis of thermal neutron counting in the ${}^6\text{LiF}$ -covered detector region, the statistical uncertainties are dominant since the HB count rate is rather small (a few HB per frame). The long-term time stability from May to November 2012 is better than 1% comparing single MPX devices with the weighted average of all the other MPX detectors.

3.6 Comparison of MPX and ATLAS luminosity measurements

The ATLAS luminosity measurements are based on several luminometers as described in Section 3.1. The stability of the luminosity measurement over the 2012 data-taking period is characterized from a distinct viewpoint: time stability of the relative response of various luminosity algorithms across the entire running period. The relative consistency across all the luminosity detectors and algorithms is used to assess the robustness of the results, and to quantify the systematic variations in the response of the various luminometers. For this comparative study of the MPX hit and thermal neutron luminosity with the ATLAS luminosity measurements, the ATLAS run-by-run consistency is relevant. The relative ATLAS run-by-run uncertainty is 0.5% [57].

Figure 3.8 shows the ratio of the integrated luminosity per ATLAS run as measured by the MPX, EMEC, and FCAL algorithms to that reported by the TileCal, which is taken as a reference [57]. The MPX exhibits a stable response similar to that of the calorimeter algorithms over the course of 2012.

The ratio of the ATLAS reference luminosity [57] L_{ATLAS} and the MPX thermal neutron luminosity is shown in Figure 3.9 as a function of time. The data of each recorded run are combined and the statistical uncertainty is indicated by the error bars. A few runs are very short (less than one hour) and thus the accumulated number of HB clusters is small, leading to a large statistical uncertainty. The relative differences between MPX and ATLAS luminosity measurements are approximately described by a single Gaussian fit with width of $(1.48 \pm 0.13)\%$, as shown in Figure 3.10 (a). The width is dominated by the statistical uncertainty of the MPX luminosity measurement. Figure 3.10 (b) shows the pull distribution, assuming that the relative uncertainty is governed only by $1/\sqrt{N_{\text{HB}}}$. The

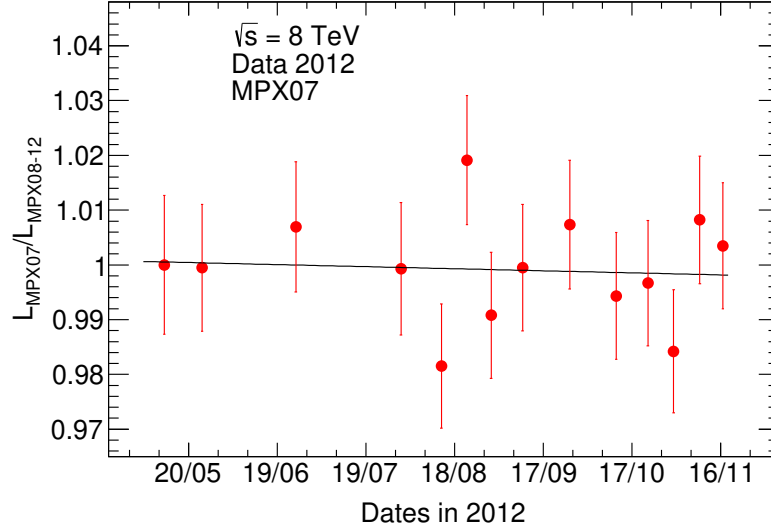


FIGURE 3.7: Time history of the luminosity ratio MPX/MPXav for the May to November 2012 data-taking period for the MPX07 detector. The error bars include only the statistical uncertainties.

TABLE 3.4: Slope of time history of luminosity ratio MPX/MPXav for the six MPX detectors with the lowest particle flux (MPX07–12) used for the thermal neutron counting analysis. The slope values and their uncertainties are given per second, and in percent for 200 days. The σ slope value results from the statistical uncertainty $1/\sqrt{N_{\text{HB}}}$ per time period. The variance of these slope measurements is $0.38 \text{ [\% per 200 days]}^2$. The corresponding standard deviation is $0.62 \text{ [\% per 200 days]}$.

MPX	Slope [10^{-10} s^{-1}]	σ Slope [10^{-10} s^{-1}]	Slope [%/200 days]	σ Slope [%/200 days]
07	−1.45	6.27	−0.25	1.08
08	4.93	4.22	0.85	0.73
09	−3.10	3.77	−0.54	0.65
10	4.57	4.40	0.79	0.76
11	1.87	9.15	0.32	1.57
12	−2.48	3.22	−0.43	0.55

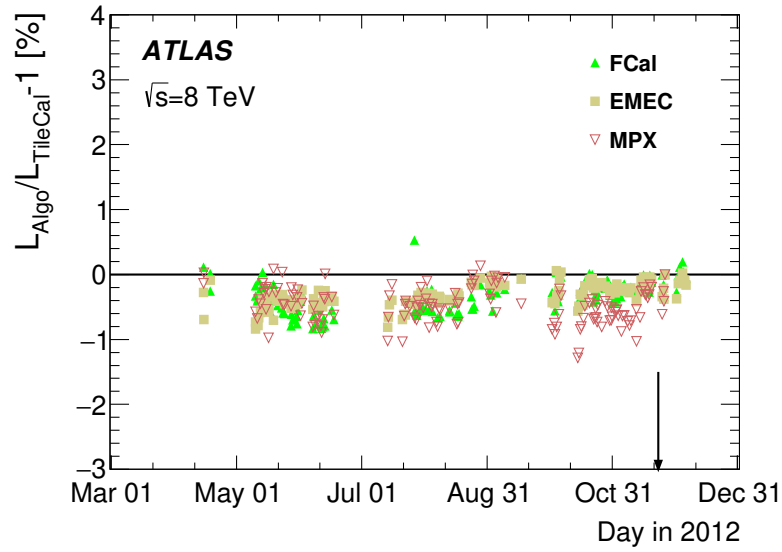


FIGURE 3.8: History of the luminosity per run, compared to the value measured by TileCal, for bunch-integrating algorithms during routine physics operation at high luminosity. Each point shows for a single run the mean deviation from a reference run taken on November 25, 2012 (LHC fill 3323). The EMEC, FCal and TileCal values are computed using the average of the luminosities reported by the two arms of the corresponding calorimeter; the MPX values reflect the average over the six detectors. The vertical arrow indicates the time of the November vdM scan [57].

Gaussian fit of the pull distribution has a width of 1.36 ± 0.08 . It demonstrates that the uncertainty of the thermal neutron counting luminosity is close to the statistical expectation.

3.7 Summary

The study presented in this chapter demonstrated that the MPX network was well suited for luminosity monitoring. This study focused on the proton-proton collisions from May to November 2012. An independent approach to determine the luminosity was presented using the thermal neutron counting. The slopes of the long-term time stability of the luminosity measurements both from the hit counting and the thermal neutron counting were below 1%. The MPX network was also used to study the van der Meer scans performed in 2012. The uncertainties for the hit analysis were dominated by systematic effects with a precision of 0.3%. The thermal neutron counting analysis was dominated by statistical uncertainties owing to the low cluster statistics. The relative precision was 1.5%. The MPX results were compared with the ATLAS luminosity results [57]. Good agreement was found within the statistical uncertainties. Although not specifically designed for luminosity measurements, the MPX network gave reliable supplementary information for the luminosity determination of LHC proton-proton collisions.

A network of Timepix (TPX) detectors (upgraded successors of the MPX detectors) was installed as a replacement of the MPX network for the LHC Run-2 operation [107].

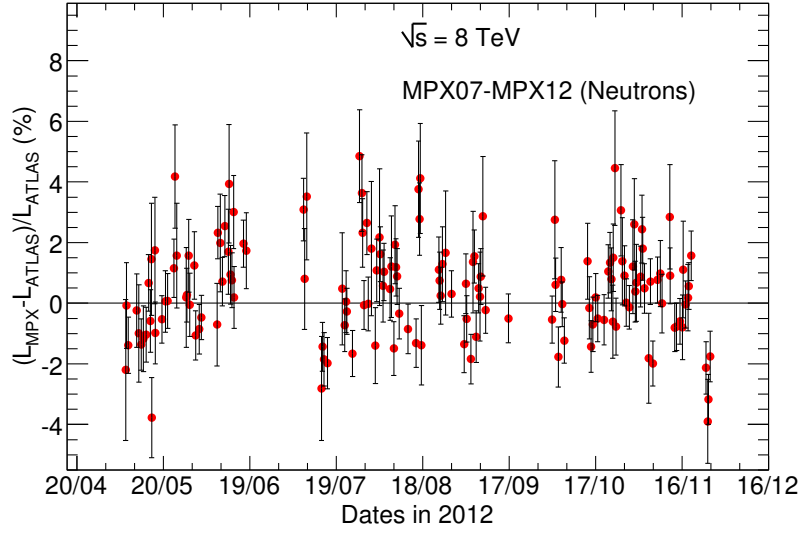


FIGURE 3.9: Evolution of time of the fractional difference in run-integrated luminosity between the MPX thermal neutron counting and the ATLAS reference luminosity. Each data point shows the mean difference for a single run as defined in the text. The MPX neutron luminosity is normalized to the MPX hit luminosity (Section 3.4) such that their ratio for data taken on 16 September 2012 is unity. The data of MPX07–12 detectors are combined. The error bars are statistical only.

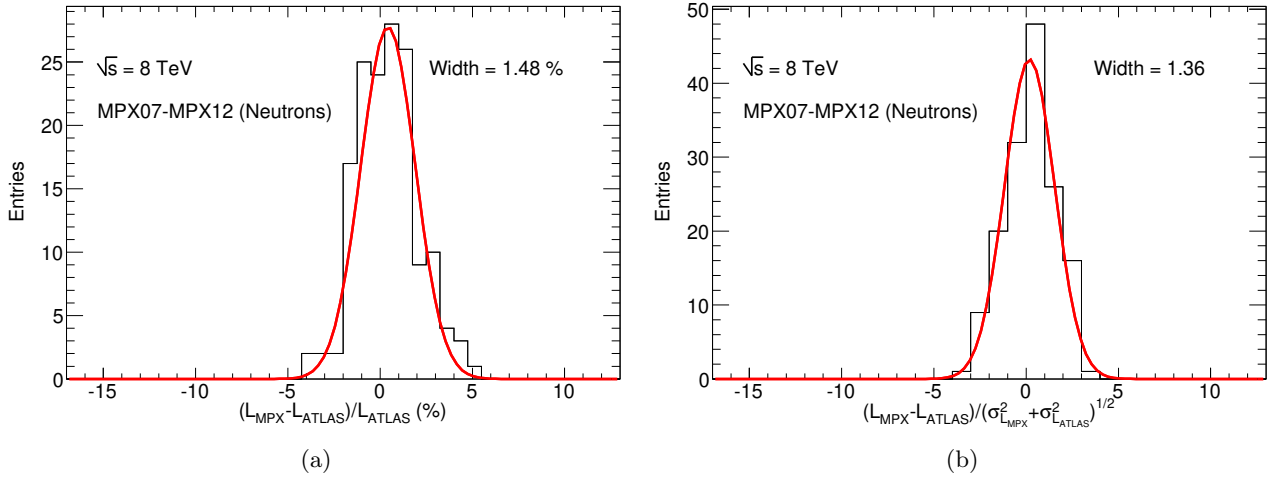


FIGURE 3.10: (a) Residual distribution defined as $(L_{\text{MPX}} - L_{\text{ATLAS}})/L_{\text{ATLAS}}$, (b) pull distribution defined as $(L_{\text{MPX}} - L_{\text{ATLAS}})/(\sigma_{L_{\text{MPX}}}^2 + \sigma_{L_{\text{ATLAS}}}^2)^{1/2}$, where $\sigma_{L_{\text{MPX}}}$ is the statistical uncertainty in the thermal neutron counting and $\sigma_{L_{\text{ATLAS}}}$ the run-by-run uncertainty in the ATLAS reference luminosity (0.5%) [57]. A Gaussian fit is applied. The MPX thermal neutron luminosity is normalized to the MPX hit luminosity, as defined in the text. The data of the MPX07–12 detectors are combined.

Chapter 4

The ATLAS tau trigger

This chapter gives an overview of the ATLAS tau trigger. Details of the tau trigger algorithms and selections are provided. The performance of the tau trigger based on the 2015 proton-proton collision data is presented.

4.1 Introduction

Tau leptons, being the heaviest of all known leptons, are a key signature in many Standard Model measurements and searches for new physics. The measurements of the SM Higgs boson coupling to fermions predominantly rely on the $H \rightarrow \tau^+ \tau^-$ decay to establish the mass generation mechanism for fermions [108]. Moreover, physics processes with tau leptons are often favored in many extensions of the SM. Hence, an efficient trigger on hadronic tau decays is crucial for many physics analyses using tau leptons.

Tau leptons have a short lifetime of $290.3 \cdot 10^{-15}$ s and a decay length of $87.03 \mu\text{m}$ [13]. Therefore, they decay inside the beam pipe and can only be identified via their decay products. Tau leptons decay hadronically, with a branching fraction of 65%, into one or three charged hadrons. The charged hadrons are mainly pions, and are often accompanied by additional neutral pions. These hadrons stemming from the tau lepton decay make up the visible decay products of the tau lepton and referred to as $\tau_{\text{had-vis}}$. A typical detector signature of hadronic tau decays is one or three tracks (prongs) from charged pions and the narrow shower (energy deposits) in the calorimeters, as shown in Figure 4.1. The quark- or gluon-initiated jets are the dominant background to hadronic tau decays at trigger level (also referred to as *online*). These jets typically have a large number of tracks (Figure 4.1). Dedicated tau trigger algorithms are designed and implemented based on the characteristic features of hadronic tau decays to efficiently identify $\tau_{\text{had-vis}}$ candidates amongst a large background of QCD jets. Owing to the high production rate of jets with features similar to hadronic tau decays, triggering on hadronic tau decays and keeping the trigger rates under control is particularly challenging. This was even more challenging in LHC Run-2 where the increase in collision energy, higher luminosity, and an increased number of pp interactions per bunch-crossing (pile-up) resulted in significantly higher production rates of jets and thus trigger rates.

In the following, the tau trigger strategy in Run-2 and the performance of the ATLAS tau trigger in 2015 is summarized. A detailed description of the tau trigger used in ATLAS during Run-2 data-taking is given in Refs. [54, 109].

4.2 Tau trigger strategy in Run-2

The ATLAS trigger and data acquisition system is designed to record events at a rate of approximately 1 kHz from the collision rate of 40 MHz. The trigger and data acquisition (TDAQ) system has undergone several changes to cope with the significant increase in trigger rate due to the higher

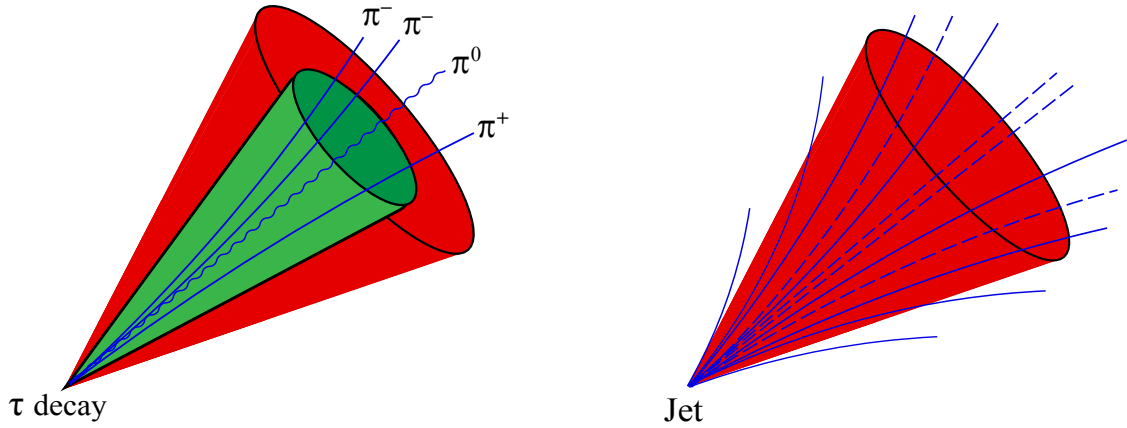


FIGURE 4.1: Typical detector signature of hadronically decaying tau lepton (left), compared to a jet arising from quark or gluon (right). The narrow green cone represents the core cone around the tau candidate and the red cone represents the isolation cone.

instantaneous luminosity and higher pile-up in Run-2, as described in detail in Section 2.2.6. As a result, the tau trigger strategy has also changed to deal with the increased rates during Run-2.

At L1, the $\tau_{\text{had-vis}}$ candidates are selected using calorimeter information. The tau trigger algorithm defines two regions for each candidate using trigger towers in both the electromagnetic and hadronic calorimeters: the core region and the isolation region around the core. The trigger towers have a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (Figure 4.2). The core region is defined as a set of 2×2 trigger towers, while the isolation region is the 4×4 perimeter surrounding the core. The L1 $\tau_{\text{had-vis}}$ candidate is identified by applying a requirement on the transverse energy sum in the two most energetic neighboring central towers in the EM calorimeter, and in the 2×2 towers in the hadronic calorimeter behind the EM layers. An isolation requirement can also be placed by setting an energy-dependent upper threshold for the EM isolation transverse energy, $E_T^{\text{EM,isol}} [\text{GeV}] \leq (E_T [\text{GeV}]/10 + 2)$, to reduce the background events and thus reduce the trigger rates. The $E_T^{\text{EM,isol}}$ is calculated as the transverse energy deposited in the 4×4 isolation ring around the 2×2 core region in the EM calorimeter. The isolation requirement has been tuned with 13 TeV simulation to yield an efficiency of 98% and is applied for $\tau_{\text{had-vis}}$ candidates with a transverse energy up to 60 GeV. Above 60 GeV, no isolation requirement is applied. In the case of combined triggers¹, the rate is further reduced using topological selections such as angular separation implemented at L1Topo. The region that satisfies the L1 requirements is called region of interest (RoI).

At the HLT, three sequential selections are applied to reduce the rates of the $\tau_{\text{had-vis}}$ candidates. First, the energy of the $\tau_{\text{had-vis}}$ candidate is calculated using the locally calibrated topoclusters of calorimeter cells found in a cone of $\Delta R < 0.2$ around the L1 tau direction. The energy is calibrated using a dedicated calibration scheme [82]. A minimum requirement is placed on the transverse energy of the $\tau_{\text{had-vis}}$ candidate. Second, the two-stage fast tracking approach is used to reconstruct the tracks in a given ΔR cone around the $\tau_{\text{had-vis}}$ candidate. The fast tracking consists of trigger-specific pattern recognition algorithms similar to those used during Run-1. In the first stage, a leading track is sought in a narrow cone of $\Delta R < 0.1$ around the $\tau_{\text{had-vis}}$ direction and along the beam line in the range $|z| < 255$ mm. In the second stage, the fast tracking is executed in an extended cone ($\Delta R < 0.4$) and narrow range along the beam line around the leading track. Tracks with $p_T > 1$ GeV are associated with the $\tau_{\text{had-vis}}$ candidate as in the offline reconstruction (Section 2.3.5), and counted in the core region $\Delta R < 0.2$ ($N_{\text{core}}^{\text{tracks}}$) and the isolation region $0.2 < \Delta R < 0.4$ ($N_{\text{isol}}^{\text{tracks}}$) around

¹ An additional electron, muon, or tau lepton is required in the event.

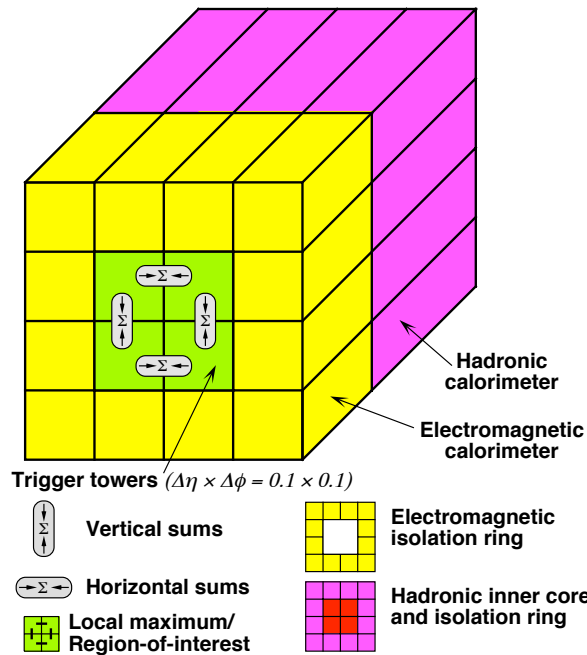


FIGURE 4.2: Schematic representation of the trigger towers in the electromagnetic and hadronic calorimeters used as input to the tau trigger algorithm [54].

the $\tau_{\text{had-vis}}$ direction. A requirement is made on the track multiplicity to select $\tau_{\text{had-vis}}$ candidates with $1 \leq N_{\text{core}}^{\text{tracks}} \leq 3$ and $N_{\text{isol}}^{\text{tracks}} \leq 4$. Third, the precision tracking algorithms similar to those used in the offline reconstruction are executed using tracks identified in the fast-tracking stages as seeds. The calorimeter information and the tracks obtained from the precision-tracking algorithm are used to calculate a set of discriminating variables. The implementation of these variables follows closely their offline counterpart as described in Ref. [81]. These variables are fed to the BDT multivariate algorithm to produce a score used for the final $\tau_{\text{had-vis}}$ identification. The discriminating variables used in the BDT are corrected as a function of the average interactions per bunch-crossing to ensure a robust response under different pile-up conditions. Three identification working points *loose*, *medium* and *tight* are available for online $\tau_{\text{had-vis}}$ candidates. These working points are tuned separately for 1-prong and 3-prong candidates [54].

4.3 Tau trigger menu and rates

The trigger system is configured via a trigger menu. The trigger menu defines trigger chains, i.e., the list of L1 and HLT trigger selections used for data-taking. The trigger chain defines the sequence of steps taken to obtain the trigger decision starting from an input trigger item. An event can be discarded at any step of the trigger chain to avoid the execution of the subsequent steps. The trigger menu is optimized for several luminosity ranges to fit within the rate and bandwidth constraints of the TDAQ system. It is composed of several categories: primary triggers, support triggers, alternative triggers, backup triggers and calibration triggers. The primary triggers are used for physics measurements and cover all signatures relevant to the ATLAS physics program, which includes electron, muons, tau leptons, b -jets and missing transverse energy.

The primary tau triggers consist of triggers for single high- p_T $\tau_{\text{had-vis}}$ and combined tau triggers, $\tau + X$, where X stands for an electron, muon, a second $\tau_{\text{had-vis}}$, or E_T^{miss} . Table 4.1 shows the primary tau triggers used in 2015 pp data-taking periods. For all tau triggers, the $\tau_{\text{had-vis}}$ candidates are required to satisfy the L1 isolation, HLT track multiplicity and the online *medium* identification criteria. An additional jet candidate with transverse momentum above 25 (20) GeV is required at L1 for

TABLE 4.1: Tau trigger menu employed during 2015. The L1 and HLT thresholds and the typical offline requirements used for each trigger are listed. ‘i’ denotes that an isolation requirement is applied at trigger level [54].

Year	2015		
Peak luminosity	$5 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$		
p_{T} threshold [GeV], selection			
Tigger	L1	HLT	Offline
Single tau	60	80	90
Ditau	20i, 12i	35, 25	40, 30
Tau + electron	12i, 15	25, 17i	30, 19
Tau + muon	12i, 10	25, 14	30, 15
Tau + $E_{\text{T}}^{\text{miss}}$	20, 45	35, 70	40, 180

combined triggers $\tau_{\text{had-vis}} + \text{electron}$ or muon ($\tau_{\text{had-vis}} + E_T^{\text{miss}}$) due to the L1 rate limitations. Trigger rates are relevant indicators of the trigger performance since they are highly sensitive to instantaneous luminosity. Figure 4.3 shows the L1 and HLT output rates as a function of the instantaneous luminosity for the primary tau triggers. These rates scale linearly with the instantaneous luminosity, which reflects the pile-up dependence of the trigger rate. No significant deviation from linearity is observed.

Trigger names provide as much information as possible on the trigger selection. Typically, a trigger name consists of multiplicity, particle type (EM for electron, MU for muon, J for jet, XE for E_T^{miss}) and the transverse momentum threshold value in GeV. For instance, L1_TAU60 requires a single tau with $p_T > 60$ GeV at L1. The HLT trigger items are written in lower case letters. The selection criteria such as identification, isolation, and L1 seed² are suffixed to the HLT trigger name (e.g. tau80_medium_L1TAU60).

4.4 Tau trigger monitoring

The ATLAS trigger monitoring system is designed to monitor the trigger rates, the quality of the selected trigger objects, and the performance of the tools to be used during the data-taking process [110]. The monitoring system consists of a set of independent software tools. The tau trigger monitoring tool is employed to monitor detailed aspects of the selected tau trigger behavior.

A dedicated data quality monitoring framework (DQMF) [111] is used to monitor the quality of the data as well as operational conditions of hardware and software elements of the detector and the TDAQ system. The data quality (DQ) monitoring of the trigger can occur both online and offline. The DQ assessment is based on an automated analyses of histograms created and filled during data-taking in the HLT trigger algorithms (online) or during raw data reconstruction at Tier-0 (offline). In the online environment, the DQMF displays histograms of trigger objects in real time to the ATLAS shift personnel, which can help to avoid taking faulty data. The shift personnel interacts with the DQMF via a graphical interface called the data quality monitoring display [112], which serves as the platform to debug problems and perform the DQ assessment. The online histogram presenter [113] tool is used to display and manipulate the online histograms available for each trigger.

On the offline side, a more sophisticated analysis is performed to ensure the quality of data for physics analyses. The offline DQ monitoring is based on histograms that include the distributions for the trigger objects. The histograms are stored for a whole ATLAS run and for all luminosity blocks within a run. An *express* stream that contains a small fraction of events is used for offline data quality

² In case, an HLT trigger is seeded by more than one L1 trigger.

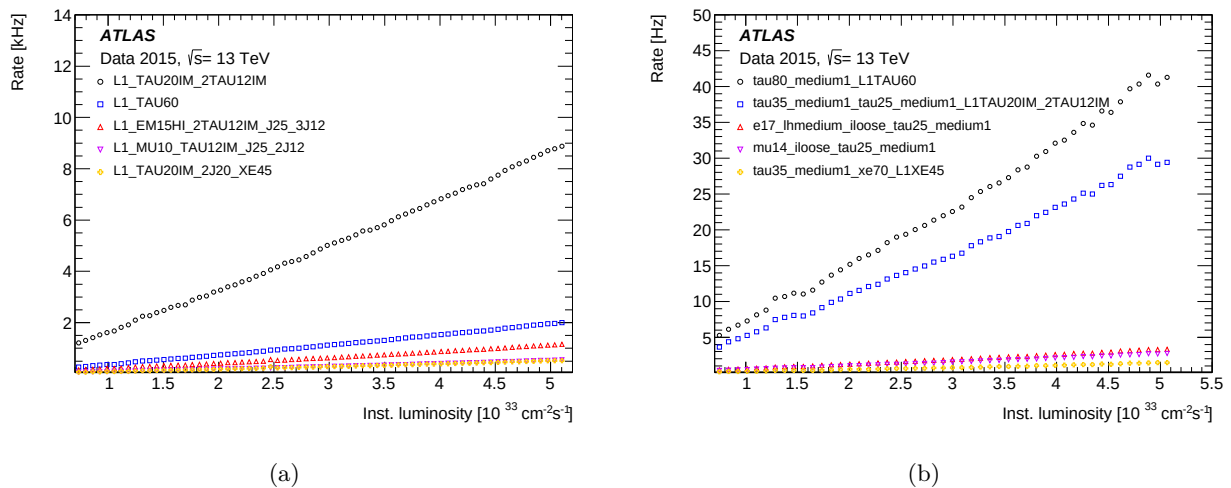


FIGURE 4.3: (a) L1 and (b) HLT trigger rates as a function of the instantaneous luminosity for the primary tau triggers in pp collisions recorded at $\sqrt{s} = 13$ TeV in 2015. The digit before the trigger names indicates the object multiplicity, while the digits after correspond to the p_T requirement. ‘IM’ and ‘HI’ indicate that isolation requirements are applied [54].

monitoring. The express stream is reconstructed promptly after data-taking and it is available within a few hours after a run has finished.

An evaluation of the trigger data quality is provided in flags reflecting the behavior of the trigger derived from the online and offline monitoring informations. A DQ flag is provided for each trigger that can have different values indicated by colors: green (good), yellow (warning) and red (bad). Every single histogram check is performed with its reference histogram computing a result in terms of good or bad. Test examples include checking the trigger object distributions width and mean or Kolmogorov-Smirnov test to that of the reference histogram. The distributions of trigger objects can be overlaid and compared with a reference. Examples of the selected distributions include transverse energy, transverse momentum, pseudorapidity, azimuth angle, track multiplicity, trigger efficiency, and several other physics motivated quantities associated with the trigger elements for a selected trigger.

4.5 Tau trigger efficiency measurement

This section describes the tau trigger efficiency measurement for the single tau triggers employed during the 2015 data-taking period. The efficiency is measured in data and compared to the simulation. The ratio of the measured trigger efficiency to the simulated one is used as a correction factor in several physics analyses. The data used for the efficiency measurement were recorded in 2015 at $\sqrt{s} = 13$ TeV, corresponds to an integrated luminosity of 3.2 fb^{-1} .

4.5.1 Methodology

A tag-and-probe method is used to measure the tau trigger efficiency in an enriched sample of $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events, where one tau lepton decays leptonically into a muon and the other tau lepton decays hadronically. Such events provide a sample of hadronically decaying tau leptons with an adequate purity and relatively low background contamination. The presence of an isolated muon coming from the leptonic decay of a tau lepton is required to *tag* the event, while the $\tau_{\text{had-vis}}$ candidate is used as an unbiased *probe* of tau trigger efficiency.

4.5.2 Event selection

Events are selected by the lowest unrescaled single muon trigger, and are tagged by an offline reconstructed and isolated muon candidate. The tag muon is required to have $p_T > 22$ GeV and $|\eta| < 2.5$. Additional track and calorimeter isolation requirements are applied to the muon. The presence of an offline reconstructed and identified $\tau_{\text{had-vis}}$ candidate fulfilling the *medium* identification criteria is required. The probe $\tau_{\text{had-vis}}$ candidate must have one or three tracks, $p_T > 25$ GeV, $|\eta| < 2.5^3$, and an absolute electric charge of one. An overlap removal is performed between the muon and the tau candidates to avoid double counting of individual objects. Any $\tau_{\text{had-vis}}$ candidate within a distance of $\Delta R < 0.2$ of the muon is discarded.

The dominant background is composed of $W(\rightarrow \mu\nu) + \text{jets}$ and QCD multijet events with a minor contribution from $Z(\rightarrow \mu\mu) + \text{jets}$ events. Further requirements are applied to the selected tag-probe pair to suppress these backgrounds and enhance the purity of $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events.

The tag muon and probe $\tau_{\text{had-vis}}$ candidates are required to have opposite-sign electric charges (OS), as expected in events from a Z boson decay. Events with more than one muon are vetoed to reduce the $Z(\rightarrow \mu\mu) + \text{jets}$ background. The angular correlations between the decay products of the Z boson in the event are exploited to reduce the background contamination from $W(\rightarrow \mu\nu) + \text{jets}$ events, where an additional jet in the event is misidentified as $\tau_{\text{had-vis}}$ candidate. Mainly two kinematic variables are built. The first variable is the transverse mass between the muon and E_T^{miss} , defined as:

$$m_T(\mu, E_T^{\text{miss}}) = \sqrt{2p_T^\mu \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi(\mu, E_T^{\text{miss}}))}. \quad (4.1)$$

The second variable is built from the difference in the azimuthal angles between the muon and E_T^{miss} and between the $\tau_{\text{had-vis}}$ candidate and E_T^{miss} , defined as

$$\sum \cos \Delta\phi = \cos \Delta\phi(\mu, E_T^{\text{miss}}) + \cos \Delta\phi(\tau_{\text{had-vis}}, E_T^{\text{miss}}), \quad (4.2)$$

where the E_T^{miss} is the vectorial sum of the momenta of the neutrinos.

In the $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ signal process, the neutrinos point mainly in the direction of one of the two leptons from Z boson decay products. The reason is that the mass of the Z boson is much higher than the mass of the tau lepton. Therefore, the tau leptons originating from the Z boson decays are boosted such that the decay products of taus are collimated along the direction of the parent tau lepton. The E_T^{miss} vector points in the direction between the $\tau_{\text{had-vis}}$ and the muon in the transverse plane, as illustrated in Figure 4.4 (a), given that the momentum of the Z boson is non-zero. Furthermore, the E_T^{miss} vector usually aligns with the lepton because there are two neutrinos on the side of the leptonic decay. In the $W(\rightarrow \mu\nu) + \text{jets}$ background process, the neutrino points away from the muon and the jet (fake τ_{had}). In this case the neutrino, the muon, and the jet point in different directions and balance the momentum in the transverse plane, as illustrated in Figure 4.4 (b). Thus, the E_T^{miss} vector points along the neutrino which is not in between the muon and the fake $\tau_{\text{had-vis}}$ candidate.

For the $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ signal events, the variable m_T tends towards zero, as the E_T^{miss} and the muon align the $\cos \Delta\phi$ tends to one. The variable $\sum \cos \Delta\phi$ is positive⁴ and usually tends to peak at zero⁵ for the signal events. For the $W(\rightarrow \mu\nu) + \text{jets}$ background events, the variable m_T peaks at larger values, indicating that the momentum vectors of the neutrino and lepton have zero z -components and that m_T is a measurement of the W mass. The value of the variable $\sum \cos \Delta\phi$ is typically negative because the E_T^{miss} vector points away from the muon and the jet for the background events. The transverse mass m_T is required to be less than 50 GeV, and the variable $\sum \cos \Delta\phi$ is required to be greater than -0.5 in the event.

³ Excluding the pseudorapidity range $1.37 < |\eta| < 1.52$.

⁴ Since the E_T^{miss} vector points towards the direction of the decay products.

⁵ For events where the p_T of the Z boson is low, and thus the tau leptons are back-to-back in the transverse plane.

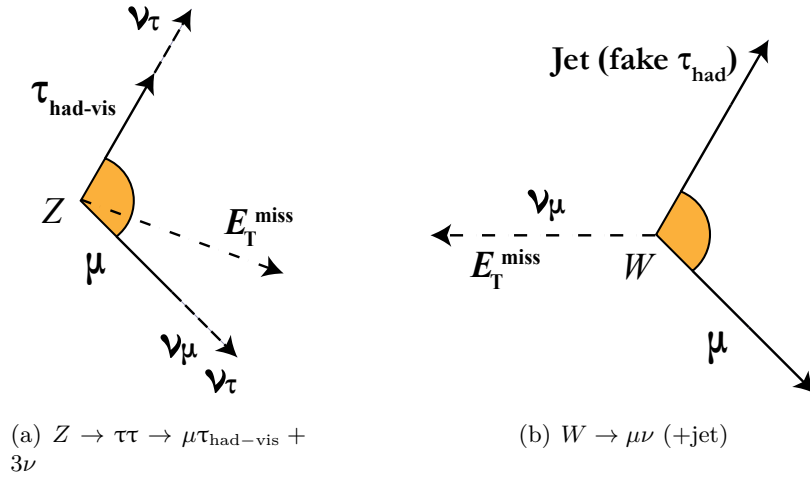


FIGURE 4.4: Illustrations of the orientation of the (a) Z and (b) W boson decay products and E_T^{miss} in the transverse plane. The shaded area represents the angle between the decay products.

Finally, the invariant mass calculated from the muon and the $\tau_{\text{had-vis}}$ candidate four momenta, the so-called visible mass $m_{\text{vis}}(\mu, \tau_{\text{had-vis}})$, is required to be between 45 and 80 GeV. For the $Z \rightarrow \tau\tau$ signal events, the m_{vis} peaks in these regions. The Z boson mass peak is shifted away from around 91.2 GeV because the neutrinos carried away the energy, which is not included in the calculation of the m_{vis} . After applying the event selection, the tau trigger efficiency is measured with respect to identified offline $\tau_{\text{had-vis}}$ candidates.

4.5.3 Background estimation

The main background for the probe $\tau_{\text{had-vis}}$ candidates are jets misidentified as hadronic tau lepton decays from $W(\rightarrow \mu\nu) + \text{jets}$ and multijet events, and their contributions are estimated via data-driven methods using dedicated control regions.

The multijet background contribution is estimated from events in the data that uses the full event selection but requires that the $\tau_{\text{had-vis}}$ candidate and the muon have the same-sign (SS) electric charges. The SS events have a negligible $Z \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ signal and form an effective control region, where the jet to τ fake background can be modeled. The contributions from other backgrounds are subtracted from the SS data. The SS data is also corrected by a normalization factor, as the number of background events depends on the charge product between the tag and the probe. This factor is the ratio of the number of events in OS and SS data derived in a multijet enriched control region, which is usually defined by inverting the isolation requirement of the tagged muon. The $W(\rightarrow \mu\nu) + \text{jets}$ contribution is estimated from events in a $W + \text{jets}$ control region, defined by inverting the $\sum \cos \Delta\phi$ requirement and removing the m_T selection. The $Z(\rightarrow \mu\mu) + \text{jets}$ contribution is estimated using simulation. More detailed information about the background estimation is given in Refs. [82, 114].

4.5.4 Results

The modeling of the $\tau_{\text{had-vis}}$ reconstruction in the tau trigger is validated by comparing data with simulation. Figure 4.5 shows the distributions of the transverse momentum and the BDT score for the HLT $\tau_{\text{had-vis}}$ candidates matched to the offline probe tau candidates after the event selection. The HLT $\tau_{\text{had-vis}}$ candidates pass the `tau25_medium` trigger, which requires an isolated candidate at L1 with $E_T > 12$ GeV and a $\tau_{\text{had-vis}}$ candidate at the HLT with $p_T > 25$ GeV satisfying the

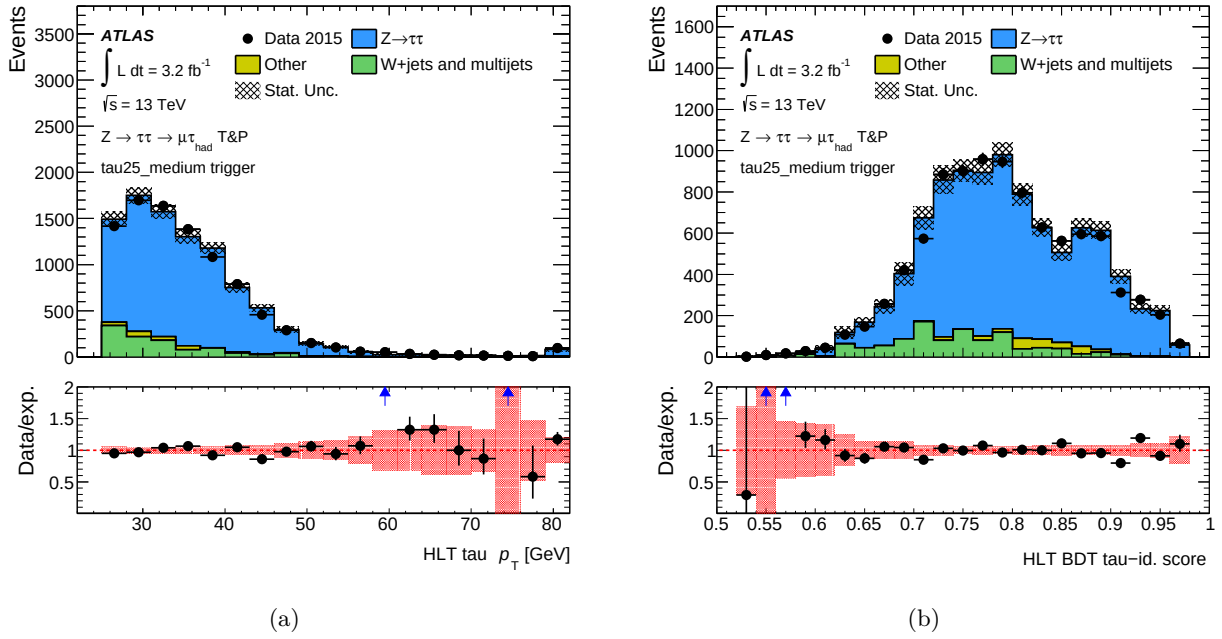


FIGURE 4.5: Distributions of the (a) transverse momentum and (b) online BDT score for the online $\tau_{\text{had-vis}}$ candidates as reconstructed at the final stage of the HLT tau trigger. The HLT $\tau_{\text{had-vis}}$ candidates are matched to the offline probe tau candidates and pass the `tau25_medium` trigger. T&P stands for tag-and-probe method. The ratio of data to the expected signal and background events is shown in the bottom panel. The uncertainty band represents only the statistical uncertainties [54].

track multiplicity and the online *medium* identification criteria. The distributions in data are in good agreement with the simulation.

The tau trigger efficiency is measured in the selected $Z \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events with respect to the offline reconstructed $\tau_{\text{had-vis}}$ candidates with $p_T > 25$ GeV, one or three tracks, and passing the offline *medium* identification requirement. The corresponding online $\tau_{\text{had-vis}}$ candidates pass the `tau25_medium` trigger. The efficiency is measured in data after the subtraction of the estimated backgrounds and compared to the simulation. The uncertainty in the subtracted background is considered as a systematic uncertainty in the measured efficiency. Figure 4.6 shows the measured efficiency for the `tau25_medium` trigger after L1+HLT as a function of the offline tau p_T . A good agreement between data and simulation is observed within the uncertainty of the measurement.

4.6 Real tau efficiency

The tau trigger monitoring tool generates a set of histograms that monitor the aspects of the tau trigger operation, as described in Section 4.4. Different quantities related to the tau trigger selection are monitored to ensure that the HLT algorithms are operating as expected. The tau trigger efficiency is an important measure of the performance of the tau trigger. The trigger efficiency is defined as the fraction of tau trigger candidates that pass the trigger decision in a trigger chain with respect to the offline $\tau_{\text{had-vis}}$ candidates. A pure sample of real $\tau_{\text{had-vis}}$ candidates is required to measure the efficiency in the data. $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events provide a sample of real $\tau_{\text{had-vis}}$ candidates through the tag-and-probe method. The method is implemented in the tau trigger monitoring tool to monitor the trigger efficiency for real $\tau_{\text{had-vis}}$ candidates.

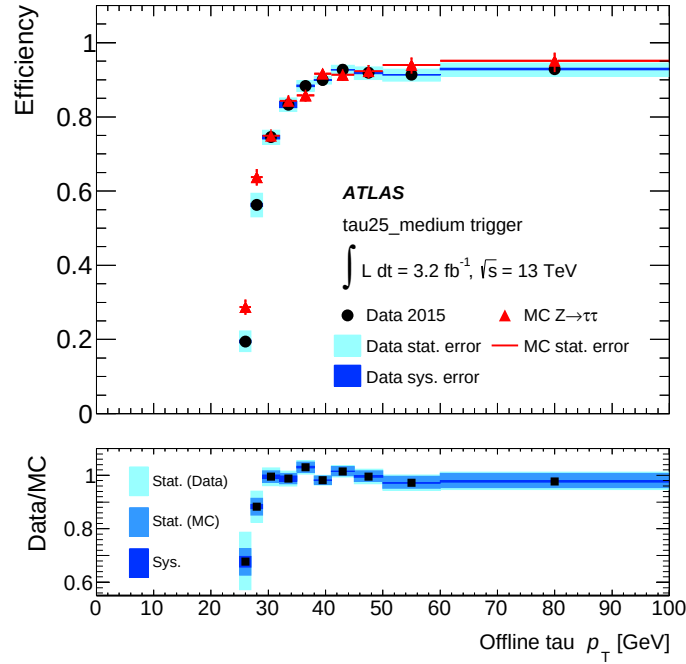


FIGURE 4.6: Efficiency of the `tau25_medium` trigger as a function of the transverse momentum of the offline reconstructed tau candidates. The statistical uncertainties in data and simulation are shown in cyan and red, respectively. The systematic uncertainty associated with the background subtraction procedure in data is shown in dark blue [54].

Events from the $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ process are selected by requiring the presence of a muon and at least one $\tau_{\text{had-vis}}$ candidate. If there are multiple $\tau_{\text{had-vis}}$ candidates, only the leading p_T candidate is considered. Table 4.2 summarizes the event selection. This selection is similar to the offline selection as described in Section 4.5.2. Additional requirements on the variables $|\Delta\eta(\mu, \tau_{\text{had-vis}})| < 1.5$ and $\Delta R(\mu, \tau_{\text{had-vis}}) > 2.9$ are applied to enhance the purity of $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events.

A dedicated data stream (TAUMU) reconstructed at Tier-0 with tagged muon and probe $\tau_{\text{had-vis}}$ selection is produced, which contains a sample enriched with real tau candidates. The TAUMU stream data is used to measure the tau trigger efficiency and compared to simulation. The $Z \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ signal sample is produced using Monte Carlo generator and reconstructed with the same algorithms as the data. The data collected during 2015 with a bunch-spacing of 25 ns was split into data-taking periods. A new period was defined when there was a significant change in the trigger and detector conditions or in the instantaneous luminosity. The data-taking periods are summarized in Table 4.3.

The tau trigger efficiency is measured with respect to $\tau_{\text{had-vis}}$ candidates identified by the offline *medium* identification as a function of the transverse momentum of the tau candidate. Figure 4.7 shows the tau trigger efficiency measured in data and simulation for the different levels of the trigger. The efficiencies are shown for a subset of the data corresponding to a specific period of time, and are compared to simulated $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events. Moreover, the efficiencies are computed for the `tau25_medium` trigger. The loss in efficiency at the HLT compared to L1 comes from the requirement on the track multiplicity and the BDT selection. Overall, the efficiency of tau trigger shows a good performance.

TABLE 4.2: Summary of the tag-and-probe event selection.

Event selection	
Muon (tag)	$\tau_{\text{had-vis}}$ (probe)
Identified muon	BDT <i>medium</i> identification
Trigger-matched	1 or 3 core tracks, $ q = 1$
track+calo isolation	No overlapping muon
$p_T > 27 \text{ GeV}$, $ \eta < 2.5$	$p_T > 20 \text{ GeV}$, $ \eta < 2.47$
Tag-probe pair selection	
muon and $\tau_{\text{had-vis}}$ with opposite-sign electric charge	
No other muon or electron	
Only leading $\tau_{\text{had-vis}}$ candidate	
$m_T < 50 \text{ GeV}$	
$\Sigma \cos \Delta\phi > -0.5$	
$45 \text{ GeV} < m_{\text{vis}}(\mu, \tau_{\text{had-vis}}) < 85 \text{ GeV}$	
$ \Delta\eta(\mu, \tau_{\text{had-vis}}) < 1.5$	
$\Delta R(\mu, \tau_{\text{had-vis}}) > 2.9$	

TABLE 4.3: Summary of the data-taking periods in 2015. The data was collected with a bunch-spacing of 25 ns [115].

Period	Dates	Runs	Integrated luminosity [pb^{-1}] recorded by ATLAS
D	12/08 – 23/08	276073 – 276954	99.7
E	06/09 – 20/09	278727 – 279928	485
F	20/09 – 26/09	279932 – 280422	346
G	26/09 – 06/10	280423 – 281075	800
H	06/10 – 12/10	281130 – 281411	607
I	12/10 – 18/10	281662 – 282482	0.72
J	20/10 – 03/11	282625 – 284484	1599

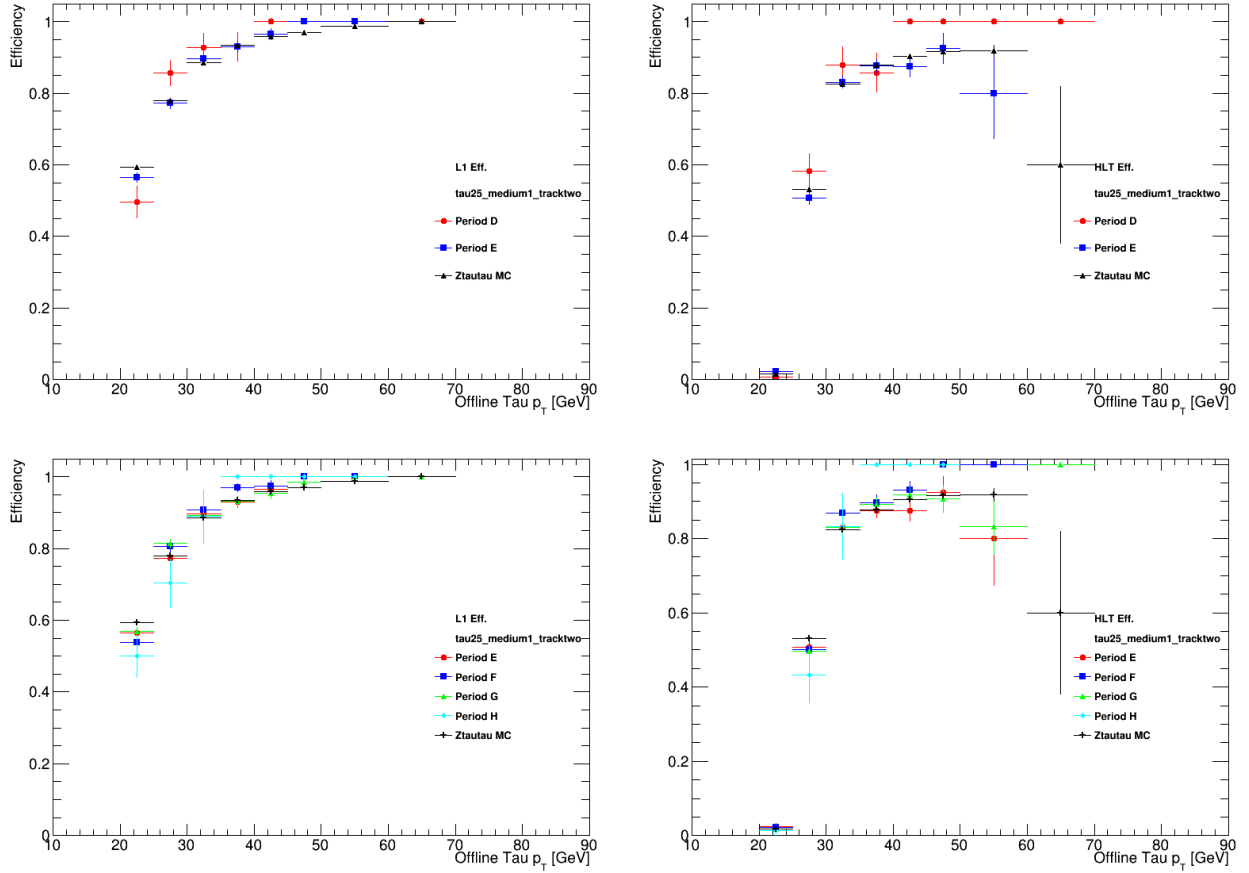


FIGURE 4.7: L1 (left) and HLT (right) efficiency of the `tau25_medium` trigger as a function of the offline tau p_T . The efficiency is measured in a subset of the selected data corresponding to periods D and E (top), and periods E, F, G, and H (bottom). The expected background contribution is not subtracted from the data. The measured efficiency is compared to simulation (black triangles). The error bars correspond to the statistical uncertainty.

4.7 Summary

The ATLAS tau trigger algorithms, menu, and performance have been presented. The tau trigger has many improvements for Run-2, including a redesigned HLT selection and an improved online BDT algorithm. These improvements were crucial to achieving high efficiency within the rate and bandwidth constraints of the TDAQ system. The tau trigger menu has been redesigned to cope with the higher rates due to increased center-of-mass energy and instantaneous luminosity. The different trigger sequences were set up according to the physics needs. The efficiency of the tau trigger has been measured in an enriched sample of $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had-vis}} + 3\nu$ events using the 13 TeV pp collision data with a bunch-spacing of 25 ns collected during 2015.

Chapter 5

Search for the $t\bar{t}H$ production in multilepton final states

This chapter describes the search for the $t\bar{t}H$ production in multilepton final states that is performed using proton-proton collision data recorded by the ATLAS detector in 2015 and 2016 at center-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} . The chapter mainly addresses the final state with two light leptons with same-sign electric charges and one hadronically decaying tau lepton, labeled as $2\ell\text{SS}1\tau_{\text{had}}$, and represents the main focus of this thesis. The overall $t\bar{t}H$ multilepton analysis strategy is explained. An overview of the signal characteristics and backgrounds in the $2\ell\text{SS}1\tau_{\text{had}}$ final state is given. Details of the collision dataset and the Monte Carlo samples are presented. A description of the object and event selection, and the multivariate analysis technique to separate $t\bar{t}H$ signal from the backgrounds is provided. Then, the estimation of different backgrounds using data-driven methods is discussed. Finally, the different sources of systematic uncertainties are discussed.

5.1 Introduction

The ATLAS Collaboration has searched for the $t\bar{t}H$ production in multilepton final states using 20.3 fb^{-1} of proton-proton (pp) collision data collected during 2012 at $\sqrt{s} = 8$ TeV [116]. The analysis was based on a simple cut-and-count approach. Five final states, categorized by the number and flavor of leptons, were examined for the presence of the SM Higgs boson. Combining all categories, the best-fit value of the $t\bar{t}H$ signal strength $\mu_{t\bar{t}H}$ was $2.1^{+1.4}_{-1.2}$, as shown in Figure 5.1. This corresponds to an observed (expected) significance of 1.8 (0.9) standard deviations. A similar search was performed by the CMS Collaboration [117].

The ATLAS Collaboration also reported preliminary results¹ of the search for the $t\bar{t}H$ production in multilepton final states using 13.2 fb^{-1} of data recorded in 2015 and 2016 at $\sqrt{s} = 13$ TeV [118]. The analysis follows the same approach as in the $\sqrt{s} = 8$ TeV analysis regarding the background prediction methods and the fit strategy. The best-fit value of $\mu_{t\bar{t}H}$ was 2.5 ± 0.7 (stat.) $^{+1.1}_{-0.9}$ (syst.), and the observed (expected) sensitivity of the search was found to be 2.2 (1.3) standard deviations. The total uncertainty in μ was dominated by the systematic uncertainties, which were mostly related to the theoretical uncertainties and the background modeling. More details can be found in Ref. [118].

With respect to the Run-1 and early Run-2 analyses, several improvements are made for the $t\bar{t}H$ multilepton analysis. These improvements include: the identification of prompt light leptons² with high efficiency, the rejection of non-prompt light leptons and electrons with misidentified charge using multivariate algorithms, a new trigger strategy, improved background estimation techniques, and separation of the $t\bar{t}H$ signal from backgrounds using multivariate techniques. A new fit strategy

¹ The results were published as a CONF note for the International Conference on High Energy Physics held in Chicago in August 2016.

² In the following, the term “light lepton”, denoted as ℓ , refers to either electrons or muons and to their antiparticles.

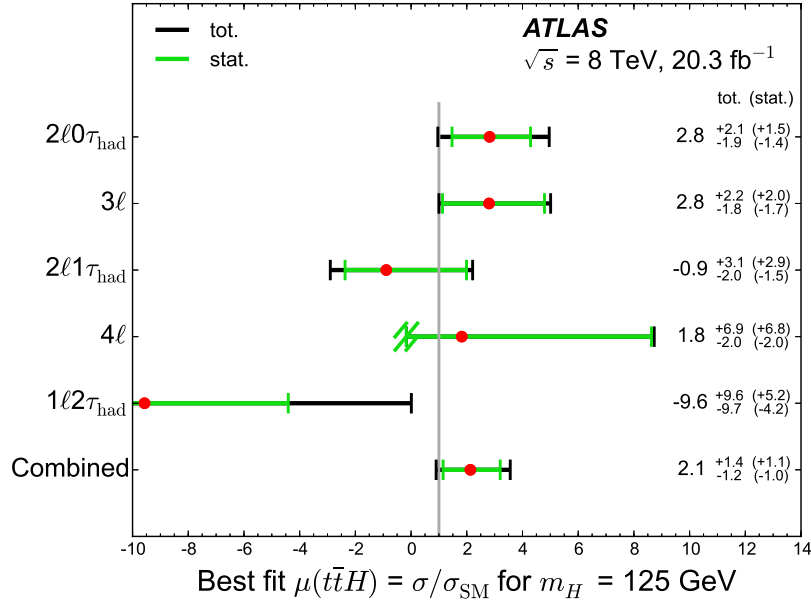


FIGURE 5.1: Best-fit values of the signal strength parameter $\mu = \sigma_{t\bar{t}H, \text{pbs.}} / \sigma_{t\bar{t}H, \text{SM}}$. The analysis uses 8 TeV data corresponding to an integrated luminosity of 20.3 fb^{-1} . For the 4ℓ category, $\mu < -0.17$ results in a negative expected total event yield and so the lower uncertainty is truncated at this point [116].

is employed to enhance the sensitivity of the search, where the signal is extracted by fitting the output of the multivariate discriminant in several final states. Furthermore, new background enriched control regions are included in the fit to better constrain the systematic uncertainties. In addition, new final states with the presence of hadronically decaying tau leptons are included in the analysis to enhance the overall sensitivity.

Much effort is made regarding the reduction of systematic uncertainties. As a result of these improvements and with the available statistical power, a significant enhancement in sensitivity with respect to the Run-1 and early Run-2 analyses is achieved.

5.2 Analysis strategy

The $t\bar{t}H$ multilepton analysis is primarily sensitive to $H \rightarrow WW^*$ or $H \rightarrow \tau^+\tau^-$ decays with a small contribution from $H \rightarrow ZZ^*$. The top-antitop quark pair decays into the b -quark and the W boson. The latter subsequently decays either to a lepton and neutrino, or to hadrons. Thus, depending on the Higgs boson decays, the $t\bar{t}H$ events contain $WWWWbb$, or $\tau\tau WWbb$, or $ZZWWbb$. Examples of tree-level Feynman diagrams are shown in Figure 5.2.

The analysis strategy is to select final states, including two light leptons with the same-sign (SS) electric charges³, or three or more charged light leptons, as well as zero, one or more hadronically decaying tau leptons. These final states cannot be produced in $t\bar{t}$ decay alone and thus their selection reduces this background. Seven final states, categorized by the number of light leptons and hadronically decaying tau lepton candidates (τ_{had}), are selected and analyzed. The light leptons and τ_{had} candidates are selected using the criteria described in Section 5.6.

Each of the seven final states is called a “channel” and certain channels are further split into categories to gain significance. The seven distinct channels, as illustrated in Figure 5.3, are:

³ A negative or positive electric charge of the light lepton.

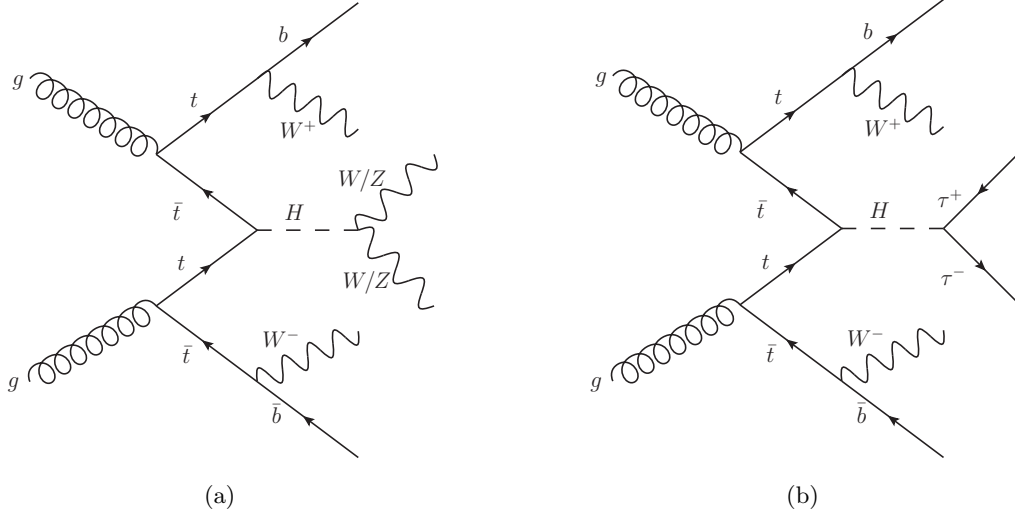


FIGURE 5.2: Examples of tree-level Feynman diagrams for $t\bar{t}H$ production where the Higgs boson decays to (a) WW^*/ZZ or (b) $\tau\tau$. The top and antitop quarks decay into a b -quark and a W boson ($t \rightarrow W^+b$, $\bar{t} \rightarrow W^-\bar{b}$).

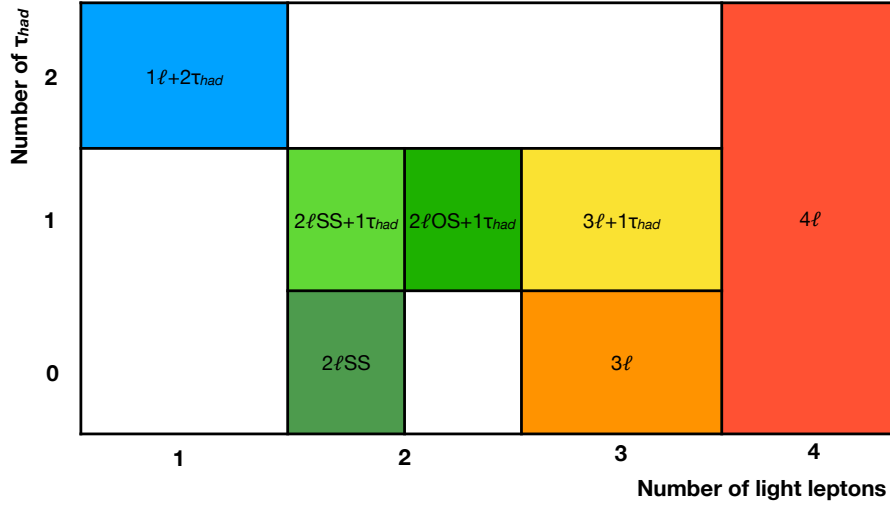
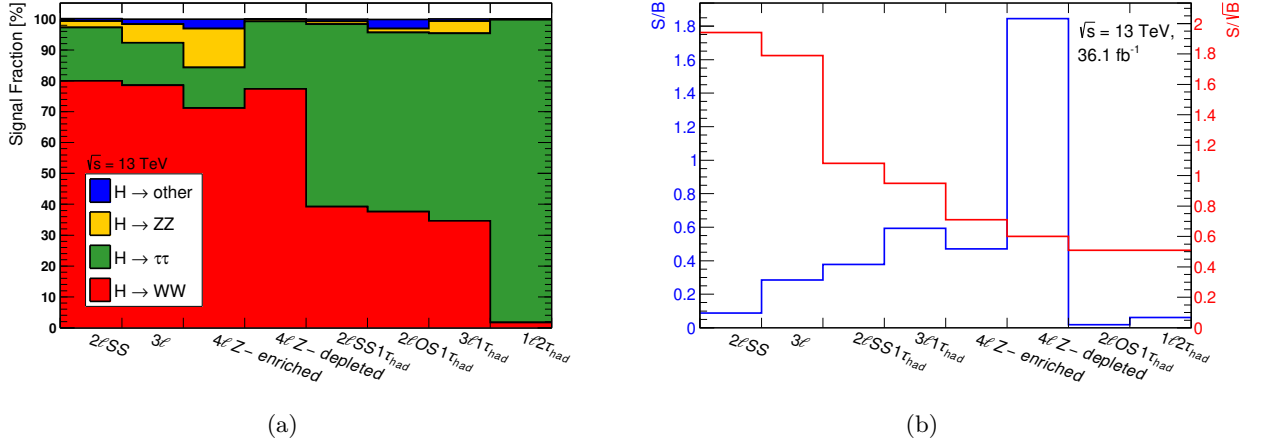
- $2\ell SS$: two same-charge light leptons and no hadronically decaying tau lepton.
- 3ℓ : three light leptons and no hadronically decaying tau lepton.
- 4ℓ : four light leptons. This channel is further divided into two categories: Z -enriched and Z -depleted.
- $2\ell SS1\tau_{\text{had}}$: two same-charge light leptons and one hadronically decaying tau lepton.
- $2\ell OS1\tau_{\text{had}}$: two opposite-charge light leptons and one hadronically decaying tau lepton.
- $3\ell 1\tau_{\text{had}}$: three light leptons and one hadronically decaying tau lepton.
- $1\ell 2\tau_{\text{had}}$: one light lepton and two opposite-charge hadronically decaying tau leptons.

All of the seven channels are defined orthogonal to each other, i.e., an event can contribute only to a single channel. Therefore, a veto on events with τ_{had} candidates is applied for the $2\ell SS$ and 3ℓ channels. In the 4ℓ channel, no requirement is applied to the number of τ_{had} candidates. The channels with τ_{had} candidates primarily target the $H \rightarrow \tau^+\tau^-$ decay; the other channels are dominated by the $H \rightarrow WW^*$ decay, and with the increasing number of light leptons there is a small contribution from $H \rightarrow ZZ^*$. The fractional contribution of the expected $t\bar{t}H$ signal arising from different Higgs boson decay modes in each channel is shown in Figure 5.4 (a). The signal-to-background ratio S/B and the ratio $S/\sqrt{B}$ for each channel are shown in Figure 5.4 (b).

The detailed criteria for each channel are summarized in Table 6.4. After the selection, assuming Standard Model $t\bar{t}H$ production, the total expected number of signal events summed over all categories is 91, corresponding to 0.50% of all produced $t\bar{t}H$ events [21]. The signal acceptance for each channel is given in Table 5.1.

5.3 $2\ell SS1\tau_{\text{had}}$ channel

In this channel, about 60% of the $t\bar{t}H$ signal events come from the $H \rightarrow \tau^+\tau^-$ decays and about 40% from $H \rightarrow WW^*$ decays, as shown in Figure 5.4 (a). A typical $t\bar{t}H$ signal event is expected to be

FIGURE 5.3: The seven distinct channels used in the $t\bar{t}H$ multilepton analysis.FIGURE 5.4: (a) Fraction of the expected $t\bar{t}H$ signal arising from different Higgs boson decay modes in each channel where the $H \rightarrow \mu\mu$ and $H \rightarrow b\bar{b}$ decay modes are referred to as $H \rightarrow \text{other}$. (b) The S/B and $S/\sqrt{B}$ ratios for each channel.TABLE 5.1: Acceptance times efficiency for the $t\bar{t}H$ signal in each channel. This includes the Higgs boson and top quark branching fractions, detector acceptance, reconstruction and selection efficiency, and it is computed relative to the inclusive $t\bar{t}H$ production considering all Higgs boson and top decays [21].

	$2\ell\text{SS}$	3ℓ	4ℓ	$Z\text{-enriched}$ ($Z\text{-depleted}$)	$2\ell\text{SS}1\tau_{\text{had}}$	$2\ell\text{OS}1\tau_{\text{had}}$	$3\ell1\tau_{\text{had}}$	$1\ell2\tau_{\text{had}}$	total
$A \times \epsilon [10^{-4}]$	23	13	0.6 (0.1)		1.7	7.8	0.8	2.3	50

characterized by the presence of two prompt⁴ light leptons with same-charge, one hadronically decaying tau lepton, missing energy from four neutrinos, high jet multiplicity, and b -quark jets. Examples of tree-level Feynman diagrams for the $t\bar{t}H$ signal in the $2\ell\text{SS}1\tau_{\text{had}}$ channel are shown in Figure 5.5.

The light leptons with same-charge, and of same- or opposite-flavor ($e^\pm e^\pm$, $e^\pm \mu^\pm$, $\mu^\pm \mu^\pm$) are produced in the subsequent decays of a τ lepton from the Higgs boson and a W boson from top quark with same-sign electric charges in the case of $H \rightarrow \tau^+ \tau^-$ decay. The hadronically decaying tau lepton is produced with opposite-charge to that of the light leptons. In such an event four reconstructed jets are expected, not taking into account the additional jets from initial and final state radiation, and two of these jets are initiated by b -quarks.

The $2\ell\text{SS}1\tau_{\text{had}}$ is the channel with the highest sensitivity compared to the other channels with τ_{had} candidates, as shown in Figure 5.4 (b). This higher sensitivity is a result of several improvements made for the channel. A rather small event rate is expected in this channel because of the presence of two same-charge light leptons, and the requirements of a τ_{had} candidate and high jet multiplicity. The remainder of this chapter is devoted to the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ channel. Unless otherwise specified, the term “analysis” is used for the $2\ell\text{SS}1\tau_{\text{had}}$ channel.

5.4 Background overview

Several SM processes can mimic the signal in the $2\ell\text{SS}1\tau_{\text{had}}$ channel and thus could be important background contributions. Figure 5.6 shows the background composition in the $2\ell\text{SS}1\tau_{\text{had}}$ channel, obtained from simulation using the Monte Carlo (MC) samples described in Section 5.5. These backgrounds are divided into two categories: irreducible backgrounds and reducible backgrounds.

5.4.1 Irreducible backgrounds

Important irreducible backgrounds include the production of a top quark pair in association with a vector boson, $t\bar{t}W$ and $t\bar{t}(Z/\gamma^*)$ in the following referred to as $t\bar{t}Z$, and diboson production, VV ($V = W, Z$), in association with jets. The light leptons with same-charge and τ_{had} candidates originate from these processes, as their final state topology is similar to the signal. Examples of leading-order Feynman diagrams for the $t\bar{t}W$ and $t\bar{t}Z$ production with the $2\ell\text{SS}1\tau_{\text{had}}$ final state are shown in Figure 5.7. The jet multiplicity of the $t\bar{t}W$ process is lower than the signal and therefore the contribution comes from events with additional jets. The major irreducible background contribution in the $2\ell\text{SS}1\tau_{\text{had}}$ channel arises from the $t\bar{t}Z$ process, as shown in Figure 5.6, because the jet multiplicity of this process is similar to the $t\bar{t}H$ signal. Furthermore, the cross section of the $t\bar{t}W$ and $t\bar{t}Z$ processes is of the same order of magnitude as the $t\bar{t}H$ production.

Diboson background contribution is very small in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. In addition, there are smaller contributions from a number of rare processes. These are tZ , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}\bar{t}$, triboson production and rare top decay. The associated production of a Higgs boson with a single top quark, $tHjb$ and WtH , is considered as background in this channel. All these backgrounds are estimated from simulation. The modeling of the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds by simulation is discussed in Section 5.11.1.

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, irreducible background events contain two same-charge prompt light leptons and a real τ_{had} candidate. However, there is a non-negligible contribution from events that contain two same-charge prompt light leptons and a fake τ_{had} candidate. Such events are estimated using a semi data-driven technique which is described in Section 5.11.3. Thus, irreducible background events are of two types in the $2\ell\text{SS}1\tau_{\text{had}}$ channel:

- Events with two same-charge prompt light leptons and a real τ_{had} candidate.
- Events with two same-charge prompt light leptons and a fake τ_{had} candidate.

⁴ An isolated lepton arising from the decay of W , Z or Higgs bosons is referred to as “prompt” or “real” lepton.

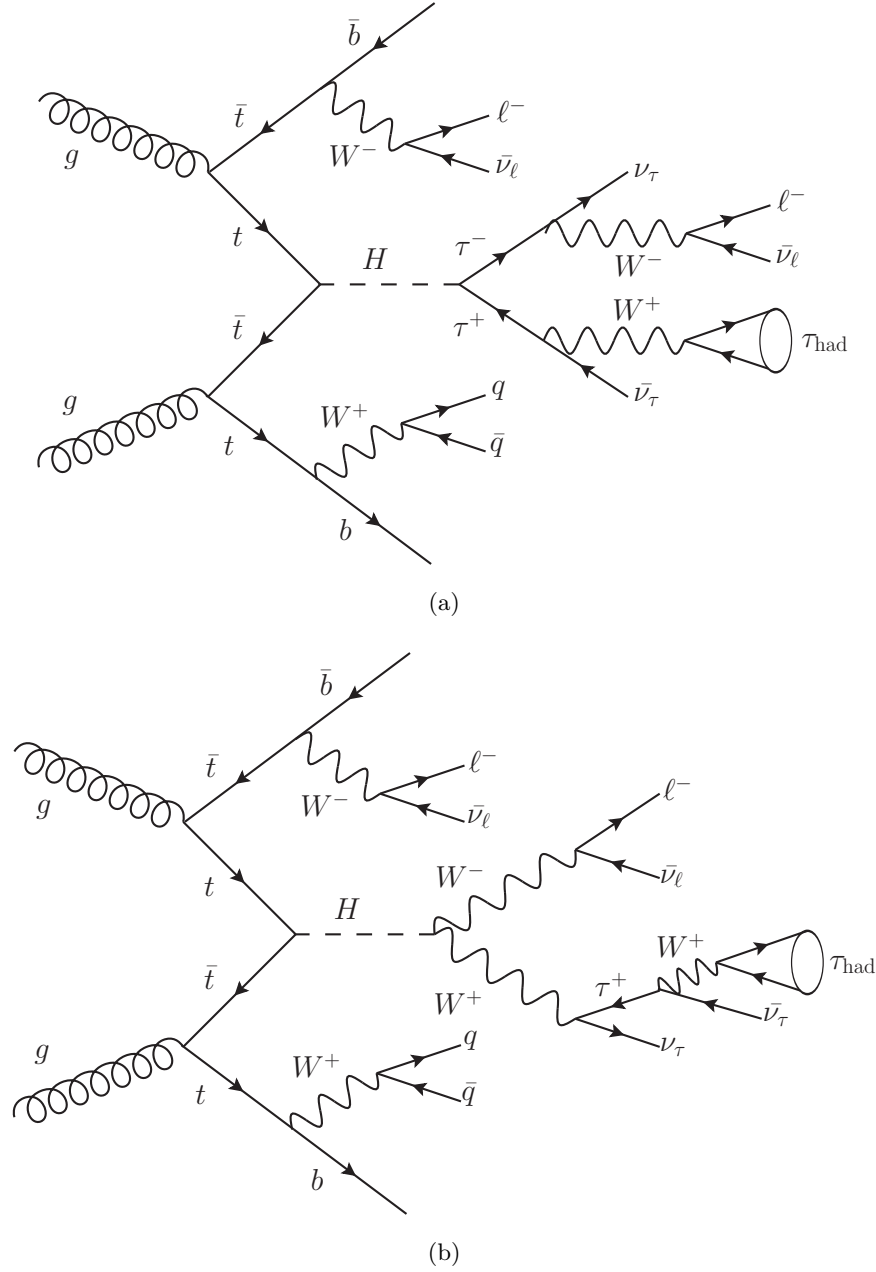


FIGURE 5.5: Examples of tree-level Feynman diagrams of a $t\bar{t}H$ signal with $2\ell\text{SS}1\tau_{\text{had}}$ final state, where the Higgs boson decays into a pair of (a) τ leptons and (b) W bosons. The hadronically decaying tau lepton, τ_{had} , is either 1- or 3-track candidate with opposite-charge to that of the light leptons.

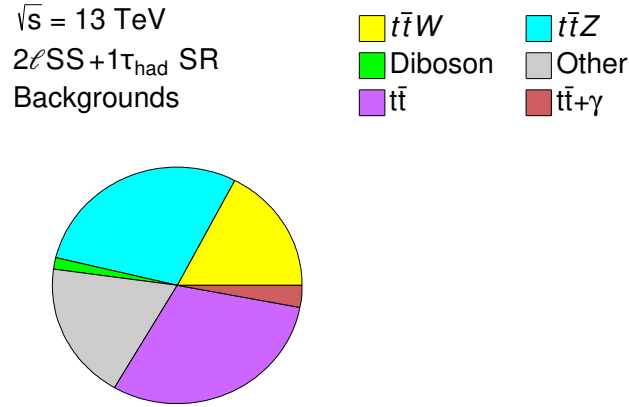


FIGURE 5.6: Fractional contribution of different backgrounds to the total background in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. Rare processes tZ , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, $tHjb$, WtH , triboson production and rare top decay are labeled as “Other”.

5.4.2 Reducible backgrounds

The reducible backgrounds arise from events where at least one of the light leptons is not produced in decays of electroweak bosons but rather originate from another source. Common sources of the reducible backgrounds are heavy-flavor hadron decays, photon conversions, misreconstruction of particles such as hadronic jets or prompt light leptons whose charge is misidentified. The light leptons originate from such sources are referred to as *fake* light leptons in the following. In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the fake light leptons mainly originate from the following three sources:

Non-prompt light leptons: A significant source of the fake light leptons is non-prompt leptons produced in decays of b - or c -flavored hadrons.

Photon conversion: A photon with energy larger than two electron masses upon interacting with the detector material can convert into an electron positron pair, e^+e^- . One of the electrons in the pair is then misidentified as a prompt electron. The probability of the photon conversion is proportional to the amount of material it traverses and that conversion can happen as early as in the beam pipe. The photons are either emitted from initial or final state radiations (in the parton showering), or radiated off the top-antitop quark, or originated from π^0 decay.

Charge misidentification: Charge misidentification typically occurs when an electron undergoes hard bremsstrahlung, followed by a pair production, the so-called *trident* event $e^\pm \rightarrow e^\pm\gamma \rightarrow e^\pm e^+e^-$. A representation of such process, which occurs in the detector material, is shown in Figure 5.8. The track of the final state electron with opposite charge to the primary electron is reconstructed and incorrectly associated to the EM cluster, leading to charge misidentification (q mis-id). Another source of charge misidentification is a mismeasurement of the curvature of the primary electron track. This effect is only important for high p_T electrons. Charge misidentification is negligible for muons, because of the long lever arm to the muon system and the fact that the charge is measured in both the inner detector and the muon spectrometer. Therefore, the misidentification rate of the muon charge is very low, and it is not considered in the analysis.

The largest reducible background contribution in the $2\ell\text{SS}1\tau_{\text{had}}$ channel arises from the $t\bar{t}$ process, as shown in Figure 5.6. The cross section of the $t\bar{t}$ process is higher than the $t\bar{t}H$ production making it a more challenging background. A typical $t\bar{t}$ decay that leads to the final state of the $2\ell\text{SS}1\tau_{\text{had}}$

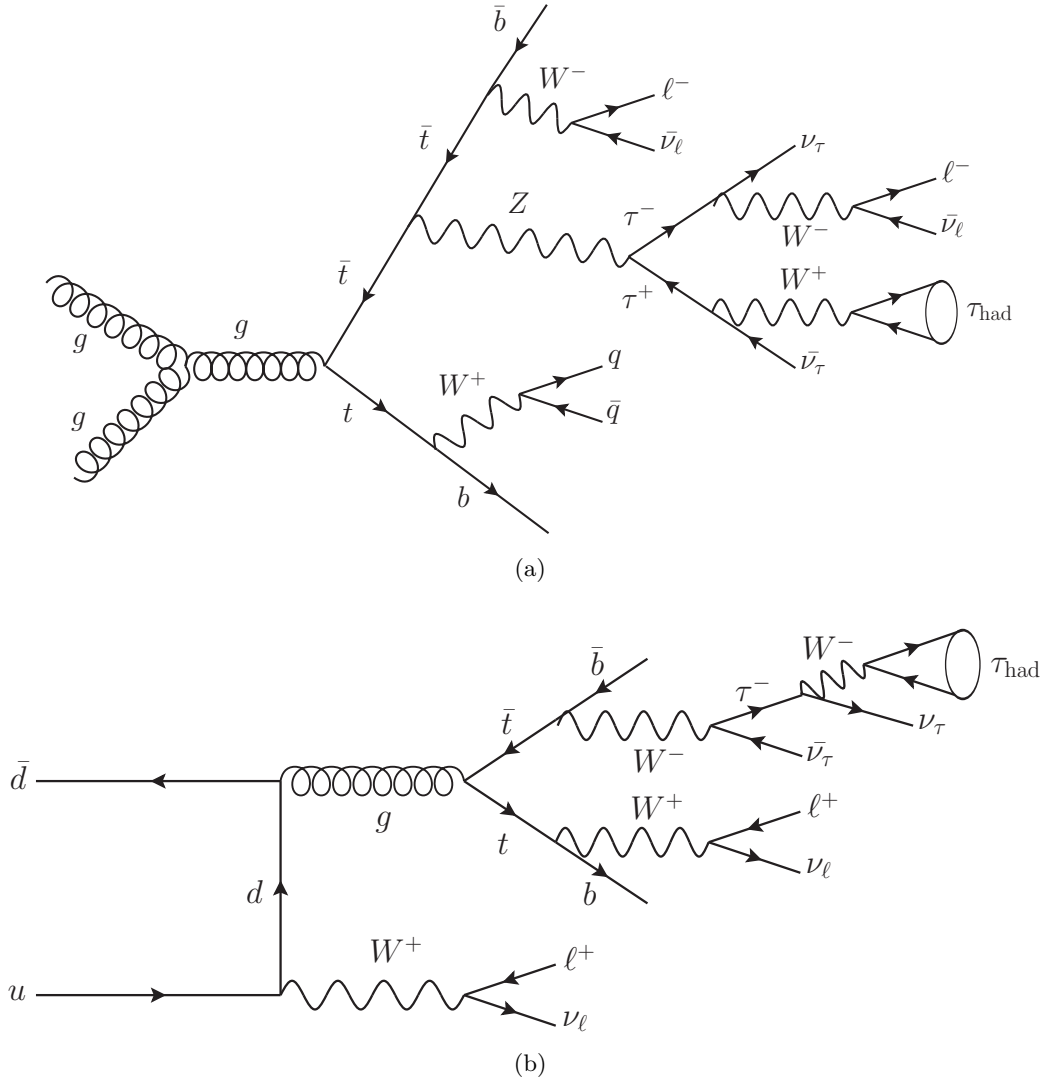


FIGURE 5.7: Examples of leading-order Feynman diagrams for (a) $t\bar{t}Z$ and (b) $t\bar{t}W$ production with the $2\ell\text{SS}1\tau_{\text{had}}$ final state. The τ_{had} is either 1- or 3-track candidate.

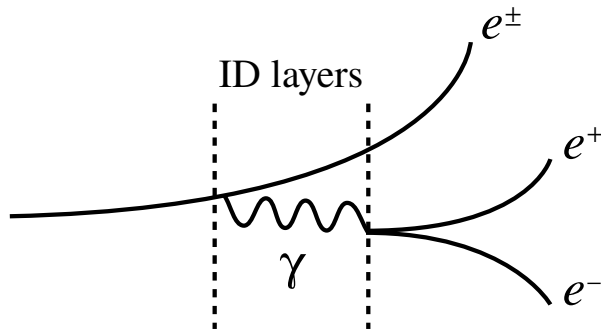


FIGURE 5.8: Production of trident electrons. An electron from the pp collisions undergoes hard bremsstrahlung in the inner detector and radiates a photon which subsequently decays into an electron and positron pair. One of the electrons in the pair with opposite-charge to the primary electron is reconstructed, resulting in charge misidentification.

is shown in Figure 5.9. In such events, reconstructing two same-charge light leptons requires that one of the light leptons is originated from any of the three sources described above. Moreover, the τ_{had} candidate arises either from $t \rightarrow Wb \rightarrow \tau\nu_\tau b$ decays or from misidentified light-quark- or gluon-initiated jets. In summary, regardless of whether the τ_{had} candidate is real or fake, there is a fake light lepton. Furthermore, such events include additional jets mainly from gluon emissions from the hard-scatter interactions in order to fulfill the $2\ell\text{SS}1\tau_{\text{had}}$ signal region jet requirements. Background contribution from the $t\bar{t}\gamma$ process is small and the contributions from other processes such as single-top, Wt , $Z + \text{jets}$ and $W + \text{jets}$ are negligible. Thus, the primary focus is non-prompt light leptons and photon conversion whereas charge misidentification is also small.

These backgrounds are called “reducible” in the sense that applying stricter criteria can reduce the size of the background relative to the signal, thus increasing the signal-to-background ratio. In order to reduce the impact of these backgrounds, the reconstructed light leptons are required to satisfy strict quality, isolation and impact parameter requirements, as well as the τ_{had} candidate is required to satisfy strict quality criteria. After such requirements there is still a non-negligible amount of fake light leptons and fake τ_{had} candidates in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The number of expected reducible background events and the associated kinematic distributions are derived using data-driven techniques, which are described in Section 5.11.2, because the MC prediction of the backgrounds with fake light leptons and fake τ_{had} candidates is unreliable. Furthermore, these backgrounds may not be accurately modeled by simulation.

5.5 Collision dataset and Monte Carlo samples

This analysis uses a dataset collected by the ATLAS detector during the years 2015 and 2016 with a peak instantaneous luminosity of $\mathcal{L} = 1.4 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. In the dataset, the mean number of pp interactions per bunch crossing is 24 and the bunch spacing is 25 ns. The integrated luminosity of the dataset is 36.1 fb^{-1} , which is obtained after applying the data quality requirements by means of a Good Run List (GRL) [119]. The GRLs contain the list of good luminosity blocks approved for the physics analyses, where all subdetectors are required to fulfill a given set of data quality criteria. The luminosity blocks with defects related to one or more subsystems are excluded from the GRLs.

The details of full ATLAS simulation are summarized in Section 2.4. The Monte Carlo samples for signal and background processes used in this analysis were produced using the full ATLAS simulation [90] based on GEANT4 [94]. A fast simulation referred to as **AFII** is used for some small

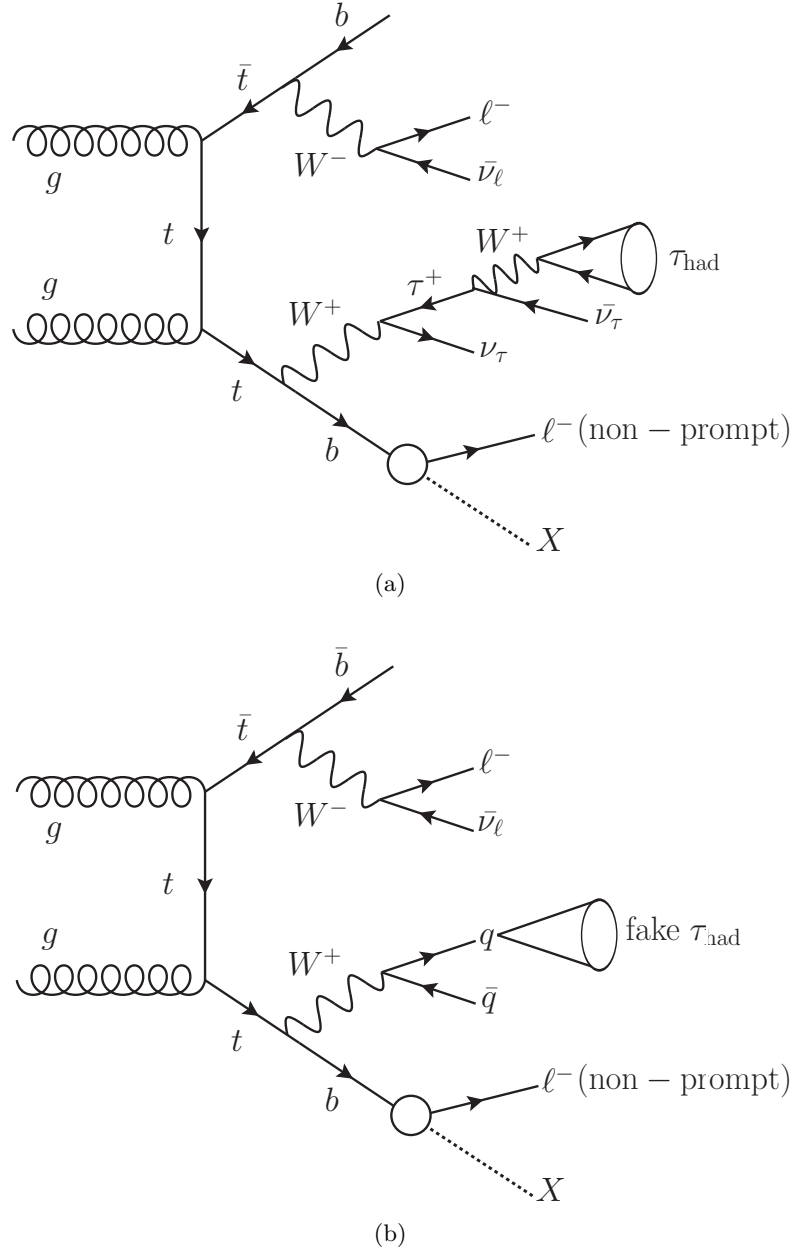


FIGURE 5.9: Examples of Feynman diagrams of $t\bar{t}$ decays in the $2\ell SS1\tau_{\text{had}}$ channel. The non-prompt light leptons originate from b -flavored hadron decay e.g., $B^- \rightarrow \ell^- \bar{\nu}_\ell + X$, where X denotes the remaining decay products. (a) A real τ_{had} candidate arises from W^+ boson decay. (b) The W^+ boson decays into a pair of quarks and one of the quark-initiated jet is misidentified as hadronically decaying tau lepton (fake τ_{had}). The $t\bar{t}$ events contribute to the $2\ell SS1\tau_{\text{had}}$ channel with (a) three and (b) two additional jets.

background samples. The effects of minimum bias pp interactions (pile-up) were simulated by generating additional interactions using PYTHIA8.1 [120] with the MSTWLO2008 [121] set of parton distribution functions (PDF) and with a set of A2 tune [122] parameters for the parton shower, hadronization, and underlying event. They are overlaid onto the simulated hard-scatter events. The contributions from the pile-up interactions were simulated in the same bunch crossing as the hard-scattering and in nearby bunch crossings. Finally, the resulting simulated events are reweighted to the pile-up distribution observed in data and processed through the same reconstruction algorithms as the data.

The $t\bar{t}H$ simulation samples are generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) matrix elements (ME) using MADGRAPH5_AMC@NLO [123] (in the following MG5_AMC) generator, interfaced to PYTHIA8 configured with A14 tune [124] for parton showering and hadronization. The PDF set used for the simulation is NNPDF3.ONLO [125] and for showering is NNPDF2.3LO [126]. The $t\bar{t}H$ signal samples used to estimate the systematic uncertainties are also generated at NLO using the MG5_AMC@NLO generator, interfaced to HERWIG++ [127] with the UE-EE-5 [128] tune for showering and hadronization. The PDF set used is CT10 [129]. The $t\bar{t}H$ production cross section is calculated at NLO in QCD and with NLO electroweak corrections [130–133]. The CERN Yellow Report [130] provides an overall $t\bar{t}H$ cross section of 507^{+35}_{-50} fb at $\sqrt{s} = 13$ TeV with the Higgs boson mass is set to 125 GeV and top quark mass is set to 172.5 GeV. Uncertainties on the cross section are due to the QCD renormalization (μ_R) and factorization scales (μ_F), PDFs, and the strong coupling α_S . The central value for renormalization and factorization scales is set to $\mu = \mu_R = \mu_F = m_t + m_H/2$. The scale uncertainties are estimated by varying the μ_R and μ_F scales by a factor two up and down. The PDF uncertainties are derived from eigenvector sets within a chosen PDF set and by comparing with other PDF sets following the recommendations of PDF4LHC [134]. The scale uncertainties are $^{+5.8\%}_{-9.2\%}$ and uncertainties due to PDF+ α_S variations are $\pm 3.6\%$.

The production of $t\bar{t}W$ and $t\bar{t}(Z/\gamma^*)$ are major backgrounds to the $t\bar{t}H$ signal. Samples for these background processes are generated at NLO in ME with the same setup as for the $t\bar{t}H$ signal sample described above. The cross section of $t\bar{t}W$ and $t\bar{t}Z$, inclusive of the process $pp \rightarrow t\bar{t}\ell^+\ell^- + X$ over the full mass spectrum of Z/γ^* , are computed at NLO in QCD including the electroweak corrections [123, 135]. The total cross section for $t\bar{t}\ell^+\ell^-$, with the requirement of $M(\ell^+\ell^-) > 5$ GeV, is 124 fb and for $t\bar{t}W$ it is 601 fb. The uncertainties on the cross section are estimated using the same procedure as for the $t\bar{t}H$. The QCD scale uncertainties are $\pm 12\%$, PDF and α_S uncertainties are $\pm 4\%$. For the scale uncertainties, the central renormalization and factorization scale choice is $\mu = \mu_R = \mu_F = H_T/2$, where H_T is defined as the scalar sum of the transverse masses $\sqrt{p_T^2 + m^2}$ of all final state particles. In order to estimate the systematic uncertainties, samples are produced using the SHERPA [93] generator at leading-order (LO) ME with additional partons. The PDF set is NNPDF3.ONLO with the parton shower tune by SHERPA. The modeling of the simulated samples for $t\bar{t}H$, $t\bar{t}W$, and $t\bar{t}Z$ processes are described in detail in Ref. [136]. Table 5.21 summarizes the cross sections and the associated uncertainties for $t\bar{t}H$, $t\bar{t}W$, and $t\bar{t}Z$ processes.

The MC samples for diboson WW , ZZ , and WZ production are generated using SHERPA v2.1.1 with up to three additional partons. The samples are classified according to the number of light leptons in the final state and described in detail in Ref. [137]. The cross sections are computed at NLO precision in QCD. The NLO cross sections are evaluated using MCFM [138, 139] with CT10 NLO PDF which are used to evaluate the systematic uncertainties.

The nominal sample of $t\bar{t}$ background is generated at NLO using the POWHEG-BOX v2 [140] generator with the NNPDF3.ONLO PDF set [141]. The parton shower and hadronization are simulated using PYTHIA8 with the A14 tune. The PDF set used for parton shower is NNPDF2.3LO. The overall $t\bar{t}$ cross section at $\sqrt{s} = 13$ TeV is 832 pb for a top quark mass of 172.5 GeV, calculated at next-to-next-to-leading order (NNLO) precision in QCD including soft-gluon resummation to next-to-next-to-leading-log order (NNLL) [142–144] using `top++2.0` [145]. The other top backgrounds such as single top t-channel and s-channel, and Wt are generated at NLO using POWHEG-BOX v1 [146–148] with CT10 PDF set, interfaced to PYTHIA6 [149] using the Perugia2012 [150] set of tune parameters.

TABLE 5.2: The generators used for the simulation of the signal and background processes. The samples used to estimate the systematic uncertainties are shown at the bottom of the table. The parton distribution function set listed is used for the matrix element calculations. The PDF set used for parton shower is NNPDF2.3LO for samples using A14 tune and CTEQ6L1 for samples using either UE-EE-5 or Perugia2012 tune. “V” refers to the production of an electroweak boson W or Z/γ^* . PYTHIA8 and PYTHIA6 refers to version 8.2 and 6.4, respectively. The background process $Z \rightarrow \ell\ell$ has a negligible contribution in the signal region, however it contributes to the control regions.

Process	Generator	ME order	Parton Shower	PDF	Tune
Signal					
$t\bar{t}H$	MG5_AMC	NLO	PYTHIA8	NNPDF3.0NLO	A14
Backgrounds					
$t\bar{t}W$	MG5_AMC	NLO	PYTHIA8	NNPDF3.0NLO	A14
$t\bar{t}(Z/\gamma^* \rightarrow \ell\ell)$	MG5_AMC	NLO	PYTHIA8	NNPDF3.0NLO	A14
$VV(\rightarrow \ell\ell XX), qqVV$	SHERPA v2.1.1	NLO	SHERPA	CT10	SHERPA default
$t\bar{t}$	POWHEG-BOX v2	NLO	PYTHIA8	NNPDF3.0NLO	A14
$t\bar{t}\gamma$	MG5_AMC	LO	PYTHIA8	NNPDF2.3LO	A14
$tHqb$	MG5_AMC	LO	PYTHIA8	CT10	A14
tHW	MG5_AMC	NLO	HERWIG++	CT10	UE-EE-5
$t(Z/\gamma^*)$	MG5_AMC	LO	PYTHIA6	CTEQ6L1	Perugia2012
$tW(Z/\gamma^*)$	MG5_AMC	NLO	PYTHIA8	NNPDF2.3LO	A14
$t\bar{t}W^+W^-$	MG5_AMC	LO	PYTHIA8	NNPDF2.3LO	A14
$t\bar{t}t, t\bar{t}t$	MG5_AMC	LO	PYTHIA8	NNPDF2.3LO	A14
VVV	SHERPA v2.1.1	NLO	SHERPA	CT10	SHERPA default
$Z \rightarrow \ell\ell$	SHERPA v2.2.1	NLO	SHERPA	NNPDF3.0NLO	SHERPA default
single top s -, t -channel, Wt	POWHEG-BOX v1	NLO	PYTHIA6	CT10	Perugia2012
$t\bar{t}H$	MG5_AMC	NLO	HERWIG++	CT10	UE-EE-5
$t\bar{t}W$	SHERPA v2.1.1	LO (multileg)	SHERPA	NNPDF3.0NLO	SHERPA default
$t\bar{t}(Z/\gamma^* \rightarrow \ell\ell)$	SHERPA v2.1.1	LO (multileg)	SHERPA	NNPDF3.0NLO	SHERPA default

A sample of the $t\bar{t}\gamma$ background process is generated at LO using the MG5_AMC with the NNPDF2.3LO PDF set. In this background process, a photon with high transverse momentum is radiated off the top quarks. The $t\bar{t}\gamma$ candidates are the subset of $t\bar{t}$ events with an additional high p_T photon. Therefore, the $t\bar{t}$ events with photon are vetoed in order to avoid double counting of events between the two samples.

The MC samples for other rare background processes such as WtH , $tHjb$, tZ , tWZ , $t\bar{t}W^+W^-$, $t\bar{t}t$, $t\bar{t}t$, and $t \rightarrow Wb\ell\ell$ are also generated. The event generator programs and configurations used for simulating these MC samples are listed in Table 5.2. The MC samples also include leading-logarithm photon emission, modeled by a parton shower generator or by the PHOTOS program [151].

5.6 Object selection

The $t\bar{t}H$ multilepton analysis channels, described in Section 5.2, use a common object selection for event categorization. In each analysis channel, tighter criteria are then applied to address the different background contributions. The object selections are detailed below. The reconstruction procedure of these objects are described in Section 2.3.

5.6.1 Light leptons

Electron candidates are required to have a minimum transverse momentum $p_T > 10$ GeV. They are required to satisfy $|\eta_{\text{cluster}}| < 2.47$, where $|\eta_{\text{cluster}}|$ is the absolute value of the pseudorapidity of the calorimeter cluster associated to the electron candidate. Electrons in the transition region between barrel and endcap electromagnetic calorimeters $1.37 < |\eta_{\text{cluster}}| < 1.52$ are excluded. Electrons are identified using working points of the likelihood-based (LH) identification algorithm. The LH method uses the signal and background probability density functions of several discriminating variables [66]. A *loose* working point of the LH identification algorithm is used to separate real prompt electrons from fake electrons coming from hadronic jets and converted photons. In order to further reduce the fake electron contribution, the electron track is required to originate from the primary vertex. The longitudinal impact parameter of the track multiplied by the sine of the polar angle is required to be $|z_0 \sin \theta| < 0.5$ mm. The transverse impact parameter significance, $|d_0|/\sigma_{d_0}$, must be less than 5.

Muon candidates are required to satisfy $p_T > 10$ GeV and to be within the region of pseudorapidity $|\eta| < 2.5$. They are required to pass *loose* identification criteria that are designed to select muons with high efficiency [71]. The longitudinal impact parameter requirement is the same as for electrons, whereas the transverse impact parameter significance is required to be, $|d_0|/\sigma_{d_0} < 3$.

5.6.2 Jets and b -tagged jets

Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. In order to reduce the contamination of jets originating from pile-up interactions, the jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to pass the jet vertex tagger selection [77]. The average efficiency of this requirement is 92% per jet from hard-scatter.

Jets containing b -hadrons are tagged (b -tagged) using a multivariate algorithm that combines an output of three b -tagging algorithms: an impact parameter-based, an inclusive secondary vertex reconstruction, and decay chain multi-vertex reconstruction algorithms (Section 2.3.4). The working point used for this analysis has an efficiency of 70% for jets containing b -hadrons with $p_T > 20$ GeV and $|\eta| < 2.5$ in $t\bar{t}$ events.

5.6.3 Hadronically decaying tau leptons

Hadronically decaying tau lepton candidates (τ_{had}) are required to have a minimum transverse momentum $p_T > 25$ GeV and $|\eta| < 2.5$. Candidates in the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$, are vetoed. They are required to have charge ± 1 , and must be either 1- or 3-track (prong) candidates. A boosted decision tree (BDT) discriminant using calorimeter- and tracking-based variables is used to identify τ_{had} candidates and to reject backgrounds from quark- and gluon-initiated jets. The τ_{had} candidates are required to pass the *medium* identification working point, corresponding to a combined reconstruction and identification efficiency of 55% (40%) for one (three)-prong τ_{had} decays [82]. An additional BDT, which uses shower shape information from the calorimeter and track quantities from inner detector, is employed to reject electrons that are reconstructed as 1-prong τ_{had} candidates. A working point with an efficiency of 95% for the τ_{had} candidates is used [82].

In order to reduce the contribution of fake τ_{had} from different sources, additional requirements on the τ_{had} candidates are applied after the overlap removal procedure is performed. In $t\bar{t}$ background, τ_{had} candidates can be faked by jets containing b -hadrons (b -jets). In order to remove this contribution, a geometrical matching within a cone of $\Delta R < 0.3$ is performed between the τ_{had} candidates and the jets. The τ_{had} candidate that matches to the jet is vetoed, if the overlapping jet is b -tagged with the 70% efficiency working point. The contribution of fake τ_{had} from muons is removed by performing an overlap removal with low- p_T (> 2 GeV) reconstructed muons that are not calorimeter-tagged. Finally, in order to reject fake τ_{had} candidates arising from pile-up, the vertex matched to the tracks of τ_{had} candidate is required to be the hard-scatter primary vertex of the event.

5.6.4 Overlap removal

After satisfying the selection requirements as discussed above, any object may still be reconstructed as two different objects. An overlap removal procedure is performed to avoid double counting of individual objects in the following order: any electron candidate within $\Delta R = 0.1$ of another electron with higher p_T is removed; the electron, which has kept, is removed if it lies within $\Delta R = 0.1$ of a muon candidate; any jet within $\Delta R = 0.3$ of an electron candidate is removed; if a muon candidate and jet lie within $\Delta R = \min(0.4, 0.04 + (10 \text{ GeV})/p_{T, \mu})$ of each other, the jet is kept and muon is removed. The value of ΔR is chosen to maximize the acceptance for prompt muons at a fixed rejection factor for non-prompt muons originating from hadron decays within the jet. Any τ_{had} candidate within $\Delta R = 0.2$ of an electron or muon candidate is removed; any jet within $\Delta R = 0.3$ of a τ_{had} candidate is removed and τ_{had} is kept. The overlap removal procedure is summarized in Table 5.3.

TABLE 5.3: Summary of the overlap removal procedure between the selected electrons, muons, hadronically decaying taus and jets. The ΔR cone size is between the two considered objects.

Keep object	Remove object	ΔR cone size
e	e (low- p_T)	0.1
μ	e	0.1
e	jet	0.3
jet	μ	$\min(0.4, 0.04 + (10 \text{ GeV})/p_{T, \mu})$
e	τ_{had}	0.2
μ	τ_{had}	0.2
τ_{had}	jet	0.3

5.7 Tight light leptons definition

In order to reduce fake light lepton contributions further, a tighter selection is applied to the light leptons defined in Section 5.6. This tight selection is based on isolation variables and the output of two multivariate algorithms. Details of the tight selection are given below.

Isolation variables

The isolation variables measure the detector activity around the light lepton candidate. Two types of variables are defined to assess the light lepton isolation:

- Calorimeter isolation, E_T^{topocone} , is defined as the sum of transverse energies of topological clusters within a cone of size $\Delta R = 0.2$ around the light lepton candidate. The clusters of the electron candidates and clusters within a smaller cone size of $\Delta R = 0.1$ of the muon candidates are excluded. The sum is corrected for the electron energy leakage outside the cluster and for the effect of pile-up using the ambient energy density in the event [152].
- Track isolation, p_T^{varcone} , is defined as the sum of transverse momenta of all tracks within $\Delta R = \min(0.2, 10 \text{ GeV}/E_T)$ around the electron candidate track and $\Delta R = \min(0.3, 10 \text{ GeV}/p_{T, \mu})$ around the muon candidate track. The tracks considered in the sum must originate from the reconstructed primary vertex of the hard collision, excluding the track of light lepton candidates with $p_T > 1 \text{ GeV}$ and satisfying quality requirements.

The *loose* isolation working point (WP) is designed to obtain a 99% efficiency for prompt and isolated light leptons in $Z \rightarrow \ell\ell$ events. This WP uses the calorimeter and track-based isolation variables and it is applied to both electrons and muons.

Non-prompt lepton BDT

In order to reduce non-prompt light lepton background, both in the Run-1 [116] and early Run-2 [118] $t\bar{t}H$ multilepton analyses, a tighter isolation requirement is imposed on light lepton candidates. Even after this tight isolation requirement, the dominant background in most channels is due to non-prompt light lepton contribution. Such leptons can also pass the tight isolation requirements since the isolation variables described above are not specifically designed to distinguish prompt light leptons from leptons arising from heavy-flavor hadron decays. The dominant systematic uncertainty due to non-prompt light lepton contribution is one of the main limiting factor to the sensitivity in Run-1 and early Run-2 $t\bar{t}H$ multilepton final states.

A multivariate algorithm known as **PromptLeptonIso** [21, 153] is used in this analysis to reject non-prompt light leptons that are produced in decays of hadrons containing b - or c -quarks. These hadrons have longer lifetimes that can be detected since they decay away from the primary vertex. This algorithm uses lifetime information associated with a track-jet that matches to the selected light lepton and identify non-prompt light leptons. A reconstructed track-jet that is matched to a non-prompt light lepton is typically a jet initiated by b - or c -quarks, and may contain a displaced decay vertex. This track-jet uses a larger cone size than the isolation variables and collect all the tracks (including the lepton track) around the light lepton direction. Additional reconstructed tracks increase the precision to identify the displaced decay vertex. Thereby, a secondary vertex may be reconstructed within a track-jet that leads to a powerful way of discriminating between the prompt and non-prompt light leptons.

The **PromptLeptonIso** algorithm is BDT trained on prompt and non-prompt light leptons from simulated $t\bar{t}$ events using a set of eight discriminating variables. Two of the selected variables use the relationship between the track-jet and the light lepton: angular distance between the light lepton and track-jet axis and the ratio of the light lepton p_T with respect to track-jet p_T . Three variables are related to the light lepton isolation: the number of tracks collected by the track-jet, the calorimeter and track isolation variables. Three variables are the output of the b -tagging algorithms. Separate BDTs are trained for electrons and muons and validated using data in various control regions.

The efficiency of the prompt light leptons, at the chosen working point (**PromptLeptonIso** < -0.5), is measured with $Z \rightarrow \ell\ell$ events using a so-called tag-and-probe method as described in Refs. [71, 154]. A control region enriched in $Z \rightarrow \ell\ell$ events is defined for efficiency measurements by applying a Z mass window selection on the invariant mass of the two leptons. Figure 5.10 shows the efficiency for the prompt muons and electrons as a function of p_T . The prompt muons (electrons) efficiency is about 70% (60%) for $p_T \sim 10$ GeV and reaches a plateau of 96% (94%) at $p_T \sim 45$ GeV. The rejection factor obtained for non-prompt light leptons from the decay of b -hadrons is about 20. Simulated events are corrected to account for the differences of the prompt light lepton efficiency between data and simulation. Correction factors (scale factors) are studied as a function of nearby light- and heavy-flavor jets. Figure 5.10 illustrates that the corrections for the efficiencies are less than 10% at low- p_T and decreases with increasing light lepton p_T . The systematic uncertainties on the corrections are about 3% at low- pt and decrease with increasing p_T , whereas the largest contribution comes from the pile-up effects.

Electron charge misidentification BDT

A dedicated multivariate discriminant known as **Electron Charge Flip Tagger** [21, 155] is used to reject electrons reconstructed with an incorrect electric charge. A BDT is trained using eight discriminating variables related to the properties of the electron clusters and tracks. The input variables used

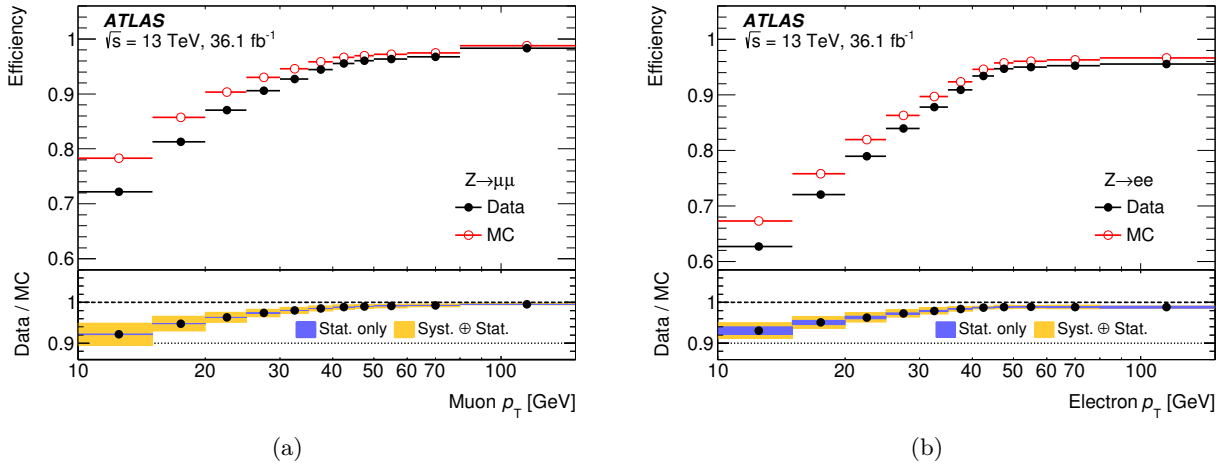


FIGURE 5.10: The efficiency of the prompt muons (a) and electrons (b), at the chosen **PromptLeptonIso** working point, as a function of p_T . The measurements in data (simulation) are shown as full black (open red) circles. The electrons are required to pass *tight* LH identification requirements. The bottom panel displays the scale factors, with the blue (yellow) band representing the statistical (total) uncertainty [21].

for training are: the p_T and $|\eta|$ of the electron, the track curvature significance which is defined as the ratio of the electric charge to the track momentum divided by the estimated uncertainty on its measurement, the electric charge times the transverse impact parameter, the cluster width along the azimuthal direction, and the quality of the matching between the track and the cluster in terms of both energy/momentum and azimuthal position. The chosen working point (**ChargeIDBDT** > 0.067) provides a 95% efficiency for electrons with correct charge reconstruction. The rejection factor for electrons passing the *tight* LH identification requirements with a wrong charge assignment is about 17. Correction factors are applied on selected electrons to match the efficiency of the discriminant in simulation to that measured in data, which are within a few percent for $|\eta| < 2.4$ but larger in the forward region of the pseudorapidity $2.4 < |\eta| < 2.47$. These correction factors are determined using $Z \rightarrow ee$ events.

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the tight light leptons are defined by requirements on light lepton identification and isolation, and on the BDT outputs of the **PromptLeptonIso** and the **Electron Charge Flip Tagger** algorithms. The tight light lepton definition in comparison with the baseline (loose) selection (Section 5.6) is summarized in Table 5.4.

5.8 Triggers

The analysis uses either single-lepton or dilepton triggers (common to all $t\bar{t}H$ multilepton channels) for the event preselection. The triggers used are the lowest unscaled triggers employed during data-taking in 2015 and 2016 and summarized in Table 5.5. The single-lepton triggers (SLT) with low p_T threshold include an isolation or identification (ID) requirement on the light lepton. These triggers have lower efficiency for high p_T leptons. In order to maximize the trigger efficiency, they are combined with triggers with high p_T thresholds but with no or looser requirement. The single-lepton triggers are a logical disjunction (OR) combination of several trigger chains with increasing p_T thresholds. The dilepton triggers (DLT) require the presence of two light leptons with same- or opposite-flavor and a minimum p_T threshold for both leptons.

The p_T threshold for the single-muon (electron) trigger was 20 (24) GeV in 2015 [54]. The single-muon trigger required a muon candidate to pass a *loose* isolation selection and the single-electron

TABLE 5.4: *Loose* and *tight* light lepton definitions used in the analysis. Selection criteria for the tight light lepton are applied in addition to the loose one. Definitions of the abbreviations are given in the text.

Electrons		
	<i>Loose</i>	<i>Tight</i>
Identification	Loose LH	Tight LH
Isolation	No	Loose WP
Non-prompt lepton BDT	No	PromptLeptonIso < -0.5
Charge misidentification BDT	No	ChargeIDBDT > 0.067
$ d_0 /\sigma_{d_0}$	< 5	< 5
$ z_0 \sin \theta $	< 0.5 mm	< 0.5 mm
Muons		
	<i>Loose</i>	<i>Tight</i>
Identification	Loose	Loose
Isolation	No	Loose WP
Non-prompt lepton BDT	No	PromptLeptonIso < -0.5
$ d_0 /\sigma_{d_0}$	< 3	< 3
$ z_0 \sin \theta $	< 0.5 mm	< 0.5 mm

trigger required the electron to pass *medium* LH identification requirements. In 2016, due to the increased luminosity and the different pile-up conditions, the lepton p_T threshold was raised to 26 GeV and more stringent requirements were applied. For the dielectron trigger, the p_T threshold was 12 GeV in 2015 which was raised to 17 GeV in 2016 for combined electron candidates. An asymmetric dimuon trigger with $p_T > 18, 8$ GeV was used in 2015 to improve the acceptance with respect to the standard dimuon triggers; the p_T threshold was raised to 22, 8 GeV in 2016. For the electron+muon triggers the p_T thresholds were 17 + 14 GeV in 2015 and 2016, and the electron was required to satisfy *loose* LH identification requirement. The p_T of the light leptons is required to be 1 GeV higher than the threshold of the lowest p_T trigger to ensure that the trigger is fully efficient.

In summary, events are selected by a logical **OR** combination of single-lepton and dilepton triggers which has improved the signal acceptance. The signal acceptance in $2\ell\text{SS}1\tau_{\text{had}}$ channel is as high as 11% using the SLT **OR** DLT combination with respect to using only single-lepton triggers, as shown in Table 5.6. Selected events belong to regions of the parameter space defined by the p_T of the two light leptons, as illustrated in Figure 5.11. The low p_T regions with only single-lepton triggers are excluded. The efficiency of this trigger requirement is within 82% to 99% for signal events passing the final $2\ell\text{SS}1\tau_{\text{had}}$ event selection (Table 5.7), depending on the 2015 or 2016 dataset.

5.9 Event selection and classification

Event selection

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, selected events are required to include exactly two light leptons with same-charge and exactly one hadronically decaying tau lepton. The reconstructed charge of the τ_{had} candidate must be opposite to that of the light leptons. The leptons are required to pass the *tight* selection as described in Table 5.4 and the τ_{had} candidate is required to pass the selection described in Section 5.6.3. The light leptons are also required to satisfy $p_T > 15$ GeV. Events must include at least four reconstructed jets and at least one of these jets must be *b*-tagged. In order to suppress the Z +jets

TABLE 5.5: Lowest unprescaled single-lepton and dilepton triggers used during the 2015 and 2016 data-taking. The online p_T threshold and the selection on the light lepton for each trigger is indicated. The offline p_T threshold is not listed but for each trigger it is 1 GeV higher than the online p_T threshold. Definitions of the abbreviations are given in the text.

Year	2015		2016	
Trigger	p_T threshold [GeV]	criteria	p_T threshold [GeV]	criteria
Single-lepton triggers				
Single-muon	20	<i>loose</i> isolation	26	<i>medium</i> isolation
	50	No	50	No
Single-electron	24	<i>medium</i> LH ID	26	<i>tight</i> LH ID AND <i>loose</i> isolation
	60	<i>medium</i> LH ID	60	<i>medium</i> LH ID
	120	<i>loose</i> LH ID	140	<i>loose</i> LH ID
Dilepton triggers				
Dimuon	18, 8	No	22, 8	No
Dielectron	2×12	<i>loose</i> LH ID	2×17	very <i>loose</i> LH ID
Electron+muon	17 + 14	<i>loose</i> LH ID	17 + 14	<i>loose</i> LH ID

TABLE 5.6: $t\bar{t}H$ signal acceptance for a logical OR combination of single-lepton and dilepton triggers with respect to single-lepton triggers in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The leptons are required to pass the *loose* selection (Table 5.4). The uncertainties are only statistical.

$t\bar{t}H$ signal acceptance ratio	ee	$e\mu, \mu e$	$\mu\mu$
(SLT OR DLT)/SLT	1.11 ± 0.11	1.10 ± 0.06	1.11 ± 0.10

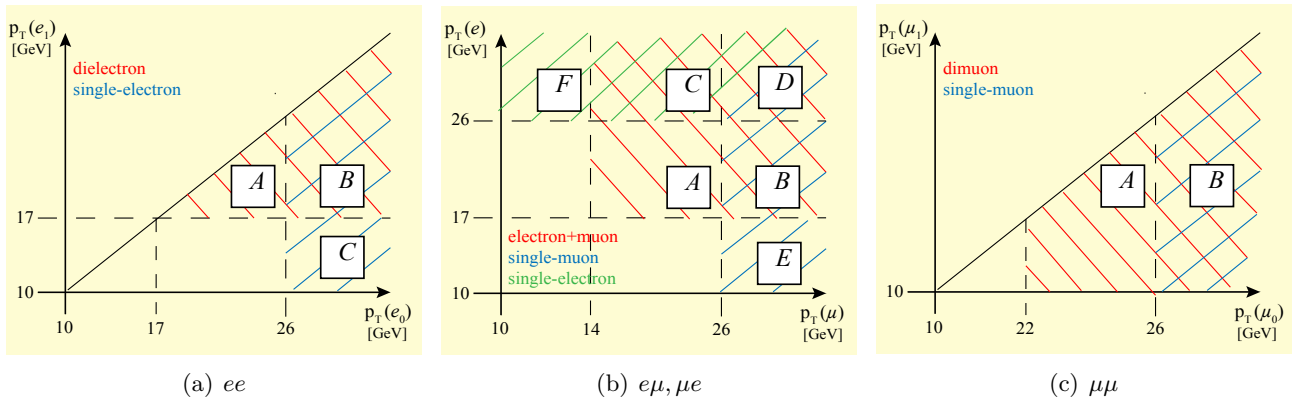


FIGURE 5.11: Acceptance parameter space defined by the p_T of the two light leptons. The dashed lines indicate the online p_T threshold for the single-lepton and dilepton triggers in 2016. A logical OR combination of single-lepton and dilepton triggers form the regions of the parameter space: (a, c) A, B and (b) A, B, C, D. (a) Region C and (b) regions E, F are excluded.

events with misidentified charge, events with dielectron invariant mass within 10 GeV of the Z mass are vetoed (Z -veto).

A logical OR combination of single-lepton and dilepton triggers is used to select the events, as described in Section 5.8. The reconstructed light leptons are required to be matched to the leptons selected by these triggers. Events are required to include at least one reconstructed vertex with at least two associated tracks with $p_T > 400$ MeV. The vertex with the highest sum of squared transverse momenta ($\sum p_T^2$) of the associated tracks is chosen as the primary vertex.

The full event selection is summarized in Table 5.7. This set of requirements targeting the $t\bar{t}H$ signal events is utilized to define the $2\ell\text{SS}1\tau_{\text{had}}$ signal region (SR).

TABLE 5.7: Selection criteria applied in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region.

$2\ell\text{SS}1\tau_{\text{had}}$ signal region
Two tight light leptons with $p_T > 15$ GeV
Same-charge light leptons ($\sum Q_\ell = \pm 2$)
Single-lepton OR dilepton triggers
Trigger matched lepton(s)
One medium τ_{had} candidate, with charge opposite to that of the light leptons ($Q_{\tau_{\text{had}}} \mp 1$)
$N_{\text{jets}} \geq 4$
$N_{b\text{-jets}} \geq 1$
$ m(ee) - 91.2 \text{ GeV} > 10 \text{ GeV}$ for ee events (Z -veto)

Event Classification

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the expected signal is much smaller compared to the total background. Both reducible and irreducible background events produce signatures similar to the $t\bar{t}H$ signal. A multivariate analysis (MVA) technique is used to discriminate signal from backgrounds. A typical MVA technique allows to combine the information from several input variables into one output discriminant.

Decision trees

A decision tree is a binary tree structured classifier. It recursively partition the parameter space into multiple regions that are eventually classified as signal or background. The MC data for signal and background is used in the training of a decision tree. The training is the process that defines the splitting criteria for each node in the tree. Each node split is determined by selecting the combination of input variables and cut threshold that provides the best separation between the signal and background. In principle, the splitting could continue until each node contains only signal or only background events resulting in a perfect discrimination. However, such a decision tree would be strongly overtrained. In order to avoid overtraining, one can optimize parameters such as number and size of the trees.

Boosted decision trees

In this analysis, a better separation between signal and background is achieved using the so-called boosted decision tree (BDT) [85–87]. Boosting is a process in which the misclassified training events (a signal event is misclassified as background or vice-versa) are reweighted (boosted), and a new tree is trained using the same input data. This procedure is then repeated for a new tree. The final discriminant (BDT output) is a weighted average of the decision tree classifications. This process stabilizes the statistical fluctuations in the training sample, improves the separation performance compared to a single decision tree, and it is less prone to overtraining. The boosting algorithm employed in the analysis is *GradientBoost* [86, 87]. After boosting, the final score (binary classification

signal or background) undergoes a transformation to map the scores on the interval -1 to $+1$ where the most background-like events have scores near -1 while the most signal-like events have scores near $+1$. The BDT output is binned in a histogram from -1 to $+1$. The Toolkit for Multivariate Data Analysis (TMVA) [156] is used for the training and evaluation of the BDT response. The parameters used for the BDT training are shown in Table 5.8.

A BDT is trained using 13 variables to separate the $t\bar{t}H$ signal from the backgrounds, mainly from the dominant $t\bar{t}$ background. The nominal signal and background MC samples, described in Section 5.5, are used for the training. In order to increase the statistics for the training, events with relaxed selection requirements are used. In this relaxed selection, the light leptons are required to pass the *loose* selection instead of *tight*, the requirement on the number of jets is reduced to 2, and the charge requirement on the τ_{had} candidate is not applied. Moreover, events with charge misidentified electrons (mainly from $t\bar{t}$ process) are also not considered. Table 5.9 summarizes the number of events after passing the relaxed selection for the signal and background samples used for the BDT training. A large set of potential variables are investigated and only those variables which lead to an improved BDT performance are used in the analysis. The definition of the BDT input variables is as follows:

- H_T^{jet} : Scalar sum of the p_T of all jets.
- N_{jets} : Number of jets.
- $b\text{-tag weight (jet}_3\text{)}$: b -tagging weight of third leading jet. Events with only two jets are given weight of -1 .
- $p_T^{\text{varcone}}/p_T(\ell_1)$: Subleading lepton track isolation variable divided by p_T .
- $\eta(\text{jet}_4)$: Pseudorapidity of fourth leading jet. Events with 2 or 3 jets are given value of -3 .
- $p_T(\text{jet}_2)$: Transverse momentum of second leading jet.
- $N_{b\text{-jets}}$: Number of b -tagged jets.
- $p_T(\ell_1)$: Transverse momentum of subleading lepton.
- $\Delta R(\ell_0, \text{jet})$: Distance between leading lepton and its closest jet.
- $\Delta R(\text{jet}, \text{jet})$: Distance between two leading jets.
- $\text{Max } |\eta|(\ell_0, \ell_1)$: Maximum of absolute pseudorapidity of leading and subleading leptons.
- $m_{\tau_{\text{had}}\ell}$: Invariant mass of τ_{had} - furthest lepton.
- $b\text{-tag weight (jet}_2\text{)}$: b -tagging weight of second leading jet.

The variables in the list are ranked from top to bottom according to their signal-to-background separation power. The separation power of a variable is related to the non-overlapping area of the normalized distributions and is defined as

$$\langle S^2 \rangle = \frac{1}{2} \sum_{i=1}^{N_{\text{bins}}} \frac{(N_i^s - N_i^b)^2}{N_i^s + N_i^b}, \quad (5.1)$$

where N_i^s and N_i^b are the number of events in bin i of the normalized signal and background histograms, respectively. The separation is zero for the signal and background distributions with complete overlapping and it is one for distributions with no overlap. The variables H_T^{jet} and N_{jets} are the ones with the highest separation power, which is expected as the number of jets in the $t\bar{t}H$ signal is higher with respect to the $t\bar{t}$ background. No significant improvement in the performance of the BDT is found by adding more variables. Figure 5.12 shows the signal and total background distributions of the 13

TABLE 5.8: Details of the BDT settings. In order to obtain better stability with low statistics, the number of trees are reduced with respect to the default settings.

Parameter	Value	Description
N_{trees}	500	Number of trees in the BDT
Minimum node size	2.5%	Minimum percentage of events allowed in a node size
Maximum depth	2	Maximum depth of the decision tree allowed
Shrinkage	1	Learning rate for the <i>GradientBoost</i> algorithm
Number of cuts	20	Number of points in variable range used in finding the optimal cut in node splitting

TABLE 5.9: Number of raw and weighted events after passing the relaxed selection for the signal and background samples used for the BDT training. Rare processes tZ , tW , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tH , triboson production and rare top decay are labeled as “Other”. Weighted events correspond to the number of raw events rescaled by the product of correction factors on reconstruction, identification and trigger efficiencies times the ratio of integrated luminosity of the data and the generated samples. The uncertainties are only statistical.

Sample	Number of events	
	Raw	Weighted
$t\bar{t}H$	14333	10.94 ± 0.31
$t\bar{t}W$	3302	9.62 ± 0.30
$t\bar{t}Z$	6128	8.77 ± 0.34
Diboson	125	5.09 ± 1.21
$t\bar{t}$	2457	670.96 ± 16.73
$t\bar{t}\gamma$	29	11.48 ± 2.63
Single-top, tW	83	18.71 ± 2.26
Other	3467	12.05 ± 0.95
$V + \text{jets}$	275	22.92 ± 3.12

input variables used in the BDT training. The separation power of each variable is also indicated. The variables which are highly correlated and with the lowest separation power are not considered for the training. Figure 5.13 shows the linear correlation coefficients of the BDT input variables for signal and background. Several high correlation coefficients between variables are observed. The largest correlation is found between H_T^{jet} and $p_T(\text{jet}_2)$ variables, which is expected since H_T^{jet} is the sum of the p_T of all jets. However, such correlations do not influence the training because of the decorrelation step is performed by a preprocessing transformation as implemented in TMVA. Moreover, the differences between the correlations are found to be consistent between the signal and background. The BDT input variables used in the training are required to be well modeled by the MC simulation. Thus, the variables are validated in the control region enriched with $t\bar{t}$ background by comparing their distributions in data and simulation, as described in detail in Section 5.11.2.

Furthermore, the training of the BDT is tested on the independent sample of the same signal and background processes. Each signal and background sample is divided into 2 subsets with even and odd events based on the `EventNumber` modulo 2. The `EventNumber` is a unique number associated to each simulated event in the MC sample. The BDT is trained on even events and tested on odd events and vice-versa. Thus, the testing of the BDT is two-fold cross-validation. In an ideal case, the BDT response distribution should be the same in both the training and testing case. Figure 5.14 (a) shows the BDT response distribution (including both even and odd events). A good agreement is observed between the shape of training and testing samples, which indicates the absence of overtraining. Figure 5.14 (b) shows the receiver operating characteristic (ROC) curve of the combined training and testing samples obtained by plotting the background rejection $1 - \varepsilon_b$ as a function of the signal efficiency ε_s . The area under the ROC curve is a measure of the performance of the BDT classifier. The larger the area under the curve, the higher the probability of the BDT classifier to correctly assign a signal or background event. A good classification performance is achieved for both training and testing subsets with even and odd events.

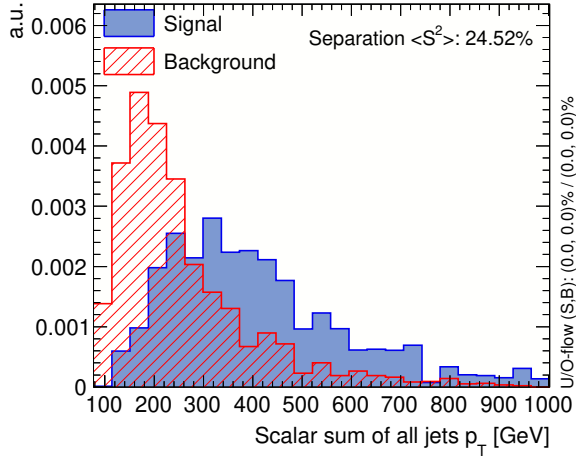
Finally, the application of the BDT is performed in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region using the event selection described in Table 5.7. The resulting BDT output distribution is used as a final discriminant in a likelihood fit to the observed data in order to extract the $t\bar{t}H$ signal strength parameter $\mu_{t\bar{t}H}$, as described in Section 6.2. In the application phase of the BDT, events with more than six jets are treated as if $N_{\text{jets}} = 6$ and events with more than two b -tagged jets are treated as if $N_{b\text{-jets}} = 2$. The number of jets is limited because the signal events are simulated at NLO accuracy and to ensure that the separation power does not come from the soft jets which are not modeled correctly by the simulation.

5.10 Cut-based analysis

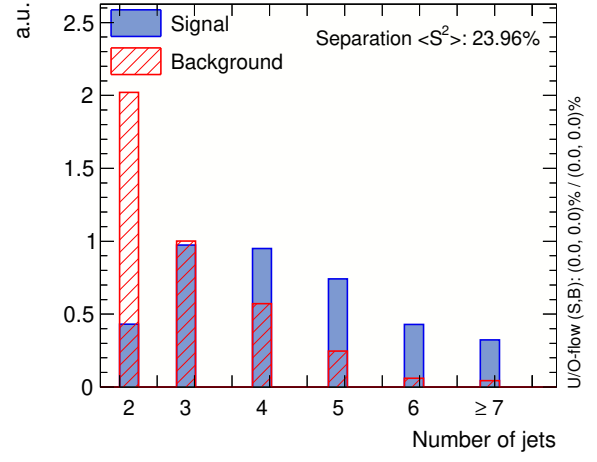
A cut-based approach is used as a cross-check to the BDT analysis, where requirements on kinematic variables are applied. In the cut-based analysis, a simple cut-and-count categorization is developed based on two discriminating variables. The signal region for the cut-based analysis is identical to that of the BDT analysis (Table 5.7), in addition the requirements on the maximum $|\eta|$ of the two light leptons and p_T of the subleading jet are applied. Three categories with different signal-to-background ratios are defined as:

- Max. $|\eta|(\ell_0, \ell_1) > 1.5$ AND $p_T(\text{jet}_2) > 70$ GeV (Cat. 1).
- Max. $|\eta|(\ell_0, \ell_1) < 1.5$ AND $p_T(\text{jet}_2) > 70$ GeV (Cat. 2).
- Max. $|\eta|(\ell_0, \ell_1) < 1.5$ AND $p_T(\text{jet}_2) < 70$ GeV (Cat. 3).

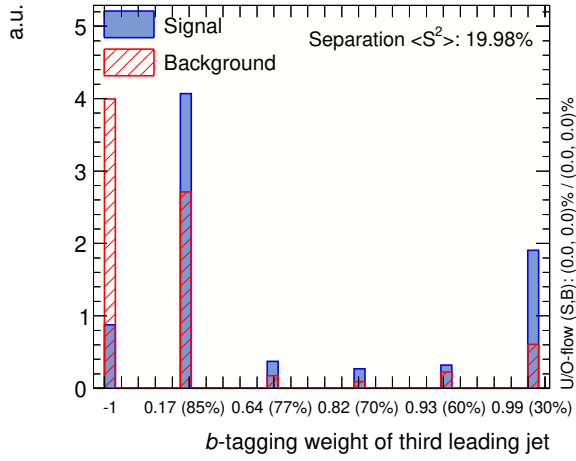
Events with maximum $|\eta| > 1.5$ and subleading jet $p_T < 70$ GeV are not used as a separate category because of the very low signal-to-background ratio. The expected sensitivity ($S/\sqrt{B}$) of the cut-based analysis obtained is about 18% lower than the multivariate analysis. The final results are derived from the combined fit to the observed data of all three categories, as described in Section 6.2.1.



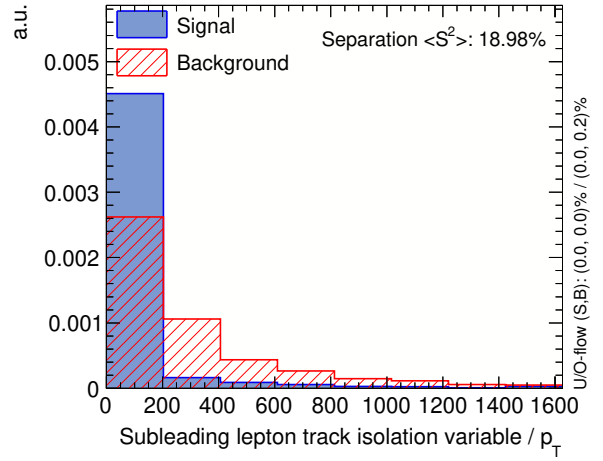
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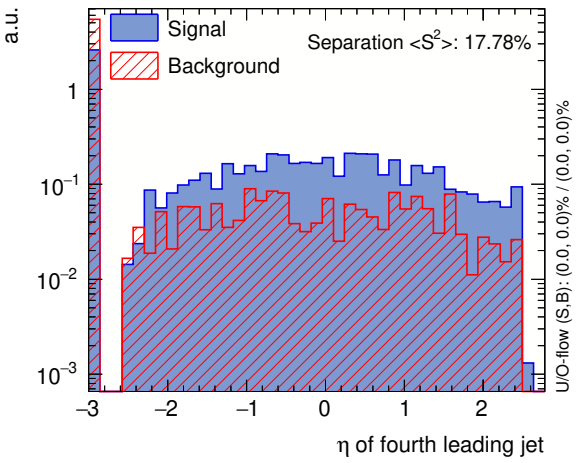
(b)



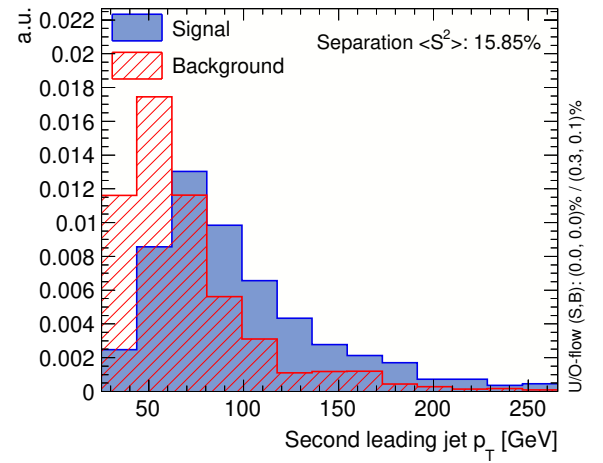
(c)



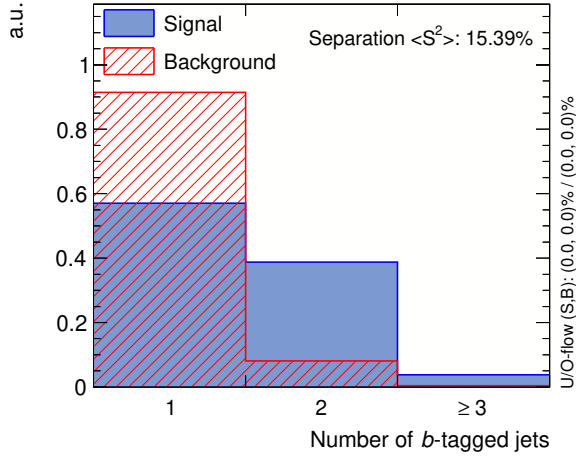
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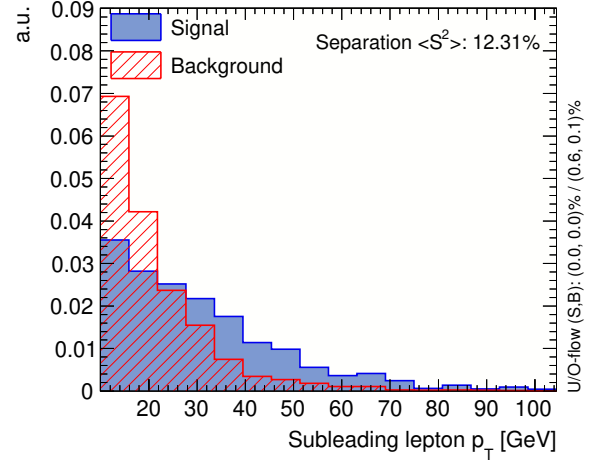
(e)



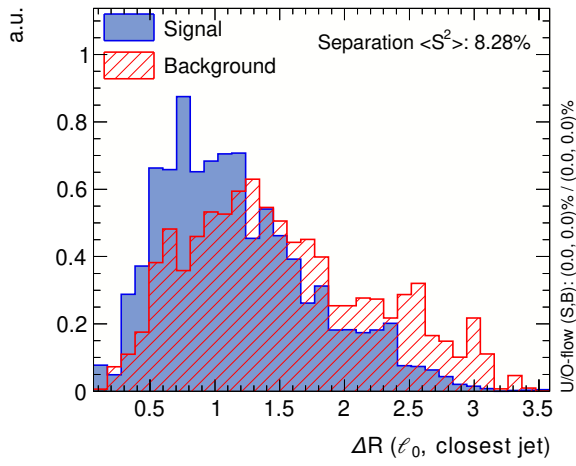
(f)



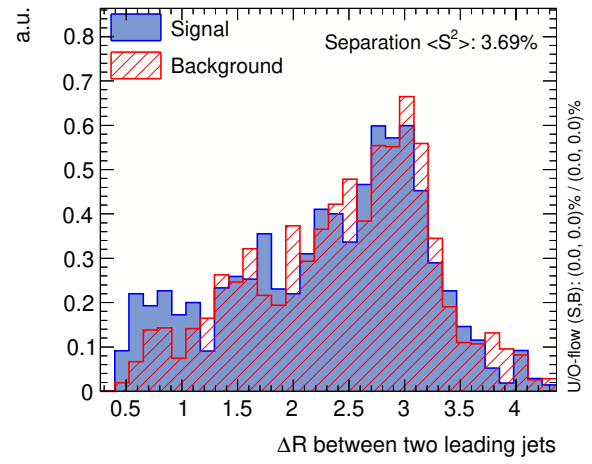
(g)



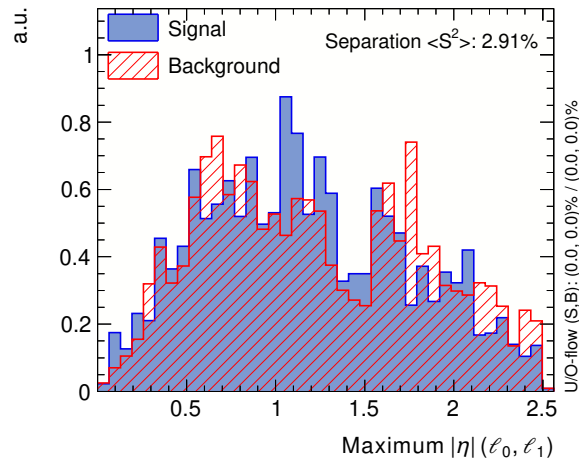
(h)



(i)



(j)



(k)

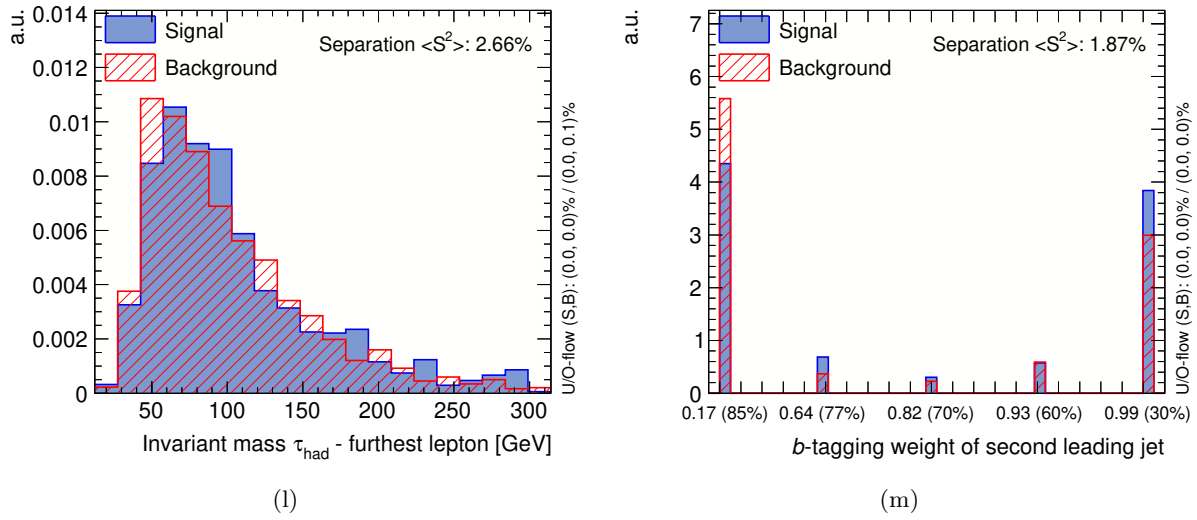


FIGURE 5.12: Signal (blue) and background (red) distributions of all the 13 variables, ordered by their BDT rankings, used for the BDT training in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The distributions are normalized to unity. The value of the separation power $\langle S^2 \rangle$ is also indicated. In (c) and (m), the numbers in parenthesis are the efficiencies of the working points. The vertical text on the right-hand side of the plots indicates the under- and over-flow.

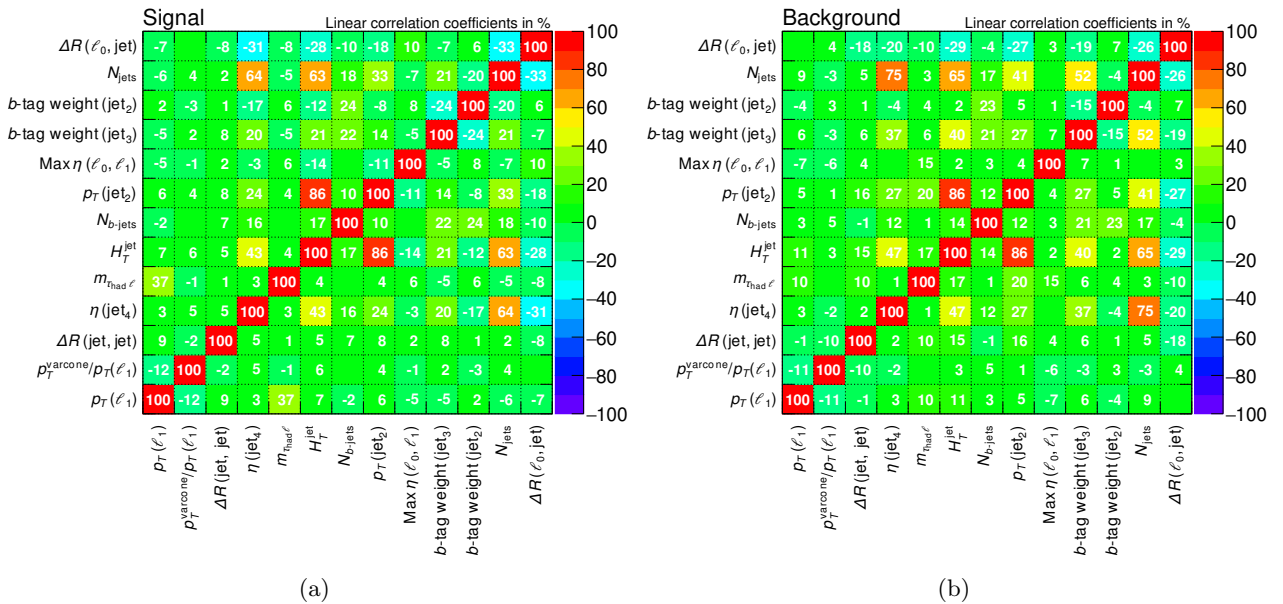


FIGURE 5.13: Linear correlations coefficients among the BDT input variables for (a) signal and (b) background training samples. Details are given in the text.

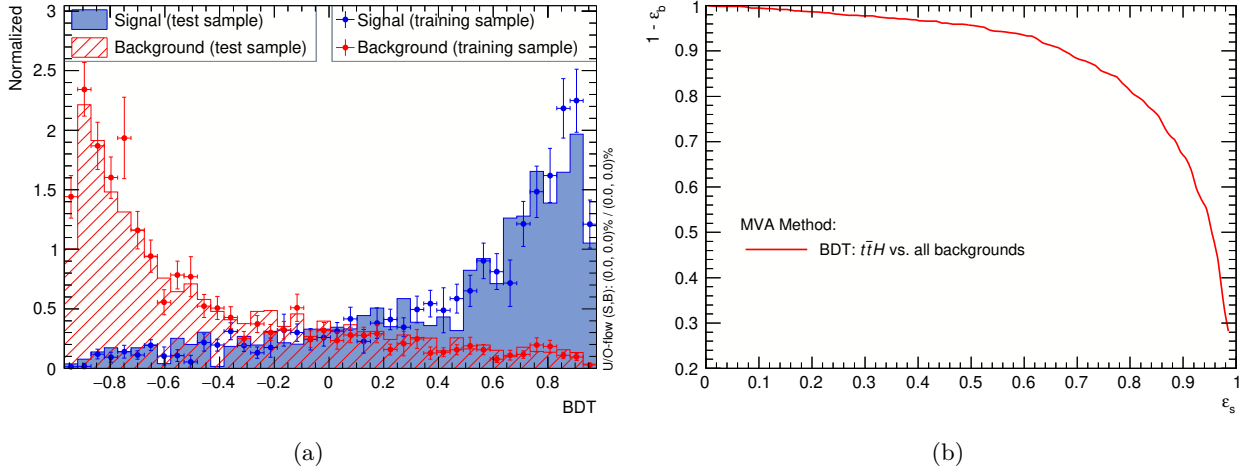


FIGURE 5.14: Distribution of the BDT response function for training and testing samples with even and odd events and their corresponding ROC curve showing the background rejection versus signal efficiency.

5.11 Background estimation

An overview of the irreducible and the reducible backgrounds is given in Section 5.4. The irreducible backgrounds are estimated using the MC simulated samples. Dedicated validation regions enriched in these backgrounds are used to verify the modeling of data by simulation. Data-driven methods are used for the estimation of reducible backgrounds. A detailed discussion of the estimation of the various background components is given in the following.

5.11.1 Validation of irreducible background

The dominant irreducible backgrounds in this analysis are $t\bar{t}W$ and $t\bar{t}Z$. The modeling of these backgrounds is an essential part of the analysis since their final state and kinematics are very similar to the signal. The modeling of the data by simulation is validated in regions that are defined to enhance the contributions from these processes and with small or negligible signal contamination. Other subleading backgrounds, including diboson, tZ , tW , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tH , triboson and rare top decay, are also modeled using MC simulation. The systematic uncertainties in the modeling of the background processes by the simulation are discussed in Section 5.12. The dilepton and trilepton validation regions are defined in order to verify the prediction of the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds from simulation. In these validation regions, the contributions from backgrounds with fake light leptons are estimated and modeled via a Matrix Method, as detailed in Ref. [21]. Moreover, a validation region including τ_{had} candidate cannot be defined with sufficient purity in $t\bar{t}W$ and $t\bar{t}Z$ processes due to the limited statistical power. Therefore, the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds cannot be validated in the region that includes a τ_{had} candidate.

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the fake τ_{had} candidates can arise from the irreducible backgrounds, mainly arising from $t\bar{t}V$ ($V = W, Z$), which are not precisely modeled by the simulation. In this case, a scale factor is applied to correct the simulation of the fake τ_{had} candidates in order to better describe the data. The scale factor is derived in the $2\ell\text{OS}1\tau_{\text{had}}$ channel, as described in Section 5.11.3.

$t\bar{t}V$ background modeling

A validation region (VR) is defined using the 2ℓ SS lepton selection to test the modeling of the $t\bar{t}W$ process. Selected events in this region are required to include two tight light leptons with positive charge and with $p_T > 30$ GeV. The presence of exactly four reconstructed jets of which exactly two jets must be b -tagged is required as well. The scalar sum of the transverse momentum of all jets, H_T , is required to be above 220 GeV for events with dielectron and opposite-flavor (OF) $e\mu$, μe leptons. For ee events the dilepton invariant mass must not be in the range 75-105 GeV; in addition the missing energy E_T^{miss} must be above 50 GeV. The event selection in this cut-based $t\bar{t}W$ VR is summarized in Table 5.10. The purity obtained for $t\bar{t}W$ is about 45%. Figure 5.15 shows the distributions of the number of electrons and the invariant mass of the light lepton pair $m_{\ell_0\ell_1}$. A good agreement is found between data and prediction.

A cut-based validation region for $t\bar{t}Z$ is defined using the 3ℓ lepton selection as summarized in Table 5.10. Selected events in this region are required to include three light leptons with a total charge of ± 1 . The light leptons with same-charge are required to pass the *tight* selection of Table 5.4 and to satisfy $p_T > 15$ GeV. The lepton (ℓ_0) with opposite-charge to the other two is required to be loose, isolated and to pass the non-prompt lepton BDT requirement, because for a $t\bar{t}$ event it is likely to be prompt originating from a W boson decay. The same-charge leptons (ℓ_1 and ℓ_2) are ordered in ΔR , ℓ_1 is the closest in ΔR to ℓ_0 and ℓ_2 is the furthest one. Events must include at least four reconstructed jets and at least two of these jets must be b -tagged. The presence of at least one pair of same-flavor opposite-charge leptons with an invariant mass within 10 GeV of the Z mass is required. In order to suppress background from resonances that decay to light leptons, all same-flavor opposite-charge lepton pairs in the event must satisfy $m(\ell^+\ell^-) > 12$ GeV. The purity of the $t\bar{t}Z$ background achieved in this VR is about 85%. Figure 5.15 shows the distributions of the number of electrons, the invariant mass $m_{\ell_0\ell_1}$, and the number of jets. A good agreement of data with prediction is observed within the total uncertainties on the background prediction.

Furthermore, the modeling of the $t\bar{t}W$ and $t\bar{t}Z$ processes is also tested in the 3ℓ control regions (CR). The selection is similar to the $t\bar{t}Z$ validation region as described above, except that events containing an opposite-charge same-flavor lepton pair with an invariant mass within 10 GeV of the Z mass are vetoed (Z -veto). The jet selection is loosened by requiring at least two jets of which at least one must be b -tagged. In addition, the three-lepton invariant mass must satisfy $|m(3\ell) - 91.2 \text{ GeV}| > 10 \text{ GeV}$ in order to eliminate potential backgrounds with Z decays to $\ell\ell\gamma^{(*)} \rightarrow \ell\ell\ell'(\ell')$, where one lepton has very low momentum and is not reconstructed. The corresponding selection is also summarized in Table 5.10. Selected events are classified using a five-dimensional multinomial boosted decision tree. The five classification targets used in the training are: $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$ and diboson. The input variables used in the training are detailed in Ref. [21]. After the training, five output scores are obtained corresponding to the target signal and background processes. The output discriminants are mapped into the five categories by using a variable multidimensional binning procedure [157]. The categories with the highest purity for the $t\bar{t}W$ and $t\bar{t}Z$ processes are called the 3ℓ $t\bar{t}W$ and $t\bar{t}Z$ control regions. The purity achieved is 38% and 68% for the $t\bar{t}W$ and $t\bar{t}Z$, respectively. The number of jets, the number of electrons, and the invariant mass $m_{\ell_0\ell_1}$ distributions are shown in Figure 5.16. They show agreement between data and prediction in both regions.

The signal contamination is less than 5% in all the regions, except in the 3ℓ $t\bar{t}W$ CR where it is about 8%. A good agreement is seen between data and prediction in the validation and control regions, therefore no corrections are applied to the $t\bar{t}W$ and $t\bar{t}Z$ simulated samples.

5.11.2 Reducible background estimation

The reducible backgrounds involving the fake light leptons and fake τ_{had} candidates are estimated using data-driven methods. The strategies used to estimate these backgrounds in the 2ℓ SS1 τ_{had} channel are motivated by the specific event topology and the statistical power available in the control regions.

TABLE 5.10: Summary of the event selection in the cut-based validation regions (top) and in the BDT-based 3ℓ control regions (bottom). The tight light lepton selection follows the definition in Table 5.4. Same-flavor opposite-charge lepton pairs are referred to as SFOC pairs.

Validation region	Purity	Selection criteria
$t\bar{t}W$	45%	Two tight light leptons with $p_T > 30$ GeV Light leptons with positive charge ($\sum Q_\ell = +2$) Zero medium τ_{had} candidates $N_{\text{jets}} = 4$ and $N_{b\text{-jets}} = 2$ $H_T^{\text{jet}} > 220$ GeV for ee and OF events $E_T^{\text{miss}} > 50$ GeV and $m(ee) < 75$ GeV or $m(ee) > 105$ GeV for ee events
$t\bar{t}Z$	85%	Three light leptons with total charge of ± 1 Opposite-charge lepton must be loose, and with $p_T > 10$ GeV Same-charge leptons must be tight, and with $p_T > 15$ GeV Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ & $N_{b\text{-jets}} \geq 2$ At least one SFOC pair with $ m(\ell^+\ell^-) - 91.2 \text{ GeV} < 10$ GeV $m(\ell^+\ell^-) > 12$ for all SFOC pairs
3 ℓ Control region		
$t\bar{t}W$ ($t\bar{t}Z$)	38% (68%)	Three light leptons with total charge of ± 1 Opposite-charge lepton must be loose, and with $p_T > 10$ GeV Same-charge leptons must be tight, and with $p_T > 15$ GeV Zero medium τ_{had} candidates $N_{\text{jets}} \geq 2$ & $N_{b\text{-jets}} \geq 1$ $m(\ell^+\ell^-) > 12$ and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10$ GeV for all SFOC pairs $ m(3\ell) - 91.2 \text{ GeV} > 10$ GeV

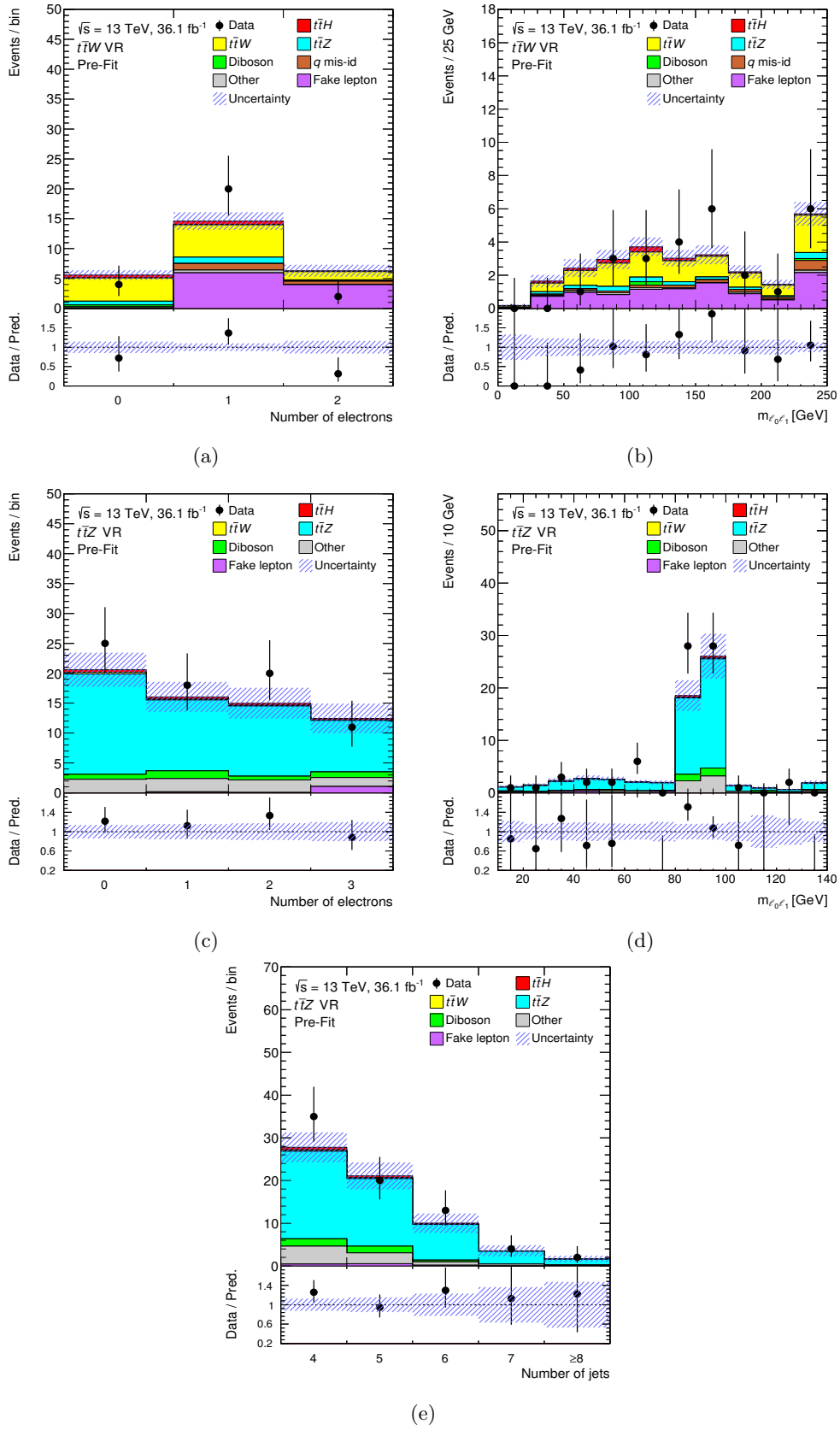


FIGURE 5.15: Distributions of (a) the number of electrons and (b) the invariant mass $m_{\ell_0 \ell_1}$ in the cut-based ttW validation region. The distributions of (c) the number of electrons, (d) the invariant mass $m_{\ell_0 \ell_1}$, and (e) the number of jets in the cut-based ttZ validation region. The hatched band represents both the statistical and systematic uncertainties (Section 5.12).

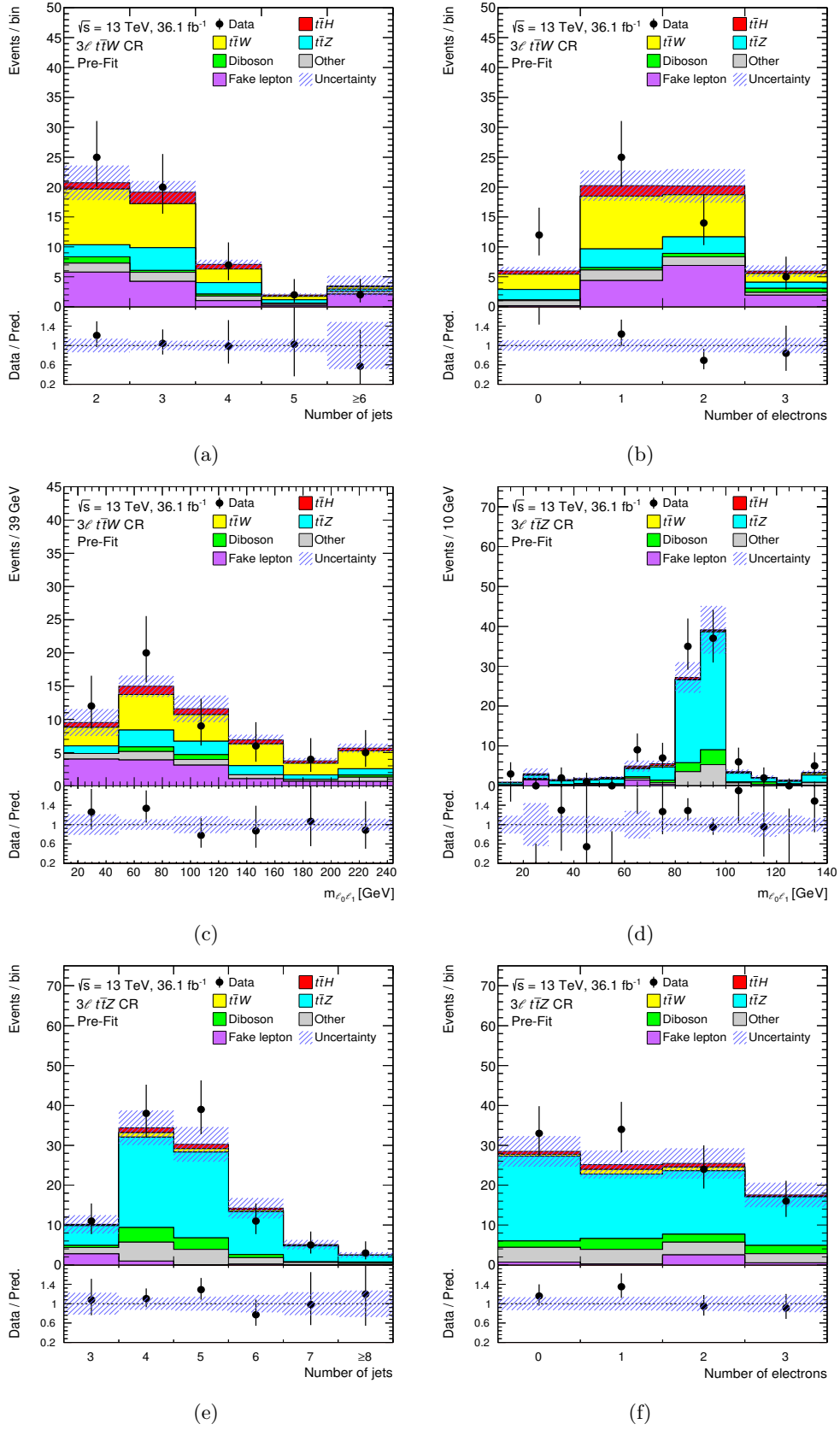


FIGURE 5.16: Distributions of the number of jets, the number of electrons, and the invariant mass $m_{\ell_0\ell_1}$ in the BDT-based $3\ell t\bar{t}W$ (a, b, c) and $t\bar{t}Z$ (d, e, f) control regions. The hatched band represents both the statistical and systematic uncertainties (Section 5.12).

Charge misidentification background

The contribution of the charge misidentification background to the $2\ell SS 1\tau_{\text{had}}$ signal region as well as control regions is estimated using data-driven technique by measuring the probability that the electron charge⁵ is misreconstructed. When a true event with an opposite-charge (OS) electron pair such as $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow be^+\nu_e\bar{b}e^-\bar{\nu}_e$ is produced, assuming ϵ is the rate of charge misidentification for an electron, there are three possibilities for this event to be reconstructed:

- $e^+e^- + X$ without any charge misidentified electron, with a probability of $(1 - \epsilon_i) \cdot (1 - \epsilon_j)$,
- $e^+e^- + X$ with two charge misidentified electron, with a probability of $\epsilon_i \cdot \epsilon_j$,
- $e^\pm e^\pm + X$ with only one of the two electrons is charge misidentified, with a probability of $\epsilon_i \times (1 - \epsilon_j) + (1 - \epsilon_i) \cdot \epsilon_j$,

where ϵ_i and ϵ_j are the charge misidentification rates for the two electrons in the event.

For given N true events with electrons of opposite-sign charge, the number of reconstructed events with electrons of same-sign and opposite-sign charges will be:

$$\begin{aligned} N^{SS} &= \epsilon_i \cdot (1 - \epsilon_j) + (1 - \epsilon_i) \cdot \epsilon_j = (\epsilon_i + \epsilon_j - 2\epsilon_i\epsilon_j)N. \\ N^{OS} &= (1 - \epsilon_i) \cdot (1 - \epsilon_j) + (\epsilon_i \cdot \epsilon_j) = (1 - \epsilon_i - \epsilon_j + 2\epsilon_i\epsilon_j)N. \end{aligned}$$

If the charge misidentification rate ϵ is known, it is possible to compute the estimated number of same-sign events N^{SS} passing a given selection from the measured number of opposite-sign events N^{OS} passing the same selection requirements for the ee and OF $e\mu$, μe events, respectively:

$$\begin{aligned} N_{ee}^{SS} &= \frac{\epsilon_i + \epsilon_j - 2\epsilon_i\epsilon_j}{1 - \epsilon_i - \epsilon_j + 2\epsilon_i\epsilon_j} N_{ee}^{OS}. \\ N_{ee}^{SS} &= w_{ee}^{q \text{ mis-id}} \cdot N_{ee}^{OS}. \\ N_{OF}^{SS} &= \frac{\epsilon}{1 - \epsilon} N_{OF}^{OS}. \\ N_{OF}^{SS} &= w_{OF}^{q \text{ mis-id}} \cdot N_{OF}^{OS}. \end{aligned} \tag{5.2}$$

The electron charge misidentification rate is measured using a likelihood fit in a data sample of $Z \rightarrow ee$ events with same-charge and opposite-charge electron pairs around the Z -peak. The rate is measured as a function of the electron $|\eta|$ and p_T , where six bins in $|\eta|$ and four bins in p_T are used. The bins are chosen based on the size of the event sample and the variation of the rate with $|\eta|$ and p_T . The background contribution is subtracted using a simple sideband method [21]. The charge misidentification measurement is validated by a closure test in $Z \rightarrow ee$ simulated events, by comparing the rates obtained from the likelihood fit to the MC predicted rates. The observed difference between measured and predicted rates is taken as the systematic uncertainty.

An additional validation is performed in data by comparing the measured number of same-charge events to the estimated number of same-charge events by scaling the opposite-charge events by the rates. The results are found to agree within uncertainties. Additional systematic uncertainties include the statistical uncertainty from the data and the variation in the rates when the Z -peak range definition is varied. The total systematic uncertainty in the charge misidentification rate is about 30% [21], with the dominant contribution at low p_T from the closure tests and at high p_T from the statistical uncertainty. Figure 5.17 shows the charge misidentification rates for electrons passing the *tight* selection of Table 5.4 measured in data as a function of $|\eta|$ for four different p_T ranges. The rate varies from $5 \cdot 10^{-5}$ for low- p_T electrons at small $|\eta|$ to 10^{-2} for high- p_T electrons ($p_T \gtrsim 100$ GeV)

⁵ In the following description both electrons and positrons are called electrons.

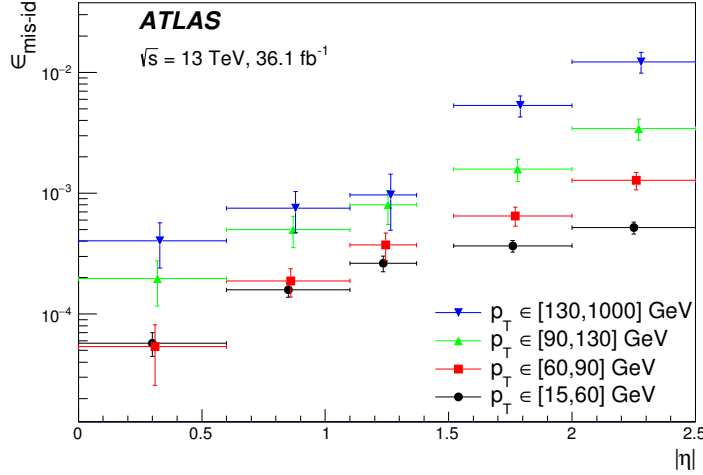


FIGURE 5.17: Charge misidentification rates as a function of $|\eta|$ for four different p_T ranges and for electrons passing the *tight* selection. The error bars include both the statistical and systematic uncertainties [158].

with $|\eta| > 2$. The strong dependence of rates on $|\eta|$ is expected because the fraction of trident events depends on the amount of material the electron traverse and that the distribution of detector material depends on $|\eta|$.

The charge misidentification background events in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region are estimated by multiplying the factor, $w^q_{\text{mis-id}}$, with the number of events in data passing the SR selection (Table 5.7), except that the light leptons are required to be opposite-charge and no charge requirement on the τ_{had} candidate is applied. The factor $w^q_{\text{mis-id}}$ according to equation 5.2 depends on the measured charge misidentification rates. Moreover, this factor is divided by two before multiplying with the number of opposite-charge events. The probability is the same for both the electron of same- and opposite-sign charge to that of τ_{had} candidate to be reconstructed with wrong charge. The total uncertainty in the charge misidentification background prediction in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region is 38%.

Non-prompt light leptons and photon conversion background

Background with non-prompt light leptons and photon conversion, mainly arising from $t\bar{t}$ and $t\bar{t}\gamma$ processes, is estimated from data. The estimation of the fake light leptons⁶ background is performed using the *fake-factor* method (FF).

The Fake Factor method

The fake-factor method is a data-driven technique used to estimate both the normalization and shape of the backgrounds with the fake light leptons. It uses a data sample of events enriched in fake light leptons in regions orthogonal to the signal region to estimate the fake light lepton background contribution in the signal region. The method accounts for the backgrounds with either one or more fake light leptons. The underlying procedure of the fake-factor method is as follows.

First, an *anti-tight* selection is defined by inverting the identification and the isolation variables of the light lepton. The *anti-tight* selection is orthogonal to the *tight* selection⁷ and the light lepton

⁶ The term fake light leptons will hereafter be referred only to non-prompt light leptons and photon conversion. In figures, the same term is labeled as “Fake lepton”.

⁷ The *tight* and *anti-tight* selections are sometimes referred to as “numerator” and “denominator” selections, respectively, in the fake-factor method.

which pass this selection is referred to as anti-tight light lepton. A fake factor is calculated using the *tight* and *anti-tight* selections in the regions, referred to as “fake factor regions”, enriched in the fake light leptons with similar kinematics and composition to those in the signal region where the background is being estimated. The fake factor represents the probability of a fake light lepton to satisfy the *tight* selection and be identified as a signal lepton, and it is defined as

$$f_\ell = \frac{N_\ell}{N_{\bar{\ell}}}, \quad (5.3)$$

where N_ℓ and $N_{\bar{\ell}}$ are the numbers of events with light leptons passing the *tight* and *anti-tight* selection, respectively. The fake factor can depend on the light lepton kinematics such as p_T , and the additional activity in the event. In this case, the fake factor is calculated as a function of the fake light lepton p_T

$$f_\ell(i) = \frac{N_\ell(i)}{N_{\bar{\ell}}(i)}, \quad (5.4)$$

where i refers to the i^{th} p_T bin.

The fake factor is applied to the events in a control region defined by a selection similar to the signal region, except that the light lepton is required to pass the anti-tight selection. The fake light lepton background estimate in the signal region is

$$N_{SR}^{\text{fake}} = \sum_i f_\ell(i) \times N_{\bar{\ell}}^{CR}(i), \quad (5.5)$$

where N_{SR}^{fake} is the estimated number of events with fake light leptons in the signal region, and the sum is over i p_T bins of the fake factor.

Estimation strategy in the $2\ell\text{SS}1\tau_{\text{had}}$ channel

In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, sideband control regions (B, C, D) are defined in a two-dimensional plane using the two variables, the number of jets (N_{jets}) and the number of light leptons passing the *anti-tight* selection ($\bar{\ell}$), to estimate the fake light lepton background contributions. A schematic representation of the control regions used in the fake-factor method is shown in Figure 5.18.

The regions C and D are the low jet multiplicity regions $2 \leq N_{\text{jets}} \leq 3$, while region B has the same jet selection as the signal region (A). Region C is required to include exactly two tight light leptons, and region D requires the presence of one tight and one anti-tight light lepton. Moreover, the requirement of zero τ_{had} in addition to one τ_{had} candidate is applied in regions C and D in order to increase the statistics, since the composition of the fake light leptons is similar in the $2\ell\text{SS}0\tau_{\text{had}}$ and $2\ell\text{SS}1\tau_{\text{had}}$ channels. The full definition of these control regions is summarized in Table 5.12. These regions are enriched in fake light leptons and are used to measure the fake factors in data separately for electrons and muons. The fake factor is defined as the ratio of the number of events with two tight light leptons (N_{TT}) to the number of events with one tight and one anti-tight light lepton, and it is determined as a function of the fake light lepton p_T as

$$f_\ell(i) = \frac{N_{TT}^C(i)}{N_{T\bar{T}}^D(i)}, \quad (5.6)$$

where N_{TT}^C and $N_{T\bar{T}}^D$ ⁸ are the number of events in regions C and D, respectively, and i refers to the i^{th} p_T bin. The contributions of charge misidentification background and the backgrounds with prompt light leptons are subtracted from N_{TT}^C and $N_{T\bar{T}}^D$. The fake factors are calculated in bins of the fake

⁸ The events with anti-tight leading light lepton ($N_{T\bar{T}}^D$) are also considered for brevity only the symbol $N_{T\bar{T}}^D$ is used in the text and equation 5.6. The same applies to region B as well in equation 5.7.

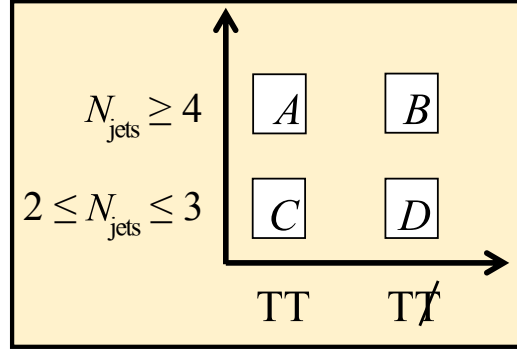


FIGURE 5.18: Schematic representation of the regions used in the fake-factor method. The fake factor f_ℓ is derived from the “fake factor regions” C and D. This fake factor is then applied to the region B to estimate the fake light lepton background in the signal region A. T ($\bar{T}$) represents the tight (anti-tight) light lepton. All the control regions are orthogonal to the signal region.

light lepton p_T because of the small dataset used in the analysis. With more data, fake factor can be characterized in bins of p_T and η . Nevertheless, the fake factor is found to be stable with respect to the η of the fake light lepton.

The region B is required to satisfy the same event selection as the signal region (Table 5.7) but with one tight and one anti-tight light lepton. Region B is also enriched in fake light leptons. The fake factors are applied to the events in region B event-by-event as a global event weight to estimate the fake light lepton background in the signal region. The final number of events with fake light leptons in the signal region is estimated as

$$N_A^{\text{fake}} = \sum_i f_\ell(i) \times N_{T\bar{T}}^B(i), \quad (5.7)$$

where $N_{T\bar{T}}^B$ is the number of events in region B, and the sum is over i p_T bins of the light lepton fake factor⁹. The contribution of the backgrounds with prompt light leptons is subtracted¹⁰ from $N_{T\bar{T}}^B$. In the case of opposite-flavor $e\mu$, μe leptons, both the pair of tight electron and anti-tight muon ($e\bar{\mu}$) and the pair of tight muon and anti-tight electron ($\mu\bar{e}$) are considered separately. Furthermore, the fake τ_{had} candidates which arise from the $t\bar{t}$ process, as described in Section 5.4.2, are not accounted for separately as it is assumed that the fraction of real and fake τ_{had} candidates is similar in the signal and the extrapolation region B. Thus, the estimated number of events with fake light leptons in the signal region A, N_A^{fake} , also include events with both fake light lepton and fake τ_{had} candidates.

The fake-factor procedure is validated by checking that it correctly reproduces the signal region event yield and the shape expected in $t\bar{t}$ simulation, as detailed in the following.

Assumptions of the method

In order for the fake-factor procedure to work in the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the following assumptions are made:

- The sources of the fake light leptons have the same composition in the signal region and the control regions.

⁹ In practice, the p_T of the anti-tight lepton in the event in region B is used to select the corresponding p_T bin of the light lepton fake factor.

¹⁰ Due to event-by-event application of the fake factors, the subtraction is done only at the end.

- The backgrounds with prompt light leptons from different processes are known and that their modeling by MC simulation is reliable, as the contribution of these backgrounds is subtracted from the control regions.
- The major source of fake light leptons is the non-prompt light leptons from the $t\bar{t}$ process, or that the fake light leptons from different sources have the same fake factor.
- The fake factor is stable with respect to the jet multiplicity.
- The fraction of real and fake τ_{had} candidates is similar in the signal region and the extrapolation region B.
- The ratio of the number of events in the signal region and the control regions fulfill: $\frac{N_A}{N_B} = \frac{N_C}{N_D}$.

Several studies are carried out to validate these assumptions and will be discussed in detail in the following. The modeling of the backgrounds with prompt light leptons is already discussed in Section 5.11.1.

Composition of the fake light leptons

The origin of the fake light leptons in the signal region and all the control regions split by lepton flavor is shown in Figure 5.19. The fraction of the fake light leptons is defined as the ratio of the fake light lepton originating from a specific source to the total number of fake leptons and is based on predictions from $t\bar{t}$ and $t\bar{t}\gamma$ simulation. The number of raw and weighted events for the $t\bar{t}$ and $t\bar{t}\gamma$ backgrounds in the signal region is summarized in Table 5.11. Owing to very limited MC statistics, the statistical uncertainty of the fraction of the fake light leptons in the signal region can be as large as 100%.

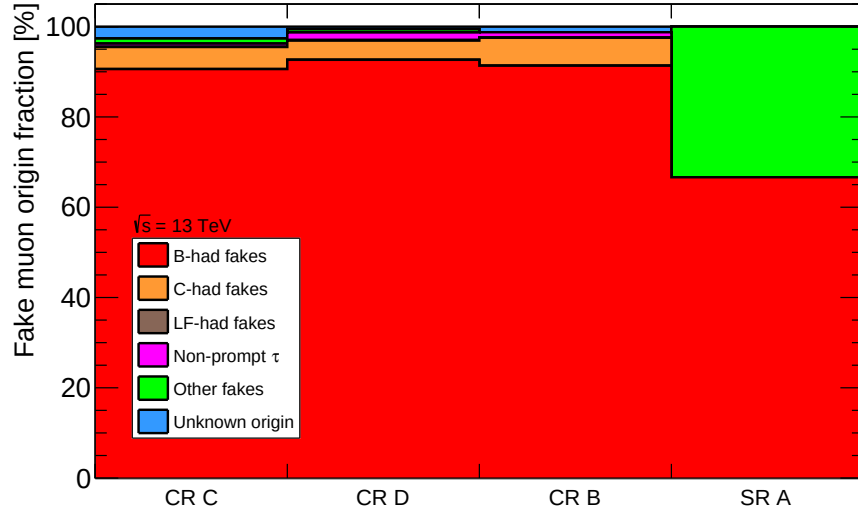
In the muon case, Figure 5.19 (a), the fakes from heavy flavored hadrons are dominated. In the control regions, about 90%, and in the signal region ($66 \pm 61\%$) of the total amount of fake muons stem from b -flavored hadrons. Other types of fakes include muons from c -flavored and light-flavored (LF) hadrons, non-prompt τ decays, and other contributions. The latter includes the pion and kaon decays. The cases where reconstructed muons cannot be assigned to a particular source are labeled “Unknown origin” and contributes only $< 2\%$ in the control regions, thus these fakes are neglected. The fraction of fakes from different sources is stable across all the regions.

For electrons, Figure 5.19 (b), the fraction of fakes from heavy-flavored hadrons dominates but a large fraction from photon conversions is also present. In the signal region, the fraction of electrons from photon conversions is 100%, which represents the one event of $t\bar{t}\gamma$ background¹¹. The large fraction from photon conversions is a consequence of the usage of the `PromptLeptonIso` algorithm, which specifically suppressed the contribution of non-prompt leptons from heavy flavor decays. The remaining fakes include electrons from c -flavored and LF hadrons, non-prompt τ decays, and pion or kaon decays. The relative fraction of electrons from heavy flavored hadrons and photon conversions is not stable across all the regions. An alternative strategy is adopted to account for these contributions as detailed in the next paragraph.

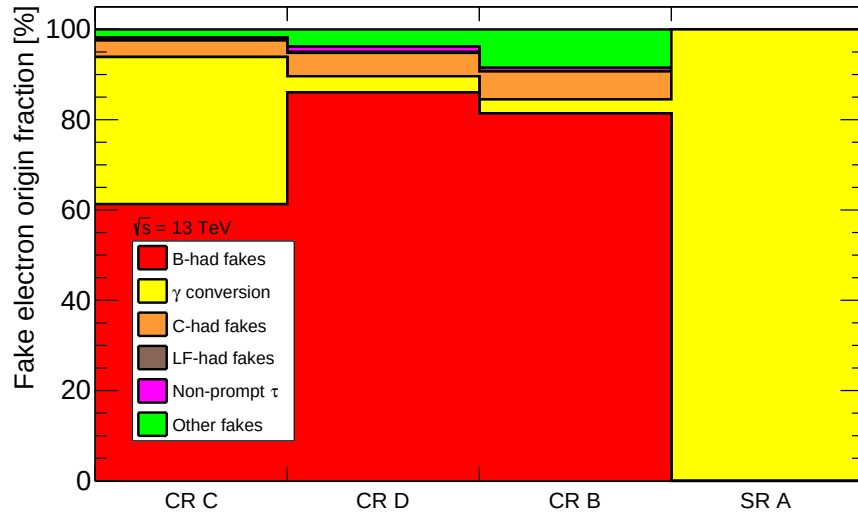
Measurement of electron and muon fake factors

The electron and the muon fake factors are determined in the regions enriched in events with the fake light leptons. Table 5.12 summarizes the selection criteria to define the control regions used for measuring the fake factors. In region C, the light leptons are required to satisfy the *tight* selection of Table 5.4, whereas in region D one lepton is required to be *tight* while the other light lepton is required to satisfy the *anti-tight* selection criteria listed in Table 5.13.

¹¹The $t\bar{t}$ background events have no electron fakes.



(a)



(b)

FIGURE 5.19: Composition of the fake muon (a) and the fake electron (b) in the signal region and all the control regions. The fraction of the fake electron is estimated in $t\bar{t}$ and $t\bar{t}\gamma$ simulation while the fraction of fake muon is estimated only in $t\bar{t}$ simulation. The control regions C and D are used to measure the fake factors that are applied to the events in the CR B to estimate the fake lepton background in the SR A.

TABLE 5.11: Event yields of the $t\bar{t}$ and $t\bar{t}\gamma$ background processes in the signal region. Weighted events are normalized to the $t\bar{t}$ and $t\bar{t}\gamma$ cross sections and to an integrated luminosity of 36.1 fb^{-1} . The uncertainties are only statistical.

Sample	Number of events	
	Raw	Weighted
$t\bar{t}$	4	1.12 ± 0.56
$t\bar{t}\gamma$	1	0.34 ± 0.34

TABLE 5.12: Definition of the control regions used for measuring the electron and the muon fake factors. The common selection criteria for regions C and D are listed under the title “Common”.

Common (CR C and CR D)		
Number of light leptons	2, with same-charge	
Lepton flavor	$ee, \mu\mu$	
Light leptons p_T	$\geq 15 \text{ GeV}$	
Z-veto	$ m(ee) - 91.2 \text{ GeV} > 10 \text{ GeV}$	
Trigger requirement	SLT OR DLT	
Trigger-matched leptons	≥ 1	
Number of jets	2 AND 3	
Number of b -tagged jets	≥ 1	
Number of τ_{had} candidate	0 OR 1	
	opposite in charge to the light leptons	
	CR C	CR D
Light leptons selection	Two tight leptons	One tight, one anti-tight lepton

The working point of the **PromptLeptonIso** algorithm is inverted with respect to the *tight* selection in order to increase the non-prompt leptons from heavy flavored hadron decays. The electron candidates are required to fail either the identification or the isolation requirements, or to pass the inverted **PromptLeptonIso** requirement. The charge misidentification requirement is also applied in order to suppress the contribution of electrons with an incorrect electric charge. The muon candidates are required to fail the isolation requirement or to pass the inverted **PromptLeptonIso** requirement. The impact parameter requirements are the same as for the loose light leptons. This *anti-tight* selection is designed specifically for the fake-factor procedure, which increases the number of events with fake light leptons in the sideband regions.

Depending on the light lepton, whether it passes the *tight* or *anti-tight* selection, the events in region D are categorized as:

1. $T\bar{T}$: Event with leading light lepton passing the *tight* selection and subleading light lepton passing the *anti-tight* selection (the total number of events: $N_{T\bar{T}}$).
2. $\bar{T}T$: Event with leading light lepton passing the *anti-tight* selection and subleading light lepton passing the *tight* selection (the total number of events: $N_{\bar{T}T}$).

The fake factor is measured according to equation 5.6 as a function of the p_T of the fake light lepton after subtracting the contribution of backgrounds with prompt light leptons and the $t\bar{t}H$ signal.

TABLE 5.13: Definition of the anti-tight selection used for the fake-factor procedure.

Electrons	Muons
NOT Tight LH identification	
OR	NOT Loose isolation
NOT Loose isolation	OR
OR	PromptLeptonIso ≥ -0.5
PromptLeptonIso ≥ -0.5	
ChargeIDBDT > 0.067	No
$ d_0 /\sigma_{d_0} < 5$	$ d_0 /\sigma_{d_0} < 3$
$ z_0 \sin \theta < 0.5$ mm	$ z_0 \sin \theta < 0.5$ mm

For numerator events where both leptons are tight, the p_T of the subleading light lepton is selected assuming it is more likely to be the fake lepton. The subleading muon (electron) is found to be fake in about 90% (71%) of the total number of events in $t\bar{t}$, $t\bar{t}\gamma$, single-top, Wt , Z + jets and W + jets simulated samples and therefore chosen for the fake factor measurement. For denominator events, the p_T of the anti-tight lepton is selected.

In the muon case, same-sign same-flavor $\mu\mu$ events are used for measuring the muon fake factors. The p_T distributions of the subleading and the anti-tight muon for the numerator (CR C) and denominator (CR D) selection, respectively, are shown in Figure 5.20. Overall the backgrounds with a fake muon are dominated, as shown in Table 5.14. The backgrounds with prompt muons to be subtracted are about 33% of the observed data yield for numerator events and only about 1.3% for denominator events. The contribution of the $t\bar{t}H$ signal events is small accounting for only 2% of the observed data yield to be subtracted at the numerator. The total amount of events with prompt muons to be subtracted is about 36% and 1.3% of the observed data yield at the numerator and denominator, respectively.

The muon fake factor is defined on a per-event basis as

$$f_\mu(i) = \frac{N_{\mu\mu}^{\text{Data}}(i) - N_{\mu\mu}^{\text{Prompt}}(i)}{N_{\mu\ell}^{\text{Data}}(i) - N_{\mu\ell}^{\text{Prompt}}(i)}, \quad (5.8)$$

where i refers to the p_T bin in question. Figure 5.21 displays the muon fake factors as a function of p_T after the subtraction. The number of bins is chosen based on the size of the data sample.

In the electron case, the picture is more complex. A pure fake-enriched region cannot be defined for electrons, as the contamination from prompt electron backgrounds as well as from charge misidentified electrons is expected. Thus, a large amount of background events needs to be subtracted, which leads to larger systematic uncertainties in the fake factor measurement. In this analysis, the electron fake factors are measured using same-sign same-flavor ee events. Figure 5.22 shows the p_T distributions of the subleading and the anti-tight electron for numerator and denominator selection, respectively.

The electron fake factor is defined as

$$\langle f_e(i) \rangle = \frac{N_{ee}^{\text{Data}}(i) - N_{ee}^{\text{Prompt}}(i) - N_{ee}^{q \text{ mis-id}}(i)}{N_{e\ell}^{\text{Data}}(i) - N_{e\ell}^{\text{Prompt}}(i) - N_{e\ell}^{q \text{ mis-id}}(i)}, \quad (5.9)$$

where i refers to the p_T bin in question. The backgrounds with prompt electrons to be subtracted are about 24%, whereas the charge misidentification background to be subtracted is about 25% of the observed data yield for numerator events. The amount of $t\bar{t}H$ signal events to be subtracted is small only about 1.3% for numerator events. Overall the total amount of events to be subtracted at the

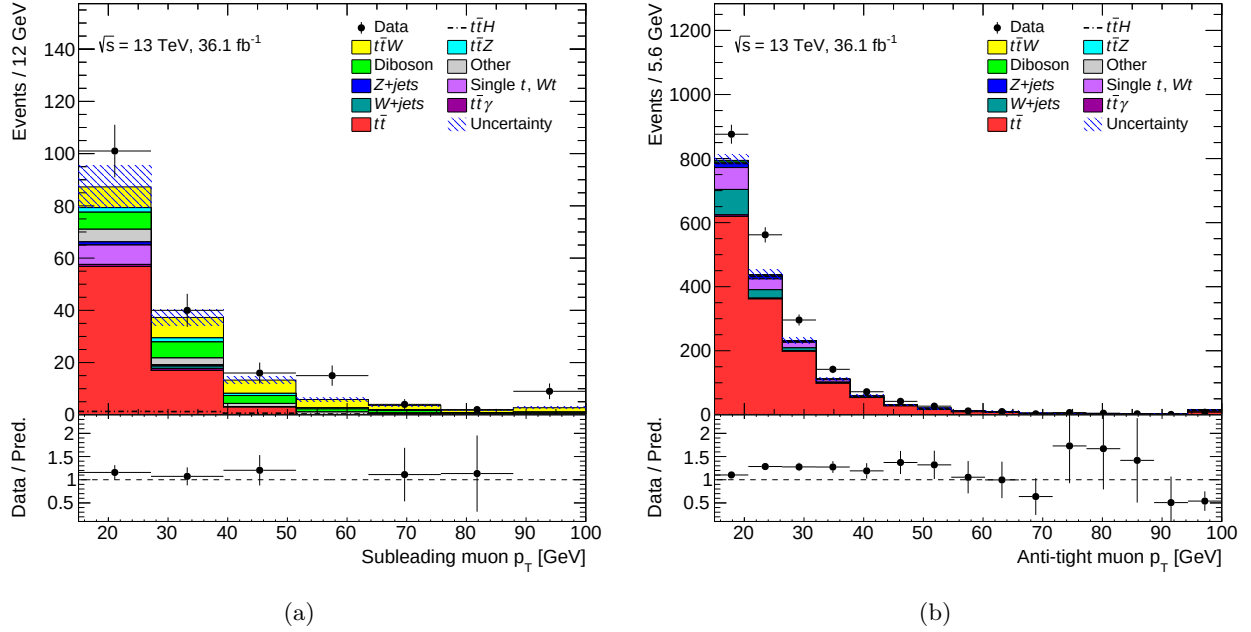
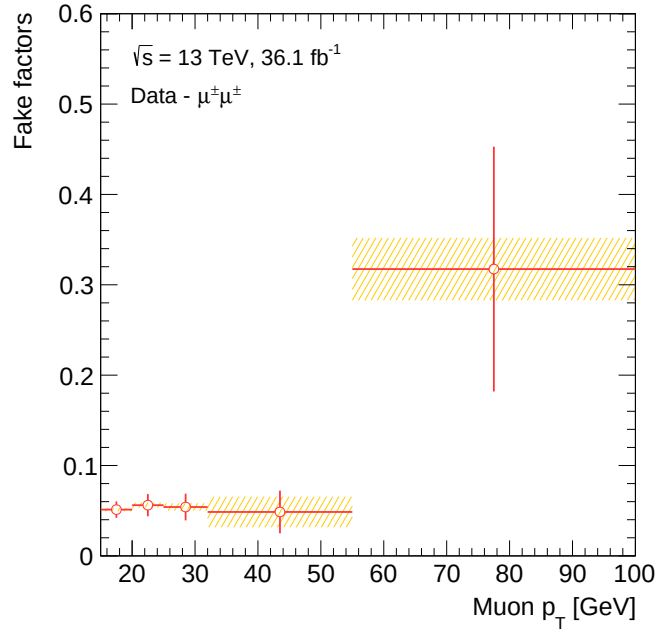


FIGURE 5.20: Distributions of the subleading muon (a) in region C (numerator) and the anti-tight muon (b) in region D (denominator). The ratio of the two distributions in data gives the muon fake factors after the subtraction of the backgrounds with prompt muons. The last bin in each figure contains the overflow. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

TABLE 5.14: Observed, signal, and background event yields in the control regions C and D with same-sign dimuon selection. The total number of events with prompt muons to be subtracted from data are indicated as “Total subtraction”. In the bottom part, the backgrounds with a fake muon are also reported. The uncertainties are only statistical.

	Muon	
	CR C (Numerator)	CR D (Denominator)
Data	187	2066
Total subtraction	66.71 ± 2.48	28.48 ± 1.59
$t\bar{t}H$	3.81 ± 0.16	1.13 ± 0.09
$t\bar{t}W$	28.18 ± 0.49	3.83 ± 0.19
$t\bar{t}Z$	5.46 ± 0.17	1.55 ± 0.13
Diboson	18.56 ± 2.36	11.57 ± 1.46
Other	10.70 ± 0.54	10.40 ± 0.57
$t\bar{t}$	77.13 ± 4.99	1415.39 ± 22.56
$t\bar{t}\gamma$	1.55 ± 0.64	12.00 ± 2.50
Single top, Wt	9.24 ± 1.66	132.78 ± 7.47
Z +jets	1.33 ± 0.45	22.26 ± 4.46
W +jets	0.00 ± 0.00	127.24 ± 11.85



(a)

FIGURE 5.21: Muon fake factors measured in data as a function of p_T . The error bars indicate the statistical uncertainty and the band represents the systematic uncertainties on the fake factors, as discussed in Section 5.12.

numerator is about 51% of the observed data yield and a small amount accounting for only about 2% of the observed data yield to be subtracted at the denominator, as can be inferred from Table 5.15. The contribution of the charge misidentification background in region C is estimated, using the technique described in the Section 5.11.2, by reweighting opposite-sign data events by the factor $w^{q_{\text{mis-id}}}$ which according to equation 5.2 depends on the probability of electron to be reconstructed with the wrong charge. In region D, the charge misidentification background is estimated from simulation¹² because of the presence of the anti-tight electron¹³. The subtraction of the charge misidentification background effectively decouples the estimation of this background from the estimation of the fake lepton (non-prompt and photon conversion). The electron fake factors as a function of p_T after the subtraction are shown in Figure 5.23. The number of bins is chosen based on the size of the data sample.

Furthermore, the relative non-prompt and photon conversion fake fractions are not same in the control regions and in the signal region, as evident in Figure 5.19. The fake factor for electrons from the photon conversions is significantly higher than that for electrons from heavy flavor decays. Thus, the contribution of the fake electron cannot be estimated exactly by the fake-factor method. Ideally, two independent control regions enriched in either type of fakes need to be defined to measure their fake factors. Since such regions cannot be defined with sufficient purity given the available statistics, an alternative approach is used to correct the measured electron fake factors. The electron fake factors $\langle f_e(i) \rangle$ as described above are an effective fake factors, as they are measured in the region where both non-prompt and photon conversion fakes are present.

A rescaling factor α is extracted from simulation where the fake factors for both non-prompt and conversion fakes are known. The measured electron fake factors are multiplied by this rescaling factor α to account for the relative proportions of non-prompt and photon conversion fakes between the

¹²The $t\bar{t}$ and diboson simulated samples are used.

¹³The charge misidentification rates are not reliable for electrons passing the *anti-tight* selection.

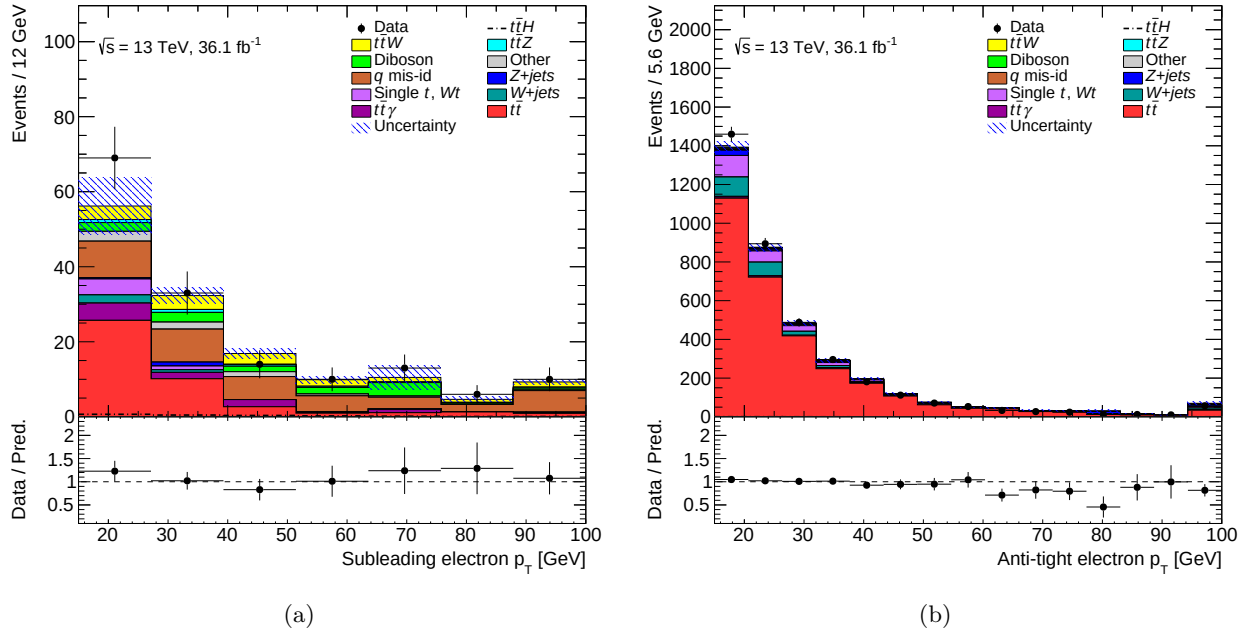
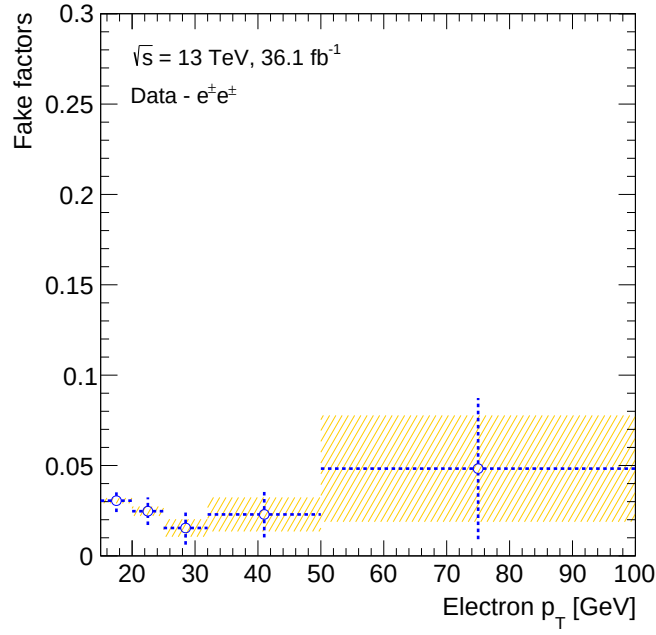


FIGURE 5.22: Distributions of the subleading electron (a) in region C (numerator) and the anti-tight electron (b) in region D (denominator). The ratio of the two distributions in data gives the electron fake factors after the subtraction of the backgrounds with prompt electrons and the charge misidentification background. The last bin in each figure contains the overflow. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

TABLE 5.15: Observed, signal, and background event yields in the control regions C and D with same-sign dielectron selection. The total number of events with prompt electrons and the charge misidentification background to be subtracted from data are indicated as “Total subtraction”. In the bottom part, the backgrounds with a fake electron are also reported. The uncertainties are only statistical.

	Electron	
	CR C (Numerator)	CR D (Denominator)
Data	155	3731
Total subtraction	79.57 ± 3.40	71.76 ± 3.27
$t\bar{t}H$	2.08 ± 0.11	2.99 ± 0.14
$t\bar{t}W$	15.32 ± 0.35	9.04 ± 0.30
$t\bar{t}Z$	3.05 ± 0.13	3.61 ± 0.22
Diboson	12.52 ± 3.30	15.62 ± 1.55
Other	6.84 ± 0.68	12.86 ± 1.03
q mis-id	39.75 ± 0.30	27.65 ± 2.66
$t\bar{t}$	42.85 ± 3.35	3063.61 ± 33.25
$t\bar{t}\gamma$	9.30 ± 1.68	33.64 ± 3.40
Single top, Wt	5.42 ± 1.54	255.65 ± 9.93
Z +jets	1.92 ± 0.61	61.79 ± 13.06
W +jets	4.35 ± 6.97	224.26 ± 22.51



(a)

FIGURE 5.23: Electron fake factors measured in data as a function of p_T . The error bars indicate the statistical uncertainty and the band represents the systematic uncertainties on the fake factors, as discussed in Section 5.12. The fake factors are multiplied by the rescaling factor α .

control regions and the signal region as

$$f_e(i) = \langle f_e(i) \rangle \times (1 + \alpha), \quad (5.10)$$

where $\langle f_e(i) \rangle$ represents the effective fake factors and $f_e(i)$ represents the electron fake factors used to estimate the contribution of the fake electron in the signal region. The α factor is defined as

$$\alpha = \left[\frac{(1 - \text{frac}_{\gamma}^{\text{SR}}) \cdot f_e^{\text{HF}} + \text{frac}_{\gamma}^{\text{SR}} \cdot f_e^{\gamma}}{(1 - \text{frac}_{\gamma}^{\text{CR}}) \cdot f_e^{\text{HF}} + \text{frac}_{\gamma}^{\text{CR}} \cdot f_e^{\gamma}} \right] - 1, \quad (5.11)$$

where $\text{frac}_{\gamma}^{\text{SR}}$ and $\text{frac}_{\gamma}^{\text{CR}}$ represent the conversion fractions in the signal region and in the control region C, respectively, and $f_e^{\text{HF}}(f_e^{\gamma})$ is the non-prompt (photon conversion) electron fake factor extracted from simulation.

In the signal region, the fraction of the electrons from photon conversions is 100% due to the one event of $t\bar{t}\gamma$ background. The identification requirement for τ_{had} candidates is relaxed to a looser working point to increase the statistics in the signal region for the estimation of the rescaling factor, based on the assumption that there is no correlation between the fake electron and τ_{had} candidate. Figure 5.24 shows the fraction of the fake electrons from photon conversions and heavy-flavored hadrons in the signal region with loose τ_{had} candidates in $t\bar{t}$ and $t\bar{t}\gamma$ simulated events. These fractions are used to calculate the rescaling factor α . The value of α with total uncertainty is summarized in Table 5.22.

The electron and muon fake factors as a function of $|\eta|$ are shown in Figure 5.25. In both the electron and muon case, the fake factors do not vary significantly and thus the η dependence of the fake factors is not considered in the estimation of the fake lepton background.

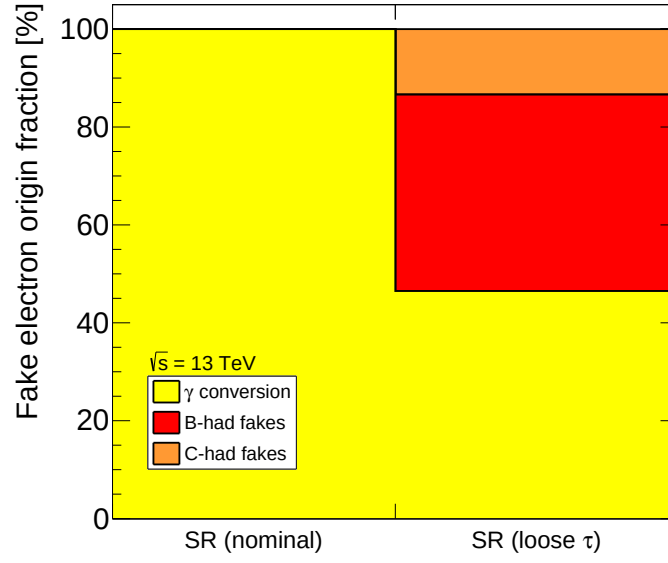


FIGURE 5.24: Composition of fake electrons in the signal region with loose τ_{had} candidates. The fraction of the fake electron in the nominal signal region is also shown for comparison. The fraction is estimated in $t\bar{t}$ and $t\bar{t}\gamma$ simulation.

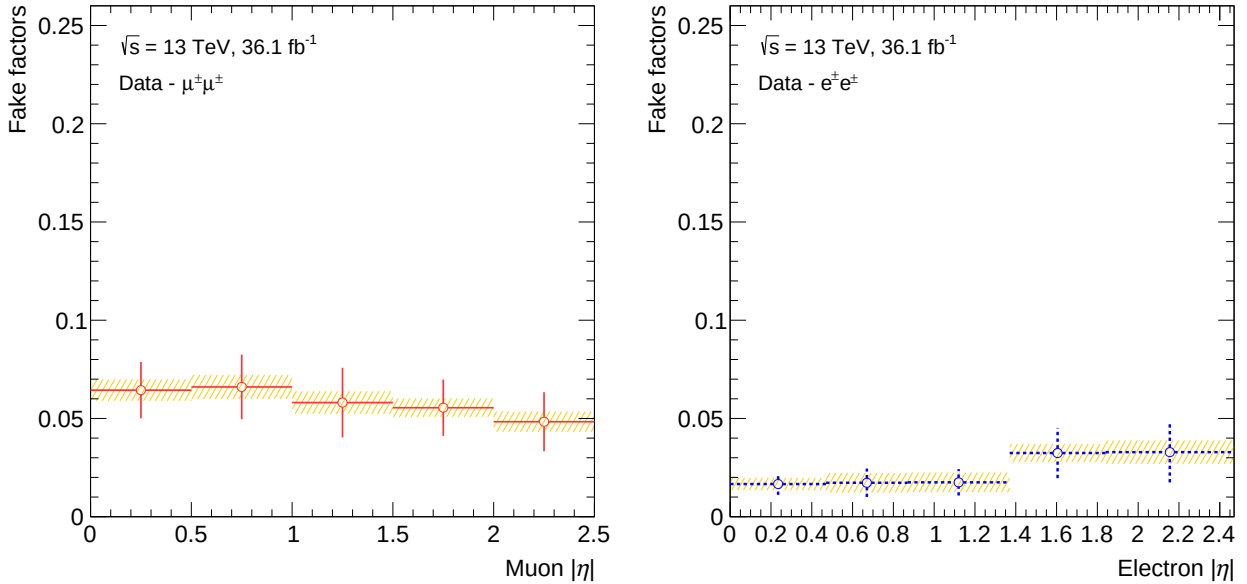


FIGURE 5.25: Muon (a) and electron (b) fake factors measured in data as a function of $|\eta|$. The error bars indicate the statistical uncertainty and the band represents the systematic uncertainties on the fake factors, as discussed in Section 5.12.

Application of the fake-factor method

In order to obtain an estimate of the number of events with fake light leptons in the signal region, the fake factors are applied to the observed data events in region B which is close to the signal region. Events in this region must satisfy all the event selection of the signal region (Table 5.7), except one light lepton is required to be tight while the other light lepton is required to pass the *anti-tight* selection. The region is enriched in $t\bar{t}$ background, however the small contribution of the backgrounds with prompt light leptons is subtracted. The fake factors are applied to the events with prompt light leptons to obtain an estimate of their magnitude and the shape which are then subtracted from the nominal fake factor estimate at the end. Thus, equation 5.7 can be rewritten as

$$\begin{aligned}
 N_{\text{SR}}^{\text{fake}} = & \sum_i \left[N_{e\ell}^{\text{Data}}(i) - N_{e\ell}^{\text{Prompt}}(i) \right] \cdot f_e(i) \\
 & + \sum_i \left[N_{\mu\ell}^{\text{Data}}(i) - N_{\mu\ell}^{\text{Prompt}}(i) \right] \cdot f_\mu(i) \\
 & + \sum_i \left[N_{e\mu}^{\text{Data}}(i) - N_{e\mu}^{\text{Prompt}}(i) \right] \cdot f_\mu(i) \\
 & + \sum_i \left[N_{\mu\ell}^{\text{Data}}(i) - N_{\mu\ell}^{\text{Prompt}}(i) \right] \cdot f_e(i),
 \end{aligned} \tag{5.12}$$

where the sum is taken over i p_T bins of the fake factor. The charge misidentification background in this region is negligible.

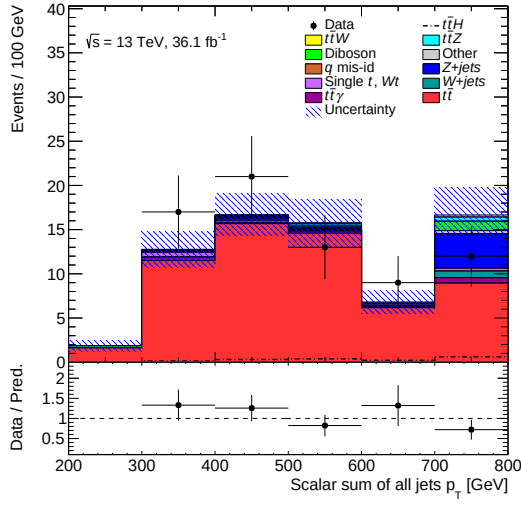
Figure 5.26 shows the distributions of the input variables to the BDT discriminant (Section 5.9) in region B. The distribution of the BDT output is shown in Figure 5.27. A good agreement between data and prediction is observed within the statistical uncertainties. Thus, events in region B weighted by the p_T -dependent fake factors correctly estimate the shape and normalization of these distributions in the signal region for the backgrounds with fake light leptons.

The distribution of the BDT output in the signal region is used as the final discriminant in the likelihood fit (Section 6.2). It is important that the fake-factor method correctly predict the distribution of the BDT output. In order to validate the distribution of the BDT output, the distribution produced by the fake-factor procedure is compared to the out-of-the-box MC distribution, as shown in Figure 5.28. The bins are chosen based on the size of the MC samples in the signal region. Overall the two distributions are compatible within the statistical uncertainty. Although, the MC prediction has a significantly large statistical uncertainty due to the limited statistics. Based on this comparison, a shape systematic uncertainty is considered as discussed in Section 5.12.

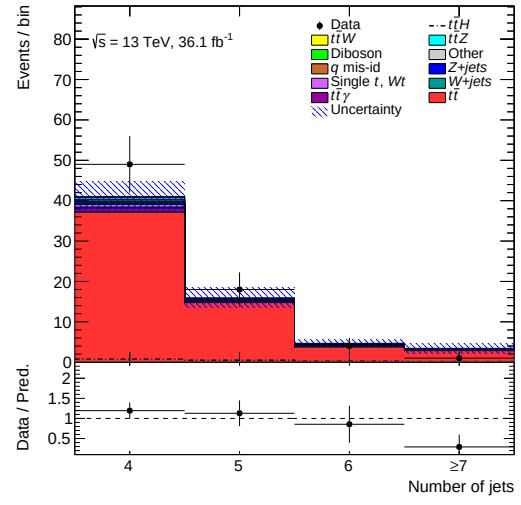
Closure test

A closure test is performed to validate the assumptions of the fake-factor method by comparing the prediction from the method to the pure simulation prediction. The fake-factor procedure, as described previously, is run on the $t\bar{t}$ and $t\bar{t}\gamma$ MC samples. The event selection in all the control regions is the same as described above. In addition, the events with truth-matched charge misidentified electrons are vetoed. Events are normalized to the $t\bar{t}$ and $t\bar{t}\gamma$ cross sections and to an integrated luminosity of 36.1 fb^{-1} .

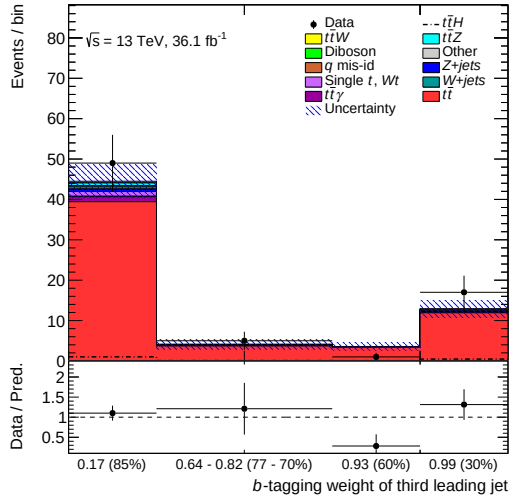
The electron and muon fake factors are calculated in the fake factor regions. The electron fake factors are measured in $t\bar{t}$ and $t\bar{t}\gamma$ events where one of the electron is required to be fake either coming from heavy-flavored hadron decays or from photon conversion at the numerator. The muon fake factors are measured only in $t\bar{t}$ events by requiring the presence of at least one fake muon, mainly arising from heavy-flavored hadron decays at the numerator. Figure 5.29 shows the electron and muon fake factors as determined from the $t\bar{t}$ and $t\bar{t}\gamma$ simulation. These fake factors are applied to the events in region B to obtain the fake lepton estimate in the signal region. The estimate is compared to the



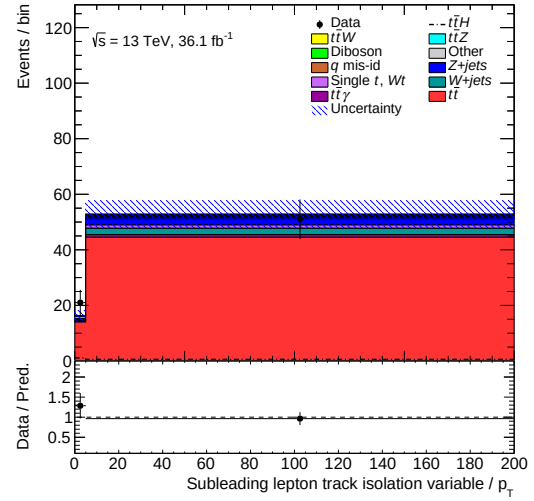
(a)



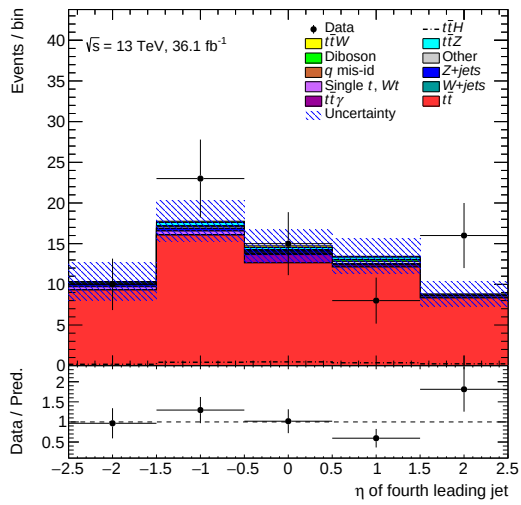
(b)



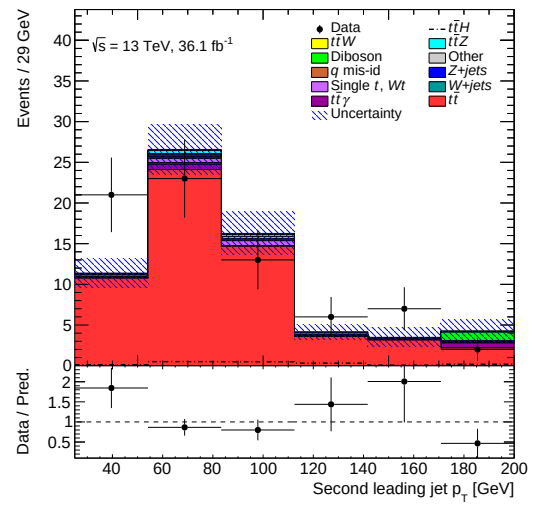
(c)



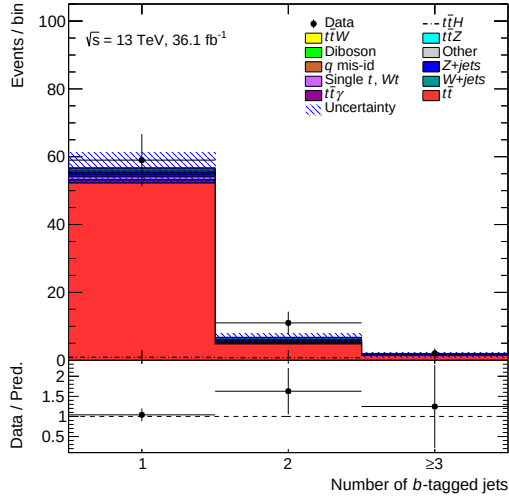
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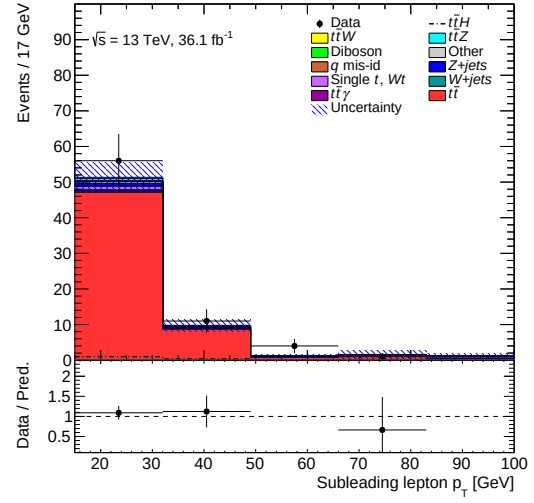
(e)



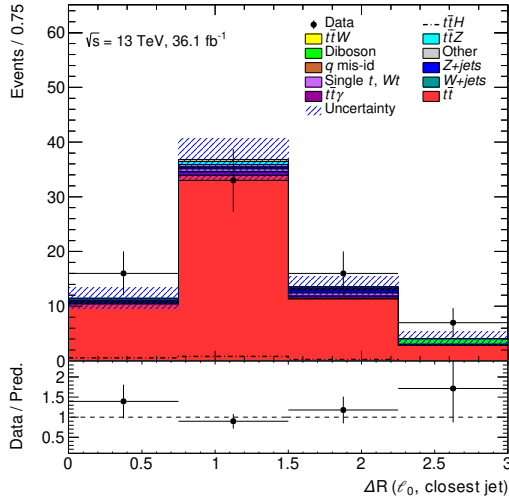
(f)



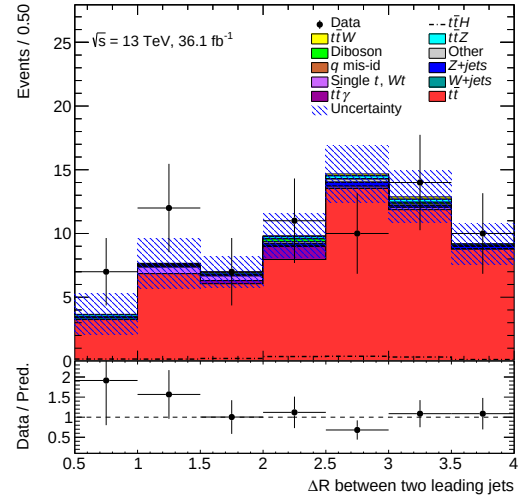
(g)



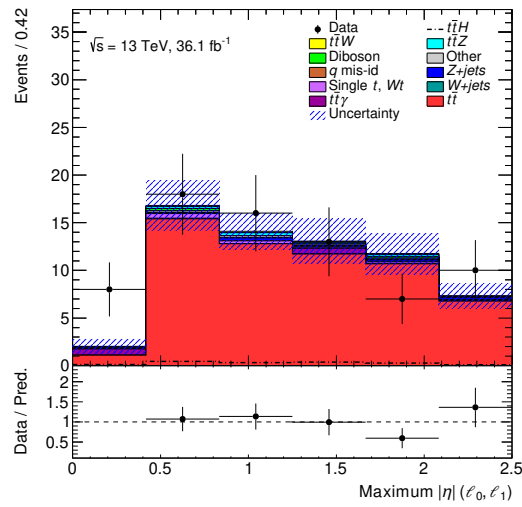
(h)



(i)



(j)



(k)

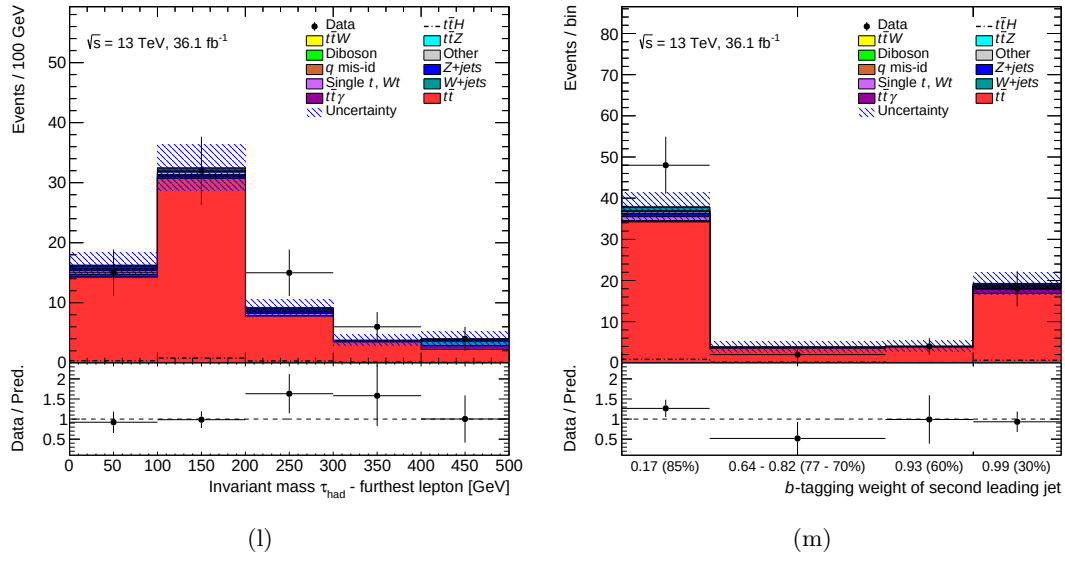


FIGURE 5.26: Comparison of data and prediction of the BDT input variables in the control region B. The last bin in each figure contains the overflow. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

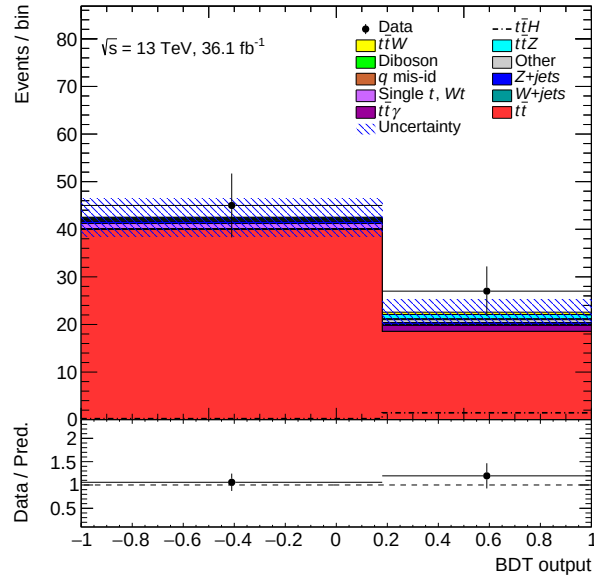


FIGURE 5.27: BDT output in the control region B. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

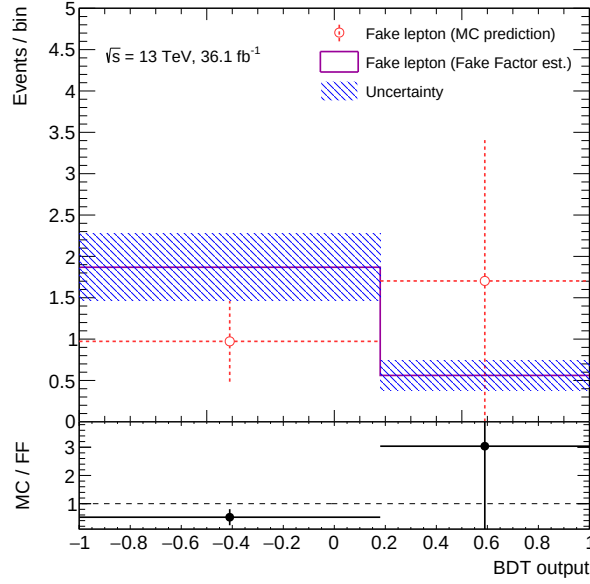


FIGURE 5.28: Comparison of the distributions of the BDT output for the fake lepton estimate by the fake-factor method (magenta histogram) based on events in the control region B weighted by the p_T -dependent fake factors, and for the out-of-the-box MC prediction (red circles) in the signal region. The hatched band in the top panel represents only the statistical uncertainty. The bottom panel displays the ratio of the two distributions. For the MC distribution, the second bin represents only one raw event with large statistical uncertainty.

out-of-the-box MC prediction in the signal region. The event yields for the fake-factor method fakes and pure simulation prediction in the signal region are shown in Table 5.16. The non-closure is defined as the relative difference between the fake-factor method fakes and the prediction from the simulation

$$\text{non-closure} = \frac{N_{t\bar{t},t\bar{t}\gamma} - N_{\text{FF fakes}}}{N_{\text{FF fakes}}}, \quad (5.13)$$

$$\sigma = \sqrt{\frac{\sigma_{t\bar{t},t\bar{t}\gamma}^2}{N_{\text{FF fakes}}^2} + \frac{N_{t\bar{t},t\bar{t}\gamma}^2 \cdot \sigma_{\text{FF fakes}}^2}{N_{\text{FF fakes}}^4}},$$

where $N_{t\bar{t},t\bar{t}\gamma}$ ($\sigma_{t\bar{t},t\bar{t}\gamma}$) and $N_{\text{FF fakes}}$ ($\sigma_{\text{FF fakes}}$) are the event yields (statistical uncertainties) for pure simulation prediction and the fake-factor method fake estimate, respectively, and σ is the uncertainty on the non-closure mostly driven by the statistical size of the signal region. For the non-closure, the uncertainties $\sigma_{t\bar{t},t\bar{t}\gamma}$ and $\sigma_{\text{FF fakes}}$ are not correlated. The latter is the statistical uncertainty in the fake-factor method fakes, which depends on the statistical size of the control regions.

The method is considered to be validated if the non-closure is consistent with zero. The maximum between the non-closure and its uncertainty is conservatively assigned as the non-closure systematic uncertainty on the fake-factor method. The non-closure in the signal region is found to be consistent with zero within its uncertainty, as shown in Table 5.16.

The closure test is also performed in $t\bar{t}$ events with only muons¹⁴ by combining the same-flavor $\mu\mu$ and opposite-flavor events to check any effect of the instability of the fake lepton composition. A non-closure of $(-4 \pm 50)\%$ is found which is consistent with zero within the uncertainty, as listed in Table 5.17. The distributions of the BDT output in the signal region for the pure simulation prediction and the fake-factor method fake estimate are shown in Figure 5.30. No significant trend is seen for

¹⁴The $t\bar{t}$ background events have no electron fakes.

the non-closure across the BDT shape. The closure test results imply that the fake factors derived in the control regions are applicable to the events with fake light leptons in the signal region.

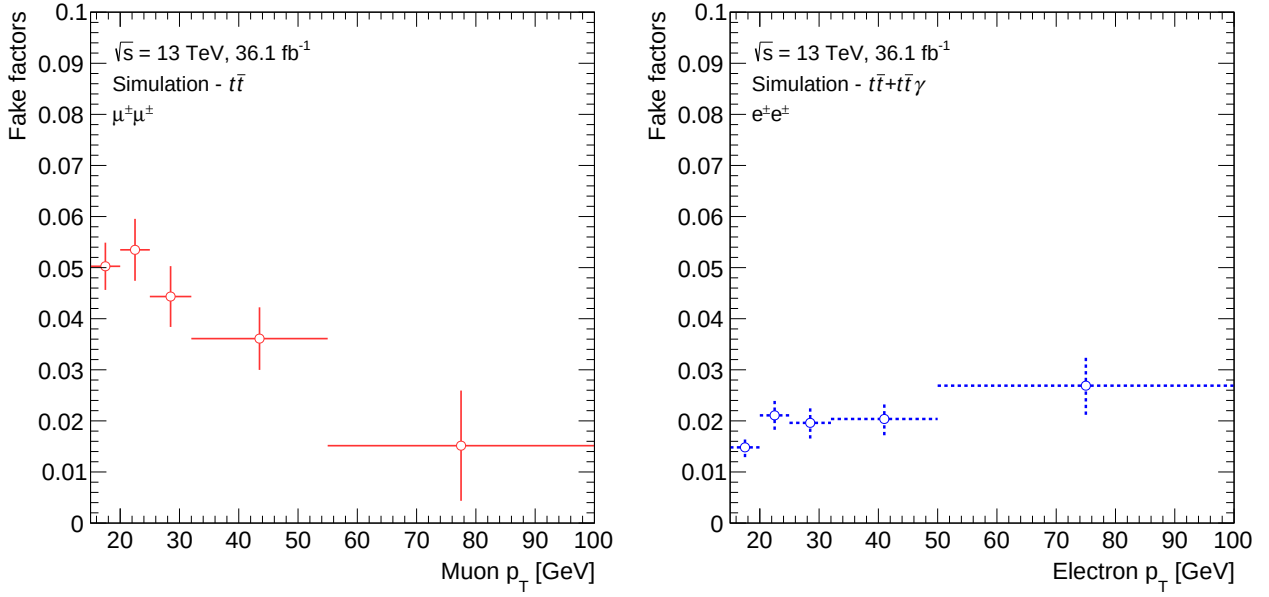


FIGURE 5.29: Muon (a) and electron (b) fake factors as measured in $t\bar{t}$ and $t\bar{t}\gamma$ simulation as a function of p_T . Fake factors are derived from the control regions C and D (Table 5.12). The error bars indicate the statistical uncertainty.

TABLE 5.16: Closure test showing the fake lepton estimate by the fake-factor method compared to the estimate from simulation in the signal region. The uncertainty on the fake-factor method fake estimate is only statistical. The non-closure and its uncertainty (in percent) is also reported.

2ℓSS1τ _{had} signal region	
$t\bar{t}, t\bar{t}\gamma$ MC prediction	1.46 ± 0.66
FF method fakes	1.99 ± 0.14
Non-closure [%]	-27 ± 34

TABLE 5.17: Closure test in $t\bar{t}$ events with only muons. The uncertainty on the fake-factor method fakes is only statistical. The non-closure and its uncertainty (in percent) is also reported and the maximum between them is taken as the non-closure systematic uncertainty.

Muons	
$t\bar{t}$ MC prediction	1.12 ± 0.56
FF method fakes	1.16 ± 0.13
Non-closure [%]	-4 ± 50

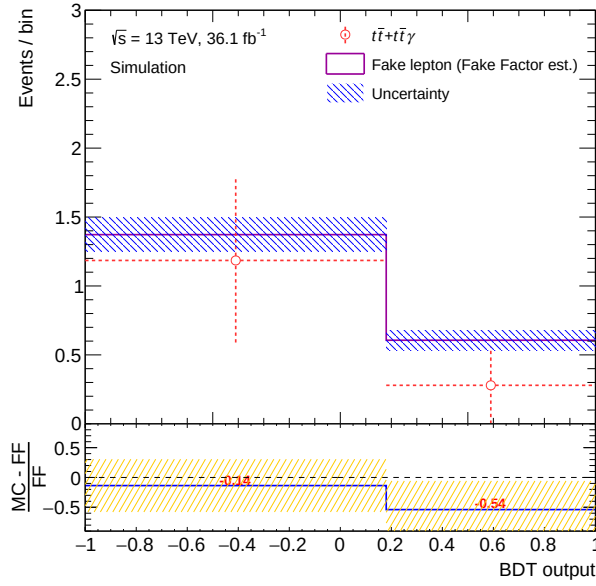


FIGURE 5.30: Distributions of the BDT output for the fake lepton estimate by the fake-factor method (magenta histogram), based on events in the control region B weighted by the p_T -dependent fake factors as measured in $t\bar{t}$ and $t\bar{t}\gamma$ events, and for pure simulation prediction (red circles) in the signal region. The hatched band in the top panel represents only the statistical uncertainty. The bottom panel displays the non-closure in each bin of the distribution, and the hatched band represents its statistical uncertainty.

Study of the influence of non- $t\bar{t}$ fake sources

The muon and electron fake factors are derived in the low jet multiplicity regions C and D using data events. These regions are enriched in $t\bar{t}$ events, however, they can be contaminated by an additional source of fake light leptons other than the $t\bar{t}$. Processes for example $W + \text{jets}$ and $Z/\gamma^* + \text{jets}$ give rise to fake light leptons. These are expected to be suppressed at high jet multiplicity, however, their contribution can be large in low-jet multiplicity regions. Difference in the fake factor f_ℓ for these processes and the $t\bar{t}$ can lead to a bias in the fake light lepton background estimate.

The impact of additional sources of fake light leptons is assessed by varying the p_T of the leading b -tagged jet, applying a requirement on the missing transverse momentum E_T^{miss} and by requiring exactly two and exactly three jets. Such requirements are expected to vary the fraction of events with other sources of fake light leptons. For each alternative selection the fake-factor procedure is repeated using only data. The muon and electron fake factors are recalculated and the fake light lepton background is estimated by applying these fake factors to the data events in region B. The estimated fake light lepton event yields for different selections are shown in Figure 5.31. This check shows the stability of the fake light lepton estimate when the control region selection is altered. No additional systematic uncertainty is considered as the fake light lepton estimate for different selections is consistent within the statistical uncertainties.

N_{jets} dependence

The fake-factor method is based on the assumption that the electron and muon fake factors are stable with respect to the jet multiplicity. Figure 5.32 displays the muon and electron fake factors as a function of the number of jets. In both cases, no significant variation is observed in the fake factors for

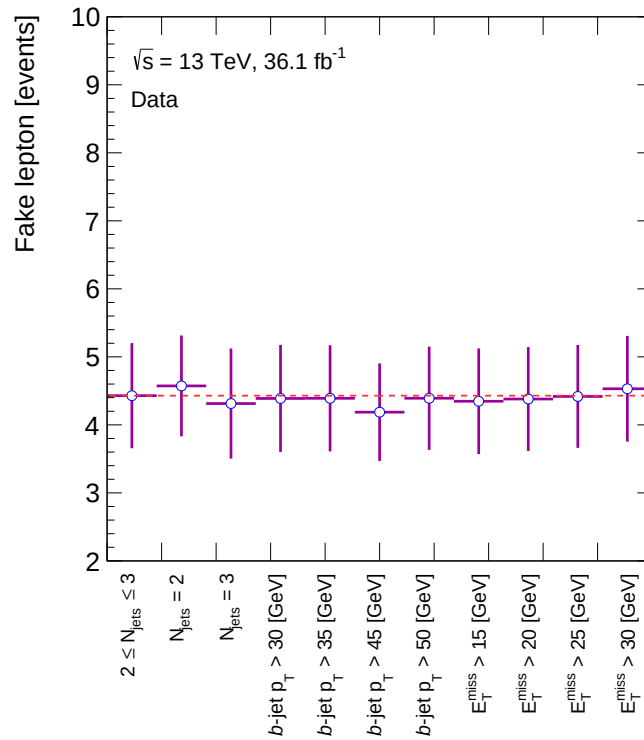


FIGURE 5.31: Stability of the fake light lepton estimate in the signal region when the selection of the control regions is altered. For the measurement of the light lepton fake factors, each selection criteria is applied in addition to the nominal selection of Table 5.12. The red dashed line represents the fake light lepton estimate using the nominal selection. The error bars indicate the statistical uncertainty.

any jet multiplicity. This implies that the N_{jet} extrapolation between the low jet multiplicity control regions and the high jet multiplicity signal region is valid.

Real and fake τ_{had} fraction

In this study, the real and fake τ_{had} fractions are investigated. The fraction of real (fake) τ_{had} candidates in the signal region and the extrapolation region B are 0% (100%) and 52% (48%), respectively, based on the prediction from $t\bar{t}$ simulation. The fraction of real τ_{had} candidates is defined as the ratio of the truth-matched¹⁵ hadronically decaying tau candidates to the total number of tau candidates. The fraction is different between the signal region and the region B. In fact, the $t\bar{t}$ decay in both the signal region and the region B is expected to be the same (Figure 5.9) because of the similar event selection. The difference in the fraction stems from the fact that the signal region has poor $t\bar{t}$ MC statistics (Table 5.11).

A study is carried out to correctly evaluate the fraction of real and fake τ_{had} candidates in the signal region. The event selection in the signal region is altered regarding the light lepton requirement to be loose in order to increase the $t\bar{t}$ MC statistics. The fraction of real (fake) τ_{had} candidates in the signal region with loose light leptons is found to be 53% (47%) which is similar to that of the region B. Further, the size of the non-closure systematic uncertainty on the fake light lepton background is large enough to account for the difference in the fraction of real and fake τ_{had} candidates between the signal region and the region B.

¹⁵The process of associating a reconstructed object with the corresponding truth particle is known as *truth matching*.

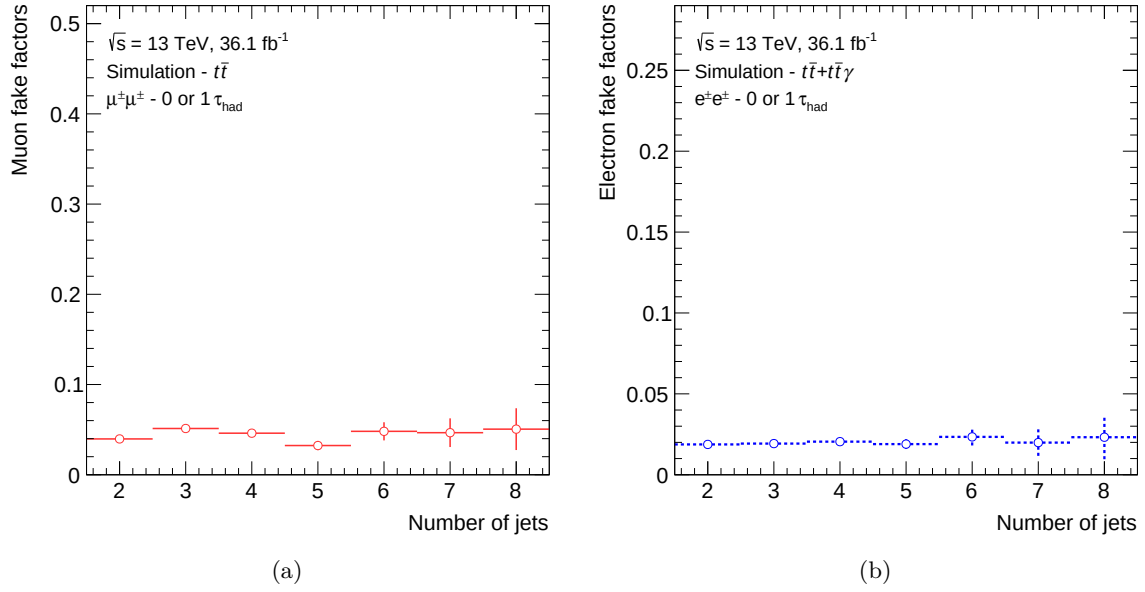


FIGURE 5.32: Muon (a) and electron (b) fake factors measured in $t\bar{t}$ and $t\bar{t}\gamma$ simulated events as a function of the number of jets. The error bars indicate the statistical uncertainty. The event selection is the same as the one used for the analysis (Table 5.12), except for the number of jets requirement which is $N_{\text{jet}} \geq 2$.

Double ratio

The fake light lepton background in the signal region A is estimated as

$$N_A = N_B \times \frac{N_C}{N_D}, \quad (5.14)$$

where N_A , N_B , N_C and N_D are the number of events in the signal region A and the control regions B, C, and D, respectively. The assumption that the ratios N_A/N_B and N_C/N_D are the same is confirmed using the $t\bar{t}$ and $t\bar{t}\gamma$ simulated samples, as shown in Figure 5.33.

Fake light lepton validation region

The estimation of the fake lepton background with the fake-factor method is validated in a dedicated validation region. The validation region is designed to be enriched in the backgrounds with fake light leptons and kinematically close to the signal region. In order to check the validity and robustness of the fake lepton background estimate, the distributions of several kinematic variables in data are compared to the predicted background in the validation region. A good modeling of the predicted distributions provides confidence that the fake factor extrapolation is valid.

The event selection in the validation region is the same as for region C (Table 5.12), except that events are required to include only OF light leptons and exactly one τ_{had} candidate to ensure the orthogonality between the validation region and the region C. The fake lepton background is estimated by applying the final electron and muon fake factors (Figures 5.21 and 5.23) to the data events with only OF leptons and exactly one τ_{had} candidate in region D. The validation region is limited by the available statistics and the purity of the fake lepton background achieved is only 47%. Figure 5.34 shows the distributions of the subleading lepton p_T , missing transverse energy, the number of b -tagged jets, and the angular distance between the subleading lepton and closest jet in the validation

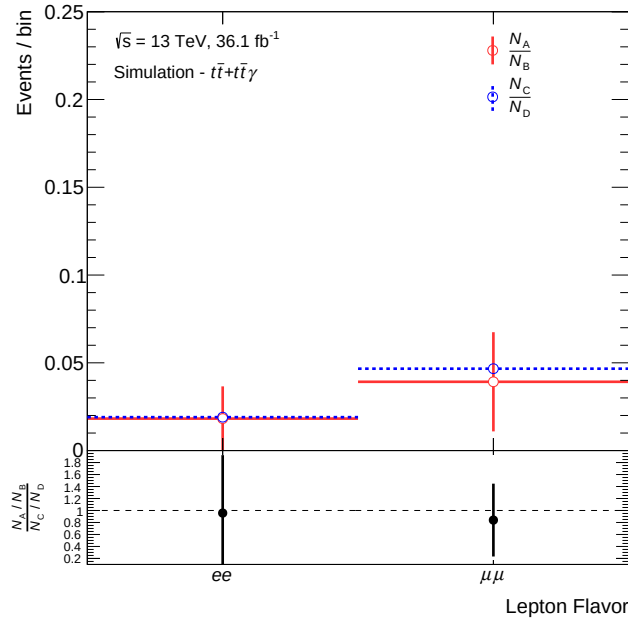


FIGURE 5.33: Ratio of the number of events in the signal region and the region B (red circles), and in the regions C and D (blue circles) for the lepton flavor composition using the $t\bar{t}$ and $t\bar{t}\gamma$ simulated samples. The bottom panel displays the double ratio. The two ratios are the same within the statistical uncertainties.

region. The normalization as well as the shape of the observed and predicted distributions are in good agreement within the total uncertainties in the background prediction.

5.11.3 Backgrounds with prompt light leptons and fake τ_{had} candidates

The irreducible backgrounds with prompt light leptons and a fake τ_{had} candidate are estimated from MC simulation and corrected with a data-driven scale factor in order to address the possible mismodeling in the case where a quark- or gluon-initiated jet is misidentified as a τ_{had} candidate. In the $2\ell\text{SS}1\tau_{\text{had}}$ channel, these backgrounds are referred to as “fake τ_{had} backgrounds” for brevity.

In the $2\ell\text{SS}1\tau_{\text{had}}$ signal region, the largest contribution to the total fake τ_{had} background arises from the $t\bar{t}W$ process and smaller contributions are from $t\bar{t}Z$ and rare processes. The signal region also has a small fraction of $t\bar{t}H$ signal events with a fake τ_{had} candidate (only about 14% of the total $t\bar{t}H$ signal events) and these are corrected with the scale factor as well. Figure 5.35 displays the origin of the fake τ_{had} candidate for different processes based on predictions from simulation. The fraction of the fake τ_{had} is defined as the ratio of the fake τ_{had} candidate originating from a specific source to the total number of fake τ_{had} candidates. The dominant source of the fake τ_{had} is the light-quark jets in all the processes, except in the $t\bar{t}Z$ process where a large fraction from electron misidentified as τ_{had} is also present. The fraction from gluon-initiated jet misidentified as the τ_{had} is small. Other types of fakes include b - and c -jets and other contributions. The latter includes muons, hadrons and the cases where the reconstructed τ_{had} cannot be assigned unambiguously to a particular source. For the total fake τ_{had} background, the statistical uncertainties of the fractions of the fake τ_{had} candidates are as large as 8%.

The scale factor (κ) is derived in the $2\ell\text{OS}1\tau_{\text{had}}$ control region and applied in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region, given that the origin of the fake τ_{had} candidate is very similar between the two channels as demonstrated in Figure 5.36. For the $t\bar{t}Z$ process, the scale factor is applied only to the events where a jet is faking the tau candidate. The events where an electron is faking the tau candidate are rescaled

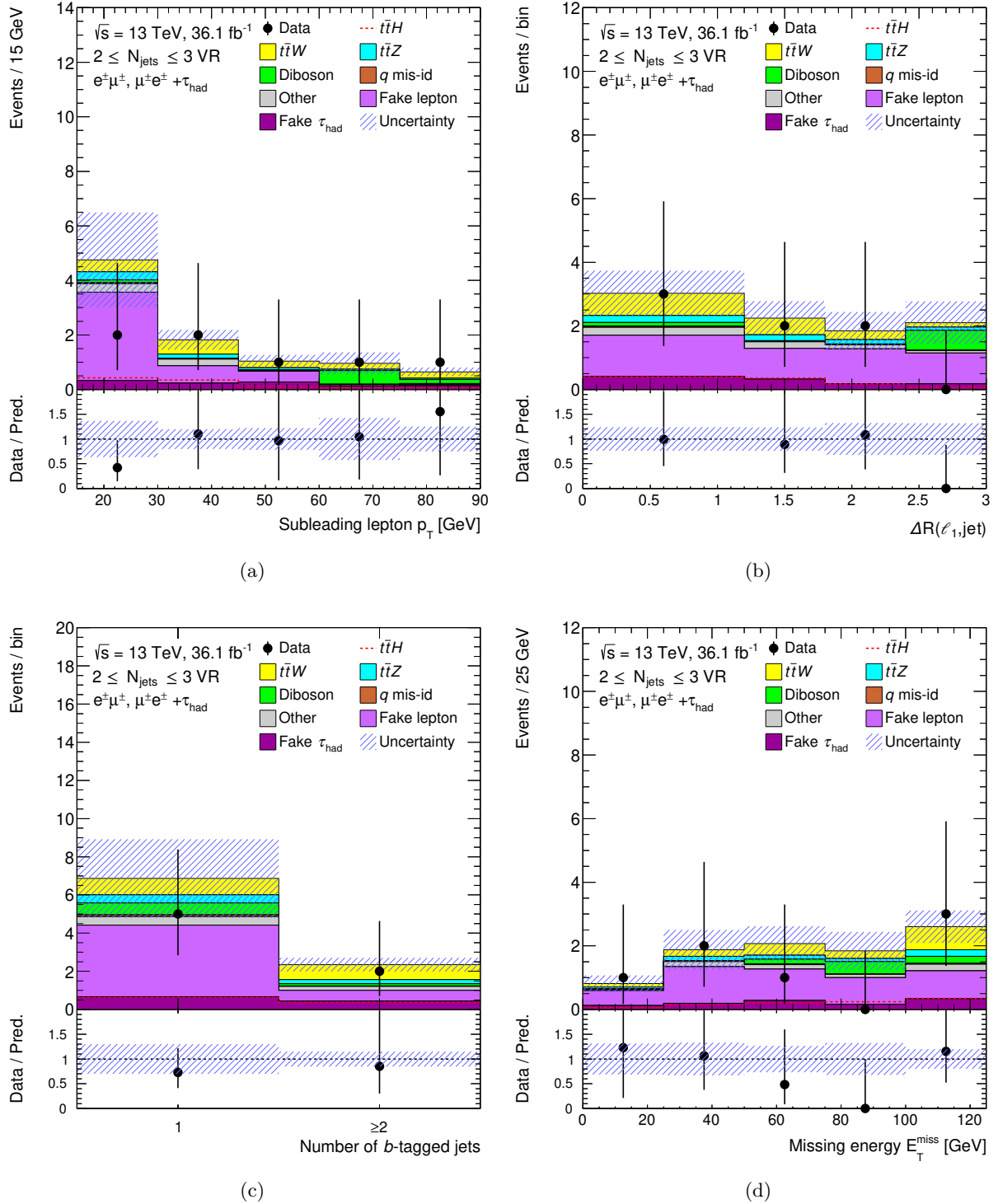


FIGURE 5.34: Distributions of (a) the subleading lepton p_T , (b) $\Delta R(\ell_1, \text{jet})$, (c) the b -tagged jet multiplicity, (d) missing energy in the low- N_{jets} , $e\mu, \mu e + \tau_{\text{had}}$ validation region. The fake lepton background is estimated by the fake-factor method. The last bin in each figure contains the overflow. The bottom panel displays the ratio of data to the total prediction. The hatched band represents the total uncertainty (statistical plus systematic) on the background prediction. The systematic uncertainties related to the fake light background, as discussed in Section 5.12, are considered. The fake τ_{had} background is estimated using the procedure described in Section 5.11.3.

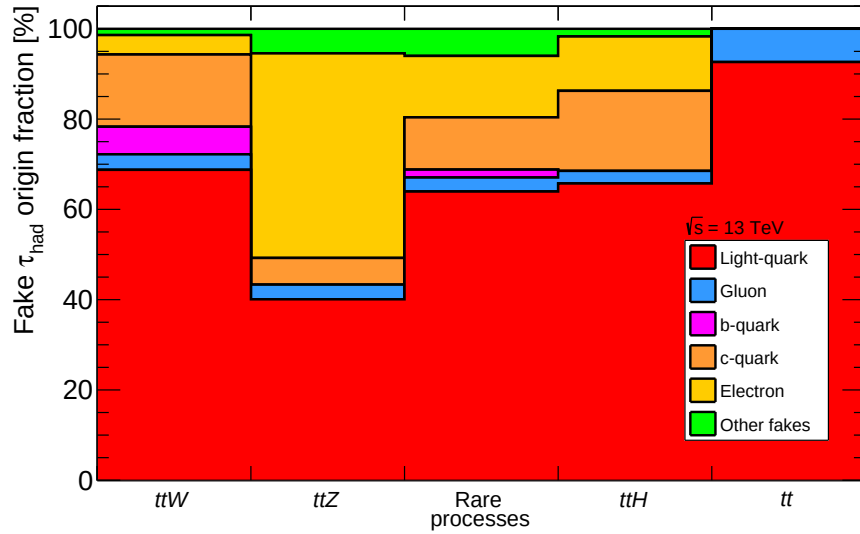


FIGURE 5.35: Composition of the fake τ_{had} in the $2\ell\text{SS}1\tau_{\text{had}}$ SR for different processes. Rare processes are tZ , tW , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tH , triboson production and rare top decay. The fake τ_{had} composition for the $t\bar{t}$ process is also shown for comparison.

by the correction factor on the probability of misidentifying an electron as a hadronic tau lepton decay [82].

Scale factor measurement

The scale factor κ is measured in the $2\ell\text{OS}1\tau_{\text{had}}$ channel. In this channel, selected events are required to include exactly two light leptons of opposite-charge (OS) with leading (subleading) $p_T > 25$ (15) GeV, and exactly one hadronically decaying tau lepton. The τ_{had} candidate is required to pass the selection criteria as described in Section 5.6.3. The light leptons are required to pass the *loose* selection criteria given in Table 5.4 and in addition an isolation requirement is applied. Thus, the selected events include loose and isolated light leptons. Events must include at least three reconstructed jets and at least one of these jets must be b -tagged. The Z -veto is applied to same-flavor lepton pairs to suppress the Z + jets background. Events containing a same-flavor lepton pair with an invariant mass below 12 GeV are removed to suppress background from resonances that decay to light leptons. The complete selection is summarized in Table 5.18.

Selecting events with the same-charge light lepton pair as in the $2\ell\text{SS}1\tau_{\text{had}}$ channel is an effective way to suppress the common Standard Model processes, such as dileptonic $t\bar{t}$ ($t \rightarrow W^+b \rightarrow \ell^+\nu_\ell b$, $\bar{t} \rightarrow W^- \bar{b} \rightarrow \ell^-\bar{\nu}_\ell \bar{b}$) and Z + jets processes¹⁶. However, these processes constitute the dominant reducible backgrounds in the $2\ell\text{OS}1\tau_{\text{had}}$ channel because of the requirement of an opposite-charge light lepton pair. The major reducible background contribution is from dileptonic $t\bar{t}$ events with prompt light leptons and a fake τ_{had} candidate. It is estimated using a data-driven method. The fake τ_{had} candidates are typically light-quark, gluon, or heavy-flavor jets. The background contribution from non-prompt light leptons is small and estimated from simulation. Background contributions with prompt light leptons and a real τ_{had} candidate from the $t\bar{t}W$, $t\bar{t}Z$, diboson and rare processes are also small. They are estimated from simulation using the MC samples described in Section 5.5.

In the $2\ell\text{OS}1\tau_{\text{had}}$ channel, all the backgrounds with prompt light leptons and a fake τ_{had} candidate are treated together and referred to as fake τ_{had} background. In this approach, contributions from dileptonic $t\bar{t}$ background, Z + jets production, as well as the part of the $t\bar{t}W$, $t\bar{t}Z$, diboson and rare

¹⁶The cross section of these processes is several orders of magnitude larger than $t\bar{t}H$.

TABLE 5.18: Summary of the selection criteria applied in the $2\ell\text{OS}1\tau_{\text{had}}$ channel. This set of requirements define the $2\ell\text{OS}1\tau_{\text{had}}$ signal region. Same-flavor opposite-charge lepton pair is referred to as SFOC pair.

$2\ell\text{OS}1\tau_{\text{had}}$ signal region
Two loose and isolated light leptons with $p_T > 25, 15$ GeV
Opposite-charge light leptons ($\sum Q_\ell = 0$)
One medium τ_{had} candidate
SLT OR DLT
Trigger matched lepton(s)
$N_{\text{jets}} \geq 3$
$N_{b\text{-jets}} \geq 1$
$m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10$ GeV for the SFOC pair

backgrounds resulting from misidentified τ_{had} candidate are included. The fake-factor method is used to estimate the fake τ_{had} background. The sideband control regions enriched in fake τ_{had} candidates are defined to measure the fake factors in the data. The fake factor is defined as the ratio of the number of events with medium τ_{had} candidate $N_{\tau_{\text{had}}}$ to the events with τ_{had} candidate satisfying the loose, but not the medium criteria $N_{\tau_{\text{had}}^{\text{loose}}}$. In this loose criteria, the τ_{had} candidates are required to pass the very loose working point of the BDT identification, $\text{BDTScore} > 0.35$, and to fail the medium working point $\tau_{\text{had}}^{\text{medium}}$, otherwise satisfying all the selection criteria as described in Section 5.6.3. The fake factors are measured as a function of the p_T of the fake τ_{had} as

$$f_{\tau_{\text{had}}}(i) = \frac{N_{\tau_{\text{had}}}(i)}{N_{\tau_{\text{had}}^{\text{loose}}}(i)}, \quad (5.15)$$

where i refers to the i^{th} p_T bin. In addition, the fake factor is found to be different for 1-track and 3-track τ_{had} candidates. Thus, the fake factors are measured separately for 1-track and 3-track τ_{had} candidates, and as a function of p_T of τ_{had} . These fake factors are applied to the data events in the extrapolation region, event-by-event as a global event weight to estimate the fake τ_{had} background in the $2\ell\text{OS}1\tau_{\text{had}}$ signal region. The extrapolation region has the same event selection as the signal region (Table 5.18), except that the τ_{had} candidate is required to satisfy the loose criteria as described above.

The τ_{had} fake factors are measured in three control regions, in the following referred to as nominal, $t\bar{t}$ and $Z + \text{jets}$ control regions. These control regions are designed to be enriched in $t\bar{t}$ or $Z + \text{jets}$ backgrounds. They are similar to the signal region in terms of kinematics and background composition. The definition of the nominal control region is summarized in Table 5.19. The selection criteria applied in the $t\bar{t}$ and $Z + \text{jets}$ control regions are similar to the nominal control region, except that in the $Z + \text{jets}$ control region events are required to include same-flavor opposite-charge lepton pair with an invariant mass within 10 GeV of the Z mass (Z -peak), whereas in the $t\bar{t}$ control region the jet selection is loosened by requiring at least two jets and exactly one b -tagged jet.

The origin of the fake τ_{had} in the $2\ell\text{OS}1\tau_{\text{had}}$ signal and the control regions is shown in Figure 5.36. The dominant source of the fake τ_{had} is the light-quark and gluon jets. A large fraction from b -jets is also present. Other types of fakes include electron, c -jets, and other contributions. The latter includes muons, hadrons and the cases where the reconstructed τ_{had} cannot be assigned unambiguously to a particular source. The fake factors measured in the nominal control region are used to estimate the fake τ_{had} background in the signal region and those measured in the $t\bar{t}$ and $Z + \text{jets}$ control regions are used to evaluate the systematic uncertainty in order to account for the differences in the fake τ_{had} composition between the signal and the control regions as well as the difference in the rate of

TABLE 5.19: Selection criteria applied in the nominal control region for measuring the τ_{had} fake factors. Same-flavor opposite-charge lepton pair is referred to as SFOC pair.

Leptons	Jets	b -tagged jets	τ_{had} Numerator	τ_{had} Denominator
$N_\ell = 2$, loose and isolated $\sum Q_\ell = 0$ $p_T > 25, 15 \text{ GeV}$ $m(\ell^+\ell^-) > 12 \text{ GeV} \forall \text{ SFOC pair}$ $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10 \text{ GeV} \forall \text{ SFOC pair}$	≥ 3	$= 0$	medium τ_{had}	τ_{had}

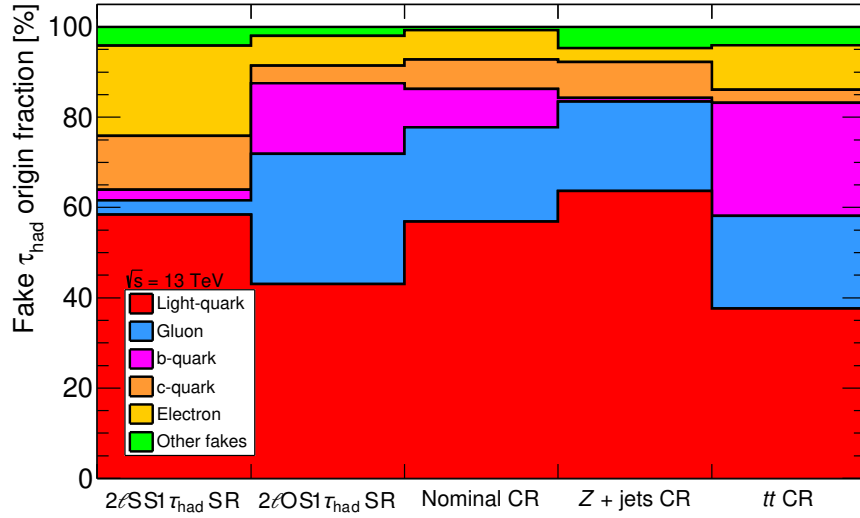


FIGURE 5.36: Composition of the fake τ_{had} in events with medium τ_{had} candidate in the $2\ell\text{OS}1\tau_{\text{had}}$ signal and control regions. The nominal, $t\bar{t}$, and $Z + \text{jets}$ control regions are used to measure the fake factors. The composition of the fake τ_{had} in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region is also shown for comparison.

misidentified τ_{had} candidates resulting from different sources.

Figure 5.37 shows the p_T distributions of the τ_{had} candidate in the nominal, $t\bar{t}$, and $Z + \text{jets}$ control regions for numerator and denominator selection. Overall the $t\bar{t}$ and $Z + \text{jets}$ processes are dominant in these regions. The contribution of the events with a real τ_{had} candidate from simulation is small accounting for only 8%, 10% and 4% of the observed data yield to be subtracted at the numerator in the nominal, $t\bar{t}$, and $Z + \text{jets}$ control regions, respectively. The total amount of events with a real τ_{had} candidate to be subtracted at the denominator is less than 2% of the observed data yield in all the control regions. The τ_{had} fake factor is defined on a per-event basis as

$$f_{\tau_{\text{had}}}(i) = \frac{N_{\tau_{\text{had}}}^{\text{Data}}(i) - N_{\text{Real},\tau_{\text{had}}}^{\text{MC}}(i)}{N_{\tau_{\text{had}}}^{\text{Data}}(i) - N_{\text{Real},\tau_{\text{had}}}^{\text{MC}}(i)}, \quad (5.16)$$

where i refers to the p_T bin. Figure 5.38 shows the fake factors for 1-track and 3-track τ_{had} candidates as a function of p_T after the real τ_{had} subtraction. The bins are chosen based on the size of the data sample. No significant dependence is observed in the fake factors as a function of the number of jets, implying that for $N_{\text{jets}} \geq 2$ the extrapolation is valid. The fake factors as a function of η are also found to be stable.

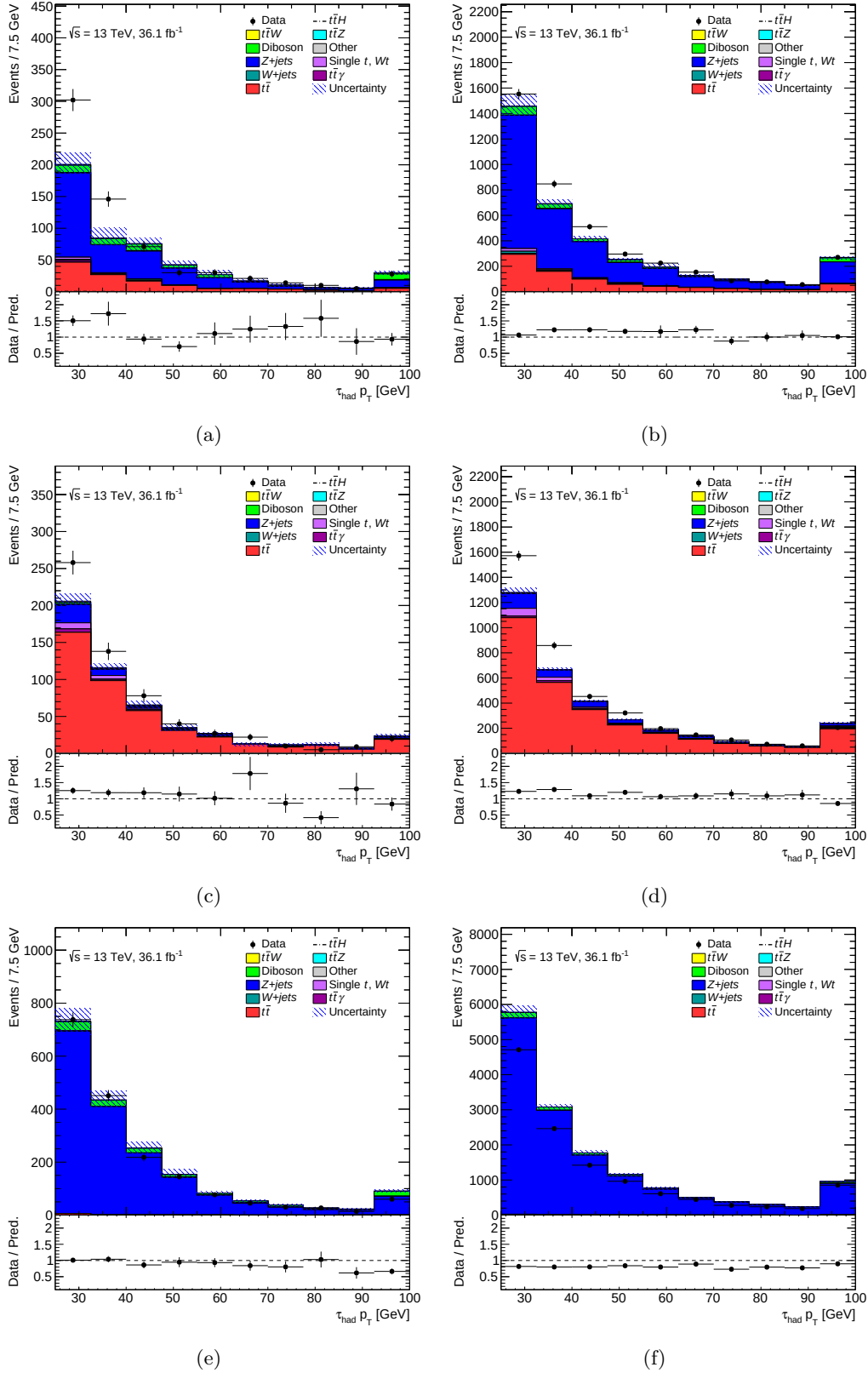


FIGURE 5.37: Distributions of the p_T of τ_{had} in (a, b) the nominal, (c, d) $t\bar{t}$, and (e, f) $Z + \text{jets}$ control regions; (a, c, e) numerator events with medium τ_{had} candidates and (b, d, f) denominator events with loose τ_{had} candidates. The last bin in each figure contains the overflow. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

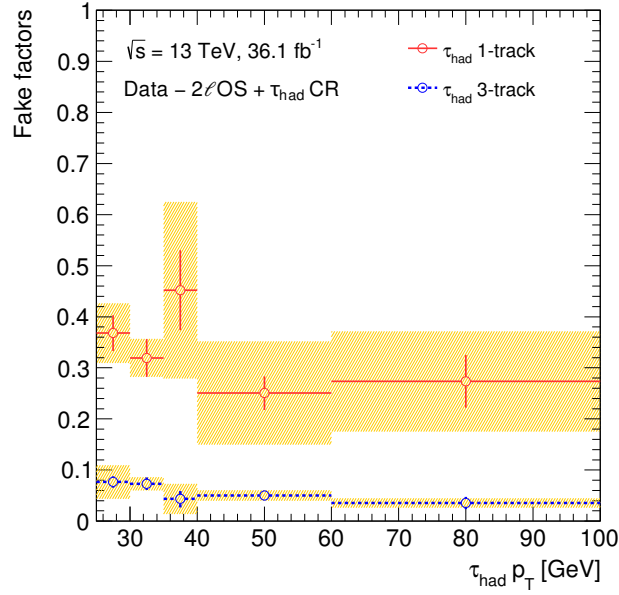


FIGURE 5.38: Fake factors for 1-track and 3-track τ_{had} candidates measured in data as a function of p_T . The error bars indicate the statistical uncertainty and the band represents the systematic uncertainty. The latter includes the variation in the fake factors between the nominal and the $t\bar{t}$ and $Z + \text{jets}$ control regions.

The fake τ_{had} background in the $2\ell\text{OS}1\tau_{\text{had}}$ signal region is estimated as

$$N_{SR}^{\text{fake}} = \sum_i \left[N_{\tau_{\text{had}}(1\text{-track})}^{\text{Data}}(i) - N_{\text{Real}\tau_{\text{had}}(1\text{-track})}^{\text{MC}}(i) \right] \cdot f_{\tau_{\text{had}}(1\text{-track})}(i) + \sum_i \left[N_{\tau_{\text{had}}(3\text{-track})}^{\text{Data}}(i) - N_{\text{Real}\tau_{\text{had}}(3\text{-track})}^{\text{MC}}(i) \right] \cdot f_{\tau_{\text{had}}(3\text{-track})}(i) \quad (5.17)$$

where $N_{\tau_{\text{had}}}^{\text{Data}}$ is the number of data events with loose τ_{had} candidates observed in the extrapolation region and the sum is over i p_T bins of the τ_{had} fake factor. The extrapolation region is dominated by the $t\bar{t}$ background, as shown in Figure 5.39.

Finally, the scale factor κ is measured as

$$\kappa = \frac{N_{\text{FF}}}{N_{\text{MC}}}, \quad (5.18)$$

where N_{FF} and N_{MC} are the total number of events with fake τ_{had} candidates estimated by the fake-factor method and from the out-of-the-box simulation, respectively, in the $2\ell\text{OS}1\tau_{\text{had}}$ signal region.

The total event yield for the fake-factor method fakes with the fake factors derived from nominal, $t\bar{t}$, and $Z + \text{jets}$ control regions is summarized in Table 5.20. The out-of-the-box MC prediction and the scale factors are also summarized in Table 5.20. Uncertainties in the scale factor are derived by comparing the value of κ in the nominal control region to those obtained in the $t\bar{t}$ and $Z + \text{jets}$ control regions. The final scale factor including statistical and systematic uncertainties is:

$$\begin{aligned} \kappa &= 1.36 \pm 0.05 \text{ (stat.)} \pm 0.13 \text{ (syst. } t\bar{t}) \pm 0.07 \text{ (syst. } Z + \text{jets)}, \\ \kappa &= 1.36 \pm 0.16. \end{aligned} \quad (5.19)$$

In order to check the dependence of the scale factor on p_T , the distribution of the p_T of the τ_{had} for the fake-factor fake estimate with the fake factors derived from the nominal control region is compared to the pure simulation prediction, as shown in Figure 5.40. No significant dependence is seen within

the total uncertainty for the scale factor across the $\tau_{\text{had}} p_T$ shape. The final scale factor is applied to the backgrounds containing prompt light leptons and a fake τ_{had} in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region.

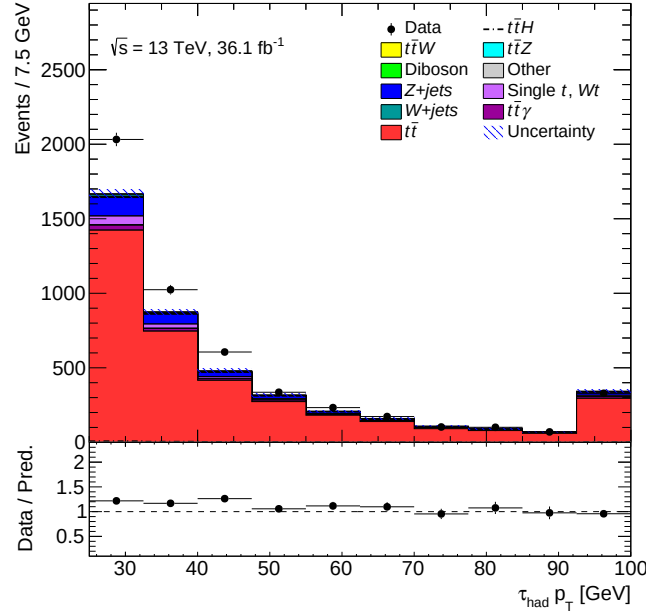


FIGURE 5.39: Comparison of data and prediction of the $\tau_{\text{had}} p_T$ in the $2\ell\text{OS}1\tau_{\text{had}}$ extrapolation region. The selection used to define this region is the same as for the signal region (Table 5.18), except that the τ_{had} candidate is required to satisfy the loose criteria. The fake factors for 1-track and 3-track τ_{had} candidates are applied to the data events in this region to estimate the fake τ_{had} background in the signal region. The last bin contains the overflow. The hatched band in the top panel represents only the statistical uncertainty in the background. The bottom panel displays the ratio of data to the total MC prediction.

TABLE 5.20: Event yields for the fake τ_{had} background estimate by the fake-factor method with the fake factors derived from nominal, $t\bar{t}$, and $Z + \text{jets}$ control regions, and for the out-of-the-box MC prediction in the $2\ell\text{OS}1\tau_{\text{had}}$ signal region. The scale factor κ is calculated according to equation 5.18. The uncertainties are only statistical.

$2\ell\text{OS}1\tau_{\text{had}}$ signal region			
Fake factors input	Nominal CR	$t\bar{t}$ CR	$Z + \text{jets}$ CR
FF method fakes	748.95 ± 14.38	677.94 ± 12.80	708.81 ± 13.82
MC prediction	550.83 ± 15.97		
Scale factor κ	1.36 ± 0.05	1.23 ± 0.04	1.29 ± 0.04

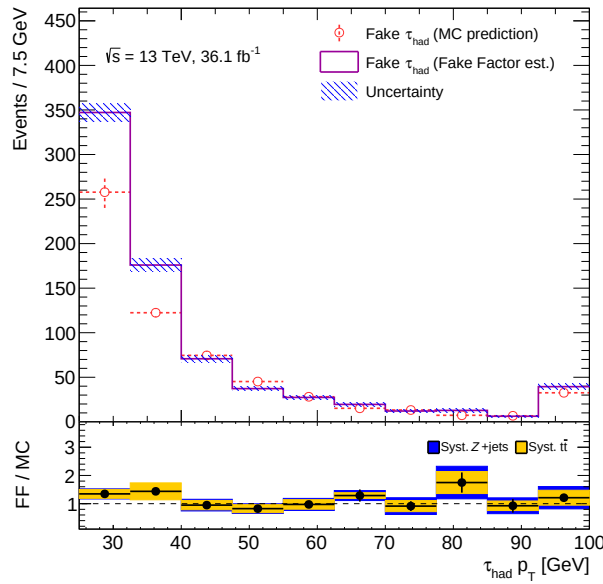


FIGURE 5.40: Distributions of the $\tau_{\text{had}} p_T$ for the fake τ_{had} background estimate by the fake-factor method with fake factors derived from the nominal control region (magenta histogram), and for pure simulation prediction (red circles) in the $2\ell\text{OS}1\tau_{\text{had}}$ signal region. The hatched band in the top panel represents only the statistical uncertainty. The bottom panel displays the scale factor in each bin of the distribution with the hatched band representing its systematic uncertainty.

5.12 Systematic uncertainties

Several sources of systematic uncertainty are accounted for in the analysis that can affect the signal and background yields. These are related to the luminosity, the reconstruction and identification of physics objects, and the modeling of signal and background processes. Each systematic uncertainty can affect either the normalization of a process, or the shape of the final distribution used in the profile likelihood fit (Section 6.1), or both the normalization and shape of the distribution simultaneously. The effect of the systematics is evaluated as $\pm 1\sigma$ variations around the nominal value of a given quantity. The systematic uncertainties considered in the analysis are described in the following.

5.12.1 Experimental uncertainties

The major experimental systematic uncertainties are related to the luminosity measurement, the reconstruction and identification of light leptons and τ_{had} candidates, the energy scale and resolution of jets, and the measurement of b -tagging efficiency and mistag rate for c -jets.

- **Luminosity:** The uncertainty in the combined 2015 and 2016 integrated luminosity is 2.1%. It is derived from a calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016, following a methodology similar to that detailed in Ref. [57]. This systematic uncertainty is applied to all the processes modeled using the MC simulation, as described in Section 5.5, and affect only the normalization. The pile-up reweighting uncertainty is also considered arising from the corrections applied to the simulated events to adjust the profile of pile-up to match the distribution in recorded data.
- **Light leptons:** Uncertainties associated with light leptons arise from the reconstruction, identification, isolation and trigger efficiencies, and from the lepton momentum scale and resolution.

These are measured in data using $Z \rightarrow \ell\ell$, $J/\psi \rightarrow \ell\ell$ decays [71, 154] and found to have negligible impact. In total, uncertainties associated with light leptons include 18 components (Table 5.24).

- **Hadronically decaying tau lepton:** Uncertainties in the τ_{had} identification efficiency are 5% (6%) for one (three) track tau candidates. The uncertainty in the reconstruction efficiency is in the range of 2-4.5%. The tau energy scale uncertainty is 2% (3%) for one (three) track tau candidates. Depending on the pseudorapidity of the tau candidate, the uncertainty for the electron rejection is between 3-14% [81, 82].
- **Jets:** Uncertainties associated with the reconstructed jet arise from the jet energy scale (JES), the jet energy resolution (JER), and the jet vertex tagger (JVT).

Several sources that contribute to the uncertainty in the jet energy scale are decomposed into 21 uncorrelated components and treated as independent sources in the analysis. Out of 21, 8 sources account for the *in situ*¹⁷ calibration uncertainties. The remaining sources include: 3 sources of modeling, statistical, and non-closure uncertainties in the η -intercalibration where an extrapolation of the jet calibration is performed from the central region to the forward regions of the detector; one source of uncertainty in the jet composition between quarks and gluons (flavor composition); 2 sources of uncertainties in the jet response of gluon-initiated jets and b -quark initiated jets (flavor response); 4 sources of uncertainties are related to the in-time and out-of-time pile-up; 2 uncertainties are related to the punch-through effect; one source of high- p_T jet uncertainty from single-particle measurements. The total uncertainty in the JES varies from 1% to 4.5% depending on the jet p_T [76]. Figure 5.41 shows the total jet energy scale uncertainty as a function of the jet η and p_T . The jet energy scale uncertainty has the largest impact on the signal strength in the analysis, given the large number of jets in the signal region. In particular, contributions come from the flavor composition, pile-up subtraction, and the *in situ* calibration uncertainties.

The uncertainty in the jet energy resolution is related to different *in situ* measurements, the change in the topoclustering algorithm, and the change in the noise thresholds [75]. All these systematic uncertainties are combined into one component to be propagated in a correlated way because the uncertainties have a similar shape. The uncertainty in the efficiency of JVT is evaluated by varying the corresponding cut.

- **Flavor tagging:** The b -tagging efficiency and the mistag rates for c -jets and light-flavor jets are measured in data with several calibration analyses [78]. The associated uncertainties are evaluated from the scale factors applied to correct for differences between data and simulation. The uncertainties arising from different sources are decomposed into 126 uncorrelated components. A large number of components is due to the calibration of the distribution of the BDT discriminant. There are 30 uncertainties associated with b -tagging efficiency and 15 (80) with the mistag rate of c -jets (light-flavor jets). The approximate relative size of the b -tagging efficiency uncertainty is 2% for b -jets, 10% for c -jets and τ -jets, and 30% for light-flavor jets. The tagging uncertainty for jets containing either c -hadrons or τ_{had} is taken as fully correlated between the two flavors.
- **Other:** The uncertainties in the energy scales or resolutions of all physics objects can affect the E_T^{miss} . These uncertainties are propagated to the missing transverse energy. A total of three additional sources of uncertainty in the scale and resolution of the E_T^{miss} soft term [89] are considered in the analysis.

¹⁷*In situ* techniques exploit the transverse momentum balance between a jet and a well-measured reference object.

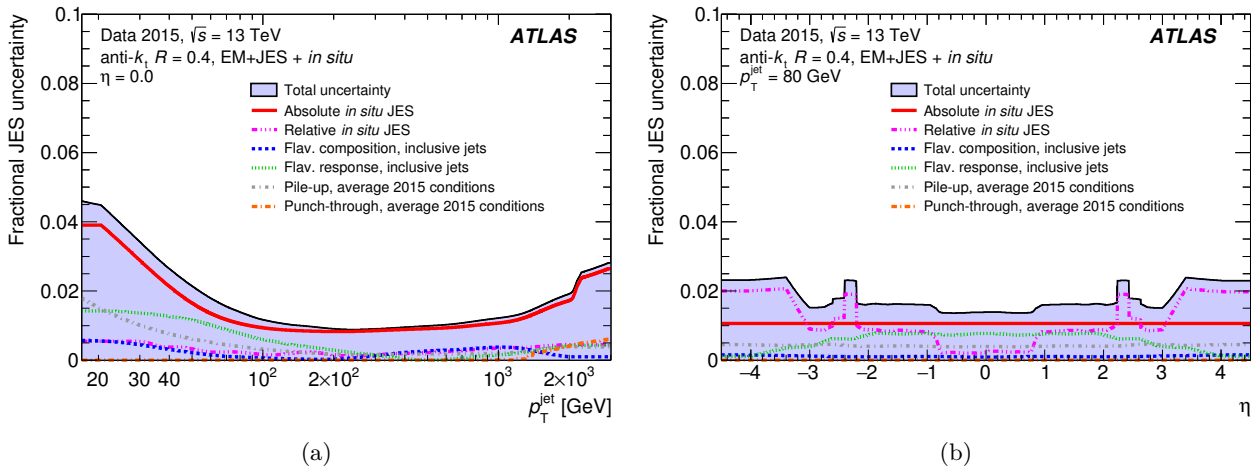


FIGURE 5.41: Combined uncertainty in the JES of fully calibrated jets as a function of (a) jet p_T at $\eta = 0$ and (b) η at $p_T = 80$ GeV. Systematic uncertainty components include pile-up, punch-through, and uncertainties propagated from the η -intercalibration and the *in situ* measurements. The flavor composition and response uncertainties assume a quark and gluon composition taken from simulation [76].

5.12.2 Theoretical uncertainties

The major systematic uncertainties associated with the generation of signal and background processes are due to uncertainties in the production cross sections and acceptance modeling for each process. The uncertainties in the production cross sections for the $t\bar{t}H$, $t\bar{t}W$, and $t\bar{t}Z$ processes are discussed in Section 5.5 and are summarized in Table 5.21. These uncertainties affect only the normalization of the process. An overall 50% uncertainty is assigned to the cross section of diboson production. The uncertainties in the cross sections of rare background processes $tHj\bar{b}$, WtH and $t\bar{t}WW$ are summarized in Table 5.21, while other rare processes tZ , tWZ , $t\bar{t}t$, $t\bar{t}t\bar{t}$, triboson production and rare top decay are each assigned an overall 50% cross section uncertainty that accounts for both the scale and PDF effects.

Moreover, the effect of the variations of renormalization and factorization scales independently and simultaneously by a factor two up and down on the shape of the kinematic distributions of the nominal $t\bar{t}H$, $t\bar{t}W$, and $t\bar{t}Z$ samples is studied. Three sources of systematic uncertainty are considered for each sample. Uncertainties in the SM Higgs boson branching ratios are also considered as three additional sources of systematic uncertainty for the decays $H \rightarrow \tau^+\tau^-$, $H \rightarrow WW^*$, and $H \rightarrow ZZ^*$ and one further source for all the other Higgs boson decays. These are normalization-only uncertainties and affect the $t\bar{t}H$, $tHj\bar{b}$, and WtH samples.

The acceptance uncertainty arises from the choice of event generator, parton shower, as well as from the shower tune. These uncertainties are estimated by comparing the predictions of nominal samples with those obtained using alternative simulated samples with different configurations, as listed in Table 5.2. The difference between the nominal and alternative predictions is symmetrized and used as a two-sided systematic uncertainty. Uncertainty related to the choice of parton shower and hadronization model for $t\bar{t}H$ is estimated by comparing the nominal MG5_AMC@NLO+PYTHIA8 sample with one generated with MG5_AMC@NLO interfaced to HERWIG++. Figure 5.42 shows the impact of the parton shower and hadronization model systematic uncertainty on the distribution of the BDT output for the $t\bar{t}H$ (with $H \rightarrow \tau^+\tau^-$) sample in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region. An overall impact of $\pm 4.7\%$ is observed and no shape dependence is seen after smoothing. The smoothing is a procedure used to decrease the statistical fluctuations in the distributions of the systematic uncertainty. Such statistical fluctuations can cause artificially large and irregular shape variations. In order to prevent

TABLE 5.21: Production cross sections of the $t\bar{t}H$ signal and irreducible background processes. The uncertainties are due to the choice of the QCD renormalization and factorization scales and the choice of PDF and α_S [123, 130].

Process	Cross section [fb]	Uncertainties [%]	
		QCD scale	PDF+ α_S
$t\bar{t}H$	507.1	+5.8 -9.2	± 3.6
$t\bar{t}W$	600.8	+12.9 -11.5	± 3.4
$t\bar{t}Z$	839.3	+9.6 -11.3	± 4.0
$tHjb$	74.25	+6.5 -14.9	± 3.7
WtH	15.17	+6.5 -6.7	± 6.3
$t\bar{t}W^+W^-$	9.904	+10.9 -11.8	± 2.1

this, the smoothing is performed by rebinning the distribution such that the relative uncertainty in each bin is below 8% threshold. If the number of derivative changes (slope) in the distribution is more than four, the tolerance is halved and the smoothing procedure is repeated. Finally, the smoothing function provided by ROOT [159] is applied to the distributions to avoid having artificially flat uncertainties due to rebinning.

For the $t\bar{t}W$ and $t\bar{t}Z$ processes, the systematic uncertainty due to the choice of ME event generator is estimated by comparing the nominal sample with alternative samples generated with SHERPA. Uncertainty associated with the choice of the shower tune is also considered as an additional source of systematic uncertainty for the $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$ and other processes.

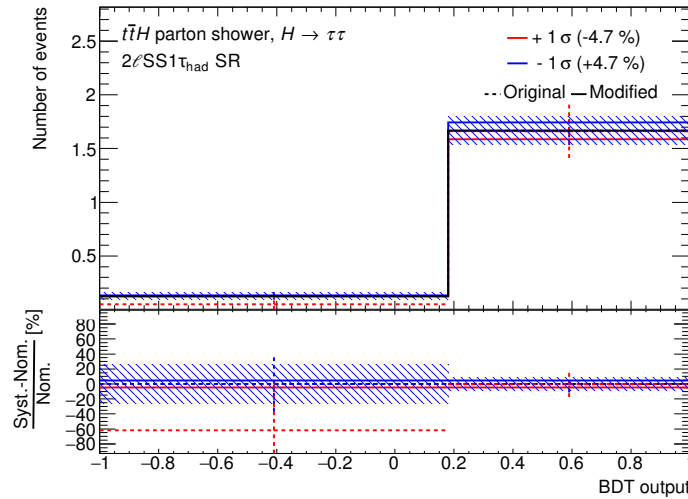


FIGURE 5.42: Impact of the parton shower and hadronization model systematic uncertainty on the distribution of the BDT output for the $t\bar{t}H$ ($H \rightarrow \tau^+\tau^-$) sample in the signal region. The black line represents the nominal distribution of the BDT output. The red (blue) solid line represents the 1σ up (down) variation. The dotted lines show the distributions before the smoothing procedure is applied.

5.12.3 Fake lepton background uncertainties

Systematic uncertainties in the fake lepton background arise from the following sources:

- The uncertainties due to the subtraction of the prompt backgrounds, charge misidentification background, and the $t\bar{t}H$ signal in the control regions.
- The statistical uncertainty in the muon and electron fake factors.
- The uncertainty associated with the α rescaling factor.
- The statistical uncertainty in the data yield in the control region, where the fake factors are applied to estimate the fake lepton background.
- The non-closure uncertainty.

In the fake factor regions (C and D), a theory uncertainty of 15% is assigned to the $t\bar{t}W$ and $t\bar{t}Z$ normalization, a 50% uncertainty is assigned to the diboson normalization, and a 30% normalization uncertainty is assigned to all the rare background processes to account for the production cross section uncertainties from QCD scales and PDF+ α_S . The total event yield of each background is varied independently by the uncertainty assigned to it and the effect on the fake lepton background is evaluated¹⁸. For the subtraction of the charge misidentification background, the total uncertainty in this background estimate is accounted for as a normalization uncertainty in the control region C, whereas an overall 30% uncertainty is considered in the control region D. The charge misidentification subtraction uncertainty in the fake lepton background is anticorrelated with the systematic uncertainty in the charge misidentification prediction in the signal region, as discussed in Section 5.11.2. All of these uncertainties are treated as fully correlated across the fake factor bins and between the control regions C and D. In total, 5 systematic uncertainties account for variations of the background subtraction (Table 5.23).

An additional uncertainty is also accounted for the subtraction of the $t\bar{t}H$ signal in the fake factor regions. This uncertainty is assessed by varying the $t\bar{t}H$ signal event yield by 100% (up) and 10% (down) in the fake factor regions and calculating the overall effect on the fake lepton background. The effect of varying the $t\bar{t}H$ signal yields by 100% is found to be smaller than the statistical uncertainty in the fake lepton background. Moreover, this systematic uncertainty is fully correlated with the signal strength $\mu_{t\bar{t}H}$.

The statistical uncertainties in the muon and electron fake factors are propagated to the final fake lepton background estimate. Each bin of the muon (electron) fake factors is varied independently by its statistical uncertainty. The effect on the fake lepton background estimate is evaluated for each bin variation. As a result, 5 (5) components are considered for the statistical uncertainty in the muon (electron) fake factors.

The systematic uncertainties in the rescaling factor α (equation 5.11) are assessed. A conservative 40% systematic uncertainty is chosen for the conversion fractions. This includes, a 20% uncertainty estimated from studies of the material of the ATLAS inner detector [160], and a 20% uncertainty from a measurement of the $t\bar{t}\gamma$ production cross section [161]. A 50% systematic uncertainty is assigned to the electron non-prompt and conversion fake factors, f_e^{HF} , f_e^γ , respectively, due to the differences observed in the average fake rates between data and simulation. The value of α with its total uncertainty is shown in Table 5.22. One systematic uncertainty is accounted for α that only affects the normalization of the electron fakes in the signal region.

The fake lepton background has a sizeable statistical uncertainty arising from the limited sample of data events in the control region B. Two uncertainties are considered, one for each bin of the BDT output distribution affecting both the normalization and shape of the fake lepton background.

¹⁸The theory uncertainty is also assigned to the prompt backgrounds in the control region B. For each variation of background subtraction, the fake-factor procedure is repeated.

TABLE 5.22: The electron fake factors for heavy flavor fakes and photon conversion fakes estimated from $t\bar{t}$ simulation. The fraction of the fake electron from photon conversion in the control region C (Figure 5.19 (b)), and in the signal region with loose τ_{had} candidates (Figure 5.24). The rescaling factor α with the total uncertainty is shown at the bottom of the table.

Electron fake factors	
f_e^{HF}	0.009
f_e^γ	0.125
γ fraction [%]	
Control region C (ee , $2 \leq N_{\text{jets}} \leq 3$)	46
Signal region (loose τ_{had} , $ee+\text{OF}$, $N_{\text{jets}} \geq 4$)	33
Rescaling factor α	
$0.32^{+0.02}_{-0.03} (\gamma \text{ frac.}) \pm 0.03 (f_e^{HF})^{+0.02}_{-0.06} (f_e^\gamma)$ $0.32^{+0.04}_{-0.07}$	

Figure 5.43 shows the impact of these uncertainties on the distribution of the BDT output for the fake lepton background in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region. An overall impact of about $\pm 19\%$ is observed, whereas the shape has also a non-negligible impact in each bin.

The largest systematic uncertainty in the fake lepton background comes from the non-closure of the fake-factor method. The statistical uncertainty of 50% in the non-closure (Table 5.17) found in $t\bar{t}$ simulation is accounted for as a systematic uncertainty, which affects the normalization of the fake lepton background. The large statistical uncertainty in the non-closure is due to the limited sample of $t\bar{t}$ events in the signal region.

The total systematic uncertainty in the fake lepton background estimate in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region is 55%, dominated by the statistical uncertainty in the non-closure. In total, 27 systematic uncertainties are associated with the fake-factor method fake estimate. These sources of the systematic uncertainties are summarized in Table 5.23.

5.12.4 Fake τ_{had} background uncertainties

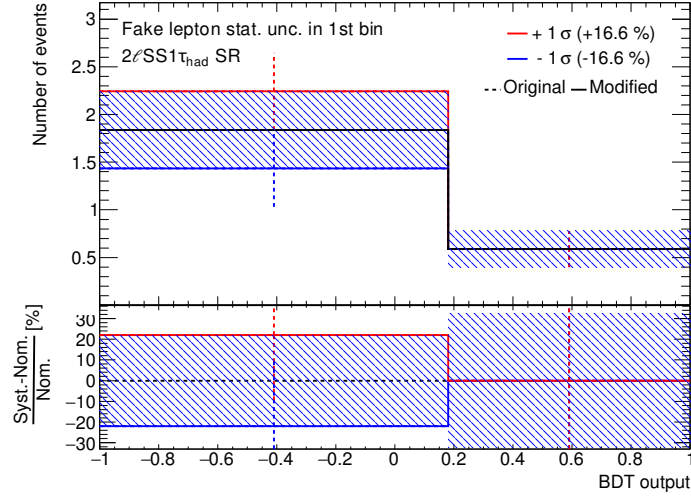
The simulation of the fake τ_{had} backgrounds is corrected with the scale factor κ . The uncertainties in this scale factor are discussed in Section 5.11.3. In total, three systematic uncertainties are accounted for:

- The statistical uncertainty in κ .
- The uncertainty due to the fake τ_{had} background composition regarding $t\bar{t}$.
- The uncertainty due to the fake τ_{had} background composition regarding $Z + \text{jets}$.

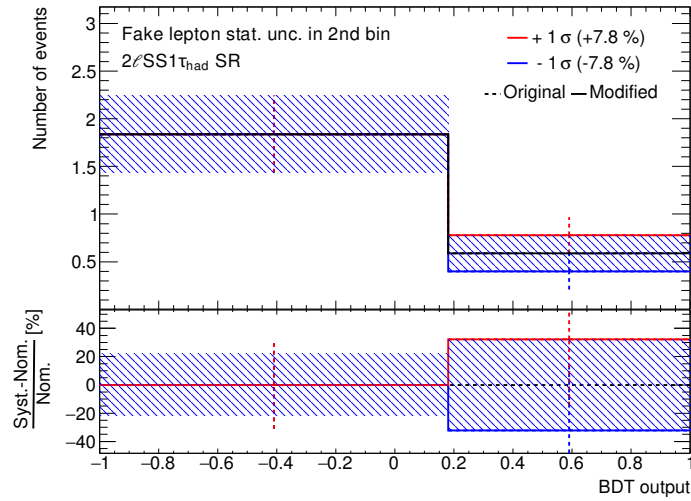
The statistical uncertainty in κ is 3.5%. The dominant systematic uncertainty in κ arises from the composition of the fake τ_{had} background $t\bar{t}$ and $Z + \text{jets}$, and the sizes of these uncertainties are 10% and 5%, respectively. These systematic uncertainties are treated as fully correlated between the $2\ell\text{SS}1\tau_{\text{had}}$ and $2\ell\text{OS}1\tau_{\text{had}}$ signal regions. In addition, all the experimental and theoretical uncertainties described in Sections 5.12.1 and 5.12.2, respectively, are also considered.

The sources of the systematic uncertainties considered in the $2\ell\text{SS}1\tau_{\text{had}}$ channel are summarized in Table 5.24. The experimental uncertainties affect all the simulated samples. The uncertainties associated with the fake light lepton and charge misidentification only affect the corresponding backgrounds

in the signal region. The fake τ_{had} background uncertainties affect all the irreducible backgrounds with the same-charge prompt light leptons and a fake τ_{had} candidate. The signal and irreducible background modeling uncertainties only affect the relevant processes.



(a)



(b)

FIGURE 5.43: Impact of the statistical uncertainty on the fake lepton background in the first bin (a) and second bin (b) of the distribution of the BDT output in the signal region. The black line represents the nominal distribution of the BDT output. The red (blue) solid line represents the 1 σ up (down) variation. The smoothing procedure is not applied for these uncertainties.

TABLE 5.23: Summary of the sources of systematic uncertainty in the fake lepton background estimate. The impact of each uncertainty on the fake lepton background in the $2\text{SS1}\tau_{\text{had}}$ signal region is shown in the rightmost column. The total systematic uncertainty is different from the sum in quadrature of the individual sources, due to the correlations between the different sources of uncertainties.

Source	Process	Up/Dn variations	Affected fake factors	Correlated across fake factor bins	Components	Size [%]	
Prompt background subtraction	$t\bar{t}W$	15%	f_e, f_μ	Yes	1	3.9	
	$t\bar{t}Z$	15%	f_e, f_μ	Yes	1	1.1	
	Diboson	50%	f_e, f_μ	Yes	1	10.5	
	Other	30%	f_e, f_μ	Yes	8	≈ 9.4	
q mis-id background subtraction	–	Numerator (Denominator) q mis-id estimate uncertainty (30%)		f_e	Yes	1	9.3
Signal subtraction	$t\bar{t}H$	100%/10%	f_e, f_μ	Yes	1	6.9	
Stat. unc. in fake factors	–	1σ	f_e, f_μ	No	10	≈ 12	
α	–	–	f_e	Yes	1	3.4	
Stat. unc. in fake lepton bkgd.	–	–	–	–	2	≈ 19	
Non-closure	–	–	–	–	1	50	
Total						55	

TABLE 5.24: Summary of the sources of systematic uncertainty considered in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. “N” means that the uncertainty affects normalization-only of all processes, whereas “S” denotes uncertainties that are considered shape-only in all processes. “SN” means that the uncertainty affects both shape and normalization. Some of the systematic uncertainties are split into several components, as indicated by the number in the rightmost column.

Systematic uncertainty	Type	Components
Luminosity	N	1
Pileup reweighting	SN	1
Physics Objects		
Electron	SN	5
Muon	SN	13
τ_{had}	SN	9
Jet energy scale and resolution	SN	22
Jet vertex fraction	SN	1
Jet flavor tagging	SN	126
E_T^{miss}	SN	3
Total (Experimental)	–	181
Fake lepton and charge misidentification backgrounds		
Background subtraction	N	12
Signal subtraction	N	1
Light lepton fake factors	SN	10
Control region statistics	SN	2
Fake-Factor method non-closure	N	1
γ -conversion fraction	N	1
Electron charge misidentification	SN	1
Total (Reducible backgrounds)	–	28
Fake τ_{had} background		
Scale factor statistics	N	1
Fake τ_{had} composition $t\bar{t}$	N	1
Fake τ_{had} composition $Z + \text{jets}$	N	1
Total	–	3
Signal and irreducible backgrounds		
$t\bar{t}H$		
Cross section (QCD scale, PDF+ α_S)	N	2
Renormalization and factorization scales	S	3
Parton shower and hadronization model	SN	1
Higgs boson branching fraction	N	4
Shower tune	SN	1
$t\bar{t}W$		
Cross section (QCD scale, PDF+ α_S)	N	2
Renormalization and factorization scales	S	3
Matrix element event generator	SN	1
Shower tune	SN	1
$t\bar{t}Z$		
Cross section (QCD scale, PDF+ α_S)	N	2
Renormalization and factorization scales	S	3
Matrix element event generator	SN	1
Shower tune	SN	1
Other backgrounds		
Cross section	N	13
Shower tune	SN	1
Total (Theoretical)	–	39
Total (Overall)	–	251

Chapter 6

Results

In this chapter, the statistical methods used in the analysis to extract the signal strength are described. The results of the $2\ell\text{SS}1\tau_{\text{had}}$ channel are presented and the $t\bar{t}H$ multilepton analysis results are summarized. These results are combined with the ATLAS searches for the $t\bar{t}H$ production using other Higgs boson decay modes. Furthermore, the result of the combined fit is presented.

6.1 Statistical analysis

A statistical analysis is performed to extract the $t\bar{t}H$ signal cross section normalized to the prediction from the Standard Model and to quantify the expected significance. The signal and background predictions as well as the observed data are incorporated in a statistical model. This model is implemented using the **TRExFitter** [162] package which is based on the **HistFactory** [163] tool in the **RooStats** framework [164]. In the following, the description of the statistical model used in this analysis is presented.

6.1.1 The likelihood function

The maximum-likelihood method is widely used in high energy particle physics in searches for new processes, where the likelihood is defined as the probability of observed data being consistent with a given hypothesis. In the search for the $t\bar{t}H$ process, the hypothesis is represented by a *signal strength* parameter, μ , defined as the ratio of the observed $t\bar{t}H$ cross section to the Standard Model predicted cross section¹:

$$\mu = \frac{\sigma_{t\bar{t}H}^{\text{obs}}}{\sigma_{t\bar{t}H}^{\text{SM}}}. \quad (6.1)$$

A value of $\mu = 0$ represents the background-only hypothesis (*null* hypothesis) where no $t\bar{t}H$ signal is present, while $\mu = 1$ represents the signal-plus-background (S+B) hypothesis which coincides with the SM Higgs boson production.

Consider a binned distribution of events in the signal region e.g., the BDT output histogram. The expected number of events in the bin i of the histogram can be expressed as

$$E[n_i] = \mu \cdot s_i + b_i, \quad (6.2)$$

where s_i and b_i represent the expected number of signal and background events, respectively, in the i^{th} bin of the distribution. The data in a given bin is expected to follow a Poisson probability distribution around its expected number of events. The statistical analysis of the data is based on a binned likelihood function, which is constructed from a product of Poisson probability terms for all bins N

¹ Assuming a Higgs boson mass of $m_H = 125$ GeV.

of the distribution as a function of μ written as

$$L(\mu) = \prod_i^{N_{\text{bins}}} \frac{(\mu \cdot s_i + b_i)^{n_i}}{n_i!} e^{-(\mu \cdot s_i + b_i)}, \quad (6.3)$$

where n_i is the number of observed data events [165].

The impact of the systematic uncertainties on the signal and background expectations is described by the nuisance parameters (NPs), $\boldsymbol{\theta}$ ². The NPs are constrained by the probability density functions (*pdfs*). The choice of the *pdf* for NP depends on the type of the uncertainty associated with it. The Gaussian *pdf* is a frequent choice for NPs, as it described the uncertainties on parameters that can be both positive and negative. The nuisance parameter is expected to be distributed as a Gaussian with a width equal to the uncertainty on the parameter, as estimated from auxiliary measurements. However, the Gaussian *pdf* is not suited for positively defined observables such as luminosity, cross sections, efficiencies etc. The log-normal *pdf* is used for nuisance parameters associated to these observables, which affect only the normalization, in order to ensure that they are always positive. The statistical uncertainty in the simulated background predictions and the fake light lepton background are included as bin-by-bin NPs using the technique described in Ref. [166]. The gamma distribution is used for describing these statistical uncertainties. The *pdfs* are included in the likelihood function as an additional terms. The full likelihood as a function of μ and the set of nuisance parameters $\boldsymbol{\theta}$ is written as

$$L(\mu, \boldsymbol{\theta}) = \prod_i^{N_{\text{bins}}} \frac{(\mu \cdot s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-(\mu \cdot s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))} \prod_{\theta_k \in \boldsymbol{\theta}} \rho(\theta_k), \quad (6.4)$$

where $\rho(\theta)$ represents the prior *pdfs* for each nuisance parameter. Thus, the expected number of signal and background events in a given bin is a function of $\boldsymbol{\theta}$.

The signal strength μ is chosen as parameter of interest (PoI) and represents a free parameter (an unconstrained parameter). The best estimate for μ and $\boldsymbol{\theta}$ is obtained by maximizing the likelihood or equivalently minimizing the negative logarithm of the likelihood (negative log-likelihood).

6.1.2 Test statistic

The compatibility of the observed data with the prediction for the given hypothesis is quantified by defining a *test statistics*. The test statistics used in the analysis is based on the profile likelihood ratio [165], where the likelihood function is defined in equation 6.4. The profile likelihood ratio as a function of μ is written as

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, \quad (6.5)$$

where the $\hat{\boldsymbol{\theta}}$ at the numerator denotes the value of $\boldsymbol{\theta}$ that maximizes the likelihood for the specified μ , it is called the conditional maximum-likelihood (ML) estimator of $\boldsymbol{\theta}$, and thus it is a function of μ . The $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ at the denominator are the unconditional ML estimators of μ and $\boldsymbol{\theta}$, respectively. The presence of the nuisance parameters broadens the profile likelihood as a function of μ relative to what one would have if their values were fixed. This reflects the loss of information about μ due to the systematic uncertainties.

The profile likelihood ratio $\lambda(\mu)$ varies between 0 and 1, with $\lambda \approx 1$ signifying good agreement between data and the hypothesized value of μ . The presence of a new signal can only increase the mean event rate beyond the background expectation. Thus, the signal strength μ has physical meaning only when it is positive $\mu > 0$ and any physical estimator for μ must be non-negative. However, it is more suitable to use an effective estimator $\hat{\mu}$ as the value of μ that maximizes the likelihood, which

² The vector $\boldsymbol{\theta} = (\boldsymbol{\theta}_s, \boldsymbol{\theta}_b)$ denotes all the nuisance parameters, where the vectors $\boldsymbol{\theta}_s$ and $\boldsymbol{\theta}_b$ represent the parameters that characterize the signal and background shape through a probability density functions.

is allowed to take on negative values ($\hat{\mu} < 0$) but providing that the Poisson mean values ($\mu.s + b$) remain non-negative. If data results in $\hat{\mu} < 0$ due to downward fluctuations, then the best agreement between data and any physical value of μ occurs for $\mu = 0$. Therefore, the profile likelihood ratio is modified as

$$\lambda(\mu) = \begin{cases} \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & \hat{\mu} \geq 0, \\ \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0, \end{cases} \quad (6.6)$$

where $\hat{\theta}(\mu)$ and $\hat{\theta}(0)$ are the conditional ML estimators of θ given a strength parameter of μ and 0, respectively. It is convenient to define the test statistics as:

$$t_\mu = -2 \ln \lambda(\mu) = \begin{cases} -2 \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & \hat{\mu} \geq 0, \\ -2 \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0. \end{cases} \quad (6.7)$$

Thus, the larger values of t_μ correspond to increasing incompatibility between data and μ . The level of disagreement is quantified by computing the p -value

$$p_\mu = \int_{t_{\mu, \text{obs.}}}^{\infty} f(t_\mu | \mu) dt_\mu, \quad (6.8)$$

where $t_{\mu, \text{obs.}}$ is the value of the test statistics observed from the data and $f(t_\mu | \mu)$ represents the pdf of t_μ under the assumption of μ .

For the discovery of a new signal with non-negative strength ($\mu \geq 0$), such as $t\bar{t}H$, the statistic t_μ is used to reject the background-only hypothesis, i.e., $\mu = 0$. Using equation 6.7 with $\mu = 0$, the test statistics (q_0) for discovery is defined as

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu} \geq 0, \\ 0 & \hat{\mu} < 0, \end{cases} \quad (6.9)$$

where $\lambda(0)$ is the profile likelihood ratio for $\mu = 0$ as defined in equation 6.5. The p -value is computed using the observed value of q_0 similarly as done with t_μ to quantify the level of disagreement between data and the null hypothesis, namely,

$$p_0 = \int_{q_{0, \text{obs.}}}^{\infty} f(q_0 | 0) dq_0, \quad (6.10)$$

where $f(q_0 | 0)$ denotes the pdf of the statistic q_0 under the assumption of the background-only hypothesis.

In particle physics, when performing searches, it is common to convert the p -value into a significance Z . The significance is defined such that a Gaussian distributed variable which is Z standard deviations above its mean has an upper-tail probability equal to p -value

$$Z = \Phi^{-1}(1 - p), \quad (6.11)$$

where Φ^{-1} is the inverse function of Φ , i.e., the quantile (inverse of the cumulative distribution) of the standard Gaussian. In the particle physics community, the significance required to reject the background-only hypothesis is set to $Z = 5$ as an appropriate level (5σ) to constitute a *discovery*. This corresponds to a value of $p = 2.87 \cdot 10^{-7}$. If the significance of $Z \geq 3$ is found, an *evidence* is reported for a new process. In order to exclude a signal hypothesis, a p -value of 0.05 (i.e., 95% confidence level) is used that corresponds to $Z = 1.64$ [165].

6.1.3 Approximate distribution of the profile likelihood ratio

In order to find the p -value of a hypothesis, it is necessary to determine the sampling distribution for the test statistic being used. Specifically for the case of discovery, the distribution $f(q_0|0)$ needs to be determined when the background-only hypothesis ($\mu = 0$) is being tested. This can be done by generating a large number of MC pseudo-experiments. That would require large computational resources. Therefore, an approximation of the distribution is used in the large sample limit (“asymptotic limit”) by applying the results from Wald [167] and Wicks [168]. The approximation is also found to provide an accurate results even for small samples.

The desired distribution is found using Wald’s approximation in the case of a single parameter of interest

$$-2 \ln \lambda(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} + \mathcal{O}(1/\sqrt{N}), \quad (6.12)$$

where $\hat{\mu}$ follows a Gaussian distribution with a mean μ' and standard deviation σ , and N represents the data sample size. By neglecting the $\mathcal{O}(1/\sqrt{N})$ term, the statistic $-2 \ln \lambda(\mu)$ follows a non-central χ^2 distribution for one degree of freedom with noncentrality parameter Λ :

$$\Lambda = \frac{(\mu - \hat{\mu})^2}{\sigma^2}. \quad (6.13)$$

The standard deviation σ of $\hat{\mu}$ is estimated from the so-called “Asimov” dataset [165]. The Asimov dataset is an artificial representative dataset which replaces the ensemble testing performed with pseudo-experiments with a single dataset. It is defined in such a way that when used to evaluate the estimators for all parameters, one obtains the true parameter values.

Assuming the Wald approximation, the test statistics for discovery q_0 (equation 6.9) can be written as

$$q_0 = \begin{cases} \hat{\mu}^2/\sigma^2 & \hat{\mu} \geq 0, \\ 0 & \hat{\mu} < 0, \end{cases} \quad (6.14)$$

where $\hat{\mu}$ is Gaussian distributed with mean μ' and standard deviation σ . From this the *pdf* $f(q_0|0)$ is determined, which has the form:

$$f(q_0|0) = \frac{1}{2} \delta(q_0) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_0}} e^{-q_0/2}. \quad (6.15)$$

It follows a half chi-square distribution, i.e., $\frac{1}{2} \chi^2$ for one degree of freedom. The corresponding cumulative distribution is found to be

$$F(q_0|0) = \Phi(\sqrt{q_0}). \quad (6.16)$$

Using equations 6.10 and 6.16, one obtains a simple expression for the significance:

$$Z_0 = \Phi^{-1}(1 - p_0) = \sqrt{q_0}. \quad (6.17)$$

6.1.4 Expected significance

In order to characterize the sensitivity of the search, it is useful to quote the expected (median) significance assuming a data distributed according to a specified signal model. In this model, the background-only ($\mu = 0$) hypothesis is excluded. In this case, the distribution $f(q_0|\mu')$ with $\mu' = 1$ has the median q_0 , and thus the median discovery significance. The Asimov dataset is used to find the median value of q_0 by using the equation 6.17 (assuming the signal strength μ'):

$$\text{med}[Z_0|\mu'] = \sqrt{q_{0,\Lambda}}. \quad (6.18)$$

In order to test the sensitivity of the search in the presence of the $t\bar{t}H$ signal the $\mu' = 1$ is assumed.

6.2 Results of the $2\ell SS1\tau_{\text{had}}$ channel

In this section, the results of the $2\ell SS1\tau_{\text{had}}$ channel are presented. Table 6.1 shows a comparison of the predicted event yields to data in the signal region before the fit to the observed data (pre-fit). The dominant backgrounds are the fake lepton, fake τ_{had} , and $t\bar{t}Z$. They account for 29%, 22%, and 22% of the total predicted background, respectively, as shown in Figure 6.1. A maximum-likelihood fit to the data is performed to extract the signal strength $\mu_{t\bar{t}H}$. The BDT output distribution is used as a final discriminant and given as input to the fit. Figure 6.2 (a) shows the pre-fit distribution of the BDT output for data and prediction in the signal region. A small excess of data over the prediction is observed in the second bin of the BDT discriminant, however, within two standard deviations of statistical fluctuations. The pre-fit distributions of the input variables to the BDT discriminant in the signal region are given in Appendix A (Figure A.1).

The fit uses templates constructed from the predicted event yields in the bins of the input distribution. The fit is based on the profile likelihood approach, as detailed in Section 6.1, where the systematic uncertainties are treated as nuisance parameters. As described in Section 5.12, several systematic uncertainties affect the final results. In total 251 NPs are considered, most having experimental origin. Systematic uncertainties that have a negligible impact on the final results are discarded to improve the speed of the fit. A normalization or a shape uncertainty is not applied if the associated variation is below 1% in all bins. Most of the neglected NPs are related to flavor tagging. Moreover, the correlations between the uncertainties are also considered. In particular, as the residual prompt (mainly $t\bar{t}W$ and diboson) background contribution is subtracted from the control regions to extract the light lepton fake factors, the associated nuisance parameters are taken as fully correlated with the theoretical cross section systematic uncertainties. The same treatment is used for the uncertainty associated to the measurement of the charge misidentification background, which is also subtracted from the control regions.

Table 6.1 also compares the data to the yields after the fit to the observed data (post-fit). The post-fit $t\bar{t}H$ signal event yield and the uncertainty reflect the best-fit production rate of $1.6^{+0.5}_{-0.4}$ times the SM prediction, and it is obtained using a maximum-likelihood global fit to the data yields of all the signal and control regions of the $t\bar{t}H$ to multilepton analysis (Section 6.3). Figure 6.2 (b) shows the post-fit BDT output distribution. The level of agreement is improved in the post-fit as the background predictions were adjusted by the fit.

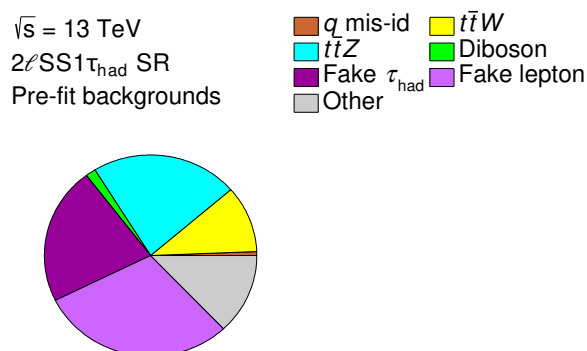


FIGURE 6.1: Fractional contributions of the various backgrounds to the total predicted background in the signal region before the fit to the data (pre-fit). The background estimation methods are described in Section 5.11. Rare processes tZ , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t$, $tHjb$, WtH , triboson production and rare top decay are labeled as “Other”.

TABLE 6.1: Background, signal and observed event yields in the signal region. Uncertainties are statistical plus systematic. Fake lepton, q mis-id and fake τ_{had} refer to the background estimates described in Section 5.11. Rare processes tZ , tW , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tH , triboson production and rare top decay are labeled as “Other”. The pre-fit values correspond to the initial values of background systematic uncertainty nuisance parameters and the signal expected from the SM prediction. In the post-fit case, the uncertainty in the total background estimate is smaller than for the pre-fit values due to anticorrelations between the nuisance parameters obtained in the fit.

	Pre-fit	Post-fit
Fake lepton	2.4 ± 1.4	1.86 ± 0.91
Fake τ_{had}	1.80 ± 0.30	1.86 ± 0.27
q mis-id	0.05 ± 0.02	0.05 ± 0.02
$t\bar{t}W$	0.88 ± 0.24	0.97 ± 0.26
$t\bar{t}Z$	1.83 ± 0.37	1.96 ± 0.37
Diboson	0.12 ± 0.18	0.15 ± 0.20
Other	1.06 ± 0.24	1.09 ± 0.24
Total background	8.2 ± 1.6	7.9 ± 1.2
$t\bar{t}H$	3.09 ± 0.46	5.1 ± 1.3
Data	18	

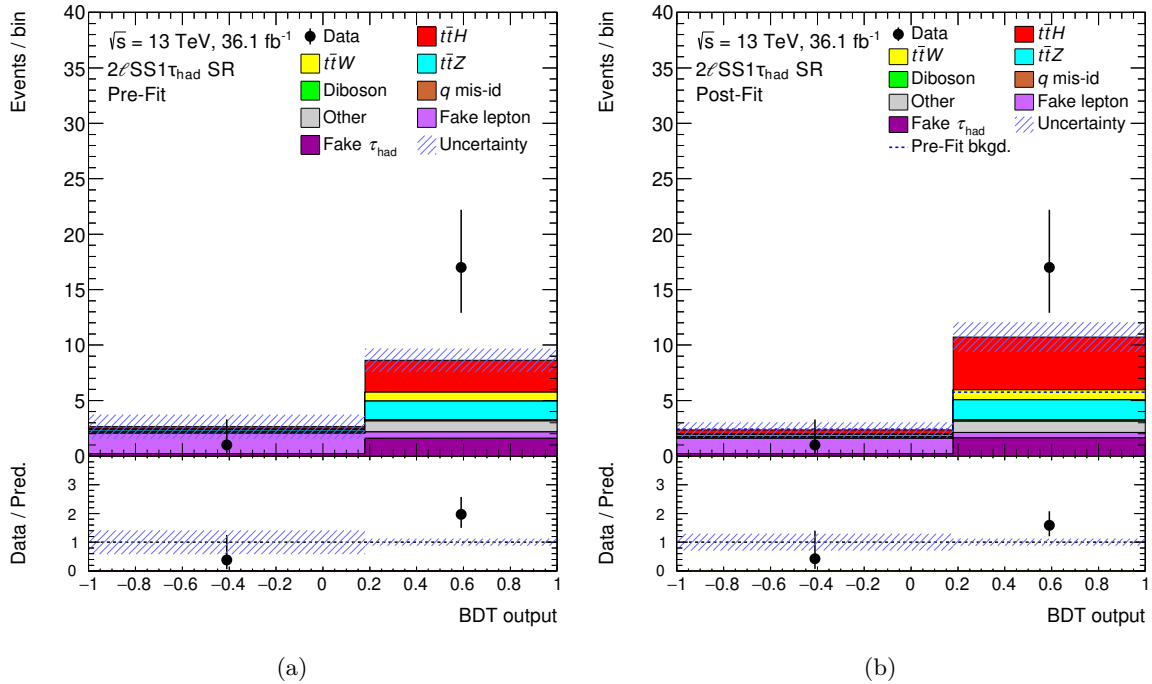


FIGURE 6.2: Comparison between data and prediction for the BDT discriminant in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region (a) before, and (b) after the fit to the observed data. The background contributions are shown as filled histograms. The $t\bar{t}H$ signal post-fit is scaled according to the results of the global fit ($\mu_{t\bar{t}H} = 1.6$) and shown as a filled red histogram superimposed on the fitted background. The size of the combined statistical and systematic uncertainty is indicated by the blue hatched band.

TABLE 6.2: Observed and expected best-fit values of the signal strength μ and associated significances relative to the background-only hypothesis in the $2\ell SS1\tau_{\text{had}}$ channel.

Best-fit μ	
Observed	$3.5^{+1.5}_{-1.2} \text{ (stat.) }^{+0.9}_{-0.5} \text{ (syst.)} = 3.5^{+1.7}_{-1.3}$
Expected	$1.0^{+1.1}_{-0.8} \text{ (stat.) }^{+0.5}_{-0.3} \text{ (syst.)} = 1.0^{+1.2}_{-0.9}$
Significance	
Observed	3.4σ
Expected	1.1σ

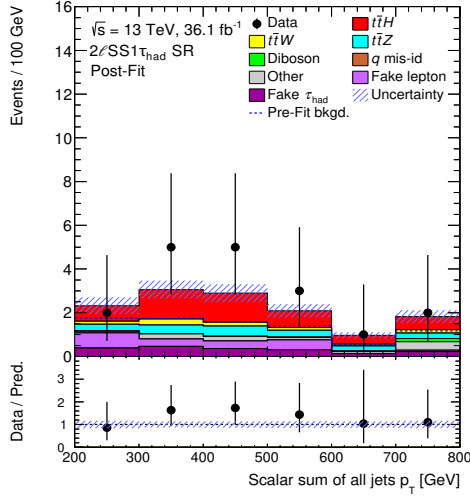
Figure 6.3 shows the post-fit distributions of the thirteen input variables of the BDT discriminant in the signal region. Within the uncertainties, good agreement is observed between data and prediction for these variables. Additional post-fit distributions of the event kinematics in the signal region are given in Appendix A (Figures A.4, A.5, and A.6).

The observed and expected best-fit values of μ are shown in Table 6.2 (top part). The observed best-fit value of μ is $3.5^{+1.7}_{-1.3} = 3.5^{+1.5}_{-1.2} \text{ (stat.) }^{+0.9}_{-0.5} \text{ (syst.)}$. The statistical uncertainty contributes more than the systematic component to the overall uncertainty of the measurement. The statistical uncertainty is determined by fixing all NPs to their best-fit values and redoing the fit. The systematic uncertainty is obtained by subtracting in quadrature the statistical uncertainty from the total uncertainty. Table 6.2 (bottom part) shows the observed and expected significances relative to the background-only hypothesis, calculated using the methods described in Section 6.1. The expected results are obtained in the same way as the observed results by replacing the data in each bin of the input distribution by the prediction from simulation and the data-driven fake lepton estimates and with all NPs set to their best-fit values obtained from the fit to data.

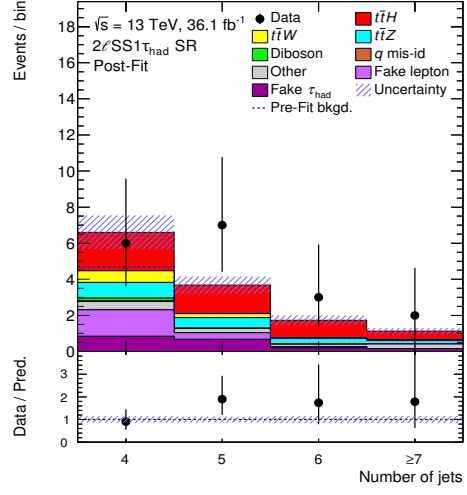
Figure 6.4 shows the log-likelihood scan as a function of $\mu_{t\bar{t}H}$ for the fit to data, obtained by minimizing the function for each value of μ . The distribution is smooth and shows no irregularity. The uncertainty in μ is determined by the values at which $\Delta(-\ln L) = 0.5$.

It is important to assess the impact of each systematic uncertainty on the final result. In particular, to investigate how far the nuisance parameters are pulled away from their nominal values and how their uncertainties are constrained. For this purpose, a ranking of nuisance parameters is introduced. For each nuisance parameter, the fit is performed again with the parameter fixed to its fitted value varied up or down by its fitted uncertainty, with all the other parameters allowed to vary. The ranking obtained for those nuisance parameters with the largest contribution to the uncertainty in the signal strength is shown in Figure 6.5. A good agreement is found between the pre-fit and post-fit values of the nuisance parameters and neither large pulls nor large constraints are observed. The nuisance parameter with the largest pull from its nominal value is the uncertainty in the fake lepton background estimate due to the fake-factor method non-closure. This pull is mainly due to the slight deficit observed in the first bin of the BDT discriminant (Figure 6.2) relative to the prediction. The systematic uncertainty in the $t\bar{t}H$ cross section due to QCD scale variations has the largest impact on μ . Other systematic uncertainties with a large impact are those associated with the signal modeling, the τ_{had} identification and the jet energy scale. The uncertainty in the jet energy scale mainly arises from the jet flavor composition of the combined $t\bar{t}H$, $t\bar{t}V$, other processes, and the pile-up subtraction.

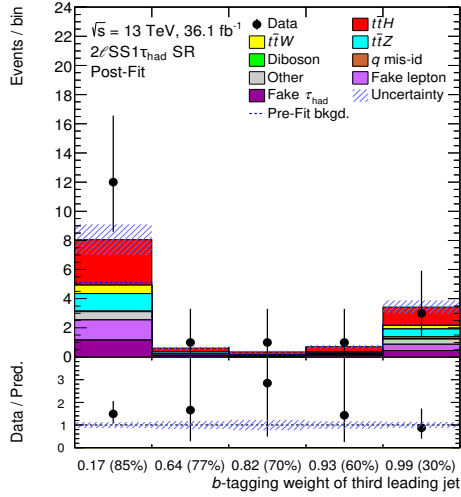
The correlations between the nuisance parameters are checked, as shown in Figure 6.6. In general, no unexpected correlations between NPs are observed. The largest correlation (18%) is observed between the $t\bar{t}H$ parton shower and the signal strength $\mu_{t\bar{t}H}$. The $t\bar{t}H$ parton shower uncertainty has an impact on the distribution of the BDT discriminant for the $t\bar{t}H$ signal samples, as discussed in Section 5.12.



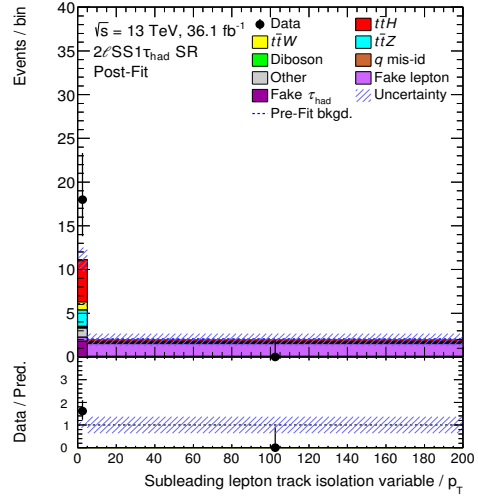
(a)



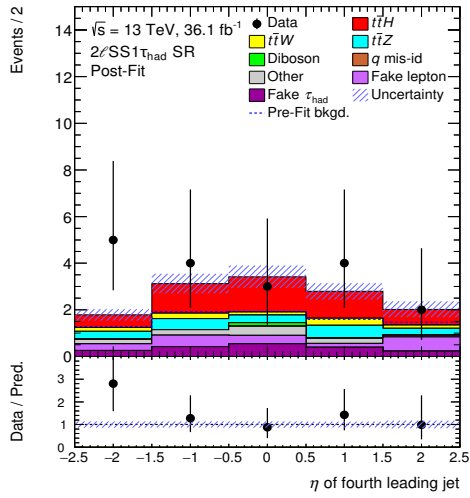
(b)



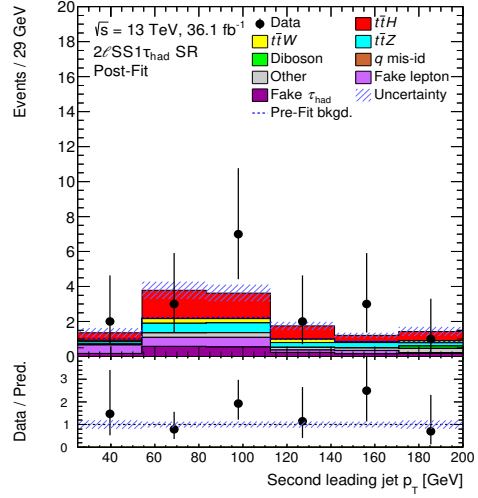
(c)



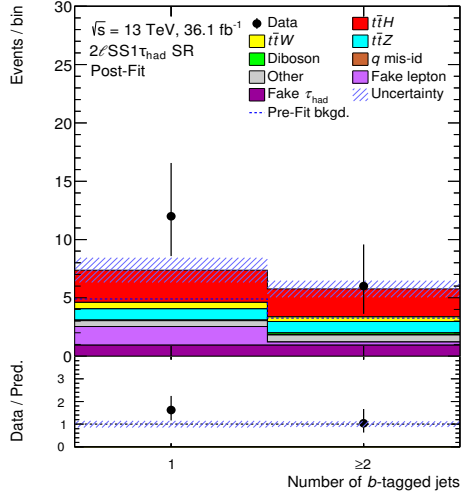
(d)



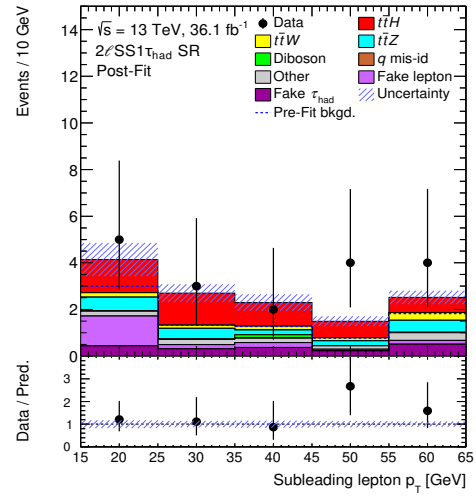
(e)



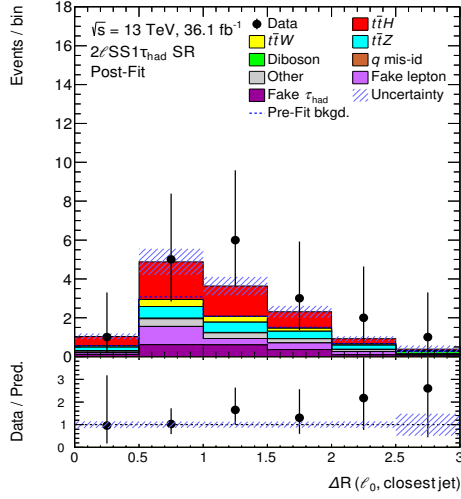
(f)



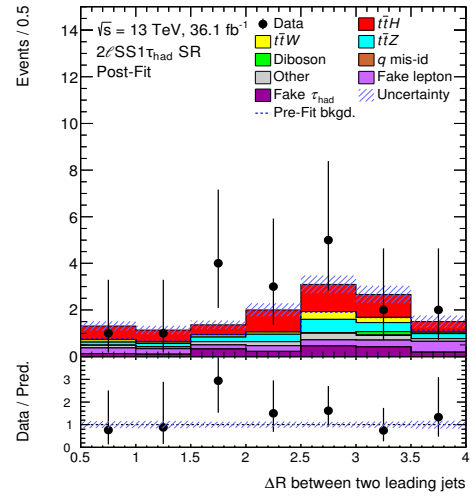
(g)



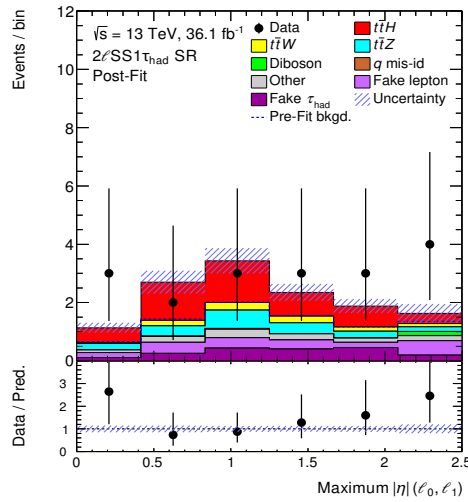
(h)



(i)



(j)



(k)

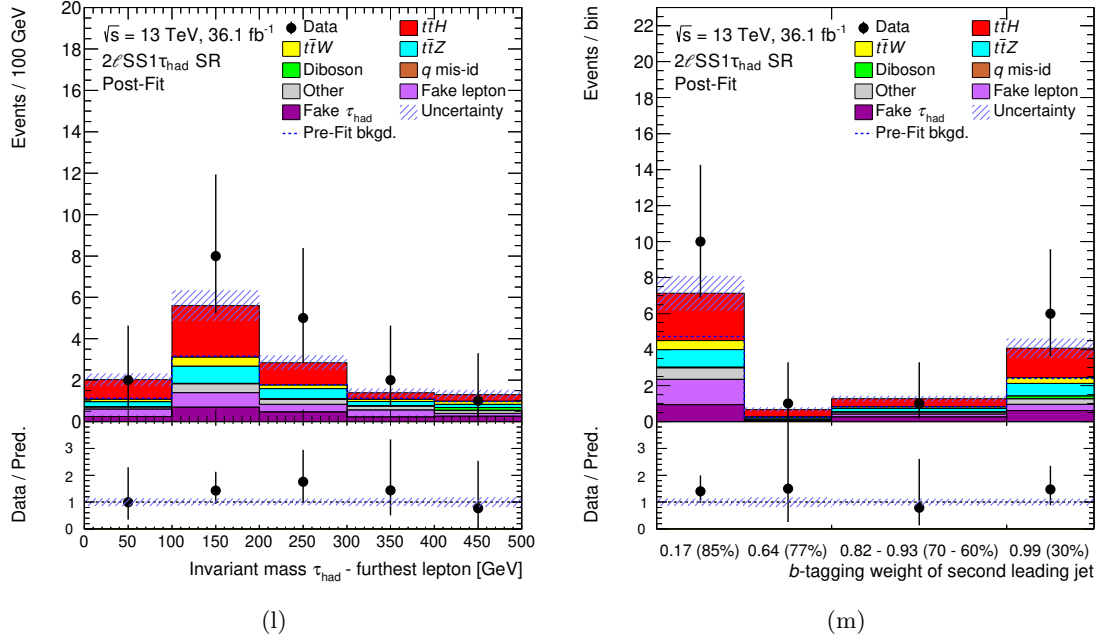


FIGURE 6.3: Comparison between data and prediction for the discriminating variables used as input to the BDT in the $2\ell\text{SS}1\tau_{\text{had}}$ signal region after the fit to data. The $t\bar{t}H$ signal contribution is shown as a filled red histogram stacked at the top of the fitted backgrounds, normalized to the fitted value ($\mu_{t\bar{t}H} = 1.6$). The total uncertainty is shown by the blue hatched band. The total background before the fit (Pre-Fit bkgd.) is shown as a dashed blue histogram. The bottom panel displays the ratio of data to the sum of the signal and fitted background.

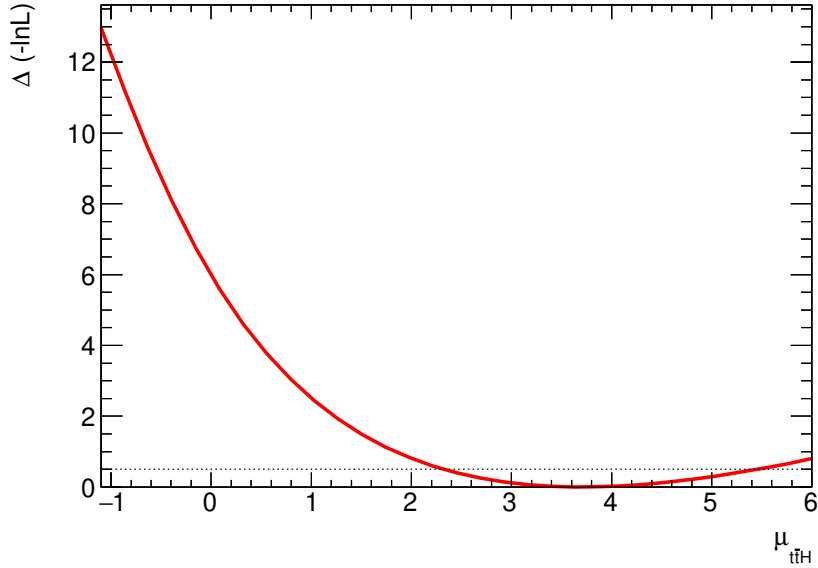


FIGURE 6.4: Profile $\Delta(-\ln L(\mu)) = -(\ln L(\mu) - \ln L(\mu_{\text{min.}}))$ as a function of the signal strength. The minimum value corresponds to the best-fit value of μ . The intersections of the curve with the horizontal dashed line at $\Delta(-\ln L) = 0.5$ corresponds to the $\pm 1\sigma$ variations of μ .

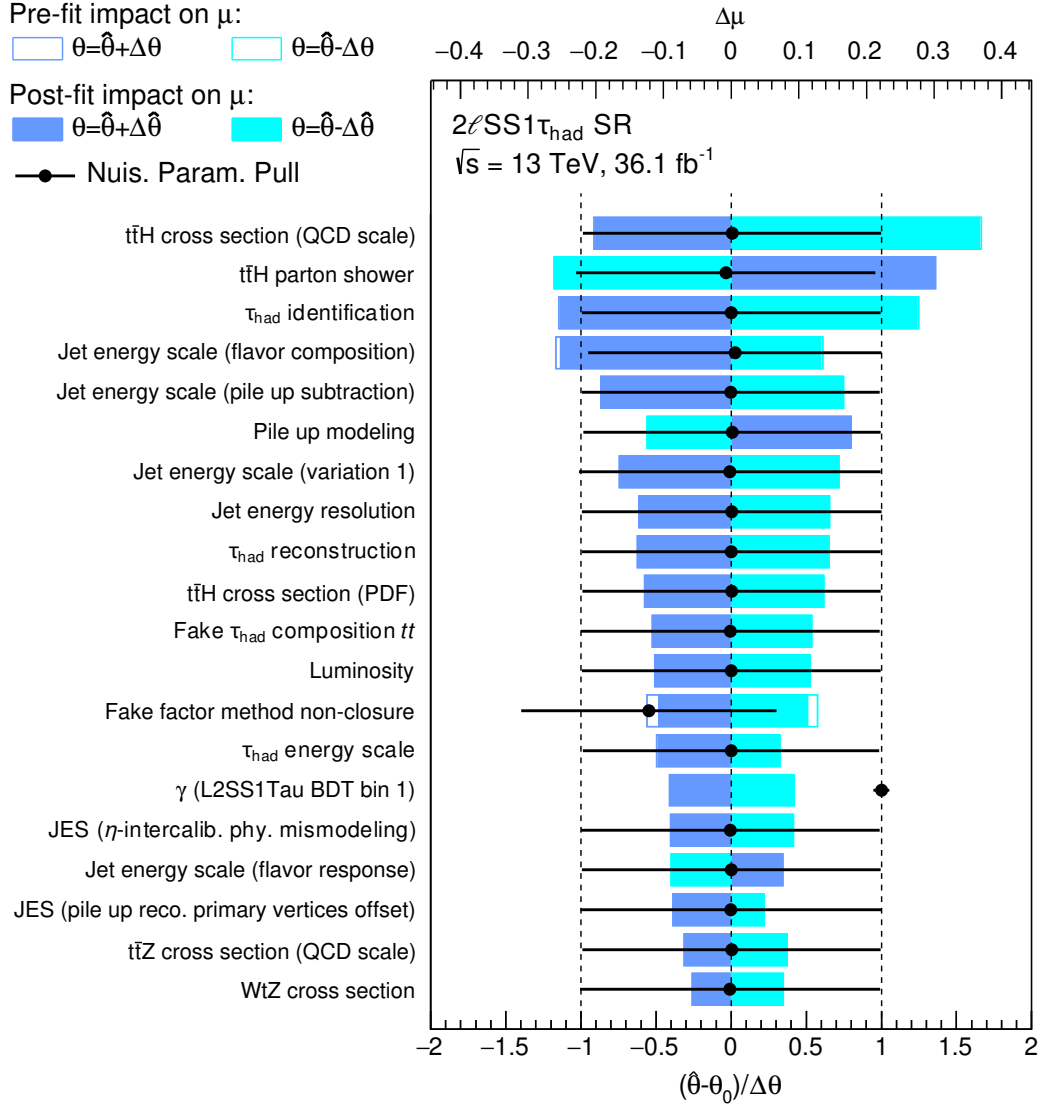


FIGURE 6.5: Impact of systematic uncertainties on the measured signal strength μ for the $2\ell SS1\tau_{\text{had}}$ channel. Only the 20 most significant systematic uncertainties are shown and listed in decreasing order of their impact on μ on the y -axis. The empty (filled) blue/cyan boxes correspond to the pre-fit (post-fit) impact on μ , referring to the upper x -axis. The impact of each systematic uncertainty, $\Delta\mu$, is calculated by comparing the nominal best-fit value of μ with the result of the fit when fixing the corresponding nuisance parameter θ to its best-fit value $\hat{\theta}$ shifted by its pre-fit (post-fit) uncertainties $\hat{\theta} \pm \Delta\theta$ ($\hat{\theta} \pm \Delta\hat{\theta}$). The black points, which refer to the lower x -axis, show the pulls of the fitted nuisance parameters, i.e., the deviations of the fitted parameters $\hat{\theta}$ from their nominal values θ_0 , normalized to their nominal uncertainties $\Delta\theta$. The black lines show the post-fit uncertainties of the nuisance parameters, relative to their nominal uncertainties, which are indicated by the dashed lines.

$t\bar{t}H$ signal strength (μ)	100.0	-17.9	-8.6	18.1	-8.7	0.1	-9.2	-17.2	9.9	-12.0	-13.5	-10.7	-9.7
$t\bar{t}H$ cross section (QCD scale)	-17.9	100.0	-0.0	0.0	-0.0	0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0
$t\bar{t}H$ cross section (PDF)	-8.6	-0.0	100.0	0.0	-0.0	0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0
$t\bar{t}H$ parton shower	18.1	0.0	0.0	100.0	-0.4	-0.1	-0.0	0.1	0.9	-0.1	0.2	-0.2	0.6
Fake factor method non-closure	-8.7	-0.0	-0.0	-0.4	100.0	-13.8	-0.0	-0.0	0.0	-0.0	-0.0	-0.1	0.1
Fake lepton stat. unc. in 1st bin	0.1	0.0	0.0	-0.1	-13.8	100.0	-0.0	0.0	0.0	-0.0	-0.0	-0.0	0.0
τ_{had} reconstruction	-9.2	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	0.0	-0.0	-0.0	-0.0	0.1
τ_{had} identification	-17.2	-0.0	-0.0	0.1	-0.0	0.0	-0.0	100.0	-0.0	-0.0	-0.0	0.0	0.0
Pile up modeling	9.9	0.0	0.0	0.9	0.0	0.0	0.0	-0.0	100.0	-0.0	-0.0	0.1	0.1
Jet energy scale (pile up subtraction)	-12.0	-0.0	-0.0	-0.1	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	0.3
Jet energy scale (flavor composition)	-13.5	-0.0	-0.0	0.2	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	0.0	0.0
Jet energy scale (variation 1)	-10.7	-0.0	-0.0	-0.2	-0.1	-0.0	-0.0	0.0	0.1	-0.0	0.0	100.0	0.2
Jet energy resolution	-9.7	-0.0	-0.0	0.6	0.1	0.0	0.1	0.0	0.1	0.3	0.0	0.2	100.0
	$t\bar{t}H$ signal strength (μ)	$t\bar{t}H$ cross section (QCD scale)	$t\bar{t}H$ cross section (PDF)	$t\bar{t}H$ parton shower	Fake factor method non-closure	Fake lepton stat. unc. in 1st bin	τ_{had} reconstruction	τ_{had} identification	Pile up modeling	Jet energy scale (pile up subtraction)	Jet energy scale (flavor composition)	Jet energy scale (variation 1)	Jet energy resolution

FIGURE 6.6: Observed correlations between the signal strength and the nuisance parameters in the fit to data. Only nuisance parameters with at least one correlation greater than 5% are shown.

The expected performance of the fit is studied using the so-called Asimov dataset built from the sum of the predicted background and the nominal signal. The expected results are given in Table 6.2. The ranking of the nuisance parameters as well as the correlation matrix can be found in Appendix A (Figures A.2, A.3).

6.2.1 Cross-check with cut-based analysis

The multivariate analysis presented above is cross-checked with the cut-based analysis with reduced sensitivity. In order to allow a straightforward comparison of results, the multivariate and cut-based analyses have common components. Both analyses use the same object and event selection, and share the same strategy for the estimation of background contributions and systematic uncertainties. As in the multivariate analysis, the irreducible backgrounds are estimated using the MC simulation samples and the reducible backgrounds using the data-driven methods, as described in Section 5.11. The same statistical methods are used to extract the signal strength μ .

In the cut-based analysis, three categories are defined based on two discriminating variables as described in Section 5.10. These categories target events which are produced via $H \rightarrow \tau^+\tau^-$ or $H \rightarrow WW^*$ decay modes, but select different phase-space regions with different signal-to-background ratios. The event categorization is designed by splitting events according to cuts on maximum $|\eta|$ of the two light leptons and p_T of the subleading jet. The events accepted in each category pass the common selection as described in Table 5.7. The background composition in each category before the fit to the data is shown Figure 6.7. The fake lepton background is dominant in each category. Figure 6.8 shows the $t\bar{t}H$ signal purity for each category before the fit to the data. Category 2 is the most sensitive category, the others are important in terms of contribution to the overall sensitivity of the cut-based analysis.

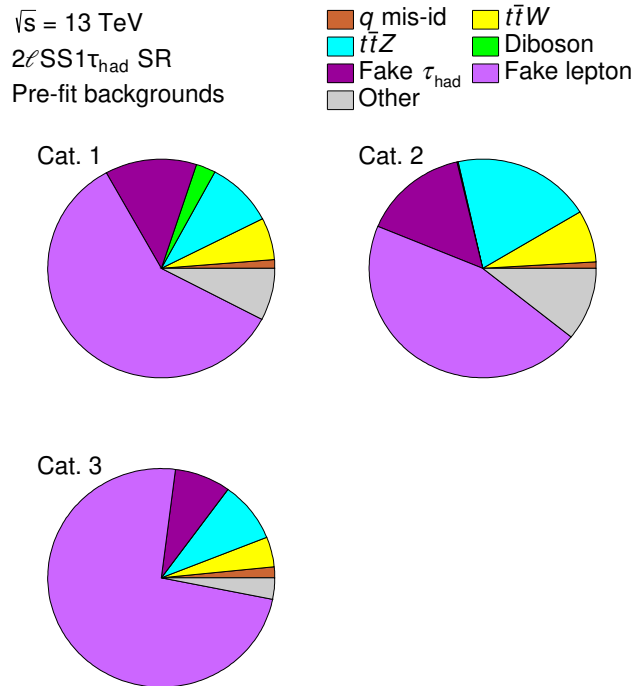


FIGURE 6.7: Fractional contributions of the various backgrounds to the total predicted background in each category before the fit. The background prediction methods are described in Section 5.11. Rare processes tZ , tWZ , $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, $tHjb$, WtH , triboson production and rare top decay are labeled as “Other”.

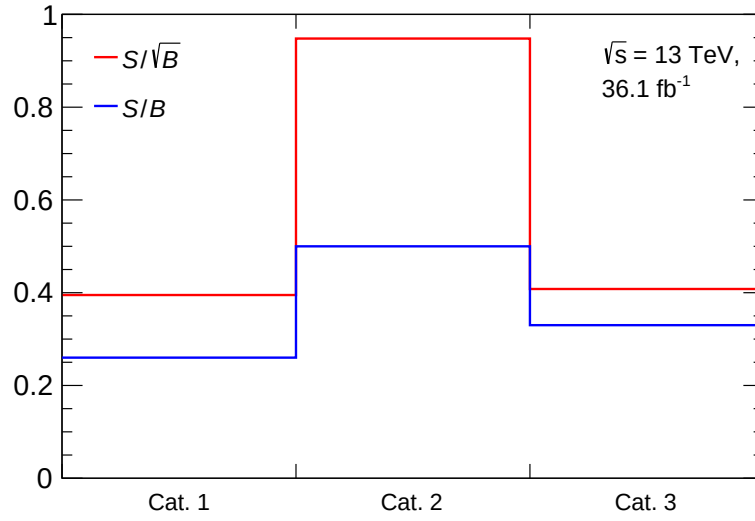


FIGURE 6.8: Pre-fit ratios $S/\sqrt{B}$ (red solid line) and S/B (blue solid line) for each category, where $S(B)$ is the number of selected signal (background) events.

The observed signal strength is determined from a combined fit to data of the three categories. As in the multivariate analysis, the fit uses the profile likelihood approach. Figure 6.9 shows the observed data compared to the event yields after the predictions were adjusted by the fit in each category. The fit results are summarized in Table 6.3. The observed best-fit value of $\mu = 2.75^{+1.71}_{-1.36} = 2.75^{+1.49}_{-1.25}$ (stat.) $^{+0.84}_{-0.54}$ (syst.) is obtained. The statistical uncertainty contributes significantly more than the systematic component to the overall uncertainty. The observed signal strength is found to be statistically compatible with the one from the multivariate analysis. Figure 6.10 shows the ranking of those nuisance parameters contributing most to the uncertainty in the signal strength. The NP with the largest impact on the signal strength is the uncertainty in the fake lepton background estimate due to the fake-factor method non-closure. The second highest-ranked NP is the uncertainty in the $t\bar{t}H$ cross section due to QCD scale variations. Other NPs contributing most are those related to the τ_{had} identification and the jet energy scale. Overall, a good agreement is found between the pre-fit and post-fit values of the nuisance parameters. Figure 6.11 displays the correlations matrix only for parameters which exhibit a correlation larger than 5%. An anti-correlation of about 24% is seen between the $\mu_{t\bar{t}H}$ and NP associated with the non-closure uncertainty, which is the dominant uncertainty in the fake lepton background estimate as discussed in Section 5.12.

TABLE 6.3: Observed and expected best-fit values of the signal strength μ and significances with respect to the null hypothesis for the cut-based analysis.

Best-fit μ	
Observed	$2.75^{+1.49}_{-1.25}$ (stat.) $^{+0.84}_{-0.54}$ (syst.) = $2.75^{+1.71}_{-1.36}$
Expected	$1.00^{+1.21}_{-0.97}$ (stat.) $^{+0.60}_{-0.45}$ (syst.) = $1.00^{+1.35}_{-1.07}$
Significance	
Observed	2.3σ
Expected	0.9σ

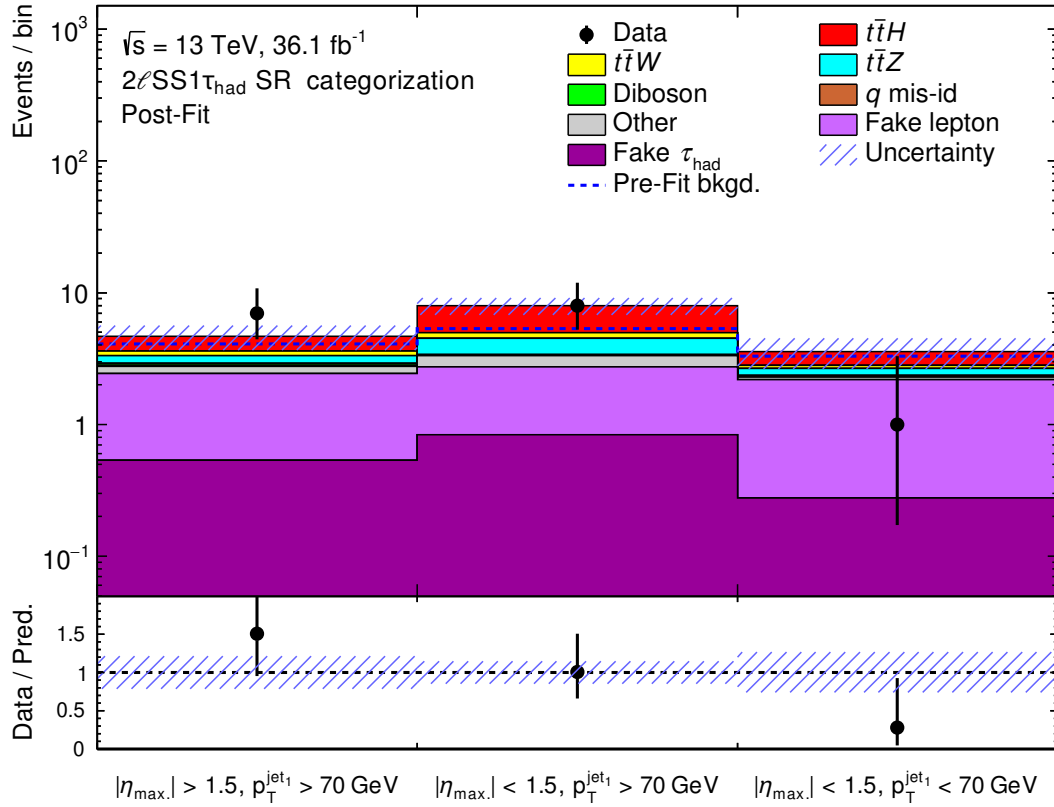


FIGURE 6.9: Comparison of predicted and observed data event yields in each category after the fit to data. The background contributions after the fit are shown as filled histograms. The total background before the fit is shown as a dashed blue histogram. The $t\bar{t}H$ signal contribution is scaled according to the results of the global fit ($\mu_{t\bar{t}H} = 1.6$) and shown as a filled red histogram superimposed on the fitted background. The size of the combined statistical and systematic uncertainty is indicated by the blue hatched band. The bottom panel displays the ratio of the data to the sum of the signal and fitted background.

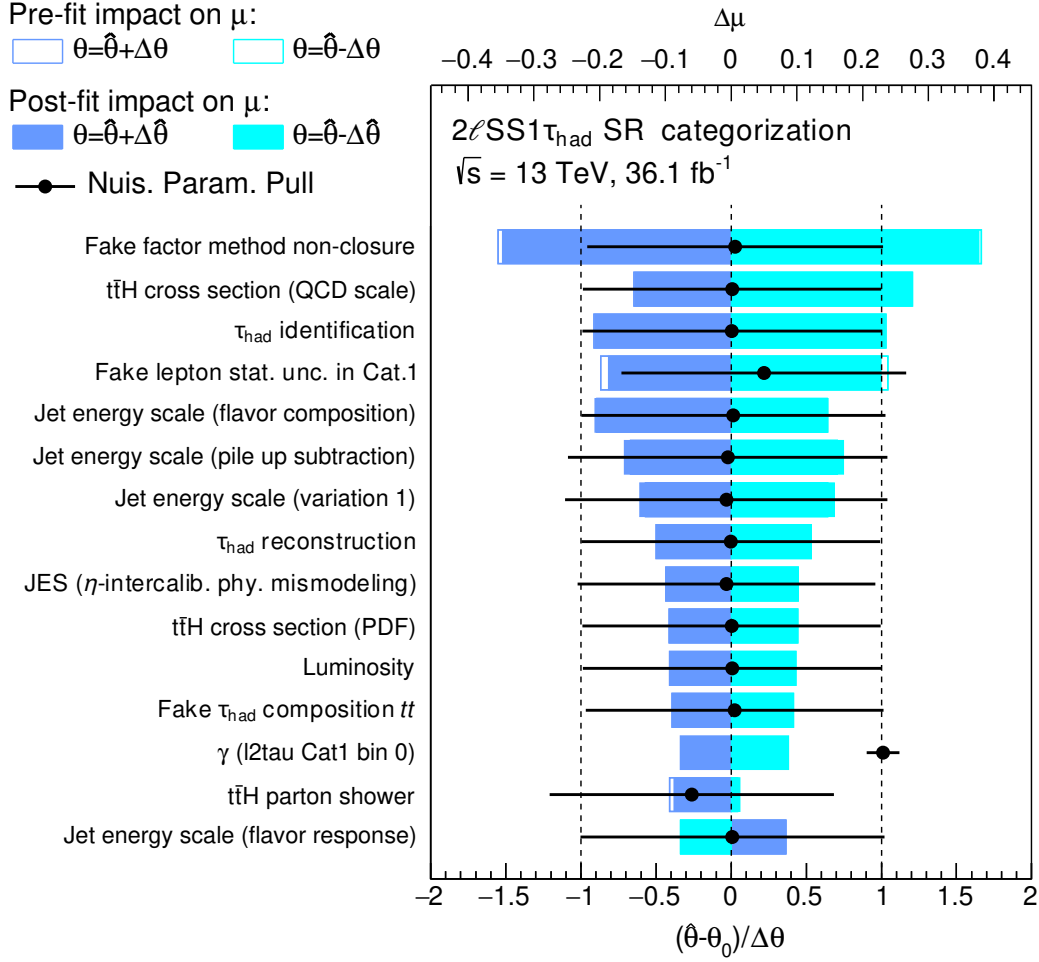


FIGURE 6.10: Ranking of the nuisance parameters with the largest impact on the measured signal strength for the cut-based analysis. Only the 15 most highly ranked parameters are shown. The empty (filled) blue/cyan boxes correspond to the pre-fit (post-fit) impact on μ , referring to the upper x -axis. The impact of each systematic uncertainty, $\Delta\mu$, is calculated by comparing the nominal best-fit value of μ with the result of the fit when fixing the corresponding nuisance parameter θ to its best-fit value $\hat{\theta}$ shifted by its pre-fit (post-fit) uncertainties $\hat{\theta} \pm \Delta\theta$ ($\hat{\theta} \pm \Delta\hat{\theta}$). The black points, which refer to the lower x -axis, show the pulls of the fitted nuisance parameters, i.e., the deviations of the fitted parameters $\hat{\theta}$ from their nominal values θ_0 , normalized to their nominal uncertainties $\Delta\theta$. The black lines show the post-fit uncertainties of the nuisance parameters, relative to their nominal uncertainties, which are indicated by the dashed lines.

$t\bar{t}H$ signal strength (μ)	100.0	-13.5	-6.5	-5.3	-24.4	-6.1	-12.4	-6.4	-7.8	-14.7	-11.4	-12.2	-6.8	-10.1
$t\bar{t}H$ cross section (QCD scale)	-13.5	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0
$t\bar{t}H$ cross section (PDF)	-6.5	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0
$t\bar{t}H$ parton shower	-5.3	-0.0	-0.0	100.0	6.0	-1.0	5.1	0.5	1.1	2.0	2.1	0.9	0.6	1.3
Fake factor method non-closure	-24.4	-0.0	-0.0	6.0	100.0	-0.5	8.5	-0.1	0.1	0.1	0.3	0.1	1.3	0.4
Fake τ_{had} composition $t\bar{t}$	-6.1	-0.0	-0.0	-1.0	-0.5	100.0	-0.4	-0.0	-0.0	-0.1	0.1	0.0	-0.1	0.0
Fake lepton stat. unc. in Cat.1	-12.4	-0.0	-0.0	5.1	8.5	-0.4	100.0	-0.1	0.0	-0.0	0.3	0.2	1.2	0.5
Luminosity	-6.4	-0.0	-0.0	0.5	-0.1	-0.0	-0.1	100.0	0.0	0.0	-0.0	-0.0	0.1	-0.0
τ_{had} reconstruction	-7.8	-0.0	-0.0	1.1	0.1	-0.0	0.0	0.0	100.0	0.1	-0.1	-0.1	0.1	-0.1
τ_{had} identification	-14.7	-0.0	-0.0	2.0	0.1	-0.1	-0.0	0.0	0.1	100.0	-0.1	-0.1	0.2	-0.1
Jet energy scale (pile up subtraction)	-11.4	-0.0	-0.0	2.1	0.3	0.1	0.3	-0.0	-0.1	-0.1	100.0	-0.1	0.3	-0.3
Jet energy scale (flavor composition)	-12.2	-0.0	-0.0	0.9	0.1	0.0	0.2	-0.0	-0.1	-0.1	-0.1	100.0	-0.0	-0.2
JES (η -intercalib. phy. mismodeling)	-6.8	-0.0	-0.0	0.6	1.3	-0.1	1.2	0.1	0.1	0.2	0.3	-0.0	100.0	0.1
Jet energy scale (variation 1)	-10.1	-0.0	-0.0	1.3	0.4	0.0	0.5	-0.0	-0.1	-0.1	-0.3	-0.2	0.1	100.0

FIGURE 6.11: Observed correlations between the signal strength and the nuisance parameters in the fit to data for cut-based analysis. Only nuisance parameters with at least one correlation greater than 5% are shown.

6.3 Results of the $t\bar{t}H$ multilepton analysis

The $t\bar{t}H$ multilepton analysis strategy is described in Section 5.2. The seven channels (including $2\ell\text{SS}1\tau_{\text{had}}$) are defined according to the number of light leptons and τ_{had} candidates. The selection criteria in each channel are designed to ensure orthogonality and summarized in Table 6.4. In order to gain significance, the 4ℓ channel is further divided into two categories; additionally four control regions are used in the 3ℓ channel. Each channel targets different Higgs boson decay modes, and has different signal purity, as shown in Figure 5.4. The $2\ell\text{SS}$, 3ℓ , and $2\ell\text{SS}1\tau_{\text{had}}$ are the most sensitive channels.

In total, twelve categories are defined in the analysis: eight signal regions and four control regions from 3ℓ . Figure 6.12 shows the background composition in each region. The channels have different background compositions which necessitate different strategies for the background estimation. An overview of the background prediction methods can be found in Ref. [21], which also includes the results of the $2\ell\text{SS}1\tau_{\text{had}}$ channel thoroughly described in this thesis.

Multivariate techniques are exploited in most channels to separate the $t\bar{t}H$ signal from the backgrounds, except one of the 4ℓ categories and the $3\ell 1\tau_{\text{had}}$ category. A maximum-likelihood fit is performed on all the twelve categories simultaneously to extract the combined signal strength $\mu_{t\bar{t}H}$. All channels share the same fit model and experimental and theoretical systematic uncertainties, as described previously for the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The combined likelihood function takes into account the product of Poisson probability terms for each region to estimate μ . The effects of the systematic uncertainties are accounted for using NPs. The experimental uncertainties are fully correlated across categories, with the exception of those related to the quark/gluon jet composition and some uncertainties associated with the reducible background determinations, which are specific to the different regions.

A BDT shape is used as a final discriminant in five of the eight signal regions. The 4ℓ Z -enriched category is defined after placing a requirement on a BDT discriminant, whereas the 4ℓ Z -depleted and the $3\ell 1\tau_{\text{had}}$ categories use a single bin because of the low statistics. A single bin is also used in the four control regions from the 3ℓ channel. The total number of bins included in the combined fit is 32 and the details of each category are summarized in Table 6.5.

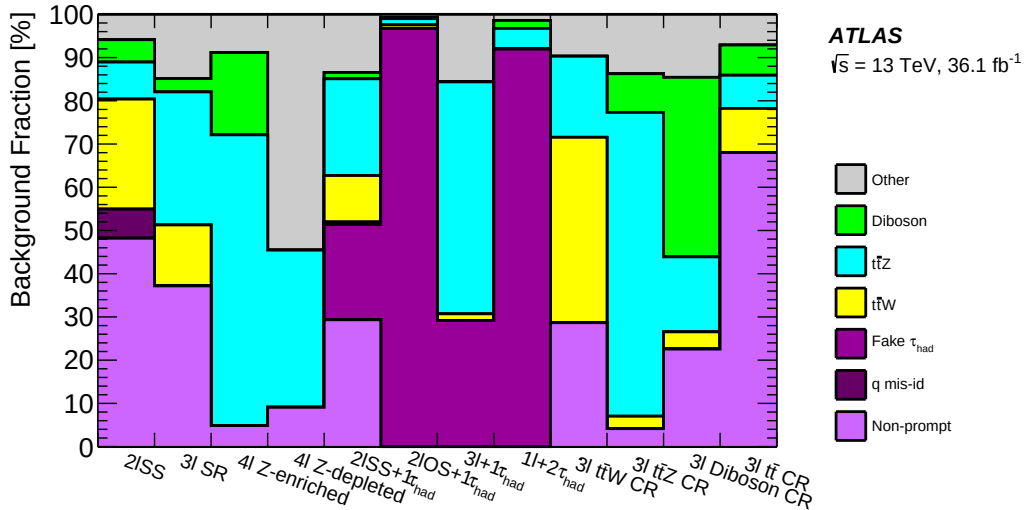


FIGURE 6.12: Fractional contributions of the various backgrounds to the total background prediction in each of the twelve analysis categories. Rare processes tZ , tW , tWZ , $t\bar{t}WW$, triboson production, $t\bar{t}t$, $t\bar{t}t\bar{t}$, $tHj\bar{b}$, WtH , and rare top decay are labeled as “Other” [21].

TABLE 6.4: Selection criteria applied in the different $t\bar{t}H$ multilepton channels. Same-flavor, opposite-charge lepton pairs are referred to as SFOC pairs. The common selection criteria for all channels are listed in the first line under the title “Common” [21].

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two tight light leptons with $p_T > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_T > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be tight and have $p_T > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10$ GeV for all SFOC pairs $ m(3\ell) - 91.2 \text{ GeV} > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10$ GeV for all SFOC pairs $ m(4\ell) - 125 \text{ GeV} > 5$ GeV Split 2 categories: Z -depleted (0 SFOC pairs) and Z -enriched (2 or 4 SFOC pairs)
1ℓ2 τ_{had}	One tight light lepton with $p_T > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2ℓSS1 τ_{had}	Two tight light leptons with $p_T > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $ m(ee) - 91.2 \text{ GeV} > 10$ GeV for ee events
2ℓOS1 τ_{had}	Two loose and isolated light leptons with $p_T > 25, 15$ GeV Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
3ℓ1 τ_{had}	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_T > 10$ GeV The opposite-charge light lepton must be loose and isolated

TABLE 6.5: Summary of the analysis strategies of all channels. In the 4ℓ channel, the two entries correspond to the Z -enriched and the Z -depleted categories. 1D and 5D refer to one- and five-dimensional BDTs respectively [21].

	2ℓSS	3ℓ	4ℓ	1ℓ2 τ_{had}	2ℓSS1 τ_{had}	2ℓOS1 τ_{had}	3ℓ1 τ_{had}
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

Figure 6.13 shows the observed and expected event yields in each region after the fit to the data. The observed best-fit value of μ is:

$$\mu_{t\bar{t}H} = 1.6^{+0.3}_{-0.3} \text{ (stat.) }^{+0.4}_{-0.3} \text{ (syst.)} = 1.6^{+0.5}_{-0.4}. \quad (6.19)$$

The statistical and systematic uncertainties have almost the same contribution to the overall uncertainty. The impact of the most important groups of systematic uncertainties on the measured value of $\mu_{t\bar{t}H}$ is shown in Table 6.6. The uncertainties with the largest impact are those associated with the signal modeling, the jet energy scale and the fake lepton estimate. The signal uncertainty is separated into two components to show the uncertainty due to the acceptance and the one due to the cross section. The uncertainties in the fake lepton estimates, the fake τ_{had} estimates and the charge misidentification have large statistical components due to small data sample size. The large impact of the luminosity uncertainty is due to its effect on both the signal and background predictions.

The best-fit value of μ for each channel and the combination of all channels, and the significance under the SM background-only hypothesis are shown in Figure 6.14 and Table 6.7. The individual channel results are extracted from the full fit but with a separate PoI for each channel. The statistical and systematic uncertainties are of comparable size for the $2\ell\text{SS}$, 3ℓ and $1\ell 2\tau_{\text{had}}$ channels, whereas for the other channels the uncertainties in μ are mainly statistical. An excess of events over the expected SM background is found with an observed (expected) significance of 4.1 (2.8) standard deviations. The excess over the SM signal-plus-background hypothesis has a significance of 1.4 standard deviation, assuming the observed signal is due to the SM Higgs boson. A model-dependent extrapolation is made to the inclusive phase space, and the measured $t\bar{t}H$ production cross section is

$$\sigma_{t\bar{t}H} = 790^{+150}_{-150} \text{ (stat.) }^{+170}_{-150} \text{ (syst.) fb} = 790^{+230}_{-210} \text{ fb}, \quad (6.20)$$

as compared with the SM prediction of $\sigma_{t\bar{t}H}^{\text{SM}} = 507^{+35}_{-50} \text{ fb}$.

An alternative fit where $\mu_{t\bar{t}H}$ is left free to float alongside the $t\bar{t}W$ and $t\bar{t}Z$ cross section modifiers $\mu_{t\bar{t}W}$ and $\mu_{t\bar{t}Z}$ is performed as a cross-check. The latter are encoded in the fit as normalization factors, and the systematic uncertainties in the cross section of $t\bar{t}W$ and $t\bar{t}Z$ are not considered in this fit setup. The observed best-fit value of $\mu_{t\bar{t}H}$ is $1.6^{+0.6}_{-0.5}$, in good agreement with the result obtained from the nominal fit. The expected sensitivity is 15% worse than with the nominal fit. The fitted values for the $t\bar{t}W$ and $t\bar{t}Z$ cross section modifiers are $\mu_{t\bar{t}W} = 0.92 \pm 0.32$ and $\mu_{t\bar{t}Z} = 1.17^{+0.25}_{-0.22}$, respectively, in agreement with the SM predictions.

6.4 Combination with other $t\bar{t}H$ searches

In addition to the results of the $t\bar{t}H$ to multilepton analysis presented in Section 6.3, searches for the $t\bar{t}H$ production have been carried out at $\sqrt{s} = 13 \text{ TeV}$ in three independent analyses, which target different Higgs boson decay modes:

- $H \rightarrow b\bar{b}$, in the lepton+jets and dileptonic $t\bar{t}$ final states [169].
- $H \rightarrow \gamma\gamma$, in lepton+jets/dileptonic and all-hadronic $t\bar{t}$ decay channels [170].
- $H \rightarrow ZZ^* \rightarrow 4\ell$, in a single category including all $t\bar{t}$ decay modes [171].

The overlap between the signal and control regions of the analyses is found to be negligible. All analyses use a proton-proton dataset corresponding to an integrated luminosity of 36.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ and use the same MC event generators for $t\bar{t}H$ production. The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ analyses utilize categories targeting $t\bar{t}H$ production in global analyses of all Higgs boson production modes. In these analyses, the $t\bar{t}H$ signal strength is measured using only the $t\bar{t}H$ -enhanced categories, details are given in Refs. [170, 171]. For the extraction of the $t\bar{t}H$ signal strength, the single top

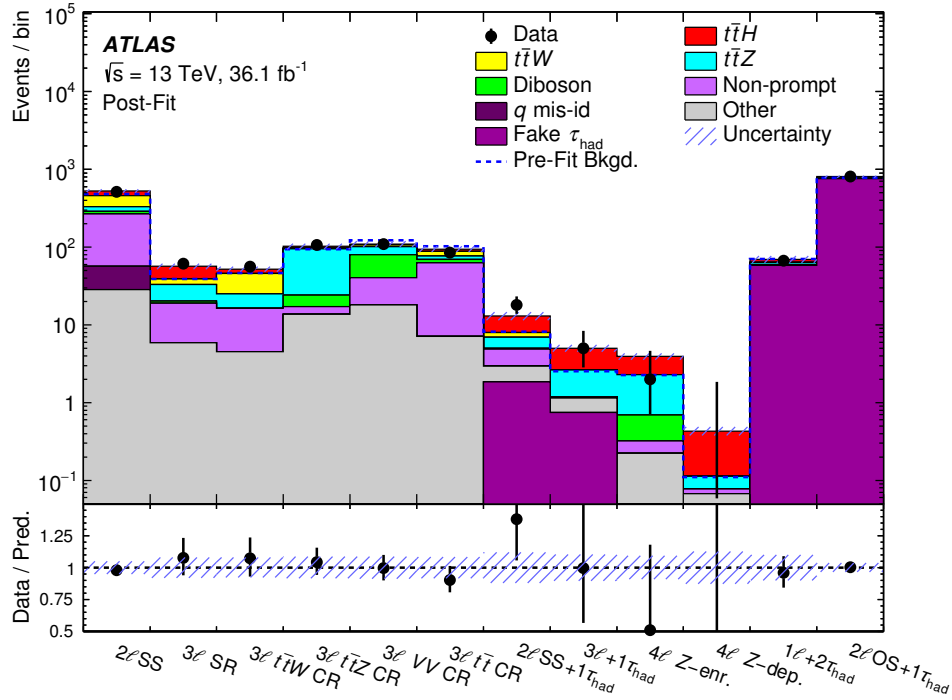


FIGURE 6.13: Comparison of prediction and data in the twelve regions of the analysis after the fit to the data. The background contributions are shown as filled histograms. The total background before the fit is shown as dashed blue histogram. The $t\bar{t}H$ signal is scaled according to the results of the global fit, is shown as a filled red histogram. The blue hatched band represents the size of the combined statistical and systematic uncertainty in the sum of the signal and fitted background. The ratio of data to the sum of the signal and fitted background is shown in the lower panel [21].

TABLE 6.6: Summary of the effects of the most important groups of systematic uncertainties on μ . Owing to rounding effects and small correlations between the different sources of uncertainty, the total systematic uncertainty is different from the sum in quadrature of the individual sources [21].

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	-0.09
Jet energy scale and resolution	+0.18	-0.15
Non-prompt light-lepton estimates	+0.15	-0.13
Jet flavor tagging and τ_{had} identification	+0.11	-0.09
$t\bar{t}W$ modeling	+0.10	-0.09
$t\bar{t}Z$ modeling	+0.08	-0.07
Other background modeling	+0.08	-0.07
Luminosity	+0.08	-0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	-0.04
Fake τ_{had} estimates	+0.07	-0.07
Other experimental uncertainties	+0.05	-0.04
Simulation sample size	+0.04	-0.04
Charge misassignment	+0.01	-0.01
Total systematic uncertainty	+0.39	-0.30

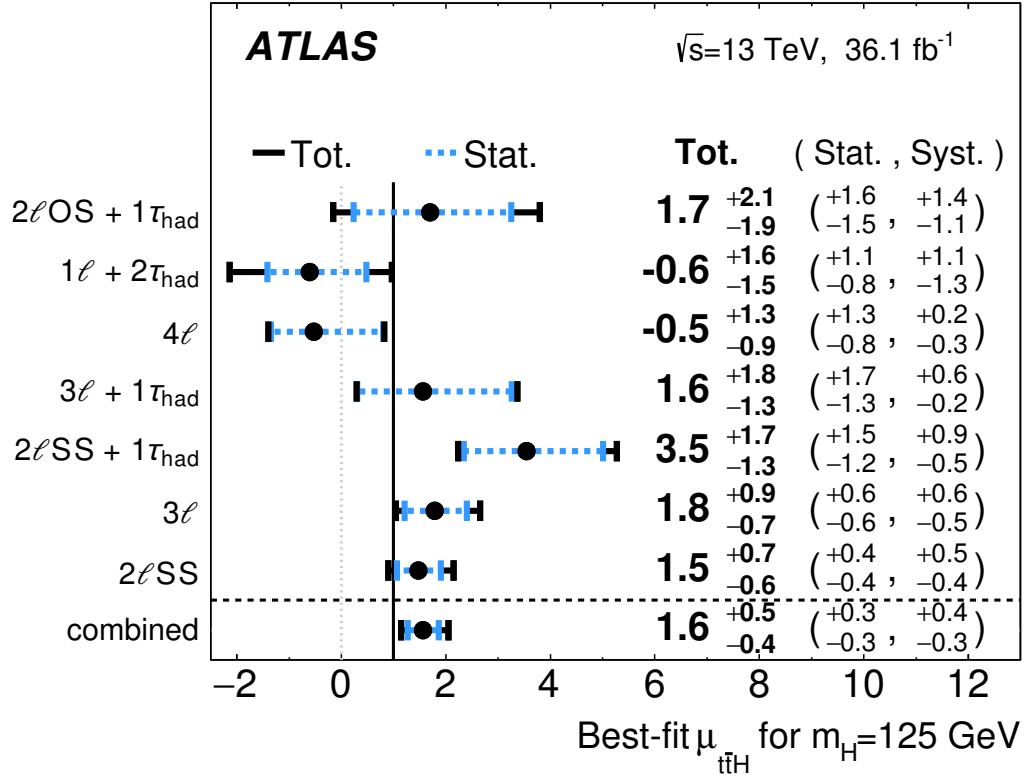


FIGURE 6.14: Observed best-fit values of the $t\bar{t}H$ signal strength $\mu_{t\bar{t}H}$ and their uncertainties by individual channel and combined. The horizontal black solid lines represent the total uncertainties, and the horizontal blue dashed lines represent the statistical uncertainties. The vertical black line at $\mu_{t\bar{t}H} = 1$ indicates the SM prediction. The individual μ values for the channels are obtained from a simultaneous fit with the signal strength parameter for each channel floating independently [21].

TABLE 6.7: Observed and expected best-fit values of the $t\bar{t}H$ signal strength $\mu_{t\bar{t}H}$ and associated significance under the SM background-only hypothesis. The expected values are shown for the pre-fit background estimates. The observed significance is indicated with a – for the channels where μ is negative [21].

Channel	Best-fit μ				Significance	
	Observed		Expected		Observed	Expected
2ℓOS1τ _{had}	1.7 ^{+1.6} _{-1.5} (stat.)	+1.4 (syst.)	1.0 ^{+1.5} _{-1.4} (stat.)	+1.2 (syst.)	0.9σ	0.5σ
1ℓ2τ _{had}	-0.6 ^{+1.1} _{-0.8} (stat.)	+1.1 (syst.)	1.0 ^{+1.1} _{-0.9} (stat.)	+1.2 (syst.)	–	0.6σ
4ℓ	-0.5 ^{+1.3} _{-0.8} (stat.)	+0.2 (syst.)	1.0 ^{+1.7} _{-1.2} (stat.)	+0.4 (syst.)	–	0.8σ
3ℓ1τ _{had}	1.6 ^{+1.7} _{-1.3} (stat.)	+0.6 (syst.)	1.0 ^{+1.5} _{-1.1} (stat.)	+0.4 (syst.)	1.3σ	0.9σ
2ℓSS1τ _{had}	3.5 ^{+1.5} _{-1.2} (stat.)	+0.9 (syst.)	1.0 ^{+1.1} _{-0.8} (stat.)	+0.5 (syst.)	3.4σ	1.1σ
3ℓ	1.8 ^{+0.6} _{-0.6} (stat.)	+0.6 (syst.)	1.0 ^{+0.6} _{-0.5} (stat.)	+0.5 (syst.)	2.4σ	1.5σ
2ℓSS	1.5 ^{+0.4} _{-0.4} (stat.)	+0.5 (syst.)	1.0 ^{+0.4} _{-0.4} (stat.)	+0.4 (syst.)	2.7σ	1.9σ
Combined	1.6 ^{+0.3} _{-0.3} (stat.)	+0.4 (syst.)	1.0 ^{+0.3} _{-0.3} (stat.)	+0.3 (syst.)	4.1σ	2.8σ

quark and Higgs boson associated production processes $tHqb$ and WtH are considered backgrounds and fixed to their SM predictions with the appropriate theoretical uncertainties.

The combined likelihood function is constructed from the product of likelihood functions of the individual analyses. The effect of the systematic uncertainties is incorporated into the fit model through nuisance parameters. The nuisance parameters associated with the same sources of systematic uncertainties are treated as correlated between the different analyses [21].

All theoretical uncertainties associated with the Higgs boson production cross section and decay branching fractions are treated as fully correlated across the different analyses. The cross section and modeling uncertainties for MC-estimated backgrounds are correlated between the $H \rightarrow b\bar{b}$ and the multilepton analyses. The experimental systematic uncertainties such as luminosity, pileup, lepton identification, isolation, and trigger efficiencies are treated as correlated between the analyses. The dominant experimental systematic uncertainties are associated with the jet energy scale, the jet energy resolution, and flavor tagging. The nuisance parameters related to the jet energy scale are correlated between analyses with the exception of the parameters associated to the fraction of jets initiated by quarks and jets, which differs between the analyses due to the different event selections. The jet energy resolution is correlated between all analyses except for the control regions of the $H \rightarrow b\bar{b}$ analysis. The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ analyses use a different calibration for the flavor tagging efficiencies and mistag rates compared to the other analyses. Therefore, flavor tagging uncertainties are correlated between $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ and between $H \rightarrow b\bar{b}$ and multilepton analyses, but are uncorrelated between the two schemes. None of the nuisance parameters in the fit are strongly constrained by more than one analysis, and the value of signal strength obtained from the combined fit does not depend on the choice of the correlation scheme [21].

The best-fit value of the $t\bar{t}H$ signal strength, as extracted from the combined fit, is:

$$\mu_{t\bar{t}H} = 1.17 \pm 0.19 \text{ (stat.) } {}^{+0.27}_{-0.23} \text{ (syst.)}. \quad (6.21)$$

The background-only hypothesis is excluded at 4.2 standard deviations, with an expected significance of 3.8 standard deviations in the case of a SM signal. This result constitutes evidence for the $t\bar{t}H$ production [21]. The results of the individual analyses, as well as the combined results are given in Table 6.8 and Figure 6.15. The cross section for $t\bar{t}H$ production corresponding to the best-fit value of the signal strength is $\sigma_{t\bar{t}H} = 590^{+160}_{-150}$ fb, which is in agreement with the SM prediction of $\sigma_{t\bar{t}H}^{SM} = 507^{+35}_{-50}$ fb.

6.5 Observation of $t\bar{t}H$ production

The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ analyses are updated with the $\sqrt{s} = 13$ TeV data collected in 2017, compared to the results reported in Refs. [21, 170, 171]. These analyses use a dataset corresponding to an integrated luminosity of 79.8 fb^{-1} at $\sqrt{s} = 13$ TeV. The updated analyses are combined with the $H \rightarrow b\bar{b}$ and multilepton analyses as described in Section 6.4. Furthermore, a combination is performed with the results based on 4.5 fb^{-1} and 20.3 fb^{-1} of proton-proton data recorded in 2011 and 2012 at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. A Higgs boson mass corresponding to the measured value of 125 GeV is assumed for the combination. The combination is performed using the profile likelihood method, as described in Section 6.1, based on simultaneous fits to the signal and control regions of the individual analyses. The correlation scheme of the systematic uncertainties between all analyses are the same, as described in Section 6.4. More details can be found in Ref. [22].

Using 13 TeV data, the likelihood fit to extract the $t\bar{t}H$ signal yield in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow b\bar{b}$, and multilepton analyses results in an observed (expected) excess relative to the background-only hypothesis of 5.8 (4.9) standard deviations. A combined fit using the 7, 8, and 13 TeV analyses gives an observed (expected) significance of 6.3 (5.1) standard deviations. This result constitutes a direct observation of the Yukawa coupling between the Higgs boson and the top quark [22].

TABLE 6.8: Summary of observed and expected μ measurements and $t\bar{t}H$ production significance from individual analyses and the combination. As no events are observed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis, a 68% confidence level (CL) upper limit on μ , computed using the CL_s method [172], is reported [21].

Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6^{+0.5}_{-0.4}$	$1.0^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \rightarrow \gamma\gamma$	$0.6^{+0.7}_{-0.6}$	$1.0^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \rightarrow b\bar{b}$	$0.8^{+0.6}_{-0.6}$	$1.0^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \rightarrow ZZ^* \rightarrow 4\ell$	< 1.9	$1.0^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2^{+0.3}_{-0.3}$	$1.0^{+0.3}_{-0.3}$	4.2σ	3.8σ

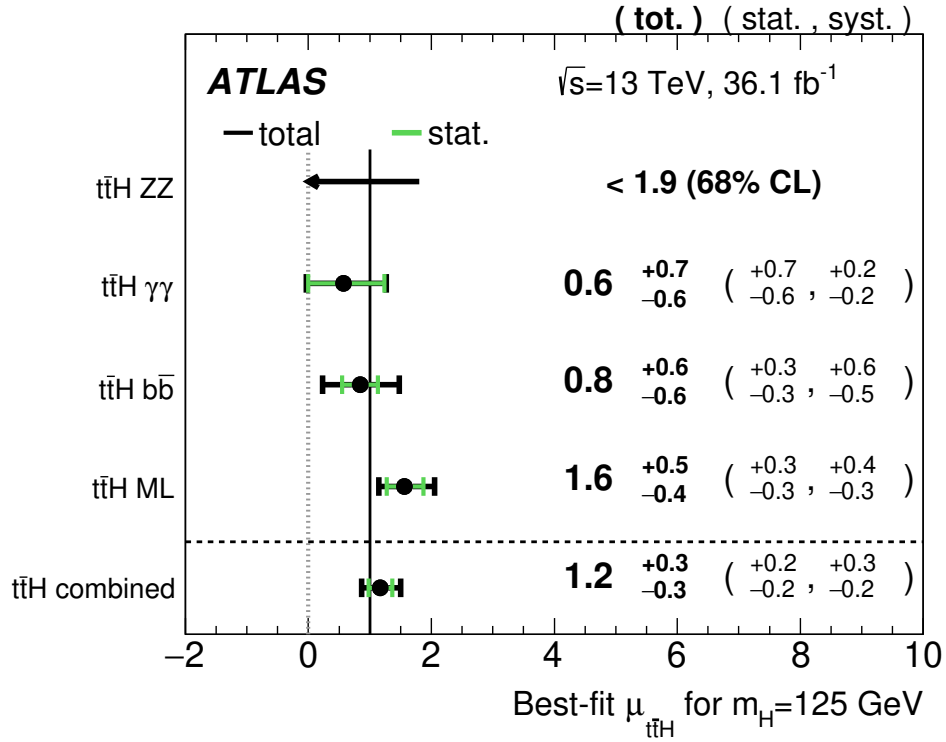


FIGURE 6.15: Summary of the measurements of μ from individual analyses and the combined result. “ML” refers to the multileptonic decay channels as described in Section 6.3. The black lines show the total uncertainties [21].

Based on the analyses performed at 13 TeV, the measured total cross section for $t\bar{t}H$ production is 670 ± 90 (stat.) $^{+110}_{-100}$ (syst.) fb, in agreement with the SM prediction 507^{+35}_{-50} fb. The cross section extracted in the combined fit as well as the results of the individual analyses are shown in Table 6.9, while their ratios to the SM predictions are displayed in Figure 6.16. The measured total cross section for $t\bar{t}H$ production at 8 TeV is 220 ± 100 (stat.) ± 70 (syst.) fb. Figure 6.17 displays the $t\bar{t}H$ production cross sections measured in pp collisions at center-of-mass energies of 8 and 13 TeV, compared to the Standard Model predictions calculated at NLO accuracy (both in QCD and electroweak).

Figure 6.18 shows the data, background and signal yields in all analyses categories as a function of the logarithm of the signal-to-background ratio, $\log_{10}(S/B)$. The discriminant bins in all signal and control regions of the individual analyses are combined into bins of $\log_{10}(S/B)$, where S is the expected signal yield and B the background yield extracted from the fit with freely floating signal. A clear $t\bar{t}H$ signal-like excess over the background is visible for high $\log_{10}(S/B)$.

TABLE 6.9: Measured total $t\bar{t}H$ production cross section at 13 TeV, as well as observed and expected significances relative to the background-only hypothesis. Since no event is observed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ analyses, an observed upper limit is set at 68% confidence level on the $t\bar{t}H$ production cross section using pseudo-experiments [22].

Analysis	Integrated luminosity [fb ⁻¹]	$t\bar{t}H$ cross section [fb]	Significance	
			Observed	Expected
$H \rightarrow \gamma\gamma$	79.8	710^{+210}_{-190} (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
Multilepton	36.1	790^{+150}_{-150} (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	36.1	400^{+150}_{-140} (stat.) $^{+270}_{-270}$ (syst.)	1.4σ	1.6σ
$H \rightarrow ZZ^* \rightarrow 4\ell$	79.8	< 900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1 – 79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1 – 79.8	—	6.3σ	5.1σ

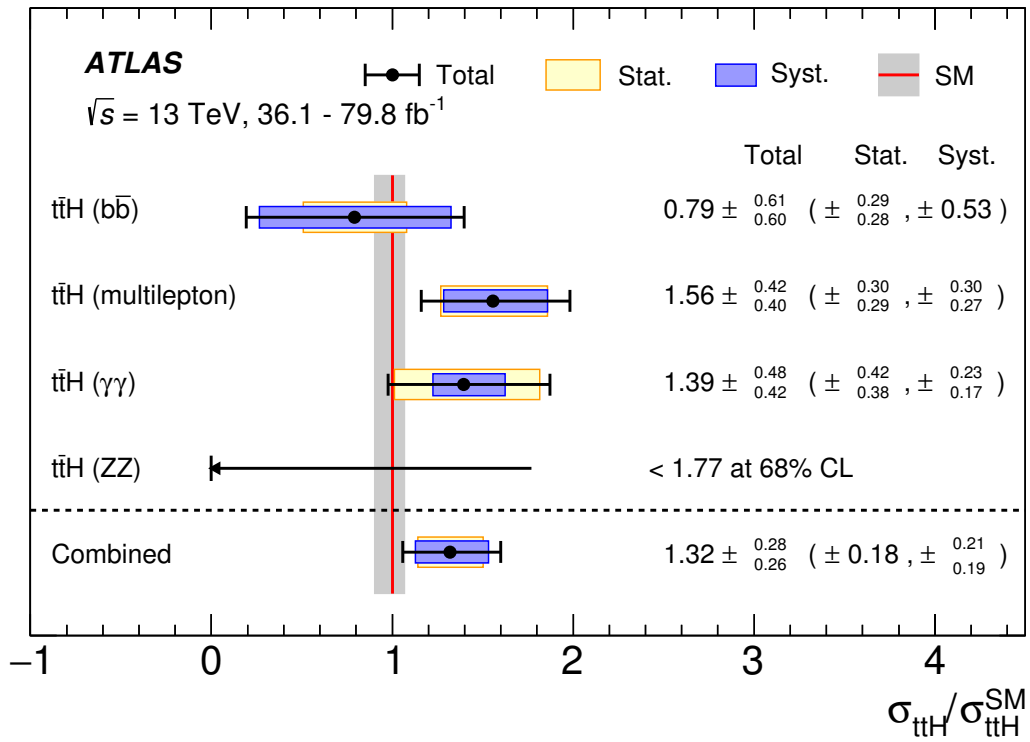


FIGURE 6.16: Summary of the measured signal strengths in the individual analyses, and the combined best-fit measurement. The black lines show the total uncertainties, and the bands indicate the statistical and systematic uncertainties. The red vertical line indicates the SM cross section prediction, and the grey band represents the PDF+ α_S uncertainties and the uncertainties due to missing higher-order corrections [22].

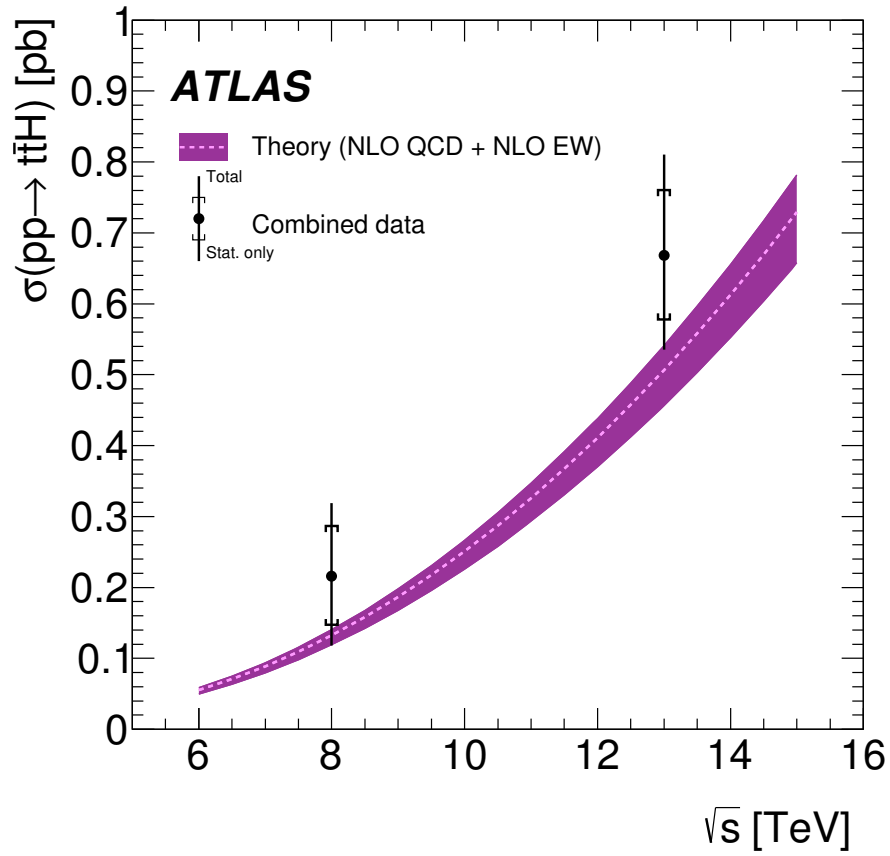


FIGURE 6.17: Measured $t\bar{t}H$ cross sections in pp collisions at center-of-mass energies of 8 and 13 TeV. The total and statistical uncertainties are displayed. The measurements are compared with the SM prediction [130]. The band around the prediction represents the PDF+ α_S uncertainties and the uncertainties due to missing higher-order corrections [22].

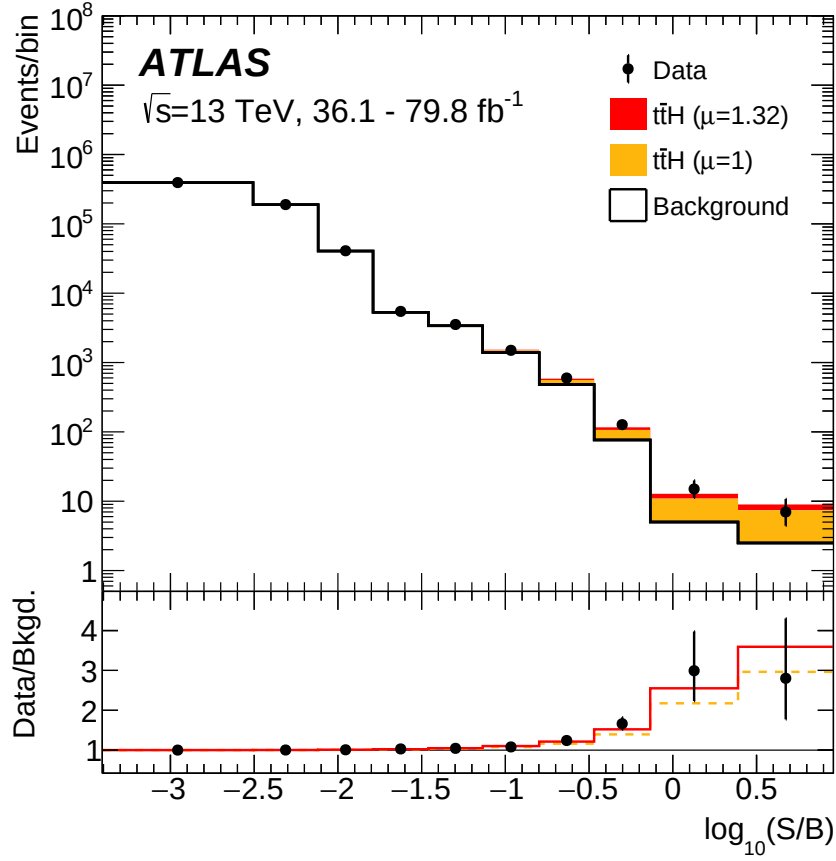


FIGURE 6.18: Event yields as a function of $\log_{10}(S/B)$ for data, background and signal. The background yields correspond to the observed fit results, and the signal yields are shown for both the observed results ($\mu = 1.32$) and the SM prediction ($\mu = 1$). The discriminant bins in all analyses categories are ranked by $\log_{10}(S/B)$. For the $H \rightarrow \gamma\gamma$ analysis, only events in the smallest $m_{\gamma\gamma}$ window containing 90% of the expected signal are considered. The lower panel shows the ratio of the data to the background estimated from the fit with freely floating signal, compared to the expected distribution including the signal assuming $\mu = 1.32$ (solid red) and $\mu = 1$ (dashed orange). The error bars on the data are statistical [22].

Conclusion

A search for the Standard Model Higgs boson produced in association with a top quark pair in multilepton final states has been presented. The search was performed using 36.1 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS experiment in 2015 and 2016. The search targeted the $H \rightarrow WW^*$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow ZZ^*$ decays. Seven final states categorized according to the number and flavor of charged leptons were analyzed. In this thesis, the $t\bar{t}H$ search in the $2\ell\text{SS}1\tau_{\text{had}}$ final state with exactly two light leptons of same-sign electric charges and one hadronically decaying tau lepton has been described. The $2\ell\text{SS}1\tau_{\text{had}}$ channel has a sensitivity of $S/\sqrt{B} = 1.1$, the largest among the other channels with τ_{had} candidates in the $t\bar{t}H$ multilepton analysis, and overall it is the third most significant channel

Various improvements were made to increase the signal sensitivity compared to Run-1 and early Run-2 analyses. A multivariate discriminant was built to reject non-prompt light leptons arising from heavy-flavor hadron decays. The rejection factor obtained for non-prompt light leptons from b -hadron decays was about 20. Another multivariate discriminant was used to reject electrons reconstructed with an incorrect electric charge. The discriminant provided a 95% efficiency for electrons with correct charge reconstruction while achieving a factor of about 17 for rejecting electrons with wrong charge assignment. A logical OR combination of single-lepton and dilepton triggers leads to an 11% increase of the signal acceptance with respect to single-lepton triggers. A boosted decision tree (BDT) exploiting kinematic properties of the event was employed to separate $t\bar{t}H$ signal from backgrounds. The BDT was trained using 13 discriminating variables on the signal and background simulated samples. Only variables that maximize the performance of the BDT were considered. The BDT output was used as the final discriminant in the analysis.

Important irreducible $t\bar{t}Z$ and $t\bar{t}W$ backgrounds were estimated from simulations, and the modeling of these processes was validated in dedicated validation regions. A good agreement between data and prediction was observed in the $t\bar{t}Z$ ($t\bar{t}W$) validation region with 85% (45%) purity. The charge misidentification background contribution was estimated by applying the charge flip probability to the number of events in data passing the signal region selection, except that the light leptons were required to be opposite-charge and no charge requirement for the τ_{had} candidate was applied.

The fake-factor method was used to estimate the normalization and shape of the backgrounds with fake light leptons. The electron and muon fake factors were derived in the sideband control regions as a function of the transverse momentum of the lepton. These fake factors were applied to events in a sideband control region containing anti-tight leptons to determine the fake lepton background in the signal region. The difference in the fraction of fake electrons from photon conversions between control and signal regions were taken into account. The fake-factor method was validated in simulation using a closure test, and by checking the fake lepton background modeling in data in the low jet multiplicity opposite-flavor validation region. Several studies were carried out to check the robustness of the fake-factor method against potential biases. The total uncertainty in the fake lepton background estimate was 55%. The largest source of systematic uncertainty was represented by the statistical uncertainty in the closure test of the method found in simulation. The uncertainty in the fake lepton background was reduced by 28% with respect to the early Run-2 analysis.

Backgrounds containing prompt light leptons and a fake τ_{had} candidate were estimated from simulation. A scale factor of 1.36 ± 0.16 was applied to these backgrounds to correct the simulation of fake τ_{had} candidates coming from quark- or gluon-initiated jets in order to better describe the data.

This scale factor was derived in a $2\ell\text{OS}1\tau_{\text{had}}$ control region, and the uncertainty was determined from statistical uncertainties and differences of background compositions in the control regions.

A maximum-likelihood fit to the observed data was performed to extract the $t\bar{t}H$ signal strength. The observed best-fit value of the $t\bar{t}H$ signal strength was

$$\mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{\text{SM}} = 3.5^{+1.5}_{-1.2} \text{ (stat.) }^{+0.9}_{-0.5} \text{ (syst.)} = 3.5^{+1.7}_{-1.3},$$

which led to an observed (expected) significance of 3.4 (1.1) standard deviations relative to the background-only hypothesis. This result of the multivariate analysis was cross-checked using a cut-based analysis. The observed significance relative to the background-only hypothesis was 2.3 standard deviations. The observed signal strength μ in the cut-based analysis was found to be statistically compatible with the one from the nominal analysis.

The $2\ell\text{SS}1\tau_{\text{had}}$ channel was combined with six other channels of the $t\bar{t}H$ multilepton analysis. A combined fit was performed in all the signal regions of the individual analyses. The observed best-fit value of the $t\bar{t}H$ signal strength was

$$\mu_{t\bar{t}H} = 1.6^{+0.3}_{-0.3} \text{ (stat.) }^{+0.4}_{-0.3} \text{ (syst.)} = 1.6^{+0.5}_{-0.4}.$$

This corresponds to an observed (expected) significance of 4.1 (2.8) standard deviations. The best-fit value for the $t\bar{t}H$ production cross section was

$$\sigma_{t\bar{t}H} = 790^{+150}_{-150} \text{ (stat.) }^{+170}_{-150} \text{ (syst.) fb} = 790^{+230}_{-210} \text{ fb},$$

as compared to the Standard Model prediction of $\sigma_{t\bar{t}H}^{\text{SM}} = 507^{+35}_{-50}$ fb.

The combination of this result with other $t\bar{t}H$ searches from the ATLAS Collaboration using the Higgs boson decays into $\gamma\gamma$, $b\bar{b}$, and $ZZ^* \rightarrow 4\ell$, had the best-fit value of the $t\bar{t}H$ signal strength of $\mu_{t\bar{t}H} = 1.17^{+0.3}_{-0.3}$. The observed significance was 4.2 standard deviations compared to an expectation of 3.8 standard deviations. This constituted evidence for the $t\bar{t}H$ production mode.

The results of the $2\ell\text{SS}1\tau_{\text{had}}$ channel presented in this thesis are statistically limited. Thus, the future analysis of this channel using the full (about four times larger) dataset recorded by the ATLAS experiment during Run-2 of the LHC will significantly improve the results.

The objectives of the thesis were successfully fulfilled.

List of papers

This thesis is based on the following papers, where the author directly contributed.

- I *MPX Detectors as LHC luminosity monitor.*
B. Ali et al., IEEE Trans. Nucl. Sci., **62**, 2015, 3225-3241.
- II *Luminosity from thermal neutron counting with MPX detectors and relation to ATLAS reference luminosity at $\sqrt{s} = 8$ TeV proton-proton collisions.*
B. Ali et al., Journal of Instrumentation, **12**, 2017, P09010.
- III *Performance of the ATLAS trigger system in 2015.*
ATLAS Collaboration, Eur. Phys. J. C **77**, 2017, 317.
- IV *Top associated Higgs boson production channel $t\bar{t}H \rightarrow 2\ell + 1\tau_{\text{had}}$ at $\sqrt{s} = 13$ TeV with the ATLAS experiment.*
B. Ali on behalf of the ATLAS Collaboration, PoS (ICHEP2016), **1137**, 2017.
- V *Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector.*
ATLAS Collaboration, Phys. Rev. D **97**, 2018, 072003.

Author's contribution

The work described in this thesis is carried out by the author within the ATLAS Collaboration. The notable contributions from the author are summarized here.

The author performed the analysis of the MPX data presented in Chapter 3, which led to the publication of Paper I and Paper II. The author used MPX detectors for the luminosity determination from the hit counting and the thermal neutron counting. The author also took part in the comparative study of the MPX hit and thermal neutron luminosity with the ATLAS luminosity measurements by other luminometers (e.g., tile calorimeter).

For the ATLAS authorship qualification, the author performed specific tasks within the ATLAS tau trigger working group. The author worked on the tau trigger monitoring tool for the validation and commissioning of the tau trigger in the 2015 data-taking. In particular, the author contributed in updating the code, and developed and implemented an online tag-and-probe method to monitor the trigger efficiency for real tau candidates, as described in Chapter 4. The performance of the ATLAS tau trigger in Run-2 was presented in Paper III.

Chapters 5 and 6 described the author's main research. All the information provided in these chapters are original work of the author, except where explicitly a reference is given to the work of others. The author was the main responsible person for the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ channel within the ATLAS HTop/Higgs working group.

At first, the author performed the analysis using 13.2 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13\text{ TeV}$ recorded by the ATLAS detector in 2015 and in part of 2016. The results of the analysis were presented by the author on behalf of the ATLAS Collaboration at the International Conference on High Energy Physics in Chicago in 2016. These results were published in Paper IV.

Afterwards, the author performed the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ channel using the full proton-proton dataset collected by the ATLAS experiment during 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb^{-1} , as described in detail in Chapter 5. The results of this analysis are summarized in Chapter 6. These results were published by the ATLAS Collaboration in Paper V. Regarding the analysis of the $2\ell\text{SS}1\tau_{\text{had}}$ channel, the author performed the following main tasks:

- Trigger study to improve the signal acceptance (Section 5.8).
- Optimization of the event selection (Section 5.9).
- A Boosted Decision Tree (Section 5.9) was trained by my colleague Simonetta Gentile, which is used to discriminate the $t\bar{t}H$ signal from background processes. The author contributed regarding the object and event selection, production of input samples, the BDT implementation in the analysis framework, cross-checks of the results, and the documentation for internal communications.
- Cut-based analysis as a cross-check to the BDT analysis (Section 5.10).
- Irreducible background estimation (Section 5.11.1).
- Charge misidentification background estimation (Section 5.11.2).
- Fake lepton background estimation using the fake-factor method. The work on the fake-factor method involved a large part of the analysis. The author carried out several studies which are

described in detail in Section 5.11.2. The author also implemented the fake-factor method in the analysis framework.

- Estimation of backgrounds with a fake τ_{had} candidate. The author measured a scale factor to correct the simulation of fake τ_{had} candidates (Section 5.11.3). This scale factor was also used in other channels with τ_{had} candidates, as described in Paper V.
- Reduction of systematic uncertainties by improving the background estimation techniques (Section 5.12.3).
- Performing the statistical analysis (running a maximum-likelihood fit) in the $2\ell\text{SS}1\tau_{\text{had}}$ channel for both BDT and cut-based analyses to extract the final results (Section 6.2), before entering it into combination with the other channels of the $t\bar{t}H$ multilepton analysis.

The author was responsible for the preparation of input (data and Monte Carlo) samples to the ATLAS HTop (multilepton) working group. The author made major contributions in developing the analysis framework. The analysis framework was used in the HTop (multilepton) working group to produce input samples. These samples were used for the fit to obtain the final results of the Paper V.



The
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Department of Physics & Astronomy

Prof. Dan Tovey,
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26th September 2017

Telephone: +44 (0) 114 222 3546
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Dear Andre,

I write to confirm that Babar Ali of Prague CTU has made a major contribution to ATLAS analysis as well as operations (tau performance and tau trigger). He has made a major contribution to the Run-2 ttH multi-lepton analyses, in particular to the analysis leading to the 2016 ICHEP CONF note (fake estimates with ABCD method for 2ltau; truth studies for 2ltau; matrix method development for 3l and 2ltau channels) and the current analysis nearing publication with the full 2015+2016 ATLAS dataset (group framework developer and common ntuples production; fake estimates with Extended Fake Factor method for 2LSS+0tau, 2L+1tau, and 3L; trigger studies in 2L+1tau).

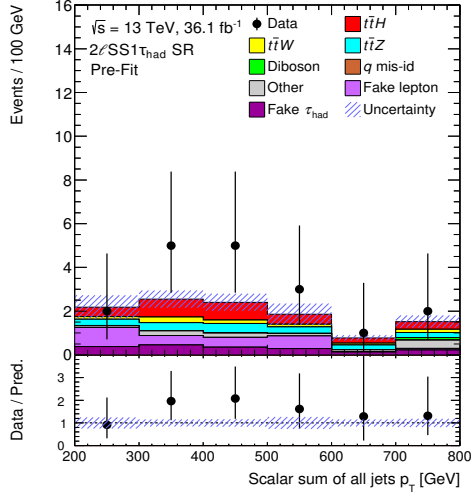
Yours sincerely,

Dan Tovey,
Professor of Particle Physics, University of Sheffield,
ATLAS Physics Coordinator

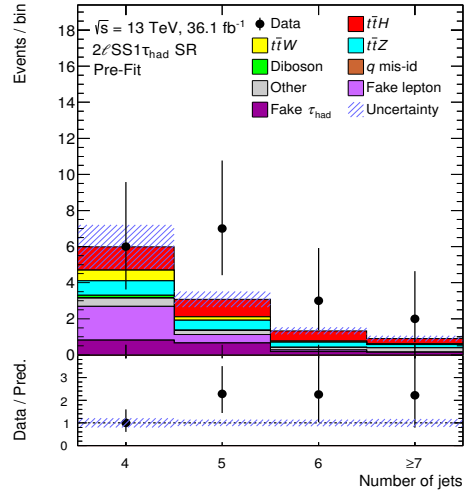
Appendix A

Additional distributions in the $2\ell\text{SS}1\tau_{\text{had}}$ channel

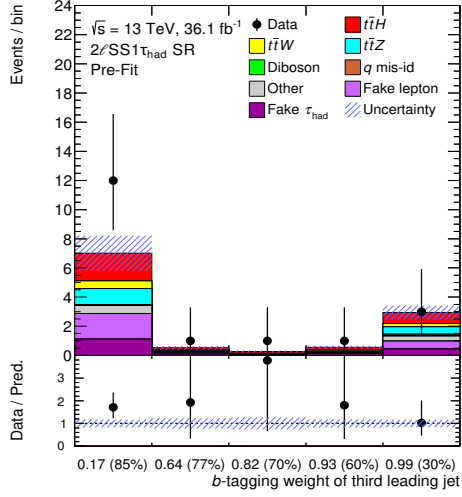
This appendix contains additional distributions in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The pre-fit distributions of the BDT input variables (Section 5.9) are shown in Figure A.1. Figures A.2 and A.3 show the ranking of the nuisance parameters obtained from the fit to the Asimov dataset and the correlations between the nuisance parameters, respectively. The distributions of the event kinematics in the $2\ell\text{SS}1\tau_{\text{had}}$ channel are shown in Figures A.4, A.5, and A.6.



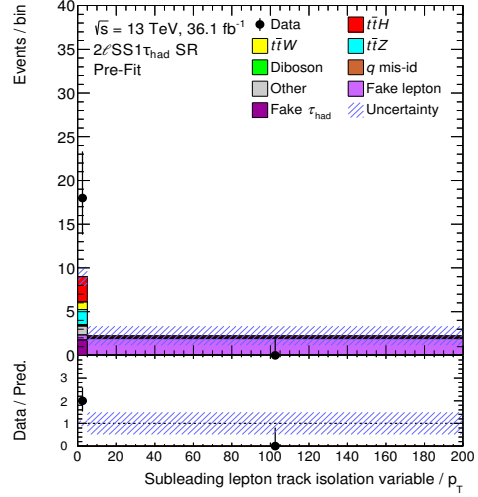
(a)



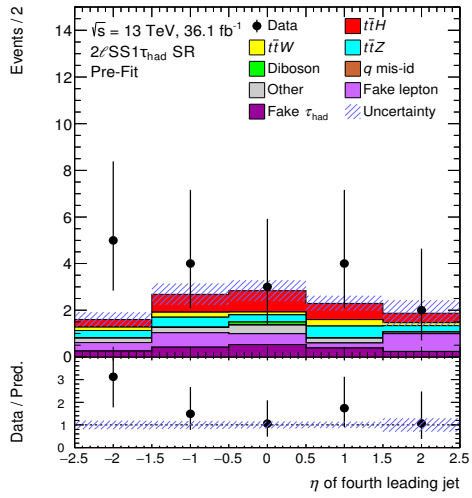
(b)



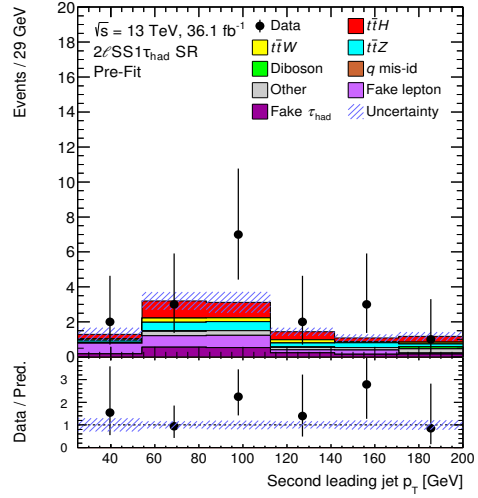
(c)



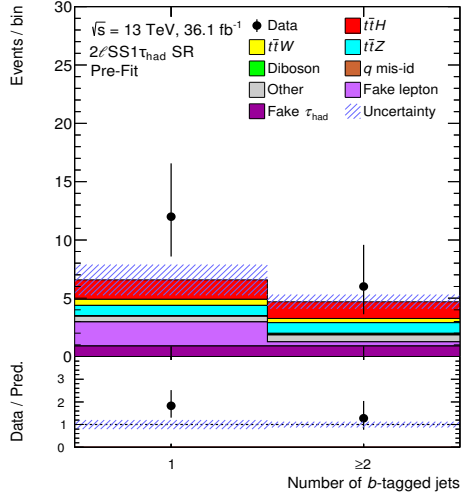
(d)



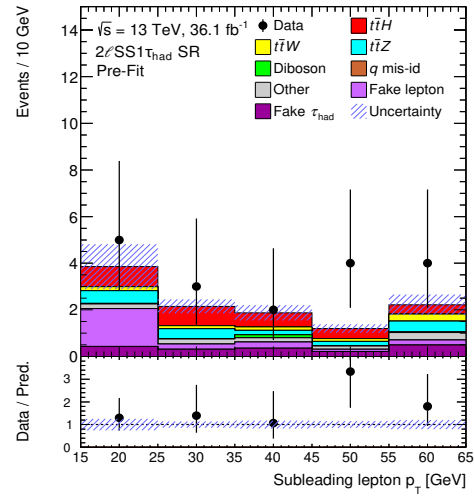
(e)



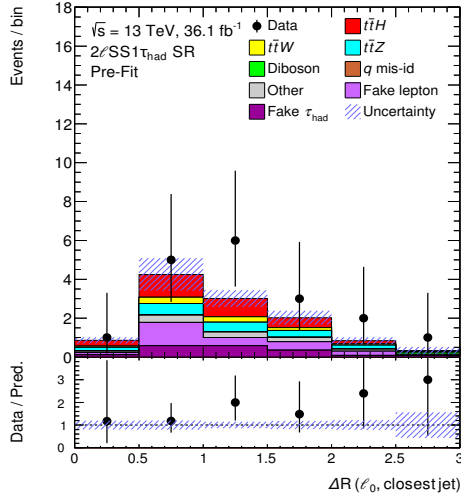
(f)



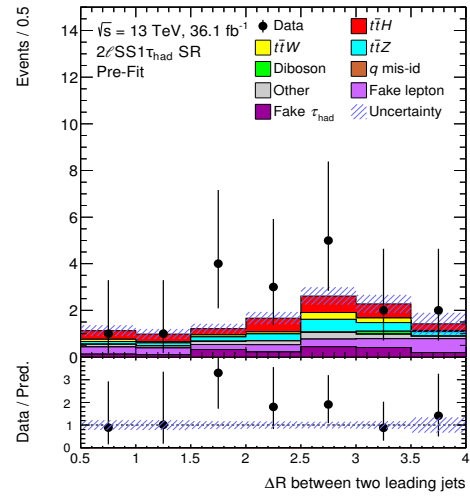
(g)



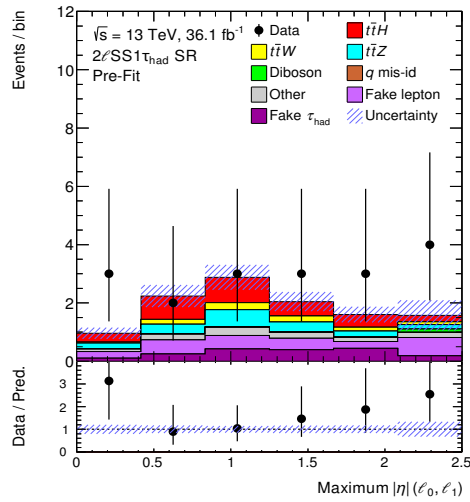
(h)



(i)



(j)



(k)

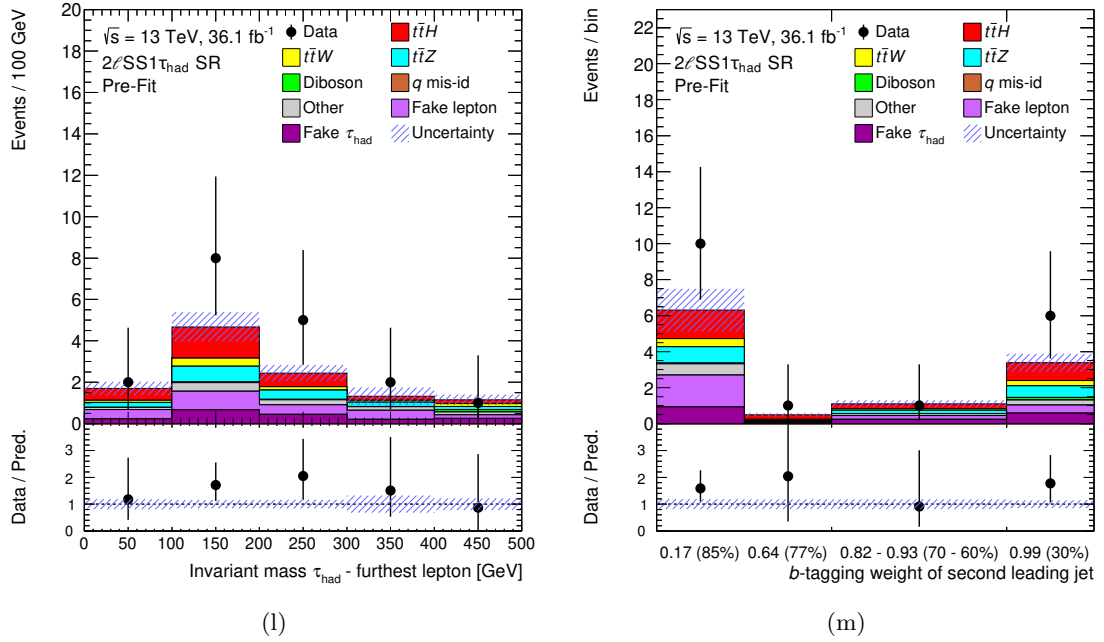


FIGURE A.1: Comparison between data and prediction of the discriminating variables used as input to the BDT in the $2\ell SS1\tau_{had}$ signal region before the fit to the data. The total uncertainty is shown by the blue hatched band. The bottom panel displays the ratio of data to the total prediction. The last bin in each figure contains the overflow.

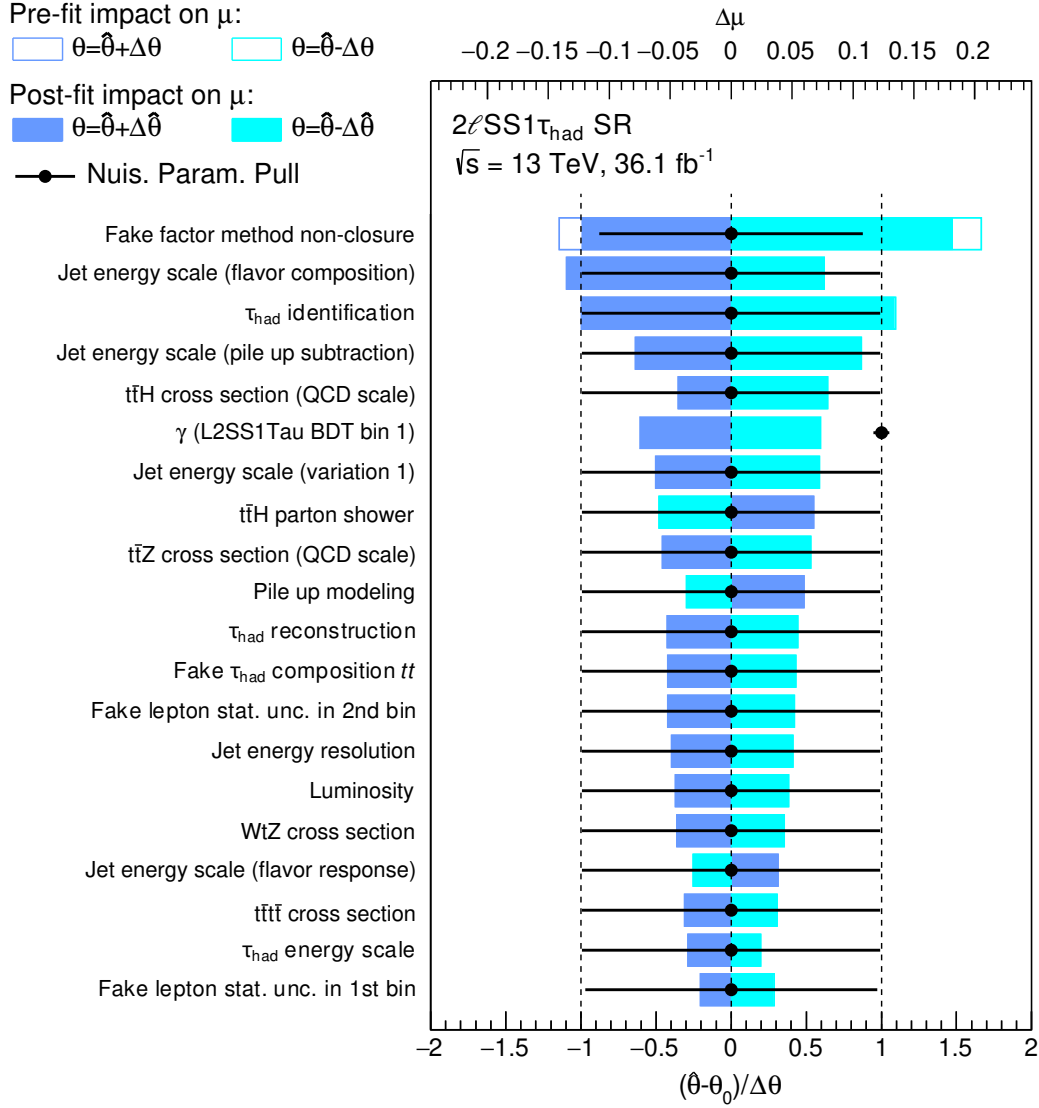


FIGURE A.2: Ranking of the nuisance parameters obtained from the fit to the Asimov dataset, listed according to their impact on the signal strength μ on the y -axis. Only the 20 most highly ranked parameters are shown. The empty (filled) blue/cyan boxes correspond to the pre-fit (post-fit) impact on μ , referring to the upper x -axis. The black points, which refer to the lower x -axis, show the pulls of the fitted nuisance parameters, i.e., the deviations of the fitted parameters $\hat{\theta}$ from their nominal values θ_0 , normalized to their nominal uncertainties $\Delta\theta$.

$t\bar{t}H$ signal strength (μ)	100.0	-7.1	-7.0	7.4	-14.6	-6.1	-1.3	-6.2	-6.3	-11.9	-9.6	-10.9	-7.9	-6.5
$t\bar{t}Z$ cross section (QCD scale)	-7.1	100.0	0.0	0.0	0.6	-0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.0
$t\bar{t}H$ cross section (QCD scale)	-7.0	0.0	100.0	-0.0	-0.0	-0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0	-0.0
$t\bar{t}H$ parton shower	7.4	0.0	-0.0	100.0	-0.4	0.0	-0.1	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0
Fake factor method non-closure	-14.6	0.6	-0.0	-0.4	100.0	0.4	-11.4	-0.3	-0.0	-0.0	-0.1	-0.1	-0.2	0.4
Fake lepton stat. unc. in 2nd bin	-6.1	-0.0	-0.0	0.0	0.4	100.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.0
Fake lepton stat. unc. in 1st bin	-1.3	0.2	0.0	-0.1	-11.4	0.2	100.0	-0.1	-0.0	-0.0	-0.0	-0.0	-0.1	0.2
Fake τ_{had} composition $t\bar{t}$	-6.2	0.0	0.0	-0.0	-0.3	0.0	-0.1	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0
τ_{had} reconstruction	-6.3	0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0
τ_{had} identification	-11.9	0.0	0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0
Jet energy scale (pile up subtraction)	-9.6	0.0	0.0	-0.0	-0.1	0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	0.0
Jet energy scale (flavor composition)	-10.9	0.0	0.0	-0.0	-0.1	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	0.0
Jet energy scale (variation 1)	-7.9	0.0	-0.0	-0.0	-0.2	0.0	-0.1	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	0.0
Jet energy resolution	-6.5	-0.0	-0.0	0.0	0.4	-0.0	0.2	0.0	-0.0	-0.0	0.0	0.0	0.0	100.0
	$t\bar{t}H$ signal strength (μ)	$t\bar{t}Z$ cross section (QCD scale)	$t\bar{t}H$ cross section (QCD scale)	$t\bar{t}H$ parton shower	Fake factor method non-closure	Fake lepton stat. unc. in 2nd bin	Fake lepton stat. unc. in 1st bin	Fake τ_{had} composition $t\bar{t}$	τ_{had} reconstruction	τ_{had} identification	Jet energy scale (pile up subtraction)	Jet energy scale (flavor composition)	Jet energy scale (variation 1)	Jet energy resolution

FIGURE A.3: Correlations between the signal strength and the nuisance parameters in the fit to the Asimov dataset. Only nuisance parameters with at least one correlation greater than 5% are shown.

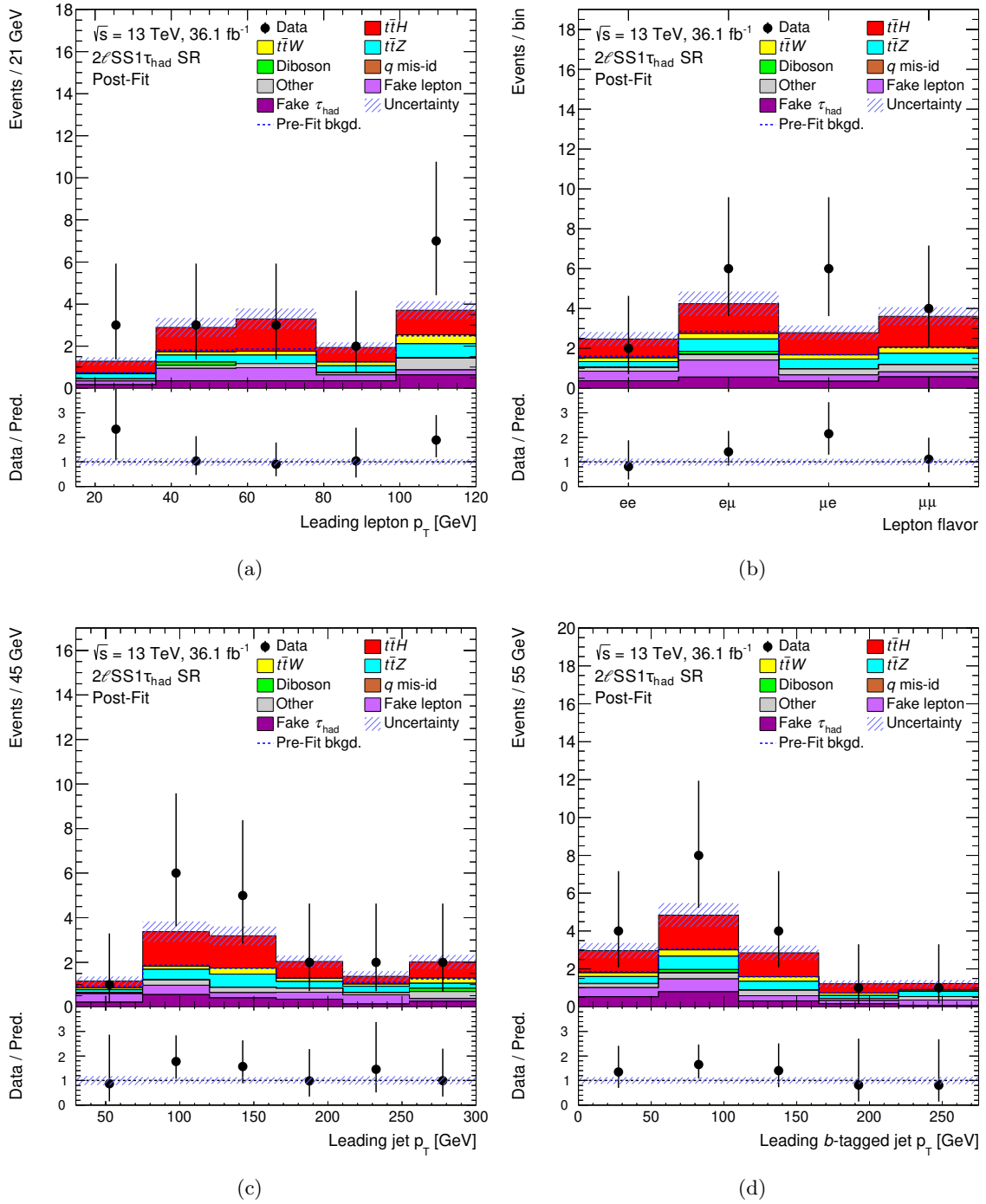


FIGURE A.4: Comparison of data and prediction after the fit to the observed data for (a) the leading lepton p_T , (b) the lepton flavor composition, (c) the leading jet p_T , and (d) the leading b -tagged jet p_T in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The bottom panel displays the ratio of data to the total prediction. The last bin in all figures contains the overflow. The hatched band represents both the statistical and systematic uncertainties. The $t\bar{t}H$ signal yield is normalized to the fitted values ($\mu_{t\bar{t}H} = 1.6$).

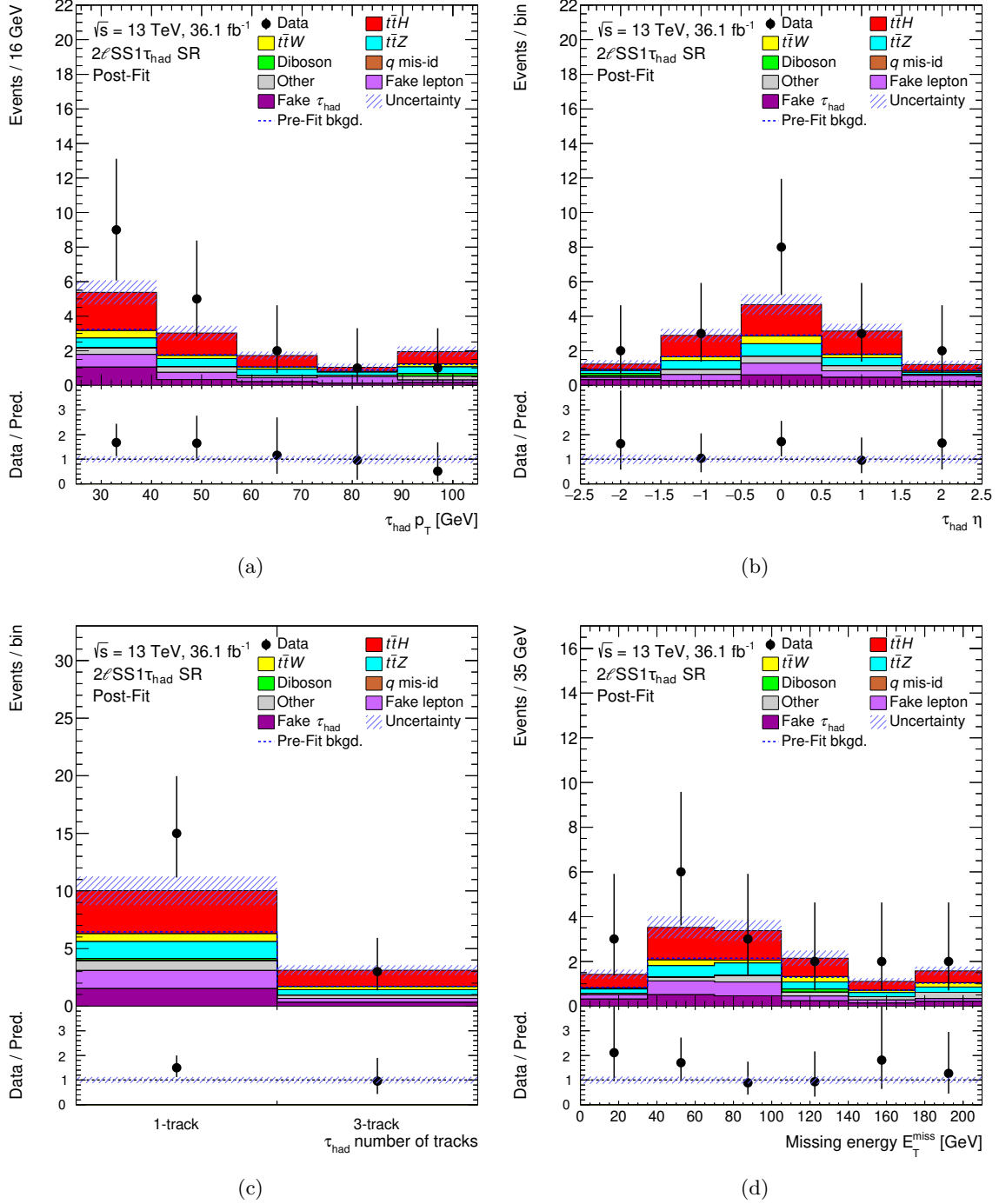


FIGURE A.5: Comparison of data and prediction after the fit to the observed data for (a) the p_T , (b) η , and (c) the number of tracks of the hadronically decaying tau lepton respectively, and (d) the missing energy in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The bottom panel displays the ratio of data to the total prediction. The last bin in all figures contains the overflow. The hatched band represents both the statistical and systematic uncertainties.

The $t\bar{t}H$ signal yield is normalized to the fitted values ($\mu_{t\bar{t}H} = 1.6$).

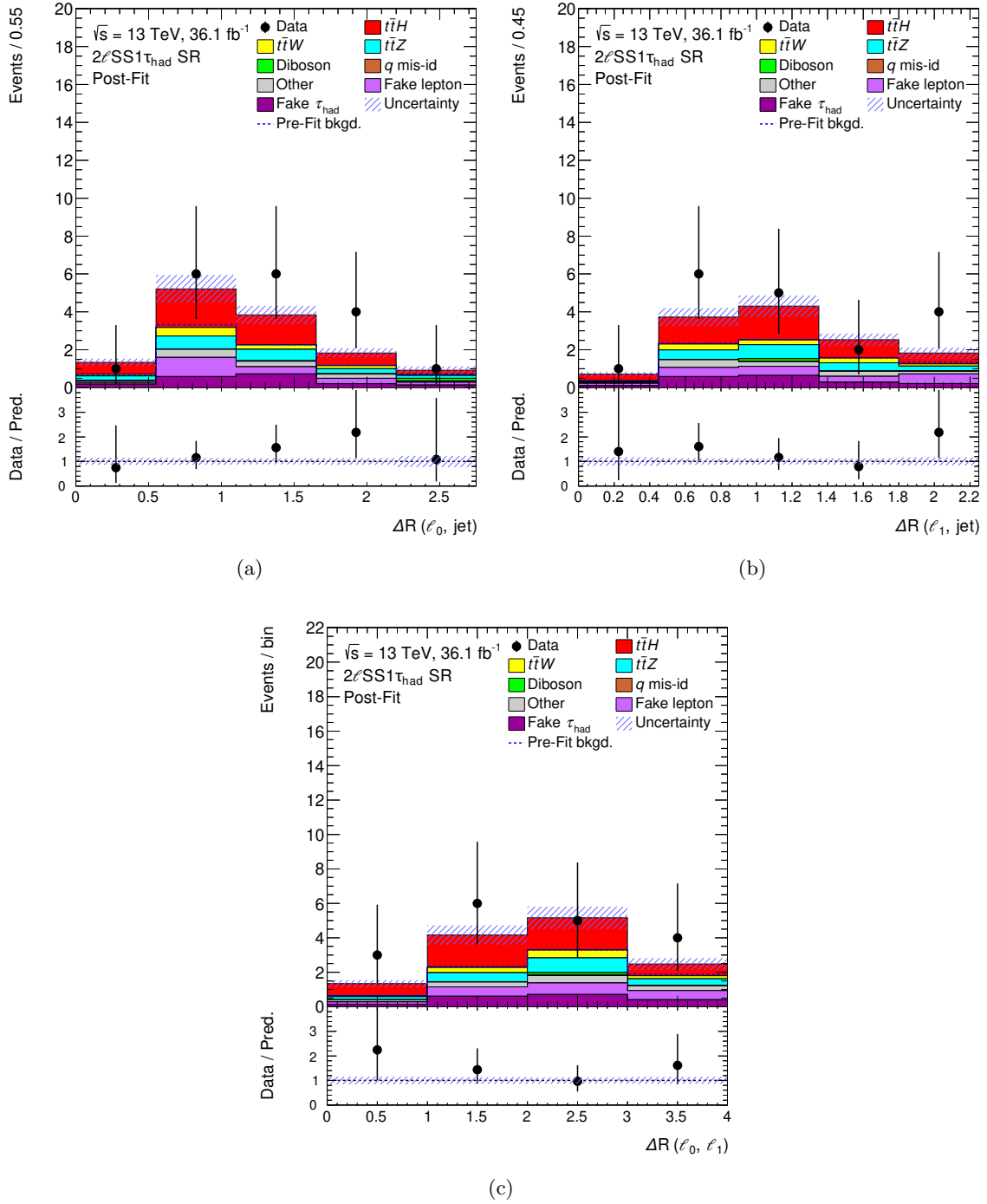


FIGURE A.6: Comparison of data and prediction after the fit to the observed data for (a) the angular distance between the leading lepton and jet, (b) the the angular distance between the subleading lepton and jet, and (c) the angular distance between the leading and subleading leptons in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The bottom panel displays the ratio of data to the total prediction. The last bin in all figures contains the overflow. The hatched band represents both the statistical and systematic uncertainties. The $t\bar{t}H$ signal yield is normalized to the fitted values ($\mu_{t\bar{t}H} = 1.6$).

Appendix B

Event display

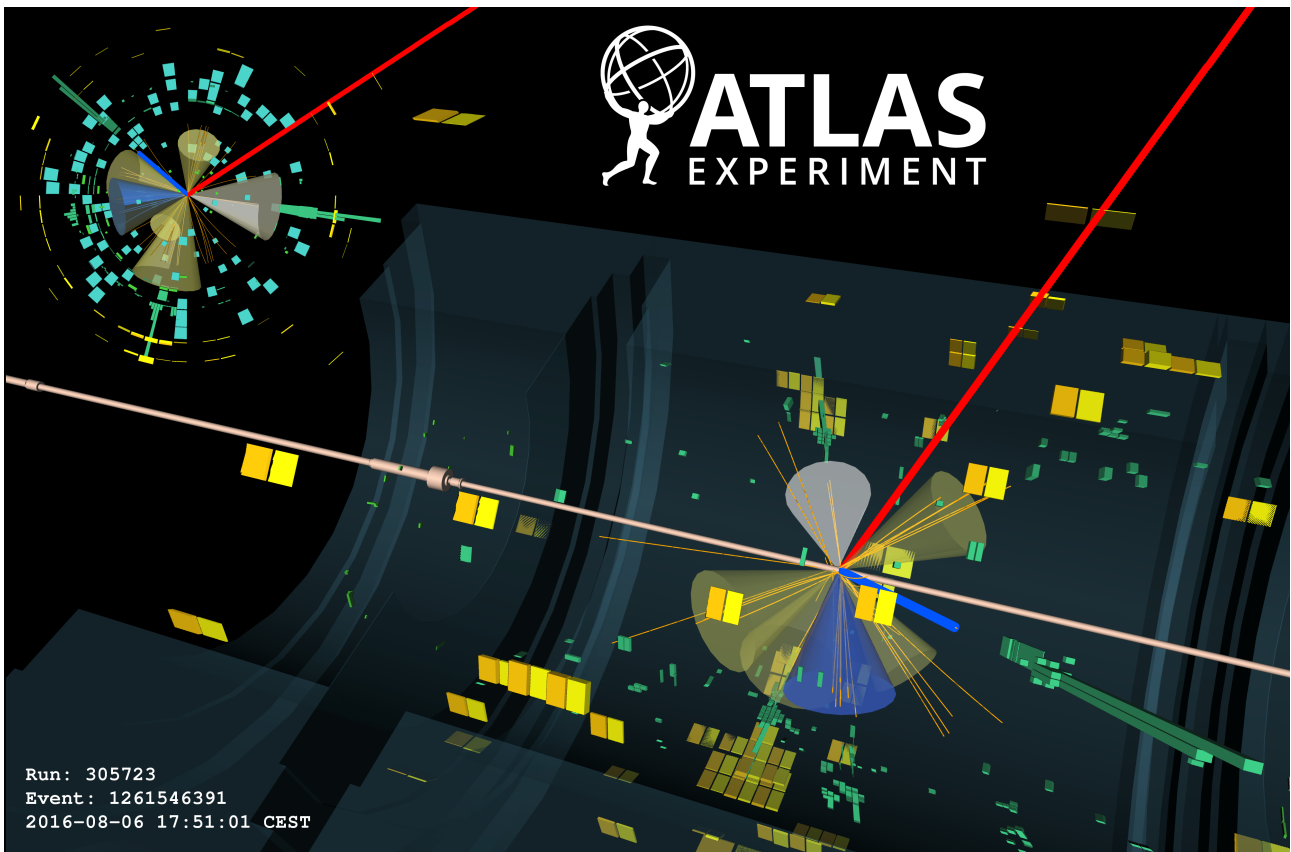


FIGURE B.1: Event display for a $t\bar{t}H$ candidate $e\mu\tau_{\text{had}}$ event in the $2\ell\text{SS}1\tau_{\text{had}}$ channel. The blue track is the selected electron; the red track is the selected muon; and the grey cone is the τ_{had} candidate. The azure cone is the selected b -tagged jet, and the four yellow cones are the non- b -tagged jets. Green and yellow bars indicate energy deposits in the electromagnetic (liquid argon) and hadronic (tile) calorimeters, respectively. The transverse momenta of the leptons are $p_{\text{T}}(e^-) = 68$ GeV, $p_{\text{T}}(\mu^-) = 72$ GeV, and $p_{\text{T}}(\tau^+) = 103$ GeV. The transverse momenta of the jets are $p_{\text{T}}(b\text{-jet}) = 83$ GeV, $p_{\text{T}}(\text{non-}b\text{-jet}) = 125, 37, 37, 29$ GeV [158].

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